Electro-optic phase modulators utilizing different phases in proton-exchanged $LiNbO_3$- waveguides

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Abstract— ***Electro-optic coefficients of annealed proton-exchanged $LiNbO_3$ waveguides containing different phases were determined. Electro-optic phase modulators, exhibiting improved electro-optic efficiency and low optical losses have been fabricated.***

Keywords - lithium niobate; waveguides; modulators; electro-optics

I. INTRODUCTION

Optical channel waveguides in lithium niobate are a very useful technique for building a variety of integrated optical components such as modulators, splitters and switches. In many of these applications, a low-loss waveguide is essential to achieve a desired device performance. For example, the key element of fiber optical gyroscope (FOG) is the multi-function integrated optics chip (MIOC), that consists the two phase modulators and represents an active necessary part of the Sagnac interferometer [1]. Annealed proton exchange (APE) is now an established technique for fabricating integrated optical devices in $LiNbO_3$ and offers possibility of obtaining low-loss waveguiding material with a good electro-optical performance [2-4]. Even though the APE technique is quite simple technologically, the resulting waveguides exhibit complex structural contents. Our recent research has identified seven different crystallographic phases $H_xLi_{1-x}NbO_3$ (proton exchanged $LiNbO_3$) [5]. However, it was recently reported [1,3,4], that APE process reduces the electro-optical coefficients and provides some marked level of propagation loss related mainly to the guide mode leakage. In this paper, we report characterization of propagation losses and electro-optic efficiency for integrated-optical phase modulators fabricated by APE technique in $LiNbO_3$, since the fabrication conditions, allowing appropriate reduction of propagation losses and recovering electro-optic efficiency, were subjected to our detailed experimental search.

II. FABRICATION AND CHARACTERIZATION TECHNIQUES

A series of power dividers utilizing the different geometries of Y-branching and straight channel guides were delineated in X-cut $LiNbO_3$ substrates, using standard photolithographic technique. The channel width W of waveguides forming an Y-branching was varied in the range from 5.6 to 6.2 μm, where formation of a low-loss single mode channel waveguide, operating within a wavelength region from 1500 to 1580 nm, is expected [2]. To fabricate these waveguide structures with the aid of the annealed proton-exchanged (APE) technique, the substrates were proton exchanged at 175 °C for 60÷90 min in pure benzoic acid and annealed at 360 °C for 6÷8.5 hours. To fabricate the electro-optic phase modulators, the Au-electrodes are deposited around the both straight channels in the after branching section of Y-splitter with an electrode gap G = 10 – 16 μm, that is much larger than the optical mode size (~ 5.5 – 7.0 μm).

Fibre pigtailing was performed with an UV-curing adhesive for two interconnections between channel waveguides and fibre coupling chips at both input and output optical ports. The fiber used in the coupling chips was a standard 5.8-μm-core-diameter, 80 μm-outer-diameter product manufactured by RPC Optolink Ltd. Each pigtailing chips consists of a small piece of lithium niobate, having crystollagraphic orientation same with integrated-optical chip, with a narrow groove for optical fiber mounted inside with the aid of the UV-curried adhesive. Fiber pigtails of coupling chips were spliced with two fibers of an optical fiber cable transmitting cw radiation from 1550-nm laser diode to MIOC and modulated optical signal from MIOC to photodiode.

III. EXPERIMENTAL RESULTS AND DISCUSSION

To study electro-optical efficiency of the phase modulators fabricated at the different technological conditions, we have measured a half wave voltage V_π. In our case of X-cut, Y-propagating geometry of single-mode APE $LiNbO_3$ waveguides V_π is inversely proportional to effective value of electro-optic coefficient r_{33} [3,4]. Thus, if the overlap factor F is known, V_π can be evaluated from a value of r_{33} for actual phase composition, $H_xLi_{1-x}NbO_3$, of waveguide:

$$V_\pi = (\lambda G/n^3_e r_{33} LF) \qquad (1)$$

where L is interaction length, i.e. length of electrodes in each arm, λ - wavelength of guided light, what was 1534 nm in our experiments, n_e -effective refractive index for TE_0 mode. The overlap factor F depends on the applied field and mode intensity profiles. The main uncertainty in F is due to random variation of mode profile, as the uncertainty of applied field profile can be eliminated entirely by choosing an electrode configuration, which produces an uniform electric field within the waveguides.

It has been found that the highest electro-optic efficiency and, hence, largest value of $r_{33} = 30.2$ pm/V are observed with modulators utilizing the lowest strained α-phase waveguide. The modulators with higher strained α-phase waveguides show significantly smaller values of r_{33} in the range of 22.5 to 24.3 pm/V, when strain $\varepsilon_{33} \geq 0.8*10^{-3}$ [5]. However, these values are rather interesting for practical application due to good mode confinement in the highly strained α-phase waveguides, that in contrast to the poor mode confinement in the less strained α-phase waveguides. This point is principal at fabrication of the real devices via fiber pigtailing. Application of the longer annealing (for 7.5 – 8.0 hours) has allowed to increase the effective values of electro-optic coefficient r_{33} in the highly strained α-phase waveguides up to 26.4 – 27.2 pm/V. After this annealing, the modulators keep a rather good mode confinement at satisfactory matching with a standard PM-fiber, providing low insertion losses ~2.4 dB, and have improved electro-optical efficiency with $V_\pi = 1.7 \div 1.8$ V for a MIOC, that utilizes two phase modulators in push-pull operation mode.

IV. OPTIMIZATION OF FABRICATION PROCESS WITH AID OF OPTICAL SPECTROSCOPY DATA

The optical absorption spectroscopy data in visible and near UV ranges were used to evaluate the electro-optical properties of proton-exchanged waveguides in $LiNbO_3$ crystals, as the shift of fundamental absorption edge has been related to the changes of spontaneous polarization P and electro-optical coefficients r_{33} [6]. Interestingly, the electro-optic coefficients estimated from optical spectra for the α, κ and β_i phases are larger than those measured by direct method. The difference may be attributed to the effect of screening (averaging over multiple crystalline phases) in strongly nonuniform layers, which reduces the “effective” value of r_{33} of the low-stress phases, as determined by direct measurements.

The phase composition of the novel waveguide structures formed with APE has been determined by Raman spectroscopy data. Raman spectroscopy study was performed with the aid of a Renishaw Ramascope spectrometer operating at the 632.8 nm and 785 nm excitation wavelengths. In the setup, a linearly polarized laser beam was focused, using a 50× objective, to approximately a 2 μm spot on the optical-grade polished endface of a waveguide under study.

The optimal fabrication conditions for obtaining homogeneous waveguiding layers via the APE techniques can be identified, using this method. It is important to note that even though different-phase waveguides prepared by APE technique have similar refractive indices and strains, there is likely to be a principal difference in some properties (including electro-optic ones [1,5,6]) of these waveguides as formed by this technique at the different fabrication conditions. Indeed, it was reported recently [5] that the dispersion of extraordinary refractive-index increment in the higher strained α-phase and β-phase waveguides formed by APE method was higher compared to that in the low-strained α-phase waveguides. Given these advantages, the control of an exact phase composition of $H_xLi_{1-x}NbO_3$ waveguide is expected to improve the performance of a MIOC device as well. Since no attempts have been reported thus far, an investigation into this possibility is in order and presents an essential task of the proposed effort.

It is worth noting that optical absorption spectroscopy data have suggested a non-monotonic dependence of r_{33} on hydrogen concentration x and strain ε_{33} ($\varepsilon_{33} \sim x$) with a minimum r_{33} reached at intermediate values of x that correspond to the κ and β_1 phases. On the contrary, the direct measurements of electro-optical efficiency of modulators show that the electro-optic effect monotonically decreases as the strain increases. The discrepancy may be ascribed to a significant disordering of crystalline layers and its effect on the r_{33} of a given phase. Our Raman data provide direct evidence of a high degree of such disordering, as a marked broadening of the Raman lines in waveguides with $\varepsilon_{33} \geq 0.7\times10^{-3}$ is clear indicative of the disorder-induced phonon damping. Low-temperature annealing, performed at 85 °C to 100 °C, is found to be effective to reduce disordering in the higher-strain α-phase waveguides. It is important to note, that compared to the low-strained α-phase, the high-strained phase has a much larger refractive index increment, which enables a better mode confinement and allows sharper waveguide bends, as confirmed by a comparative analysis of the MIOCs utilizing waveguides fabricated with the differently strained α-phase compositions.

V. SUMMARY

The experimental samples of phase modulator fabricated at the optimal technological conditions exhibit the improved electro-optical efficiency with superior propagation and insertion losses compared to the common APE:$LiNbO_3$ modulators. The electro-optical efficiency has been gained by appropriate choice of exchange/annealing ratio.

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