Second-Harmonic Generation in Periodically-Poled Thin Film Lithium Niobate on Silicon

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Abstract: Thin films of lithium niobate are wafer-bonded onto oxidized silicon substrates and periodically poled for quasi-phase matching to demonstrate second-harmonic generation in submicron waveguides with a record-high conversion efficiency of 730 $\%W^{-1}cm^{-2}$.

OCIS codes: (130.3120) Integrated optics devices; (190.4390) Nonlinear optics, integrated optics; (130.3730) Lithium niobate.

Silicon lacks intrinsic second-order optical nonlinearity ($\chi^{(2)}$) due to the centrosymmetry of its crystalline structure. Heterogeneous integration of non-centrosymmetric materials, with strong $\chi^{(2)}$ nonlinearity, on Si substrates can potentially revolutionize nonlinear integrated photonics. $\chi^{(2)}$ nonlinearity is not only typically stronger that the $\chi^{(3)}$ counterpart, but important effects, such as second-harmonic generation (SHG), are conveniently achievable using second-order nonlinearity and much more difficult based on $\chi^{(3)}$ nonlinearity. It is well known that lithium niobate (LN) possesses one of the highest $\chi^{(2)}$ values. However, conventional LN waveguides suffer from low refractive index contrast. This leads to large mode sizes and low overlap between different optical modes, such as the fundamental and second-harmonic modes involved in SHG. Consequently, the nonlinear conversion efficiency of commercial periodically-poled LN (PPLN) waveguides is on the order of 40 $\%W^{-1}cm^{-2}$ [1]. Slightly higher conversion efficiency of up to 46 $\%W^{-1}cm^{-2}$ has also been reported in ridge, but yet large, LN waveguides [2]. Clearly, in addition to incompatibility with silicon photonics, the existing approaches suffer from large mode areas and, subsequently, limited normalized conversion efficiencies.

To address these challenges and utilize the respective advantages of both LN and Si, we have demonstrated that thin films of LN can be reliably bonded onto oxidized silicon substrates and rib-loaded with an index-matching material to form submicron waveguides [3,4]. In this work, periodic poling for SHG is applied on our novel LN-on-Si platform for the first time. It is demonstrated that the smaller mode area increases the normalized conversion efficiency for SHG by about an order of magnitude to record-high values of 730 $\%W^{-1}cm^{-2}$.

Ion implantation, wafer bonding and slicing are used to transfer 400-nm-thick *X*-cut LN films onto thermal SiO_2 lower cladding layers grown on Si substrates [3,4]. Periodicity of ~ 5 µm is required for quasi-phase matching (QPM) according to COMSOL™ simulations for a fundamental wavelength in the telecommunication band. Periodic metallic electrodes are fabricated on the LN thin films by e-beam lithography, metallization and etching techniques. Periodic poling is achieved by applying high-voltage pulses across the *z*-axis of the LN films. Index-matching silicon nitride (SiN) is then deposited by chemical vapor deposition. The SiN films are patterned and dry-etched to form the rib-loaded region and achieve single-mode waveguides, as depicted in Figure 1(a). The electrodes are > 3 µm away from the SiN rib layers and COMSOL simulations confirm that they do induce insignificant optical loss. Finally, a 2-µm-thick SiO_2 layer is deposited as the top cladding layer. The final device length is 4 mm. A micrograph of the device with poled electrodes prior to SiN deposition is shown in Fig. 1(b).

Transverse-electric (TE) polarized light is coupled in and out of the waveguides by butt coupling using lensed fibers. The optical spectrum of the 120-fs pulsed input to the waveguide is shown in Fig. 2(a). Figure 2(b) shows the output spectrum at the end of an unpoled waveguide. This is used as a reference to Fig. 2(c), which shows the spectrum at the output of a poled waveguide. Evidently, QPM occurs between a 1600 nm fundamental wave and a generated 800 nm harmonic wave. The normalized conversion efficiency is 730 $\%W^{-1}cm^{-2}$. This is a record high efficiency for any integrated PPLN frequency converter, to the best of our knowledge. Figure 3(a) is a normalized plot of the second harmonic output power versus the input optical power. On a logarithmic scale, the straight line plot has a slope of 2.05, which is close to the expected value of 2. Figure 3(b) compares the normalized conversion efficiency obtained in this work to the mentioned reported commercial efficiency [1]. The figure also presents the extrapolated propagation-length dependency of both cases based on theoretical models, confirming potential for higher linear power conversion efficiency.

In conclusion, periodic poling is used for the first time, on a novel heterogeneous LN on silicon integrated platform, to obtain SHG with a record efficiency of 730 $\%W^{-1}cm^{-2}$. The use of a silicon substrate demonstrates the compatibility of $\chi^{(2)}$ nonlinearity with silicon photonics for potential on-chip nonlinear and quantum-optic applications.

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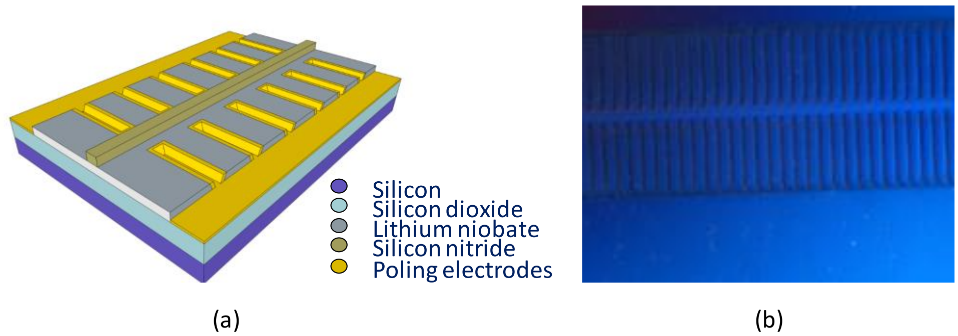

Fig. 1: (a) Schematic of the demonstrated novel device for SHG; (b) Micrograph of a fabricated device prior to silicon nitride deposition.

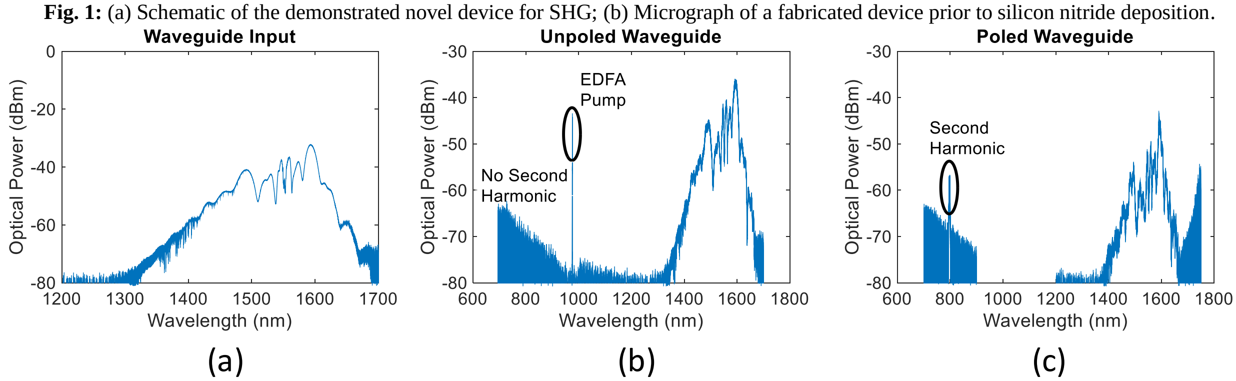

Fig. 2: Optical spectra for: (a) Input to the PPLN waveguides; (b) Output at the end of an unpoled waveguide; (c) Output at the end of a poled waveguide exhibiting 730 $\%W^{-1}cm^{-2}$ normalized conversion efficiency.

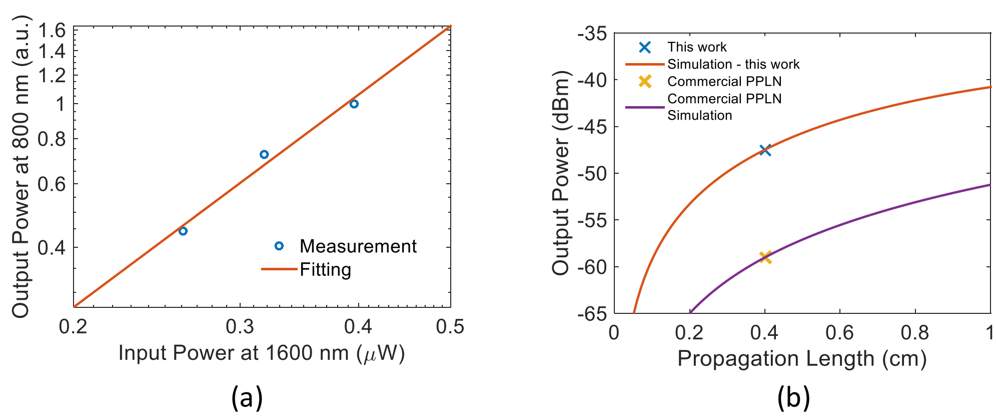

Fig. 3: (a) Log-log plot of the output second harmonic power vs. the input power level, exhibiting a fitted slope of 2.05; (b) Comparison of simulated and measured output power vs the propagation length.

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