Second-harmonic generation in etchless lithium niobate nanophotonic waveguides with bound states in the continuum

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Abstract: We experimentally demonstrated second-harmonic generation from telecom to near-visible wavelengths on an etchless lithium niobate platform by using a photonic bound state in the continuum for the second-harmonic mode. © 2022 The Author(s)

1. Introduction
Recently, it was proposed and demonstrated that photonic bound states in the continuum (BICs) can exist in a low-refractive-index waveguide on a high-refractive-index substrate [1, 2]. Light in such a BIC mode is confined transversely to the region of high-refractive-index substrate below the low-refractive-index waveguide and is guided longitudinally along the low-refractive-index waveguide. The destructive interference among various loss channels leads to forbidden energy dissipation in the BIC-based waveguide, resulting in theoretically zero propagation loss. Under this mechanism, low-loss waveguides and high-Q microcavities were experimentally demonstrated and photonic integrated circuits were realized without the need for etching the substrate [2].

Lithium niobate is arguably the most popular nonlinear optical material because of its large $\chi^{(2)}$ nonlinear coefficients and wide transparency window (350 nm to 5 µm). To date, nonlinear optical processes have been realized on integrated lithium niobate platforms by lithographic patterning and dry etching of the lithium niobate thin film [3, 4]. Here, we report experimental demonstration of efficient second-harmonic generation on a lithium niobate integrated platform which does not need etching of lithium niobate [5]. By fabricating a polymer waveguide with carefully chosen dimensions on a lithium-niobate-on-insulator substrate, we obtained modal phase matching between the orthogonally polarized fundamental and second-harmonic modes, both with low propagation loss, at the telecom and near-visible wavelengths respectively, where the second-harmonic mode is a TM-polarized BIC.

2. Designing BIC waveguide for second-harmonic generation

Fig. 1. (a) Cross-sectional illustration of the waveguide structure. (b), (c) Electric field (E) profiles of the TE$_{00}$ mode at pump wavelength (b) and the TM$_{00}$ mode at second-harmonic wavelength (c). (d) Propagation loss of the TM$_{00}$ mode as a function of the waveguide width $w$ and wavelength $\lambda$. (e) Required waveguide width $w$ for achieving the BIC (green dash-dotted line) and phase-matching (purple solid line) conditions. (f), (g) Simulated propagation loss and effective refractive index of the TE$_{00}$ mode and TM$_{00}$ mode at the respective wavelengths as a function of the waveguide width $w$, with the waveguide thickness of $t = 600$ nm (f) and $t = 450$ nm (g). (h) Optical microscope image of an entire fabricated device consisting of a 5-mm-long nonlinear waveguide, grating couplers, and directional couplers. (i) Optical microscope image of a fabricated control device for loss calibration consisting of only grating couplers and directional couplers. (j), (k) False-color scanning electron microscope images of a grating coupler for the second-harmonic light and a part of the directional coupler (k).
Figure 1a illustrates the cross-sectional structure of the device for second-harmonic generation. Figures 1b and 1c depict the electric field (E) profiles of the TE$_{00}$ mode at the pump wavelength $\lambda_{\text{pump}} = 1559.4$ nm and of the TM$_{20}$ mode at the second-harmonic wavelength $\lambda_{\text{SH}} = 779.7$ nm, respectively, simulated with a finite-element method. It is important to obtain low propagation loss in both the TE$_{00}$ and TM$_{20}$ modes to achieve high efficiency for the second-harmonic generation. Figure 1d shows the simulated propagation loss of the TM$_{20}$ mode in a straight waveguide as a function of the waveguide width $w$ and wavelength $\lambda$, with the waveguide thickness $t$ fixed at 600 nm. The BIC point is where the TM$_{20}$ mode has zero propagation loss, and the phase-matching point is where the effective refractive indices of the two modes are equal. Figure 1e plots the required waveguide widths for achieving the BIC and phase-matching conditions as a function of the waveguide thickness $t$. The BIC and phase-matching condition can be achieved simultaneously in a waveguide with $w = 2.48$ $\mu$m and $t = 600$ nm.

3. Device fabrication and characterization

Figure 1f shows an entire fabricated device consisting of a long main waveguide for second-harmonic generation, grating couplers for coupling light between the on-chip waveguides and optical fibers (Fig. 1j), and directional couplers (Fig. 1k). Two pairs of grating couplers are used for input/output coupling of light at the fundamental and second-harmonic wavelengths separately. Figure 1i shows a fabricated control device for loss calibration consisting of only grating couplers and directional couplers.

Figure 2a shows the measured normalized spectrum of second-harmonic conversion efficiency from a fabricated device. The maximal on-chip second-harmonic conversion efficiency measured at the BIC point is 0.175% W$^{-1}$ cm$^{-2}$, which agrees well with the theoretical value (0.20% W$^{-1}$ cm$^{-2}$) when taking into consideration the measured propagation loss of the waveguide at both fundamental and second-harmonic wavelengths. Figure 2b plots the peak second-harmonic power as a function of the pump power coupled into the on-chip waveguides, which shows an approximately quadratic power dependence of the second-harmonic power on the input pump power. Figure 2c shows the measured normalized second-harmonic conversion efficiency of the waveguides as a function of the waveguide width $w$. It is clear that the maximum is reached for the waveguides with the optimal waveguide width $w = 2.48$ $\mu$m at the BIC point. As the device structures deviate from the optimal design for the BIC, the second-harmonic generation efficiency drops dramatically.

![Fig. 2. (a) Measured (orange circles) and theoretical (blue line) normalized spectra of second-harmonic conversion efficiency of a fabricated device. (b) Measured (orange dots) and fitted (blue line) second-harmonic power as a function of the pump power in the device. (c) Measured second-harmonic conversion efficiency as a function of the waveguide width $w$.](image)

Acknowledgment

This work was supported by the Research Grants Council of Hong Kong (No. 14208717, 14206318, 14209519).

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