OPTICAL MODE SIZE CONTROL BY MgO INDIFFUSION IN Ti:LiNbO$_3$ WAVEGUIDES

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ABSTRACT

In this paper, the use of magnesium oxide (MgO) indiffusion in combination with Ti:LiNbO$_3$ through appropriate control of pre- and post-diffusion parameters is investigated as a way of controlling optical mode size. The co-diffusion of pre-patterned Ti with various patterned MgO films on LiNbO$_3$ has been compared experimentally. This method has been applied to study straight waveguides and couplers. The waveguides were optically characterized by near-field mode size and loss measurements methods at a wavelength of 1.55μm. Reduction of inter-mode coupling between adjacent waveguides with the introduction of MgO has been observed.

1. INTRODUCTION

LiNbO$_3$ has become the industry standard electro-optic material and is widely used for the realization of high-speed integrated electro-optic devices. One such device is the Mach-Zehnder optical intensity modulator. Waveguide formation is most commonly achieved by locally increasing the refractive index of the LiNbO$_3$ substrate through indiffusion of a small amount of Ti (Ti:LiNbO$_3$). Such waveguides offer relatively low propagation loss and fairly good mode matching to standard single mode optical fibres, but have very low index contrast. Thus, unlike high contrast systems such as planar silica or semiconductor rib waveguides, very gradual transitions and bends must be used to maintain low propagation loss.

One possibility for increasing the index contrast of Ti:LiNbO$_3$ waveguides is through the codiffusion of MgO. Diffusion of MgO in LiNbO$_3$ causes a localized reduction in the refractive index[1]. Thus if MgO is diffused into the cladding region while Ti is diffused into the core, a comparatively high index contrast waveguide will be formed. The effect of MgO indiffusion on Ti:LiNbO$_3$ has been studied by a number of researchers over the last two decades. Simultaneous codiffusion of MgO and Ti has been proposed as method for inhibiting LiO$_2$ out-diffusion as well as index contrast control[2]. The diffusion of MgO as a post-process to improve Ti:LiNbO$_3$ waveguides has been characterized by Ti/Mg elemental maps and numerical studies[3]. A theoretical study of Mg indiffusion as a means of optimizing Mach-Zehnder optical intensity modulators has also been reported[4]. MgO diffusion has also been suggested as a means of improving the coupling efficiency between LiNbO$_3$ waveguides and single mode optic fibers[5].

Our investigations of optical intensity modulators have suggested that MgO indiffusion could be used in the optimization of the devices performance[6]. If the mode sizes in the active region can be reduced, enhanced efficiency should result due to stronger electro-optic interaction. Further, if the coupling between the adjacent arms of the optical modulator can be minimized, then the waveguide spacing could be reduced allowing both Mach-Zehnder arms to be positioned close to the modulators active electrode. This should also have a beneficial impact on the modulator drive efficiency[7].

In this paper, we present an investigation of the use of MgO indiffusion as a means of controlling the properties of Ti:LiNbO$_3$ Optical waveguides. Attention is paid particularly to the reduction of optical mode size and minimization of coupling between closely spaced waveguides. Section 2 presents an overview of Ti and MgO diffusion, waveguide formation and how these techniques may be applied to the optimization of optical intensity modulators. Section 3 presents the experimental details that were used in the realization of the Ti:LiNbO3 waveguides and the sputter deposition, photolithography and diffusion of the MgO films. Section 4 presents the experimental results, including quantification of the achieved mode size reduction and coupling suppression. A discussion of the results and suggestions for future work are presented in Section 5.

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2. DEVICE OPTIMISATION THROUGH MgO DIFFUSION

Overview of Ti:MgO codiffusion

Figure 1 presents an overview of both Ti and Ti:MgO indiffusion. Typically, waveguides are formed by depositing a thin film of Ti and patterning as shown in Figure 1a). The waveguides are then diffused into the $LiNbO_3$ substrate by heating to a temperature of around 1025C for about 6 hours as presented in Figure 1b). The refractive index of the $LiNbO_3$ is increased marginally where the Ti concentration is strongest as depicted in Figure 1c). Conversely to the indiffusion of Ti, MgO reduces the refractive index of $LiNbO_3$ and thus can be used to improve the refractive index contrast in waveguides. After patterning of the Ti film, MgO can be sputter deposited and patterned as shown in Figure 1d). The waveguides are again formed by high temperature diffusion with the regions of high Ti concentration becoming the high index waveguide cores as shown in Figure 1e). The MgO diffused into the gaps has the effect of reducing the refractive index and thus strengthens the waveguides. In the regions of overlap, where both MgO and Ti are present, the effects of the diffused materials tend to cancel one another. An indicative index profile is shown in Figure 1f).

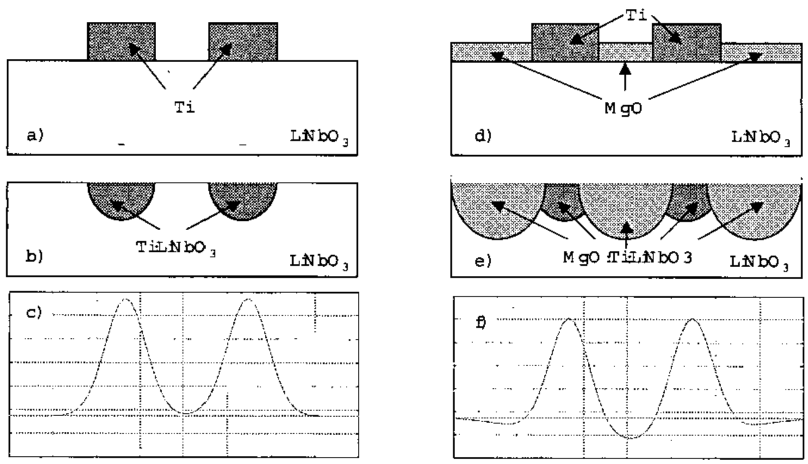

Figure 1: Overview of co-diffusion: a) Patterned Ti on $LiNbO_3$ surface, Ti:$LiNbO_3$ waveguides after diffusion, c) indicative Ti:$LiNbO_3$ refractive index profile; d) patterned Ti and MgO on $LiNbO_3$ surface, e) Ti:MgO:$LiNbO_3$ wavegudies after diffusion, f) indicative Ti:MgO:$LiNbO_3$ refractive index profile

Proposed use in LiNbO3 Mach-Zehnder modulator optimization

A diagram of the cross-section of a Mach-Zehnder optical intensity modulator is presented in Figure 2. The device is switched by inducing a 180° phase shift between the two Mach-Zehnder arms to cause destructive interference at the output. The efficiency of the device depends strongly on the interaction of the applied electric field from the coplanar electrode and the optical fields of the two adjacent Mach-Zehnder arms. The strongest electric field is found at the corners of the central electrode. The ideal situation would be to locate the two optical arms at these electric field maxima. Unfortunately Ti:$LiNbO_3$ optical waveguide modes are generally large and thus the interaction cannot be concentrated in the region of maximum field.

Further, in order to maintain a good extinction ratio, it is important that the two arms of the Mach-Zehnder do not couple. It is thus necessary to isolate the two arms with a significant separation as shown in Figure 2b). In this instance, the device efficiency can be optimised by locating one of the waveguides optimally close to the hot electrode, as shown in Figure 2c) with the other providing only a minor contribution to the modulation. Unfortunately, this asymmetry can lead to temperature instability and can also contribute undesirable phase modulation which is termed 'chirp'.

It is proposed that if the optical mode size can be reduced then the efficiency can be improved by concentrating the light closer to the hot electrode as shown in Figure 2d). Also, if the waveguide isolation can be improved, then the second waveguide may also be brought into its optimal position as depicted in Figure 2e) improving drive voltage, temperature stability and reducing chirp. It is the aim of this investigation to show that MgO:Ti codiffusion can be used to manipulate $LiNbO_3$ waveguides in this manner.

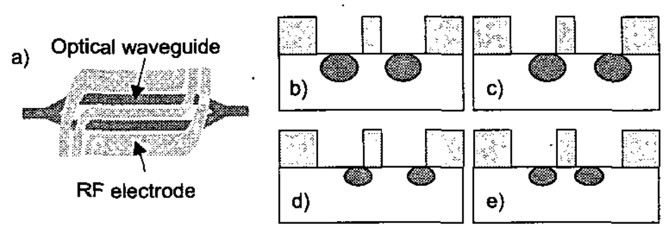

Figure 2: a) Mach-Zehnder modulator, b) symmetric Ti , c) asymmetric Ti, d) asymmetric MgO:Ti, and e) symmetric MgO:Ti waveguide configurations

3. DEVICE FABRICATION

To investigate the impact of MgO diffusion on the optical mode size and coupling of Ti:$LiNbO_3$ waveguides, a range of waveguide samples were prepared and diffused with MgO films of different thicknesses. The test pattern consisted of pairs of waveguides of 7μm width and with separations varying from 8μm to 32μm centre to centre. Samples were 2.5cm long. The waveguides were fabricated in X-cut Y-propagating congruent $LiNbO_3$. A Ti film of 850Å thickness was deposited via electron beam evaporation. Standard photolithography was used to etch the waveguide pattern into the Ti film. The patterned photoresist was retained and a film of MgO was sputter deposited onto the patterned sample. In this way, the MgO film could be patterned using the lift-off technique.

The deposition of MgO was achieved through RF magnetron sputtering using 80W of RF power, a substrate target separation of 3.5cm and in a 7mTorr pure Ar atmosphere. A deposition rate of 40Å/min was observed. Films were thus deposited for 5, 7 and 9 minutes to achieve film of thickness 200, 280 and 360Å respectively. The MgO lift-off was achieved by immersing the samples in a hot acetone ultrasonic bath for 45 minutes followed by an isopropanol and then DI water rinse. The Ti and MgO were then co-diffused into the $LiNbO_3$ for 6 hours at 1025°C. A wet O_2 atmosphere was maintained to suppress LiO_2 out diffusion. The sample end-faces were then mechanically polished and the optical waveguides were characterized using near-field imaging and fibre-to-fibre loss measurements.

4. EXPERIMENTAL RESULTS

Waveguide mode size analysis

Figure 3 presents the horizontal and vertical mode profiles of the Ti:MgO co-diffused waveguides at 1550nm. It is evident that the co-diffusion of MgO has had a significant impact on the confinement of the guided optical mode, particularly in the vertical direction. The mode sizes are summarized in Table 1.

The propagation loss measured for each of the realized waveguides is also presented in Table 1. Since the samples were short (2.5cm) it was difficult to obtain a precise measurement of the attenuation per unit length. It is clear, however, that the indiffusion of MgO has caused a significant increase in the propagation loss. Slight crazing was observed around the waveguides of the MgO samples and it is proposed that this may be responsible for the increased attenuation. The cause of this crazing is currently under investigation. Further research is also required to establish the relationship between propagation loss and MgO thickness.

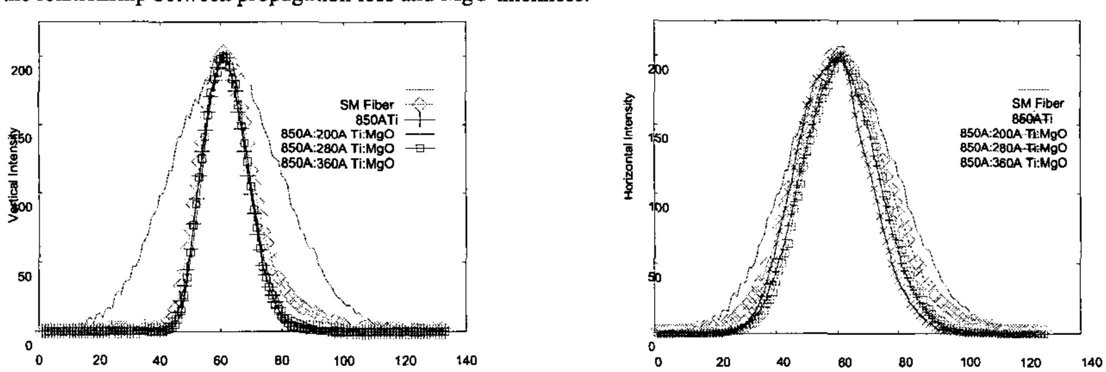

Figure 3: Horizontal a) and vertical b) mode profiles for Ti:MgO codiffused optical waveguides at 1550nm. The profile of a single mode fibre is included for reference.

Table 1: Summary of optical waveguide properties for various Ti:MgO codiffusions

Codiffusion parameters	Horizontal size (full width, 1/e μm)	Vertical size (full width, 1/e μm)	Propagation loss (dB/cm)	Coupling loss (dB to SM fibre)
850A Ti only	5.79	3.17	0.25	1.34
850:200 Ti:MgO	4.74	2.83	0.70	1.90
850:280 Ti:MgO	4.72	2.80	1.03	1.90
850:360 Ti:MgO	4.58	2.64	0.56	2.26

Waveguide coupling analysis

Figure 4a) presents the optical power measured at the output of pairs of waveguides as a function of their separation for a number of MgO diffusion conditions. It is evident that a waveguide separation of more than 28μm is required to suppress the coupling between the Ti diffused waveguides. Thus a separation of 30μm is often used in the design of the parallel arms of the Mach-Zehnder modulator devices. Figure 4b) presents the implied coupling length of the adjacent waveguides. It is evident that the MgO:Ti co-diffusion significantly improves the isolation of the waveguides with a separation of only 20μm needed to approach the isolation of the Ti only sample with a separation of 30μm.

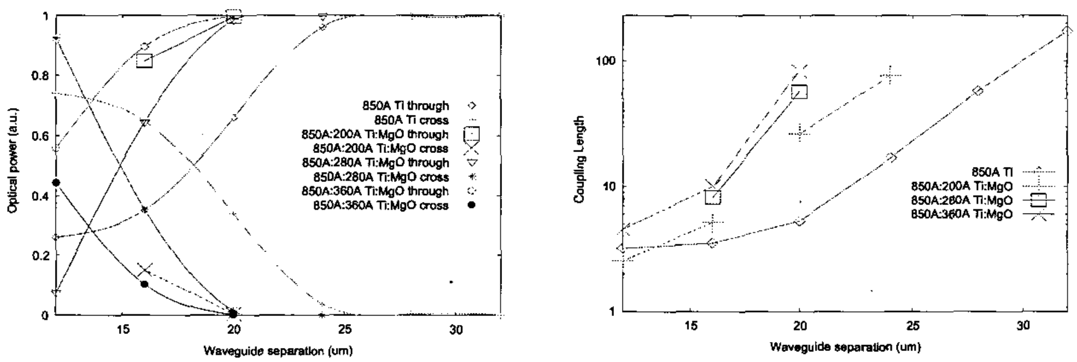

Figure 4: a) Coupled and transmitted optical power vs. waveguide separation, b) implied coupling length vs. separation

5. SUMMARY

We have demonstrated the use of MgO:Ti co-diffusion as a technique for controlling both the mode size and isolation of LiNbO3 optical waveguides. A significant reduction in the size of the optical mode has been observed, particularly in the vertical direction. Reduced coupling between adjacent waveguides has also been achieved with MgO:Ti co-diffusion. An increase in optical propagation loss has been observed, however further research is required to identify the source of this attenuation. It has been proposed that after further development, this technique may be applied to the optimisation of drive voltage and temperature stabilisation of Mach-Zehnder optical intensity modulators.

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