2168

Submitted to CLEO Pacific Rim 2001 on 17th Jan 01

Non-reciprocal transmission in a direct-bonded photorefractive Fe:$LiNbO_3$ waveguide buried in MgO:$LiNbO_3$.

Corin B. E. Gawith, Gary Cook*, Ping Hua, and Peter G. R. Smith.

Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, UK. Email: cbeg@orc.soton.ac.uk
**Defence Evaluation and Research Agency, St. Andrews Road, Great Malvern, Worcestershire, WR14 3PS, UK.*

Abstract: We report a 20-μm-thick Fe:$LiNbO_3$ waveguide buried in MgO:$LiNbO_3$ by direct bonding. Non-reciprocal transmission measurements in a 3-mm-long device with a cw 532 nm source gave a relative change in optical density of 2 and response time of 4-5 milliseconds.

Non-reciprocal transmission [1] has received considerable attention as a means of achieving rapid optical limiting of low power continuous wave (cw) lasers, necessitating the development of efficient photorefractive materials and devices. Iron-doped lithium niobate (Fe:$LiNbO_3$) is an important photorefractive crystal which features an exceptionally high optical small signal gain coefficient of up to 100 cm^{-1} [2]. In a simple focal plane geometry this has led to reported changes in optical density (ΔOD) of up to 4 with 1/e switching speeds of a few milliseconds [3]. At lens apertures below f/20, bulk Fe:$LiNbO_3$ crystals have been found to work exceedingly well in a focal plane geometry. However, at wider apertures the degree of optical limiting decreases rapidly, becoming negligible towards f/1 [3]. This effect is thought to arise from competition with the dark conductivity, which reduces the effective optical interaction length within the Fe:$LiNbO_3$ crystal [3]. An ideal solution is therefore to replace the bulk crystal with a photorefractive optical waveguide in which the interaction length can be made arbitrarily long and the focussed intensity is no longer related to the effective interaction length.

This paper describes our initial study towards producing an Fe:$LiNbO_3$ photorefractive waveguide device buried in MgO:$LiNbO_3$ by direct bonding (DB) [4,5]. DB is a fabrication technique used to create low-loss, seamless, vacuum tight bonds between dissimilar material layers, and has been previously used in the design and realisation of efficient lithium niobate waveguide devices [6]. Here, the combination of photorefractive Fe:$LiNbO_3$ waveguide with direct-bonded non-photorefractive MgO:$LiNbO_3$ cladding layers has resulted in an efficient buried waveguide device for optical limiting experiments.

Fabrication of the device began with a sample of $LiNbO_3$ doped with 0.08 molar % of iron, a value previously investigated for good optical limiting performance [7]. Magnesium-doped lithium niobate (MgO:$LiNbO_3$) was chosen for both the substrate and cladding layers of our buried waveguide device as this material has a refractive index lower than that of either undoped lithium niobate or Fe:$LiNbO_3$ [8] and features similar thermal properties to those of the iron-doped waveguide layer. MgO doping also suppresses the photorefractive effect, ensuring that non-reciprocal transmission will only be observed in the buried waveguide region of our device. For this experiment 5 molar % of magnesium was added to the melt during crystal growth, a value associated with photorefractive resistance in lithium niobate [9].

From each crystal type a 1-mm-thick x-cut substrate of 6 mm × 6 mm surface area was diced and polished to provide an optically flat surface suitable for DB. After cleaning, a mixture of H_2O_2-NH_4OH-H_2O (1:1:6), followed by several minutes of rinsing in deionised water, was applied to both materials in order to render their surfaces hydrophilic [10]. The Fe:$LiNbO_3$ and MgO:$LiNbO_3$ layers were then brought into contact at room temperature, with both samples aligned along the same crystalline orientation. Annealing of the bonded sample at 350 °C for 6 hours provided a sufficient bond strength for further machining and the Fe:$LiNbO_3$ region was then polished down to obtain a waveguiding layer of 20-μm-thickness. A further cladding layer of MgO:$LiNbO_3$ was then added with the same procedure as above. The device was completed by removing any residual unbonded regions with dicing equipment and polishing the end faces of the waveguide to a parallel optical finish. The final device dimensions are given in Figure 1.

Measurement of non-reciprocal transmission in our Fe:$LiNbO_3$ waveguide was performed using two-beam coupling in a counter-propagating beam geometry. This allows the signal beam to be derived from the weak Fresnel reflection of the incident beam at the exit face of the crystal [7]. The device was inserted into the beam along the z-axis of the crystal, providing access to the material's highest effective electro-optic coefficient, $r_{eff} = \pm r_{13} \approx 9.6$ pm V^{-1} [3]. A 532 nm frequency-doubled YAG source was focussed onto the front face of the buried Fe:$LiNbO_3$ waveguide with an f/5 spherical lens. A fast-response shutter mechanism was used to block the pump beam prior to each crystal exposure and a photodiode

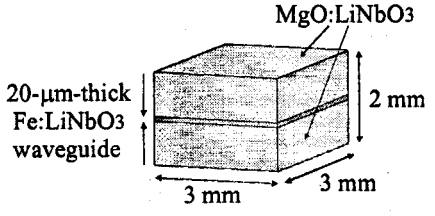

FIG.1: Schematic diagram of the direct-bonded Fe:$LiNbO_3$ buried planar waveguide device.

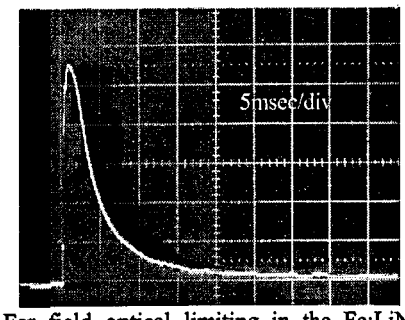

FIG.2: Far field optical limiting in the Fe:$LiNbO_3$ buried waveguide at 80 kW cm^{-2} peak focused intensity at 532 nm.

was used to measure the transmission characteristics of the device. Upon exposure, the pump transmission in the waveguide declines due to the formation of a volume reflection grating in the photorefractive material as the pump and reflected signal beams interfere. At high intensities (photogeneration rate >> erasure rate from the dark conductivity), optical limiting occurs with a response time inversely proportional to intensity such that the rate of decline is rapid at first but becomes progressively slower as the intensity declines at the rear of the device. This effect is demonstrated in the oscillograph of Figure 2. From this trace, the relative change in optical density (ΔOD) of our photorefractive waveguide was calculated as 2, with a 1/e response time of 4-5 milliseconds for an input peak focused intensity of approximately 80 kW cm^{-2}. The intensity required to achieve millisecond order response times was higher than expected from similar experiments with bulk crystals, indicating a change in local material properties during the direct bonding process.

Investigation of the material properties of our waveguide was performed using a scanning electron microscope (SEM) which measured iron and magnesium concentrations across the polished end face of our device, the results of which are given in Figure 3. The graph shows significant inter-diffusion of the iron and magnesium ions across the two bonded interfaces of the sample, indicating ion-exchange between the atomically-contacted substrate layers. Such a change in chemical composition is due to the high-temperature annealing used in DB [11] and represents degradation in the optical

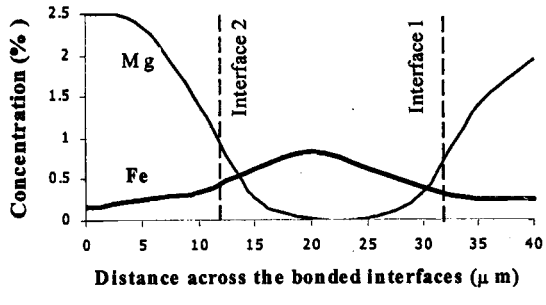

FIG. 3: Chemical composition versus distance across the direct-bonded interfaces of the device.

limiting efficiency of the Fe:$LiNbO_3$ layer. For example, reduced iron content leads to reductions of the charge generation and recombination rate, the electron trap density and photoconductivity, reducing the coupling gain and slowing down the response time of the photorefractive material. Further, the presence of magnesium at the edges of the buried waveguide suppresses the photorefractive effect in these areas, reducing the active volume within the passive waveguide. This reduces the average two-beam coupling gain and increases the input intensity needed to achieve a given reduction in optical transmission. However, optimisation of material composition and annealing conditions should reduce these effects in future devices.

In conclusion, we report the fabrication of a 20-μm-thick photorefractive Fe:$LiNbO_3$ waveguide buried in MgO:$LiNbO_3$ by direct bonding and precision polishing techniques. Characterisation of optical limiting in this device was performed using two-beam coupling in a counter-propagating beam geometry with a 532 nm cw frequency-doubled YAG laser source. For an input peak focused intensity of approximately 80 kW cm^{-2} a relative change in optical density of 2 and a response time of less than 5 milliseconds were achieved using f/5 focusing optics. This result represents an efficient waveguiding structure allowing access to wide aperture imaging systems for high speed optical limiting applications.

The Optoelectronics Research Centre is an interdisciplinary research centre supported by the Engineering and Physical Sciences Research Council (EPSRC). This work has been supported by a DERA funded CASE award.

References:

[1] A. Krumins, Z. Chen, and T. Shiosaki, *Opt. Comm.* **117**, p147-150, 1995.

[2] G. Cook, C. J. Finnan, and D. C. Jones, *Appl. Phys. B.* **68**, p911-916, 1999.

[3] G. Cook, D. C. Jones, C. J. Finnan, L. L. Taylor, and A. W. Vere, *SPIE Proc.* **3798**, p2-16, 1999.

[4] J. Haisma, B. A. C. M. Spierings, U. K. P. Biermann, and A. A. van Gorkum, *Appl. Opt.* **33**, p1154-1169, 1994.

[5] A. Plößl, and G. Kräuter, *Mat. Sci. Eng.* **R25**, 1-2, p1-88, 1999.

[6] C. B. E. Gawith, D. P. Shepherd, J. A. Abernethy, D. C. Hanna, G. W. Ross, and P. G. R. Smith, *Opt. Lett.* **24**, 7, p481-483, 1999.

[7] G. Cook, J. P. Duignan, L. L. Taylor, and D. C. Jones, *SPIE Proc.* **4106**, p230-244, 2000.

[8] J. Noda, M. Fukuma, and S. Saito, *J. Appl. Phys.* **49**, p3150-3154, 1978.

[9] T. Volk, N. Rubinina, and M. Wohlecke, *J. Opt. Soc. Am. B.* **11**, 6, p1681-1687, 1994.

[10] Y. Tomita, M. Sugimoto, and K. Eda, *Appl. Phys. Lett.* **66**, p1484-1486, 1995.

[11] C. B. E. Gawith, T. Bhutta, D. P. Shepherd, P. Hua, J. Wang, G. W. Ross, and P. G. R. Smith, *Appl. Phys. Lett.* **75**, 24, p.3757-3759, 1999.