**A heterogeneously integrated lithium niobate-on-silicon nitride photonic platform**

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**Abstract:** We present a LiNbO₃ integrated photonic platform with wafer-scale bonding to a Si₃N₄ photonic circuit. The platform exhibits <0.1 dB/cm propagation loss and <2.5 dB/facet fiber-chip coupling loss. We demonstrate phase shifters, frequency-agile lasers, optical splitters, and other devices. © 2023 The Author(s)

Lithium niobate (LiNbO₃) is known as the most common χ²-material for electro-optic devices and it remains unique in terms of its physical properties and commercial availability [1]. Wafer-scale transfer of LiNbO₃ thin-films, combined with improvements in etching of LiNbO₃, have recently enabled low-loss integrated electro-optic platforms to emerge [2, 3]. This has led to demonstrations of electro-optic frequency combs generation [4], frequency converters [5], and other applications relying on the strong Pockels effect and low-loss of the material. LiNbO₃ photonic integrated circuits have mostly been fabricated using non-standard etching techniques and partially etched ridge waveguides, that lack the reproducibility routinely achieved in silicon photonics. Moreover, efficient fiber-to-chip coupling on these platforms can be achieved only with complicated multi-layer etching techniques [6]. Here we demonstrate a heterogeneously integrated LiNbO₃-Si₃N₄ photonic platform by employing wafer-scale bonding of thin-film LiNbO₃ to planarized low-loss silicon nitride photonic integrated circuits [7] thus providing a reliable and scalable solution using standard processing and precise lithographic control.

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**Fig. 1. Heterogeneous integration.** (a) Schematics of the wafer-scale bonding approach. (b) Broadband optical transmission of a hybrid microresonator with a corresponding resonance linewidth (inset). (c) SEM pseudo-color image of the hybrid waveguide cross-section. (d) Optical microscope image of a phase shifter with gold electrodes. (e) Mach-Zehnder interferometer transmission as a function of the applied drive voltage to 2 types of 4 mm long phase shifters. Red line corresponds to the 52% participation factor geometry, blue line - to the 38% factor. (f) FEM optical mode simulation for the 38% participation geometry.
We perform full wafer-bonding (see Fig. 1(a)) with the subsequent lithium niobate processing that does not require smoothness and lithographic precision, as the light propagation is mainly defined by the underlying silicon nitride waveguides. The intrinsic quality factors of individual microring resonators reach up to $Q = 4.5 \times 10^6$ (linear propagation loss of 8.5 dB/m) and are uniform across a broadband wavelength range (see Fig. 1(b)). Despite partial mode confinement in the LiNbO$_3$ layer, the electro-optic performance of our platform reaches the values, comparable to the modern thin-film LNOI platforms. Figure 1(h) shows the performance of phase modulators with the $V_L \pi$ product of approximately 8.8 V·cm and 6 V·cm for different waveguide geometries with mode participation of 38% and 52% respectively.

![Image](image_url)

**Fig. 2.** Adiabatic mode transitions and optical splitters. Colored SEM image of a LiNbO$_3$ taper fabricated. (b) Optical microscope image of a test chip. Horizontal dotted lines mark waveguides with 2, 4, 6, and 10 interface transitions. (c) Schematic of a tapered (adiabatic) interface transition. (d) Transmission measurements of breakout waveguides described in (b) as well as a typical straight (non-adiabatic) transition for comparison (orange line). (e) Optical image, FDTD simulation, and schematic of a W-type 3-dB splitter. (f) Splitter transmission measurements.

To achieve a smooth transition from Si$_3$N$_4$ into the hybrid mode, we implemented adiabatic tapers in the LiNbO$_3$ layer, as shown in Fig. 2(a)-(c). All the functional photonic components do not depend on the etching of the chip interface, which is employed only at mode transition regions and which does not require low roughness. We fabricated waveguides with 2, 4, 6, and 10 transitions to determine the increase in loss, and observe a difference of maximum 0.8 dB additional loss for 10 transitions (Fig. 2(d)). We also implement of a 3-dB splitter (see Fig. 2(e)) that is defined solely by underlying Si$_3$N$_4$ inverse tapers. Transmission measurements of the device reveal a flat response, with power asymmetry between the two arms not exceeding 1.7 dB and on-chip insertion loss not exceeding 1 dB in the 1500-1620 nm wavelength range (Fig. 2(f)).

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