ISSN 2186-7437

# NII Shonan Meeting Report

No. 2011-6

# Hybrid Quantum Devices

Gerard Milburn
Jörg Schmiedmayer
Yasuhiro Tokura
Kae Nemoto

November 5–9, 2011

National Institute of Informatics
2-1-2 Hitotsubashi, Chiyoda-Ku, Tokyo, Japan

# Shonan Workshop Report on “Hybrid Quantum Devices”

**Organizers: Gerard Milburn, (UQ)**

**Jörg Schmiedmayer, (TU-Wien)**

**Yasuhiro Tokura, (NTT)**

**Kae Nemoto, (NII)**

In recent years techniques for quantum control have dramatically improved and resulted in a number of demonstrations in different physical systems at the few qubit level. Based on these new developments, many proposals to implement quantum devices have been mushrooming both in number and variety. At this stage of quantum information device research, it is essential to make sure the fundamental quantum control has its future as a practical device for the future technologies. The implementation of quantum devices, however, is usually not carefully considered as a fundamental device for larger scale quantum information processing and could potentially limit the scalability of the system. Recent theoretical analysis shows that hybrid and distributed quantum devices exhibit better scalability and so are promising for scalable architectures in large-scale quantum information systems. In this workshop, we focused on such hybrid and distributed devices bringing such state of the art quantum information systems together. In particular, devices from optics to microwave were extensively investigated.

We divided our efforts into the following six sessions and focused on current problems, future directions and what can be achieved in the next few years. Each session was targeted a different aspect of hybrid quantum devices. Even though hybrid quantum nature in these topics is common, the background knowledge for each topic is rather different. We spent enough time to share the recent progress and problems in each field in the beginning of each session.

**Session: Hybrid Quantum Systems – Theory**

**Speakers: G J Milburn (session leader), “Hybrid quantum systems”**

**W Munro, “ Heterotic quantum systems”**

**S. Devitt, “Large scale NV diamond based quantum computing”**

Milburn gave many examples of hybrid quantum systems that included; optomechanical systems, superconducting devices coupled mechanical resonators and 2DEG quantum dots and spins in NV diamond, cold atoms coupled to mechanical resonators and quantum opto-electronic systems. He then gave a detailed description of a optical to microwave quantum interface based on coupling both light and microwaves to a common mechanical element. He concluded with some general comments on the promise of hybrid quantum systems and some open questions posed by such systems. These included;

Understanding decoherence and dephasing at the systems-level
Understanding how to integrate very different time scales for subsystems.
Developing ways to deal with a mix of discrete (error correction) and continuous dynamics (master equations).
Developing a systems-level descriptions of complex hybrid dissipative dynamics.

Munro discussed the concept of a heterotic quantum systems --- somewhat more general that a hybrid quantum system. He stressed that a key element in complex multi-element hybrid systems will be defect tolerance, citing the HP Teramac project [2] as an example form the field of conventional computing, He discussed in detail a number of specific examples that combine spins in NV diamond and optics. He also briefly mentioned the coupling an NV ensmeble to a flux qubit.

Devitt gave a detailed high-level description of an optical quantum computing system based on NV diamond and integrating topological codes into the systems design. He stressed that such systems have an inherent problem arising form the probabilistic nature of the connections.

[1] “Entangling optical and microwave cavity modes by means of a nanomechanical resonator”, Sh. Barzanjeh, D. Vitali, P.Tombesi, G.J. Milburn, Phys. Rev. A 84, 042342 (2011).
[2] J. R. Heath et al., *Science* **280**, 1716 (1998);
[3] Michael Trupke, William J. Munro, Kae Nemoto, and Joerg Schmiedmayer, Enhancing photon collection from quantum emitters in diamond, Progress in Informatics 8 3337 (2011).
[4] Alp Sipahigil, Michael L. Goldman, Emre Togan, Yiwen Chu, Matthew Markham, Daniel J. Twitchen, Alexander S. Zibrov, Alexander Kubanek, Mikhail D. Lukin, Quantum interference of single photons from remote nitrogen-vacancy centers in diamond, arXiv:1112.3975
[5] Xiaobo Zhu, Shiro Saito, Alexander Kemp, Kosuke Kakuyanagi, Shin-ichi Karimoto, Hayato Nakano, William J. Munro, Yasuhiro Tokura, Mark S. Everitt, Kae Nemoto, Makoto Kasu, Norikazu Mizuochi and Kouichi Semba, Coherent coupling of a superconducting flux-qubit to an electron spin ensemble in diamond, Nature 478, 221-224 (2011).
[6] Simon J. Devitt, Austin G. Fowler, Ashley M. Stephens, Andrew D. Greentree, Lloyd C.L. Hollenberg, William J. Munro and Kae Nemoto, Architectural design for a topological cluster state quantum computer, New J. Phys. 11, 083032 (2009).

[6] Simon J. Devitt, William J. Munro, and Kae Nemoto, High performance quantum computing, Progress in Informatics 8 4955 (2011).

[7] Simon J. Devitt, Ashley M. Stephens, William J. Munro and Kae Nemoto, Integration of highly probabilistic sources into optical quantum architectures: perpetual quantum computation, New J. Phys. 13, 095001 (2011).

**Session: Optomechanics**

**Speakers: Simon Gröblacher (session leader), “Hybrid optomechanical systems”**
**Kai Stannigel, “Optomechanical transducers for quantum information processing”**
**Matthew Rakher , “Realization of an Optomechanical Interface between Ultracold Atoms and a Micromechanical Membrane”**

In the session on optomechanics, the three speakers presented different aspects of coupling light to a mechanical oscillator and other (quantum) systems.

The work Simon Gröblacher presented focused on the efforts of cooling mechanical resonators into their quantum ground-state using the radiation-pressure force of light. He described different approaches realized at the University of Vienna and the California Institute of Technology, where at the latter they recently achieved ground-state cooling using an optomechanical crystal [1]. In Vienna, Gröblacher et al. also realized a strongly coupled opto-mechanical system, in which coherent energy exchange between the optical and the mechanical subsystems is possible [2]. The efforts at both institutions ultimately aims at realizing quantum experiments with massive macroscopic systems, which with the recently demonstrated experiments is now within reach.

Kai Stannigel presented a proposal for a qubit-light interface based on a cavity-optomechanical system [3]. The interface (also termed 'optomechanical transducer', OMT) is primarily intended for 'dark' qubits that do not couple coherently to light, such as phosphor donors in silicon or superconducting qubits, and converts quantum states of such qubits into propagating photons. Thereby, the OMT enables long-distance quantum communication for this class of quits, but may also be used, e.g., as an alternative read-out channel. In particular, the realization of a state-transfer between two distant qubits has been discussed, and for numbers corresponding to present-day technology fidelities of up to 0.9 are predicted. As an outlook, the speaker presented an alternative scheme for entanglement distribution in quantum networks that does not rely on a specific pulse-sequence, but realizes pure entangled states as steady-states of a driven-dissipative dynamics, also within large networks [4].

Matthew Rakher talked about optomechanical systems that exploit optical forces for cooling and control of mechanical oscillators. Such systems can be used in precision force and displacement sensing as well as for fundamental studies of quantum physics at macroscopic scales. This burgeoning field has many similarities with the study of ultracold atoms, where radiation pressure forces are routinely used for laser cooling and optical dipole forces are used for trapping and manipulation of atomic motion in optical lattices. Matthew Rakher and co-workers have recently performed an experiment which aims to combine these systems in a meaningful way. In particular, they have realized a hybrid optomechanical system where the center of mass motion of an ultracold atomic ensemble is coupled to the motion of a micromechanical membrane by optical forces [5]. This coupling is accomplished by retroreflecting a laser beam off of the dielectric membrane to create an optical lattice potential for the atoms. In doing so, Rakher et al. have demonstrated both the effect of the membrane vibrations onto the atoms as well as the backaction of the atomic motion onto the membrane [6]. Their work represents an initial step towards the quantum control of mechanical motion by coupling to ultracold atoms.

[1] J. Chan et al., Nature 478, 89 – 92 (2011)
[2] S. Gröblacher et al., Nature 460, 724 – 727 (2009)
[3] K. Stannigel et al., PRL 105, 220501 (2010)
[4] K. Stannigel et al., arXiv: 1112.1690 (2011)
[5] K. Hammerer et al., PRA 82, 021803 (2010)
[6] S. Camerer et al., PRL 107, 223001 (2011)

**Session: “Crystal optics and Memory”**

**Speakers: Wolfgang Tittle (session leader), "Mapping quantum states between photons and RE crystals"**
**Jevon Longdell, "Quantum memories using photon echoes"**
**Masahide Sasaki, “Next generation technologies for quantum communication”**

This session included presentations by Drs. Wolfgang Tittel from the University of Calgary/Canada, and Jevon Longdell from the University of Otago/New Zealand. The presentation by Dr. Masahide Sasaki from the National Institute of Information and Communications Technology/Japan was also loosely attached to this session. However, due to it covering a different topic, it will be discussed elsewhere.

The session started with an invited presentation by Dr. Tittel, who gave a general introduction why rare-earth-ion doped crystals at cryogenic temperatures are currently of large interest for quantum information procession. More specifically, they allow the reversible mapping of quantum information between different carriers, light and matter, and thereby constitute a key element for quantum repeaters, which promise overcoming the current distance barrier for quantum communication (including quantum key distribution). Dr. Tittel then discussed the current state-of-the-art of quantum memory research worldwide, and gave an overview (with examples) about different ways to achieve reversible mapping. This part was followed by the presentation of a particular implementation of quantum memory, which has allowed the storage and unperturbed retrieval of entangled photons in and from a Thulium doped Lithium Niobate waveguide.

Dr Tittel's presentation was followed by the presentation by Dr. Longdell, who focused on some new aspects related to the use of rare-earth-ion doped crystals in quantum information science. More specifically, he discussed the use of using optical pulses for rephasing optical coherences. While a simple use of optical rephasing pulses for quantum memories leads to noise in the recalled light there are ways around this. Dr. Longdell showed preliminary experiments working towards quantum memories using this technique as well as a method for creating time separated entangled light fields. Dr Longdell also described the work his group is doing with rare earth ion dopants coupled to whispering gallery mode resonators.

The complementary presentations were very well received. Discussions arose during and after the presentations, and were continued during the subsequent days of the workshop (we point out that discussion already happened before the presentations as quantum memory using rare-earth-ion-doped crystals has become known in the scientific community, including the workshop participants, over the past few years). A lot of interest was in further hybridization (i.e. hybridization beyond light and impurities in crystals), which may lead to subsequent mapping of quantum information between atomic levels and superconducting qubits. The latter have been another topic featured in this workshop.

**Session: "Superconducting systems**

**Speakers: Yasunobu Nakamura (session leader), "Superconducting qubits and circuits"**
**Semba Koichi, "Toward hybrid quantum systems --- A Quest for a Quantum Memory"**
**Robert Amsüss, "Coupling NV Centers to a Superconducting Resonator".**

Yasu Nakamura (NEC/RIKEN) gave an introductory talk on superconducting qubits and circuits. Recent progress in the field was reviewed with an emphasis on versatility of the superconducting systems in quantum optical experiments in the microwave domain. In the end of the talk, prospects towards hybrid quantum systems were presented.

Kouichi Semba (NTT-BRL) reported their recent achievement of coherent coupling between a superconducting flux qubit and an ensemble of electron spins in diamond NV centers. Thanks to its localized distribution of the zero-point current fluctuations, flux qubit allows larger coupling strength to each spin compared with a coplanar waveguide resonator. Vacuum Rabi oscillations between the flux qubit and a collective excitation among $3\times10^7$ spins was observed. As the decoherence time in the spin ensemble is still limited to a few tens of nanoseconds, improving the coherence is one of the next targets.

Robert Amsüss (TU Wien) discussed strong coupling between superconducting coplanar waveguide resonator and an ensemble of electron spins of NV centers. Scaling of the coupling strength with $\sqrt{N}$ was confirmed experimentally. It was also impressive to see the effect of hyperfine interaction resolved clearly in the spectrum. There was a good discussion on the effect of inhomogeneous broadening. In solid-state spin ensembles inhomogeneous broadening seems to be one of the most important issues to be overcome.

In the general discussion at the end of the session, there was an argument about the necessity of spatial mode matching in the future interface between optics and microwave. How to implement spin-echo in spin ensemble experiments were also discussed.

**Session: “Diamond and solid state devices”**

**Speakers: Boris Naydenov (session leader), “NV Centers in Diamond”**

**Mark Everitt, "A single NV- Centre"**

In this session there were two talks dealing with the Nitrogen-Vacancy defect centers (NV) in diamond. In the first talk Boris Naydenov gave a general introduction to the NVs, where he showed their remarkable properties which make them ideal candidates for solid state quantum bits (qubits) and high sensitive nano-scale magnetic sensor. Since he was asked by many participants of the workshop how to improve the production efficiency, stability and coherence time $T_2$ of the NVs, he addressed these topics in the rest of his presentation. The main results are that the implantation of carbon ions additionally to the nitrogen ones increases the NV creation yield [1], annealing the diamonds at high temperature in vacuum improves both $T_2$ and the stability of implanted NVs [2] and that for as grown NVs in ultra pure diamonds by using dynamical decoupling $T_2$ can reach the relaxation time $T_1$ [3].

Mark Everitt discussed in his presentation how we can efficiently use the nuclear spin of the NV center as a qubit.

[1] B. Naydenov et al., App. Phys. Lett. 96, 163108 (2010)

[2] B. Naydenov et al., App. Phys. Lett. 97, 242511 (2010)

[3] B. Naydenov et al., Phys. Rev. B 83, 081201(R) (2011)

**Session: "Optical systems"**

**Speakers: Jeremy O'Brien (session leader), "Integrated Quantum Photonics"**

**Keiichi Edamatsu, "Multi-photon Quantum Interference and Quantum Information"**

**Stefanie Barz, "Blindfolding a quantum computer"**

O'Brien gave an overview of optical approaches to quantum information processing , including cluster state and circuit based approaches, summarizing theoretical and experimental developments over the last five to ten years. He then described the integrated quantum photonic approach, starting with circuits for quantum communication , quantum logic gates , quantum algorithms , quantum walks , and quantum metrology . He then described how the outstanding issues of scaling , miniaturisation , and reconfigurability are being addressed. Finally he discussed nonlinear and diamond single emitter single photon sources, and superconducting single photon detectors .

Prof Edamatsu described a technical tour-de-force experimental demonstration of four-photon quantum interference using telecom-wavelength photons: Realization of multi-photon quantum interference is essential to linear optics quantum information processing and measurement-based quantum computing. The Edamatsu group have developed a source that efficiently emits photon pairs in a pure spectrotemporal mode at a telecom wavelength region, and have demonstrated the quantum interference exhibiting the reduced fringe intervals that correspond to the reduced de Broglie wavelength of up to the four photon 'NOON' state. These results should open a path to practical quantum information processing using telecom-wavelength photons. He also described experimental activation of bound entanglement: Entanglement is one of the essential resources in quantum information and communication technology (QICT). The entanglement thus far explored and applied to QICT has been pure and distil- lable entanglement. Yet there is another type of entanglement, called 'bound entanglement', which is not distillable by local operations and classical communication (LOCC). The Edamatsu group have demonstrated the experimental 'activation' of the bound entanglement held in the four-qubit Smolin state, unleashing its immanent entanglement in distillable form, with the help of auxiliary two-qubit entanglement and LOCC. This is anticipated to open the way to a new class of QICT applications that utilize more general classes of entanglement than ever, including bound entanglement.

Stefanie Barz described an experimental demonstration of blind quantum computing . Quantum computers, besides offering substantial computational speedups, are also expected to provide the possibility of preserving the privacy of a computation. Barz showed the first such experimental demonstration of blind quantum computation where the input, computation, and output all remain unknown to the computer. They exploited the conceptual framework of measurement- based quantum computation that enables a client to delegate a computation to a quantum server. They demonstrated various blind delegated computations, including one- and two-qubit gates and the Deutsch and Grover algorithms. Remarkably, the client only needs to be able to prepare and transmit individual photonic qubits. This demonstration is crucial for future unconditionally secure quantum cloud computing and might become a key ingredient for real-life applications, especially when considering the challenges of making powerful quantum computers widely available.

[1] For reviews see: Science, 318, 5856 (2007), Nature Photonics, 3, 687 (2009), Nature 464, 45 (2010)

[2] Phys. Rev. A 82, 012304 (2010)

[3] Science 320, 5876 (2008)

[4] Science 325 1221 (2009)

[5] Science 329 1500 (2010)

[6] Nature Photonics 3, 346 (2009), Phys. Rev. Lett. 107, 163602 (2011), arXiv:1009.3128

[7] Nature Communications 2, 413 (2011), arXiv:1110.4276, arXiv:1111.4147

[8] Nature Communications 2, 224 (2011), arXiv:1201.6537

[9] Nature Photonics 6, 45 (2012), Phys. Rev. Lett. 108, 053601 (2012)

[10] Appl. Phys. Lett. 99, 081110 (2011), Appl. Phys. Lett. 98, 051101 (2011)

[11] Appl. Phys. Lett. 97 241901 (2010), Appl. Phys. Lett. 98 133107 (2011)

[12] Appl. Phys. Lett. 96, 211101 (2010)

[13] arXiv:1112.2019

[14] Science 335, 303 (2012)