

# Characterization of Static and Photorefractive Scattering in Channel LiNbO<sub>3</sub> Waveguides Fabricated by Novel High Temperature Proton Exchange Technique

S.M. Kostritskii, Yu.N. Korkishko, V.A. Fedorov, A.N. Alkaev, V.S. Kritzak  
Moscow Institute of Electronic Technology, Optolink Ltd, 103498, Zelenograd, Russia;  
[skostritskii@optolink.ru](mailto:skostritskii@optolink.ru)

P. Moretti, S. Tascu, and B. Jacquier  
Laboratoire de Physico-Chimie des Matériaux Luminescents, Université de Lyon 1, France

Insertion losses, mode profiles and photorefractive damage were measured in channel HTPE-LiNbO<sub>3</sub> waveguides. The guided modes scattering was mapped by scanning near-field optical microscopy. These measurements offer important information about loss mechanisms in our waveguides.

**Keywords:** Lithium niobate, waveguides, scanning near-field optical microscopy

## Introduction

Optical channel waveguides in lithium niobate are a very useful technique for building a variety of integrated optical components. Proton exchange (PE) is now an established technique for fabricating integrated optical devices in LiNbO<sub>3</sub> and offers possibility of obtaining low-loss waveguiding material with a good electro-optical performance [1,2]. Annealing is an important step in the common fabrication sequence of PE waveguides. In fact, most of the published results have been obtained using heavily annealed PE (APE) waveguides, whose index profiles indicate that they are in the  $\alpha$ -phase. However, it was recently reported [3,4], that APE process reduces the electro-optical coefficients and provides some marked level of propagation loss related mainly to the guided power leakage. The two primary sources of this leakage are the following: (1) static light scattering caused by residual distortion of a near-surface waveguide part, where several phase transitions occur during annealing [2]; and (2) time-dependent photorefractive damage [5]. To avoid these undesirable effects, we propose the new method of high temperature proton exchange (HTPE) [3], as there is no any phase transition when the  $\alpha$ -phase waveguides are fabricated by HTPE and a concentration of photorefractive defects are smaller comparatively to the APE process.

In this paper, we report characterization of propagation loss sources related to guided modes scattering in the LiNbO<sub>3</sub> optical waveguides fabricated by HTPE technique.

## Experimental

A series of straight channel guides, ranging from 3 to 7  $\mu\text{m}$  in 0.2- $\mu\text{m}$  steps were delineated in optical grade X-cut LiNbO<sub>3</sub> substrates, using standard photolithographic technique. The substrates were proton exchanged with the aid of the HTPE method at 370<sup>o</sup>C for 3 – 6 hrs in stearic acid diluted by lithium stearate (0.7 - 0.85 wt.%). The mentioned above fabrication parameters were chosen by us in accordance with results obtained by X-ray diffraction, prism coupling modal spectroscopy and IR-reflection in test samples of a planar waveguide. This study of test samples gives possibility to determine roughly a range of fabrication parameters, where formation of a low-loss single mode channel waveguide, operating at a certain wavelength region, is expected. A target wavelength of our optimization procedure was 810 - 840 nm, as fabrication of an integrated optical phase modulator is developed. Final optimization of the fabrication parameters was made according to data of direct measurements of the modes shape and insertion losses in channel waveguides.

The modes shape was measured by coupling depolarized light from a superfluorescent diode (a center wavelength is 830 nm) into the waveguides with the aid of an isotropic single mode fiber. The output light of waveguides was imaged on CCD camera, operating in its linear region. To determine insertion losses and evaluate a propagation loss, we use a fiber-to-fiber coupling set-up.

Scanning near field optical microscopy (SNOM) has been also used to investigate the guided mode in the waveguides. In situ optical near field investigation of the waveguides has been performed by using a “Twin SNOM-OMICRON” system in collection mode. A three directional small micromechanical system has been added on the piezoelectric table of the microscope supporting the samples in order to end-fire couple light by mean of a PM optical fiber. Light from an He-Ne laser (632.8 nm) is endfire coupled into the waveguide by mean of a SM fiber while the evanescent field is probed at the waveguide surface through the small aperture of the optical fiber of the SNOM which position is controlled by shear force measurements. The guided mode intensity is therefore mapped with a sub-wavelength resolution (<100 nm).

## Experimental results and discussion

The crucial influence of lithium stearate concentration on properties of channel waveguides has been established. In order to examine these properties, two techniques were employed. The first, a more qualitative analysis, involved tracking change in the region of single-mode operation range at 830 nm in terms of waveguide channel width. The range of waveguide widths supporting only extraordinary fundamental mode was recorded and monitored as function of both the lithium stearate concentration  $C_{LS}$  in ion-exchanging melt and proton-exchange time. Along these measurements, we studied the qualitative confinement of fundamental mode. According to this study, a smaller  $C_{LS}$  within used range provides better mode confinement in the waveguides of widths from 3.4 to 4.6  $\mu\text{m}$  at appropriate choice of proton exchange time for each certain  $C_{LS}$  value. This width range corresponds to acceptable level of matching the fundamental modes of channel  $\text{LiNbO}_3$  waveguide with both in-coupling and out-coupling fibers. Note, that the term “waveguide width” used here means the width of window (gap) in a  $\text{Cr/SiO}_2$  mask used at proton exchange.

In order to quantify the waveguiding properties change, a second technique using fiber-to fiber coupling was employed. Here, the difference in light level between the input and output fibers was related to the corresponding insertion losses. It was established that a minimum of the insertion losses  $\alpha_{\min}$  for a given IOC is observed always in the mentioned above range of waveguide widths at some specific value of the proton exchange time. This specific time  $t_s$  and the minimum losses available  $\alpha_{\min}$  are dependent on  $C_{LS}$ . While dependence of  $t_s$  on  $C_{LS}$  is monotonous, i.e. a smaller  $C_{LS}$  is shorter  $t_s$ ,  $\alpha_{\min}$  is smallest at intermediate values of  $C_{LS}$  from 0.75 to 0.78 wt % (Fig. 1).

As the use of  $C_{LS}$  values larger than 0.78 wt % decreases sharply a surface refractive index and, therefore, requires a relatively long exchange for  $t_s \geq 4.5$  hrs, the observed growth of insertion losses can be related to the fact that the waveguides are becoming weakly confining and their mode size is more larger than the fiber mode. The insertion losses growth with  $C_{LS}$  decrease, within the  $C_{LS}$  range < 0.75 wt %, is more surprising, as waveguide mode confinement became better and no evident mismatch of fundamental mode with fiber mode was observed. However, a comparative study of channels with different lengths has shown a very high level of propagation loss ( $\geq 2$  dB/cm) in waveguides fabricated with  $C_{LS} < 0.75$  wt %.

The comparison of waveguides fabricated with different  $C_{LS}$  was performed by measurement of insertion losses at a fixed level of the low in-coupled powers (around 100  $\mu\text{W}$ ), as the pronounced time-dependent growth of insertion losses is observed with increase of in-coupled power, when it is larger than 200  $\mu\text{W}$ . Such behavior is typical consequence of the photorefractive damage effect in channel  $\text{LiNbO}_3$  waveguides [5].

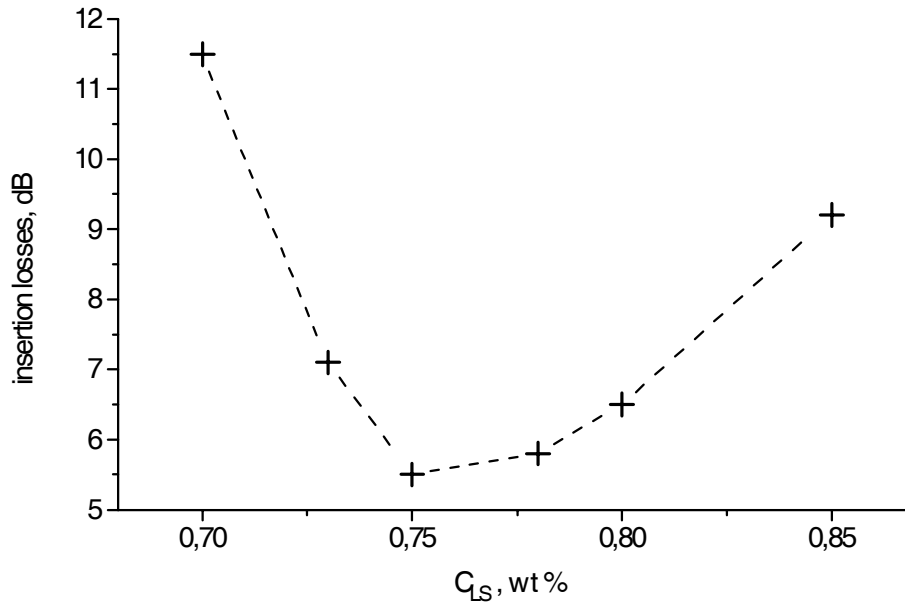


Fig. 1. Dependence of minimum insertion losses  $\alpha_{\min}$  on lithium stearate concentration  $C_{LS}$  in melt used for waveguides fabrication. These minimum values were found among the waveguides of different widths in the samples proton-exchanged for varied time at a given  $C_{LS}$ . Optimal values of the width and proton-exchange time  $t_s$  were changed with variation of  $C_{LS}$ .

The growth of propagation loss, when  $C_{LS}$  drops below 0.75 wt %, may be related to our IR-reflection data on appearance of phase-composition inhomogeneity,. For example, at very oblique incidence (incidence angle  $\Theta = 70^\circ$ ) of IR radiation on waveguide surface, the OH-libration band (wavenumbers range is  $960\text{-}980\text{ cm}^{-1}$ ) specific for  $\kappa_1$  phase [2] was observed only in waveguides fabricated with  $C_{LS} < 0.75$  wt %. Such band was not observed into spectra measured at  $\Theta = 20^\circ$ , where depth of photometered area is much larger than at  $\Theta = 70^\circ$ . Thus, we can conclude existence in an upper part of  $\alpha$ -phase waveguide of the shallow near-surface  $\kappa_1$ -phase layer, which is not detected by X-ray diffraction method. Actually, an extremely high level of propagation loss in the  $\kappa$ -phase and compositionally inhomogeneous waveguides is well known fact [1,3].

To investigate mechanisms of this contribution and other marked sources of the loss, we used SNOM technique. By probing the evanescent field present in the air region above a waveguide, we can measure with near field spatial resolution the optical power distribution associated with the optical waveguide as well as the effective index of refraction of the structure [6]. It has been established, that guide light is scattered due to inhomogeneity at the proximity of the surface of the waveguide. These scatterings offer some information about loss mechanisms in our waveguides. Fig. 2 shows the measured intensity-distribution profile of guided mode and the topographical image of a straight channel waveguide within a scanned area  $16 \times 100\ \mu\text{m}^2$ . The results show the strong topographical strip structure that is correlated to the SNOM image of the guided mode. There are some bright spots in a mode image of any waveguide studied. Random distribution allows to assume that these bright spots are observed due to scattering on composition inhomogeneities at the proximity of waveguide surface [7]. For example, a very strong intensity independent static contribution in mode scattering is observed in the multiphase waveguides, having most pronounced

IR-spectroscopy evidence of  $\kappa_1$ -phase shallow layer on a surface of the  $\alpha$ -phase waveguides fabricated by HTPe technique at  $C_{LS} \leq 0.7$  wt %, or standard APE technique. In monophasic HTPe waveguides, containing mainly  $\alpha$  phase, this contribution is much smaller, but exists always and correlates with variation of the propagation loss in the fiber-to-fiber coupling experiments. Thus, fabrication conditions allowing minimize the propagation loss in HTPe waveguides have been identified:  $0.75 \leq C_{LS} \leq 0.78$  wt.%, and exchange time should be in a range from 3.5 to 4.1 hours.

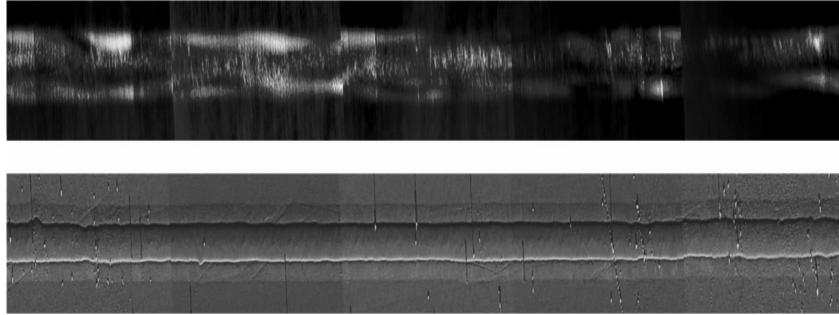


Fig. 2. SNOM data on intensity-distribution profile of guided modes (upper picture) and the topographical image (down picture) of a straight channel double-mode waveguide fabricated by HTPe technique. Guided light propagates from left to right side of upper picture.

The temporal evolution of SNOM images between successive scans of the same area of high-intensity mode allows us to determine the light-induced scattering related to photorefractive damage because of specific kinetics of photorefractive response [5] in the waveguide. This temporal evolution becomes detectable only with in-coupled powers higher than  $40 \mu\text{W}$ . The threshold values of in-coupled power for light-induced changes observed by fiber-to-fiber coupling and SNOM experiments are significantly different, but there is clear correlation between these two threshold values at comparison of different waveguides. It was established, that this photorefractive damage is smaller than in APE waveguides and can be decreased for a desirable level by prefabrication treatment of a  $\text{LiNbO}_3$  wafer and appropriate choice of in-coupled power.

## Conclusion

By using SNOM, the very strong intensity-independent static contribution in mode scattering is found to be the specific feature of proton-exchanged  $\text{LiNbO}_3$  waveguides. This contribution correlates clearly with additional losses observed with fiber-to-fiber coupling experiments and related to leakage of a guided mode into substrate. Time-dependent growth of light scattering is observed only at in-coupled powers above some threshold related to intensity dependence of photorefractive damage. Fabrication conditions allowing a significant reduction of such static and photorefractive scatterings in HTPe- $\text{LiNbO}_3$  channel waveguides have been identified.

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