Heterogeneously integrated low-loss lithium niobate photonic platform

(Student paper)

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We demonstrate a hybrid $LiNbO_3$-Si_3N_4 photonic integrated platform with a propagation loss of 8.5 dB/m at wafer-scale for various devices. The platform exhibits low fiber-to-chip insertion loss, high power handling, and precise lithographic control.

Keywords: *hybrid integration, thin-film lithium niobate, silicon nitride, electro-optics, microresonators, nonlinear photonics*

INTRODUCTION

Recent breakthroughs in thin-film lithium niobate on insulator (LNOI) have enabled low-loss photonic integrated circuits (PICs) based on $LiNbO_3$ [1-2]. Excellent physical properties together with commercial availability have made this material extremely compelling for the photonics community. Despite the achievements to date, widespread adoption of $LiNbO_3$ integrated photonics is still impeded by several key issues such as CMOS compatibility, wafer-scale yield, and edge fiber-to-chip coupling [3]. As an alternative to conventional bulk $LiNbO_3$ and ridge waveguide-based photonic devices, hybrid platforms emerged recently, combining thin-film $LiNbO_3$ with waveguides made of Si, Si_3N_4, or Ta_2O_5 [4-5]. However, direct wafer bonding at the wafer-level was not achieved (only small chiplets were used), and the approaches could not retain the ultra-low propagation losses of Si_3N_4. Here we overcome the challenges mentioned above and demonstrate a high-yield, low-loss, integrated $LiNbO_3$ photonic platform with efficient edge coupling that harnesses the mature Si_3N_4 PDK and endows the platform with selective electro-optic functionality.

RESULTS

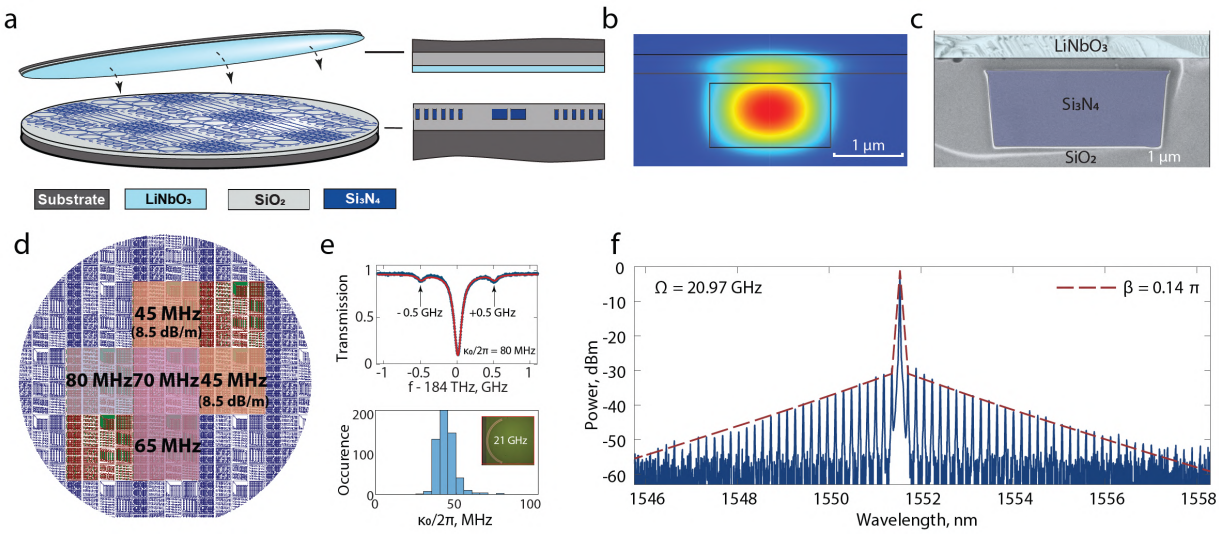

Fig. 1. (a) Full wafer bonding approach illustration. (b) Optical mode profile in the hybrid structure. (c) SEM cross-section of a resulting hybrid waveguide. (d) Wafer map of microresonator resonance linewidth distribution. (e) Examples of one resonance fit and statistical analysis of more than 500 resonances linewidth. (f) Electro-optical frequency comb generation in a hybrid microresonator.

The process flow of our hybrid PIC starts with the fabrication of Si3N4 PIC based on the photonic Damascene process [6]. As depicted on Figure 1(a), all the photonic designs are imprinted on the Si_3N_4 layer and therefore the process does not depend on the $LiNbO_3$ etching. The photonic Damascene process used for the donor silicon nitride wafer, has several particular advantages, in particular a flat wafer surface planarized with CMP for heterogeneous

integration. After planarization, a commercially available LNOI wafer is bonded with subsequent substrate removal. The resulting waveguide cross-section and optical mode distribution are depicted on Figure 1 (b)-(c). The mode is partially confined in the slab $LiNbO_3$ layer, while the Si_3N_4 layer serves for guiding the optical signal. In the current configuration, we use 300 nm $LiNbO_3$ layer bonded to 950 nm thick silicon nitride layer with a silica interlayer of approximately 100 nm between two materials. The silica layer is used to maintain homogeneous and flat surface of the donor wafer for the wafer-scale bonding. With the waveguide width of 1.8 um, this configuration gives approximately 12% of the optical mode in lithium niobate. One of the advantages of lithium niobate heterogeneous integration is that fiber to chip coupling can be achieved via the Si_3N_4 layer, which offers low insertion loss. In order to increase the coupling efficiency, we remove lithium niobate from the chip facet regions and achieve in total 18% fiber-to-fiber transmission.

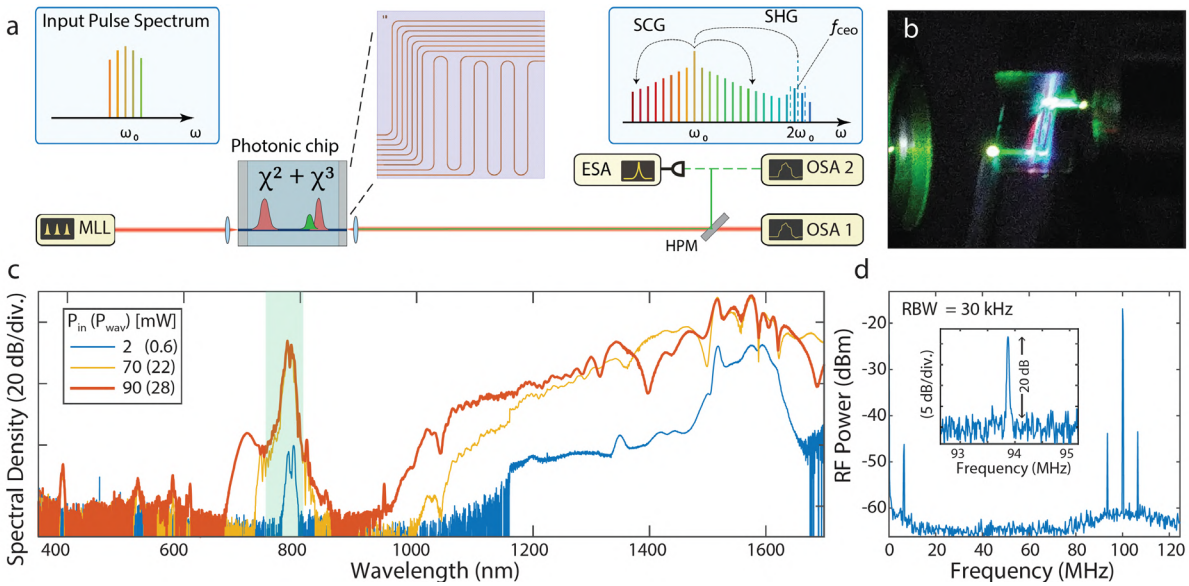

Fig. 2. (a) Experimental schematic for supercontinuum generation in a χ(2), χ(3) $LiNbO_3$ waveguide. (b) Photo of the supercontinuum process in experiment. Blue and Green light corresponds to higher harmonic generation. (c) Total output spectrum for different incident (in waveguide) power levels P_{in} (P_{wav}). (d) f_{ceo} beatnote and f_{rep}=100 MHz repetition rate beatnote, detected at P_{wav}=28 mW.

To illustrate the versatility, lithographic precision, and yield of our process, we fabricate a reticle with a variety of devices. We study optical losses by measuring intrinsic linewidth of hybrid microresonators with 1 mm radius. The wafer map of mean linewidth values is depicted in Fig. 1(d). Some of the wafer areas show 45 MHz linewidth, which corresponds to quality factors of $Q = 3\times10^6$ and approximately 8.5 dB/m linear optical loss value. Importantly this corresponds to not a single issolated resonance, but to a statistical ensemble of more than 500 resonances (cf. Fig 1(e)). We also use the same microring resonators combined with metal electrodes for electro-optic frequency comb generation [7]. Even though the electro-optic coupling is limited in our case by the mode participation in lithium niobate (around 12% in this experiment), we observe a broad comb with 60 sidebands within a 25 dB span (cf Figure 1(f)). This is achieved due to ultra low losses of our structure combined with flat integrated dispersion. With a further geometry optimization, there is only a minor reduction in electro-optic efficiency ($2\times V_{\pi}L$ product) in comparison to approaches using ridge waveguides, while enabling lower propagation losses on wafer-scale, independent on quality of the $LiNbO_3$ etching [8].

Besides electro-optics, the low loss of our platform is also a key for nonlinear photonics applications. We demonstrate supercontinuum generation with combined $\chi^{(2)}$ and $\chi^{(3)}$ nonlinear optical processes using the hybrid waveguides, as shown in Fig. 2(a). We observe octave-spanning supercontinuum generation mediated by the $\chi^{(3)}$ nonlinearity, together with simultaneous second harmonic generation (SHG) due to optical field in $LiNbO_3$ [9]. As shown in Fig. 2(d), we obtain the fundamental repetition rate of the supercontinuum as well as the f_{ceo} in the RF spectrum, which shares similar laser noise as the seed mode-locked laser input.

DISCUSSION

To sum up, we demonstrate a novel, hybrid $LiNbO_3$ and Si_3N_4 photonic integrated circuit using direct wafer bonding. The high yield and wafer-scale nature of the process enables complex photonic architectures relying on low optical loss and high-speed optical modulation, and enables $LiNbO_3$ to be confined in regions of interest on the chip (e.g. as modulators).

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