3rd IFQMS

The 3rd International Forum
on Quantum Metrology and Sensing

PROCEEDINGS

December 16th - 18th, 2020

Online Conference (Zoom)

The 3rd International Forum on Quantum Metrology and Sensing (3rd IFQMS)

Foreword

On behalf of the organizing committee, it is my great pleasure to extend a warm welcome to all participants of the 3rd International Forum on Quantum Metrology and Sensing (3rd IFQMS) held in December 2020. In consideration of COVID-19, the 3rd IFQMS takes place as an online conference for ensuring the safety and health of all the participants.

The field of quantum metrology and sensing technology is one of the three research areas in the Q-LEAP program of the MEXT, which was launched in 2018 as a long-term research initiative aimed at bringing about disruptive innovation in society via quantum technologies. In this area, the Quantum Solid-State Sensing Flagship project and seven Basic Research projects started and have already achieved several excellent results toward various applications of the quantum technologies such as magnetoencephalography, automotive battery diagnostics, infrared spectroscopic analysis, and seismic measurement. Furthermore, a new Flagship project, the Quantum Life Flagship project, was launched this year. The main objectives of this Flagship project are to create new quantum life technologies and to innovate in medicine and life sciences.

The past two IFQMSs have mainly focused on promoting international cooperation and strengthening the activities of young researchers for future innovations in science, industry and society. The 3rd IFQMS will emphasize the mutual understanding between ongoing projects and the newly initiated Flagship project on quantum life science.

The 3rd IFQMS brings together more than 220 participants to discuss recent advances in quantum metrology and sensing technology. This forum features two opening talks by the two flagship project leaders and eight invited lectures given by the overseas leading researchers. The general sessions consist of eight oral presentations and fifty short presentations. The short presentations are divided into eight groups, and each group has several presentations by young researchers and free discussion together with overseas and domestic mentors.

We hope all participants, especially young researchers and students, will deepen their understanding of the cutting-edge quantum technologies through fascinating presentations. We wish you enjoy this forum in an attractive virtual conference format.

December, 2020

Chairperson, the 3rd IFQMS

Yasuhiko Arakawa
Program Director
Professor, The University of Tokyo

Outlines

Date

December 16th – 18th, 2020
Japan (JST): 17:00pm (16th) – 12:00am (18th)
France (CET): 9:00am (16th) – 4:00am (18th)
U.S.A. (EST): 3:00am (16th) – 22:00pm (17th)
U.S.A. (PST): 0:00am (16th) – 19:00pm (17th)

Language

English

Organized by

The Ministry of Education, Culture, Sports, Science and Technology (MEXT)

Chairperson

Yasuhiko Arakawa The University of Tokyo

Program Committee

Keigo Arai	Toyko Institute of Technology
Ryuji Igarashi	National Institutes for Quantum and Radiological Science and Technology
Takayuki Iwasaki	Toyko Institute of Technology
Norikazu Mizuochi	Kyoto University
Takeshi Ohshima	National Institutes for Quantum and Radiological Science and Technology
Sigeki Takeuchi	Kyoto University

(in alphabetical order)

[Secretary]

Tadashi Sakai	Toyko Institute of Technology

Program on Wednesday December 16th, 2020

Start (JST)

17:00 - 17:05 (0:05)	**Opening Remarks**	Yasuhiko Arakawa	Program Director of the MEXT Q-LEAP The University of Tokyo	-
		[Chair] Hidemi Ishiuchi (Sub Program Director of the MEXT Q-LEAP)		
17:05 - 17:10 (0:05)		Susumu Kajiwara	Deputy Director-General, Science and Technology Policy Bureau, Ministry of Education, Culture, Sports, Science and Technology (MEXT)	-
		[Chair] Hidemi Ishiuchi (Sub Program Director of the MEXT Q-LEAP)		
17:10 - 17:35 (0:25)	**Opening Talks**	Mutsuko Hatano	Tokyo Institute of Technology National Institutes for Quantum and Radiological Science and Technology	MEXT Quantum Leap Flagship Program (MEXT Q-LEAP) on Development of Innovative Sensor Systems by Highly Sophisticated Control of Solid Quantum Sensors
		[Chair] Yasuhiko Arakawa (Program Director of the MEXT Q-LEAP, The University of Tokyo)		
17:35 - 18:00 (0:25)		Yoshinobu Baba	National Institutes for Quantum and Radiological Science and Technology Nagoya University	MEXT Quantum Leap Flagship Program (MEXT Q-LEAP) on Innovations in Medicine and Life Sciences through Development of Quantum Life Technology
		[Chair] Yasuhiko Arakawa (Program Director of the MEXT Q-LEAP, The University of Tokyo)		
18:00 - 18:30 (0:30)	**Session 1-1 Invited Lectures**	Fedor Jelezko	Ulm University, Germany	Quantum Sensing with Diamond Spin Qubits
		[Chair] Mutsuko Hatano (Tokyo Institute of Technology)		
18:30 - 19:00 (0:30)		Johnjoe McFadden	The University of Surrey, UK	Does Life Need Quantum Mechanics?
		[Chair] Yoshinobu Baba (National Institutes for Quantum and Radiological Science and Technology, Nagoya University)		
19:00 - 19:20 (0:20)	break			
19:20 - 19:50 (0:30)	**Session 1-2 Invited Lectures**	Peter J. Hore	University of Oxford, UK	Avian Magnetoreception: Using Biochemistry to Sense Weak Magnetic Fields
		[Chair] Kiminori Maeda (Saitama University)		
19:50 - 20:20 (0:30)		Ulrik Lund Andersen	Technical University of Denmark (DTU), Denmark	Enhancing Stimulated Raman Scattering with Nonclassical Light
		[Chair] Shigeki Takeuchi (Kyoto University)		
20:20 - 20:50 (0:30)		Frank Schlawin	The Hamburg Centre for Ultrafast Imaging Max-Planck Institute for the Structure and Dynamics of Matter, Germany	Nonlinear Spectroscopy with Entangled Photons
		[Chair] Akihito Ishizaki (National Institites of Natural Sciences)		

Program on Thursday December 17th, 2020

Start (JST) End (JST)

9:00 - 9:30 (0:30)	**Session 2 Invited Lectures**	Ronald Walsworth	University of Maryland, U.S.A.	Quantum Diamond Sensors
		[Chair] Mutsuko Hatano (Tokyo Institute of Technology)		
9:30 - 10:00 (0:30)		David Simpson	The University of Melbourne, Australia	Diamond Based Quantum Sensors for Bio-sensing and Imaging
		[Chair] Mutsuko Hatano (Tokyo Institute of Technology)		
10:00 - 10:30 (0:30)		Luke P. Lee	Harvard University, U.S.A. Sungkyunkwan University, Korea	Ultrafast Quantum Plasmonic PCR for Rapid Detection of COVID-19
		[Chair] Yoshie Harada (Osaka University)		
10:30 - 10:45 (0:15)	break			
10:45 - 11:10 (0:25)	**Session 3 Oral Presentations**	Norikazu Mizuochi	Kyoto Univerisity	Quantum Sensing Techniques and Extension of Spin Coherence Times of NV Centers Toward Higher Sensitivity
11:10 - 11:35 (0:25)		Hirotaka Sugiyama	Yazaki Corporation	Development of Diamond Quantum Sensor for Automobile Battery Monitor
11:35 - 12:00 (0:25)		Susumu Takahashi	University of Southern California, U.S.A	NV-Detected Electron Spin Resonance Spectroscopy at High Magnetic Field
12:00 - 12:25 (0:25)		Jean-Philippe Tetienne	The University of Melbourne, Australia	Applications of Quantum Diamond Microscopy in Condensed Matter Physics
		[Session chairs] Takayuki Iwasaki (Tokyo Institute of Technology) Takeshi Ohshima (National Institutes for Quantum and Radiological Science and Technology (QST))		
12:25 - 15:00 (2:35)	break			
15:00 - 16:20 (1:20)	**Session 4-1 Short Presentations** Including Group discussion	Session 4-1-A	Session 4-1-B	Session 4-1-C
16:20 - 16:40 (0:20)	break			
16:40 - 18:00 (1:20)	**Session 4-2 Short Presentations** Including Group discussion	Session 4-2-D	Session 4-2-E	Session 4-2-F
18:00 - 18:50 (0:50)	break			
18:50 - 19:15 (0:25)	**Session 5 Oral Presentations**	Akihito Ishizaki	National Institites of Natural Sciences	Dynamics in Photosynthetic Systems: Quantum Dissipation, Vibrational Assistance, and Quantum Light Spectroscopy
19:15 - 19:40 (0:25)		Yu Mukai	Kyoto Univerisity	Photonic Quantum Sensing Using Frequency Entangled Photons - Infrared Quantum Abosrption Spectroscopy -
19:40 - 20:05 (0:25)		Nobuhiro Yanai	Kyushu University	Materials Chemistry of Triplet Dynamic Nuclear Polarization
20:05 - 20:30 (0:25)		Kiminori Maeda	Saitama University	Quantum Control of Radical Pair Reaction by AWG-Based Electron Spin Resonance
		[Session chairs] Ryosuke Shimizu (The University of Electro-Communications) Makoko Negoro (Osaka University)		
20:30 - 20:40 (0:10)	**Closing Remarks**	Hidemi Ishiuchi	Sub Program Director of the MEXT Q-LEAP	-

Program on Friday December 18th, 2020

Start (JST) End (JST)

9:00 - 10:20 (1:20)	**Session 6-1** **Short Presentations** Including Group discussion	Session 6-1-G
10:20 - 10:40 (0:20)	break	
10:40 - 12:00 (1:20)	**Session 6-2** **Short Presentations** Including Group discussion	Session 6-2-H

Opening Remarks 1

Yasuhiko Arakawa

Institute for Nano Quantum Information Electronics, The University of Tokyo

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Short Biography

Yasuhiko Arakawa received his PhD degree in Electrical Engineering from The University of Tokyo in 1980. He became a full Professor, the Institute of Industrial Science, The University of Tokyo in 1993. He has been a Specially-Appointed Professor and a Professor Emeritus at The University of Tokyo since 2018. He is also a Program Director of the MEXT Q-LEAP program and the Supervisor of the CREST Quantum Technology project. His main research field is quantum dot photonics, including physics of quantum dots, quantum dot lasers, single photon sources, semiconductor cavity-QED and silicon photonics. He is a Foreign Member of the US National Academy of Engineering (MAE) and the Past President of International Commission for Optics (ICO). He published more than 800 journal papers and presented over 400 invited papers including more than 80 plenary/keynote papers at international conferences

He received numerous awards, including ISCS Quantum Devices Award in 2002, Leo Esaki Award in 2004, IEEE/LEOS William Streifer Award in 2006, Fujiwara Award in 2007, IEEE David Sarnoff Award in 2009, Prime Minister Award in 2009, the Medal with Purple Ribbon in 2009, C&C Prize in 2010, Heinrich Welker Award in 2011, OSA Nick Holonyak Jr. Award in 2011, the Japan Academy Prize in 2017 and IEEE Jun-ichi Nishizawa Medal in 2018. He is a Fellow of IEEE. OSA, IEICE and JSAP.

Opening Remarks 2

Susumu Kajiwara

Deputy Director-General, Science and Technology Policy Bureau

Ministry of Education, Culture, Sports, Science and Technology (MEXT)

Short Biography

Dr. KAJIWARA Susumu was appointed as a deputy director-general, MEXT in September 2019. He's got a Doctor of Science at Tokyo Institute of Technology (Tokyo Tech) and then joined Kirin brewery Co. Ltd. He moved to Tokyo Tech as an assistant professor in 1995 and worked as an associate professor from 2001 to 2012. During that term, he also served as a deputy director, Council of Science and Technology Policy (CSTP), Cabinet Office of Japan (2003-2005). He served as a professor of Tokyo Tech in 2012 and then he was appointed as a vice president, Tokyo Tech in April 2018 (to 2019).

MEXT Quantum Leap Flagship Program (MEXT Q-LEAP) on Development of Innovative Sensor Systems by Highly Sophisticated Control of Solid Quantum Sensors

Mutsuko Hatano
Department of Electrical and Electric Engineering, School of Engineering, Tokyo Institute of Technology and National Institutes for Quantum and Radiological Science and Technology
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Abstract

A co-creative center (5 universities, 2 national institutes, 4 companies) to conduct collaborative R&D seamlessly from physics to applications of innovative solid quantum sensor systems has been launched. Developing prototypes of quantum sensors by utilizing diamond NV center (nitrogen–vacancy pair). NV centers have superior physical properties at room temperature for multi-modal quantum sensing (magnetic field, electronic field, temperature) and enabling scalable applications from atomic-scale to macroscopic range.

We would like to introduce the flagship project in the metrology and sensing field MEXT Q-LEAP program, and our core technologies on material, devices, sensor systems, and applications for healthcare (Fig.1) and energy electronics (Fig.2).

This work was supported by MEXT QLEAP Grant Number JPMXS0118067395.

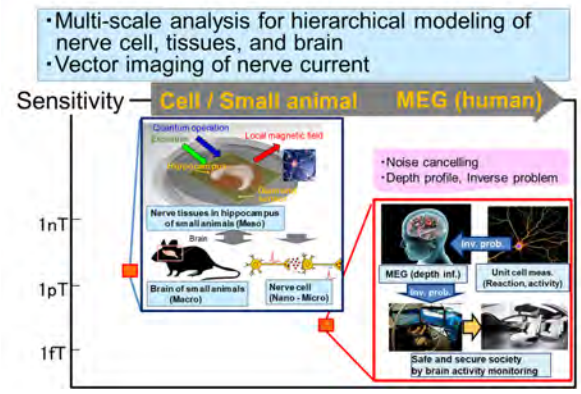

Figure 1 Target-A:Healthcare and Io-nanoT

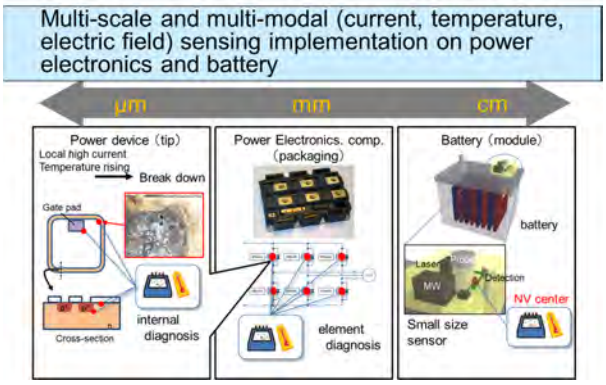

Figure 2 Target-B: Energy electronics

Short Biography

Mutsuko Hatano received the Ph.D. degree from Keio University. She joined Central Research Laboratory, Hitachi Ltd., Tokyo, Japan, and was engaged in research and development on the superconducting devices, mobile displays, and power electronics. She was a chief researcher at the CRL and the project manager of the environment electronics. She was a visiting researcher at the University of California, Berkeley from 1998 to 2000. In 2010, she joined Tokyo Institute of Technology as a professor of Electrical and Electronic Engineering. She is also a Section Manager of National Institutes for Quantum and Radiological Science and Technology. Her main research field is wide-gap semiconductor devices for power electronics and for quantum sensing. She is a fellow and a president of the Japan Society of Applied Physics.

MEXT Quantum Leap Flagship Program (MEXT Q-LEAP) on Innovations in Medicine and Life Sciences through Development of Quantum Life Technology

Yoshinobu Baba

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Abstract

National Institutes for Quantum and Radiological Science and Technology (QST) launched Institute for Quantum Life Science as the National Center of the emerging interdisciplinary research field of quantum life science in 2019. QST's Institute for Quantum Life Science has not only been actively investigating quantum sensors, room temperature hyperpolarization based highly sensitive MRI/NMR, quantum biology, quantum biotechnology, and their medical applications, but also organizing global quantum life science community including universities, national institutions, and industries. The proposal of QST on Innovations in Medicine and Life Sciences through Development of Quantum Life Technology, collaborating with thirteen universities, three national institutions, and ten industries, were accepted by MEXT Quantum Leap Flagship Program (MEXT Q-LEAP) for quantum life science in 2020. In this MEXT Q-LEAP, the interdisciplinary industrial-academia collaborations enable us to develop NVC(nitrogen-vacancy center)-containing nanodiamond quantum sensors of cellular and animal functional imaging for cancer science, neuroscience, brain science, immunology, liquid-liquid phase separation, and regenerative medicine. Photo-excited triplet electron spin based dynamic nuclear polarization technique as well as hyperpolarized molecular probes have been investigating to develop room temperature hyperpolarization techniques for ultra-highly sensitive MRI/NMR, which will be applicable to drug discovery and early-stage diagnosis for cancer and dementia. We are also studying quantum effects in photosynthesis, olfactory system, magnetoreception, and genetic mutations. To accelerate these studies, novel metrologies for quantum coherence and quantum entanglement in the biological systems have been developing. Quantum structural biology and quantum chemistry simulations have been applying to these studies as well. In the opening talk, I will describe the research activities and future perspective of the MEXT Q-LEAP on Innovations in Medicine and Life Sciences through Development of Quantum Life Technology.

Short Biography

Dr. Yoshinobu Baba received PhD degree in 1986 from Kyushu University. After Assistant Professor at Oita University and Associate Professor at Kobe Pharmaceutical University, he was promoted to the full professor at The University of Tokushima in 1997. He was moved to Nagoya University in 2004. He is now a Professor of Department of Chemistry and Biotechnology, School of Engineering, a Professor of Department of Advanced Medical Science, School of Medicine, and a Director of Institute of Nano-Life-Systems, Nagoya University. He is also a Director General of Institute for Quantum Life Science, National Institutes for Quantum and Radiological Science and Technology (QST), a Program Director of JST CREST "Extracellular fine particles" Project, and a Project Leader of MEXT Quantum Leap Flagship Program (MEXT Q-LEAP) on Innovations in Medicine and Life Sciences through Development of Quantum Life Technology. He is a co-initiator for the world largest Nanotech International Meeting and the world largest Microfluidics International Meeting. He is a general chair of numerous international meetings (microTAS, MSB, nanotech, ISMM). He is an Associate Editor of *Anal. Chem*. of ACS and serving to over 10 scientific journals as an editorial/advisory board member. He has been admitted as a Fellow of the Royal Society of Chemistry and received over 90 awards for his contributions in nanobiotechnology. Dr. Baba's research studies are directed at the development of nanobiodevices for omics, systems biology, medical diagnosis, tissue engineering, and molecular imaging. He is the author or co-author of 1,051 publications, including research papers, proceedings, reviews, and books and is also an inventor of over 100 patents. He has delivered more than 1,010 plenary and invited lectures at conferences. His work has been cited on 488 occasions by newspapers and television.

Quantum Sensing with Diamond Spin Qubits

Fedor Jelezko
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Abstract

A particularly interesting application of diamond-based quantum sensing is the detection of nuclear magnetic resonance on nanometer scales, including the detection of individual nuclear spins or small ensembles of external nuclear spins. Single nitrogen vacancy (NV) color centers in diamond currently have sufficient sensitivity for detecting single external nuclear spins and resolve their position within a few angstroms. The ability to bring the sensor close to biomolecules by implantation of single NV centers and attachment of proteins to the surface of diamond enabled the first proof of principle demonstration of proteins labeled by paramagnetic markers and label-free detection of the signal from a single protein. Single-molecule nuclear magnetic resonance (NMR) experiments open the way towards unraveling dynamics and structure of single biomolecules. However, for that purpose, NV magnetometers must reach spectral resolutions comparable to that of conventional solution state NMR. New techniques for this purpose will be discussed. Most of mentioned above results obtained so far with diamond centers are based on optical detection of single NV color centers. Recently it was shown that photoelectrical detection of NV centers based on spin selective photoionization can provide robust and efficient access to spin state of individual color center.

Short Biography

Fedor Jelezko is a director of the Institute of Quantum Optics and fellow of the Center for Integrated Quantum Science and Technology (IQST) at Ulm University. He studied in Minsk (Belarus) and received his Ph.D. in 1998. After finishing the habilitation in 2010 at Stuttgart University he was appointed as a professor of experimental physics in Ulm in 2011. His research interests are at the intersection of fundamental quantum physics and application of quantum technologies for information processing, communication, sensing, and imaging.

Does Life Need Quantum Mechanics?

Johnjoe McFadden

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Abstract

Quantum mechanics is the weirdest of sciences that allows particles to inhabit multiple locations in space and time at once, travel through classically-impenetrable barriers and possess spooky connections across vast regions of space. Yet the science is usually considered to be limited to the tiniest components of matter, such as protons or atoms. As systems get bigger, classical behaviours in which particles tend to be in one place or another, cannot penetrate impenetrable barriers and are not spookily connected, tends to dominate. However, several; decades ago, one of the founders of quantum mechanics, Erwin Schrödinger, proposed in his book, 'What is Life?' published in 1944 that "a gene – or perhaps the whole chromosome fibre … [is] an aperiodic crystal [in which] every atom, and every group of atoms, plays an individual role … which has to be a masterpiece of highly differentiated order, safeguarded by the conjuring rod of quantum theory.' He went on to claim that life was fundamentally quantum mechanical.

In this talk I will examine Schrödinger's claim from the perspective of modern quantum biology and molecular biology. I will discuss evidence for the quantum tunnelling, quantum coherence and even quantum entanglement a wide range of biological phenomena such as avian navigation, enzyme action, photosynthesis, the sense of smell and mutation. I will also discuss advances in relation to that most fundamental question of biology: what is life? I will propose that what makes life unique is that it operates at the border between the quantum and classical realm.

Reference

McFadden, J. and J. Al-Khalili (2018). "The origins of quantum biology." Proceedings of the Royal Society A 474(2220): 20180674.

Al-Khalili, J. and J. McFadden (2014). Life on the Edge: The Coming of Age of Quantum Biology. London, Bantam Press.

Short Biography

Johnjoe McFadden is Professor of Molecular Genetics and Director of the Quantum Biology Doctoral Training Centre at the University of Surrey. As well as his molecular genetics research over the past 20 years, McFadden pioneered the proposal that quantum mechanics is fundamental to biology with his book, Quantum Evolution, published in 2001 and most recently and with co-author, Jim Al-Khalili, Life on the Edge, which provides an update on the emerging field of quantum biology. His current research is focussed on quantum biology, investigating many different areas, from magnetoreception to mutation and the role of EM fields in the brain. He is currently writing a book on the role of Occam's razor, the principle that, given a choice, we should always accept the simplest solutions.

Avian Magnetoreception: Using Biochemistry to Sense Weak Magnetic Fields

Peter J. Hore

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Abstract

Although it has been known for half a century that night-migratory songbirds can detect the direction of the Earth's magnetic field as a navigational aid, the primary sensory mechanism of this remarkable ability is still obscure. The currently leading hypothesis centres on the quantum mechanical properties of short-lived chemical intermediates known as radical pairs — in particular radical pairs formed when a cryptochrome protein, located in the birds' retinas, is excited with blue light [1].

In this talk, I will outline how the quantum spin dynamics of radical pairs in non-equilibrium spin states could lead to changes in the yield of a cryptochrome signalling state even though the interaction with the geomagnetic field is six orders of magnitude smaller than the thermal energy, k_BT. This will be followed by a summary of experiments and calculations supporting the proposal that European robin cryptochrome-4 has the magnetic properties required of a light-dependent magnetoreceptor.

[1] P. J. Hore and H. Mouritsen, *The radical-pair mechanism of magnetoreception*, *Annu. Rev. Biophys.*, 45, 299-344 (2016).

Short Biography

Peter J. Hore has spent most of his life in the Chemistry Department of the University of Oxford, first as an undergraduate and a graduate student (1973-80) and then, after a two-year postdoc at the University of Groningen, as a Junior Research Fellow at St John's College. In 1983 he was appointed to a University Lecturership in Physical Chemistry and a Tutorial Fellowship at Corpus Christi College.

Much of his research has been in the area of Spin Chemistry. He has worked on topics such as photosynthetic energy conversion, protein structure and folding, spin hyperpolarization, spin dynamics, new magnetic resonance techniques, and the effects of weak electromagnetic fields on chemical and biological processes. For the last ten years, he has been trying to unravel the biophysical mechanism by which migratory birds detect the direction of the Earth's magnetic field as a navigational aid.

Enhancing Stimulated Raman Scattering with Nonclassical Light

Ulrik Lund Andersen
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Abstract

Stimulated Raman Scattering (SRS) spectroscopy is a very powerful technique to perform real-time vibrational imaging of living cells and organisms. It is based on the stimulated excitation of a Raman transition of the sample under interrogation, thereby resulting in a measurable stimulated Raman loss and gain of the two input beams. In SRS, the sensitivity and imaging speed are fundamentally limited by the noise level (often shot-noise) of the probing laser, but can in principle be arbitrarily improved by simply increasing the power of the input beams. However, in biological systems, especially in living systems, the power must be kept low to avoid changing the biological dynamics of the specimens, and in particular to avoid damage due to excessive heating. Leaving the optical power at a constant level, the sensitivity and bandwidth of the SRS can be boosted by reducing the shot-noise level using squeezed states of light. In this talk, we present a demonstration of a quantum-enhanced continuous-wave (cw) SRS spectrometer using amplitude squeezed light. We demonstrate its functionality and superiority by spectroscopically measuring the carbon–hydrogen (C-H) vibrations of polymethylmethacrylate (PMMA) and polydimethylsiloxane (PDMS) with a sensitivity improvement of approximately 56¥% relative to shot-noise limited Raman spectroscopy. Our measurement method has the potential to enable new measurement regimes of Raman bio-imaging that are inaccessible by conventional shot-noise limited Raman spectroscopy.

Short Biography

Ulrik Lund Andersen is a Full professor in quantum optics and quantum information, heading the section for Quantum Physics and Information Technology (QPIT) and leading the Center of Excellence on Macroscopic Quantum States (2017-2023). He is also heading a cross-disciplinary center on quantum technology at DTU (www.quantum.dtu.dk). Over the course of his career he has made a very broad range of significant, high-impact contributions to quantum optics, technology, and information including the development of new techniques to generate, control and optimally measure non-classical states of light (Gaussian, non-Gaussian and entangled states). His impact is reflected by the publication of numerous articles in Nature magazines and Physical Review Letters. For these contributions he won several prizes, e.g. the advanced Sapere Aude award in 2015 and the prestigious Eliteforsk prize of the Danish Research Council in 2013.

Nonlinear Spectroscopy with Entangled Photons

Frank Schlawin[1,2]

[1] *The Hamburg Centre for Ultrafast Imaging*

[2] *Max-Planck Institute for the Structure and Dynamics of Matter, Germany*

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Abstract

Quantum light sources are promising candidates for novel spectroscopic applications due to their nonclassical intensity fluctuations, which can enhance the nonlinear response of a sample. For instance, it has long been established that squeezed states of light show a linear, rather than quadratic, intensity scaling of the two-photon absorption signal [1]. This could enable nonlinear spectroscopy of photosensitive samples at much lower photon fluxes.

In addition, entangled states of light can feature strong time and frequency quantum correlations that can be further used to manipulate nonlinear optical signals [2, 3]. In my talk, I will discuss how this entanglement can control excited state populations in the sample and as a consequence provide a new way of probing ultrafast dynamics in molecular aggregates. Finally, I will present how a coherent control theory of quantum light allows us to quantify the possible advantage of the use of entangled photons in spectroscopy [4].

[1] N. P. Georgiades et al., *Phys. Rev. Lett.* 75, 3426 (1995).

[2] K. E. Dorfman, F. Schlawin and S. Mukamel, *Rev. Mod, Phys.* 88, 045008 (2016).

[3] F. Schlawin, K. E. Dorfman and S. Mukamel, *Acc. Chem. Res.* 51, 2207 (2018).

[4] F. Schlawin and A. Buchleitner, *New J. Phys.* 19, 013009 (2017).

Short Biography

Frank Schlawin completed his PhD at the University of California, Irvine, USA, under the supervision of Prof. Shaul Mukamel, and at the University of Freiburg, Germany, from which he received his degree, under the supervision of Prof. Andreas Buchleitner. In 2015, he joined the group of Prof. Dieter Jaksch at the University of Oxford. In 2020, he then moved to Hamburg to work as a group leader at the Centre for Ultrafast Imaging (CUI). His research interests span current research areas concerning the interaction of quantum light with complex quantum systems. Since the time of his PhD, he works on the theory of nonlinear spectroscopy with quantum light. He is particularly interested in the role of photonic quantum correlations in absorption processes, and how these can be employed for spectroscopic applications. Besides, he is also interested in how optical cavities can be employed to manipulate material properties in the strong coupling regime.

Quantum Diamond Sensors

Ronald Walsworth

Quantum Technology Center, University of Maryland, U.S.A.

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Abstract

The nitrogen–vacancy (NV) quantum defect in diamond is a leading modality for magnetic, electrical, temperature, and force sensing with high spatial resolution (nanometers to millimeters) under ambient conditions. This technology has wide-ranging application across the physical and life sciences — from probing magnetic materials to biomedical diagnostics to NMR of single cells and proteins. I will provide an overview of quantum diamond sensors and their diverse applications, with a focus on life science applications.

Short Biography

Prof. Ronald Walsworth is a Minta Martin Professor in the Department of Electrical and Computer Engineering and the Department of Physics at the University of Maryland. He is also the Founding Director of the Quantum Technology Center (QTC), a cross-disciplinary center at the University of Maryland focusing on the translational applications of research in quantum science; and a Fellow of the Joint Quantum Institute (JQI). Prior to joining the University of Maryland in 2019, Walsworth held appointments as a faculty member at Harvard University in the Department of Physics; and as a Senior Physicist with the Smithsonian Astrophysical Observatory.

Prof. Walsworth leads an active interdisciplinary research group focused on developing precision measurement tools for applications in the physical and life-sciences based on quantum science. He has advised over 100 students and postdoctoral researchers, and has published nearly 200 peer-reviewed scientific papers. Walsworth is an inventor on 14 allowed U.S. Patents, including the original patents covering conventional techniques for magnetometry using nitrogen vacancy (NV) quantum defects in diamond. He has co-founded four technology companies and served on the Scientific Advisory Board of four companies.

Prof. Walsworth holds a PhD in Physics from Harvard University (1991) and a B.S. in Physics from Duke University (1984). He currently serves on the NASA Fundamental Physical Science Standing Review Board; and has previously been a member of the NAS/NRC Committee on Atomic, Molecular and Optical Sciences (2010-2013), the NAS/NRC Decadal Survey on Biological and Physical Sciences in Space (2009-2011); and served as Chair of the DOE Quantum Sensor Roundtable (2016). Walsworth received the Francis M. Pipkin Award from the American Physical Society (2005) and the Exceptional Service Award from the Smithsonian Institution (1993). He was elected a Fellow of the American Physical Society (2001) and currently serves as a Distinguished Traveling Lecturer for the American Physical Society.

Diamond Based Quantum Sensors for Bio-sensing and Imaging

David A. Simpson
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Abstract:

The nitrogen vacancy (NV) centre in diamond[1] has emerged as a promising system for nanoscale sensing and imaging due to its size and sensitivity to a range of physiological parameters including temperature[2], magnetic[3] and electric fields[4]. The optical and quantum properties of the NV centre in diamond are ideal for biological imaging, the material itself is bio-compatible, the NV fluorescence is photo-stable and the quantum properties of the NV centre can be manipulated and readout at room temperature. These attributes have driven application of these quantum probes into biological systems[5, 6]. Diamond quantum probes can be found in nanodiamonds <100 nm in size or engineered into 2D NV imaging arrays using single crystal diamond. Here, I will describe our recent work exploiting 2D NV imaging arrays for magnetic imaging applications. In particular, I will show how these imaging arrays in diamond can be used to non-invasively map the magnetic properties of iron-oxide complexes in biological systems at the sub-cellular scale[7, 8]. I will also discuss the future possibilities of this technology and how it can be applied to address significant and outstanding questions in biology.

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Short Biography

David Simpson is a Senior Lecturer in Physical Biosciences within the School of Physics at The University of Melbourne. He obtained his PhD in applied physics from Victoria University in 2008 and has spent the past decade researching and commercialising quantum technology. His current research focuses on the development of novel diamond-based sensors for precision sensing and imaging of biological systems. He has established new technology platforms to image the magnetic and electrical properties of biological systems with unpreceded resolution. In 2013, Dr Simpson was part of the team awarded, Eureka Prize for Interdisciplinary Research, for work on quantum probes in biology. His broader research interests include quantum measurement, precision sensing, nanoscale magnetic resonance spectroscopy and the material properties of diamond.

Ultrafast Quantum Plasmonic PCR for Rapid Detection of COVID-19

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Abstract

Polymerase Chain Reaction (PCR) is a fundamental tool for basic life sciences and clinical, veterinary, agricultural, food, and forensic applications. Fast PCR will reduce the discovery times of biological mechanisms, signaling pathways, biomarkers, and drugs and mitigate the spread of infectious diseases. Rapid and accurate identification of the disease is the first step for promptly determining appropriate treatments. However, conventional PCR still requires cumbersome and labor-intensive sample preparation steps such as DNA extraction, purification, and quantification (1-3 hours) due to sample preparation steps and large heating elements with high power consumption (300-600 W). Due to these problems, current PCR is not suitable for sample-to-answer point-of-care home diagnostics for infectious diseases like COVID-19 and severe acute respiratory syndrome coronavirus (SARS-CoV). In this talk, I will present ultrafast photonic PCR[1] (< 3 min) and its applications[2-3], quantum biological electron transfer[2], and quantum plasmonic PCR. The ultrafast quantum plasmonic PCR will generate a broad-ranging impact and innovative future applications in molecular diagnostics for COVID-19 and the precise identification of any other viruses or pathogens as well as other diseases, including cancer and neurodegenerative diseases. Understanding fundamental plasmon resonance energy or electron transfer[4-6] via a collective oscillation of conduction electrons induced by an electromagnetic wave will provide insights for quantum plasmon resonances and quantum biological tunneling in enzyme reactions. These quantum plasmonic effects will help us to control speedy enzyme reactions during DNA amplification. Moreover, investigating a resonant electromagnetic wave to enhance enzyme activity via quantum plasmonics will open new life science and medicine era.

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Prof. Luke P. Lee received both his BA in Biophysics and PhD in Applied Physics and Bioengineering from UC Berkeley. He joined the faculty at UC Berkeley in 1999 after more than a decade of industry experience. He became the Lester John and Lynne Dewar Lloyd Distinguished Professor of Bioengineering in 2005. He also served as the Chair Professor in Systems Nanobiology at the ETH Zürich from 2006 to 2007. He became Arnold and Barbara Silverman Distinguished Professor at Berkeley in 2010. He founded the Biomedical Institute for Global Healthcare Research & Technology (BIGHEART). He served as Associate President (International Research and Innovation) and Tan Chin Tuan Centennial Professor at the National University of Singapore from 2016 to 2018. He is the founding director of the Institute of Quantum Biophysics, Sungkyunkwan University, Korea. He is now serving as Professor of Medicine at Harvard Medical School and Brigham Women's Hospital. He is a Fellow of the Royal Society of Chemistry and the American Institute of Medical and Biological Engineering. His work at the interface of biological, physical, and engineering sciences for translational medicine has been recognized by many honors, including the IEEE William J. Morlock Award, NSF Career Award, Fulbright Scholar Award, and the HoAm Prize. Lee has over 350 peer-reviewed publications and over 60 international patents filed. His current research interests are quantum biology, smart optofluidic systems for the early detection of infectious diseases, cancer, and neurodegenerative diseases, and *in vitro* neurogenesis, and solving ill-defined problems of global healthcare.

Quantum sensing techniques and extension of spin coherence times of NV centers toward higher sensitivity

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Quantum sensor of NV centers is highly sensitive since it capitalizes on fragile quantum property of coherence. Recently we focus on extension of coherence times, improvement of sensitivity, development of quantum sensing techniques and electrical control and detection of NV centers in diamond [1-6].

Recently, we investigate n-type diamond synthesized by chemical vapor deposition (CVD) technique toward higher sensitivity, longer spin coherence times and charge state stabilization. In our sample, we realized that the longest inhomogeneous spin-dephasing time ($T_2^* \approx 1.5$ ms) and Hahn-echo spin-coherence time ($T_2 \approx 2.4$ ms) of single electron spins in NV centres, ever observed in room-temperature solid-state systems [1]. It leads best AC magnetic field sensitivity of 9.1 nT/(Hz)$^{1/2}$ and AC magnetic field sensitivity of 6 nT/(Hz)$^{1/2}$ of single NV center at room temperature [1]. In addition to the native NV center created during the CVD growth, we investigated NV centers produced by the ion-implantation technique at a depth of ~15 nm in phosphorus-doped n-type diamond [2]. The longest T_2 of about 580 μs of a shallow NV center approaches the one in bulk diamond limited by a natural abundance of ^{13}C nuclear spins. The averaged T_2 in n-type diamond is over 1.7 times longer than that in pure non-doped diamond. Moreover, the stabilization of the charge state and the more than twofold improvement of the creation yield are confirmed.

Regarding development of quantum sensing techniques, we investigate dynamic range quantum measurement retaining its sensitivity [3]. For sensing, the crux is to minimize the measurement uncertainty in a chosen range within a given time. However, basic quantum sensing protocols cannot simultaneously achieve both a high sensitivity and a large range. We demonstrate a non-adaptive algorithm for increasing this range, in principle without limit, for AC field sensing, while being able to get arbitrarily close to the best possible sensitivity, which can be applied to any modulo-limited sensor. We experimentally demonstrated a dynamic range of ~10^7, an improvement of two orders of magnitude compared to previous algorithms. Also, we explore this algorithm thoroughly by simulation, and discuss the T^{-2} scaling, as opposed to the $T^{-1/2}$ of the standard measurement. In addition, regarding the utilization of quantum state, we experimentally generated dressed states in a single NV centre in diamond based on Autler-Townes splitting. We observed the extension of the coherence time to T_2 ~ 1.5 ms which is more than two orders of magnitude longer than that of the undressed states [4].

Regarding electrical control and detection, we investigate the electrical control for extension of the spin coherence times of 40 nm-deep ion-implanted single NV center by suppressing magnetic noises. We applied 120 V DC across two contacts spaced by 10 micrometers. The T_2^* and T_2 were increased up to about 10 times (reaching 10 microseconds) and 1.4 times (reaching 150 microseconds), respectively [5]. As for the electrical detection, We demonstrate electrical detection of the 14N nuclear spin coherence of NV centres at room temperature, which is the first electrical detection of nuclear spin coherence at room temperature [6].

Acknowledgments

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Development of diamond quantum sensor for automobile battery monitor

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Introduction

Recently, major countries around the world are responding to climate change and tightening regulations on carbon emissions. There is an urgent need to popularize environment-friendly automobiles such as EVs. The most important issue in the popularization of EVs is the improvement of mileage. One of the solutions is highly accurate control of the battery state by measuring the current. It is required to develop a novel current sensor which can measure a large current with high resolution even in a severe environment in EVs. Because a diamond NV center has a wide dynamic range and can sense large currents with high sensitivity, it is expected to be used as a sensor for automotive battery monitors. Furthermore, it is considered to be suitable for automobile sensors that require high safety and reliability due to non-contact measurement and high robustness of diamond materials. Here, we report the results of our study on the application of the diamond NV center to automotive current sensors.

Method

Conventional methods using the change of intensity in ODMR spectra cannot be applied to automotive current sensors because they need to measure a magnetic field of up to several tens of millitesla. It is necessary to develop a method using the change of frequency in ODMR spectra and an antenna to generate microwaves corresponding to several tens of millitesla.

In order to measure the frequency of two independent minima in ODMR spectra, we developed the feedback control method to lock and follow two minima of ODMR spectra. It was confirmed that the frequency change could be accurately measured without the frequency lock being released even under the condition that the frequency division and the shift caused by the fluctuation in magnetic field and temperature occur simultaneously as shown in Figure 1.

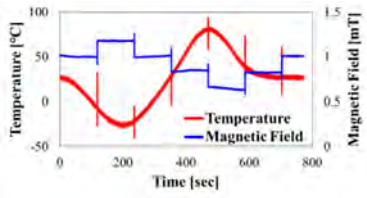

FIG. 1. The results of the magnetic field and temperature measurement.

An antenna requires to generate uniform microwaves over a wide frequency range without heat generation. We designed an antenna composed of a plurality of loop coils having different resonance points. From the simulation results, it is confirmed that a uniform magnetic field is generated from 1GHz to 5GHz without heat generation as shown in Figure 2.

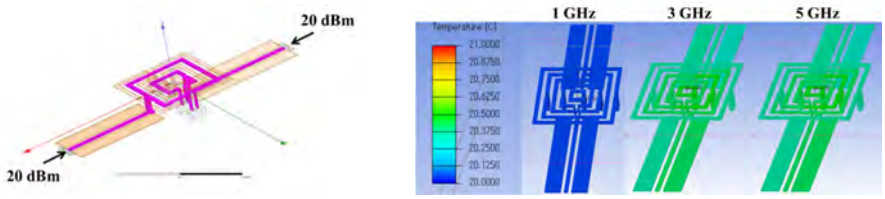

FIG. 2. The simulation results of heat generation from the microwave antenna.

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NV-detected electron spin resonance spectroscopy at high magnetic field

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Introduction

The nitrogen-vacancy (NV) center has unique properties that make it an excellent candidate for high sensitivity magnetic sensing. The NV center is a two-atom defect in the diamond lattice, with the capacity for optical spin-state initialization and readout, long coherence times, and high sensitivity to external magnetic fields. NV-detected electron spin resonance (ESR) offers the capability to detect a single or a small number of electron spins and to investigate biological molecules at the single molecule level. Such an ESR technique with single spin sensitivity potentially eliminates ensemble averaging in heterogeneous and complex systems and has great promise to directly probe fundamental interactions and biochemical functions. In ESR, the measurement of the g-factor is extremely useful for the identification of spin species. However, a featureless "g = 2" signal is often observed, causing the spectral overlap with target ESR signals, which may prevent spin identification. Similar to nuclear magnetic resonance (NMR) spectroscopy, pulsed ESR spectroscopy at higher frequencies (HFs) and magnetic fields becomes more powerful for finer spectral resolution, enabling clear spectral separation of systems with similar g values. This is advantageous in the investigation of complex and heterogeneous spin systems. A high frequency of Larmor precession is also less sensitive to motional narrowing, enabling the ESR investigation of structures for molecules in motion. In addition, a high Larmor frequency provides greater spin polarization: improving sensitivity and providing control of spin dynamics. Within this talk we present our recent demonstration of NV-detected ESR from both single and ensemble NV spin systems at the highest magnetic field to date, 4.2 Tesla [1,2].

Method

Figure 1 shows an overview of a home-built HF ODMR system used in the experiment. The HF ODMR system consists of a HF microwave source, quasioptics, a 12.1 Tesla cryogenic-free superconducting magnet, and a confocal microscope system for ODMR. The HF ODMR system is built upon the existing HF ESR spectrometer that was described previously [3,4]. Therefore the system enables *in-situ* experiments of both ESR and ODMR. As seen in Fig. 1, the HF source contains two microwave synthesizers (MW1 and MW2), a power combiner, and a frequency multiplier chain. An IQ mixer controlled by an arbitrary wave generator has recently been implemented in MW1 for pulse shaping of high frequency microwaves. Two synthesizers are employed for double electron-electron resonance (DEER) experiments. The frequency range of the microwave source is 107-120 GHz and 215-240 GHz. In this experiment, we use a frequency range of 107-120 GHz where the output power of the HF microwave is 480 mW at 115 GHz. HF microwaves are propagated to a sample using a home-built quasioptical bridge and a corrugated waveguide. As demonstrated previously, quasioptics are suitable for a high-frequency ESR spectrometer because of their capacity for low-loss and broadband propagation. A sample is mounted at the end of the corrugated waveguide and positioned at the field center of a room temperature bore within a superconducting magnet system.

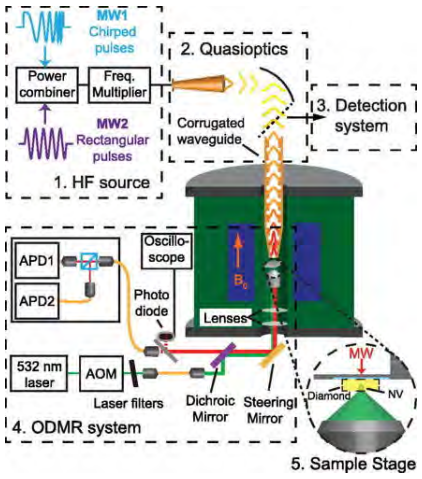

FIG. 1. Overview of HF ODMR system. See Ref. [1] for details.

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Applications of quantum diamond microscopy in condensed matter physics

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Abstract

Quantum sensing based on the nitrogen-vacancy (NV) defect in diamond has emerged as a promising tool for the study of microscopic phenomena across physical and materials sciences[1]. In this talk, I will present our work on the development of quantum diamond microscopy, which exploits arrays of NV defects to allow magnetic/electric/strain imaging of samples and devices with sub-micron spatial resolution, and several applications of this technology in condensed matter physics[2,3]. This includes our recent demonstration of a cryogenic quantum diamond microscope[4] and its application to the study of ultrathin van der Waals ferromagnets[5].

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Dynamics in Photosynthetic Systems: Quantum Dissipation, Vibrational Assistance, and Quantum Light Spectroscopy

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Essentially, any quantum systems can never be regarded as "isolated systems." Quantum systems are always in contact with "the outside world," and hence their quantum natures are sometimes sustained and sometimes destroyed. In condensed phase molecular systems, especially, quantum systems are affected by the huge number of dynamic degrees of freedom such as solvent molecules, amino acid residues in proteins, and so forth. Balance between robustness and fragility of the quantum natures may dramatically alter behaviors of chemical dynamics and spectroscopic signals. In this presentation, we will be talking about two topics related to this subject [1, 3].

The first topic is regarding natural photosynthetic systems. The energy conversion of oxygenic photosynthesis is triggered by primary charge separation in proteins at the photosystem II reaction center. Here, we investigate the impacts of the protein environment and intramolecular vibrations on primary charge separation at the photosystem II reaction center. This was accomplished by combining the quantum dynamic theories of condensed phase electron transfer with quantum chemical calculations to evaluate the vibrational Huang-Rhys factors of chlorophyll and pheophytin molecules. We report that individual vibrational modes play a minor role in promoting charge separation, contrary to the discussion in recent publications. Nevertheless, these small contributions accumulate to considerably influence the charge separation rate, resulting in subpicosecond charge separation almost independent of the driving force and temperature. We suggest that the intramolecular vibrations complement the robustness of the charge separation in the photosystem II reaction center against the inherently large static disorder of the involved electronic energies [1].

As the second topic, we discuss quantum light spectroscopy for probing exciton and charge dynamics in complex molecules. Quantum light, such as entangled photons, is a key resource for promoting cutting-edge quantum technology. One class of this technology aims to improve the precision of optical measurements via non-classical photon correlations. In this light, it is hoped that quantum light will open new avenues for optical spectroscopy using the parameters of quantum states of light [2]. In this presentation, we address transmission measurement of frequency-entangled broadband photon pairs generated via parametric down-conversion with a monochromatic laser. It is observed that state-to-state dynamics in the system under study are temporally resolved by adjusting the path difference between the entangled twin beams when the entanglement time is sufficiently short. The non-classical photon correlation enables time-resolved spectroscopy with monochromatic pumping instead of a pulsed laser. It is further demonstrated that the signal corresponds to the spectral information along anti-diagonal lines of, for example, two-dimensional Fourier-transformed photon echo spectra. This correspondence inspires us to anticipate that more elaborately engineered photon states would broaden the availability of quantum light spectroscopy [3].

These works were supported by MEXT KAKENHI Grant No. 17H06437 in Innovative Areas "Innovations for Light-Energy Conversion" (for the first topic) and MEXT Quantum Leap Flagship Program Grant No. JPMXS0118069242 (for the second topic).

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Photonic quantum sensing using frequency entangled photons - infrared quantum absorption spectroscopy -

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Introduction

Photonic quantum sensing using frequency entangled photons, such as quantum absorption spectroscopy [1,2], optical coherence tomography [3,4], and imaging with undetected photon [5], have been attracting great interest because of their potential to exceed the performance of classical measurement techniques. Quantum infrared absorption spectroscopy (IR-QAS) is a promising spectrometric technique using a nonlinear interferometer with visible-infrared photon pair sources, where information about optical properties of a sample probed by infrared photon can be converted to the generation probability for correlated visible photon. This feature of IR-QAS enables determination of infrared absorption spectrum of the sample, using only visible light source and detectors.

Kalashnikov et al. have reported the first demonstration of IR-QAS [1], where it is necessary to spectrally resolve the visible detection photon using spectrometer, to obtain an infrared absorption spectrum. Another possible approach, which does not need the spectral selection, is to apply Fourier analysis to the nonlinear interferometric signal. Very recently, Lindner et al. have experimentally demonstrated that an infrared transmittance spectrum can be inferred from a Fourier spectrum of quantum interferograms, the visible photon count rate measured as a function of the optical path length difference between the visible and infrared photons [6]. However, the theoretical background for the Fourier analysis of the quantum interferograms has not been provided. In this study, we present a theoretical framework for quantum Fourier transform infrared (Q-FTIR) spectroscopy, which provides a clear procedure to determine the infrared spectrum via Fourier analysis, showing that this scheme allows us to measure not only the magnitude of the transmittance spectrum but also the phase information of that. We constructed a Michelson-type nonlinear interferometer and experimentally demonstrated the complex transmittance measurement in the near-infrared region around 1500 nm by Q-FTIR spectroscopy.

Method

Figure 1 shows the experimental setup of Q-FTIR system employing a Michelson-type nonlinear interferometer. Visible-infrared photon pairs are generated via SPDC process in a nonlinear crystal, 5% MgO-doped $LiNbO_3$ (thickness, 0.5 mm) pumped by 532 nm CW laser. The propagation angle of the pump beam against the optic axis of the crystal is set around 70° , so that the SPDC wavelengths are phase-matched around 810 nm (signal) and 1550 nm (idler). The pump and signal photons are reflected by a dichroic mirror and propagate together along an interferometer arm. They are reflected back to the nonlinear crystal by a concave end mirror. The idler photon transmitted by the dichroic mirror is sent into the other arm of the interferometer with a variable path length. An end mirror reflects the idler photon back to the nonlinear crystal. The optical path length difference between the two arms, ΔL, can be tuned by the translation of this mirror. The pump beam reflected back to the nonlinear crystal causes second SPDC process and if all the spatial modes of SPDC photons are matched with each other, the quantum interference between the SPDC processes results in variation of the photon pair generation probability depending on the relative phase between the pump, signal and idler photons. The complex transmittance of a sample (silica glass plate) placed in the idler path can be determined from the ratio of the complex Fourier amplitudes of the quantum interferograms taken with and without the sample. The complex refractive index of the sample can be determined from the obtained complex transmittance spectra, showing fair agreement with a literature value.

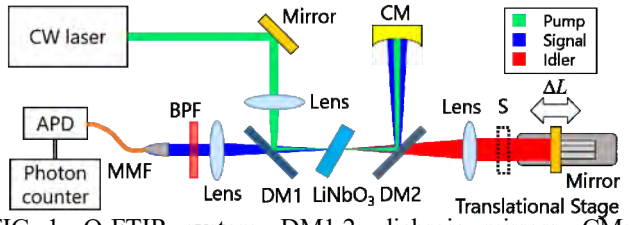

FIG 1. Q-FTIR system. DM1,2: dichroic mirrors, CM: concave end mirror, BPF: band pass filter, APD: Si avalanche photodiode, S: sample (silica glass plate).

This work was supported by MEXT Q-LEAP Grant Number JPMXS0118067634, JST-CREST (JPMJCR1674), and JST-PRESTO (No. 10435951).

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Materials chemistry of triplet dynamic nuclear polarization

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Introduction

Nuclear magnetic resonance (NMR) spectroscopy and magnetic resonance imaging (MRI) are powerful and versatile methods in modern chemistry and biology fields. Nevertheless, they suffer from intrinsically limited sensitivity due to the low nuclear spin polarization at ambient temperature. One of the promising methods to overcome this limitation is dynamic nuclear polarization (DNP) that transfers spin polarization from electrons to nuclei. In particular, DNP based on photo-excited triplet (triplet-DNP) is promising, since it allows the hyperpolarization at room temperature.[1-3] In typical scheme of triplet-DNP (FIG. 1), the spin-selective intersystem crossing (ISC) produces the large electron spin polarization in the excited triplet state sublevels, and this polarization is effectively transferred to nuclear spins by a pulsed microwave irradiation for satisfying Hartmann-Hahn condition, so-called integrated solid effect (ISE).

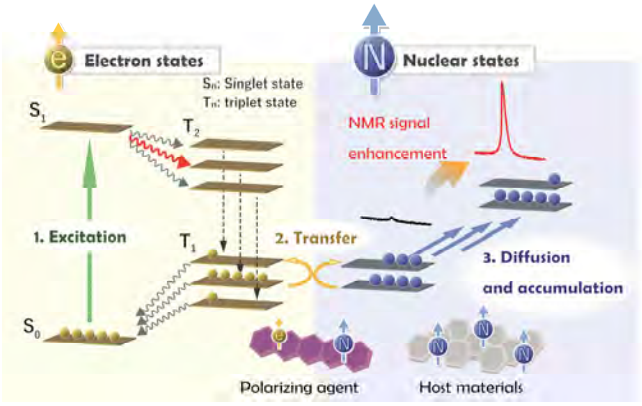

FIG. 1. Mechanism of triplet-DNP. Reproduced from ref. 4.

Method

While much efforts have been devoted to obtaining the large nuclear polarization based on triplet-DNP, the application of triplet-DNP has been limited to nuclear physics experiments. Towards biological applications, we have proposed to introduce materials chemistry into the field of triplet-DNP,[4] which realizes the hyperpolarization of nanomaterials such as nanoporous metal-organic frameworks (MOFs)[5] and nanocrystal dispersion in water[6] (FIG. 2). In addition, we have developed the first examples of air-stable[7] and water-soluble[8] polarizing agents, which allows us to hyperpolarize crystalline ice.

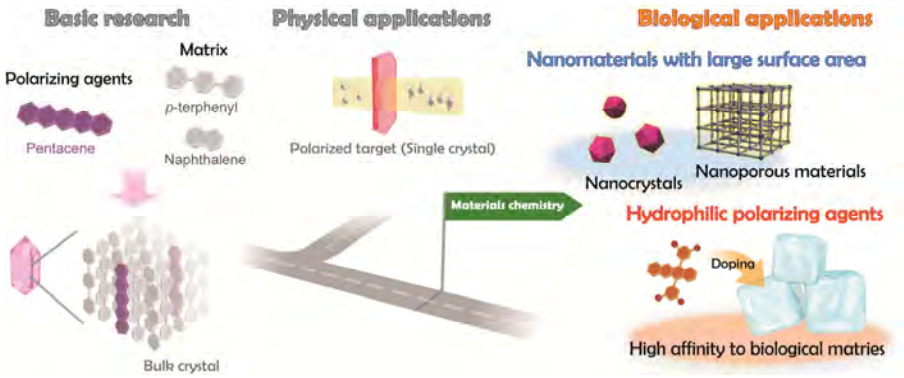

FIG. 2. Introduction of materials chemistry to triplet-DNP. Reproduced from ref. 4.

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Quantum Control of Radical Pair Reaction by AWG-based Electron Spin Resonance

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Introduction

The application of controlling of quantum systems to the chemical reaction by electromagnetic waves are one of the interesting topics in the field of chemical physics. For example, it has been theoretically shown that the vibrational states of the molecule are controlled by an arbitrary waveform infrared (IR) laser pulse field designed based on the optimization theory[1]. However, it may be technically difficult to generate arbitral waveforms of light even in the developed laser technology. In contrast, various radiowave (RF) or microwave (MW) pulses for electron and nuclear magnetic resonance can be easily generated using AWG (Arbitrary Waveform Generator). In previous research, we showed the possibility of reaction control of radical pair (RP) through manipulating electron spins by AWG based magnetic resonance.[2]
The present talk, we focus on the anisotropic reaction control and coherent control of RP by AWG-RF fields.

a) Anisotropic reaction control.

One of the examples of the calculation is shown in Fig. 1. We modelled a singlet born RP system with one nucleus having an anisotropic hyperfine interaction and designed RF targeting T_+ and T_- states for longer RP lifetime from the geminate recombination reaction from singlet RPs. The designing of radio waves was carried out by local optimization theory.

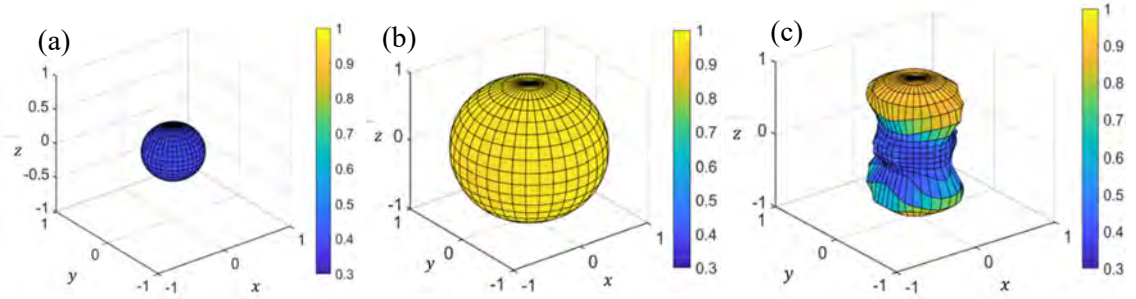

Fig.1 Results of model calculation in the RP system having one nuclear spin (principal hfc constants are $A_{xx} = 1.2$, $A_{yy} = 1.5$, $A_{zz} = 1.8$ mT. The static magnetic field ($B_0 = 3.6$ mT) is oriented to Z axis and the RF is directed to X axis in the laboratory coordinate. The population of RP at 2 μs with respect to the orientation of the long hfc axis (z in molecular axis) is plotted in the polar plot. (a) The RP population without RF field. (b) The RP population with RF field homogeneously pumping all orientation of RP sub ensembles to T_+ and T_- states. (c) The RP population with the optimized RF field stimulating anisotropic selective population pumping.

b) Coherent control of RPs.

It is possible to drive the system to a target non-eigenstate of the spin Hamiltonian at a specific time t_f as shown in Fig.2a. Using reverse time evolution from the final target state, time dependent targets were calculated. As same as the static state population control, we can calculate the optimized RF field for the system to approach the calculated moving target. Fig. 2b, shows a model calculation of the coherent control of a RP with one nuclear spin in B_0=0.05 mT.

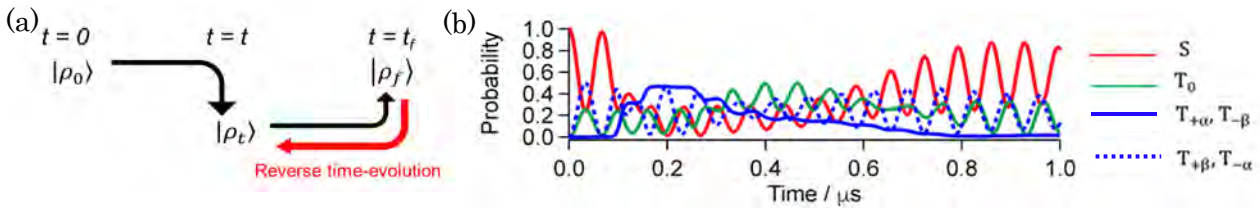

Fig.2. a) Concept of the coherent control. b) Calculation result in the system of a singlet born RP with single nuclear spin. RF field once store the population to $T_{+\alpha}$ and $T_{-\beta}$. After that, the optimized RF transfer the state to T_0, $T_{+\beta}$, and $T_{-\alpha}$ states, and these states are to refocus to the singlet state by the coherent spin dynamics. In the model calculation, 80% of the RP return to the Singlet state at 1 μs.

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Closing Remarks

Hidemi Ishiuchi

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Short Biography

Hidemi Ishiuchi received the B.S. and M.S. degrees in physics at the University of Tokyo in 1978 and 1980, respectively. Since he joined Toshiba Corporation in 1980, he has been working on DRAM development. From 1988 to 1989, he has been at Stanford University as a Visiting Scholar to study BiCMOS technologies. From 1993 to 1995, he has been at IBM East Fishkill as a member of 256M bit DRAM joint development project among IBM, Siemens, and Toshiba. From 1996 to 2006, he has been working on development of advanced CMOS technologies including SOI MOSFETs, RF mixed signal CMOS technology, embedded DRAM technology, TCAD (Technology CAD), etc. In 2007, he moved to Corporate Research and Development Center, working on semiconductor devices and HDD. He was Director of Center for Semiconductor Research and Development Center in 2008 and Chief Technology Executive of Semiconductor Company from 2009 to 2013. From 2016 to 2019, he has been President of EIDEC, a consortium for R&D of semiconductor process technology including EUV (Extreme Ultra Violet) lithography. Since 2019, he has been Assistant to General Manager of Technology and Innovation Division, Kioxia Corporation. He retired from Kioxia Corporation in October, 2020.

He is currently a Sub Program Director of the MEXT Q-LEAP, which is a national project on quantum technology. He is a member of the Japan Society of Applied Physics, the Physical Society of Japan, and IEEE.

List of short presentations

Session 4-1-A

[Chair] Dr. Moriyoshi Haruyama (National Institute of Advanced Industrial Science and Technology (AIST))
[Co-chair] Dr. Akihiro Kuwahata (The University of Tokyo)

No.	Title	Name	Affiliation
A-1	Quantum Sensing: Enlarging Range with Negligible Loss in Sensitivity	David Herbschleb	Kyoto University
A-2	Improvement of the Uniformity of the Magnetic Field in a Magnetic Shield Box Using Steel Tiles	Shixu Jin	The University of Tokyo
A-3	Hydrogenated Diamond Surfaces and their Use in Nitrogen-Vacancy Sensing Applications	Daniel McCloskey	University of Melbourne
A-4	Electron Spin Contrast of High Density and Perfectly Aligned Nitrogen-Vacancy Centers Synthesized by Chemical Vapor Deposition	Kosuke Mizuno	Tokyo Institute of Technology
A-5	Photoelectrical Detection of NV Centers Utilizing Lateral p–i–n Diode	Takuya Murooka	Toyko Institute of Technology
A-6	Evaluationof Magnetic Sensitivityof Photoelectrical Detection of NV Centers in a Lateral Diamond p-i-n Diode	Masafumi Shiigai	Tokyo Institute of Technology
A-7	Temperature Sensing Using Group-IV Color Centers in Diamond	Motoki Nakamura	Tokyo Institute of Technology

[Overseas mentors]
Prof. Fedor Jelezko (Ulm University)
Dr. David A. Simpson (University of Melbourne)
[Domestic mentors]
Prof. Mutsuko Hatano (Toyko Institute of Technology)
Prof. Norikazu Mizuochi (Kyoto University)
Prof. Masaki Sekino (The University of Tokyo)

Session 4-1-B

[Chair] Dr. Fumihiro Kaneda (Tohoku University)
[Co-chair] Dr. Yuta Michimura (The University of Tokyo)

No.	Title	Name	Affiliation
B-1	Towards Suspension Noise Measurements of Crystalline Fibres at Cryogenic Temperatures for Torsion Pendulums	Ching Pin Ooi	The University of Tokyo
B-2	Cryogenic Monolithic Torsion Pendulum Made of Silicon for Gravity Gradient Sensing	Satoru Takano	The University of Tokyo
B-3	Quantum Radiation Pressure Fluctuation in a Linear Optical Cavity	Takuya Kawasaki	The University of Tokyo
B-4	High-Q Monolithic Pendulum for Quantum-Limited Sensing	Seth Benjamin Catano-Lopez	Tohoku University
B-5	Angular Dependence of Photon-Pair Generation via Biexciton	Hiroya Seki	The University of Electro-Communications
B-6	Temperature Dependence of Photon-Pair Generation via Biexciton	Donggeun Son	The University of Electro-Communications

[Overseas mentor]
Dr. Frank Schlawin (Max-Planck Institute for the Structure and Dynamics of Matter)
[Domestic mentors]
Prof. Masaki Ando (The University of Tokyo)
Prof. Akihito Ishizaki (National Institutes of Natural Sciences)
Prof. Ryosuke Shimizu (The University of Electro-Communications)
Prof. Satoshi Yamasaki (Toyko Institute of Technology)

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[Chair] Dr. Yu Mukai (Kyoto University)
[Co-chair] Prof. Nobuyuki Matsuda (Tohoku University)

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C-1	Demonstration of Three-Dimensional High-Resolution Quantum Optical Coherence Tomography Using Frequency-Entangled Photon Pairs	Naofumi Abe	Kyoto University
C-2	Direct Observation of Parametric Fluorescence in the Mid-Infrared Region Using an InSb Detector	Masaya Arahata	Kyoto University
C-3	Ultra-Coherent Fundamental Mode Mechanical Resonators Designed Using Topology Optimization	Dennis Hoj	Technical University of Denmark
C-4	Generation of Correlated Photon Pairs from a Silicon Micro-Ring Resonator with a Gain-Switched Laser Diode	Fan Yang	Tohoku University
C-5	Plasmon-Enhanced Polarized Single Photon Source Coupled to an Optical Nanofiber at Room Temperature	Masakazu Sugawara	Tohoku University

[Overseas mentor]
Prof. Ulrik Lund Andersen (Technical University of Denmark)
[Domestic mentors]
Prof. Shigeki Takeuchi (Kyoto University)
Prof. Keiichi Edamatsu (Tohoku University)
Prof. Kenichi Nakagawa (The University of Electro-Communications)
Dr. Kosuke Shibata (Gakushuin University)

Session 4-2-D

[Chair] Dr. Akihiro Kuwahata (The University of Tokyo)
[Co-chair] Dr. Moriyoshi Haruyama (National Institute of Advanced Industrial Science and Technology (AIST))

No.	Title	Name	Affiliation
D-1	CVD Growth Parameter Dependence of Aligned Dense Nitrogen Vacancy Centers for Magnetometry	Moriyoshi Haruyama	National Institute of Advanced Industrial Science and Technology (AIST)
D-2	Nitrogen Concentration Control in Diamond Growth for NV Center Formation	Tokuyuki Teraji	National Institute for Materials Science (NIMS)
D-3	Optimal Amount of Vacancy in Diamond for Negative-Charge Stability of NV Centers at Various Nitrogen Concentration	Chikara Shinei	National Institute for Materials Science (NIMS)
D-4	Performance of Implanted Nitrogen Vacancy Centers as a Figure of Merit for the Quality of Diamond in Quantum Applications	Johannes Lang	Ulm University
D-5	Effect of Mis-Orientation Angle for CVD Grown Perfectly Aligned NV Center on (111) Diamond Substrate	Takashi Yamamoto	Tokyo Institute of Technology
D-6	Evaluation of NV Centers in Bulk Diamond Formed by Electron Beam Irradiation	Shuya Ishii	National Institutes for Quantum and Radiological Science and Technology (QST)
D-7	Fabrication of SiV Centers Inside Nanodiamonds Using Ion Implantation	Konosuke Shimazaki	Kyoto University

[Overseas mentors]
Prof. Fedor Jelezko (Ulm University)
Dr. David A. Simpson (University of Melbourne)
[Domestic mentors]
Prof. Takayuki Iwasaki (Toyko Institute of Technology)
Dr. Takeshi Ohshima (National Institutes for Quantum and Radiological Science and Technology (QST))
Dr. Hiromitsu Kato (National Institute of Advanced Industrial Science and Technology (AIST))

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[Chair] Dr. Naota Sekiguchi (Gakushuin University)
[Co-chair] Dr. Yoshitaka Miura (National Institute of Advanced Industrial Science and Technology (AIST))

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E-1	Spin Squeezing Induced by Consecutive Imaging of a Bose-Einstein Condensate	Naota Sekiguchi	Gakushuin University
E-2	Development of Photon Number Resolving Detector by Small Size Ti/Au-TES	Yoshitaka Miura	National Institute of Advanced Industrial Science and Technology (AIST)
E-3	Nonlocal Variable-Strength Measurements of N Qubits Using GHZ-like Entanglement	Pierre Vidil	Tohoku University
E-4	Development of Single-Photon Detectors with Spatial Resolution	Kemeng Chen	The University of Electro-Communications
E-5	Probing Excited-State Dynamics with Quantum Entangled Photons: Two-Photon Coincidence Counting Measurement with Tripartite Entangled Photons	Yuta Fujihashi	National Institutes of Natural Sciences

[Overseas mentors]
Prof. Ulrik Lund Andersen (Technical University of Denmark)
Dr. Frank Schlawin (Max-Planck Institute for the Structure and Dynamics of Matter)
[Domestic mentors]
Prof. Keiichi Edamatsu (Tohoku University)
Prof. Takuya Hirano (Gakushuin University)
Prof. Akihito Ishizaki (National Institutes of Natural Sciences)

Session 4-2-F

[Chair] Dr. Ryuji Igarashi (National Institutes for Quantum and Radiological Science and Technology (QST))
[Co-chair] Dr. Lewis M Antill (JST PRESTO, Saitama University)

No.	Title	Name	Affiliation
F-1	Ab-Initio Quantum Chemical Theory of Long-Distance Electron Tunneling in Proteins	Hirotaka Kitoh-Nishioka	JST PRESTO, Kobe University
F-2	X-Ray Induced Cell Cycle Arrest and Raises the Cellular Temperature	Tomokazu Ihara	Ibaraki University
F-3	13C Pulsed Dynamic Nuclear Polarization Using Pentacene or NV-Centers in Diamond at Room Temperature	Koichiro Miyanishi	Osaka University
F-4	High Efficiency Rf-to-Light Conversion through Improved Electromechanical Coupling for NMR Detection	Yusuke Tominaga	Kyoto University
F-5	Magnetic Characterisation of Cuticulosomes in the Inner Ear Hair Cells of Pigeons	Robert de Gille	University of Melbourne
F-6	A Simple Deaggregation Method Producing Single-Digit Detonation Nanodiamonds	Frederick Tze Kit So	Kyoto University

[Overseas mentor]
Prof. Johnjoe McFadden (University of Surrey)
[Domestic mentors]
Prof. Yoshinobu Baba (National Institutes for Quantum and Radiological Science and Technology (QST), Nagoya University)
Prof. Tetsuya Suhara (National Institutes for Quantum and Radiological Science and Technology (QST))
Prof. Makoto Negoro (Osaka University)

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Session 6-1-G

[Chair] Dr. Hiroki Morishita (Kyoto University)
[Co-chair] Dr. Keigo Arai (Toyko Institute of Technology)

No.	Title	Name	Affiliation
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G-2	Label-Free Phase Change Detection of Lipid Bilayers Using Nanoscale Diamond Magnetometry	Hitoshi Ishiwata	JST PRESTO, Tokyo Institute of Technology
G-3	Biomagnetic Field Measurement System Using NV Centers in Diamond	Daisuke Nishitani	Tokyo Institute of Technology
G-4	Wide Field Detection of Inverse Magnetostrictive Effect Using NV Centers in Diamond Towards Biological Mass Microscopy	Ryota Kitagawa	Tokyo Institute of Technology
G-5	Brain Mapping of Visual Cortex with Quantum Magnetoencephalography Devices	Zonghao Xin	The University of Tokyo
G-6	Development of Bio-Nanoprobe for NVC-SPM	Takeshi Nakayama	Hitachi, Ltd.

[Overseas mentors]
Prof. Ronald Walsworth (University of Maryland)
Prof. Susumu Takahashi (University of Southern California)
[Domestic mentors]
Prof. Takayuki Iwasaki (Toyko Institute of Technology)
Prof. Satoshi Yamasaki (Toyko Institute of Technology)
Dr. Tokuyuki Teraji (National Institute for Materials Science (NIMS))

Session 6-2-H

[Chair] Dr. Keigo Arai (Toyko Institute of Technology)
[Co-chair] Dr. Hiroki Morishita (Kyoto University)

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H-2	Electrical Detection of Magnetic Resonance of NV Centers in Diamond Around Zero Bias Voltage	Hiroki Morishita	Kyoto University
H-3	Improvement of Charge Stability and Spin-Coherence Properties of Near-Surface NV Centers in Diamond	Tetsuri Nishikawa	Kyoto University
H-4	Canceling Environmental Magnetic Noise by Gradiometer Using NV Centers in Diamond Pair	Katsumi Suzuki	Tokyo Institute of Technology
H-5	Crossed Two-Layer Coplanar-waveguide Circuit for Extending Spin Dephasing Time T2* of Ensemble NV Centers in a Bulk Diamond	Yuki Kamitsubo	Tokyo Institute of Technology
H-6	Optical Properties of Lead Vacancy Centers in Diamond	Peng Wang	Tokyo Institute of Technology
H-7	Numerical Optimization of Grating Coupler on Bulk Diamond with Nitrogen-Vacancy Center	Tetsu Takahashi	Toyohashi University of Technology

[Overseas mentors]
Prof. Ronald Walsworth (University of Maryland)
Prof. Susumu Takahashi (University of Southern California)
[Domestic mentors]
Prof. Mutsuko Hatano (Toyko Institute of Technology)
Prof. Takashi Yatsui (Toyohashi University of Technology)
Dr. Shinobu Onoda (National Institutes for Quantum and Radiological Science and Technology (QST))

Quantum sensing: enlarging range with negligible loss in sensitivity

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Introduction

Quantum sensing has a promising future due to its high sensitivity and potential for high resolution. Magnetic-field sensing [1] and temperature sensing [2] are examples possible utilising the phase of the electron spin of nitrogen-vacancy (NV) centres. An important property for sensors is the dynamic range, which is the ratio of the largest range attainable and the sensitivity. This exposes the downside of such sensitive sensors, since the range is rather limited due to the rotational symmetry of the spin, because the phase of the spin can be determined within 2π only. Previously, an improvement of the dynamic range with 2^6 was achieved for DC magnetic fields [3], while a recent technique for AC magnetic fields increased the range by a theoretical maximum of 5,000 times [4]. These techniques improve the range, but generally at the cost of sensitivity. Here, we propose an algorithm to increase the range for quantum sensing while retaining the high sensitivity, and we demonstrate it for AC magnetic-field sensing.

Method

We use individual electron spins of NV centres in phosphorus-doped diamond for our room-temperature experiments. Our sample was epitaxially grown by chemical-vapour deposition onto a Ib-type (111)-oriented diamond substrate with enriched ^{12}C (99.998%) and a phosphorus concentration of 6×10^{16} atoms cm^{-3} [5].

At first, we simulated our designed algorithm to explore its details, revealing that even with increasing range, the sensitivity can get arbitrarily close to the best possible sensitivity of a small-range standard measurement. As demonstration, we measured AC magnetic fields showing a dynamic range of about 10^7 (see FIG. 1), which is an improvement of two orders of magnitude over the previous best algorithm [6]. Our results are limited by technical constraints only, and could in principle be improved further by using ensembles of NV centres (improving the sensitivity) or improved equipment/techniques (increasing the range). The demonstrated algorithm is not limited to be utilised by NV centres or for AC magnetic-field sensing. It is suitable for systems with limitations similar to the 2π-ambiguity, and any spin-sensed quantity can be measured, such as DC magnetic-field and temperature.

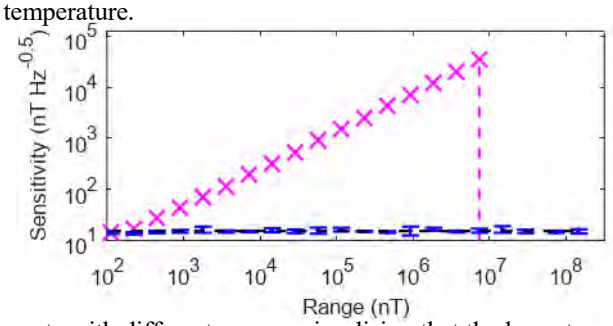

FIG. 1. Sensitivity for measurements with different ranges, visualising that the lowest sensitivity is reached for each range. Blue dots display the sensitivity for the proposed algorithm, while magenta crosses plot the sensitivity of a standard measurement. Please note that the standard measurement reaches its limit for the range earlier with the same settings.

This work was supported by MEXT Q-LEAP (No. JPMXS0118067395), KAKENHI (No. 15H05868, 16H06326), and the Collaborative Research Program of ICR, Kyoto University (2020-110).

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Improvement of the Uniformity of the Magnetic Field in a Magnetic Shield Box using Steel Tiles

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Introduction

One of the significant challenges for recent wearable magnetoencephalography (MEG) devices is the large signal perturbations caused by head movements under a non-uniform magnetic field inside a shielded room[1)]. The purpose of this study was to propose a method to improve the uniformity of the magnetic field inside the magnetic shield room by placing steel tiles on its faces. From our results, this method shows possibility to applicate in future wearable MEG system, such like Diamond NV sensor and OPM.

Method

We simulated uniform external magnetic field for 46.6 μT. We analyzed forward problem by attaching steel plates of 60×60×1 mm in size to the inner surface of a shield box of 200×200×350 mm in size. We simulated 16 shimming locations around the shield box, and the magnetic field uniformity was evaluated by standard deviation. We solved an inverse problem to identify the locations to attach the shimming tiles for a given target distribution of the magnetic field. We used the Tikhonov regularization[2)] and the L-curve method[3)] to determine the optimal parameters.

Results

We chose lambda=5e-8 corresponding to the corner of the L-curve considering the results of the forward problem. And then we solve the inverse problem to determine the amount of shimming steel plates to minimize the magnitude of residual magnetic field inside of simulated magnetic shield box. FIG. 1 shows the result of before shimming and after shimming. The center of residual magnetic field inside magnetic shield box reduced nearly 5 μT, which means the shielding factor of magnetic shield box has improved 131% after shimming steel plates with the results of inverse problem. The standard deviation of 9 measurement points inside magnetic shield box is 0.379 before shimming and 0.211 after shimming, respectively.

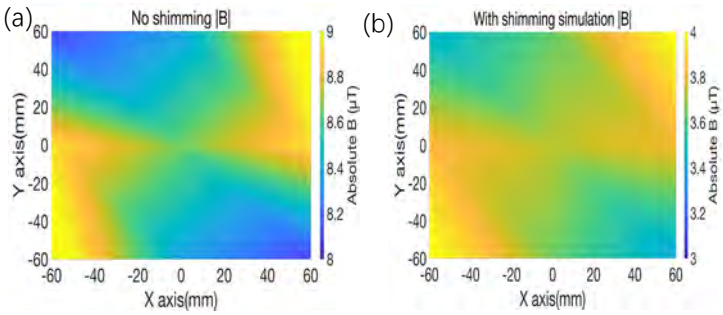

FIG. 1: Absolute value of magnetic field distribution of (a) no shimming and (b) with shimming.

Conclusion

From our uniformity comparison between no shimming and after shimming, magnetic uniformity has improved 44% after using shimming steel plates in 2D simulation, which means we could control the magnetic field uniformity with combination of shimming steel plates, this shows feasibility in future wearable MEG system.

Reference

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Acknowledgement

This work was supported by MEXT Q-LEAP with the Grant Number JPMXS0118067395.

Hydrogenated Diamond Surfaces and their Use in Nitrogen-Vacancy Sensing Applications

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Introduction

Hydrogen-terminated diamond surfaces exhibit a remarkable property whereby the highly-insulating diamond bulk transitions to being quasi-metallic over the span of just a few nanometers. This transition has its origin in the negative electron-affinity resulting from the hydrogen-carbon dipole moment at the surface, which causes spontaneous transfer of valence electrons from the diamond bulk into the lowest unoccupied molecular orbitals of adsorbed atmospheric molecules [1]. Numerous proposed sensing applications of the negatively-charged nitrogen-vacancy (NV^-) centers in diamond require them to exist as close to the surface as possible, which ordinarily would exclude the utility of hydrogenated surfaces since they tend to discharge NV^- into neutral NV. Here, we perform calculations using our newly developed depth-dependent Schrödinger-Poisson solver to show that, when the effects of surface sp^2-related defects [2] are taken together with existing knowledge of the density of atmospheric adsorbates, the near-surface electric field as measured using optically-detected magnetic resonance imaging [3] can be predicted with a high degree of accuracy. These results strongly suggest that predictions of the diamond surface potential and NV charge-state populations would be similarly accurate, opening up the possibility of imaging the in-plane (at the diamond surface) electric field profiles of fabricated devices using the NV charge-state alone, eliminating the need for near-surface NV^- for this particular application.

Methods

Calculations are performed using our own Schröinger-Poisson solver to extract the NV charge-state populations and depth-distribution, the diamond surface potential, and the electric field profile normal to the surface (FIG. 1). Changes to the NV charge-state population (and therefore fluorescence) resulting from the surface potential changes due to the operation of electronic devices (FIG. 2) should in principle allow for in-plane electric field imaging provided our model can reliably relate the surface potential to the charge-state, and therefore the observed changes in PL

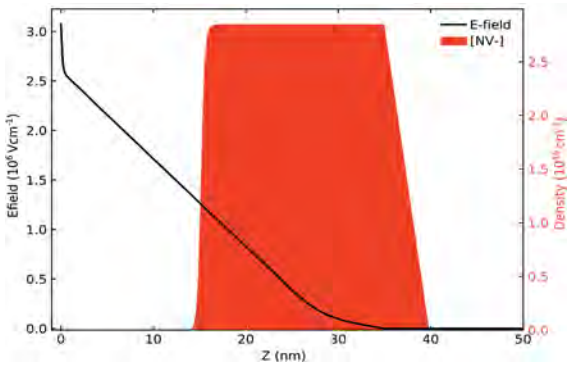

FIG. 1. An example of the calculated E field and NV^- distribution from our Schrödinger-Poisson solver using a surface adsorbate density of 10^{13}cm^{-2} and assuming a 10keV nitrogen implant with a dose of 10^{13}cm^{-2}.

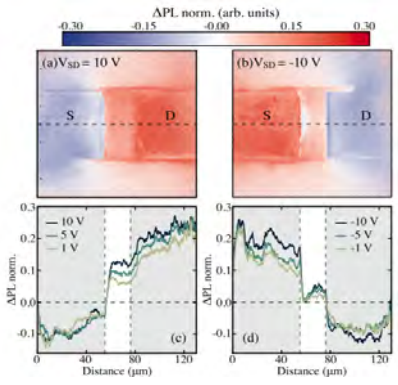

Fig. 2. Changes in NV- PL as measured during the biasing of a hydrogen-terminated diamond ribbon between the source and drain contacts. Credit: [4]

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Electron Spin Contrast of High Density and Perfectly Aligned Nitrogen-Vacancy Centers Synthesized by Chemical Vapor Deposition

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Introduction

Preparation of high-quality ensemble nitrogen-vacancy (NV) centers is a key for high sensitivity magnetometer. Several techniques are used to fabricate a high-density NV ensemble, e.g., electron beam irradiation and chemical vapor deposition (CVD). Although the highest NV concentration has been reported using the irradiation method,[1] only one-fourth of the ensemble can be utilized for sensing due to the NV center's structural symmetry. CVD growth with a step-flow condition provides a perfectly aligned NV ensemble, leading to a four-fold higher contrast.[2] We have achieved a perfectly aligned NV center with a high concentration of up to 4 ppm[3] and indicated a possibility to improve the generation yield, a central challenge of the CVD method.[4] However, the details of spin and optical characteristics are not yet studied well. In this study, we investigate six samples with varying nitrogen concentrations from 10 to 170 ppm.

Method and Result

Using confocal microscopy and electron spin Rabi measurement, we found that the electron spin contrast decreases as nitrogen concentration increases (Table I and Fig. 1(a)). However, the fluorescence intensity increases, and the perfect alignments are kept in all samples (Fig. 1(a)). We speculate this can be attributed to the excited-state dynamics of the NV center. Using time-resolved fluorescence analysis with subnanosecond timing resolution, electron spin populations exhibit a negative correlation with the nitrogen concentration (Fig. 1(b)). Moreover, the excited-state lifetimes of the synthesized NV centers are shorter than one of an individual NV center, and this shortening is also correlated with the nitrogen concentration. Our results indicate that nitrogen-related defects can interact with optically excited NV centers, providing another relaxation pathway from the excited state. This additional relaxation is a non-radiative and spin-mixing process working as a competitive relaxation against the intersystem crossing (ISC), which is a crucial process of optical initialization of the NV center. The spin selectivity of ISC is effectively impaired, the electron spin-0 population gets low, and then the Rabi contrast deteriorates. Although the concrete process and defects limiting the NV's property are still unclear, our result is consistent with previous studies involving other fabrication techniques.[5,6] Time-resolved analysis will pave the way to understand NV—defect interaction, which is significant to improve the sensitivity of quantum sensors.

Table I. Characteristics of each sample.

Sample	[N] (ppm)	Intensity (cps)	Contrast (%)
#6-2	11.7	1.2E7	29.7
#6-1	23.3	2.8E8	28.3
#8-3b	23.4	2.6E8	31.7
#8-1	108.9	6.6E9	24.8
#3-2	154.3	7.3E9	19.3
#3-4	171.3	1.2E10	18.5

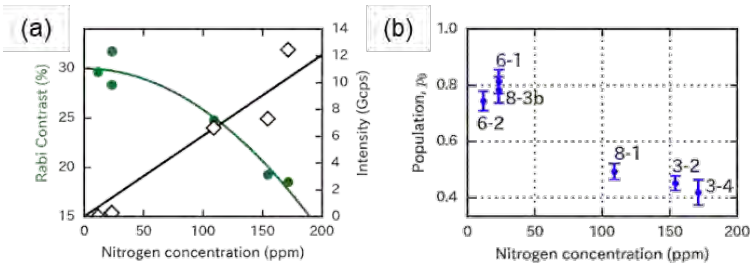

Fig 1. (a) Rabi contrast and Fluorescence intensity as a function of nitrogen concentration in the CVD film. (b) Excited sate population of spin-0 measured by time-resolved analysis.

This work was supported by the MEXT Quantum Leap Flagship Program (MEXT Q-LEAP), Grant Number JPMXS0118067395, MEXT JSPS KAKENHI Grant No. 18H01472 and No. 17H01262, and JST, PRESTO, Grant Number JPMJPR17G1, Japan.

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Photoelectrical Detection of NV Centers Utilizing Lateral p–i–n Diode

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Introduction

Negatively charged nitrogen-vacancy (NV) centers in diamond have great potential as solid-state quantum magnetometers. Spin states of NV centers are often read out by detecting fluorescence emitted from NV centers. However, the photon detection efficiency is as low as a few percent because of its high refractive index of 2.4. Instead of the optical detection, photoelectrical detection techniques have been proposed to detect spin states as a spin-dependent photocurrent [1–4]. For this detection technique, efficient current detection is essential to obtain high sensitivity. In this study, we demonstrate photoelectrical detection by utilizing a diamond lateral p–i–n diode incorporating NV centers.

Method

Fig. 1 shows a schematic of the fabricated diamond p–i–n diode. A 5 μm-thick intrinsic diamond layer lightly doped with phosphorus ([P]: ~10^{16} cm^{-3}) was grown onto a (111) Ib-type HPHT diamond substrate with microwave plasma-enhanced chemical vapor deposition (MPCVD). The patterned boron-doped p^+-type ([B]: ~10^{20} cm^{-3}) and the phosphorus-doped n^+-type ([P]: ~10^{20} cm^{-3}) diamond regions were individually grown on the top of the i-layer by MPCVD with metal masks. ^{14}N ions were implanted with a dose of 10^{12} cm^{-2} at an acceleration energy of 350 keV, leading to a projected depth of 350 nm. Finally, Ti (30 nm)/Pt (30 nm)/Au (100 nm) stacks were formed as ohmic electrodes.

Fig. 2 shows the excitation-laser-power dependence of the photocurrent measured in the i-layer under the p^+-layer under a zero-bias condition (photovoltaic-mode operation). The fact that the photocurrents are detected under the photovoltaic-mode operation implies that photocarriers excited from NV centers are efficiently collected by the electric field generated in the depletion layer. A quadratic increase of photocurrent is due to a two-step excitation process. The increasing tendency of the photocurrent becomes linear rather than quadratic over 6 mW because the transition from the $^3A_2$ to ^3E was saturated. Fig. 3 shows the photoelectrically detected magnetic resonance (PDMR) spectra measured under the photovoltaic-mode operation. The obtained PDMR spectra show a dip at 2.87 GHz without a bias magnetic field, corresponding to the zero-field splitting of NV^-. The dip split into four dips when a magnetic field was applied with a permanent magnet. We measured the spin-dependent photocurrent even without bias application to the device, which will be an important technology for the fabrication of an integrated quantum system.

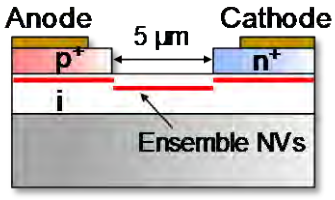

FIG. 1 Schematic of the lateral diamond p–i–n diode incorporationg NV centers.

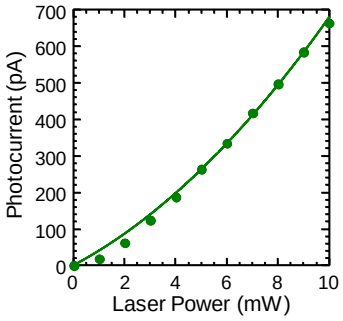

FIG. 2 Laser-power dependence of the photocurrent measured under the photovoltaic-mode operation.

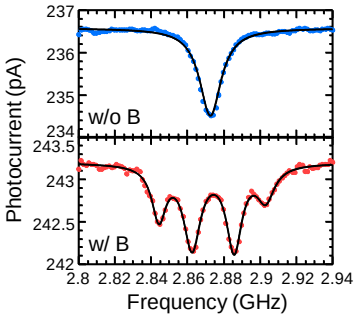

FIG. 3 PDMR spectra measured under the photovoltaic-mode operation.

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Evaluation of magnetic sensitivity of photoelectrical detection of NV centers in a lateral diamond p-i-n diode

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Introduction

Negatively charged nitrogen-vacancy (NV^-) centers in diamond are expected as a high-sensitive and high-resolution magnetic field sensor. Generally, the spin-state is read out as fluorescence emitted from the NV^- centers. However, the fluorescence detection efficiency is limited by a high refractive index of diamond, 2.4. Alternative method which is readout by photocurrent solves this issue[1-3]. In this study, we evaluate the magnetic sensitivity of the photoelectrical detection of the NV centers incorporated in a lateral diamond p-i-n diode.

Method

Fig. 1 shows a schematic cross-section of the diamond p-i-n diode. First, a 5 μm-thick i-layer was grown onto a (111) Ib-type substrate by microwave plasma CVD. Next, an n^+-layer ([P]: ~10^{19} cm^{-3}) and a p^+-layer ([B]: ~10^{20} cm^{-3}) were grown onto the i-layer. Ensemble NV centers were fabricated by ion implantation and annealing. Ti/Au/Pt (30/30/100 nm) electrodes were fabricated by electron beam deposition. Photocurrent was detected with differentially connected preamplifiers under green laser (532 nm) illumination. For electron spin resonance measurements, microwave was irradiated through a Cu wire above the p-i-n diode and a magnetic field was applied by a permanent magnet.

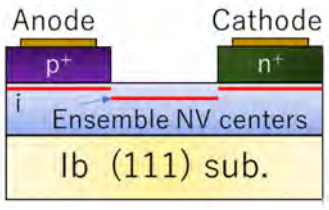

FIG. 1 Schematic of lateral diamond pin-diode

Fig 2 (a) shows a photoelectrically detected magnetic resonance (PDMR) spectrum under a static magnetic field without voltage application to the diode. Thus, the photocurrent is efficiently extracted by the depletion layer generated in the p-i-n diode. A DC magnetic field sensitivity of the photocurrent detection method was estimated to be ~20 $\mu T/\sqrt{Hz}$. Fig 2 (b) shows a magnetic field noise density spectrum. It is found that the 50 Hz multiple noise, especially 50 and 150 Hz, has a large effect on the evaluated magnetic sensitivity. A lock-in detection would suppress the low frequency noises and improve the magnetic sensitivity.

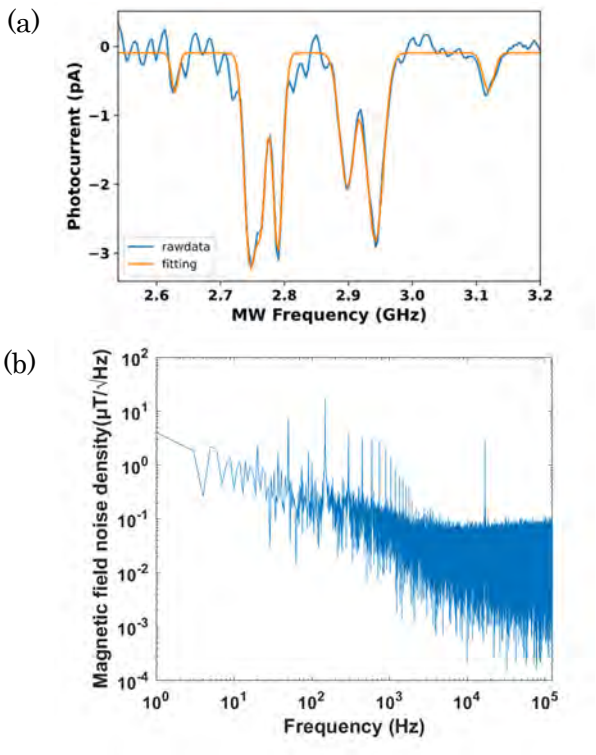

FIG. 2 (a)PDMR spectra measured under magnetic field (b)Magnetic field noise density

Reference

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Acknowledgments

This work was supported by MEXT Quantum Leap Flagship Program (MEXT Q-LEAP) Grant Number JPMXS0118067395, and MEXT/JSPS KAKENHI Grant Number 18H01472.

Temperature sensing using group-IV color centers in diamond

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Introduction

Temperature measurement methods with a high spatial and temporal resolution are required in a wide range of fields such as electronic devices and biological cells. Group-IV color centers in diamond work as a nanoscale temperature sensor. So far, two methods have been reported, the observation of the shift of the wavelength with spectrometer[1], lowering the temporal resolution, and photoluminescence excitation (PLE) requiring a tunable laser[1]. In this study, a new simple method for temperature sensing is proposed and performed using GeV centers in diamond.

Method and Results

Fig. 1a shows the principle of the temperature sensing method we developed in this study. As the temperature rises, the zero-phonon line (ZPL) of the GeV centers at around 602 nm shifts to a longer wavelength and its intensity decreases. Thus, the temperature can be detected by monitoring this fluorescence change with an ultra-narrow bandpass filter (BPF). Figs. 1b and 1c show a high-pressure and high-temperature grown microdiamond[2] with a size of 8 μm placed on a quartz substrate. The emission from the GeV centers was observed upon optical excitation using a 532 nm laser.

First, we selected the wavelength of BPF (λ_{BPF}) to efficiently observe the fluorescence change. Fig. 2 shows spectra of the GeV centers from 303 K to 363 K. Between 599 and 605 nm, we analyzed the change of the fluorescence intensity with a 3 nm band width. The long wavelength region of ZPL does not show monotonous attenuation because of the redshif of ZPL. Consequently, we selected a BPF with a center wavelength of 601 nm and a bandwidth of 3 nm. Then, the characteristics of fluorescence intensity with respect to temperature changes were measured. Fig. 3 shows a linear decay trend from 30 to 90 ° C. The temperature response of the intensity signal was estimated to be $(\Delta I/I_0)/\Delta T = 0.67\ [\%/K]$, indicating the temperature change can be read out with nanoscale resolution using this method.

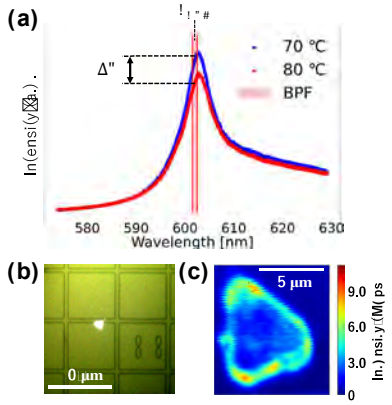

FIG. 1 Principle of temperature sensing method and microdiamond containing GeV centers as sensing probe. (a) Change of GeVs fluorescence as a function of temperature. (b) optical image. (c) confocal microscope image.

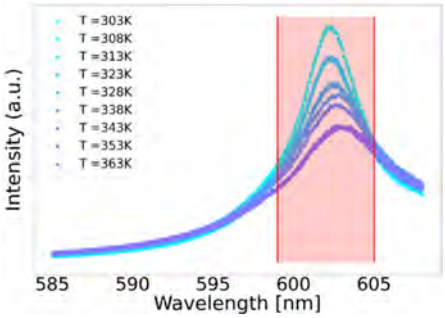

FIG. 2 PL spectra of GeVs from 303K to 363K.

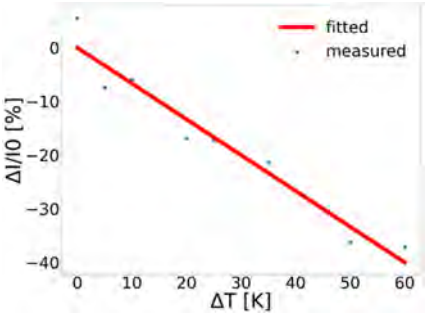

FIG. 3 Fluorescence extracted with a narrow BPF as a function of temperature.

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Acknowledgement

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Towards suspension noise measurements of crystalline fibres at cryogenic temperatures for torsion pendulums

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Introduction

Thermal noises are an intrinsic part of mechanical systems, and limits the sensitivity of measuring systems. For the case of TOrsion-Bar Antenna (TOBA)[1], a proposed gravitational wave/gravitational gradient sensor, the suspension thermal noise is one such limit.

Crystalline fibres have intrinsically low mechanical loss, making them a good fit for the suspension fibre of TOBA. TOBA is a cryogenic torsion pendulum, and there has not been much available literature for suspension noise measurements for cryogenic torsion pendulums.

This works aims to fill in this gap in the literature, with an eye for TOBA, but will be useful for any project working with cryogenic torsion pendulums, with a high sensitivity requirement.

We review here the current progress towards the measurements of cryogenic Q values of crystalline fibre suspensions in torsion pendulums. The goal is to achieve $Q \approx 10^8$ at 4 K, for use with TOBA.

Method

An experimental setup is being assembled, for cryogenic Q factor measurements using the ringdown method. An optical lever will be used to measure the angular amplitude of the torsion pendulum. Sapphire fibers 1 mm in diameter will be measured, with the possibility of using other crystalline materials. These fibres have been measured to have $Q \approx 10^5$ at room temperature[2].

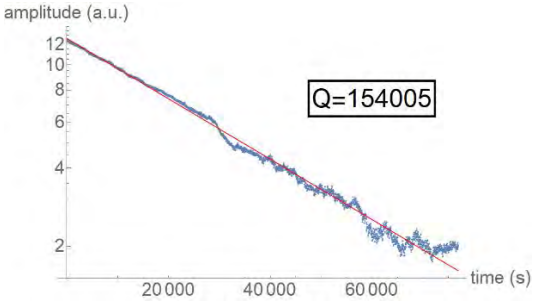

FIG. 1. Q factor and ringdown measurement for a torsion pendulum suspended by a 1 mm diameter sapphire fibre at room temperature, at 1.3 Hz

This work is supported by MEXT Q-LEAP Grant Number JPMXS0118070351

Reference

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Cryogenic Monolithic Torsion Pendulum Made of Silicon for Gravity Gradient Sensing

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Introduction

Gravity gradient fluctuations are essential observation targets for precise measurement of motion of masses. From their measurement we obtain information about their source behavior. Recently fluctuations at low frequency, around 0.1 Hz, has been aimed for earthquake early alert using transient change of gravity potential [1] and for observation of GWs from mergers of intermediate-mass black holes [2].

A torsion-bar antenna (TOBA) is a ground-based gravity gradiometer proposed for measurement of gravity gradient fluctuations in such frequencies [2]. It measures torsional rotation angle of horizontally suspended mass(es) induced by gravity gradient fluctuations. Several prototypes and related technologies have been developed [3,4], and now we are planning to make a 30-cm scale prototype (Phase-III TOBA). Here we show design for Phase-III TOBA and future prospects.

Method

The goal of Phase-III TOBA is to achieve the strain sensitivity 10^{-15} / √Hz at 0.1 Hz and demonstrate noise reduction, especially thermal noise by cooling the suspension system down to 4 K. Figure 1 shows the design setup of Phase-III TOBA. 2 bars (test masses) will be suspended horizontally, and the pendulums are kept at cryogenic temperature. Motion of the bars will be read out by interferometers. Figure 2 shows the design sensitivity of Phase-III TOBA.

One of the key technologies to reach the target sensitivity is reduction of thermal noise of suspensions. Thermal noise depends on temperature and mechanical loss of the suspension system. Suspending wires and the test masses will be made of silicon, which has very small loss at cryogenic temperature, and cooled down to 4 K. Another benefit of the silicon test masses is decrease of magnetic coupling. From previous measurement with metal (cupper) test masses, magnetic coupling from induced current flowing the metal was problematic. Using silicon will reduce the coupling drastically because of its small electrical conductivity at cryogenic temperature.

Another necessary technology is reduction of sensing noise of interferometer. Extra motion of the optical components consisting of the readout interferometer limits the measurement of motion of the test mass. To suppress motion of the optics we will make a monolithic interferometer. Monolithic interferometer consists of optical components directly glued on a plate.

We have developed a cryostat system to develop the technologies above (silicon suspension systems and monolithic interferometer). About the monolithic interferometer, we plan to make a small prototype to evaluate effects of cooling using this cryostat. For silicon suspension system, we are now designing the suspension system in detail.

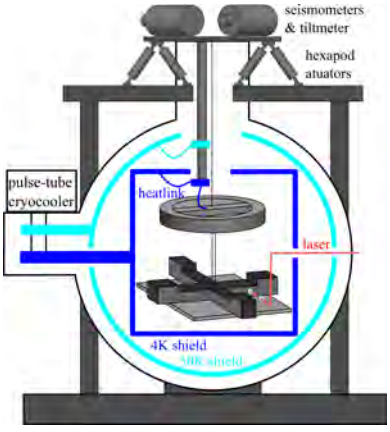

FIG. 1. Setup of Phase-III TOBA.

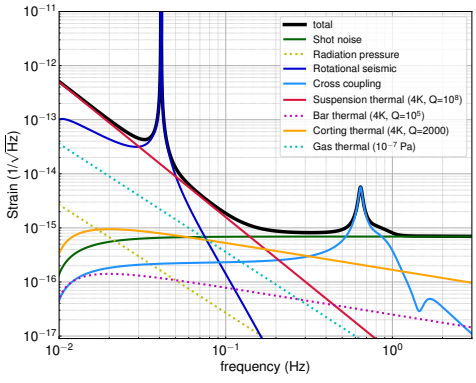

FIG. 2. Target Sensitivity of Phase-III TOBA.

Acknowledgement

This work was supported by MEXT Q-LEAP Grant Number JPMXS0118070351.

Reference

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[3]K. Ishidoshiro *et al.*, *Phys. Rev. Lett.*, 106, 161101 (2011) [4]A. Shoda *et al.*, *Phys. Rev. D*, 95, 082004 (2017)

Quantum radiation pressure fluctuation in a linear optical cavity

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Introduction

One fundamental noise in optomechanical force sensors is the quantum noise. Towards realizing optomechanical highly sensitive gravity gradiometer, the quantum noise should be reduced. To elucidate the nature of quantum noises and the reduction technics of quantum noises, observation of the quantum noise is necessary at the first step.

In our experiment, we aim at the observation of the quantum radiation pressure fluctuation that is one kind of quantum noises. To observe quantum radiation pressure fluctuation in a cavity, we need high power intracavity power; therefore, the stable trapping of the test mass mirror is essential when the test mass is light. In this article, we focus on the stability in rotation of the suspended test mass mirror and on the response of the cavity to the input noise fluctuation that mimics the quantum noise.

Method

To observe quantum radiation pressure fluctuation, we used a high finesse cavity with a tiny 8 mg mirror. Such a tiny mirror is sensitive to weak force fluctuation, and the cavity can enhance the quantum radiation pressure fluctuation. To trap the 8 mg mirror, we utilize the geometry of the cavity. The 8 mg mirror surface is concave, and the cavity is in the negative-g regime. Therefore, the radiation pressure acts as a spring in the rotational direction of the suspended 8 mg mirror.

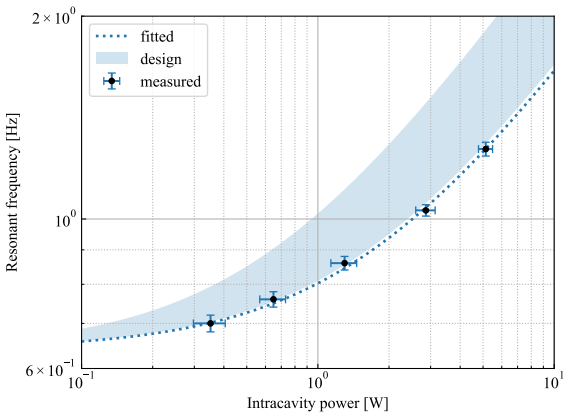

FIG. 1. The resonant frequency of the 8 mg mirror in the rotational direction depending on the intracavity power of the cavity.

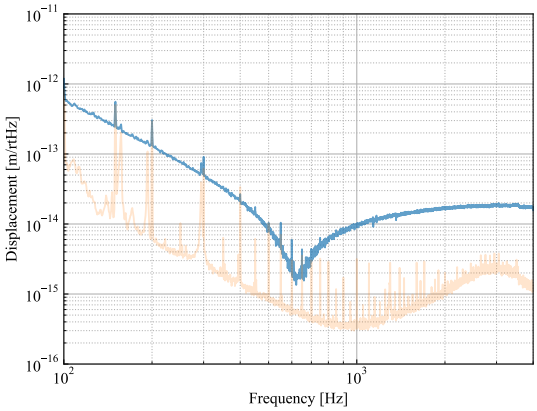

FIG. 2. Sensitivity spectral (blue: input laser intensity noise injected, orange: no injection). When the laser intensity noise that mimics the quantum noise were injected, the sensitivity was limited by the injected noise, and the dip-shaped sensitivity enhancement can be observed.

Result

We evaluated the stability in rotation of the suspended mirror by measuring the resonant frequency of the mirror. As shown in FIG. 1, we observed that the resonant frequency got higher when the intracavity power was higher. Therefore, we concluded that our configuration of the cavity could trap the 8 mg mirror stably.

FIG. 2 shows the noise cancellation of the input laser intensity noise that mimics the quantum noise. This is a demonstration of the quantum noise reduction technics.

Acknowledgement

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High-Q Monolithic Pendulum for Quantum-limited Sensing

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Introduction

Recently, advances in the field known as quantum optomechanics have allowed unprecedented level of precision in the measurement and control of mechanical motion, allowing the observation of quantum phenomena up to the nanomechanical scale. In these experiments of mechanical motion, thermal (Brownian) noise poses a fundamental classical limit of measurement precision, enforced by the fluctuation-dissipation theorem and manifesting due to coupling to the environment. The realization of low-dissipation mechanical oscillators to suppress thermal noise is crucial to achieve quantum-noise-level sensitivity.

In this short talk, we will discuss our latest report [1] on the development of an ultra-low dissipation mechanical oscillators (pendulum) for applications in table-top macroscopic quantum optomechanics experiments. We achieve the lowest dissipation to date for a table-top experiment (around 1 μHz as characterized by its pendulum mode), and with this push the boundary of possible quantum sensing and control up to the mg-scale. By employing this new suspension system, the optomechanical displacement sensor for gravity measurements we previously reported in [2] will be improved to realize quantum-noise-limited sensing. We will also discuss on prospects and feasibility for reaching the Standard Quantum Limit (SQL) of precision with this system. This achievable level of sensitivity of a macroscopic oscillator will open the door to experimental tests of macroscopic quantum mechanics, experimental tests on the interface between gravity and quantum mechanics, and in the search for dark matter through the gravitational interaction.

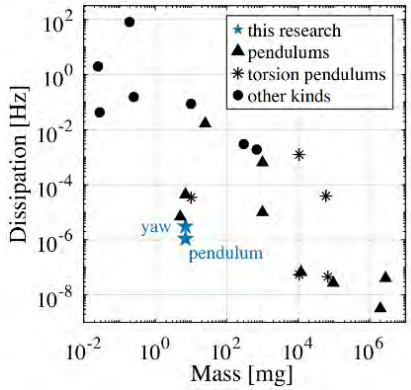

Figure 1. Mechanical mode's dissipation vs mass for published experiments with macroscopic oscillators [1].

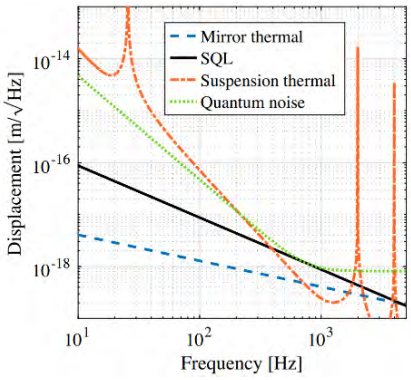

Figure 2. Noise budget for reaching the SQL in quantum optomechanics experiments with this pendulum as suspension system [1].

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Angular dependence of photon-pair generation via biexciton

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Introduction

Two-dimensional plots of a two-photon frequency distribution, known as joint spectral intensity (JSI), have been used to evaluate spectral characteristics of photon pairs generated from parametric down-conversion. The JSI can bring us information on the constituent photon's spectrum and the spectral correlation between the photons [1]. We expect the JSI measurement may have potential application to nonlinear spectroscopy with two-photon emission. To clarify the advantage of the JSI measurement, we observe two-dimensional spectra of photon pairs generated from biexciton in a semiconductor.

Method & Result

We utilized the photon-pair generation from resonant hyper-parametric scattering (RHPS) process via biexciton in CuCl single-crystal. A biexciton state was resonantly excited by the second harmonics of mode-locked Ti: sapphire laser, operating at 778.3 nm [2]. Scattered polaritons created via RHPS propagate inside the crystal and then transferred into photons at the crystal surface. Photon pairs are emitted into symmetric directions with respect to the pump beam, satisfying the phase-matching condition. Although the spectral distribution of the photons via RHPS would be affected by the phase-matching condition and the intraband relaxation of biexciton [3, 4], it cannot be estimated separately by conventional spectroscopy. In this work, we present how the spectral change determined by the phase-matching condition is reflected in the JSI. Since the phase-matching condition depends on the scattering angle of polaritons, we measured JSI at the scattering angle of 20° and 50° to investigate the correspondence between the phase-matching condition and the JSI. The experimental results of JSI measurements at each scattering angle are shown in FIG. 1 (a) and (b). The difference in peak energies of the photon-pairs in JSI indicates that the photon pair is nondegenerate. For more analysis, we obtain the projection spectra of the JSI onto the -45° or +45° axis and estimate the peak position along these axes. The projection spectra onto -45° (+45°) means the difference (sum) -frequency spectrum of the constituent photons.

The peak energy of difference- and sum-frequency spectra at the scattering angle of 20° were 7.0 meV and 6.37eV, and those at 50° were 15.6 meV and 6.37 eV. The change by phase-matching condition appeared only in the difference frequency-spectra. On the other hand, the sum-energies of photon pair kept constant as corresponding to the biexciton energy. These results indicate that JSI can estimate the phase-matching effects, separating from the intraband relaxation of biexciton.

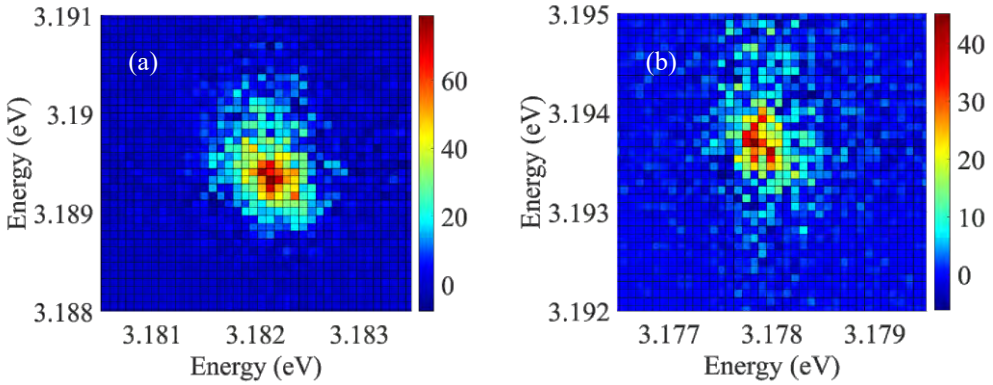

FIG. 1. JSI of photon pairs at the scattering angle of (a) 20 ° and (b) 50 °.

Acknowledgement

This work was supported by MEXT Q-LEAP Grant Number JPMXS011806924.

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Temperature dependence of photon-pair generation via biexciton

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Introduction,

The nonclassical nature of light has a potential application to nonlinear spectroscopy at the single-photon level. In practice, time-frequency entangled photons allow selective two-photon excitation in dense energy levels of a matter [1]. However, it is difficult to carry out an experimental demonstration for nonlinear spectroscopy with the entangled photons due to the lack of light intensity for the nonlinear excitation. On the other hand, quantum optical measurements in order to characterize the time-frequency correlation of photons might have the potential as a new tool for nonlinear spectroscopy at the single-photon level. The most common method for characterizing the degree of spectral correlation of photon pairs is the joint spectral intensity(JSI), representing the two-photon spectral probability distribution in a 2D space. Here we report experimental results for the temperature dependence of the JSI using a photon-pair from a CuCl single crystal. We expect to make connections between the nonclassical nature of light and the properties of the exciton.

Method & Result

Resonant hyper-parametric scattering (RHPS) is a method that generates photon-pairs in a semiconductor material [2]. Generally, biexciton luminescence in CuCl is composed of the intraband-relaxation in biexciton and the interband-relaxation from biexciton to the other state. However, in the process of RHPS, the two pump photons resonantly create the biexciton. Then the biexciton coherently decays into two polaritons that satisfy the phase-matching condition with the energy and momentum are conservation. In classical spectroscopic measurement, since the phase-matching effect is dominant, it is hard to observe the spectrum reflecting the intraband-relaxation. In contrast, the JSI measurement allows us to observe the effect of intraband-relaxation. In this work, we examine how the intraband-relaxation effect is appeared in the JSI by changing the crystal temperature.

Figure1(a) and (b) show that the JSI at 6K and 45K, respectively. We observed a negative correlation elongated along a -45 degree direction at 6K. In contrast, a circular shape distribution, implying no spectral correlation, at 45K was observed. It can be seen that the shape is broadened in a +45 degree direction with the increase of the crystal temperature from 6K to 45K. The spectral dispersion in the +45 degree direction could be related to the intraband-relaxation of biexciton.

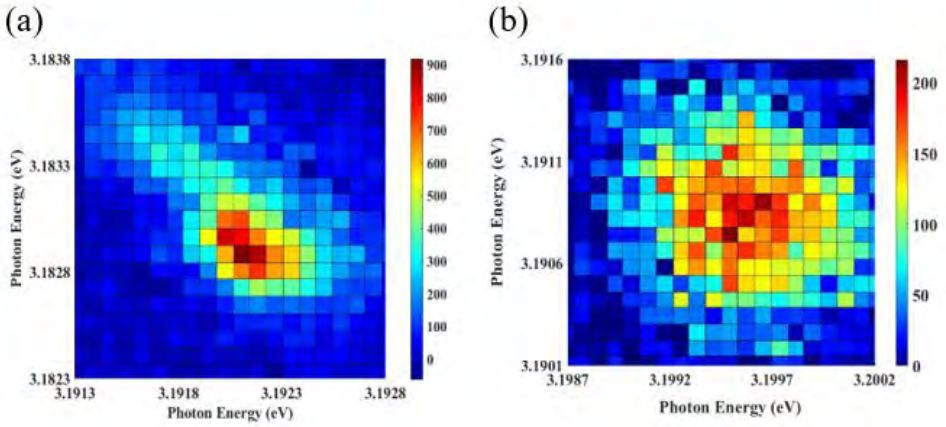

FIG. 1 (a) : The JSI at the 6K (b) at the 45K

Acknowledgment

This work was supported by MEXT Q-LEAP Grant Number JPMXS011806924.

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Demonstration of three-dimensional high-resolution quantum optical coherence tomography using frequency-entangled photon pairs

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Introduction

Optical coherence tomography (OCT) is a non-invasive and label-free tomographic imaging technique utilizing low-coherence interferometry. OCT has been widely used in vast applications ranging from medical diagnosis to industrial inspection. However, it is known that depth resolution of OCT is limited by the chromatic dispersion of a sample.

To overcome the problem, quantum OCT (QOCT) utilizing two-photon interference with frequency-entangled photon pairs has been actively developed recently [1-4]. QOCT has automatic dispersion cancellation and higher depth resolution than conventional OCT for the same bandwidth of the probe light. Recently, we demonstrated two-photon interference with FWHM of the dip of 0.54 μm, which accords with the depth resolution of QOCT [4]. This corresponds to, to our knowledge, the highest depth resolution among QOCT and conventional OCT measurements. On the other hand, 2D images of QOCT were successfully demonstrated with the depth and lateral resolution of about 7.5 and 12 μm, respectively [2]. It is desired that higher three-dimensional resolution QOCT for practical applications. Therefore, in this work, we developed 4 μm^3-resolution QOCT by combining a two-photon interferometer utilizing broadband frequency-entangled photon pairs and an achromatic microscopic lens. We believe that such realization of three-dimensional high-resolution QOCT with automatic dispersion cancelation paves the way for new biological discoveries and accurate diagnosis of diseases and industrial products.

Methods and results

Figure 1 shows the experimental setup for 4 μm^3-resolution QOCT. For high depth resolution, we utilized broadband frequency-entangled photon pairs generated via a spontaneous parametric down-conversion on a β-barium borate (BBO) nonlinear crystal, where the phase-matching condition was set to be type-I, non-collinear, and degenerate in wavelength (center wavelength 790 nm and FWHM 140 nm). For high lateral resolution, we used an achromatic lens (NA 0.2), which compensates for chromatic aberration, as a focusing lens for a sample. Using this experimental setup, we rigorously evaluated the depth resolution by FWHM of measured Hong-Ou-Mandel dips and the lateral resolution by periodical rectangular patterns obtained by measurements of a Ronchi ruling. As a result, we confirmed that the depth and lateral resolution are 3.83(20) μm and 4.05(5) μm, respectively. In the presentation, we are going to report on the experimental results in more detail and further imaging results.

This work was supported by MEXT Q-LEAP Grant Number JPMXS0118067634 and JST-CREST JPMJCR1674.

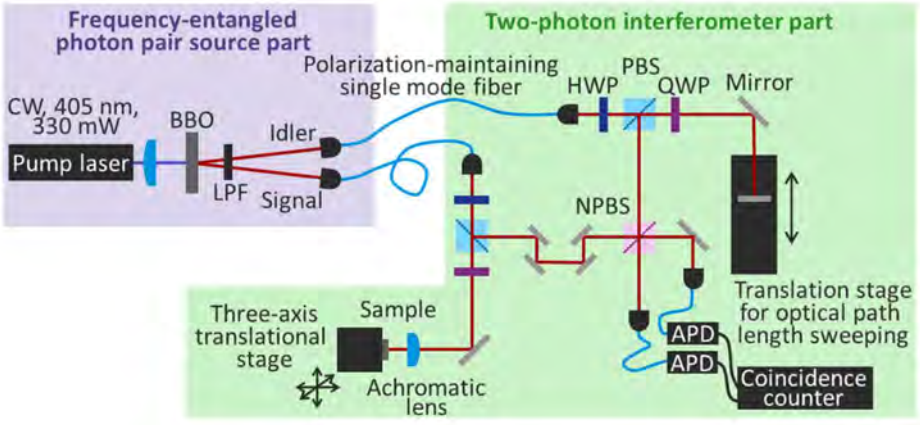

FIG. 1 Experimental setup for 4 μm^3-resolution QOCT.

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Direct observation of parametric fluorescence in the mid-infrared region using an InSb detector

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Introduction

In recent years, quantum entangled photons in mid-infrared region are attracting intense attention because of potential applications such as quantum imaging [1] and quantum infrared spectroscopy [2]. In the latter application, spectral measurements in the infrared range become possible just using a visible-light source and a detector, overcoming the current problems due to relatively low-efficiency infrared light sources and detectors. For these investigations, it is indispensable to characterize the emitted parametric fluorescence using the photon detectors in the mid-infrared region. For this purpose, coincidence detection of photons using up-conversion have been reported, however, the bandwidths of detectable photons were strictly limited below 200 nm [3,4]. For broadband detection, superconducting nanowire single photon detector (SNSPD) may be used, however, detection of parametric fluorescence is limited below 2300 nm [5].

Here, we report the direct observation of parametric fluorescence in the mid-infrared region from 3200 to 5000 nm using an InSb detector. To the best of our knowledge, the detection of parametric fluorescence for such a broad bandwidth in the mid-infrared region has not been realized. We also estimated the sensitivity of the InSb detector using the correlation between visible and infrared entangled photons. Our experimental results will be useful for development of photonic quantum sensing technologies in the mid-infrared region, and will provide a novel accurate method to calibrate the sensitivity of the infrared photodetectors.

Method

Figure 1 shows the experimental setup. To generate the visible-infrared entangled photon pairs, a 2-mm-thick type-I MgO:$LiNbO_3$ (LN) crystal is pumped by a CW-laser beam with a wavelength 532 nm. The pump is chopped using a mechanical chopping wheel and is focused into the crystal by a lens (f=200 mm). Signal (visible) with the wavelength of 692 nm and Idler (infrared) with the wavelength of 2300 nm photons are generated when the crystal is fixed (θ=0°). We rotate the crystal θ=8-36° to generate photon pairs with a signal wavelength 590-657 nm and an idler wavelength 2800-5400 nm. When they are separated by a dichroic mirror, the signal photons and pump photons pass through while the idler photons are reflected. The residual pump beam is eliminated by long pass filter 1s. Then, the signal photons are coupled to a multimode fiber and guided to a spectrometer to measure signal wavelengths. The idler photons are focused into an InSb detector by a lens after passing through a long pass filter 2 and a band pass filter. The amplitude of voltage signal form an InSb detector is recorded with a lock-in amplifier. The results indicate that we directly observed the idler photons of visible-infrared photon pairs in the mid-infrared regions 3200-5000 nm. In this presentation, we will report on the observed idler signal in more details and the calibration method of the sensitivity of the InSb detector using visible-infrared photon pairs.

This work was supported in part by the foundation of MEXT Q-LEAP (JPMXS0118067634), JST-CREST (JPMJCR1674), JST-PRESTO (JPMJPR15P4), Grant-in-Aid for JSPS Fellows 20J23408, and WISE Program, MEXT.

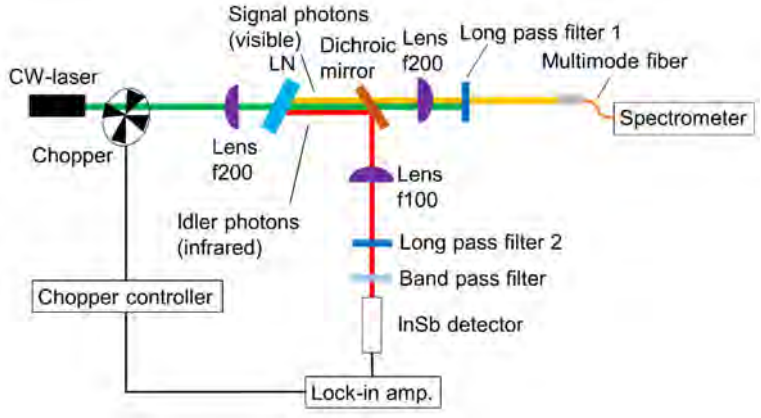

FIG. 1. Experimental setup for the detection of idler photons in a wavelength region 3200-5000 nm.

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Ultra-coherent fundamental mode mechanical resonators designed using topology optimization

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Introduction

Micromechanical resonators has attracted a great deal of interest in multiple fields including biosensing [1], detection of single spin [2], as well as quantum optomechanic [3]. Membranes, strings and trampolines based on thin tensile stressed silicon nitride have resulted in resonators with high coherence defined by their outstandingly high quality factors. Combined with their extremely low mass makes them a great platform for sensing and to test out various quantum experiments. The quest for high coherence resonators has inspired researchers to continually push the quality factors to new heights in recent years. The continuous improvements of these devices opens up new applications, like testing ideas for quantum gravity [4].

High tensile stress increases the frequency and thereby energy of the device with limited increase of the damping in what is known as dissipation dilution [5]. The best performing designs utilize soft-clamping by using phononic crystal patterns to confine a mode to a defect [6]. Unfortunately, their complicated designs combined with high local stress can be difficult to fabricate. Furthermore, the defect confined modes lie within a bandgap surrounded by dense mode distributions.

Trampolines have previously been demonstrated to achieve great coherence for a fundamental mode resonator [7]. Their coherence is ultimately limited high bending losses along the boundary. Topology optimization [8] has demonstrated great ability to generate unique designs with exceptional performance on an array of problems. Its use in these types of resonators is still unexplored. This poses a unique opportunity to push the limits of fundamental mode resonators.

In this work topology optimization has been used to generate designs (FIG. 1.) optimized for maximizing the Qf product of a fundamental mode resonator. An improvement of a factor of five has been demonstrated experimentally (FIG. 2.) compared to a reference trampoline design [7]. These results demonstrate how topology optimization can potentially revolutionize the designs of micromechanical resonators and push their coherence to higher levels.

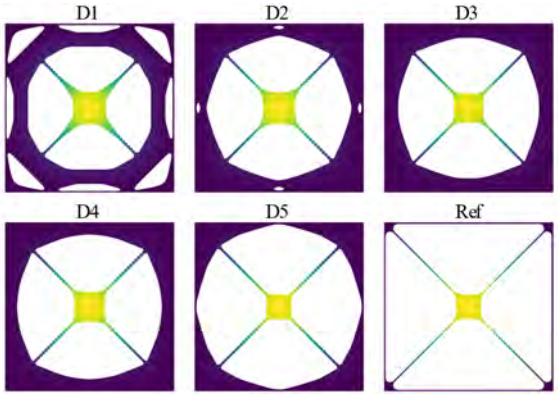

FIG. 1. Overview of topology optimized designs (D1-D5) and a reference design (Ref) together with their fundamental modeshape. D1 is optimized assuming intrinsic losses only. D5 is optimized assuming phonon tunneling losses only. D2-D4 are various combinations of both damping mechanisms. The outer window is 700 × 700 μm^2.

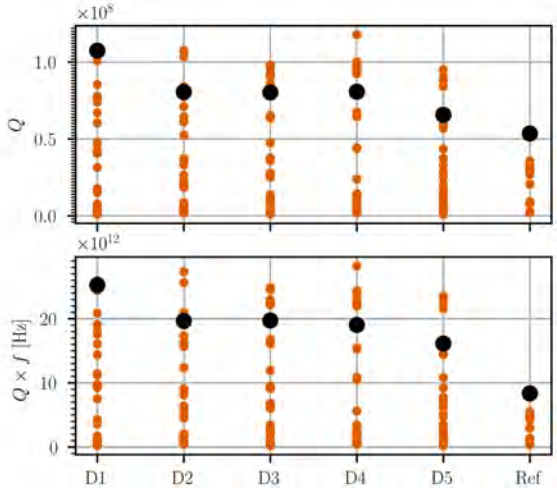

FIG. 2. Overview of experimental results for 13 nm thick trampolines. Black dots are predicted results assuming intrinsic losses only.

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Generation of Correlated Photon Pairs from a Silicon Micro-ring Resonator with a Gain-Switched Laser Diode

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Introduction

A compact heralded single photon source is required in quantum technologies. For an integrated chip-scale photon pair source, silicon micro-ring resonators (MRRs) are employed due to its enhancement of optical nonlinearity. The picosecond lasers are required to obtain a spectrally-pure heralded single photons from an MRR, which typically exhibits a Q-value of ~ 10^4. However, the picosecond laser source such as optical parametric oscillators or mode-lock solid-state lasers are much larger than the silicon chip, hindering the true miniaturization of the source. Here we attempt to use a semiconductor laser as the pump pulse source aiming at the realization of a compact heralded single photon source. A gain-switched laser diode (GSLD) enables us to obtain picosecond optical pulses [1, 2]. In this work, we demonstrate the generation of correlated photon pairs from a silicon MRR using a GSLD pump pules.

Method

We show a schematic of the experimental setup in FIG. 1. The GSLD generates optical pulses with a center wavelength of 1548.91 nm, a repetition rate of 1 MHz, and the temporal width of 8.7 ps. A polarization controller is used to obtain the TE-polarized pump pulses. We control the silicon chip temperature to match a resonant wavelength of the MRR to the pump center wavelength. The silicon waveguide core is 220-nm high and 440-nm wide. The MRR (ring radius: 20 μm, FSR: 4.4 nm) is coupled to a silicon wire waveguide with a 250 nm gap. The signal and idler resonances are centered at λ_s = 1540.1 nm and λ_i = 1557.7 nm, each of which is two FSRs apart from the resonant mode coupled to the pump. The quality factor of the MRR is approximately 3 × 10^4. Wavelength-division multiplexer (WDM)1 (bandwidth: 1.1 nm) is used to eliminate the side-mode noise of the pump pulse. Signal and idler photons are separated with WDM2 and 3. Finally, the photons are detected by two InGaAs single photon avalanche diodes (SPADs).

In FIG. 2, we plot the coincidences-to-accidentals ratio (CAR), which can be obtained through the time-correlation histogram (see inset). In FIG. 2, the CAR is shown as a function of pump power. The peak CAR is 33 at a pump power of P_p = 2.6 μW. Thus, we have successfully generated the correlated photons from the MRR with GSLD.

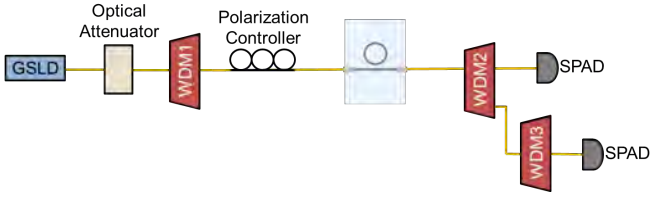

FIG. 1. Schematic of the experimental setup.

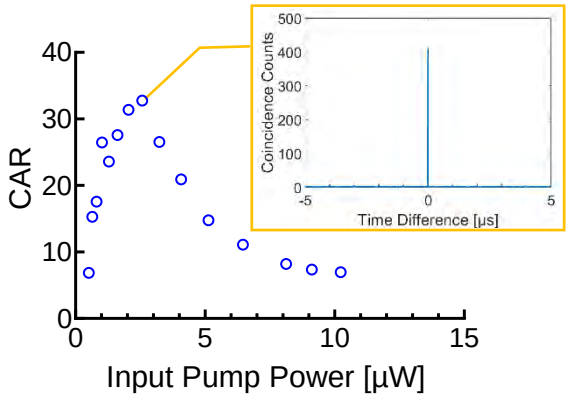

FIG. 2. CAR as a function of the input pump power. Inset: a time-correlation histogram for P_p = 2.6 μW.

This work was supported by MEXT Quantum Leap Flagship Program (MEXT Q-LEAP) Grant Number JPMXS0118067581.

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Plasmon-enhanced polarized single photon source coupled to an optical nanofiber at room temperature

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Introduction

For the realization of quantum networks, optical nanofibers are promising tool because of the high coupling efficiency of single photons from a quantum emitter on the nanofiber surface into the guided modes of the optical fiber. A lot of research has been done to enhance the properties of quantum emitters on nanofibers over the last decade, but control of photon polarization in the fiber has not been achieved.

Using the plasmonic resonance of metal nanoparticles, we can confine light to a volume on the order of the nanoparticle volume (~ a few hundred nm^3) – i.e. below the diffraction limits set by the wavelength of light. Therefore, if we position a quantum emitter near to a metal nanoparticle, enhancement of light-matter interaction takes place, which leads to large enhancement of spontaneous emission from the quantum emitters (Purcell effect). Furthermore, if we choose anisotropic-shaped metal nanoparticles such as gold nanorods (GNRs) as shown in Fig. 1, the plasmonic resonance occurs for a specific polarization mode. Thus, by placing a quantum emitter near to a GNR as shown in Fig. 1, it is expected that emitted photons from the coupled system will be polarized along the long axis of the GNR.

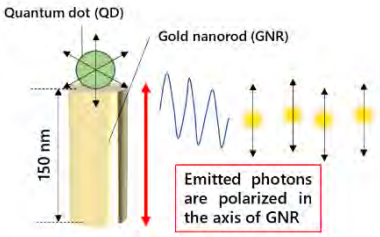

FIG. 1: Schematic figure of the interaction between QD and GNR.

Here, we developed a composite polarized single photon source at room temperature directly coupled to an optical fiber by combining a CdSeTe/ZnS colloidal quantum dot (QD), a GNR and an optical nanofiber. We observed large Purcell enhancement of about 22 times, and an increase of the degree of photon polarization coupled to the optical fiber. We believe that this work is a major step forward towards the realization of a polarized single photon source coupled to an optical fiber network.

Method

We first fabricated a nanofiber (diameter: 530 nm) by heat-pull method and then deposited QDs (emission center wavelength: 800 nm) and GNRs (plasmonic resonance center wavelength: 790 nm) by dipping a droplet of particle solution onto the surface of the nanofiber. After sample fabrication, we connected each end of the nanofiber pigtails to filtering systems as shown in Fig. 2. Note that the filter configuration is modified depending on the type of measurements. In optical measurements, we scan laser light (wavelength = 637 nm) along the nanofiber surface and find deposited particles by detecting peaks in photoluminescence from QDs or scattered light from GNRs. After detection, we focus on the position where the peaks from two kinds of particles are overlapped and measure the intensity correlation function $g^{(2)}(\tau)$ and the polarization of photons emitted from the coupled particles as shown in Fig. 3 and 4. For the results of $g^{(2)}(\tau)$, we observed drastic modification of the shape of $g^{(2)}(\tau)$ because of the Purcell effect due to the GNR in the vicinity of the QD. By analysis of the power dependence of $g^{(2)}(\tau)$, the enhancement factor was estimated to be ~22-fold. In addition, we measured the increase of the degree of polarization P compared to the value for the case of QD only. In the short presentation, we will explain the details of these results.

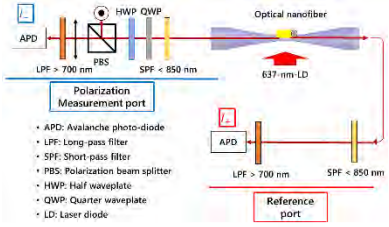

FIG. 2: Experimental setup for photon polarization measurement.

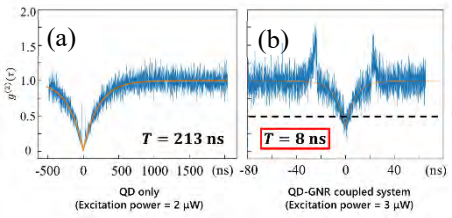

FIG. 3: $g^{(2)}(\tau)$ for (a) QD only and (b) QD-GNR coupled system

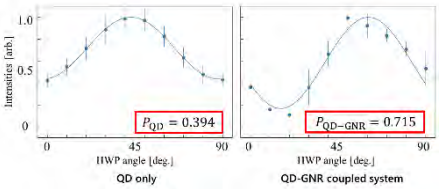

FIG. 4: The degree of photon polarization P (a) QD only and (b) QD-GNR coupled system

Acknowledgement

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CVD growth parameter dependence of aligned dense nitrogen vacancy centers for magnetometry

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Introduction

Nitrogen Vacancy (NV) center in diamond is one of the most studied color centers. In recent years, there is increasing interest in magnetometry. Magnetometry based on NV center is expected as high sensitivity detection method, while the sensitivity has not reached the theoretical value. In order to improve the sensitivity, it is important to increase number of NV centers, long coherence time, and align the NV axis[1]. Chemical vapor deposition (CVD) method is effective because perfectly aligned NV center can be created[2]. However, there is room for improvement in the number of NV centers and the coherence time. It is required that CVD growth with efficiently creating NV center and reducing spin noise that degrades coherence time for example substitutional site nitrogen atom (P1 center) and hydrogen related center. In previous our study, we performed CVD diamond growth under various conditions. As a result, dense NV centers were created by increasing N_2 gas flow rate, while NV axis alignment growth under high rate CH_4 and N_2 were degraded. It was considered that NV axis alignment was degraded due to high rate growth by high gas flow rate. In this study, we perform CVD growth under low rate CH_4 and high rate N_2 to create dense aligned NV centers.

Methods and Results

Samples used in this study were (111) single-crystalline diamond layer grown by microwave plasma enhanced CVD changing gas flow rate of N_2 and keeping flow rate of CH_4, 1 sccm. Impurity concentration for example nitrogen and hydrogen was evaluated by using Secondary Ion Mass Spectrometry (SIMS) measurement. NV center was observed by using home build confocal fluorescent microscopy. Photon counts of NV centers was evaluated as average counts of fluorescent map. NV axis orientation and coherence time were evaluated by optically detected magnetic resonance (ODMR) spectrum and Hahn echo measurement.

We measured fluorescent intensity from NV center. Dense NV centers were observed in all samples. From ODMR spectrum, NV axis of all samples were confirmed to be perfectly aligned along <111> crystal orientation. FIG. 1. (a) shows photon counts from NV centers as a function of the nitrogen concentration. Photon counts, which mean number of NV centers increase with increase nitrogen concentration. FIG. 1. (b) shows sensitivity factor which is defined by photon counts × coherence time as a function of nitrogen concentration. The highest sensitivity was given in 6×10^{-18} cm^{-3} of nitrogen concentration. Sensitivity decreased in 10^{19} cm^{-3} of nitrogen concentration. It is suggested that NV center creation was suppressed due to inducing of other defects such as interstitial nitrogen, NVN, NVH, etc., at high nitrogen concentration, resulting in reduced sensitivity.

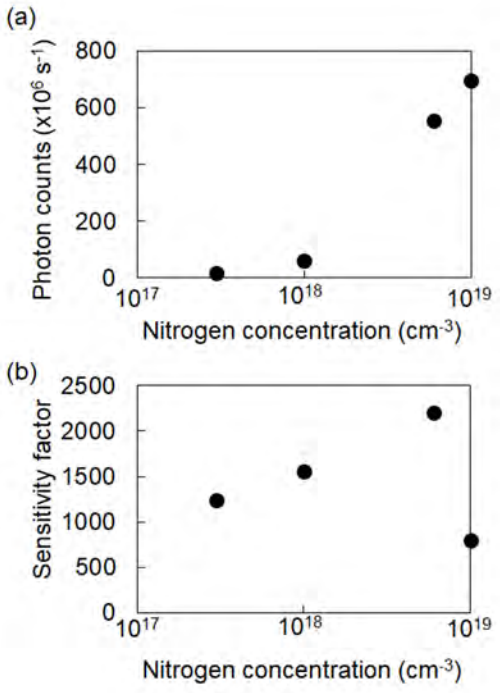

FIG. 1. (a) Photon counts and (b) sensitivity factor as a function of Nitrogen concentration

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Acknowledgement

This study was supported by MEXT Q-LEAP (JPMXS0118067395).

Nitrogen concentration control in diamond growth for NV center formation

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Introduction

Diamond growth is a key technology for the developing quantum sensing device using NV centers. Desired concentration of NV centers varies from 1ppb to 10ppm depending on the type of quantum sensing devices. Then, precise control of nitrogen concentration in wide doping range is requested for diamond growth. Carbon isotope control[1] is another important issue of diamond growth to prolong the spin coherent time. Here, research activity of diamond growth in National Institute for Materials Science (NIMS) by chemical vapor deposition (CVD) and high-pressure and high-temperature (HPHT) will be introduced focusing on the NV center formation.[1, 2]

Diamond Growth by CVD Method

Thick (>500 μm) nitrogen-doped homoepitaxial diamond films were grown with feeding nitrogen during growth. Fig. 1 shows nitrogen concentration of diamond crystals measured either by secondary ion mass spectrometry (SIMS) or confocal photoluminescence. This result indicates that nitrogen concentration in CVD diamond is controllable between 0.005 and10 ppm (10^{14}-2×10^{18} cm^{-3}) by changing nitrogen gas ratio to methane gas. In order to create NV centers, electron beam irradiation with total fluence of 1×10^{18} $e\cdot cm^{-2}$ followed by vacuum annealing at 1000°C for 2h was performed for CVD diamond plate with nitrogen concentration of 0.2 ppb. UV-PL measurements revealed that NV^0 center and 389 centers[3] are dominant color centers created in this diamond sample. For the preferential creation of NV^- centers, an optimization of both nitrogen concentration in diamond and the electron beam irradiation fluence are needed.

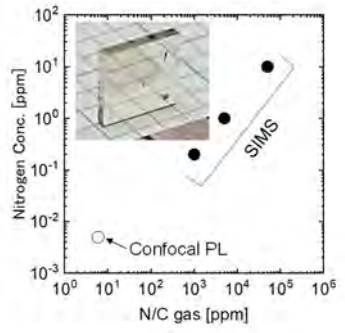

Figure 1. nitrogen concentration in CVD diamond crystals.

Diamond Growth by HPHT Method

Diamond crystals were grown by using a modified belt-type HP apparatus. A temperature-gradient method was applied with a solvent of Co-Ti-Cu alloy system. Pressure, temperature and growth duration were 5.5 GPa, 1400°C, 20–40hrs, respectively. By cutting single crystals grown with (100) seed crystals into (111) direction, diamond plate on (111) were obtained as shown in the inset of Fig. 2. Figure 2 shows the concentration of P1 center (substitutional nitrogen) of diamond crystals measured by Electron spin resonance (ESR). This result indicates that P1 concentration is controlled in the range of 0.4-20 ppm with high reproducibility by controlling amount of Ti additives in the solvent. In addition, by optimizing total fluence of the electron irradiation, about one-tenth of the substitute nitrogen were successfully converted into NV^- centers with high negative charge stability.

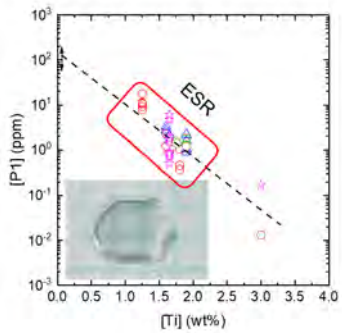

Figure 2. P1 concentration as a function of titanium weight percentage in the solvent. Inset is a typical HPHT diamond crystal after cutting/polishing.

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Acknowledgements

This work was partially supported by MEXT Q-LEAP (JPMXS0118068379 and JPMXS0118067395), JST CREST (JPMJCR1773) and JSPS KAKENHI (No. 20H02187 and 20K21096).

Optimal amount of vacancy in diamond for negative-charge stability of NV centers at various nitrogen concentration

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Introduction

Negatively-charged NV center (NV^-) is promising color centers for high sensitivity magnetometer due to its long coherence time (~2 ms) and clear Rabi and Ramsey contrast due to spin dependent fluorescence [1]. NV centers has also neutral charged state (NV^0) which shows no spin dependent fluorescence. Since NV^- and NV^0 often coexist, fluorescence of NV^0 becomes background and reduces fluorescence contrast of NV^-. Thus, suppression of NV^0 formation while increasing NV^- concentration is important for improving the sensitivity. So far, it is reported that the concentration ratio $[NV^-]/[NV^0]$ becomes higher as substitutional nitrogen concentration [P1] increases [2]. In addition, the report by Waldermann *et al.* [3] indicates that NV^-/NV^0 ratio become smaller when the amount of vacancy created in diamond is comparable to nitrogen concentration.This fact suggests that an excess formation of vacancy increases $[NV^0]$. Understanding of NV^0 formation mechanism under various [P1] and $[NV^-]$ condition is a key for efficient formation of NV^- centers with desired concentration.

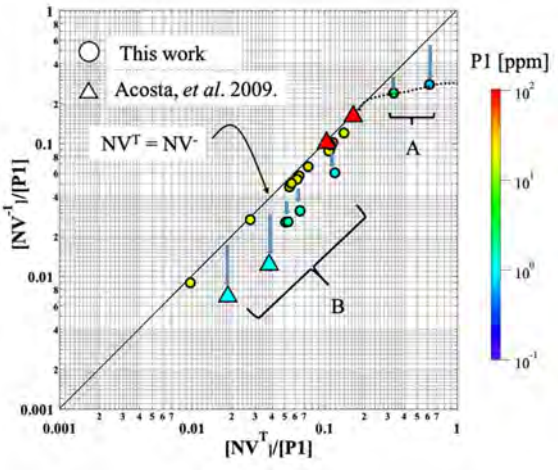

Fig.1 Relationship between the ratio NV^T/P1 and NV^-/P1

Here, we consider the total amount of NV center ($NV^T = NV^- + NV^0$) as an indicator of amount of vacancy assuming all vacancies created in diamond were coupled with nitrogen during the consecutive annealing. In this study, we investigate the dependence of the negative-charge stability of NV centers, $[NV^-]/[NV^0]$ ratio, on the percentage of vacancies to nitrogen, $[NV^T]/[P1]$ ratio. Our result indicates that the negative-charge stability ($[NV^T] = [NV^-]$) is realized at $[NV^T]/[P1] < 0.2$ except for the case in which [NV-] is compatible to residual [B].

Method

Diamond single crystals used in this study were grown using either HPHT synthesis or CVD method. Nitrogen concentration was controlled by tuning concentration of Ti in the metal solvent for the former while flow rate nitrogen gas was tuned for the later. After the nitrogen doped diamond growth, an electron beam irradiation was applied with the total fluence of 10^{17}-10^{18} cm^{-2} to create vacancies in the diamond. it was followed by vacuum annealing at 1000℃ for 2h to form NV center in the diamond crystals. The number density ratio of NV^- to NV^0 is estimated from the intensity ratio of their ZPL. The concentration of NV^- and P1 was estimated using EPR method at room temperature.

Result and Discussion

Fig. 1 shows relationship between the ratio NV^T/P1 and NV^-/P1. The solid line is an eye-guide when $[NV^T] = [NV^-]$. The deviation from the line in region A may be due to the fact that [P1] is not sufficient to negatively charge the NV center due to the high ratio of NV^T/P1 of $>$ 0.3. NV center in the region of B was found to be less negatively charged even though the NV^-/P1 ratio is smaller than 0.2. We realized [P1] of the diamond is as small as < 1 ppm. The concentration of residual boron accepter in HPHT crystal ranges from 0.01 ppm to 0.1 ppm. This value is compatible to the small concentration of NV^- At the moment, we speculated that residual boron accepter compensates an electron of negatively charged NV center. So, we believed reducing residual B is leading to $[NV^T] = [NV^-]$ at [P1] < 1 ppm.

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This work was supported by MEXT Q-LEAP Grant Number JPMXS0118068379 and JPMXS0118067395.

Performance of Implanted Nitrogen Vacancy Centers as a Figure of Merit for the Quality of Diamond in Quantum Applications

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Introduction

The nitrogen vacancy center is amongst the most studied defects in diamond. It is a promising candidate for various applications such as e.g. nanoscale imaging [1] or ultrasensitive magnetic field detection [2]. To achieve a high sensitivity to external spins the NV^- centers must be positioned only a few nanometers below the diamond's surface. The tailored fabrication of these NV^- centers within the purest diamond material is therefore key in the enabling of the applications mentioned above. Low energy ion implantation is the method of choice featuring nanometer precise depth positioning of the sensors [4]. However, in order to engineer the quantum sensors reliably and reproducibly, two aspects are of major importance. First, influencing factors originating from the implantation process itself which alter the NV^- center (spin) properties need to be identified and controlled [5]. Second, the diamond substrate itself, since it plays a unique role being the host material for the nano sensors [6]. The development of a figure of merit for the "quantum quality" of ultrapure type IIa diamond is essential because it can be a performance indicator which uses the NV^- centers themselves to determine the quality of the diamond substrate.

Experiment

In order to establish a figure of merit for the diamond material and the suitability of NV^- centers for a given application involving shallow color centers, spin coherence times such as Hahn echo T_2 can serve as an indicator for the quality of the sensors and the substrate. However, since the distance to the diamond surface mainly limits the coherence times, tracking of the depth of the individual color centers is as important. Simulations for the stopping and range of the ions can predict the depth of the resulting NV^- centers. As shown in FIG. 1(a), we compare the depth distribution of shallowly implanted NV-centers with two simulations, SRIM (assumes amorphous substrate) and CTRIM (crystalline substrates) and determine their coherence times to receive a depth-T_2 chart as in FIG. 1(b). This chart is then compared to a different substrate of same type where a difference is obvious, thus resembling the necessity of the establishment of a figure of merit for the quality of diamond in quantum applications.

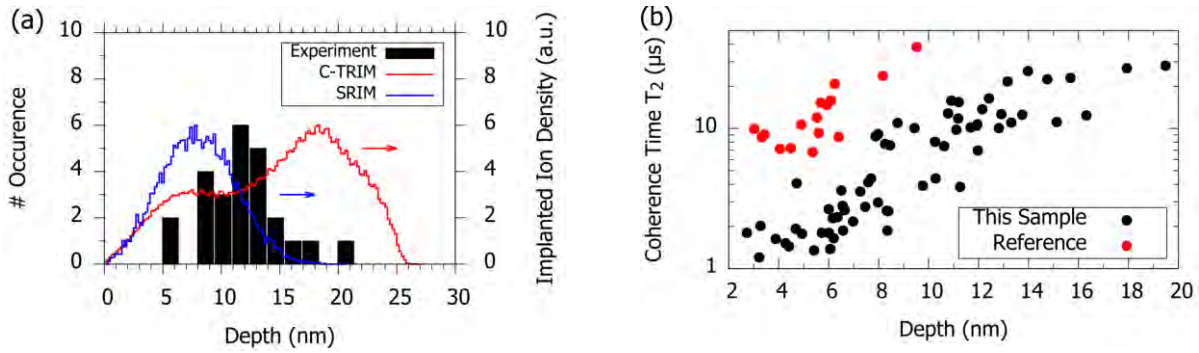

FIG. 1: Figure of merit for NV sensor quality; (a): depth distribution of individual NV^- centers peaked between amorphous and crystalline implantation simulation. (b): Chart of coherence time T2 versus depth of two samples of same type showing obvious difference in overall coherence attributed to a different crystal substrate quality.

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Effect of mis-orientation angle for CVD grown perfectly aligned NV center on (111) diamond substrate

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Introduction

For practical application of NV center in biomagnetic field detection that requires femto tesla sensitivities, improvement on magnetic sensitivity of Nitrogen Vacancy (NV) center is critical. The sensitivity of NV centers is determined by the atomic alignment, and generation yield of NV centers. Step-flow growth performed with Chemical Vapor Deposition (CVD) system allow formation of perfectly aligned NV center (more than 99%) on (111) diamond substrate with theoretical maximum contrast of 30%[1,2]. However, generation yield of CVD grown NV center is limited to few percent, order of magnitude lower than NV centers produced by other techniques such as electron irradiation. In this study, we varied mis-orientation angle of pre-grown (111) diamond substrate from 2 degrees to 6 degrees to change terrace width and therefore reaction sites for CVD growth and investigated its effect on NV center formation. Our results indicate highest NV center yield for mis-orientation angle of 6 degrees with 3.6% generation yield while maintaining perfect alignment of NV center. Detail on effect of mis-orientation angle for growth rate[3,4], nitrogen introduction[4] and generation yield of NV center will be discussed in the presentation.

Method & Result

Mis-orientation angles of 2 degrees (had been used in our previous study[1]), 4 degrees, and 6 degrees in the equivalent direction for <$1\bar{1}2$> were formed on type Ib (111) diamond substrate (FIG. 1). The diamond film containing NV centers was deposited by MPCVD at temperature: 800°C, CH_4 concentration: 0.5%, N_2 concentration: 0.2%, and deposition time: 5 h. AFM measurement on all samples confirmed step-flow growth. Confocal microscope was used to estimate NV density and ODMR measurement was used to quantify alignment of NV center (FIG.2). Fig.3 shows typical example of ODMR observed on all samples. ODMR confirmed perfect alignment with more than 99% alignment. Generation yield of NV center was evaluated by $\eta = \text{NV density/nitrogen density}$. NV density was calculated from comparison of photon counts with single NV center and nitrogen density was evaluated by results from SIMS measurement. Highest generation yield of NV center at 3.6% was obtained at 6 degrees mis-orientation. Mechanism for increased generation yield with larger mis-orientation angle will be further investigated with additional results from higher mis-orientation angles.

"This work was supported by MEXT Q-LEAP Grant Number JPMXS0118067395."

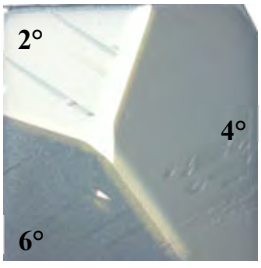

FIG. 1. Optical Microscope image of CVD sample with mis-orientation angle of 2,4 and 6° in three areas.

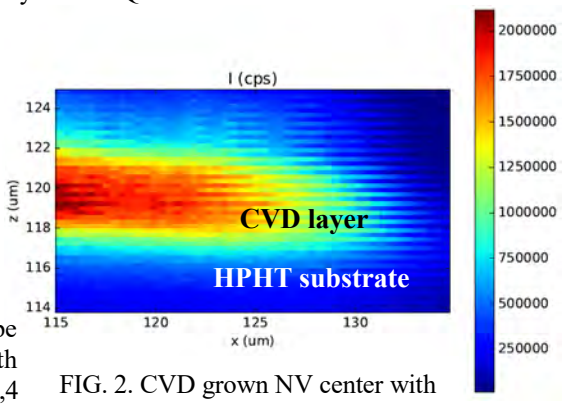

FIG. 2. CVD grown NV center with 6 degrees mis-orientation angle.

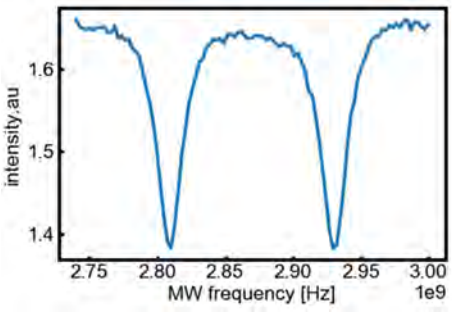

FIG. 3. ODMR of perfectly aligned NV centers with mis-orientation angle of 6 degrees.

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Evaluation of NV centers in bulk diamond formed by electron beam irradiation

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Introduction

Negatively charged nitrogen-vacancy (NV^-) center in diamond is known as quantum sensor, can be used to measure small changes in physical quantities, such as magnetic field and temperature [1]. To enhance the sensitivity of the quantum sensor, increasing NV^- and decreasing neutral charge state NV^0 in diamonds are needed since NV^0 does not act as quantum sensor. The electron irradiation is a good method to create high concentration of NV centers (Fig. 1). The high energy electrons create vacancies in diamond. Annealing allows the vacancies to move and to be trapped by substitutional nitrogen (P1 centers), forming NV centers. In this study, we irradiate diamonds containing different initial P1 concentrations with electrons and evaluate the fluence dependence of the charge state and the amount of created NV centers, for the purpose of determining appropriate fluence to form NV centers efficiently.

Method

The commercial diamonds synthesized by High Pressure and High Temperature (HPHT) were used. 2 MeV electrons were irradiated with fluences up to 3×10^{18} cm^{-2} at room temperature. Then, the samples were annealed at 1000°C for 2 hours to create NV centers. The concentration of P1 (number of electron spins) was measured by Electron Spin Resonance (ESR) (Fig. 2). The initial concentration of P1 was in the range from 50 ppm to 100 ppm. The ratio of NV^- to NV^0 was evaluated from photoluminescence (PL) spectrum (Fig. 3). All these measurements were performed at room temperature.

Results & Discussion

The concentration of P1 decreased with increasing fluence. In contrast, total amount of NV centers increased with increasing fluence and only NV^- was detected when the fluence of 3×10^{18} cm^{-2}. The result suggests that remained P1 centers act as electron donor, and provide electron to NV^0. Further irradiation with higher fluence will be needed to achieve the adequate one to maximize NV^- concentration for diamonds remaining the charge state only in NV^-.

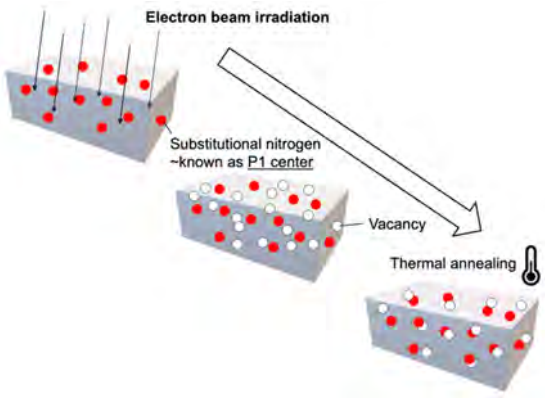

Fig.1 Schematic illustration of fabrication process of NV center

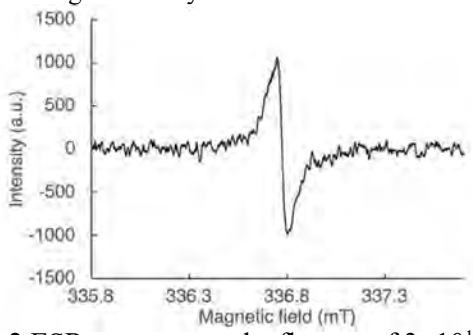

Fig.2 ESR spectrum at the fluence of 3×10^{18} e/cm^2

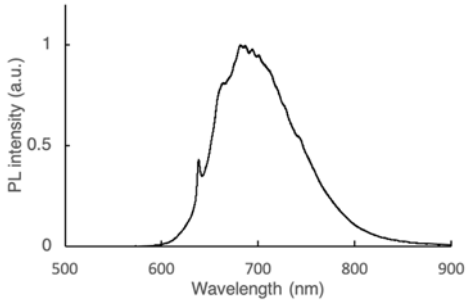

Fig.3 PL spectrum at the fluence of 1.5×10^{18} e/cm^2

Acknowledgement

This work was supported by Quantum Leap Flagship Program (Q-LEAP; JPMXS 0118067395 and JPMXS0118068379) of MEXT.

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Fabrication of SiV centers inside nanodiamonds using ion implantation

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Introduction

Small nanodiamonds containing color centers have been attracting attention as a hybrid system with nanophotonic devices to realize photonic quantum information devices such as highly efficient single photon sources. In various color centers, silicon vacancy (SiV) centers are especially interesting because of high photo-stability, high brightness, high Debye-Waller factor (about 70%), and lifetime-limited fluorescence linewidth [1,2]. The small nanodiamonds containing SiV centers have been usually fabricated by milling large nanodiamonds with SiV centers, which are synthesized by chemical vapor deposition (CVD). However, this milling method has an issue with the production yield. Here, we report on the fabrication of SiV centers inside nanodiamonds by direct implantation of Si ions, which allows the creation at a high production yield due to no requirement of the milling process. By implanting Si ions into small nanodiamonds (median size of 25 nm) with an ion fluence of 10^{13} ions/cm^2, we fabricate SiV centers exhibiting a narrow linewidth of about 7 nm at room temperature [FIG. 1(b)]. This linewidth is more than twice as narrow as previous reports on the implantation of Si ions into nanodiamonds [3,4].

Method

In order to fabricate the nanodiamonds containing SiV centers, we spin-coated small amount of pure water dispersed nanodiamonds (median size of 25nm) on silicon substrates and then implanted ^{28}Si ions at 30keV with an ion fluence of 10^{13}ions/cm^2. After ion implantation, the samples were treated by two-step high temperature and high vacuum annealing.

Figure 2 is an experimental setup to evaluate the annealed samples. A continuous-wave laser (λ=685nm) was used as excitation laser. The laser light was reflected by a dichroic mirror and then focused on the sample by an oil immersion objective lens. The fluorescence was collected by the same objective lens and coupled to multi-mode fiber after filtered by the dichroic mirror and long pass filter (715nm). A confocal image and emission spectrum were obtained by a single photon counting module and a spectrometer equipped with a charged coupled camera, respectively.

Figure 1 (b) is an emission spectrum of a bright spot (white arrow) in a confocal image of FIG. 1 (a). A sharp emission peak with the linewidth of about 7nm was observed at 738 nm, which corresponds to zero phonon line (ZPL) of SiV center. Besides these results, we will discuss the nanodiamonds fabricated under different conditions.

This work was supported by MEXT KAKENHI (26220712), JST CREST (JP MJCR1674), MEXT Q LEAP Grant Number JPMXS0118067634.

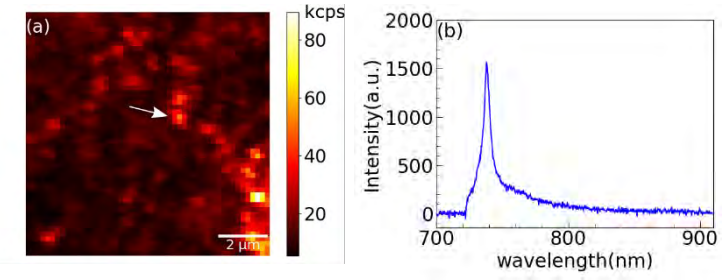

FIG.1 (a) Confocal scanning image. Length of white bar is 2 μm. (b) An emission spectrum at a bright spot (whit arrow).

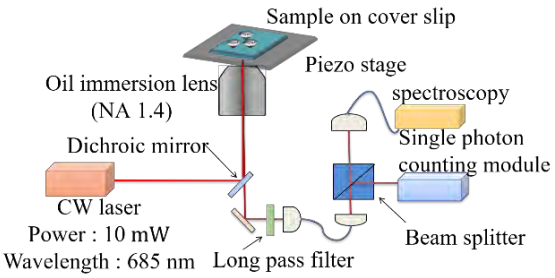

FIG.2 Experimental Setup.

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Spin squeezing induced by consecutive imaging of a Bose-Einstein condensate

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Introduction

Spatial magnetometers using Bose-Einstein condensates (BECs) exhibit precise sensitivities superior to $10\ \mathrm{pT}/\sqrt{\mathrm{Hz}}$ with high spatial resolutions of micrometers [1]. The sensitivity and spatial resolution provide new tools such as the Scanning Quantum Cryogenic Atom Microscope applied to study of a nematicity in a high-temperature superconductor [2]. Recently, we achieved a sensitivity of $7.7\ \mathrm{pT}/\sqrt{\mathrm{Hz}}$ for a DC magnetic field over a measurement area of $28\ \mu\mathrm{m}^2$ [3]. The achieved sensitivity per unit area is the best among the spatial BEC magnetometers. Because the sensitivity is almost limited by the quantum noises, i.e., the atomic spin projection noise and the photon shot noise due to the probe light, the quantum noise squeezing is desired for further improvement. With respect to the atom shot noise, our magnetometry is designed to experience QND (quantum nondemolition)-measurement-based spin squeezing. We are now conducting experiments to observe the spin squeezing.

Experiment

We perform non-destructive consecutive imaging of a spinor ^{87}Rb BEC of $F = 2$ in an optical dipole trap. The experimental setup is schematically shown in FIG. 1. A linearly polarized probe laser that is near-resonant to the D_1 line illuminates the BEC. The dispersive interaction between the probe light and atoms is approximately represented by the QND-type Hamiltonian $H_{\mathrm{int}} = gS_zF_z$, where g is a coupling constant, S_z is the Stokes operator, and F_z is the collective spin operator, if the tensor interaction is cancelled. While the interaction imprints the information of the projection of the collective spin along the probe axis on the rotation of the polarization plane (paramagnetic Faraday rotation), the interaction itself does not cause evolution of F_z and satisfies the QND condition [4, 5]. The QND measurement squeezes the uncertainty in F_z.

Our imaging setup realizes the QND measurement of F_z. The phase plate induces a fixed phase shift (approximately $\pi/2$) between the scattered light by the BEC and the unscattered light, generating a phase contrast image. The phase contrast image is decomposed into orthogonal circularly polarized components by a quarter waveplate and a Nomarski prism. The decomposed phase contrast images allow us to track F_z, as well as the atom number. The QND feature should appear in the correlation between the polarization rotation angles in the consecutive measurement.

This work was supported by MEXT Quantum Leap Flagship Program (MEXT Q-LEAP) Grant Number JPMXS0118070326.

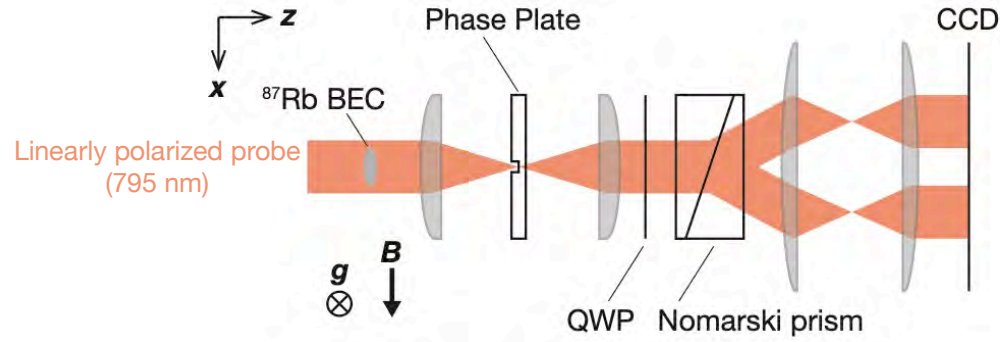

FIG. 1. Experimental setup for consecutive imaging of a spinor BEC. QWP: quarter waveplate.

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Development of photon number resolving detector by small size Ti/Au-TES

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Introduction

It is currently important issues in photon metrology and quantum information to measure a single photon or few photons [1]. In this measurement, the photon number-resolving detector (PNRD) with fast response speed and high quantum efficiency is demanded for various applications based on quantum optics. One of PNRDs is a transition edge sensor (TES) which has photon-number resolution, high detection efficiency, and a very low dark-count rate [2]. A TES is one kind of microcalorimeter and consists of superconducting thin films operated in the steep temperature region between the normal and superconducting state. Recently, we achieved 50 ns response time and 0.27 eV energy resolution for 1550 nm single photon in the 5 μm square size TES fabricated by titanium (Ti) and gold (Au). In general, the energy resolution and the response speed of the TES is improved by using smaller heat capacity and higher critical temperature (T_c) of the superconducting film. To improve these performances, we designed and fabricated smaller size Ti/Au-TES (1 μm square sizes) and will report some results in this conference.

Fabrication

Firstly, on a silicon wafer, silicon dioxide (SiO_2) was sputtered in order to control T_c of Ti/Au-TES. Secondly, Ti and Au were sequentially deposited by DC sputtering on SiO_2. A thickness of Ti and Au was approximately 40 nm and 10 nm. After sputtering, Ti and Au films were patterned to 1 μm square sizes by wet etching. Finally, superconducting niobium electrodes were fabricated by lift-off process (Fig.1).

Results

The T_c of the Ti/Au-TES greatly affects response speed so that it is important to determine the operating temperature of the device. For this reason, we have measured the relationship between electrical resistance and temperature by sweeping the base temperature in the refrigerator with the four-terminal resistance measuring method. Fig.2 shows the transition curve of the fabricated 1 μm square sizes Ti/Au-TES. We observed a sharp transition at T_c = 313 mK and the critical current around T_c above 1 μA, which is enough to detect the number of photons at in telecommunication wavelengths. In the future, we will setup PNRD system with easily achieved high detection efficiency which consists of the small size Ti/Au-TES combined into a wave guide with optical cavity structure.

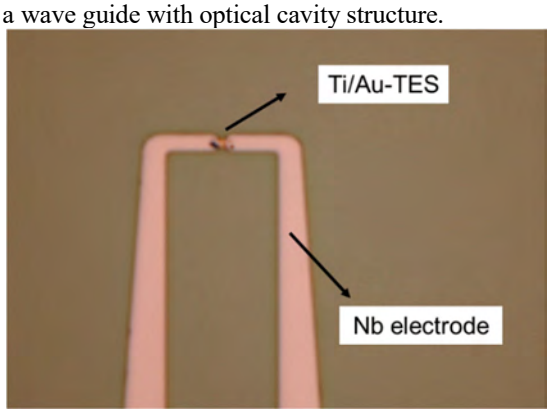

FIG. 1. The picture of Ti/Au-TES (1 μm square sizes).

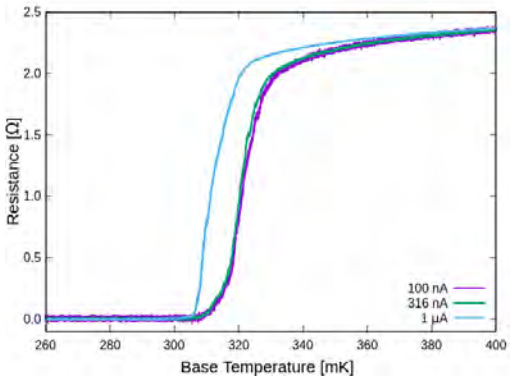

FIG. 2. The transition curve of the Ti/Au-TES

Acknowledgment

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Nonlocal Variable-strength Measurements of N Qubits Using GHZ-like Entanglement

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Introduction

The discovery of so-called nonlocal quantum states, that is multipartite quantum states exhibiting correlations that cannot be explained by classical local hidden variables, has led to what some called "the second quantum revolution". Indeed, the existence of such states showed that the relation between spacetime and quantum theory is far from trivial, and that such states could be used as a kind of new quantum resource, quantum entanglement. Using quantum entanglement opens the door to new potential quantum information and communication technologies, such as quantum teleportation.

However, similarly to the case of quantum superposition, quantum entanglement is extremely fragile, as any *local* measurement will unavoidably destroy it. Even in the simplest case, that of two entangled qubits distributed between space-like separated locations, one needs additional resources beyond local meters to realize ideal nonlocal measurements, which leave nonlocal eigenstates undisturbed. In previous works, we showed that such nonlocal measurements could be realized in the two-qubit case by using an indirect measurement scheme where the quantum meter state is itself entangled[1]. We also derived a connection between the amount of meter entanglement and the global measurement strength[2]: the more entangled the meter, the closer to a projective measurement the resulting statistics are. The strong measurement case corresponds to using a maximally-entangled nonlocal meter state. In this situation only, one can implement joint measurements of commuting nonlocal variables by using two such nonlocal meters in sequence, to realize nonlocal Bell state measurements in particular. The generalization to arbitrary-strength joint nonlocal measurements and to three or more qubits remained an open question.

Method

In this work, we show how to extend our previous scheme to such situations by using a nonlocal meter in a superposition of GHZ states. Even for non-strong measurements, one can jointly measure nonlocal observables by using a single, bigger nonlocal qubit meter. For instance, one can realize a variable-strength Bell State Measurement using not two 2-qubit meters, but a single 4-qubit entangled meter state (see Fig. 1). The same logic allows us to generalize our procedure to an arbitrary number of qubits, for any joint measurement of commuting nonlocal observables. We also prove a generalization of the relation between meter entanglement and nonlocal measurement strength in the multipartite case, using the n-tangle as an entanglement measure.

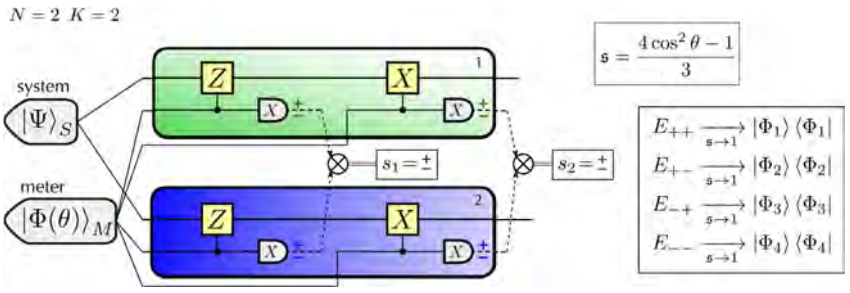

FIG. 1. Schematic representation of a Variable Strength Bell State Measurement using a 4-qubit nonlocal meter depending on a single real parameter θ. As the parameter θ approaches the value 0, one is able to distinguish with high confidence between the 4 orthogonal Bell states looking at the measurement outcomes s1 and s2. When θ gets close to π/3, the measurement outcomes become random and uncorrelated to the input state.

This work was supported by MEXT Quantum Leap Flagship Program (MEXT Q-LEAP) Grant Number JPMXS0118067581.

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Development of single-photon detectors with spatial resolution

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Introduction

It is crucial to develop a photon detection technique with high spatial resolution. To characterize the spatial distribution of photons, we often used an inefficient method to obtain the image of photons by scanning a large area with conventional single-photon detectors. Instead of scanning, 2D imaging devices, e.g., multipixel single-photon avalanche diode (SPAD), has been developed recently. However, it might be challenging to perform a coincidence measurement due to the lack of temporal resolution [1]. Here, we introduce single-photon detectors with a photocathode followed by a microchannel plate and delay-line anodes, allowing the arrival positions and time of photons with high accuracy. The microchannel plate with the delay-line anode has been utilized for coincidence measurements of charged particles [2]. Therefore, our detectors may have the ability to measure two photons with high spatial resolution. To measure coincidence images of photons, we evaluate the spatial or temporal resolutions of the detectors and then take the composited image of the photon pairs.

Method

Firstly, we confirmed the detectors could obtain images at the single-photon level. To this end, we placed a double-slit at 31.5 cm position from the detector and irradiated the second harmonics of a mode-locked Ti:S laser to the center of the double-slit. Here, we attenuated the laser power below 10 pW, ensuring the number of photons is under 0.003 per pulse. We obtained a clear image of Young's interference pattern at the single-photon level as shown in Fig. 1(a). To ensure spatial resolution, we also measured the image of a test-target. Based on the Rayleigh criteria [3], we estimated the spatial resolution as approximately 46 μm. Secondly, we tested the temporal resolution through time-correlation measurements. We put the attenuated laser pulses from the Ti:S laser with the repetition rate of 76 MHz into the two detectors through a branched fiber and then took a coincidence image as shown in Fig. 2(b). From the time-correlation measurement in Fig. 2(a), we estimated the temporal resolution of the detector as ~600 ps, implying the detectors have the ability to pick up one pulse out. After the spatial resolution and temporal resolution were confirmed, we composited images from one specific pulse. After we balanced the light power in each detector, the double-slit images were observed by setting the time window for a specific pulse in Fig. 2(a). For further application of this technique, we also tried to detect the photon pairs from CuCl crystal.

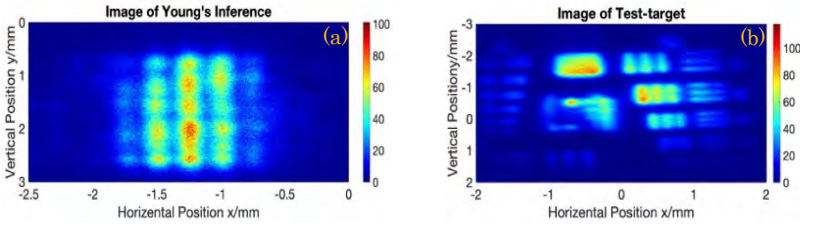

Fig. 1: (a) Image of Young's Inference observed by a single-photon detector with the spatial resolution. (b) Image of the test-target detected by the single-photon detector.

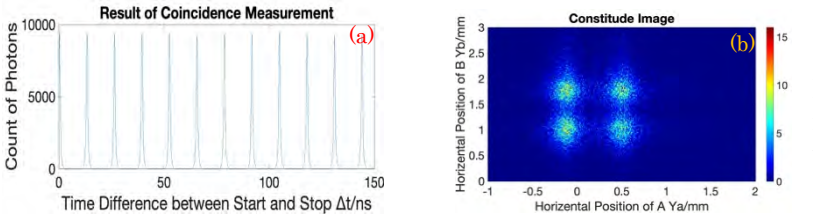

Fig. 2: (a) Result of the time-coincidence measurement. (b) Coincidence image on vertical positions of the two photons.

Acknowledgement

This work was supported by MEXT Q-LEAP Grant Number JPMXS011806924

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Probing excited-state dynamics with three entangled photons generated via cascaded parametric-down conversion

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In the presentation, we will talk about the theoretical investigation of the frequency dispersed two-photon coincidence counting measurement of three entangled photons generated via cascaded parametric down-conversion with a monochromatic laser (Fig. 1). We theoretically demonstrate that the two-photon counting measurement via the tri-photon state enables time-resolved spectroscopy, which provides the same information as two-dimensional Fourier-transformed photon-echo spectra. This correspondence is similar to the result of the transmission measurement of entangled photon pairs [1]. We further explored the influences of finite entanglement time upon the spectrum. The possibility to filter specific spectral region in the two-photon counting signal by adjusting the phase-matching conditions of the cascaded parametric down-conversion is discussed.

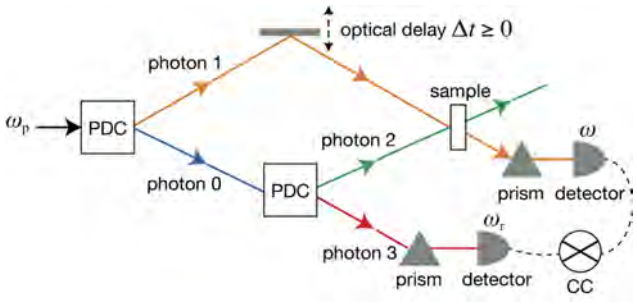

FIG. 1. Schematic of frequency-dispersed two-photon coincidence counting measurement with three entangled photons generated via cascaded parametric down-conversion pumped with a monochromatic laser. In this setup, photon 2 is employed as the pump field, whereas photon 1 is used for the probe field with time delay Δt. Photon 3 does not interact with the molecular sample and serves as the reference for the coincidence measurement.

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Ab-initio Quantum Chemical Theory of Long-distance Electron Tunneling in Proteins

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Biological electron-transfer (ET) reactions that play significant roles in photosynthesis and respiration proceed via the long-distance electron-tunneling steps in proteins. The rate of the ET reaction is generally expressed by the Marcus formula as follows:

$$k_{\mathrm{DA}} = \frac{2\pi}{\hbar}|T_{\mathrm{DA}}|^2 \frac{1}{\sqrt{4\pi\lambda k_{\mathrm{B}}T}} \exp\left[-\frac{(-\Delta G - \lambda)^2}{4\lambda k_{\mathrm{B}}T}\right],$$

where T_{DA} is the tunneling matrix element between electron donor (D) and acceptor (A). ΔG and λ are the Gibbs free energy difference and the reorganization energy, respectively. Since the redox centers in ET proteins are often separated by distances greater than 10 Å, the T_{DA} is usually small ($<\sim$100 cm^{-1}) and mostly arises from the super-exchange mechanism where the electronic states of the protein environment are involved as virtual intermediate states for the electron tunneling. Therefore, the T_{DA}-value significantly depends on the tunneling-mediating protein structure. However, ab initio-based studies on the T_{DA}-values for biological ET systems have been still limited due to the enormous computational costs of protein electronic-structure calculations.

In this study[1], we have developed practical ways to calculate the T_{DA} and analyze the tunneling pathways for protein ET reactions with the linear-scaling ab-initio electronic structure method called fragment molecular orbital (FMO) method. The current FMO codes have been interfaced with density functional theory (DFT), polarizable continuum model (PCM), and model core potentials (MCPs), with which the FMO-based protein ET calculations can consider the effects of electron correlation, solvation, and transition-metal redox centers. We obtained the reasonable performance of the FMO-based ET calculations for the different sets of protein-ET model molecules.[1]

FIG. 1(a) schematically shows the ET between ruthenium (Ru) and copper (Cu) complexes covalently bridged by a stretch of a polyglycine linker as a model for Ru-modified derivatives of azurin. The FMO-based protein ET calculations can provide the proper D/A MOs for the two transition-metal centers and the corresponding T_{DA}-value with ab-initio accuracy, as shown in FIG. 1(b).

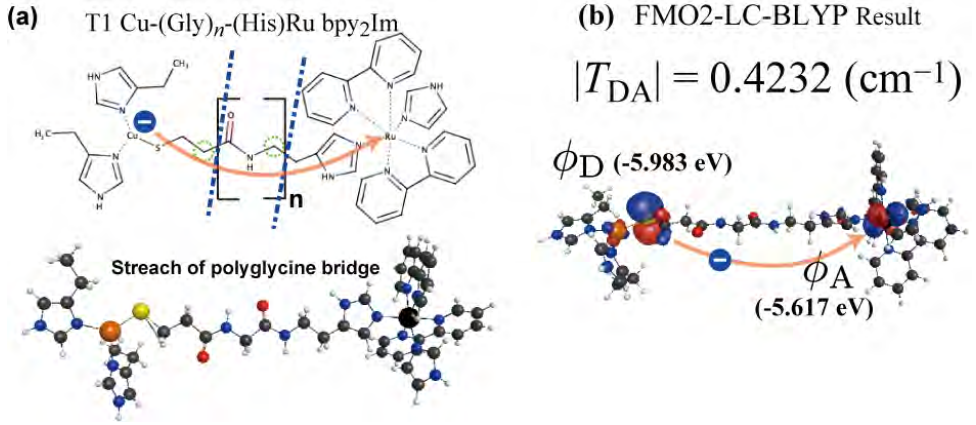

FIG. 1. (a) Structure and FMO fragmentation of type-I (T1) Cu-(Gly)n-(His)Ru bpy2Im. (b) Donor/acceptor MOs and T_{DA}-value obtained from the FMO-based ET calculations with the long-range corrected (LC) density functional, LC-BLYP.

This work was supported by JST, PRESTO, Grant No. JPMJPR17G4.

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X-ray induced cell cycle arrest and raises the cellular temperature

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Introduction

Mammalian fibroblast cells undergo cellular senescence by high dose X-ray irradiation. Although the senescence is distinct from those caused by telomere shortening, both exhibit similar characteristic such as being irreversible cell cycle arrest and releasing bioactive substances that promote carcinogenesis or induce further senescence in surrounding cells. The evidence suggests that intracellular physiological reaction of senescent cells might be different from those of normal cells. We focused on intracellular temperature, as one of physicochemical index to evaluate the physiological changes in senescent cells. ATP molecules consumed in various reactions transfer energy to conjugated reactions, and then some of the energy might be converted to heat which possibly raises intracellular temperature. To clarify whether cellular temperature correlated with radiation-induced senescence, we performed measurements of the cellular temperature by introducing a thermoprobe, Cellular Thermoprobe for Fluorescence Ratio, into immortalized human fibroblast cells.

Method

The cells were exposed to 20 Gy X-rays. More than 90% of cells were confirmed undergoing senescence on eighth day after irradiation by SA-β-gal staining method. The thrmoprobe was introduced into the cultured cells, and then the ratio of red and green fluorescence intensity was determined with microscopic fluorescent images. Intracellular ATP levels was also measured by a luciferin-luciferase method.

Result and Discussion

The temperature of senescent cells was about 4°C higher than that of normal cells. This suggest that heat release reaction may be increasing in senescent cells. We also found a higher level of intracellular ATP in senescent cells than that in normal cells. This may be due to reduced ATP consumption with the arrest of the cell cycle. From these observations, it is inferred that deconjugation in mitochondria in senescent cells results in temperature evaluation without any ATP consumption.

^{13}C pulsed dynamic nuclear polarization using pentacene or NV$^-$ centers in diamond at room temperature

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Dynamic nuclear polarization (DNP), a technique to transfer spin polarization from electrons to nuclei, has extensively been studied since its early discovery [1] and has opened the way for high sensitive nuclear magnetic resonance spectroscopy and magnetic resonance imaging [2,3]. In DNP using unpaired electrons as the source of polarization, the polarization enhancement factor is limited to γ_e/γ_n, where $\gamma_{e(n)}$ are the gyromagnetic ratios of the electron (nuclear) spins.

Since spins of optically polarized electrons can have much higher polarization than their thermal equilibrium value, the electron polarization leads to nuclear hyperpolarization beyond the limit of DNP using thermal electron polarization. DNP using optically-polarized electron spins was originally demonstrated in a single crystal of naphthalene doped with pentacene [4], and this DNP technique using pentacene achieved ^{1}H polarization of 34% at room temperature and a magnetic field of 0.4 T [5]. Recently, DNP of an ensemble of ^{13}C nuclear spins using negatively charged nitrogen-vacancy (NV^-) color centers in a bulk diamond single crystal has also been demonstrated at room temperature and a ^{13}C polarization of 6% has been achieved via the combination of the thermal mixing and the solid effect [6]. Furthermore, DNP using NV^- in powdered microdiamonds has been reported by Ajoy et al., who took advantage of the reduced width of the anisotropic electron spin resonance (ESR) powder pattern of the NV^- centers at the magnetic field of ca. 30 mT [7].

In this work, we compare triplet-DNP of pentacene doped in [carboxyl-^{13}C] benzoic acid (PBA) and NV^- color centers in diamond at room temperature. We study the behavior of the ^{13}C polarization buildup in terms of the polarization efficiency of the transfer from the electron to nuclear spins, exchange rate, and the ^{13}C spin diffusion. In both cases, the optically-polarized triplet electron spins are the source for DNP. As a result, we obtained a ^{13}C polarization of 0.01% in the microdiamonds, and of 0.12% in PBA at room temperature in a magnetic field of 0.4 T by using the integrated solid effect and the obtained exchange rate was 0.87% for microdiamonds and 3.5% for PBA.

This work was supported by MEXT Q-LEAP Grant Number JPMXS0120330644, JPMXS0118067634 and JPMXS0118067395.

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High efficiency rf-to-light conversion through improved electromechanical coupling for NMR detection

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Introduction

Radio-frequency (rf) signals can be converted to optical signals through a mechanical oscillator interacting with electrical circuits and light [1]. Using a metal-coated SiN membrane serving for both a capacitor electrode and an optical mirror, we have successfully upconverted rf nuclear magnetic resonance (NMR) signals into the optical regime [2, 3]. Even though this approach, called Electro-Mechano-Optical (EMO) NMR, potentially leads low-noise measurements, the sensitivity has been far less than ideal. In this study, the performance of the EMO NMR was dramatically improved by a more efficient rf-to-light transducer.

Method

Figure 1 shows a diagram of the EMO system, in which the Al-deposited SiN membrane oscillator interfaces the electrical part and the optical part of the system. Here, the drive signal is applied to induce the electromechanical coupling. The displacement of the membrane is optically measured, and the photo-detected signal is then mixed with a reference signal at the drive frequency, and digitized. Here, we have designed and fabricated a new membrane capaitor with a capacitance of 1.6 pF, which is ca. 20 times larger than that in our previous work. As a result, the electromechanical coupling strength became ca. 3000 times higher than that in our previous work [2, 3].

To characterize the performance of the system, continuous rf tone signals were converted into light and the signal-to-noise ratio (SNR) of the optically detected rf signals were compared to that measured with the conventional electrical approach. The SNR of the EMO scheme became ca. 1000 times better than that of our previous work [3]. As shown in Fig.2, when the power of the drive signal was increased, the SNR became quite comparable to that of the conventional electrical detection. Although the SNR of the EMO scheme is still lower than that of the electrically amplified scheme, the difference in SNR was within a factor of 10. Since there is still much room for improving the transducer in terms of the Q factor of the membrane oscillator, the EMO approach is expected to eventually become superior to the conventional electrical detection.

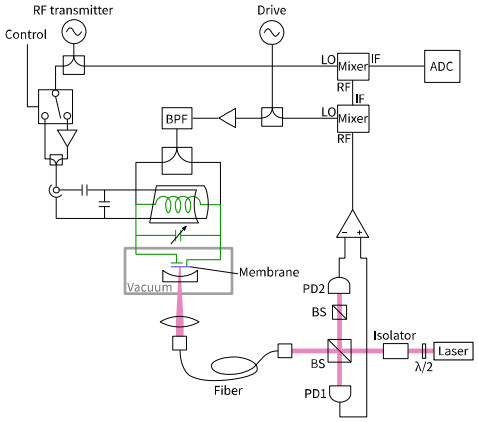

FIG. 1. A schematic of the EMO system. Abbreviations are as follows; BS: beam splitter, PD: photo-detector, BPF: band-pass filter, ADC: analog-to-digital converter.

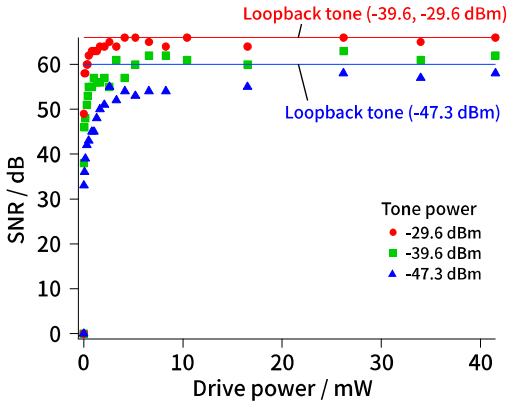

FIG. 2. Drive-power dependence of SNR of the transduced tone signals at 200 MHz with power of −29.6 dBm (circles), −39.6 dBm (squares), and −47.3 dBm (triangles). The SNR of the loopback signal is shown as a red and blue straight lines for tone signal strengths of −29.6 dBm and −39.6 dBm, and for that of −47.3 dBm, respectively.

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Magnetic Characterisation of Cuticulosomes in the Inner Ear Hair Cells of Pigeons

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It has long been known that magnetoreception is a sense which is present in avian species including pigeons. This has been established through behavioral studies dating back to the 1960s in which the effect of the magnetic field on the navigational ability of the birds is observed [1]. The precise mechanisms underlying magnetoreception, however, are still not understood. Three main hypotheses exist to explain the mechanism by which magnetic fields are converted to neural signals. The ferrimagnetic particle-based hypothesis relies on a particle within the pigeon experiencing a torque with this mechanical signal then being transmuted to a neural signal [2]. The radical pair hypothesis describes a chemical reaction involving free radicals in which the yield of the reaction product depends on the local magnetic field [3]. The electromagnetic induction model postulates that conductive loops within the inner ear pigeons experience an inductive current as the bird rotates its head relative to the magnetic field. The resultant electrical signal forms the basis of magnetoreception under the inductive model [4].

Experiments involving the response of immediate early genes to changing magnetic fields have implicated the inner ear in pigeon magnetoreception [5]. Quasi-spherical iron-based structures were subsequently found in the hair cells of the lagena, basilar papilla, utricle and saccule of the pigeon inner ear [6]. These structures are referred to as 'cuticulosomes' due to their localization within the cuticular plate of the hair cells. The size, rate of occurrence in the hair cells and chemical composition of these structures have been analysed using TEM, Prussian blue staining, and energy filtered TEM and electron energy loss spectroscopy respectively. However, the magnetic properties of cuticulosomes are not well understood. Obtaining magnetic images of these objects poses a significant technological challenge due to their small size and magnetic moment. The challenge of meeting both the required spatial resolution and magnetic sensitivity has here been met using quantum diamond microscopy based on ensembles of nitrogen vacancy centres in diamond. The magnetic images obtained provide new insights into the magnetic properties of cuticulosomes as well as providing a new tool with which to screen for cuticulosomes. Both outcomes will aid in understanding the functionality of cuticulosomes, and crucially, whether they have any relevance to magnetoreception.

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A simple deaggregation method producing single-digit detonation nanodiamonds

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Detonation nanodiamonds (DNDs) are a class of very small and spherical diamond nanocrystals. They are used in polymer reinforcement materials[1], as drug delivery systems in the field of nanomedicine or as fluorescent biomarkers. Synthesized by detonation, only the final deaggregation step down to the single-digit nanometer size (< 10 nm) unfolds their full potential. In this work, we report a method to produce highly stable single-digit DNDs in a colloidal solution. This is a key step for many DND-based applications, ranging from material science to biological or medical applications and opens a way for inexpensive mass production on industrial scale.

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SABRE-enhanced NMR spectroscopy using quantum defects in diamond

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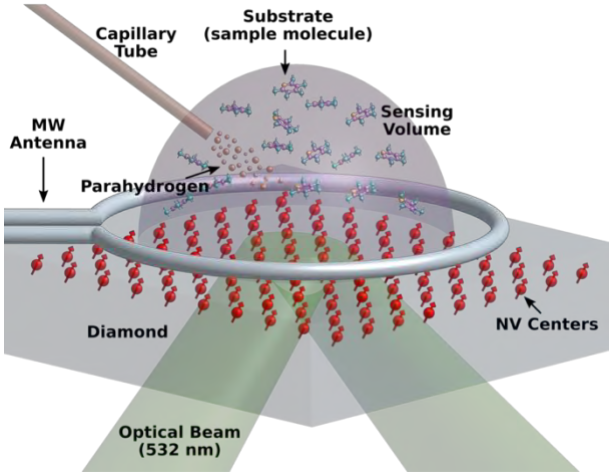

FIG. 1: NV-NMR sensor integrated with signal amplification by reversible exchange (SABRE)

Optically-probed nitrogen-vacancy (NV) quantum defects in diamond can detect nuclear magnetic resonance (NMR) signals with high-spectral resolution from micron-scale sample volumes of about 10 picoliters [1, 2]. However, a key challenge for NV-NMR is detecting samples at millimolar concentrations. In this talk, I will discuss our recent experiments where we demonstrate an improvement in NV-NMR proton concentration sensitivity of about 10^5 over thermal polarization by hyperpolarizing sample proton spins through signal amplification by reversible exchange (SABRE). Thus, enabling micron-scale NMR of small molecule sample concentrations as low as 1 millimolar in picoliter volumes [3]. The SABRE-enhanced NV-NMR technique may facilitate detection and chemical analysis of low concentration molecules and their dynamics in complex micron-scale systems such as single-cells.

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Label-free phase change detection of lipid bilayers using nanoscale diamond magnetometry

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Introduction

The NV center in a diamond is a quantum sensor with exceptional quality for highly sensitive nanoscale analysis of NMR spectra and thermometry. In this study, we investigate nanoscale phase change detection of lipid bilayers utilizing ensemble-averaged nuclear spin detection from small volume ~ $(6\ \mathrm{nm})^3$, which was determined by the depth of the NV center. Analysis of nanoscale NMR signal confirm thickness of lipid bilayer to be 6.2 nm ± 3.4 nm with proton density of 65 proton/nm^3 verifying formation of lipid bilayer on top of diamond sample. Correlation spectroscopy from nanoscale volume reveals quantum oscillation at 3.06 MHz corresponding to the Larmor frequency of proton at an applied magnetic field of 71.8 mT. The result of the correlation spectroscopy was compared with the 2D molecular diffusion model constructed by Monte Carlo simulation combined with results from molecular dynamics simulation. There is a change in diffusion constant from 1.5 $\mathrm{nm}^2/\mu\mathrm{s}$ to 3.5 $\mathrm{nm}^2/\mu\mathrm{s}$ when the temperature changes from 26.5 °C to 36.0 °C. Observation of diffusion constant reveals different phases of lipid bilayer which identifies sub-compartment domains that are critical for cellular functions. Our method builds foundation for label-free imaging of cell membranes for observation of phase composition that determines cellular functions.

Result

FIG.1 shows NV measurement system and pulse sequence used for measurement of lipid bilayer. NV center measurements were performed using a home-built optical microscope based on Olympus IX73. Lipid bilayer was formed on top of perfectly aligned shallow ensemble NV center [1]. The sample was placed in an incubator to control temperature and maintain a steady temperature. FIG.2 show correlation spectrum obtained for 1.6 μsec to 20 μsec at (a) 26.5 °C and (b) 36.0 °C. Oscillation at 3.06 MHz corresponding to applied magnetic field of 71.8 mT is confirmed at both temperatures. The obtained data are compared with 2D molecular diffusion model constructed from Monte Carlo simulation. Correlation spectrum obtained at 26.5 °C shows relaxation characteristic comparable to the simulation with a diffusion constant Dt of 1.5 $\mathrm{nm}^2/\mu\mathrm{sec}$. As the temperature is increased to 36.0 °C, the relaxation characteristic shows result similar to the simulation with a diffusion constant of 3.5 $\mathrm{nm}^2/\mu\mathrm{sec}$. In this talk, we report determination of diffusion constant of a lipid bilayer, a biological parameter that determines the dynamics of the lipid bilayer, by making use of extremely small detection volume offered by nanoscale NMR [2]. Our method builds foundation for label-free imaging of cell membranes for observation of phase composition and pristine dynamics that determines cellular functions.

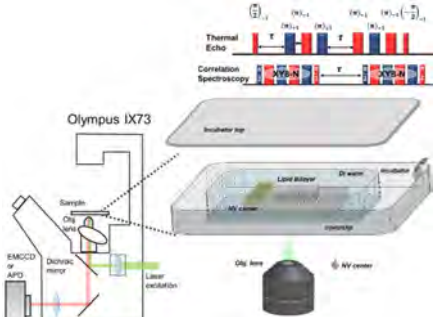

FIG. 1. NV center measurement system and pulse sequence used for lipid bilayer measurements.

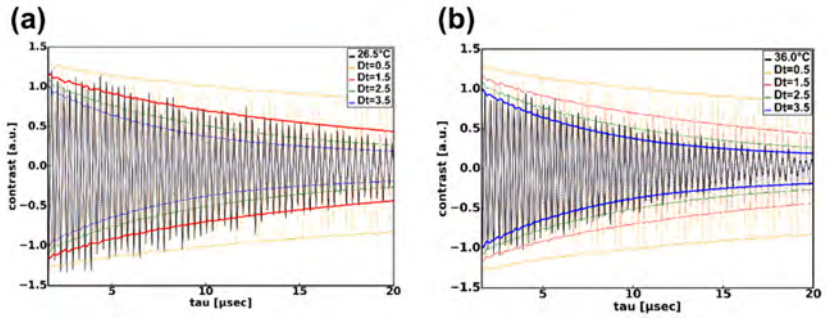

FIG. 2. Nanoscale correlation spectrum compared with 2D diffusion model (a) Data obtained at 26.5℃ (b) data obtained at 36.0℃.

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Biomagnetic field measurement system using NV centers in diamond

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Introduction

The imaging of the biological magnetic field has potential applications in disease diagnosis[1]. Magnetic sensors using NV centers in diamond, which have the feature of high spatial resolution and the room temperature operability in solid-state, are currently attracting attention with a sensitivity of 15 pT/Hz$^{1/2}$[2]. In this study, we constructed a compact measurement system that fits into a small magnetic shield box for biomagnetic imaging of small animals. Magnetic field image induced from the current flowing through the Cu line, which simulates the signal of nerves and heart activity, was confirmed to be observed correctly.

Equipment Configuration

A compact system was constructed by dividing it into two stages. The lower excitation system consists of a laser, a mirror, and a half-wave plate. The upper measurement system consists of a diamond, XY stage, and a photodiode. The overall size is smaller than 45 x 45 x 70 cm^3. To compensate for the temperature fluctuations, by using both the paired resonance frequencies of the NV center, the paired microwaves with different modulation frequencies were simultaneously radiated to the diamond and the fluorescence from the diamond was demodulated by two channels of a lock-in amplifier synchronized to the two modulation frequencies, respectively.

Results

We imaged a magnetic field in 11x11 121 pixels over a 10 mm square within the distribution of about 1 nT generated by a copper wire. The current distribution from the magnetic field image could be reconstructed correctly. Moreover, it was found that our temperature-compensating system was stable over one-hour measurement.

Acknowledgments

This work was supported by the MEXT, Q-LEAP (JPMXS0118067395)

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Wide field detection of inverse magnetostrictive effect using NV centers in diamond towards biological mass microscopy

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Introduction

Mass imaging techniques for multiple length-scales from single cells to tissues are necessary for a wide range of applications such as elucidating cell activity [1,2]. We focused on a hybrid quantum sensor that combines the Nitrogen-Vacancy (NV) center in diamond with a magnetostrictive (MS) thin-film [3]. In the hybrid sensor, stress is converted into the magnetization rotation by inverse magnetostrictive effect, inducing the change in the fringe magnetic field, and it is imaged by optically detected magnetic resonance (ODMR) in NV centers. Theoretical predictions have shown that this method can realize cellular mass imaging [3]. In this study, we demonstrate operation of hybrid sensor, detecting the stress as a change in the magnetic field. We deposited $SmFe_2$, a MS material, on a piezoelectric substrate. $SmFe_2$ exhibits perpendicular magnetic anisotropy [4], realizing higher sensitivity than that with in-plane magnetic anisotropy. Then, we applied stress on $SmFe_2$. We placed NV center thin-film on the $SmFe_2$ layer and aimed to detect the stress-induced change in the magnetic field.

Method

The measurement setup is shown in Fig. 1(a). We deposited $SmFe_2$ on PMN-PT (100) substrate by facing target sputtering and formed perfectly aligned NV center thin-film on Ib (111) diamond substrate by chemical vapor deposition (CVD) [5]. We applied stress to the $SmFe_2$ layer by applying a DC voltage of +200 V to -200 V to the piezoelectric substrate. We also applied a bias magnetic field of 200 mT perpendicular to the $SmFe_2$ layer, which is necessary for magnetization rotation. The perfectly aligned NV center thin-film detected the fringe field from the $SmFe_2$ layer, and a CCD camera imaged their fluorescence. ODMR images were acquired while changing the voltage applied to the piezoelectric substrate.

Result

Fig. 1(b) shows magnetic field images. The voltage applied to the piezoelectric layer was swept from -200 V to 200 V. We observed a change in the magnetic field distribution within the same field of view. This distribution is considered to reflect the strain distribution induced by ferroelectric domain in the piezoelectric substrate. These results imply that we detected strain signals via the inverse magnetostrictive effect and ODMR.

This work was supported by MEXT Quantum Leap Flagship Program (MEXT Q-LEAP) Grant Number JPMXS0118067395.

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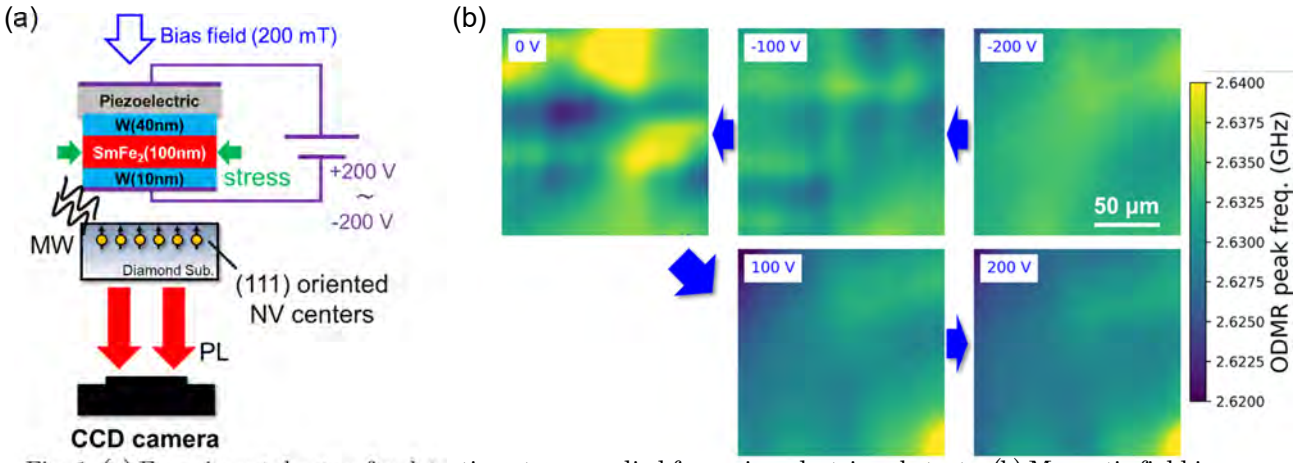

Fig. 1. (a) Experimental setup for detecting stress applied from piezoelectric substrate. (b) Magnetic field images within the same field of view. Color bar shows ODMR peak frequency, which reflects the magnetic field. The scale bar is 50 micrometers.The voltage applied to the piezoelectric layer was swept from -200 V to 200 V.

Brain mapping of visual cortex with quantum magnetoencephalography devices

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Introduction

Magnetoencephalography (MEG) can be used to non-invasively measure magnetic fields induced by neuronal electrical activity and thus promise the recording of neuronal signals with millisecond temporal resolution. The recent development of the wearable detection system employing nitrogen-vacancsy (NV−) centers in diamond has provided a candidate for the next generation MEG detection devices[1]. Considering the promising future application of NV diamond MEG, here we established a protocol and collected MEG data with conventional MEG systems which could be exploited for the comparison with this new technique. In this work, we compared the MEG signal measurements of human Steady state visually evoked magnetic field (SSVEF) responses against a Flash stimulation using both superconducting quantum interference devices (SQUID) and optically pumped magnetometers (OPMs) systems[2]. Since the retinotopic mapping in visual cortical areas of the human brain follows well-established patterns, that is the left and right visual field locations are represented in the respective contralateral cortical hemispheres[3], we exploited this visual pathway to evaluate the feasibility of OPMs to measure SSVEF against variable stimulation patterns.

Method

Data were recorded using a 306-channel whole-head MEG system (The University of Tokyo Hospital) at a sampling rate of 600 Hz, from 3 participants all of whom gave their written informed consent to participate.

The visual stimulation was implemented with flashes projected on a screen generated by a LED driver with wavelength of 523nm, frequency of 10Hz. To investigate the regional representations of the visual cortex, we designed the flashes paradigm as both full-circle and 4 direction semi-circle shapes with 5 patterns in all. The distance from the eyes to the screen and the stimulus size were adjusted such that the outer diameter of the coherent circle to be a visual angle of 20°. The stimulus contained 5 sessions with 1s flash-on time and 1s flash-off time for each session. Every participant received 10 repetitive stimuli meaning a total of 50 times MEG signals were collected. We performed all MEG analysis using the Matlab software.

Results:

We applied a Signal-Space Projection (SSP) methods on SQUID measurement data and a bandpass filter on both SQUID and OPMs data constraining the frequency between 5 and 15Hz. Consequently, we observed obvious SSVEF response from the MEG data measured by both devices corresponding to the frequency of the visual stimuli. By co-registrating the time series signals of all SQUID sensor channels on the corresponding anatomical position to the scalp, the mapping demonstrates regional characteristics that SSVEF response induced by left and right semi-circle flash showed larger signal intensity in right and left cortical hemispheres respectively. This spatial tendency of the signal intensity distribution is consistent with MEG signals acquired by OPMs, whereas the amount of the sensors is relatively limited in comparison with SQUID. The results of this work demonstrate the feasibility of evaluating the sensitivity of the MEG systems using SSVEF and retinotopic mapping.

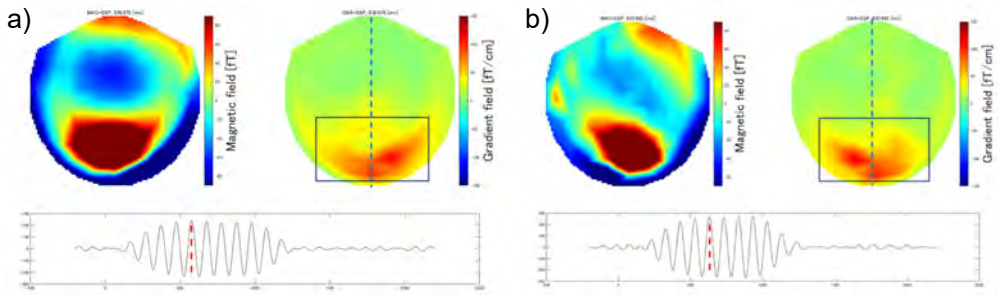

FIG. 1. Magnetic field distribution obtained from MEG results by SQUID. a) Left semi-circle stimulation. b) Right semi-circle stimulation

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Development of bio-nanoprobe for NVC-SPM

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Introduction

With the development of cell engineering, high-resolution measuring method for evaluating the function and characteristics of cells has become necessary. Focusing on the highly sensitive quantum measurement and sensing functions of diamond nitrogen-vacancy center (NVC), we are proceeding with research of probing technology that can measure intracellular signals and temperature. In particular, since fluorescent labeling exerts a chemical effects on cells and it is difficult to remove nano-diamonds after observation once they are injected into cells, we aim to realize a probing technology that is less invasive and can be used, repeatedly.

Method

Probe was fabricated by FIB-SEM (Hitachi High Tech NB5000) using micro-sampling technique [1] from 1b diamond substrate irradiated with electron beam at National Institutes for Quantum and Radiological Science and Technology. The tip surface was cleaned by plasma processing (FISHIONE model 1020, Ar + O2, 80W, 1 hour) after FIB fabrication to improve surface condition. The needle was inserted into mouse egg cells with a radius of a hundred microns in the culture liquid and the fluorescence images were obtained.

Results

The probe with a cross section of 1 μm x 1μm and 20 um length could be fabricated. In this probe, NVC was successfully localized only in the probe tip about 1um as shown as dark area in FIG. 1. This probe could be repeatedly inserted into and removed from the fertilized egg cell with mechanically hard membrane without breaking. It was confirmed that the probe could be positioned to each visible organelle. In the state of the probe being stabbed in an egg cell, red fluorescence detection centered at a wavelength of 630 nm from NVC was confirmed under the irradiation at 535 nm.

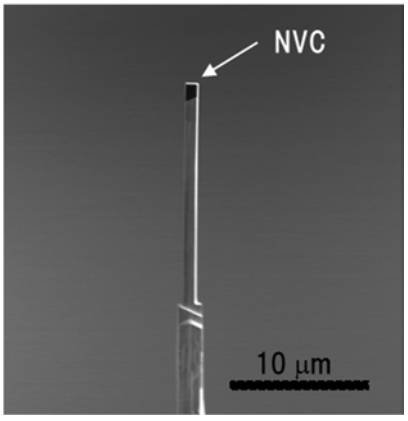

FIG. 1. SEM image of the fabricated probe.

We thank Dr. Shinobu Onoda and Dr. Takeshi Ohshima of National Institutes for Quantum and Radiological Science and Technology for making diamond substrates with high density NVCs. We also thank Dr. Toshiharu Makino of The National Institute of Advanced Industrial Science and Technology for plasma processing. This work was supported by MEXT Quantum Leap Flagship Program (MEXT Q-LEAP) Grant Number JPMXS0118067395.

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Optical properties of silicon vacancy in SiC under simultaneous optical and electrical excitation

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Introduction

Silicon vacancy (V_{Si}) in Silicon carbide (SiC) is one of spin defects applicable to quantum sensor [1,2]. A V_{Si} based quantum sensor is expected to directly measure the inside of the SiC device during operation, which will greatly help to improve SiC through designing device structure and simulating its performance. For this purpose, optical properties of V_{Si} under simultaneous optical and electrical excitation should be elucidated. In this work, we show that optical properties of V_{Si}, including optically detected magnetic resonance (ODMR) contrast, can be explained by a balance of each pumping rate for optical and electrical excitation.

Method

A pn junction diode was used to limit a current path. The three-dimensional arrayed V_{Si} was created into the current path by particle beam writing using a focused (~1 μm) He beam and dot pattern with 10 μm pitch. The depth of V_{Si} was changed by changing ion energy ranging 0.5-3 MeV. Optical properties of V_{Si} was measured by a home-built confocal microscope (CFM) equipped a 671 nm laser. All measurements were performed at room temperature.

Results

Our study elucidated that photo-excitation and electro-excitation pathways compete under simultaneous excitation in the case of V_{Si}, which modifies the effective pumping rates (weighted average). Figure 1 shows luminescence intensity as a function of current under various laser powers from a dot where current was injected. No remarkable change was observed for a dot not current injected. A numerical simulation based on the rate equations using the effective pumping rates can reproduce the luminescence change. The evolution of ODMR contrast can also be explained by the normalized effective pumping rate of photo-excitation (= k^*_{12}) as shown in FIG.2.

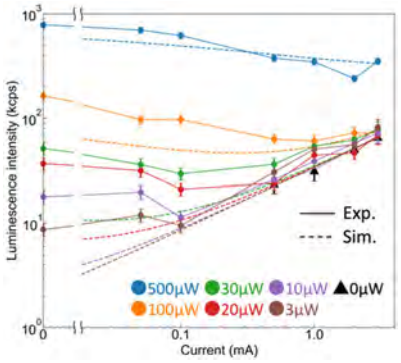

FIG. 1 (left). Luminescence intensity as a function of current under various laser powers from a dot where current was injected.

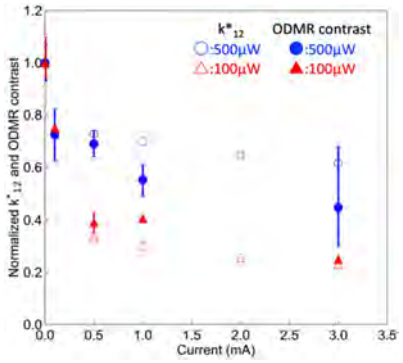

FIG. 2 (right). Normalized k^*_{12} and ODMR contrast as a function of current for 100 and 500 μW for a dot where current was injected.

Acknowledgements

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Electrical Detection of Magnetic Resonance of NV Centers in Diamond Around Zero Bias Voltage

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Introduction

Nitrogen-vacancy (NV) centers in diamond have a long coherence time at room temperature, and hence they are candidates for quantum-information processing devices and quantum sensors [1]. For the development and integration of these devices, the electrical detection of NV spin states, called electrically detected magnetic resonance (EDMR), is an essential technology [2-6]. When we measure an EDMR spectrum of NV centers under the application of a bias voltage, an electrical field generated by the bias voltage interacts with the NV electron spin [7,8]. Then, the electrical field influences the sensitivity of the NV-diamond magnetometry. Thus, it is essential to study the electrical field's influences on the sensitivity of the NV-diamond magnetometry with the EDMR technique. In this study, we perform the EDMR measurements of the ensemble of NV centers around zero bias voltage to study the influences of the electrical fields generated by the bias voltages on the sensitivity of the NV-diamond magnetometry.

Method & Result

In this study, we performed the EDMR measurements around zero bias voltage using the ensemble of NV centers (concentration of ~ 1.4×10^{17} cm^{-3}) created by electron-beam irradiation followed by annealing. Figure 1 shows an EDMR spectrum at a zero magnetic field in the absence of bias voltage. It shows that we have successfully observed the EDMR signal of the ensemble of the NV centers in the absence of a bias voltage. In this presentation, we discuss the EDMR signals' dependence on the bias voltage and detection mechanism of EDMR signals around zero bias voltage.

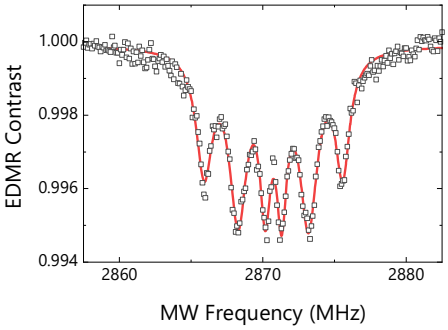

Fig. 1 EDMR spectrum of the ensembles of NV centers in the absence of a bias voltage.

Acknowledgments

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Improvement of charge stability and spin-coherence properties of near-surface NV centers in diamond

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Introduction

The electron spin of negatively charged nitrogen vacancy (NV) centers in diamond has long spin coherence time (T_2) at room temperature, and therefore it is candidate for quantum information devices and quantum sensors. For the development of the magnetic field sensor, NV centers which have long T_2 and be near the diamond surface, are necessary for highly spatial resolution and magnetic field sensitivity. However, it was reported that the NV centers near the surface in usual diamond substrate have poor charge stabilities and spin coherence properties [1].

For the improvement of the magnetic field sensor using a single NV centers, we focused on phosphorus doped *n*-type diamond. In previous research using NV centers in *n*-type diamond, our group reported the realization of pure negatively charged state of NV centers in *n*-type diamond [2], and also observation the longest T_2 in solid state electron spin system at room temperature [3]. In this research, to improve the magnetic field sensor using single NV center, we investigated the spin coherence properties and charge stability of near surface single NV centers in *n*-type diamond.

Method

We prepared two diamond samples; one is the CVD growth phosphorus doped *n*-type diamond on IIa-type diamond substrate with the thickness of 670 nm and phosphorus concentration is about 5×10^{16} cm^{-3}, and other is a IIa-type undoped diamond. Single NV centers were fabricated near the diamond surface (~10-20 nm) by the ion implantation and thermal annealing in both samples with same condition.

We measured coherence time T_2 of fabricated NV centers in both samples with the Hahn-Echo method. As a result, we observed T_2 up to ~600 μs of NV centers in *n*-type diamond, and it is longer than in undoped diamond (FIG. 1). And we also performed the single shot charge state measurement for both samples and observed the improvement of charge state stability of NV centers in *n*-type diamond.

Acknowledge

This work was supported by KAKENHI (16H06326), MEXT Q-LEAP (Grant Number JPMXS0118067395), and the Collaborative Research Program of Institute for Chemical Research, Kyoto University (Grant Number 2020-110).

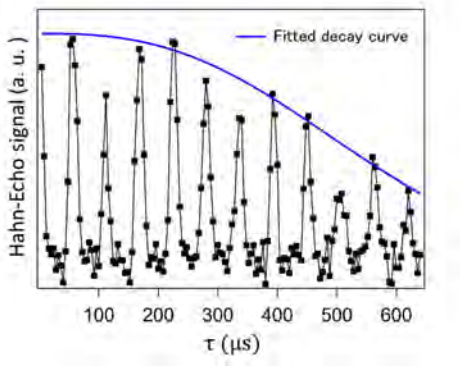

FIG. 1. The Hahn-Echo measurement of a single NV center in *n*-type diamond. Coherence time T_2, the time constant of the envelop of the fitting function, is about 600 μs.

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Canceling environmental magnetic noise by gradiometer using NV centers in diamond pair

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Introduction

Biomagnetic measuring requires highly sensitive magnetic sensors such as superconducting quantum interference devices (SQUIDs) and alkali vapor cells. Because of stronger environmental magnetic field noises than biomagnetic fields, noise canceling system is needed for the measuring. Gradiometer configuration which cancels noises by the differential signal of two sensing positions is a common way to suppress magnetic noises. Nitrogen vacancy (NV) center in diamond which can be operated at room-temperature and have a high dynamic range [1] is one of the most promising candidates for biomagnetic sensor. However, little work [2-3] has been done on gradiometers using the NV center. In this study, we constructed the gradiometer using NV centers and demonstrated canceling of environmental magnetic noises by the gradiometer.

Method

Figure 1 shows a setup of the gradiometer using NV centers. Our gradiometer uses the spatially-isolated equal-quality diamond pair fabricated from type Ib diamond which contains nitrogen concentration more than 10^{19} atoms/cm^3 with electron beam irradiation. In each sensor, each diamond sample attached to an optical fiber is mounted on a coplanar-waveguide (CPW) antenna [4]. Each fluorescence from NV centers is collected through the optical fiber and digitized simultaneously. The differential signal (Ch.1 – Ch.2) eliminates common-mode environmental noises for measuring. Furthermore, we compared noise suppressions by a magnetic shield and the difference detection. Figure 2 shows noise spectra of each measuring. These spectra shows that environmental magnetic noises in laboratory within the dotted line are suppressed by the shield and the difference detection. This result indicates that the gradiometer has a potential to measure a weaker signal than environmental magnetic noises without a magnetic shield.

This work was supported by MEXT Quantum Leap Flagship Program (MEXT Q-LEAP) Grant Number JPMXS0118067395.

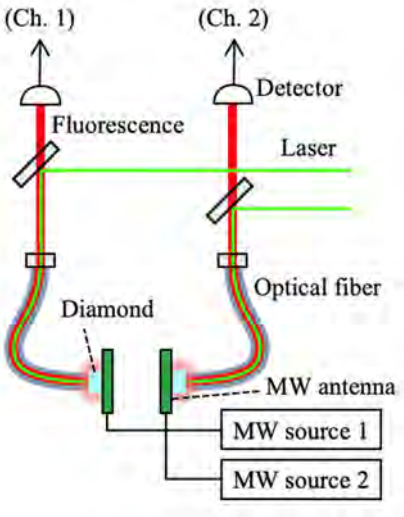

FIG. 1. Setup of the gradiometer using NV centers in a pair of diamonds.

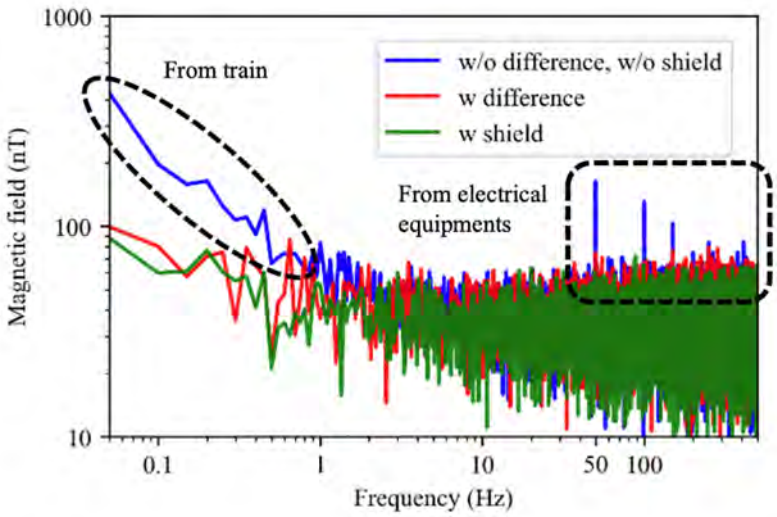

FIG. 2. Canceling environmental magnetic noises by the difference detection and the magnetic shield

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Crossed two-layer coplanar-waveguide circuit for extending spin dephasing time T_2^* of ensemble NV centers in a bulk diamond

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The nitrogen-vacancy (NV) center in diamond is extensively studied for a next-generation high-sensitivity magnetometer. The DC magnetic sensitivity can be improved by extending the inhomogeneous spin dephasing time (T_2^*) through suppressing the effects of inhomogeneous fluctuations or by increasing the number of effective NV centers through expanding the sensor volume. It has been demonstrated that strain-induced dephasing can be suppressed by double quantum (DQ) technique with two-tone microwaves (MW), and spin bath-induced dephasing can be suppressed by spin bath drive (SBD) technique with multi-tone radio-frequency (RF) to drive the P1 centers: For [P1] = 1 ppm, T_2^* was 15-times extended by combination of DQ and SBD techniques at 1 MHz bath Rabi frequency [1]. To combine these T_2^*-extension techniques with a bulk diamond, it is necessary to apply MW and RF uniformly to the sample. A coplanar waveguide (CPW) circuit has been reported to be useful for uniform microwave irradiation to a bulk sample [2].

In this study, we have designed and fabricated a cross-aligned two-layer CPW circuit (FIG. 1). By applying MW through the top CPW and RF through the bottom CPW of this circuit, Rabi frequencies of NV and P1, respectively, were mapped over a millimeter-wide diamond sample with P1 and ^{13}C concentrations of 1 ppm and 50 ppm. FIG. 2(a) shows a typical P1 Rabi oscillation measured with a Double Electron-Electron Resonance (DEER) sequence at a bias magnetic field of 12.2 mT along the surface normal [111]. The map of P1 Rabi frequencies over this sample in FIG. 2(b) indicates a uniform RF field applied over (0.8 mm)^2. The spatial uniformity of MW has been confirmed similarly. Furthermore, both the DQ and SBD techniques have been implemented by applying two-tone MW as well as six-tone RF to evaluate their effects on extension of T_2^*. While the optical excitation volume was set to ~10^{-4} mm^3 for the mapping, uniform excitation of the entire diamond sample (0.7 mm^3) will enhance the DC magnetic sensitivity by a factor of 80.

This work was supported by MEXT Q-LEAP Grant Number JPMXS0118067395 and JPMXS0118068379.

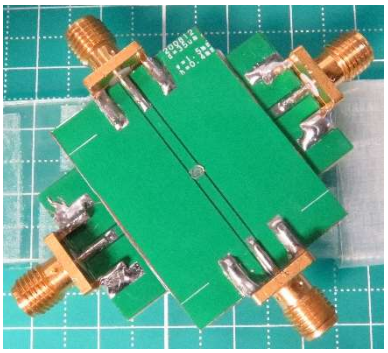

FIG. 1. 2-layer coplanar waveguide circuit with a diamond sample on the crossing center.

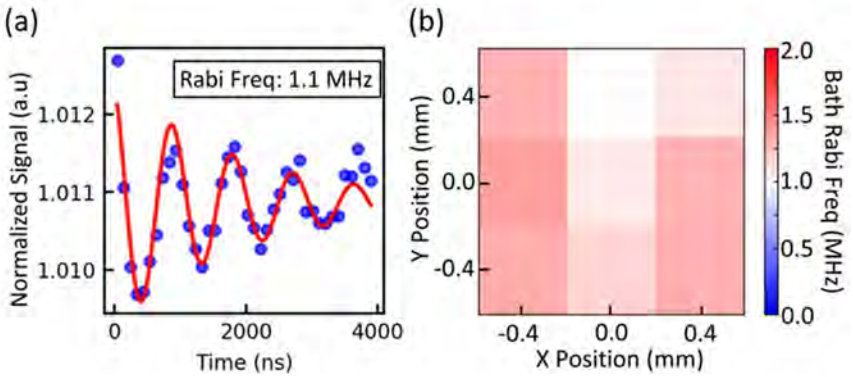

FIG. 2. (a) P1 Rabi oscillation with 2527-MHz MW and 242.5-MHz RF measured at the center (0 mm, 0 mm) of the diamond. (b) P1 Rabi frequency mapped over 0.8 × 0.8 mm^2.

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Optical properties of lead vacancy centers in diamond

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Introduction

Color centers in diamond are promising candidates for quantum network applications due to their excellent optical and spin properties. Compared with most intensively studied NV^- centers, color centers based on group-IV elements show sharp ZPLs with suppressed phonon side bands. As increasing the atomic number, Group-IV color center possess larger ground state splitting. Thus, the spin-orbit interaction in the ground state is suppressed, leading to long spin coherent time even in the Kelvin range [1]. Color centers using the heaviest IV group element of lead (Pb) have been reported [2,3]. However, the reported ZPLs are not consistent, requiring further studies to determine the true ZPL of the PbV center. Group-IV color centers in diamond, SiV^-, GeV^-, and SnV^- have D_3d symmetry, leading to a four-level fine structure. The polarization of the two prominent peaks, called C- and D-peaks, are orthogonal each other [4]. Thus, the observation of the polarization is expected to clarify the ZPL and symmetry of the PbV center. In this study, we investigated optical polarization of the fine structure of the PbV centers formed by ion implantation and subsequent anneal over 2000 °C.

Method and Results

The PbV centers were fabricated in (001) single-crystal diamond substrates. The optical properties of the PbV centers were investigated using a cryostat confocal fluorescence microscope system with an excitation laser of 515 nm. In a PL spectrum in Fig. 1, the doublet peaks are observed at 550.3 nm and 554.3 nm, which are thought to be the C and D peaks, respectively. The splitting of the peaks corresponds to the ground state splitting, and the value of 3893 GHz agrees well with theoretical calculation (4385 GHz) [5]. Then, by using a beam polarizer and a 1/2 wave-plate with a rotation mount, the polarization of the two peaks was measured by spectrometer. We measured at a spot where approximately three PbV centers exist. Figure 2 show the measured polarization of the two peaks. Both peaks show 8-like polarization orientating to the <1 1 0> direction, and the polarization of C-peak is orthogonal to that of D-peak, strongly indicating that the observed fine structure corresponds to the PbV^- with the D_3d symmetry.

This work was supported by MEXT/Q-LEAP (JPMXS0118067395) and Toray Science Foundation.

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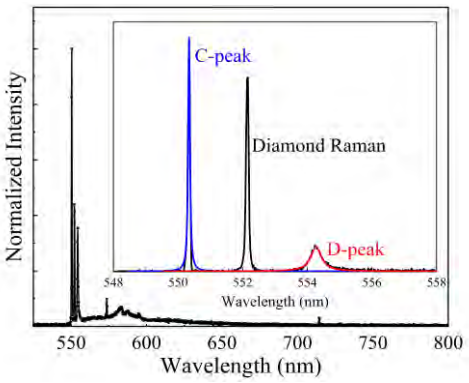

Figure 1. Spectra of PbV^- center at low temperature (4.18 K). The center peak is due to Raman scattering under 515 nm laser.

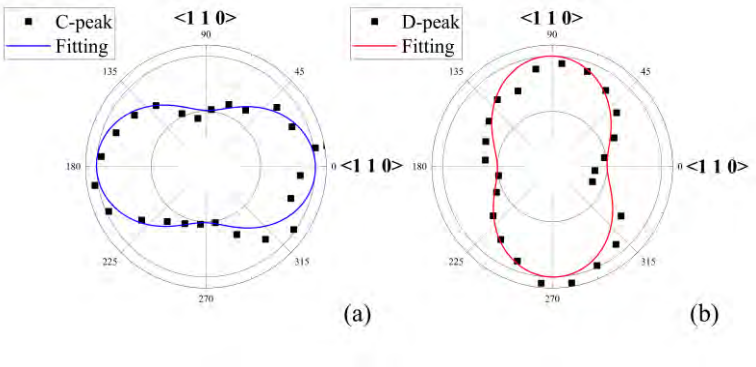

Figure 2. Polarization of ZPL fine structure for the (001) surface. Polarization of the C- and D-peaks.

Numerical optimization of grating coupler on bulk diamond with nitrogen-vacancy center

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Introduction

Based on the magnetic sensing system to investigate tumor metastases using Hall sensor with permanent magnet[1)], we are developing the magnetic sensor using Nitrogen-Vacancy (NV) center in a bulk diamond[2)]. However, light extraction efficiency of diamond is low because of the high refractive index of diamond. Since the minimal magnetic sensitivity is determined by $\eta \propto \Delta\nu / C\sqrt{I_0}$ [2)], we are trying to enhance the light intensity from NV center (I_0) in the diamond substrate. To meet the requirement, we performed the numerical optimization using a Finite-Difference Time-Dominant (FDTD) method.

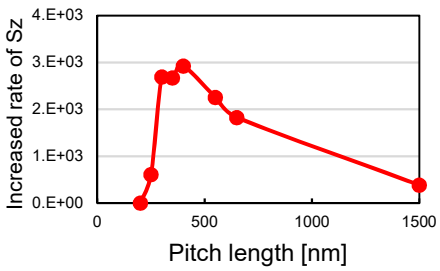
Method

To realize higher light extraction efficiency, we introduced the grating coupler over the diamond substrate. To optimize the structure of the grating, we performed the light sources and the increased intensity of light at a single wavelength and other wavelengths using the FDTD method of the grating coupler over the diamond substrate. We compared the enhancement of the optical intensity with and without grating. FIG. 1 shows each pointing vector with and without grading, poynting vector when the number of light sources increases.

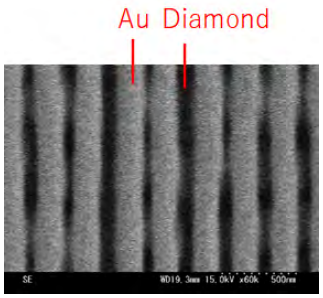
Result and discussion

Figure 1(a) shows that the light extraction efficiency as a function of the pitch length, and highest efficiency was achieved with the grating pitch of 400nm. The result was consistent with theoretical value of 264 nm determined by the formula $n_c sin\theta_i = N_1 - \lambda/\Lambda$ (Λ is optimum pitch of grating)[4)].

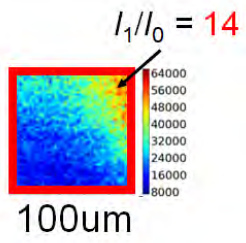
Based on the numerical results, we fabricated the Au grating with a pitch length of 300 nm on the diamond substate using electron beam lithography (Fig. 1(b)). We evaluated the emission intensity of diamond NV by introducing the grating using the confocal microscope (Fig. 1(c)). By comparing the light intensity without the grating (I_0), the light intensity with the grating (I_1) increased by 14 times.



(a)



(b)



(c)

Fig.1 (a) Calculated increased rate as a function of pitch length of the grating. (b) SEM iamge of the grating on the diamond substrate. (c) Conforcal image of NV emission.

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