Frontiers in Optics + Laser Science 2024 (FiO/LS) © Optica Publishing Group 2024

# Cryogenic packaging for scalable hybrid quantum PICs

**Robert Bernson,[1,*] Alexander Witte,[2,*,†] Genevieve Clark,[2] Kamil Gradkowski,[1] Matthew Saha,[2] Andrew Leenheer,[4] Kevin Chen,[3] Gerald Gilbert,[2] Matt Eichenfield,[4,5] Dirk Englund,[3] Peter O'Brien[1]**

*[1]Tyndall National Institute, Lee Maltings Complex Dyke Parade, Cork, Cork, T12 R5CP, Ireland*
*[2]The MITRE Corporation, 202 Burlington Road, Bedford, Massachusetts 01730, USA*
*[3]Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
*[4]Sandia National Laboratories, P.O. Box 5800 Albuquerque, New Mexico 87185, USA*
*[5]College of Optical Sciences, University of Arizona, Tucson, Arizona 85719, USA*

*[*]These authors contributed equally, [†]awitte@mitre.org*

**Abstract:** We demonstrate a robust packaging method for PICs using surface grating couplers. We use this method to create diamond color center quantum memory modules with active photon routing, strain tuning, and operation to millikelvin temperatures. 

Recent progress in integrated optics has seen the use of optical fibers for scalable, low-loss packaging of photonic integrated circuits (PICs) [1,2]. Quantum systems relying on PICs for photon management have the additional requirements of cryogenic temperatures, broad wavelength operation, and minimal photon loss. Optical packaging must also incorporate electrical co-packaging for qubit control and photon routing, while often accommodating high channel count and heterogeneous integration of diverse materials [3]. Multi-channel optically packaged PICs have recently been demonstrated at cryogenic temperatures using fiber arrays coupled to edge couplers [5], however this relied on extremely high fabrication tolerances, strain relief structures, complex bonding procedures.

We demonstrate a straightforward approach based on grating couplers and angle polished fiber arrays, compatible with operation at both visible and telecom wavelengths. Our method uses off the shelf components in a process that is robust to temperature cycling and alignment tolerant enough for automated packaging. Selection of an extremely strong adhesive (Fig. 1a) removes the need for strain relief structures or large amounts of epoxy, placing no requirements on the photonic platform itself. Angle polished fiber arrays are aligned to the PIC and a thin layer of adhesive is deposited between the two. After UV curing, the packaged PIC is robust enough to remove from the setup and tested further without the need of extra strain relief. We demonstrate operation at cryogenic and room temperature of visible and telecom grating coupled loopbacks (Fig. 1b). We then apply our packaging approach to foundry-process PICs optimized for low loss integration of diamond quantum memories (Fig. 1c). We achieve successful operation of packaged PICs down to millikelvin temperatures, allowing interrogation of both optical and spin degrees of freedom. Finally, we demonstrate a fully electrically and optically packaged active quantum memory module with on-chip optical routing and strain tuning.

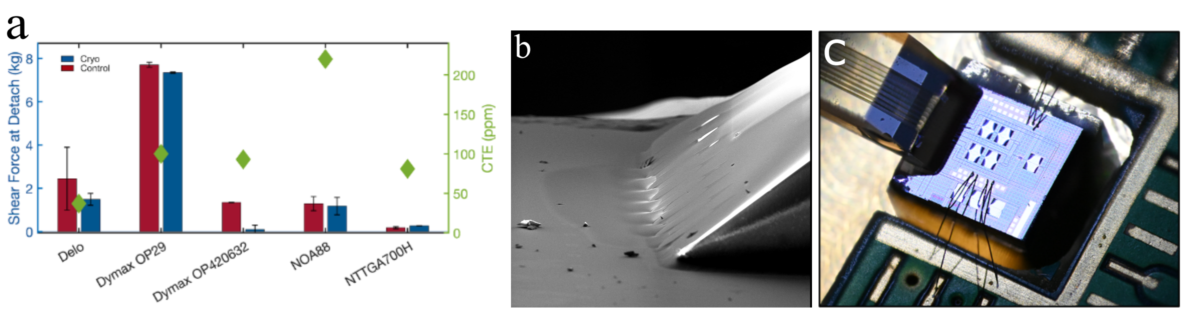


Fig. 1: Fiber glued packaging. a) Adhesive testing results. Dymax OP29 was selected due to its high sheer strength both before and after thermal cycling. b) Scanning electron microscope (SEM) image of packaged loopback chip. Individual fibers as well as the adhesive layer can be seen. c) Fully packaged diamond quantum memory module. Both optical and electrical packaging are implemented.

Frontiers in Optics + Laser Science 2024 (FiO/LS) © Optica Publishing Group 2024

Fig. 2a shows the behavior of a packaged sample at cryogenic temperatures. We observe stable operation across the temperature scale. We also measure the optical spectra for the grating at both room temperature as well as at 6K. We observe a blue shift in the peak wavelength, which we attribute to the shrinking dimensions of the grating coupler, which effectively change the pitch of the grating teeth. 3D modeling is being conducted to fully understand this relationship. We next apply our optical packaging approach to quantum memory modules consisting of diamond microchiplets (QMCs) heterogeneously integrated into CMOS-process photonic chips. We use grating-coupled optical loopback structures to quantify optical losses arising from heterogeneous integration. QMCs hosting silicon vacancy color centers are integrated into sockets in the center of each loopback, where a window etch removes the oxide overcladding allowing direct contact between the QMC and SiN waveguides. We determine a typical transmission of -.22dB at each window transition and -1.25dB at each diamond-SiN transition for well aligned QMCs. With modest grating coupler performance (-7dB transmission at 737 nm) this yields a fiber - PIC - QMC interface with less than 10dB total loss, with the potential for losses closer to 6dB with high performing grating couplers. Finally, we apply our technique to an active, memory-integrated PIC with electrical packaging for color center control and on-chip optical modulation. Figure 1c shows an image of the packaged PIC on a copper mount, wirebonded to a PCB for electrical signal routing. Within the PIC (Fig. 2b), piezoelectric cantilever modulators allow on-chip control of SiV fluorescence while cantilevers mechanically contacting the diamond chiplet apply controllable strain to SiVs in the QMC for frequency tuning. Figure 2ci shows PLE spectra from SiVs in two channels of the QMC with frequency control to overcome inhomogeneity in their transition energies. Applying a DC voltage to the cMZI allows high contrast optical routing of SiV fluorescence between the two output ports and can function as an on-chip beamsplitter for coincidence counting or interference (Fig. 2cii).

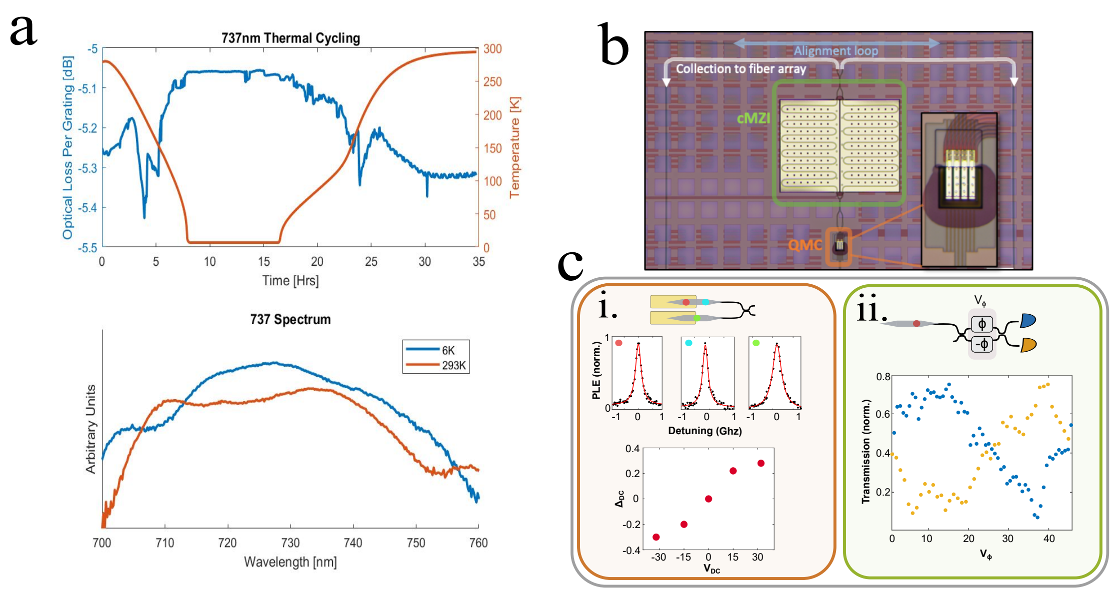


Fig. 2: Packaged chip results. a) Thermal results stable coupling to cryogenic temperatures at 737nm. The packaged device is stable at cryogenic temperatures. b) Zoom-in showing the PIC with QMC, cantilevers for strain control of quantum memories, and optical modulators. Both collection channels are packaged with the same fiber array. c) i.PSB florescence from SiV's in channels 3 and 4 of the QMC. PLE measurements reveal high optical quality, while integrated cantilevers allow frequency shifting of the ZPL transmission. ii. Integrated MZI splits output for auto-correlation measurements. The MZI can route flourescence between the two output channels with high extinction.

## References


1. L. Carroll, *et al*. "Photonic Packaging: Transforming Silicon Photonic Integrated Circuits into Photonic Devices," NATO Adv. Sci. Inst. Ser. E Appl. Sci. 6, 426 (2016).
2. L. Ranno, *et al*. "Integrated Photonics Packaging: Challenges and Opportunities," ACS Photonics 9, 3467–3485 (2022).
3. G. Moody, *et al*. "2022 Roadmap on integrated quantum photonics," J. Phys. Photonics 4, 012501 (2022).
4. D. Witt,*et al*. "Packaged Cryogenic Photon Pair Source Using an Effective Packaging Methodology for Cryogenic Integrated Optics," arXiv [physics.optics] (2024).
5. D. Starling,*et al*."Fully Packaged Multichannel Cryogenic Quantum Memory Module" Phys. Rev. Applied 19, 064028 (2023)