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Proposal and analysis of a hybrid silicon photonic-lithium niobate waveguide for difference frequency generation

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ABSTRACT

Integrated optics devices for nonlinear optics may be made by using unpatterned thin films of a nonlinear crystal such as lithium niobate in conjunction with (for example, bonded to) an easily-patterned material such as silicon or silicon nitride which is commonly used in a silicon photonics platform. We propose and analyze a device for difference-frequency generation in a hybrid waveguide which uses the strongest nonlinear tensor coefficient without ion-exchanging, etching, or periodically-poling lithium niobate, which can considerably simplify the fabrication process.

1. Introduction

The conventional fabrication techniques of periodically-poled crystals for nonlinear optics [1] are quite different from the fabrication methods used to make modern micro-electronics integrated circuits and silicon photonics. Based on this observation, the intention of this paper is to describe a hybrid silicon photonics waveguide for optical wavelength conversion. Here, we propose and study a simple way of incorporating the nonlinearity of lithium niobate (LN), the workhorse material for nonlinear optics, and similar materials in a silicon photonics device, without periodically poling or etching the crystal, and relying only on bonding [2].

As shown in Fig. 1, our proposed waveguide consists of an unpatterned thin film of LN bonded (or otherwise placed in proximity to) to a thin film of a dielectric material (e.g., silicon nitride, SiN), semiconductor (e.g., crystalline or amorphous silicon, Si) or polymer [3–8]. This second film is patterned before bonding to create a rib-loaded waveguide in the transverse cross-section, and a periodic pattern along the direction of propagation. This is a standard lithography procedure in silicon photonics. Thin-film LN on low-refractive-index handle (e.g., SiO_2) is available commercially (e.g., NanoLN or SRICO, Inc.). It may be simply left as an unpatterned slab. The optical mode is thus a hybrid one, partially distributed in the LN slab, and partially in the second material.

The main advantages of this new device arise from taking advantage of modern CMOS-compatible silicon photonics fabrication methods to simplify the processing of LN:

1. This geometry allows us to use the lowest-order (quasi)-TE polarization modes in each of the waves, which is preferred for planar integrated optics, and the highest-magnitude nonlinear coefficient (d_{33}) of LN in the convenient *x*-cut orientation. In contrast, challenges with periodically poling x-cut LN have usually led researchers to require z-cut LN, thus forcing the use of TM-polarized waves, which are not the lowest-order modes in silicon photonic waveguides, and suffer from higher propagation and bending losses [9].
2. The LN film is not etched; instead, a transverse mode is defined by the rib of the second material, made of Si, SiN, or some material, which is easier to pattern, and in which high-quality and complex waveguiding structures have already been shown [9,10]. In contrast, conventional approaches have attempted etching, ion-milling or sawing LN, which can increase the propagation loss or impact the nonlinear coefficient [11,12].
3. LN does not have to be periodically poled. As an alternative to the conventional technique of periodic poling, one may use the technique of “balanced phase matching” (BPM) whereby the second of each pair of segments along the direction of propagation of the hybrid mode is used to periodically compensate for the phase mismatch incurred in nonlinear interactions in the first segment [1,13,14]. Although periodic poling will, in

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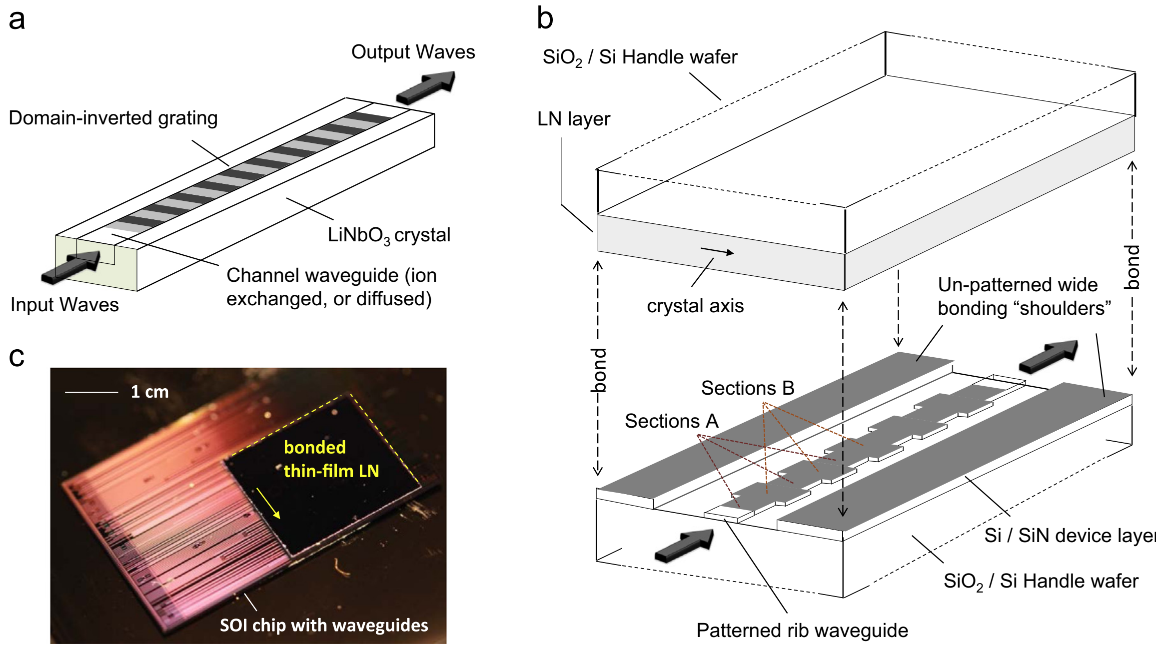

Fig. 1. (a) Conventional devices rely on creating a waveguide in lithium niobate (LN) e.g., by annealed proton exchange or ion diffusion, and then fabricating a domain-reversed grating by poling for quasi-phase-matching. (b) The proposed hybrid waveguide does not require any patterning or periodic poling of LN; instead, transverse confinement and axial phase matching is defined by a lithographically-patterned rib of a bonded material such as SiN or Si. (c) An example of our recent work in room-temperature bonding of a thin-film LN (300 nm x-cut orientation, on SiO_2/Si handle) chip to a patterned silicon photonic chip (150 nm Si layer, 2 μm SiO_2, Si handle).

general, result in a higher conversion efficiency, the simple approach for implementing BPM in this hybrid silicon photonics platform may be attractive for many cost-sensitive applications.

2. Nonlinear optics: difference frequency generation

Some crystals such as LN have a strong second-order optical nonlinearity based on the $\chi^{(2)}$ tensor, and are widely used for optical wavelength conversion, in which one or more optical waves (or spectral components of a pulse or a frequency comb) mix and generate new spectral tones at the sum and/or difference frequencies [1]. This process is governed by the principles of energy conservation and phase-matching.

Focusing here on the case of difference frequency generation (DFG) in order to be specific, if we label the input optical radial frequencies as ω_2 and ω_3 (assuming $\omega_3 < \omega_2$), then the newly generated frequency is at $\omega_1 = \omega_2 - \omega_3$, and it is required that the wave vectors satisfy the phase-matching relationship $\mathbf{k}(\omega_2) - \mathbf{k}(\omega_3) - \mathbf{k}(\omega_1) = 0$. The most convenient technique of phase-matching requires “assisting” the wave vector sum by some induced technique, e.g., using lithography and poling to periodically reverse the sign of the nonlinear coefficient along the waveguide [see Fig. 1(a)], which is known as quasi-phase matching (QPM) [15].

2.1. Formulation

To study the device in detail, we write the nonlinear Helmholtz equation for the field evolution of a field $\mathbf{E}_1$ generated by DFG from undepleted pump fields $\mathbf{E}_2$ and $\mathbf{E}_3$,

$$\nabla^2(\mathbf{E}_1)_i + \frac{\omega_1^2}{c^2}\epsilon_{\rm rel}(\mathbf{r})(\mathbf{E}_1)_i + \frac{\omega_1^2}{c^2\epsilon_0}2\epsilon_0\chi_{ijk}^{(2)}(\mathbf{E}_2)_j(\mathbf{E}_3^*)_k = 0 \tag{1}$$

where $\epsilon_{\rm rel}(\mathbf{r})$ describes the pattern in the (relative) dielectric permittivity shown in Fig. 1, and the subscripts in $\chi_{ijk}^{(2)}$ and the fields describe which tensor coefficient is involved, based on the ‘i’, ‘j’ and ‘k’ polarizations of $\mathbf{E}_1$, $\mathbf{E}_2$ and $\mathbf{E}_3$, respectively.

Based on the dielectric distribution shown in Fig. 1(b), we assume a solution of the form

$$\mathbf{E}_1 = \begin{cases} A_1(z)\mathbf{E}_1^A(\mathbf{r}_\perp)\exp(i\beta_1^A z) + \text{c. c.}, \\ \quad \text{for } 0 < z - m\Lambda \le \Lambda^A \\ B_1(z)\mathbf{E}_1^B(\mathbf{r}_\perp)\exp(i\beta_1^B z) + \text{c. c.}, \\ \quad \text{for } \Lambda^A < z - m\Lambda \le \Lambda^A + \Lambda^B \end{cases} \tag{2}$$

where $\Lambda = \Lambda^A + \Lambda^B$ is the periodicity, and m is an integer. Here, we are describing devices in which $\Lambda^{A,B}$ are far from Bragg resonance, and strong coupling to counter-propagating modes can be ignored. The amplitude coefficients A_1 and B_1 are linked by field continuity conditions at the interfaces between the segments. We have assumed a normalization in which the optical power of the field is defined in terms of the amplitude by the relationship $P = 2n\epsilon_0 c|A|^2$, with n the mode effective index.

Substituting Eq. (2) in Eq. (1), and under the usual slowly-varying envelope approximation, we get

$$\frac{dA_1}{dz} = +i\frac{2\omega_1^2}{c^2\beta_1^A}A_2A_3^*\overbrace{\int d\mathbf{r}_\perp\frac{1}{2}\chi_{ijk}^{(2)}(\mathbf{E}_1^A)_i(\mathbf{E}_2^A)_j(\mathbf{E}_3^A)_k}^{\Gamma_{ijk}^A} \times \exp[i\underbrace{(\beta_2^A - \beta_3^A - \beta_1^A)}_{\Delta\beta^A}z] \tag{3}$$

and a similar equation for segment B, obtained by substituting the letter ‘A’ by ‘B’ everywhere in Eq. (3). The second-order nonlinear coefficient (Γ) and phase-mismatch ($\Delta\beta$) are defined as indicated, and may take different values in segments A and B.

In the following discussion, we choose the fields to be TE-polarized waveguide modes polarized along the crystal axis [see Fig. 1(b)] so that we may use the (Kleinman contracted notation) Γ_{33} coefficient which is the largest-magnitude second-order nonlinear tensor coefficient in LN. In this case, $\Delta\beta$ is not zero and the governing equations are