Subsurface Disorder and Electro-Optical Properties of Proton-Exchanged $LiNbO_3$ Waveguides Produced by Different Techniques

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Abstract: It has been established, that subsurface disorder in soft proton-exchanged (SPE) waveguides is much smaller than in annealed proton-exchanged (APE) ones. The experimental samples of phase modulators fabricated by SPE technique exhibit the improved electro-optical efficiency and superior propagation losses compared to the $LiNbO_3$ modulators produced by the standard and improved APE techniques. According to our data, low DC bias drift behavior of such SPE modulators is expected.

Introduction: Proton exchange is now an established technique for fabricating integrated optical devices in $LiNbO_3$, as it offers potential possibility of obtaining low-loss waveguides with a good electro-optical (EO) performance[1]. Note that a significant degradation (more than one order of magnitude) of the EO coefficients occurs immediately after the proton exchange process[1,2]. However, after appropriate annealing the EO coefficients are almost re-established and reach maximum values in the so-called α-phase annealed proton-exchanged $LiNbO_3$ waveguides[2]. By the way, EO coefficients cannot be restored completely even after a long annealing at the standard fabrication conditions that is in common use today[1-3]. It was shown[4] that the extended annealing in dry air at $T \geq 320$ °C leads to the precipitation of disordered phases in a subsurface layer (depth ≤ 0.5 µm), causing undesirable degradation of the EO properties of the waveguide. Such degradation could be interpreted as the field-screening effect in the highly structurally disordered parts of the proton exchanged regions below the surface. Besides, these structural defects are observed to increase the conductivity, believed to be a key reason for a DC-voltage bias drift of the EO modulators[4]. Besides, it was recently reported[3] that this subsurface disorder provides some marked level of propagation loss related mainly to guided mode scattering within inhomogeneous near-surface part of waveguide. It has been established[4] that the loss of water during annealing is a major contributor to the formation of crystalline disorder and, hence, annealing under a high pressure of water vapor is shown to decrease such a disorder. However, this method allows only for partial suppression of the both subsurface disorder and related degradation of waveguide properties. To avoid these undesirable effects completely, the method of the soft proton exchange (SPE) has been proposed to use in this work, as there is no any water losses when the α-phase waveguides are fabricated by SPE[5].

Samples Fabrication and Characterization Techniques: APE waveguides were fabricated with standard technique[2] (APE1 sample was annealed in dry air at 360 °C) and improved APE technique[4] (APE2 sample was annealed for appropriate time[2] in wet air at 360 °C). SPE waveguides were fabricated by special method[5] with benzoic acid melts containing the various concentration of lithium benzoate (LB): for SPE1 and SPE2 samples [LB] was 2.4 and 1.5 mol%, respectively.

Subsurface disorder was studied by depth profiling with micro-Raman spectrometer and oblique IR-reflection with spectrophotometer. Electro-optic coefficient r_{33} values were estimated from data[2] on band gap and disorder factor F values in different waveguides. Finally, the fiber-pigtailed phase modulators were formed on basis of these waveguides and effective values of r_{33} were measured with the aid of a fiber-optical Sagnac interferometer.[2]

Experimental Results: Broadening of Raman phonon bands is well-established clear indication[2,6] of a marked structural disorder in $LiNbO_3$. According to the significant difference in FHWM (Fig.1 and Table 1) between waveguides studied, it's evident that subsurface disorder in SPE waveguides fabricated at optimal [LB] values is much smaller than in any APE samples.

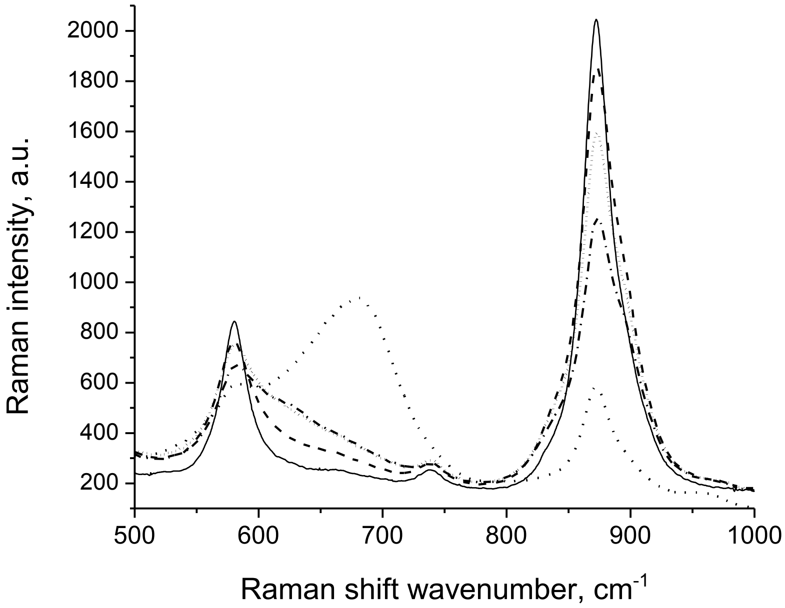

Fig. 1. Raman spectra of a subsurface part of the different samples: PE, APE1, APE2, SPE1 and z0 (notation meaning is given in text). This samples order corresponds to spectra sequence from bottom to top at 871 cm^{-1}.

Attenuation of Raman intensity (I_{LO}) of the LO-phonon band at 871 cm^{-1} and intensity (I_{extra}) increase of specific extra band at 656-690 cm^{-1} are related to decrease of local electro-optic response[2,6]. Indeed, a local value of electro-optic coefficient r_{33} may be rather smaller than its effective value because of the field-screening effect in a disordered subsurface part of waveguide[2].

Table 1. Sample notation, FWHM of Raman band at 871 cm^{-1}, disorder factor F, Raman intensities (I_{LO} and I_{extra}) of LO-phonon and extra Raman bands, and the effective values of electro-optic coefficient r_{33}.

sample	*FWHM, cm^{-1}*	*F*	*I_{LO}, a.u.*	*I_{extra}, a.u.*	*r_{33}*
z0, (pure LN)	29.7	0	3.5	0	1
SPE1	35.3	0.05	3.2	0.14	0.90
SPE2	38.7	0.074	2.7	0.3	0.82
APE2	40.5	0.082	3.1	0.18	0.85
APE1	44.1	0.095	3.0	0.24	0.80

The experimental samples of phase modulators fabricated by SPE technique exhibit the improved electro-optical efficiency (Table 1) and superior propagation losses compared to the $LiNbO_3$ modulators produced by the standard and improved APE techniques. Low DC bias drift is expected in SPE modulators, as subsurface disorder is shown[4] to be a key reason of such a drift.

References

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