Integrated Lithium Niobate Platform for Nonlinear Optics and Electro-Optic Applications

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Abstract: We demonstrate an integrated lithium niobate platform with sub-wavelength light confinement and low propagation loss (3dB/cm). We show efficient second harmonic generation in phase-matched waveguides (41% $W^{-1}cm^{-2}$), as well as high-speed electro-optic modulation (40 Gbps).

OCIS codes: (230.0230) Optical devices; (230.3990) Micro-optical devices; (230.4320) Nonlinear optical devices.

1. Introduction

Lithium niobate ($LiNbO_3$, LN) has been the most widely used material for both nonlinear wavelength conversion and electro-optic modulation, owing to its excellent second order susceptibility ($\chi^{(2)}$), wide transmission window and relatively high refractive index [1-3]. However, conventional LN devices are usually realized in ion-exchanged waveguides with rather low index contrast between core and cladding (Δn ~ 0.02) [3]. As a result, these devices feature large dimensions, high bending radii, low efficiency, and poor integrability. Thin-film LN on insulator has recently emerged as a promising candidate to shrink the optical mode volume and boost the nonlinear interaction strength [4]. We have previously demonstrated high-quality micro-resonators (quality factors > 10^5) by directly micromachining LN thin films into sub-wavelength photonic structures [5]. Here, we demonstrate an integrated LN platform that consists of micro-resonators, Mach-Zehnder interferometers (MZI) and low-loss nanowaveguides, and is promising for both nonlinear wavelength conversion and electro-optic (EO) modulation applications. We experimentally demonstrate phase-matched second harmonic generation (SHG), with normalized conversion efficiencies as high as 41% $W^{-1}cm^{-2}$, as well as efficient EO modulation, with data rates up to 40 Gbps.

2. Nonlinear wavelength conversion

We present two methods to address the phase mismatch in SHG process from ~ 1550 nm to ~ 775 nm. The first method achieves modal phase matching between the fundamental TE mode at pump wavelength and the 3rd order TE mode at second harmonic wavelength in uniform LN waveguides. The second method utilizes a periodically-grooved (PGLN) structure to achieve quasi-phase matching between fundamental TE modes at both wavelengths. The waveguide width is spatially modulated with a period of Λ, which provides an additional momentum "kick" $\Delta k = 2\pi/\Lambda$, which compensates for the phase mismatch. Theoretical analysis of this method can be found in Ref. [6].

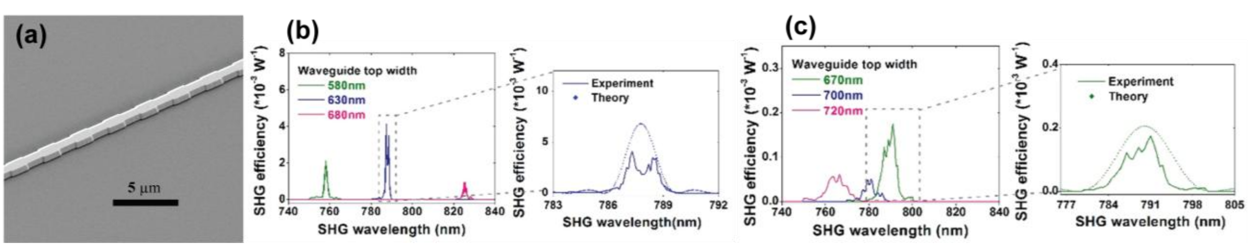

Fig. 1.(a) Representative SEM images of a fabricated PGLN waveguide before oxide cladding, with a spatial modulation period of 2.77 µm and a groove depth of 80 nm. (b-c) Measured SHG efficiencies for phase-matched LN (b) and PGLN (c) waveguides with different waveguide widths. Insets show comparisons of theoretical and experimental SHG responses.

Figure 1(a) shows the scanning electron microscope (SEM) image of a typical PGLN waveguide, fabricated using a similar process as is described in [5]. Typical propagation loss in our waveguides is 3 dB/cm. Figures 1(b-c) show the measured SHG efficiencies for both phase matched LN waveguides (1 mm long) and quasi-phase matched PGLN waveguides (0.5 mm long). For each scheme, a set of waveguides with different widths are characterized. SHG peak wavelengths shift as a function of waveguide widths in both cases, but in the opposite directions, which agrees with theoretical prediction. When normalized by waveguide lengths, the conversion efficiencies for phase matched and quasi-phase matched cases are 41% $W^{-1}cm^{-2}$ and 7.0% $W^{-1}cm^{-2}$, respectively, which are comparable to the state of the art ion-exchanged PPLN [3].

3. Electro-optic (EO) modulation

We fabricate and characterize two types of LN EO modulators: micro-racetrack resonators and MZIs. Figure 2(a) shows the fabricated micro-resonator modulator (purple) with microelectrodes (yellow). Figure 2(b) shows the corresponding transmission spectrum, with loaded quality (Q) factor ~ 50,000. The resonance wavelength shifts as a function of the applied voltage, with an EO efficiency of 7.0 pm/V [Fig. 2(b)]. For the MZI type modulators, we measure a V_π of ~ 10 V in a 2 mm long device, which translates to a voltage-length product of ~ 2V•cm (data not shown), an order of magnitude higher than bulk LN devices.

We measure an EO 3 dB bandwidth of 30 GHz for a racetrack modulator with Q=8000 [Fig. 2(c)] and 15 GHz for the 2 mm long MZI modulator [Fig. 2(d)]. For the racetrack modulator, the EO bandwidth is limited by the cavity photon lifetime, which could be further improved by engineering the optical quality factor. For the MZI, the EO bandwidth is due to the drive impedance and the device capacitance (~ 0.2 pF), which could be improved using a low-impedance drive or transmission line design. We demonstrate data transmission rate as high as 40 Gbps with our integrated LN modulators. Figure 2(e) shows non-return-to-zero open eye diagrams for both racetrack and MZI modulators at various data rates, obtained with 2^7-1 (pseudo-) random binary sequence at 5.66 V peak to peak.

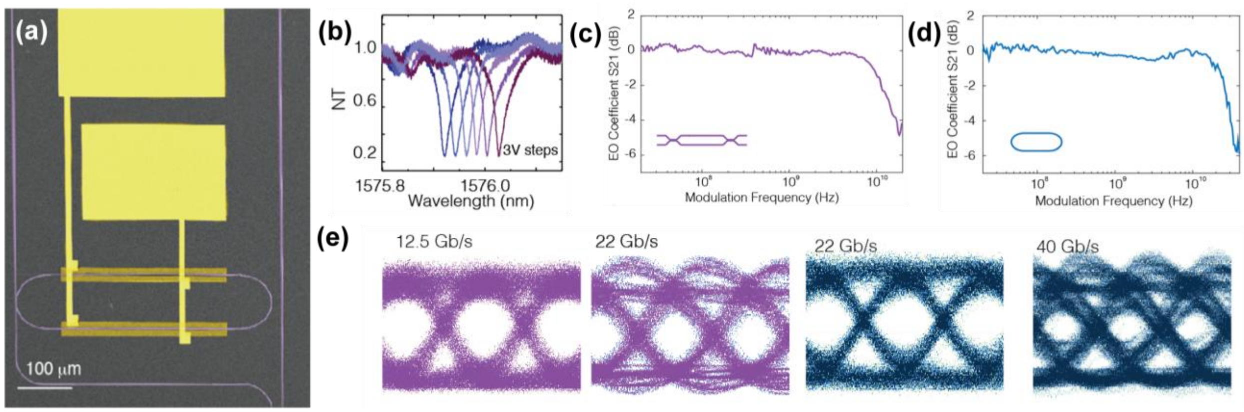

Fig. 2. (a) False-color SEM image of a micro-racetrack LN EO modulators. (b) Optical transmission spectra of a micro-racetrack modulator when a DC voltage is applied, showing an EO efficiency of 7pm/V. (c-d) EO bandwidth characterization of a 2 mm long MZI modulator (c) and a micro-racetrack modulator (d) with Q = 8000, showing 3dB EO bandwidths of 15 GHz and 30 GHz respectively. (e) Eye-diagrams for the MZI (purple) and racetrack (blue) modulator showing data rates up to 22Gbps (MZI) and 40Gbps (micro-racetrack).

4. Summary

We demonstrate the design, fabrication and experimental characterization of a nanophotonic LN platform that features high light confinement, low propagation loss and versatile device configurations. We show both efficient nonlinear wavelength conversion and high-speed EO modulators. The active micro-resonators and low loss waveguides could enable a chip-scale photonic circuit that is densely integrated with novel switches, filters and nonlinear wavelength sources and operates in a wide wavelength range (from visible to mid-IR).

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6. References

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