Advanced Photonics Congress (BGPP, IPR, Networks, NOMA, NP, SOLED, SOF, SPPCom) © Optica Publishing Group 2024

Near-Ultraviolet to Midwave Infrared devices for Quantum Sensing and Information Processing

Cheryl Sorace-Agaskar[1], Colin Bruzewicz[1], Patrick Callahan[1], Christopher Heidelberger[1], Dave Kharas[1], William Loh[1], Thomas Mahony[1], Ryan Maxson[1], Robert McConnell[1], Alexander Medeiros[1], Rachel Morgan[2], Alkesh Sumant[1], Meghan Schuldt[1], Reuel Swint[1], Kerri Cahoy[2], Jelena Notaros[2], John Chiaverini[1], Paul Juodawlkis[1]

[1]MIT Lincoln Laboratory, Lexington MA 02421, USA, [2]Massachussets Institute of Technology, Cambridge, MA 02139
Corresponding Author: cheryl.sorace-agaskar@ll.mit.edu

Abstract: This talk reviews photonic integrated circuit materials, devices and integration techniques developed at MIT Lincoln Laboratory to support the needs of next generation quantum systems across the wavelength spectrum from the near-ultraviolet to the midwave-infrared.

1. Introduction

Applications in quantum computing, communication, and sensing rely on many underlying photonic functionalities. In photon-based quantum computing or quantum communication systems (quantum key distribution [QKD], remote entanglement distribution) photons serve as the qubits. In other systems, such as trapped-ion, neutral atom or solid-state based quantum computers or sensors (optical clocks, magnetometers, electric field and inertial sensors) optics serve as the interface to ion, atom or color-center based qubits, and light is central to preparing, manipulating and reading out the quantum states. Furthermore, photonic systems are often desired for ancillary functions; for example, providing low-power classical readout from cryogenic systems (such as those needed for superconducting qubits), or providing the low noise and mode-locked lasers needed in optical atomic clocks.

As many of these applications mature, there is a desire to scale up in the number of physical qubits contained within a single system or to scale down in system size, weight and power. Photonic integrated circuits (PICs) are increasingly recognized as not just a promising but a necessary technology to allow for such increases in overall complexity and number of qubit unit cells, and for the miniaturization of quantum systems, especially those expected to perform in the field (outside of laboratory conditions) such as sensing and communication systems. Further, PIC-based systems may be more environmentally robust than traditional discrete optics-based systems[1-2].

The large variety of applications, qubit modalities, and desired photonic functionalities means that a large variety of integrated photonic platforms and materials will be needed not just to support future quantum systems generally, but even within individual ones [3]. For example, a trapped-ion based quantum computer will likely require (1) passive waveguide materials and detector arrays integrated into ion-trap chips to allow for quantum state preparation, manipulation, and readout (dielectric waveguides, silicon APDs or superconducting nanowire detectors, metal trap electrodes), (2) additional chips containing laser sources with sophisticated locking loops to provide and stabilize these necessary optical sources (III-V gain materials, waveguides, active materials and devices to allow for high speed tuning and modulation, high finesse cavities and possibly vapor cells or nonlinear optical materials), and perhaps, eventually (3) underlying digital optical communications circuits to allow for low-power communication between a classical computer and a large qubit array (traditional silicon photonics) [3-6]. Optical clock applications require not just the above, but also other scheme-specific devices such as ultralow-loss SiN waveguides for ultralow-noise lasers, or III-V or solid-state gain materials for mode-locked lasers [6]. Both the aforementioned systems as well as quantum sensing systems and quantum memories may require photonic chips that interface closely with color centers in solid state materials or with vapor cells [7-9]. Thus, our vision for complex, compact quantum systems includes several different PIC chips tightly integrated to perform all necessary optical functionalities.

Moreover, the optical wavelengths at which functionalities such as passive routing, light generation, modulation, and detection are desired vary significantly from system-to-system. Atom, ion and solid-state systems often require shorter near-ultraviolet (NUV) to near-infrared (NIR) wavelengths, while photon-based quantum computing and communication systems prefer to stay close to the telecommunications bands where quantum applications can benefit from the low loss and high maturity of platforms developed by the telecommunication and datacom industry. However, certain applications, notably free-space optical quantum communication, including quantum key distribution, may also benefit from operating at midwave-infrared (MWIR) wavelengths to take advantage of specific atmospheric transparency windows and/or the ability to directly produce amplitude-squeezed states in MWIR laser sources (such as interband cascade lasers, ICLs) [10]. This talk will focus on the optical devices and materials developed at MIT Lincoln Laboratory to support these maturing quantum systems across different applicable wavelength bands from the near ultraviolet to the midwave infrared.

2. Photonic Integrated Circuit Platforms

2.1 Near-Ultraviolet to Near-Infrared Photonics

Many atomic, ion, or color-center-based quantum systems require shorter wavelength light in the visible, ultraviolet or near-infrared to address, manipulate or read out quantum states. To this end, MIT Lincoln Laboratory has developed a visible light photonics platform using a 200-mm CMOS toolset aimed at quantum applications and, specifically at trapped-ion based quantum computing and sensing. This platform consists of three waveguide layers: two plasma-enhanced chemical vapor deposition PECVD SiN_x layers with losses < 0.5 dB/cm for ~500-1100 nm optical wavelengths (and loss of ~0.25 dB/cm at 674 nm), and one atomic layer deposition (ALD) alumina (Al2O3) layer for ~370-500 nm optical wavelengths (losses < 1.5 dB/cm from 405-600 nm, ~ 3 dB/cm at 370 nm). A large device library has been developed along with a design methodology to create commonly desired passive devices at these wavelengths (splitters, waveguide crossings, grating couplers, escalators, etc…). Further description of the platform can be found in [4-5, 11]. These waveguide layers have been integrated with ion-traps and avalanche photodiodes to allow for the creation of a full "atomic physics package" and used to demonstrate trapped-ion based systems [1-2], but are also applicable to other quantum systems and PICs addressing ancillary functions. This platform, including next steps and applications beyond trapped-ion-based systems, will be discussed in the talk.

2.2 Midwave Infrared Photonics

While MWIR photonic integrated circuits are not traditionally associated with quantum systems, there is emerging interest in them for quantum communication and sensing applications, such as free space quantum key distribution, due to MWIR atmospheric transition windows and potential advantages of MWIR optical sources [10]. We have developed a MWIR PIC platform, again using a 200-mm CMOS toolset, aimed at the 2-5 µm range. The platform is based on germanium-on-silicon waveguides both with and without at top-cladding, and achieves losses of 0.6–2.5 dB/cm for both TE and TM light for unclad (aka air-clad) and 3.5–4.4 dB/cm for dielectric-clad waveguides [12]. A larger passive and active device library is under development and will be discussed in the presentation.

2.3. Ancillary PIC functions and PICs at telecommunication wavelengths

To support ancillary photonic functions such as miniaturization of III-V laser and amplifier systems containing optical gain materials, high-speed or high-precision modulation devices, and frequency locks; miniaturization of precision laser systems to support classical processing of quantum data such as ultralow-noise narrow linewidth lasers or mode-locked lasers; traditional digital optical communication circuits for system level control and read-out; and integration with non-PIC based atomic physics packages (solid state or gas based devices), MIT Lincoln Laboratory has developed a variety of other platforms, devices, and integration techniques. These include traditional telecommunications-based silicon and silicon nitride platforms [11], ultralow-loss silicon nitride waveguides [6], hybrid and heteroepitaxial integration of III-V materials [13-14], and heterogenous integration of thin-film materials. These will be discussed further in the talk.

3. Conclusions.

A wide variety of integrated photonic materials, devices and integration techniques will be needed to support next generation quantum systems. This talk reviews developments at MIT Lincoln Laboratory in passive and active components and subsystems to support quantum computing, communication, and sensing systems across the wavelength spectrum.

4. Acknowledgements

This material is based upon work supported by the Under Secretary of Defense for Research and Engineering (USDR&E) under Air Force Contract No. FA8702-15-D-0001. Support is also acknowledged from the Dept of the Navy, U.S. Department of Energy, Office of Science, National Quantum Information Science Research Centers, Quantum Systems Accelerator, and from NSF QLCI Q-SEnSE (award # 2016244). Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the Department of Defense. Delivered to the U.S. Government with Unlimited Rights, as defined in DFARS Part 252.227-7013 or 7014 (Feb 2014). Notwithstanding any copyright notice, U.S. Government rights in this work are defined by DFARS 252.227-7013 or DFARS 252.227-7014 as detailed above. Use of this work other than as specifically authorized by the U.S. Government may violate any copyrights that exist in this work. DISTRIBUTION STATEMENT A. Approved for public release. Distribution is unlimited.

5. References

[1] R. J. Niffenegger, *et al*., "Integrated multi-wavelength control of an ion qubit," Nature **586**, p. 538 (2020).
[2] K.K. Mehta et al., Nature 586, 533 (2020)
[3] Moody, Galan, et al. "2022 Roadmap on integrated quantum photonics." Journal of Physics: Photonics 4.1 (2022): 012501.
[4] Sorace-Agaskar, Cheryl, et al. "Integrated Photonics for Trapped Ion-Based Quantum Computing and Sensing." 2023 IEEE Photonics Society (SUM). IEEE, 2023.
[5] Sorace-Agaskar, Cheryl, et al. "Integrated Photonic Circuits and Platform Development for Trapped-Ion Quantum Computing and Sensing." *Integrated Photonics Research, Silicon and Nanophotonics*. Optica Publishing Group, 2021.
[6] McConnell, R., et al. "Integrated Technologies for Portable Optical Clocks." *Optical Sensors*. Optica Publishing Group, 2021.
[7] Fancher, Charles T., et al. "Rydberg atom electric field sensors for communications and sensing." IEEE Transactions on Quantum Engineering 2 (2021): 1-13.
[8] Bhaskar, M.K., et al. Experimental demonstration of memory-enhanced quantum communication. Nature 580, 60–64 (2020).
[9] Starling, David J., et al. "Fully packaged multichannel cryogenic quantum memory module." Physical Review Applied 19.6 (2023): 064028.
[10] F. Grillot, et al. "Free-space communications and quantum photonics: advancements in mid-infrared interband cascade lasers", Proc. SPIE 12895, Quantum Sensing and Nano Electronics and Photonics XX, 1289502 (8 March 2024);
[11] C. Sorace-Agaskar, *et al*., "Versatile Silicon Nitride and Alumina Integrated Photonic Platforms for the Ultraviolet to Short-Wave Infrared," IEEE JSTQE, **25**, 5 (2018).
[12] Morgan, Rachel, et al. "Low-loss germanium-on-silicon waveguides and ring resonators for the mid-wave infrared." CLEO: Science and Innovations. Optica Publishing Group, 2022.
[13] Kharas, Dave, et al. "High Power (> 300 mW) 1550 nm On-Chip Laser Realized Using Passively Aligned Hybrid Integration." CLEO: Science and Innovations. Optica Publishing Group, 2020.
[14] Heidelberger, Christopher, et al. "Efficient Optical Coupling between III-V Semiconductor and SiN x Waveguides via Heteroepitaxial Integration." 2021 IEEE Photonics Conference (IPC). IEEE, 2021.