Lithium Niobate Nanophotonic Waveguides for Tunable Second-Harmonic Generation

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Primary CNF Tools Used: JEOL 9500 electron beam lithography, AJA ion mill

Abstract:

We report on-chip second-harmonic generation (SHG) that simultaneously achieves a large tunability and a high conversion efficiency inside a single device. We utilize the unique strong thermo-optic birefringence of LN to achieve flexible temperature tuning of type-I inter-modal phase matching. We experimentally demonstrate spectral tuning with a tuning slope of 0.84 nm/K for a telecom-band pump, and a nonlinear conversion efficiency of 4.7% W^{-1}, in a LN nanophotonic waveguide only 8 mm long.

Summary of Research:

Lithium niobate (LN) has attracted considerable attention in nonlinear optics for decades, due to its wide bandgap and large $\chi^{(2)}$ nonlinearity that support efficient second-harmonic generation (SHG), sum-/difference-frequency generation, and parametric down-conversion, which are conventionally enabled by quasi-phase matching in periodically-poled LN waveguides made from reverse proton exchange [1-3]. Recent advance in LN nonlinear photonics has shown the great advantages of the LN-on-insulator platform, which exhibits not only sub-micron mode confinement that enhances nonlinear conversion efficiencies, but also more degrees of freedom in waveguide geometry for dispersion engineering [4-8], which offer potentials for novel functionalities. Here, we demonstrate highly-efficient thermal control of phase-matched wavelengths for SHG in a LN nanophotonic waveguide, with a measured tuning slope of 0.84 nm/K for a telecom pump [9]. Our device is of great potential for on-chip wavelength conversion that produces highly-tunable coherent visible light, essential for various integrated photonic applications such as particle and chemical sensing in aqueous environments, while taking advantage of the mature telecom laser technology.

In order to effectively tune the phase-matching window of SHG, we need a controlling mechanism that is able to induce a significant relative change in effective indices at the two involved wavelengths. We take advantage of the large thermo-optic birefringence of LN, i.e.

$$\left|\frac{dn_e}{dT}\right| \gg \left|\frac{dn_o}{dT}\right|,$$

which allows us to introduce disparate index changes between two interband modes with orthogonal polarizations, by simply varying the temperature [10,11]. This effect is maximized on a Z-cut wafer, which supports high-purity polarization modes. Thus, in a Z-cut LN waveguide [see Figure 1(a)], we designed the geometry for phase matching between $TE_{0,\mathrm{tele}}$ in the telecom and $TM_{2,\mathrm{vis}}$ in the visible [see Figure 1(b)(c)]. As presented in Figure 1(d)(e), by simulation with the finite-element method (FEM) that takes temperature- and wavelength-dependent thermo-optic effects into account [10], we get a phase-matched pump wavelength λ_{PM} of around 1540 nm at T = 20°C, and it is shifted to 1574 nm at T = 70°C, with a fitted tuning slope of 0.69 nm/K [see Figure 1(f)].

To confirm our simulation results, we fabricated waveguides on a Z-cut LN-on-insulator wafer with electron-beam lithography and ion milling [6,9,11]. Scanning electron microscope (SEM) pictures [see Figure 2(a), insets] show very smooth sidewalls, indicating a low propagation loss. Then we conducted experiments for SHG, with the setup shown in Figure 2(a), where pump light from a continuous-wave tunable telecom laser is coupled into a LN waveguide via a lensed fiber, and collected together with the frequency-doubled light by a second lensed fiber; after being separated from its second-harmonic by a 780/1550 WDM, the telecom pump light is directed to an InGaAs detector for monitoring, while the generated visible light is sent to a spectrometer for detection. We employed a waveguide with a length of about 8 mm. The fiber-to-chip coupling loss is about 5 dB/facet, and the waveguide propagation loss is estimated to be 0.54 dB/cm. By scanning the laser wavelength, we could find pump wavelengths that generate second-harmonic light.

As shown in Figure 2(b), at T = 18.7°C, significant SHG is achieved by pump light around 1559 nm, with a sinc^2-like spectrum, from which we extract a peak conversion efficiency of 4.7%W^{-1}. As we increase the device temperature, λ_{PM}, the phase-matched pump wavelength that exhibits the peak conversion efficiency, is gradually shifted to longer wavelengths.

As shown in Figure 2(c), the experimentally measured $d\lambda_{PM}/dT$ is 0.84 nm/K, which agrees very well with our simulation [see Figure 1(f)]. The larger experimental value potentially results from a positive contribution by pyroelectric and thermo-expansion effects that were not considered in the simulation.

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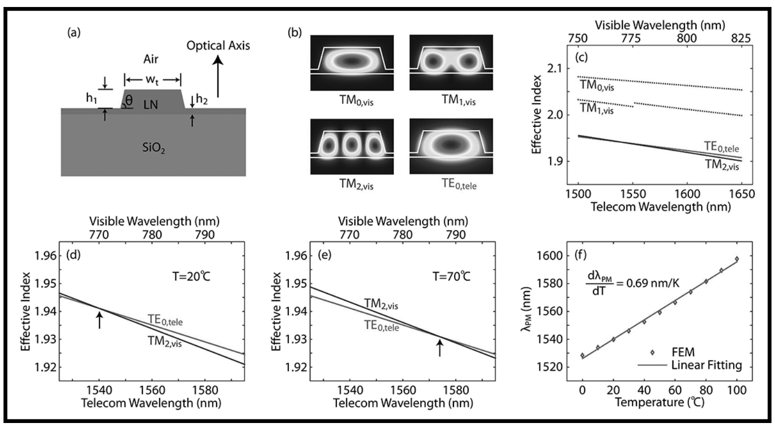

Figure 1: (a) Schematic of our Z-cut LN waveguide. FEM simulation of (b) mode profiles, and (c) effective indices as functions of wavelength, of $TE_{0,tele}$ in the telecom band and $TM_{j,vis}$ (j = 0, 1, 2) in the visible, where w_t = 1200 nm, h_1 = 460 nm, h_2 = 100 nm, and θ = 75°, at 20°C. The discontinuity in the effective index of $TM_{1,vis}$ is due to its coupling with $TE_{2,tele}$ (not shown). Zoom-in of the wavelength-dependent effective indices of $TE_{0,tele}$ and $TM_{2,vis}$ at (d) 20°C, and (d) 70°C, with black arrows indicating phase matching. (f) Simulated λ_{PM} as a function of temperature.

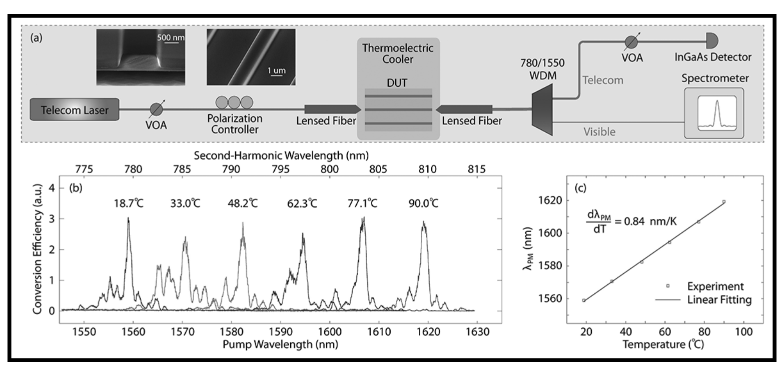

Figure 2: (a) Experimental setup. Insets are SEM pictures showing the waveguide facet and sidewall. (b) SHG spectrum at different temperature. (c) Measured λ_{PM} as a function of temperature.