Waveguide lasers in (Yb,Nb):$RbTiOPO_4$

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***Abstract*—In this paper we present lasing results with a planar (Yb,Nb):$RbTiOPO_4$ waveguide device. We also demonstrate channel waveguiding in an ion-beam etched (Yb,Nb):$RbTiOPO_4$ thin film for the first time with a loss of 2.4 dB/cm. To reduce the losses, a study of reactive ion etching of $RbTiOPO_4$ was carried out resulting in structures with a surface roughness of 6.6nm and an etch rate of 13nm/minute.**

Keywords- liquid phase epitaxy, waveguide, laser, $RbTiOPO_4$, ion-beam milling, reactive ion etching

I. INTRODUCTION

Ytterbium (Yb^{3+}) doped materials are very good active media for making power-scalable solid-state lasers operating around 1μm as they have a broad absorption band suitable for diode pumping, a small quantum defect (thus a lower thermal load), a long lifetime and almost no losses due to up-conversion and excited state absorption. Efficient laser operation has been demonstrated in a number of Yb^{3+}-doped crystals [1], and this has recently included Yb^{3+}, Nb^{5+} co-doped bulk RTP [2]. $RbTiOPO_4$ (RTP) belongs to the $KTiOPO_4$ (KTP) family of orthorhombic crystals, which have various applications in non-linear optics. When doped with Yb^{3+}, RTP crystals have a broad emission bandwidth making them very promising candidates for ultrashort pulse generation with pulses as short as 155 fs being demonstrated [3]. Fabrication of these lasers in a waveguide geometry is of interest for making compact ultrafast laser sources with high repetition rates for applications such as metrology [4] or biological imaging [5]. The nonlinear properties of the host crystal also offer the potential for self-frequency-doubling [3]. Towards these goals, liquid phase epitaxy (LPE) has been used to fabricate thin-film planar waveguides exhibiting a loss of 0.7 dB/cm [6]. In this paper, we present the first lasing results with an LPE (Yb,Nb):RTP planar waveguide. We then discuss the fabrication of rib waveguides in an LPE-grown (Yb,Nb):RTP film by ion-beam milling, and finally we describe the etching of RTP substrates by reactive ion etching (RIE).

II. FABRICATION AND RESULTS

A. (Yb,Nb):RTP planar waveguide laser

An 11μm-thick (Yb,Nb):RTP film was grown on an RTP substrate for the planar waveguide laser experiments. The doping concentration for Yb^{3+} ions is $2x10^{20}cm^{-3}$. The measured refractive index contrast is 0.006 and this waveguide supports 3 modes at 1μm. Co-doping with Nb^{5+} allows a higher concentration of Yb^{3+} due to charge compensation [7]. The planar waveguide was pumped by a Ti:sapphire laser operating at 900nm to correspond with the absorption peak for (Yb,Nb):RTP with the electric field polarised parallel to the c-axis. Thin dielectric mirrors were butted directly onto the waveguide end-faces to form the laser cavity. Using an optical chopper to chop the pump source, the characteristic rise and decay of the fluorescence intensity was monitored on a photodiode. On increasing the pump power, a fast and very strong increase in intensity indicated the point at which laser threshold had been achieved. A threshold absorbed power of 276 mW was observed for an HR/HR cavity. Insufficient pump power prevented us from measuring values of slope efficiencies, however, experiments with a high-power laser diode pump are ongoing at the moment and results obtained will be discussed at the conference.

B. Ion- beam milling of Yb:RTP

The laser threshold should be reduced by fabricating channel waveguides within the thin film as long as the waveguide propagation losses are not increased to too high a level. This is especially important in (Yb,Nb):RTP as the Yb^{3+} doping level, and hence maximum gain, is relatively low [2]. As an initial trial, ion-beam milling was used to fabricate rib waveguides in a 5μm-thick (Yb,Nb):RTP film grown on an RTP substrate by LPE. A photoresist layer was spun on the (Yb,Nb):RTP layer, which was then exposed to UV light through a chromium mask. Subsequent development of the resist resulted in the mask pattern being transferred onto the photoresist layer. This was then etched using Ar^+ ion beam milling and after removal of the resist (by plasma ashing), rib waveguides were formed in the active layer. The sample was etched for 2 hours and 20 minutes (min) with a current of 100mA and a voltage of 500V resulting in an etch depth of 3μm. This sample was then edge polished for the waveguiding experiments. The ion-beam milling of the (Yb,Nb):RTP sample resulted in a trapezoidal shaped waveguide with a width of 16μm at the bottom and 6μm at the top.

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900 nm pump light was launched into the waveguide and the fluorescence output was captured by a CCD camera. A filter was used to remove the pump light and the remaining fluorescence intensity is shown in Fig.1. The mode is asymmetric, as expected, with near-Gaussian profiles with $1/e^2$ beam radii of 8.7μm and 3.3μm in the x and y direction respectively. Numerical modeling carried out using OlympIOs software for the trapezoidal features resulted in $1/e^2$ beam radii of 7.4μm and 2.2μm in the x and y direction respectively for the TM_{00} mode. The difference between the measured and simulated mode profile can be due to higher order modes in the waveguide. The fluorescence spectra was measured and was found to be similar to that observed in bulk (Yb,Nb):RTP [3], as was the measured fluorescence lifetime of 2.2 ms. Losses were measured by the Fabry-Perot method [8] and were found to be 2.4 dB/cm which is higher than the value of 0.7 dB/cm reported in a planar (Yb,Nb):RTP waveguide [6]. The increased losses in the waveguide motivated an attempt to optimise the etching process using RIE.

C. Reactive ion etching of RTP

Optimisation of the RIE process was carried out in RTP substrates (which should give similar results to the etching of Yb^{3+},Nb^{5+} co-doped film). A 300nm thick chromium mask was used to transfer the rib features onto the RTP substrate. Etching was carried out with SF_6 and Ar gases and the gas ratio, gas pressure and RF power were varied in order to optimise the etching process. On varying the ratio of the SF_6:Ar mixture, the etching could be varied between a purely physical process (all Ar) and purely chemical (all SF_6). It was found that the surface quality improved when moving away from the physical etching (similar to the Ar^+ ion beam milling process used previously). After measuring roughness and etch rates versus gas ratio, gas pressure and RF power, optimised RIE parameters were found and used to etch rib features in an RTP substrate. The optimised process resulted in an etch rate for RTP of 13 nm/min and for Cr of 2.3 nm/min giving a selectivity of 5.7. The RMS surface roughness was measured to be 2.4nm in the un-etched region and 6.6nm in the etched region which is a very low value from the point of waveguiding applications. The 3-d profile was measured by a non-contact profiler and is shown in Fig.2. It can be seen that the rib has much steeper sides than found by ion-beam milling, having a side wall angle of 57º compared to the 31º described earlier.

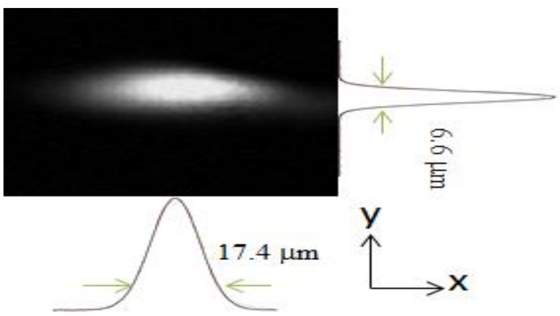

Figure 1. Near field fluorescence intensity for a waveguide etched by ion-beam milling in (Yb,Nb):RTP along with the x and y mode profiles.

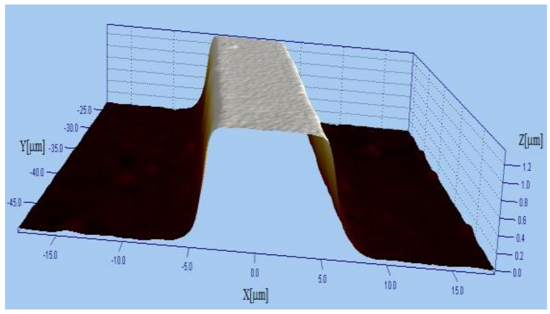

Figure 2. 3-d image of an RIE etched rib feature in RTP

III. CONCLUSIONS AND FUTURE WORK

We have demonstrated lasing in a planar (Yb,Nb):RTP waveguide and will use a higher power diode to pump this waveguide and fully characterise its laser performance. We have also demonstrated rib waveguiding in an ion-beam milled (Yb,Nb):RTP waveguide for the first time but found significantly increased propagation losses. Finally, we have optimised the RIE process in RTP in order to reduce the surface roughness of the etched features and to create steep side walls. Future work will use RIE to produce low-loss rib waveguides in (Yb,Nb):RTP and realise lasers with low threshold powers. Such laser devices could then be the platform for highly compact ultrafast laser sources when combined with integrated passive modelocking elements.

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REFERENCES

[1] W.F. Krupke, "Ytterbium solid-state lasers. The first decade," IEEE J. Sel. Topics Quantum Electron., vol.6, pp.1287-1296, 2000.

[2] X. Mateos, V. Petrov, A. Peña, J. Carvajal, M. Aguiló, F. Díaz, P. Segonds, and B. Boulanger, "Laser operation of Yb^{3+} in the acentric $RbTiOPO_4$ codoped with Nb^{5+}," Opt. Lett., vol. 32, pp.1929-1931, 2007.

[3] J. Carvajal, G. Ciatto, X. Mateos, A. Schmidt, U. Griebner, V. Petrov, G. Boulon, A. Brenier, A. Peña, M. Pujol, M. Aguiló, and F. Díaz, "Broad emission band of Yb^{3+} in the nonlinear Nb:$RbTiOPO_4$ crystal: origin and applications," Opt. Express , vol. 18, pp.7228-7242, 2010.

[4] A. Bartels, R. Gebs, M. Kirchner, and S. Diddams, "Spectrally resolved optical frequency comb from a self-referenced 5 GHz femtosecond laser," Opt. Lett., vol. 32, pp.2553-2555, 2007.

[5] S. Chu, T. Liu, C. Sun, C. Lin, and H. Tsai, "Real-time second-harmonic-generation microscopy based on a 2-GHz repetition rate Ti:sapphire laser," Opt. Express , vol. 11, pp.933-938, 2003.

[6] J. Cugat, R. Solé, M.C. Pujol, J.J. Carvajal, X. Mateos, F. Díaz and M. Aguiló, "Waveguiding demonstration on Yb:Nb:$RbTiOPO_4$/$RbTiOPO_4$ (001) epitaxies grown by LPE", Opt. Mat., vol. 32, pp.1648-1651, 2010

[7] J. J. Carvajal, V. Nikolov, R. Solé, Jna. Gavaldà, J. Massons, M. Aguiló, and F. Díaz, "Crystallization region, crystal growth, and characterization of rubidium titanyl phosphate codoped with niobium and lanthanide ions," Chem. Mater., vol. 14, pp.3136-3142, 2002.

[8] R. Regener and W. Sohler. "Loss in low-finesse Ti-$LiNbO_3$ optical wave-guide resonators." Appl. Phys. B, vol. 36, pp.143-147, 1985.