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Technological Implementation of Bragg Grating Reflectors in Ti:LiNbO$_3$ Waveguides by Proton Exchange

B.-E. Benkelfat, R. Ferrière, B. Wacogne, and P. Mollier

***Abstract*—The authors propose and demonstrate a simple and novel method for fabrication of efficient Bragg grating reflectors at telecommunication wavelengths in titanium-indiffused lithium niobate single-mode channel waveguides. This technique is based on the patterned proton-exchanged process. The validity of the method is verified by the good agreement of the spectral responses and the Bragg phase-matching condition. Reflectivity as high as 94% at 1546 nm was measured with 4-mm distributed parameter waveguides in *z*-cut lithium niobate.**

***Index Terms*—Gratings, integrated optics, LiNbO$_3$, optical waveguides, tunable filters.**

I. INTRODUCTION

PERIODIC and aperiodic distributed parameter waveguides have many applications in integrated optical components (IOCs) dedicated to dense wavelength-division-multiplexing (DWDM) photonic networks [1]. In addition, the aperiodic structures were recognized like excellent candidates for the compensation of dispersion. Usually, fabrication methods are based on photorefractive [2], [3] and dry-etching techniques [4]. Furthermore, UV-induced surface-relief gratings on LiNbO$_3$ channel waveguides with a bandwidth of 1.8 nm at 1534.3 nm have been obtained [5]. More recently, a laser ablation technique has been employed for realizing gratings in LiNbO$_3$ channel annealed-proton-exchanged waveguides. Using this approach, 6% reflective gratings have been fabricated [6].

In this letter, we propose for the first time, to our knowledge, a simple and reproducible method of grating fabrication in titanium-indiffused lithium niobate single-mode waveguides based on the patterned proton-exchanged technique. Proton exchange (PE) process is an attractive method for the fabrication of IOCs in lithium niobate (LiNbO$_3$) and lithium tantalate (LiTaO$_3$). Because of its easy implementation and large index modulation, this technique has been used to realize many useful PE-integrated optical devices such as optical frequency translator, second-harmonic generators [7], polarizers, modulators, or Fresnel lenses [8]. When compared to standard holographic and dry-etching methods, the process offers great flexibility and greatly simplifies the grating fabrication.

II. PRINCIPLE AND DISCUSSION

When Bragg gratings are used to provide feedback in titanium lithium niobate waveguides they can serve both as reflectors in Fabry–Pérot structures and as optical filters. On the other hand, the refractive index of a lithium niobate waveguide can be controlled through an applied electric voltage. The structure can hence be tuned electrically. According to the coupled mode theory, efficient coupling between the forward and backward traveling waves occurs when the phase-matching condition [9] is satisfied

$$m\lambda_{\text{Bragg}} = 2 \cdot n_{\text{eff}}\Lambda \tag{1}$$

where n_{eff} is the effective index of the propagation mode at λ_{Bragg}, Λ is the grating period, and m is the Bragg-scattering order. Wavelengths not satisfying this condition will be transmitted without attenuation. Under phase-matching conditions, the reflectivity $\Re$ and the bandwidth $\Delta\lambda$ are expressed as

$$\Re_{\max} = \tanh^2(\kappa \cdot L) \tag{2}$$

$$\Delta\lambda = \frac{\lambda_B^2}{n_{\text{eff}} \cdot L}\sqrt{1 + \left(\frac{\kappa \cdot L}{\pi}\right)^2} \tag{3}$$

where κ and L are the coupling coefficient between the contrapropagating modes and grating length, respectively. The coupling coefficient is directly related to the index perturbation. Moreover, the dependence on Bragg order m is represented by the multiplicative factor $[\sin(\pi m w/\Lambda)]/m$, where w/Λ is the ratio of the tooth width to the period for a rectangular grating.

In order to obtain maximum reflectivity with a high-order Bragg grating, it will be necessary to implement a periodic dielectric waveguide with a significant index and/or length perturbation. The filter bandwidth is inversely proportional to the length of the grating provided the product $\kappa L \ll \pi$. One of the ways to increase and control the coupling coefficient of the grating is to produce a large and variable index modulation. The proton exchange process is expected to produce large changes in the refractive indexes: the extraordinary index increases ($\delta n_{e,\max} \sim 0.12$) while the ordinary index decreases by $\sim$ 0.04. This large and controllable change in refractive index will allow fabrication of high efficiency Bragg filters.

Results on fabrication and characterization of proton-exchanged optical waveguides in *x* cut, *y* cut, and *z* cut LiNbO

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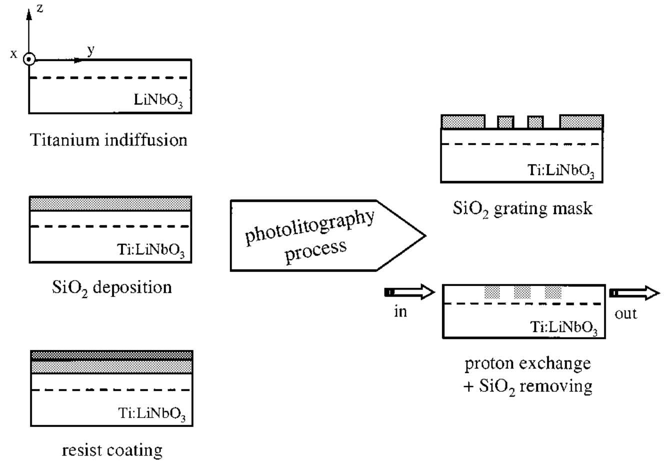

Fig. 1. Fabrication steps of patterned proton-exchanged Bragg grating in Ti:LiNbO$_3$ waveguides.

have already been presented [10]. PE takes place when the substrate is immersed in a proton source such as molten benzoic acid. Proton-exchanged waveguides present a step-like refractive index profile. They support only TM mode in *z*-cut material and TE mode in *x* and *y* cut materials. The depth of the proton-exchanged layer is determined by the immersion time and the diffusion coefficient $D(T)$at different temperatures. Several authors [11] have reported the diffusion coefficients of titanium-indiffused proton-exchanged (TIPE) layers for various melt temperatures. The main drawback of the proton-exchange process is a large scattering loss as compared to the titanium diffusion process. One of the ways to reduce the undesirable effects is to anneal the samples in wet air at a temperature between 250 °C and 400 °C with the time ranging from minutes to hours. Such an annealing process increases the depth of the proton-exchanged layer while reducing δn_e. This results in more controllable refractive index profiles.

III. FABRICATION PROCESS

Proton-exchanged grating waveguides were implemented in two steps (Fig. 1). In the first step single-mode optical waveguides in the 1550-nm window were fabricated on *z*-cut (*y*-propagating) LiNbO$_3$ substrates by standard diffusion of 80-nm-thick and 7-μm-wide titanium layers at 1100 °C during 10 h in a wet Ar–O$_2$ atmosphere. Next, a 2000-Å-thick SiO$_2$ layer was deposited on the waveguide for the proton-exchange mask layer.

The SiO$_2$ was chosen for its excellent proton diffusion blocking, good adhesion to the substrate, and ease of deposition and etching. Moreover, this transparent mask allows an approximate measurement of the grating characteristics before its removal. The Bragg grating pattern was directly written by UV exposure through a Cr mask in a resist layer. The pattern was transfered to the SiO$_2$ layer by chemical (or reactive ion) etching. The proton exchange was performed in molten benzoic acid, and finally the SiO$_2$ mask was removed by chemical etching. The waveguide was subsequently annealed in wet air. As a consequence, the electrooptic effect would be restored and propagation losses reduced.

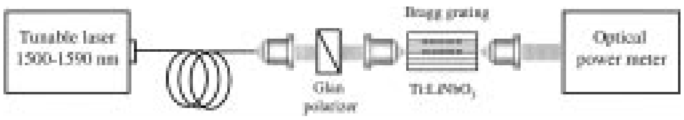

Fig. 2. Measurement setup to characterize Bragg grating reflectors.

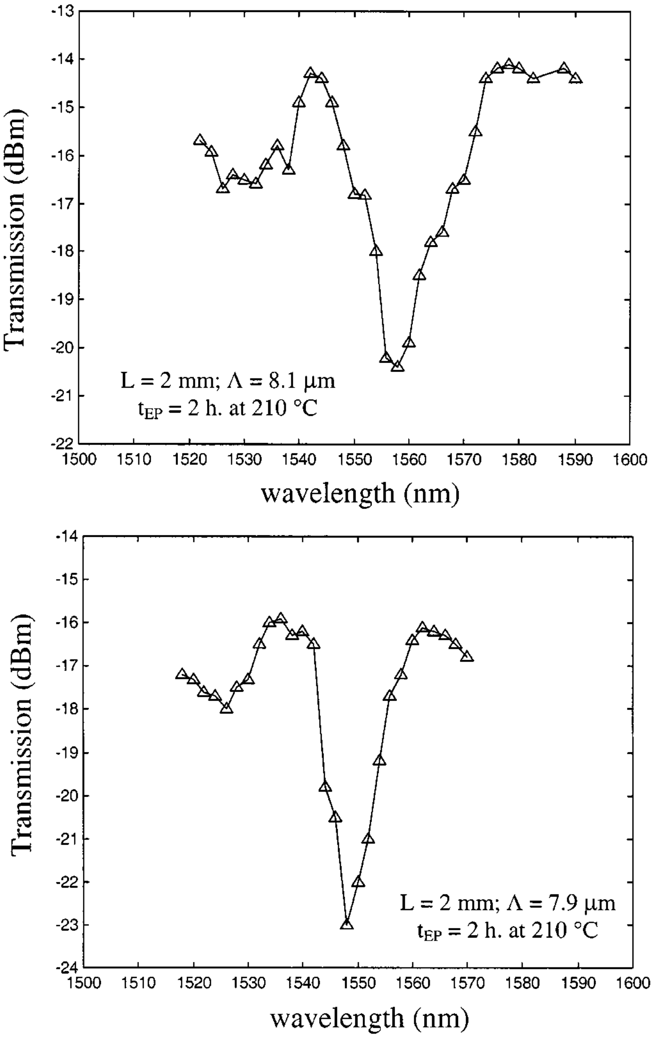

Fig. 3. Wavelength dependence of the measurement transmission spectrum of distributed-parameter Ti:LiNbO$_3$ waveguides, reflectivity $\Re_{\max} \sim 75\%$. The samples were annealed at 400 °C for 20 min.

The experimental parameters of the proton exchange and annealing process are based on the preliminary investigations (e.g., refractive index profile) which have been carried out on TIPE optical waveguides in z-cut LiNbO$_3$ substrates. The samples were proton-exchanged at temperature between 150 and 230 °C with the time ranging from 1 to 4 h. The annealing process was performed at various temperatures (from 250 °C to 400 °C) with different times (from 10 mn to 3 h).

IV. EXPERIMENTAL RESULTS

To assess the spectral responses of the Bragg gratings, we used a narrow-linewidth tunable diode laser with linearly polarized output power between 1510 and 1590 nm and a power meter to measure the output power (Fig. 2). A Glan polarizer

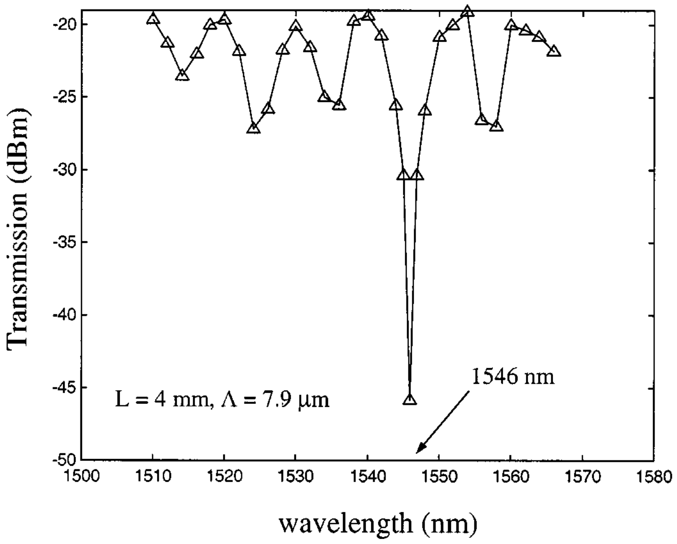

Fig. 4. Spectral response of a 4-mm-long periodic distributed-parameter Ti:LiNbO$_3$ waveguide, reflectivity $\Re_{\max} \sim 94\%$. The sample was proton-exchanged during 3 h at 230 °C and annealed at 400 °C for 1 h 10 min.

was placed in front of the grating waveguide to selectively probe TM mode.

The preliminary results were obtained for Bragg gratings with periods equal to 7.9 and 8.1 μm. The process was realized in benzoic acid for 2 h at 210 °C, and the gratings were annealed at 400 °C for 20 min. Fig. 3 shows transmission spectrums of a 2-mm-long high-order proton-exchanged Bragg grating reflectors in single-mode channel Ti:LiNbO$_3$ waveguide. The spectral responses show that the resonance wavelengths are in good agreement with the Bragg phase-matching condition. At the Bragg wavelength the relative transmission drops to 25%. A 3-dB (FWHM) bandwidth of approximatively 9 nm at 1558 nm was achieved. Furthermore, the reduced transmittivity for wavelengths shorter than 1558 nm is attributed to the guided-to-substrate mode coupling. An estimate of the excess losses, due to the presence of the grating, is obtained by comparing two adjacent waveguides, one with the grating and the other without. The excess grating reflector loss is approximatively 0.4 dB. Narrower bandwidth and higher reflectivity can be obtained by optimizing the coupling coefficient and grating length.

Fig. 4 shows the measured transmission spectrum of distributed parameter Ti:LiNbO$_3$ waveguide with period $\Lambda = 7.9$ μm which was proton-exchanged during 3 h at 230 °C and annealed at 400 °C for 1 h and 10 min. Reflectivity as high as 94% at 1546 nm is hence deduced showing a bandwidth of $\sim$ 2 nm for 4-mm grating length. The oscillations observed around the transmission dip are related to processing inhomogeneities and undesirable effects in the measuring setup.

V. CONCLUSION

We have reported the first implementation of the proton exchange technique for the fabrication of Bragg grating reflectors in Ti:LiNbO$_3$ waveguides. This process offers great flexibility and simplifies the fabrication steps involved in standard holographic and dry-etching methods. The experimental results are in good agreement with the modeling of the grating for which, in particular, a reduction of its bandwidth is expected with optimized technology parameters. The annealing process reduces the refractive index modulation ($\sim$ 0.12) induced by proton exchange and then allows the increase of the effective length of the distributed parameter waveguide. This results in reduction of the bandwidth.

Investigations are being carried out in order to improve the reflector uniformity and to reduce the grating period. Patterned proton-exchanged technology can also be used to realize optical waveguide reflectors and tailored optical filters with specific spectral response characteristics.

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