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Microwave-optical transduction with integrated gallium phosphide devices

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Abstract *Optomechanical resonators provide a route to interconversion of microwave and optical photons for quantum interconnects. We present a platform comprising a GaP photonic crystal cavity integrated on prefabricated niobium circuits, with mechanical modes at ~3.2 GHz and optomechanical coupling rates up to $g_0/2\pi \approx 300$ kHz. ©2022 The Author(s)*

Electromechanically actuated optomechanical resonators offer an attractive route to coherent interconversion of microwave and optical photons [1-5]. Such devices could enable optical interconnection of quantum computers based on qubits operating at microwave frequencies, providing both scalability and added functionality. Here, we present a platform for microwave-to-optical conversion utilizing an optical cavity made of gallium phosphide (GaP) integrated on prefabricated microwave circuits and present early results demonstrating coherent transduction at room temperature [6].

GaP possesses an attractive combination of a large refractive index ($n > 3$) and a wide electronic bandgap (2.26 eV) [7]. These values offer the possibility of creating devices with strong light confinement, enhanced light-matter interaction, and low two-photon absorption at telecommunication wavelengths. In addition, GaP has a non-centrosymmetric crystal structure and is thus piezoelectrically active.

Despite this uncommon confluence of properties, the use of GaP in integrated photonics

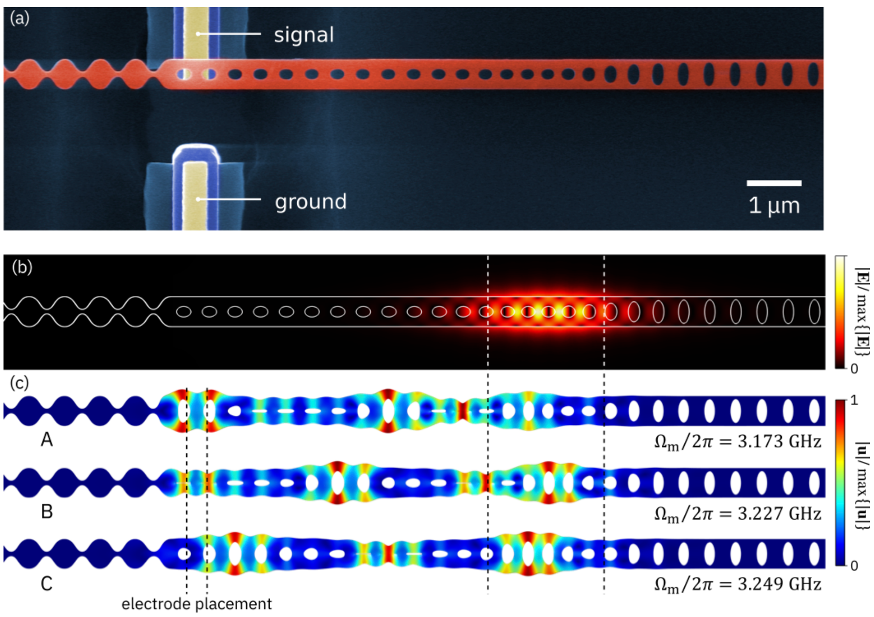

Fig. 1: (a) False-color scanning electron microscope image of a GaP photonic crystal cavity suspended above integrated niobium electrodes. (b) Finite-element-method (FEM) simulation of the localized optical mode. The color scale indicates the magnitude of the electric field |**E**|. (c) FEM simulation of three extended mechanical breathing modes. The color scale indicates the magnitude of the mechanical displacement |**u**|.

has remained largely unexplored. The main challenge has been the lack of methods for obtaining GaP on low-refractive-index substrates and patterning it into structures with nanometer precision while maintaining good material quality. To address these issues, we have developed a direct wafer-bonding approach to integrate high quality, epitaxially-grown GaP onto silicon dioxide on a silicon carrier wafer as well as optimized reactive-ion-etching techniques for pattern transfer defined by electron-beam lithography [8,9].

Making use of these processing capabilities, we fabricate transducers comprising a quasi-one-dimensional photonic crystal cavity made of single-crystal GaP [10] integrated on niobium circuits on an intrinsic silicon substrate (Fig. 1). We exploit spatially extended, sideband-resolved mechanical breathing modes at ~3.2 GHz. The mechanical modes are actuated by the niobium electrodes via the inverse piezoelectric effect at a location remote from the optical mode to reduce losses. The extended modes nevertheless maintain substantial optomechanical coupling, up to 300 kHz. With such a device, we demonstrate and fully characterize coherent transduction of microwave signals to optical frequencies at room temperature.

The maximum total transduction efficiency for the device as measured is $\eta = 1.4 \times 10^{-11}$. This low value is a consequence of coupling to a highly impedance-mismatched transmission line instead of a resonant microwave cavity. We therefore consider instead the more meaningful situation of coupling to a superconducting qubit and estimate through simulations the expected electromechanical coupling rate. We predict that the system could achieve a coupling rate to a transmon qubit of ~200 kHz and would be deep enough in the strong coupling regime to permit a faithful swap of the qubit and mechanical resonator states if the qubit lifetime $T_1 \gtrsim 10$ μs.

This work represents a first step towards integration of GaP electro-opto-mechanical transducers with superconducting quantum processors.

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References

[1] A. H. Safavi-Naeini, D. van Thourhout, R. Baets, and R. van Laer, "Controlling phonons and photons at the wavelength scale: integrated photonics meets integrated phononics," *Optica*, vol. 6, no. 2, pp. 213–232, 2019, DOI: 10.1364/OPTICA.6.000213.

[2] N. Lambert, A. Rueda, F. Sedlmeir, and H. G. L. Schwefel, "Coherent Conversion Between Microwave and Optical Photons–An Overview of Physical Implementations," Advanced Quantum Technologies, vol. 3, 1900077 (pp. 15), 2020, DOI: 10.1002/qute.201900077.

[3] N. Lauk, N. Sinclair, S. Barzanjeh, J. P. Covey, M. Saffman, M. Spiropulu, and C. Simon, "Perspectives on quantum transduction," *Quantum Science and Technology*, vol. 5, 020501 (pp. 15), 2020, DOI: 10.1088/2058-9565/ab788a.

[4] Y. Chu and S. Gröblacher, "A perspective on hybrid quantum opto- and electromechanical systems," *Applied Physics Letters*, vol. 117, no. 15, 50503 (pp. 6), 2020, DOI: 10.1063/5.0021088.

[5] X. Han, W. Fu, C.-L. Zou, L. Jiang, and H. X. Tang, "Microwave-optical quantum frequency conversion," *Optica*, vol. 8, no. 8, pp. 1050–1064, 2021, DOI: 10.1364/OPTICA.425414.

[6] S. Hönl, Y. Popoff, D. Caimi, A. Beccari, T. J. Kippenberg, and P. Seidler, "Microwave-to-optical conversion with a gallium phosphide photonic crystal cavity," *Nature Communications*, vol. 13, 2065 (pp. 9), 2022, DOI: 10.1038/s41467-022-28670-5.

[7] D. J. Wilson, K. Schneider, S. Hönl, M. Anderson, Y. Baumgartner, L. Czornomaz, T. J. Kippenberg, and P. Seidler, "Integrated gallium phosphide nonlinear photonics," *Nature Photonics*, vol. 14, pp. 57-62, 2020, DOI: 10.1038/s41566-019-0537-9.

[8] S. Hönl, H. Hahn, Y. Baumgartner, L. Czornomaz, and P. Seidler, "Highly selective dry etching of GaP in the presence of $Al_xGa_{1-x}P$ with a $SiCl_4/SF_6$ plasma," *Journal of Physics D: Applied Physics*, vol. 51, no. 18, 185203 (pp. 12), 2018, DOI: 10.1088/1361-6463/aab8b7.

[9] K. Schneider, P. Welter, Y. Baumgartner, H. Hahn, L. Czornomaz, and P.Seidler, "Gallium Phosphide-on-Silicon Dioxide Photonic Devices," *Journal of Lightwave Technology*, vol. 36, no. 14, pp. 2994-3002, 2018, DOI: 10.1109/JLT.2018.2829221.

[10] K. Schneider, Y. Baumgartner, S. Hönl, P. Welter, H. Hahn, D. J. Wilson, L Czornomaz, and P. Seidler, "Optomechanics with one-dimensional gallium phosphide photonic crystal cavities," *Optica*, vol. 6, no. 5, pp. 577–584, 2019, DOI: 10.1364/OPTICA.6.000577.