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Semi-analytical analysis of lithium niobate photonic wires

Pranabendu Ganguly *

Advanced Technology Development Centre, Indian Institute of Technology, Kharagpur 721302, India

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ABSTRACT

Lithium niobate ($LiNbO_3$) photonic wires are of growing interest in the field of nonlinear optics and to fabricate micro-ring resonators. In this paper the design and analysis of $LiNbO_3$ photonic wires by a semi-analytical technique is presented. The two-dimensional refractive index profile of the waveguide is transformed into lateral one-dimensional equivalent-index profile by the effective-index method. A transfer matrix method is then applied to this lateral equivalent-index profile of the waveguide to determine the propagation constants and electric-field distributions of the guided modes. Single mode photonic wires at 1.31 μm transmitting wavelength are designed for both TE and TM polarizations and finally, the matrix method is employed along with the conformal mapping technique to determine the bending loss of the curved photonic wires for different radii of curvature. The process needs less computation power, both in terms of elapsed time and memory, and can also be applicable to other photonic materials.

1. Introduction

Lithium niobate ($LiNbO_3$) possesses excellent electro-optic, nonlinear-optic, piezoelectric and acousto-optic properties and has been used in versatile photonic applications. Conventionally, a waveguide in $LiNbO_3$ crystal is fabricated using metal diffusion, ion exchange, or proton exchange methods [1–4]. A very small index change (10^{-3}–10^{-2}) in the crystal is induced using these methods for waveguide fabrication. Hence light confinement within these waveguides is weak and the mode size is large. Since the nonlinear wave mixing efficiency is directly proportional to the light intensity in the waveguide, smaller mode size will result in more efficient devices [5]. Moreover due to the small index contrast, bending waveguides with a radius of curvature less than a few mm are not possible since the light will leak out during bending [6].

Strongly confined $LiNbO_3$ photonic wire waveguides with high refractive index contrast are of growing interest during the last few years [7–9]. Their ultra-small waveguide cross-sections and low bending loss will enable ultra-compact optical integrated circuits and devices in $LiNbO_3$. Using crystal-ion-slicing and wafer bonding, submicron films of $LiNbO_3$ are transferred to a lithium niobate substrate with silicon dioxide as a cladding layer. It was demonstrated that the transferred layers have bulk crystalline quality and have identical optical and electro-optical properties to those of $LiNbO_3$ single crystals. This 'Lithium-Niobate-On-Insulator' (LNOI) platform is used to fabricate $LiNbO_3$ photonic wires of submicron dimensions [10]. These have already been used successfully for second harmonic generation by the periodic poling technique [11]. For most applications, single-mode waveguides at the desired wavelengths are essential in order to achieve optimized device performance and hence theoretical design of single-mode photonic wires with specific height and width of the $LiNbO_3$ core layer is important.

In this paper, we focus on the design and analysis of $LiNbO_3$ photonic wires by a semi-analytical technique. The two-dimensional (2D) refractive index profile of the waveguide is transformed to lateral one-dimensional (1D) equivalent-index profile by the effective-index method [12,13]. A transfer matrix method [14], which involves multiplication of 2×2 transfer matrices of the layers, is then applied to this lateral equivalent-index profile of the waveguide to determine the propagation constants and electric-field profiles of the guided modes. Single mode photonic wires at 1.31 μm transmitting wavelength are designed for both TE and TM modes of the waveguide. Finally, the matrix method is employed along with the conformal mapping technique [15,16] to determine the bending loss of the bent photonic wires at different radii of curvature. As expected, these bent waveguides exhibit low bending losses even for small bending radii on the order of 10 μm.

2. Theoretical approach

The diagram of a $LiNbO_3$ photonic wire is presented in Fig. 1. The optical and geometrical parameters of the waveguide are as

* Tel.: +91 3222 281936; fax: +91 3222 255303.
E-mail addresses: pranabendu.gangopadhyay@rediffmail.com, pran@ece.iitkgp.ernet.in

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follows: refractive indices of the waveguide core ($LiNbO_3$) n_1, of the SiO_2 n_b and of the cover (air) n_c, as well as the thickness of the photonic wire core h and its width w_1. The SiO_2 film is considered to be sufficiently thick ($\sim$1.5 μm) so that there is no substrate mode during waveguide excitation.

The analysis of the photonic wire waveguide is carried out in two steps: initially, for the vertical refractive index profile, we have used the effective index method [13,17] and in the second step, the matrix method [14,18] is applied to the effective lateral index profile. Among the many numerical and approximate methods, the effective index method is probably the most widely used technique for the analysis of dielectric waveguides of rectangular shapes. It provides a simple way to convert a two-dimensional waveguide problem into a one-dimensional problem. The diagram of the effective index method is illustrated in Fig. 2. We analyze the asymmetric waveguide of refractive index profile $n(z)$ (Fig. 2b) corresponding to the depth profile of the photonic wire. The determined effective refractive index n_{eff} is used for the construction of the equivalent slab waveguide (Fig. 2c). The dispersion equation of the uniform asymmetric slab waveguide of refractive index profile $n(z)$ can be obtained as [17]

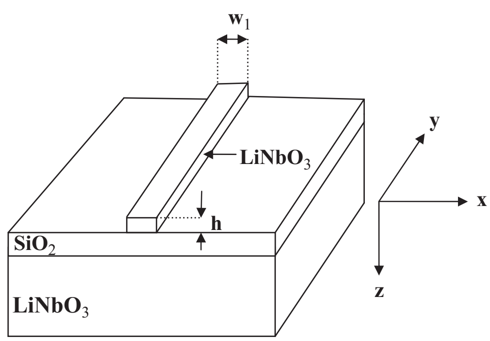

Fig. 1. Schematic structure of a photonic wire.

$$K_o h\sqrt{n_1^2-n_{eff,m}^2} = m\pi + \sum_{x=b,c} \tan^{-1}\left[\left(\frac{n_1}{n_x}\right)^{2\rho}\sqrt{\frac{n_{eff,m}^2-n_x^2}{n_1^2-n_{eff,m}^2}}\right] \tag{1}$$

Where $\rho=0$ for the transverse electric (TE) polarization and $\rho=1$ for the transverse magnetic (TM) polarization, $n_{eff,m}$ is the effective index of the mode with the mode number m (= 0, 1, 2,…), and K_o ($=2\pi/\lambda$) is the free space wave number. Eq. (1) leads to a set of discrete angles of propagation corresponding to

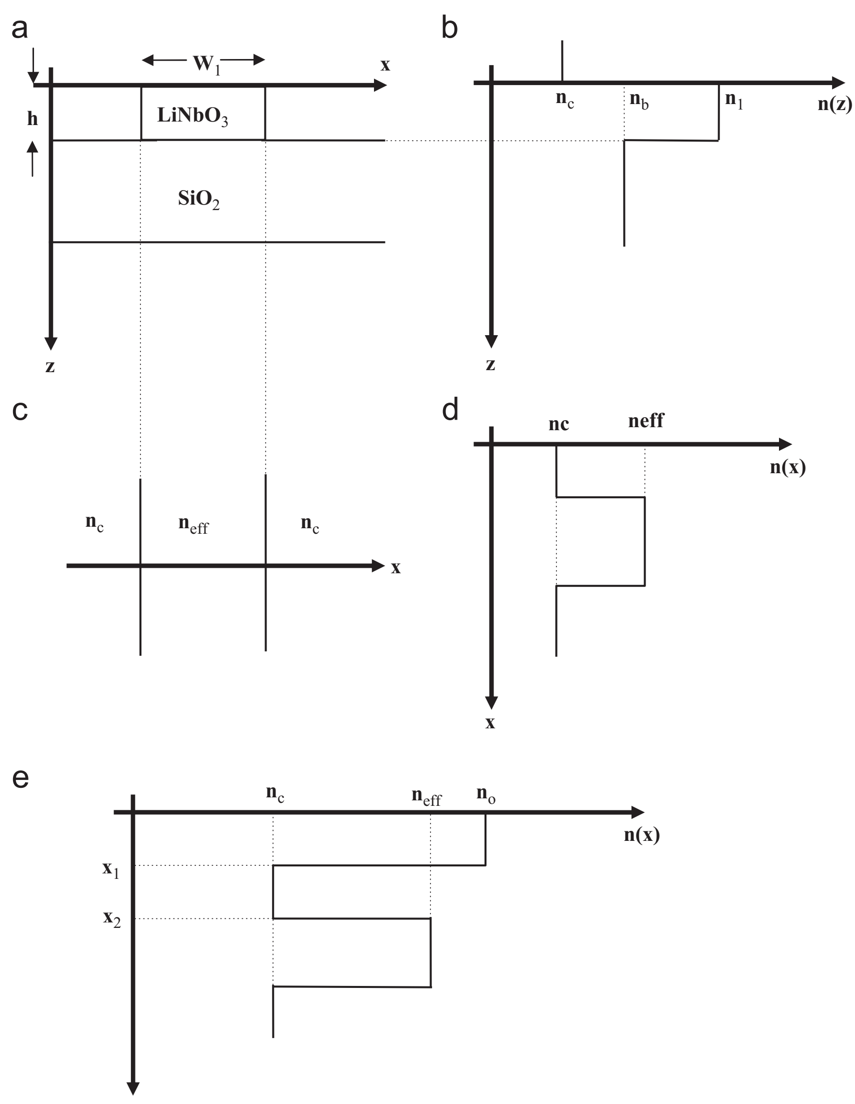

Fig. 2. Description of the theoretical method. (a) the original wire waveguide, (b) the depth refractive index profile of the waveguide, (c) the effective slab waveguide, (d) lateral effective index profile of the waveguide, and (e) the prism coupling method.