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PROTON-EXCHANGE OPTICAL WAVEGUIDES ON LITHIUM NIOBATE: DEVICES, CHARACTERISATION AND FUTURE PROSPECTS

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Invited Paper

Proton-exchange optical waveguides on lithium niobate: devices, characterisation and future prospects

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Abstract

In the past few years proton-exchange has developed into a very promising method for fabrication of optical waveguides on $LiNbO_3$. In this paper we shall review the applications of proton-exchange waveguides, to date, and discuss the relatively new method of proton-exchange using dilute melts.

Introduction

Since its discovery in 1982, the proton-exchange process has been the subject of a substantial research effort in laboratories in a number of countries. Interest in proton-exchange stems from the comparatively large change in refractive index ($\Delta n \sim 0.12$) available, the simplicity of the guide-formation process and the ease with which the refractive index profile can be modified in one or two dimensions.

A range of devices has been demonstrated, including purely passive structures, electro-optic, acousto-optic and non-linear optical devices. Several variations on the basic waveguide formation process have been demonstrated and applied to specific devices. Major practical problems have emerged and some possible solutions to these problems have been proposed.

In this presentation we shall firstly review work (mostly on devices) carried out by various authors and then present recent results of our own work on waveguide characterisation, with particular emphasis on waveguides produced from 'dilute' melts in which a small percentage of lithium benzoate is added to concentrated benzoic acid. Finally, we will suggest areas for investigation which are important if reliable and efficient devices are ultimately to be obtained.

Passive structures

A natural area for the application of a large-Δn process is that of gratings and lens structures. A simple and efficient Bragg-grating was demonstrated by Pun et al[1] and this was followed by demonstration of a chirp-grating lens by Warren et al[2]. Planar equivalents of aspheric bulk lens structures were demonstrated by Yu[3]. Because these structures all use lithographic pattern definition they are attractive components for a completely planar integrated optics technology. A combination of dilute-melt exchange and, perhaps, some subsequent annealing should make such passive structures inherently low-loss and low-scatter, provided that the original lithographic pattern definition is of adequate quality. Dawar et al[4] found that, even with electron-beam writing, the pattern quality for an analog Fresnel lens deteriorated considerably towards the edges of a 2mm aperture.

A quite different passive structure has been described by Papuchon and Vatoux[5], exploiting the fact that proton-exchange both increases the extraordinary refractive index and decreases the ordinary index to couple TM polarised light out of a titanium-diffused stripe guide, giving a polarising action. Recently, Haruna et al[6] made an interferometric temperature sensor in proton-exchange lithium niobate, exploiting the large Δn to give low-loss stripe waveguide bends and permit a large interferometer arm length-difference in a compact structure.

Electro-optic devices

Wong et al[7] described the use of a proton-exchange stripe-waveguide modulator as a serrodyne frequency shifter. For this application, operation with a zero average (d.c.) voltage level was possible, so that drift problems identified at non-zero d.c. voltage levels could be avoided. It was found that the operating voltage requirements were similar to those

for a comparable structure using a titanium-diffused guide. Becker[8] compared performance of titanium-diffused and proton-exchanged Mach-Zehnder modulators with a silica buffer layer between the electrodes and the substrate. Becker's observations indicated a reduction of the effective electro-optic activity in proton-exchange guides to approximately one third of that in titanium-diffused guides. Such a reduction could, however, be the result of ionic mobility either during device fabrication or during device operation. It may also be possible to obtain useful electro-optic activity, for shallow guides, via the evanescent part of the optical field outside of the region where proton-exchange takes place. Recently, Wong et al[9] have reported that electro-optic efficiency is preserved in guides made from dilute melts.

Acousto-optic devices

In the last year, several workers[10,11,12,13] have described investigations of acousto-optic devices using proton-exchanged waveguides. Dawar et al[4,10] found that annealing of waveguides on Y-cut lithium niobate, while reducing in-plane scattering, was accompanied by a drastic reduction in acousto-optic interaction efficiency, even though care was taken to avoid placing the transducers on the proton-exchanged region. Davis[12] used proton-exchange guides formed after an initial titanium diffusion (the TIPE process) and found reduced piezo-electricity and a consequently reduced piezo-electro-optic contribution to the acousto-optic interaction efficiency, as well as increased accustic wave propagation loss.

Hinkov et al[13] used surface acoustic waves at 85MHz in a co-linear interaction with light guided in a TIPE guide on Y-cut lithium niobate. A very long, high-temperature, exchange process was used (18 hours in pure benzoic acid at 250°C in a sealed ampoule). The reported TE_0-TM_0 conversion efficiency of 5% at 4 Watt input electrical power was rather low. Hinkov et al also noticed a reduction in surface acoustic wave propagation velocity. This reduction in velocity has been confirmed by Dransfeld[14].

Nonlinear effects

De Micheli[15] and Neveu et al[16] have investigated the use of proton-exchange waveguides for non-linear optical interactions such as second harmonic generation (SHG). In the latter paper, waveguides were formed by exchange in benzoic acid for 20 hours at 200°C. By an appropriate rotation of propagation direction on X-cut $LiNbO_3$, phase-matched coupling was obtained between a low order (TE_2) mode at 1.06μm and a high-order (TE_{13}) mode at 0.53μm wavelength, via the d_{33} coefficient. The much smaller than expected harmonic generation efficiency was attributed to an optical frequency effect corresponding to a reduced electro-optic effect at low frequency.

Dilute melt waveguide characterisation

All the results reported here are for proton-exchange waveguides fabricated in a benzoic acid melt to which a small percentage of lithium benzoate has been added. The most immediate effect of using such 'dilute' melts is a considerable reduction in the speed of the process- even at 0.5% lithium benzoate the fabrication time, for a given waveguide depth, is reduced by a factor of approximately five. Furthermore, at low lithium benzoate percentages, the index change, Δn, is similar to that for a pure benzoic acid melt. The reduction in process speed is of immediate value where single-mode guides are required as it permits more accurate control of the waveguide properties. Another motivation for using dilute melts is that, where desired, long fabrication times, leading to multimode guides, can be used on Y-cut lithium niobate which, for pure benzoic acid, shows considerable surface damage after only a few minutes immersion.

We have studied waveguides fabricated in dilute melts on all three major-axis lithium niobate cuts. The primary microanalytical tool used has been Rutherford Back-Scattering (RBS) which can detect the presence of a proton-exchange region by the associated increased alpha-particle back-scattering yield in comparison with the yield for the underlying single-crystal substrate, in the aligned (i.e. enhanced channelling) condition. Close agreement has been found between optical waveguide measurements and RBS data. In particular, the waveguides have been shown to have nearly a step-index profile to the same depth as obtained by calculation from the energy at which there is a step change in the back-scattering yield. This depth increases as a $t^{\frac{1}{2}}$ function of the exchange time, so that a temperature dependent diffusion coefficient can be assigned to the process and, furthermore, this coefficient can be fitted, with moderate accuracy, to an Arrhenius law.

Figure 1 shows typical RBS data obtained on X-cut lithium niobate in the 'aligned' condition. The much greater back-scattering yield for the sample produced in a pure benzoic acid melt, in comparison with the yields for the four dilute-melt samples, is clearly apparent. As the index change, Δn, is similar for the pure and dilute melts it is obvious that the height of the RBS curve is not directly related to the index change. The position of the step-change in height is, however, in all cases a good measure of both the depth of

the exchanged region and of the high-index guide region. In all of these dilute melt samples, a 0.5% lithium benzoate concentration was used.

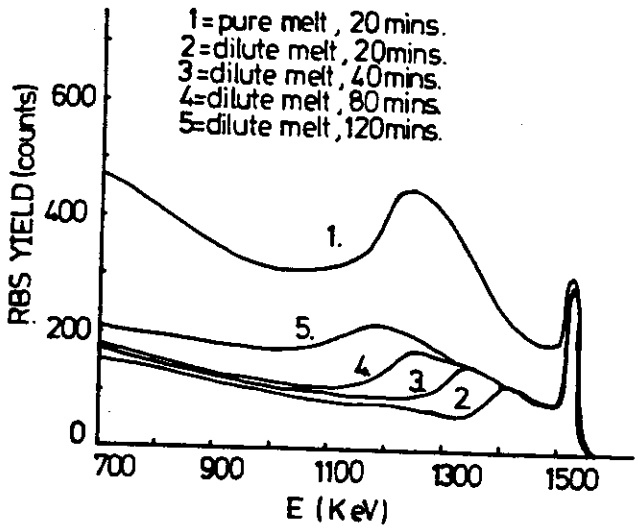

Figure 1. RBS Data for proton-exchange on X-cut $LiNbO_3$ with melt temperature of 200°C.

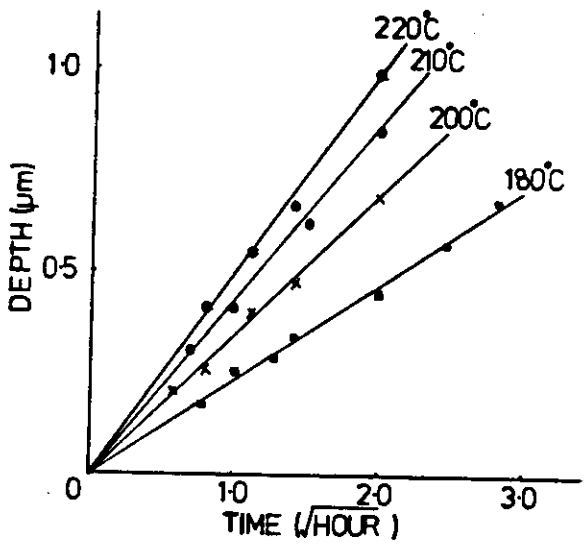

Figure 2. Dependence of guide depth on (time)$^{\frac{1}{2}}$ for X-cut $LiNbO_3$ with 0.5% lithium benzoate dilute melt at various temperatures.

Figure 2 shows plots of optically estimated waveguide depth vs $t^{\frac{1}{2}}$ for X-cut lithium niobate with the same melt dilution, at several different temperatures. Clearly the data give straight lines through the origin and diffusion coefficients can therefore be estimated, taking guide depth as $\sqrt{2Dt}$. At 220°C. D_x is estimated to be 0.058μm^2/hour, while at 180°C D_x is estimated to be 0.0116μm^2/hour. Plotting of D_x versus 1/T gives estimated values of D_{xo} = 2.8.10^6 μm^2/hour and Q = 73 kJ/mole in the Arrhenius law: $D_x = D_{xo}.\exp(-Q/RT)$. Both the pre-exponential term, D_{xo}, and the activation energy, Q, are smaller than those found previously for exchange in a pure melt on X-cut material (D_{xo} = 4.85.10^{8}μm^2/hour and Q = 84kJ/mole). However, with limited data accuracy, the most important result is that the dilute melt process has much smaller D_x values.

Generally similar behaviour is observed for dilute melt proton-exchange waveguides on Z-cut $LiNbO_3$. On Y-cut $LiNbO_3$ it is again possible to get good estimates for waveguide depth from the steps in RBS data. However presently available data indicate variations in lattice distortion with processing time for dilute melt guides (in contrast to the situation shown in Figure 1 for X-cut guides) and we are currently attempting to verify these results on additional samples.

Detailed results for waveguide depth as a function of melt dilution up to 2% will be given in the conference presentation.

TIPE waveguides

We have recently investigated waveguides on Y-cut lithium niobate formed by the TIPE process[17] and found good evidence that the combined process permits much longer fabrication times because of the opposite and partially compensating strains produced. RBS data obtained on X-cut lithium niobate TIPE guides (Figure 3) indicates that much smaller lattice distortion occurs for exchange from a pure benzoic melt when there has been a previous titanium diffusion and also shows that the titanium diffusion causes some slowing in the proton-exchange process.

In-plane scattering measurements

We have previously reported that annealing of proton-exchanged waveguides on Y-cut $LiNbO_3$ can give a substantial reduction in in-plane scattering. It should also be noted that in-plane scattering is much greater for pure melt guides on Y-cut $LiNbO_3$ as the onset of surface damage is approached. Both results suggest that in-plane scattering in proton-exchange guides is closely linked to the level of lattice disruption and strain.

Rutile prism-coupler observations of in-plane scattering were carried out with a scanning

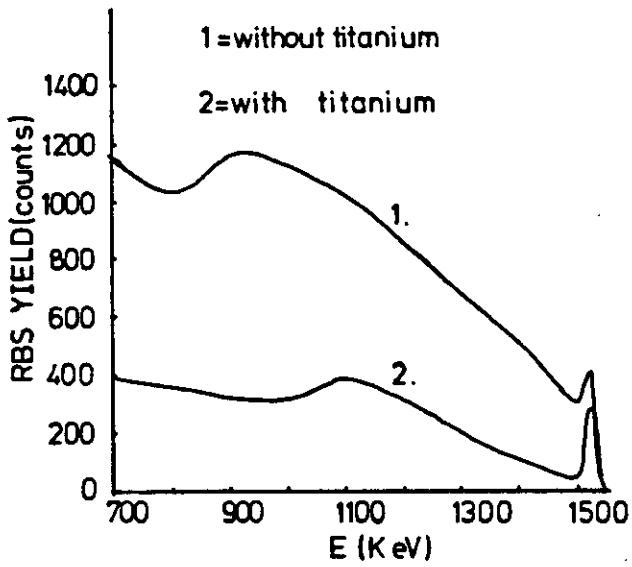

Figure 3. RBS data for proton exchange on X-cut lithium niobate, 180 minutes at 180°C: (1) without previous titanium diffusion, (2) with previous titanium diffusion.

photodetector on X-cut, dilute-melt, proton-exchanged waveguides. At 1° in air (corresponding to approximately ½° in the lithium niobate waveguide) waveguides formed at 200°C and 220°C gave in-plane scattering levels typically around -28dB. Wong et al[9] have reported in-plane scattering levels below 40dB for the same angle of ½° in multimode guides formed by 5 hours exchange at 239°C in a 1% dilute melt. Comparison between these results can only be conjectural but we believe that further work is needed to relate in-plane scattering to melt dilution, exchange temperature and RBS and X-ray data on structural distortion.

Future prospects

The prospects for use of proton-exchanged lithium niobate waveguides depend on long term solutions being found to the problems of stability and propagation loss. For passive device structures such as gratings and lenses, waveguide stability is likely to be adequate provided that prolonged operation at temperatures above 200°C[9] is not required. More work is needed to determine whether refractive indices can be predicted with sufficient accuracy, for a chosen process, to give precise focal length control in lenses and power division ratio in gratings. Gratings and lenses usually present a relatively short propagation path so that absorption losses and, to a lesser extent, scattering losses need not be very low, provided that most of the optical propagation path has low propagation loss (e.g. because formed by titanium diffusion). Scattering at interfaces between different waveguide regions could however still be a problem.

More widespread application of proton-exchanged waveguides will require clear demonstration of adequate retention of bulk electro-optic, piezoelectric, acoustic and non-linear properties. There is a clear need for a systematic investigation of the various proton-exchange processes already demonstrated, with comparative measurements using microanalytical techniques such as RBS and X-ray diffraction and measurements of electrical conductivity (both with guided light present and with it absent) and infra-red absorption. The causes of optical propagation loss and in-plane scattering need to be identified unambiguously at relevant wavelengths for systems applications - ultimately absorption due to the presence of large numbers of OH bonds is likely to be the limiting factor.

Success in the above quest is far from certain, but our view is that further fundamental work is justified by the potential benefits. Further modifications of the proton-exchange process could also prove to be useful.

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