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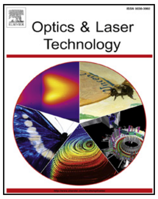

Full length article

Evaluation of low index contrast in lithium niobate waveguides at telecom wavelengths

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HIGHLIGHTS

- Index contrast evaluation in lithium niobate waveguides at telecom wavelengths.
- Index profile reconstruction of planar waveguides.
- Fundamental mode analysis of channel waveguides.
- Dependence of index contrast on the wavelength.

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ABSTRACT

For a wide range of applications in modern photonics, the low index contrast lithium niobate waveguides still offer the most established solutions to integrate a number of functions on a single optical chip. These waveguides are mostly single-mode at telecom wavelengths and knowing their index contrast (IC) in this spectral range is not straightforward. Unfortunately, the single mode behavior of the propagation at telecom wavelength makes impossible to use the M-lines technique which allows retrieving the IC only if the waveguide is multi-mode. Here, we propose and test a new hybrid (experimental and numerical) method to determine the IC at 1310 nm and 1550 nm for typical low-IC lithium niobate waveguides by fitting the experimental in-depth optical mode profiles with the Finite Element Method simulated ones. Then, by using different versions of Sellmeier equation, we reconstruct the dependence of IC on the wavelength in VIS and near-infrared (NIR) range. This hybrid method can be of use in the analysis of any surface graded-index waveguides fabricated in low-IC range.

1. Introduction

Low-IC lithium niobate (LN) waveguides, fabricated with precise control and reproducibility are of high interest for nonlinear and/or electro-optical highly efficient and compact devices for a wide range of applications in modern photonics, including quasi-phase-matched frequency convertors, multi-path Mach-Zehnder interferometers, light amplification, lattice filters, optical switches and modulators, wavelength selectors, array waveguide grating and also for many other all-optical signals processing. Performances in term of propagation losses, polarization sensitivity, thermal stability, the electro-optical and nonlinear efficiency and ultimately the maturity of fabrication techniques, namely the Ti-indiffusion [1,2] and Proton Exchange (PE) techniques [3–11], mean that the integrated optics using LN waveguides are still superior to many other photonic platform. The efficiency of nonlinear interactions critically depends on different conditions and parameters. For this reason, the uncertainties in the wavelength dependences of IC in waveguides, could lead to deviations from the theoretical prediction and thus to drastically reduce the experimental efficiencies of the devices. But, designing and fabricating a waveguiding structure with a precise control of IC is not straightforward because of some parameters that are still difficult to control. As an example, the residual water amount in the acidic bath during the PE process plays a crucial role in the enhancement of the refractive index with respect to the bulk. We recently proposed the High Vacuum Proton Exchange (HiVacPE) method for improving the waveguides fabrication reproducibility by reducing, as much as possible, the residual water amount in the acidic bath in a high-vacuum configuration [11]. Even so, for single-mode waveguide structures at telecom wavelengths, the low-IC remains experimentally inaccessible by using well-known M-lines characterization technique which requires a multimodal propagation in order to obtain reliable values of IC [12]. Values reported in literature for low-IC LN

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waveguides are given for wavelength between 400 nm and 1100 nm for waveguides fabricated by Annealed Proton Exchange (APE) [13] and between 405 nm and 1319 nm for waveguides fabricated by Soft Proton Exchange (SPE) [14], but for multimode propagating behavior.

In this paper we propose and test a new hybrid method (mixing of experimental and numerical methods) to evaluate the IC at the telecom wavelengths (namely 1310 nm and 1550 nm) for waveguides fabricated in low-IC range. We achieve this goal by following the steps below: (*i*) one determines the in-depth waists of the experimental fundamental optical modes profile recorded at the output of channel waveguides with different widths; (*ii*) for different width values and by using the IC as parameter, one simulates by Finite Element Method the fundamental mode of the channel waveguides, (*iii*) one finds the IC values for which the simulated waists of the optical modes match as good as possible the experimental measured waists. In the last section of the paper, we reconstruct the dependence of IC on the wavelength in VIS and NIR by fitting the IC values with several Sellmeier type equations.

2. Waveguides fabrication

The waveguides investigated in our study were fabricated by recently proposed High Vacuum Proton Exchange (HiVacPE) technique [11]. The exchange process was performed in a hermetically sealed hourglass tube. Prior to be sealed, the bottom part of the tube was filled with a powder mixture composed of Benzoic Acid (BA) and Lithium Benzoate (LB) as proton source. The concentration of 2.7% LB in the melt, allowing to obtain low-IC LN waveguides, is measured by $\rho_{LB} = 100 \times [m_{LB}/(m_{LB} + m_{BA})]$ where m_{LB}, and m_{BA} are the mass of LB and BA in the powder mixture. The sample to be processed is placed in the top part of the tube. Then the tube is pumped down to a pressure as low as $p = 3.5 \times 10^{-5}$ mbar by using a turbo pumping station (HiCube 80 Eco - Pfeiffer). This very low pressure is the key point of the HiVacPE technique that allows diminishing as much as possible the residual water adsorbed by the internal surface of the glass tube and mainly the large amount absorbed by powders. After the glass tube is sealed, it is placed into a metallic tube container ensuring a uniform heating and an easy and safe manipulation. Placed in a pre-heated oven (300 °C), the metallic tube is turned upside down after 30 min when both the melted proton source and the sample have reached the exchange temperature. Thus, the sample is dipped into the melt and the proton exchange starts. At the end of the exchange period ($t = 72$ h), the tube is turned upside down again and allowed to cool down. When it reaches the room temperature, breaking the sealed-end allows getting out the sample. The samples fabrication by HiVacPE process does not suppose any annealing or heat treatment after the proton exchange process itself.

Using this protocol, channel waveguides were fabricated by using SiO_2 masks with openings of different width (4, 5, 6, 7 and 8 μm). Using standard UV photolithography, Ion Assisted Deposition (IAD) of SiO_2 layer and a lift-off process, the masks were fabricated on the surface of Z-cut LN samples (supporting only TM modes), diced from wafers supplied by Gooch & Housego. Besides a set of channel waveguides, the so prepared samples have the advantage to present on the opposite surface, a planar waveguide exhibiting the (quasi) same IC and hence offering, by M-lines characterizations, reliable and useful information. To allow characterizing the channel waveguides, the input and the output edges of the samples were polished with high quality.

It is worth to note that the channel waveguides fabricating along X-axis are sufficiently thin and then supporting optical modes with one lobe only in-depth (Z-axis) and few lobs in lateral direction (Y-axis) at 1310 nm and 1550 nm depending on the waveguide width. The 4 μm width waveguides are single-mode (TM_{00}), but the larger waveguides are not, they supporting besides the fundamental TM_{00} the first-order superior mode namely TM_{01}. So, in practice, it is likely that experimental output maps have a small contribution from the first-order superior TM mode (i.e. the one with two lobes in lateral direction). That is why we focused on the characterization of the in-depth optical profile at y = 0 (waveguide center) where the eventual undesired contribution of the first-order superior mode is irrelevant. It is worth to note that depending on the openings in the SiO_2 mask, some of the channel waveguides may exhibit smaller depths than the planar waveguide or/and edge effects, as through narrow opening, the lateral diffusion is no longer negligible.

3. Experimental characterization of the waveguides

3.1. Index profile reconstruction by M-lines measurements on planar waveguides

In order to obtain the surface index, and hence the IC of the waveguide, one has to reconstruct the spatial index profile of the planar waveguide by using M-lines technique [12]. To do so, the waveguide must be multi-mode, as the reconstruction means in fact the sampling of the spatial profile in several points (i.e. the guided modes). That is why one uses a M-lines set-up made of two rutile (TiO_2) prisms for in-coupling and out-coupling of a laser beam in visible spectral range at 632.8 nm, 611.8 nm, 593.9 nm and 543.3 nm respectively. At the output of the out-coupling prism, bright lines are observed and for each one the angle with the normal to the prism output surface is measured with an autocollimator. This angle characterizes the propagation constant of the guided mode and thus we can determine the effective index N_{eff} of each guided mode. With the full-set of N_{eff} of a given waveguide, one can reconstruct its index profile using the iWKB numerical method described in [15]. Also, this method allows us to determine the surface index, and hence, the IC as the difference Δn_e between the surface index and the bulk extraordinary index of the substrate ($n_e = 2.2025$ for Gooch & Housego virgin substrate at room temperature). In Fig. 1 we present extraordinary index profile for a 4-modes planar waveguide at λ = 632.8 nm. The depth associated to each mode and the surface index (depth = 0) are reconstructed by the iWKB method. At this wavelength we find IC = 0.022. For fitting of the experimental index profile points several analytical functions can be used, depending on the steepness of the profile, but as we shown in our previously work [11] there is one that fits very well almost all kind of profiles. It is the combination of two generalized exponential functions, expressed as:

$$n(z) = n_e + A_1 \exp(-(z/w_1)^{e_1}) + A_2 \exp(-(z/w_2)^{e_2}) \tag{1}$$

where n_e is the extraordinary refractive index of bulk LN, A_i is the amplitude, w_i is the width at 1/e of the maximum and e_i is its decaying factor.

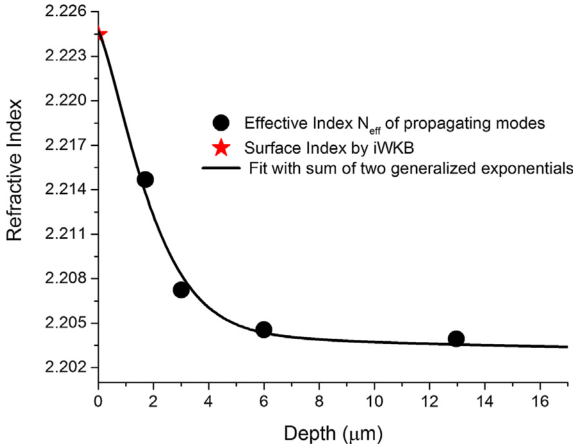

Fig. 1. Extraordinary index profile at λ = 632.8 nm reconstructed by iWKB for planar waveguides fabricated in Z-cut LN. The symbols represent the measured N_{eff} of the propagating modes, except that on the ordinate (star symbol) that represents the surface index calculated by iWKB. The solid line is the fit with sum of two generalized exponential functions.