Memory-Integrated Photonic Integrated Circuits for Quantum Networks

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Abstract—*This talk discusses recent progress in photonic integrated circuits for quantum networks and modular quantum computing.*

I. INTRODUCTION

Photonic integrated circuits (PICs) increasingly important in classical communications applications over the past decades, including as transmitters and receivers in long-haul, metro and datacenter interconnects. Many of the same attributes that make PICs attractive for these applications — compactness, high bandwidth, and the ability to control large numbers of optical modes with high phase stability — also make them appealing for quantum information processing. This talk reviews our recent progress in developing PIC architectures for quantum communications and quantum computing applications.

II. PICS FOR QUANTUM KEY DISTRIBUTION

We recently realized[1] a field trial of polarization-based QKD with a PIC-based transmitter in the telecom band, implemented on the CMOS-compatible silicon-on-insulator photonics platform. The systems reaches composable secret key rates of nearly 1 Mbit/second in a local test (on a 103.6-m fiber with a total emulated loss of 9.2 dB) and >100 kbps in an intercity metropolitan test (on a 43-km fiber with 16.4 dB loss).

One of the advantages of PICs is that they can manage a large number of optical devices in a phase-stable and compact platform. We will describe a four-channel wavelength-division multiplexed quantum key distribution (WDM-QKD) transmitter near a 1550-nm wavelength implemented on the CMOS-compatible silicon-on-insulator photonics platform.

NANOPHOTONIC QUANTUM REPEATER DEVICES

The reach and speed of quantum communications is limited by optical loss. There has been significant progress in recent years in the development of quantum repeater nodes based on spins in diamond, in particular the nitrogen vacancy (NV) center[2]. Here, we address an outstanding challenge: to improve the optical properties of the NV-diamond memory by coupling to a nanophotonic diamond cavity. We will discuss in particular recent advances in diamond 1D and 2D photonic crystal cavities with quality factors near or above 10,000[3,4]. Coupling to such cavities can significantly improve the NV's zero-field branching ratio, but an outstanding challenge concerns increased spectral diffusion. These trade-offs and will be discussed.

INTEGRATION OF QUANTUM MEMORIES INTO PICS

An important next step of quantum repeater nodes is the developing of multiplexed quantum memories. To this end, we will discuss photonic integrated circuits based on the AlGaN-sapphire material system that are transparent in the visible spectrum. This platform now allows quality factors in excess of 20,000 for wavelengths as short as 369nm[5]. In separate work, we have already demonstrated the assembly of pre-selected, high-quality NV-based quantum memories into similar photonic integrated circuits, as well as on-chip integration of single-photon resolving detectors [6,7].

ARCHITECTURE FOR MODULAR QUANTUM COMPUTING

Finally, we describe an architecture for on-chip scalable cluster-state quantum computing that builds on large numbers of cavity-coupled NV -diamond centers networked by photonic switches and waveguides. A major barrier to scaling up spins for quantum computing systems lies in the need to efficiently entangle neighboring atomic memories by conversion of the qubits to photons and establishing entanglement via Bell measurements in the optical domain, all within the coherence time. We show that a percolation approach can significantly reduce the time required to create a universal-QC-capable cluster of atomic memories, compared with recently-studied architectures that rely on repeat-until-success entanglement connections. This reduction puts our architecture in an operational regime where demonstrated collection, coupling and detection efficiencies may be be sufficient for scalable QC with experimentally demonstrated coherence times.

References:

[1] D. Bunandar, A. Lentine, C. Lee, H. Cai, C. M. Long, N. Boynton, N. Martinez, C. DeRose, C. Chen, M. Grein, D. Trotter, A. Starbuck, A. Pomerene, S. Hamilton, F. N. C. Wong, R. Camacho, P. Davids, J. Urayama, and D. Englund, arXiv [quant-Ph] (2017).

[2] B. Hensen, H. Bernien, A. E. Dréau, A. Reiserer, N. Kalb, M. S. Blok, J. Ruitenberg, R. F. L. Vermeulen, R. N. Schouten, C. Abellán, W. Amaya, V. Pruneri, M. W. Mitchell, M. Markham, D. J. Twitchen, D. Elkouss, S. Wehner,

T. H. Taminiau, and R. Hanson, Nature **526**, 682 (2015).

[3] S. Mouradian, N. H. Wan, T. Schröder, and D. Englund, Appl. Phys. Lett. **111**, 021103 (2017).

[4] N. H. Wan, S. Mouradian, and D. Englund, Appl. Phys. Lett. **112**, 141102 (2018).

[5] T.-J. Lu, M. Fanto, H. Choi, P. Thomas, J. Steidle, S. Mouradian, W. Kong, D. Zhu, H. Moon, K. Berggren, J. Kim, M. Soltani, S. Preble, and D. Englund, Opt. Express, OE **26**, 11147 (2018).

[6] F. Najafi, J. Mower, N. C. Harris, F. Bellei, A. Dane, C. Lee, X. Hu, P. Kharel, F. Marsili, S. Assefa, and Others, Nat. Commun. **6**, (2015).

[7] D. Zhu, Q.-Y. Zhao, H. Choi, T.-J. Lu, A. E. Dane, D. R. Englund, and K. K. Berggren, arXiv [physics.ins-Det]; to Appear in Nature Nanotechnology (2017).

Zhu, Di, Qing-Yuan Zhao, Hyeongrak Choi, Tsung-Ju Lu, Andrew E. Dane, Dirk R. Englund, and Karl K. Berggren. 2017. “A Scalable Multi-Photon Coincidence Detector Based on Superconducting Nanowires.” *arXiv [physics.ins-Det]*. arXiv. http://arxiv.org/abs/1711.10546