Impact Objectives

- Exploit the rich potential of spins in gem crystals for quantum technology applications
- Perform scientific proof-of-concept demonstrations of the potential applications

Spinning gems for quantum technologies

***Dr Yuimaru Kubo** believes in the potential of quantum information research as well as the need for a better understanding of spins in gem crystals in order to develop 'hybrid quantum technologies' in the future*

Can you explain in lay-person terms what quantum information is and why it is an important topic to research?

Quantum mechanical objects, such as atoms, ions, photons, or spinning electrons or nuclei (spins), are only allowed to be in particular 'states', such as in particular orbitals, motions, polarisations or directions pointing. In the 20th century, researchers have successfully developed ways to control and measure these quantum mechanical states in the field of quantum information science (as celebrated by the 2012 Nobel prize in physics). And now, in the 21st century, the knowledge and technologies invented and accumulated in the field are turning into near-future industrial technologies and products. The most obvious example is the quantum computer, in which many IT giants started investing large sums to develop. Besides the quantum computer, the 'quantum technologies' also cover sensing and communication.

Your work in this area specifically covers 'spins' in solid materials like diamonds. How will this contribute to future quantum technologies?

We believe that spins in gem crystals can be used as a quantum information transducer and/or quantum RAMs which may be integrated inside a quantum computer. We also hope that spins can be exploited as a good microwave amplifier at millikelvin temperatures, which may also be integrated in a quantum computer, or a magnetic resonance imaging or spectrometer. Now we are trying to perform several scientific proof-of-concept demonstrations for those applications.

What are some of the tools and methods you are using to conduct this research?

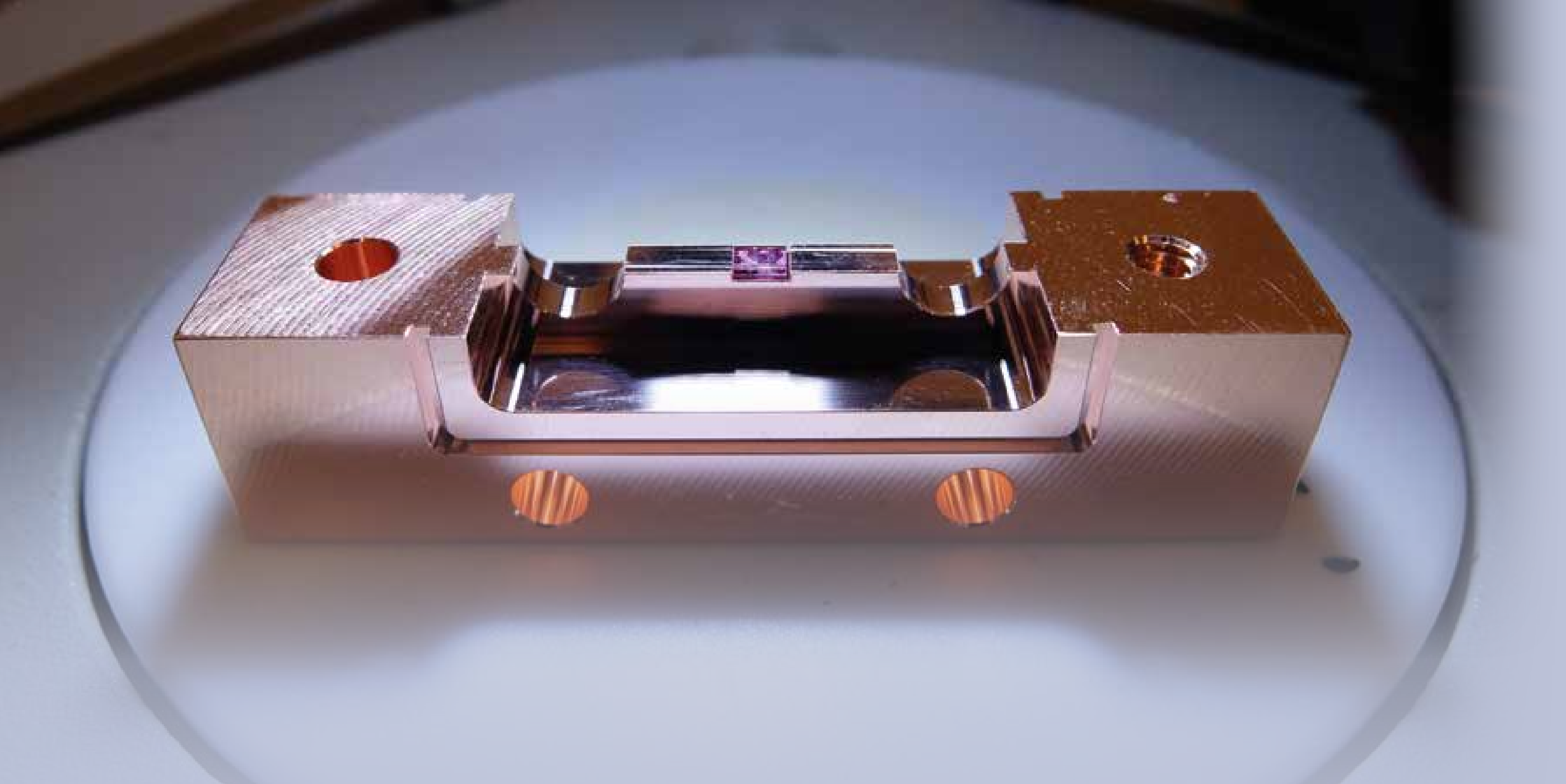
We use a lot of microwaves, similar to the ideas behind the cell-phone or Wi-Fi technologies. We encode and decode (quantum) information on microwave signals. A dilution refrigerator, which cools down samples to near absolute zero temperature, typically about 10 mK, is also crucial. The reason for this is that the energy of photons at microwave frequencies are so small that their 'quantumness' can only emerge at such low temperatures; at higher temperatures the quantumness of the photons would be hidden or killed by thermal noise.

Has this work presented unique challenges, and what have those taught you about the field of quantum information?

As is always the case in scientific research, sometimes you encounter unexpected or strange results. These required a lot of our time to understand, but some of them have given us new insights or ideas, and led us to explore new physics or research subjects. For example, we are very excited about the spin-based amplifier. The discovery of which was triggered by a complete coincidence. We are hoping that it may lead to future quantum technologies and create a new research field.

How do you think the research outcomes can be translated into real-world application?

The transducer we are working on will be used to build a 'quantum network' consisting of a quantum computer in a refrigerator at each node, which are connected via optical links. Quantum RAM function may then be added to the transducer for parallel quantum information processing and/or quantum error corrections. A spin-based low noise amplifier may be integrated into a quantum computer, and might also be used for future magnetic resonance spectrometer or MRI. After proof-of-concept demonstrations though, we have to seriously consider how to make the devices better so they can be practical and useful. The transducer must work with unit efficiency for the use for real quantum network, and likewise for quantum RAM that should function as high fidelity as possible, and a useful amplifier must have a large gain and bandwidth with a large dynamic range. ▶



Transmitting Quantum Information

Understanding the quirky properties of particles in the quantum world brings us closer than ever to the first quantum computer, but in order for quantum information to breakthrough the ability to transmit it must be achieved

The field of quantum information research is based on the discoveries of quantum mechanics and the behaviours of particles in the quantum world, such as at the level of individual electrons. Dr Yuimaru Kubo is an expert on spin-based quantum information science and technologies based at the Okinawa Institute of Science and Technology (OIST). He says that a simplified explanation of this is that in quantum mechanics the properties of particles like electrons do not exist in one state or another exclusively. 'Instead they can exist in two states at the same time, a so-called 'superposition' state', he confirms. 'Because of this unique quality rather than a binary, it is or isn't system, a system based on multiple possible superpositions is possible, meaning the qubit holds significantly more data.' Such quantum information that can be encoded in the spins of electrons or nuclei is currently under thorough investigation as a means of storing and transmitting quantum information by Kubo and his research team at OIST. 'We are investigating quantum information science and technologies by mainly focusing on spins in solids, such as gem crystals, at microwave frequencies,' Kubo highlights. 'Hopefully, we can combine these with other quantum systems to form hybrid quantum systems in the future.' Kubo became interested in the field of quantum information science while working on his PhD. 'I learned that a lot of exciting things were going on in the field of quantum information science using superconducting circuits, an area in which I was super interested and excited,' he says. After his PhD he worked as a postdoc studying hybrid quantum devices with superconductors and spins. He says this experience gave him the inspiration and ideas that now forms the basis of his work at OIST.

SUPER COOL DATA TRANSMISSION

While the promise of a quantum computer seems achievable using superconducting quantum circuits, there are several challenges that Kubo is aiming to overcome. One major focus of his work is solving the problem of transmitting quantum information between superconducting processers. These processors operate with superconducting qubits, which are extremely versatile and scalable. 'However, since their energy scale is at microwave frequencies, they must be placed at millikelvin temperature in a dilution refrigerator to prepare in the quantum ground state,' explains Kubo. 'The problem then becomes how to send quantum information processed by superconducting qubits out of a dilution refrigerator to somewhere else. In classical forms of communication networks, electrical signals produced by computers are converted to optical signals, transmitted long distances and then converted back to electrical signals once received.' To achieve this transduction of quantum information between microwave and optical frequencies Kubo is designing a transducer. 'However, realising such a transducer is challenging in the quantum regime, because it should be entirely noiseless and operate with unit efficiency in order for the optical (microwave) quantum state to faithfully reproduce the incoming quantum state at microwave (optical) frequency,' he outlines.

The design of the transducer exploits the properties of the spins in solid gems like diamonds. 'I propose a quantum state transducer using spins in solids, some of which possess transitions both in spin and orbital degrees of freedom,' he says. 'This provides an intrinsic nonlinear coupling between microwave and optical photons, which can be mode-matched in the same device.' With this lofty goal in mind the team is producing proof-of-concept demonstrations and filling in the gaps required to make this technology work. The team published results last year showing that loop-gap microwave resonators are viable in the prospect of spin-based hybrid quantum systems, a step required for the feasible design for an ensemble quantum memory or a quantum transducer. 'We are hoping to realise a quantum transducer, a quantum RAM and an ultra-low noise amplifier for quantum microwaves, all of which are based on spins in gem crystals,' confirms Kubo.

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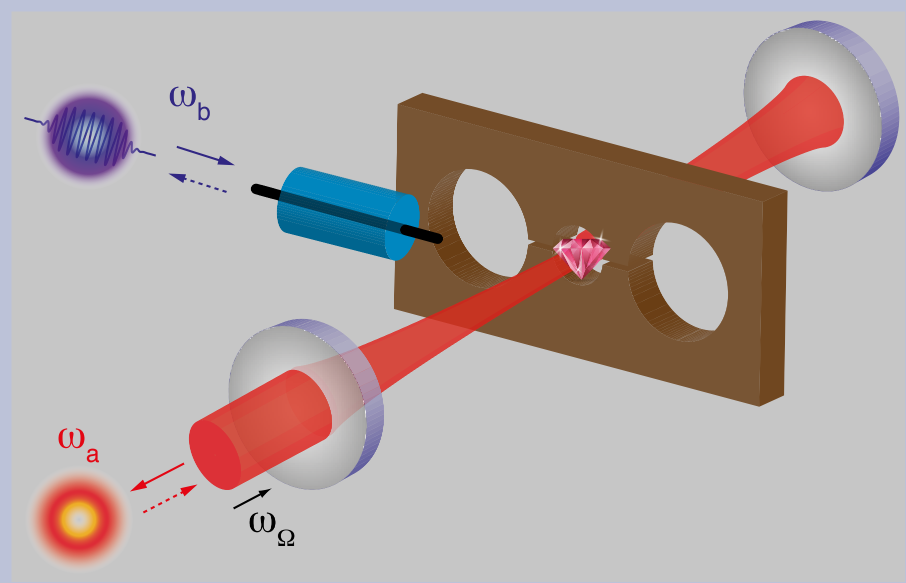
CHOICE MATERIALS AND PEOPLE

'After those proof-of-concept demonstrations, proper material choices and difficult engineering works are necessary for further development, which may require the involvement of business and industries,' says Kubo. Within the team itself Kubo is supervising a team consisting of two staff scientists, a postdoctoral researcher, a PhD student and a part-time technician. 'We help each other and work together. Everybody has specialties and particular skills; thus, each contribution is significant, important and necessary.' However, Kubo must reach beyond this team to complete the work. 'We are collaborating with a couple of experts on material science and engineering of diamonds in other research institutes in Japan.' These teams are providing some of the diamond crystals necessary because they can produce them to precise quality levels with properly controlled amounts of impurities and/or isotopes.

With a great team and collaborations in place Kubo is uniquely positioned to excel in this research. Since the beginning of his postdoctoral work, Kubo has developed close collaborations with Japanese scientists who are international experts on diamond synthesis, and together they have greatly contributed to the field of hybrid quantum circuits. ●



Cartoon image of the proposed spin-based quantum transducer. A diamond containing impurity spins is coupled to both an optical cavity (two mirrors with red waist beam) and a microwave resonator (brown). The optical (red, ω_a) and microwave photons (blue, ω_b) are shown. To compensate the large energy difference between those two photons, a pump laser with a frequency of ω_Ω (= ω_a - ω_b) is applied to the optical cavity (black arrow).

Project Insights

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BIO

Dr Yuimaru Kubo completed his undergraduate study at the University of Tsukuba, and his PhD at the National Institute for Materials Science. Upon completion of his PhD, Yui moved to France and joined the Quantronics Group at CEA-Saclay as a postdoctoral scholar in June 2009. At Saclay, he worked on hybrid quantum devices with superconducting circuits and impurity spins in diamond or silicon. After spending six and a half years in France, he came back to the island where his mother was born and joined Quantum Dynamics Unit in the very end of 2015 as a Staff Scientist.