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SPECTRA AND ENERGY LEVELS OF THE TRIVALENT YTTERBIUM ION DOPED INTO LITHIUM NIOBATE BY THERMAL INDIFFUSION

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ABSTRACT

An X-cut $LiNbO_3$ substrate has been doped with Yb^{3+} ions by thermal diffusion from an Yb metal film of thickness 7nm. Polarised absorption and fluorescence spectra of the dopant ion have been measured using Ti-diffused y-propagating channel waveguides prepared in the doped region. Yb is a diode pumpable laser ion with characteristics that can be compared favourably with those of Nd in some respects; for example the small energy difference between pump and laser photons reduces thermal load facilitating high power operation. A waveguide laser geometry is particularly advantageous for Yb due to the quasi-3-level nature of the laser transition. The simple fabrication technique described here has been used to produce a system which may have the potential to operate as an Yb waveguide laser in an electro-optic host crystal.

INTRODUCTION

Diffusion is a highly flexible technique for doping crystals. $LiNbO_3$ can be readily doped by this method at high temperatures as its Curie temperature is of the order of 1142°C. With this method different dopants and levels of doping can be introduced into undoped wafers of $LiNbO_3$, avoiding the large investment in time and equipment needed to produce bulk doped samples. Diffusion also allows local definition of dopants of different types and concentrations on one substrate. $LiNbO_3$ is of interest for its nonlinear and electro-optic properties, and also because low loss titanium-indiffused waveguides can be fabricated in this material. Channel waveguides in diffusion-doped $LiNbO_3$ have been shown to operate as efficient miniature lasers in Nd-doped $LiNbO_3$ at 1084nm[1] and Er-doped $LiNbO_3$ at 1532[2], 1563 and 1576nm[3]. The linear electro-optic susceptibility has been exploited to produce FM modelocking in a $LiNbO_3$ laser of this type[4]. Furthermore a Nd:$LiNbO_3$ waveguide laser was electro-optically Q-switched, and the output from this frequency doubled via the nonlinear susceptibility in an undoped $LiNbO_3$ waveguide [5]. $LiNbO_3$ titanium-diffused waveguides offer an interesting system for a potential Yb doped laser. The trivalent Yb ion has an energy level structure as shown in figure 1, from which it can be seen that there are only two manifolds. This feature greatly reduces the effects, such as concentration quenching and excited state absorption, that are normally a consequence of high doping levels. Yb^{3+} ions offer a number of other interesting features for laser systems. The pump and signal wavelengths, for example, are separated by only about 100nm. This leads to high pumping efficiencies and low thermal loading of the crystal, as can be seen in Yb:YAG [6]. A feature of Yb^{3+} lasers is that they are quasi-3-level in nature, that is the lower laser level is thermally populated at room temperature. As a consequence,

reabsorption losses at the signal wavelength occur, reducing the laser efficiency. To alleviate this problem the trivalent Yb ion can be incorporated into a waveguide, whereby high pump intensities can be produced using much lower pump powers than would be the case in bulk crystal. Waveguides normally suffer in comparison with bulk lasers since they are generally more lossy. Waveguides in quasi-3-level materials, however, have largely the same loss as the bulk material since the loss is dominated by reabsorption.

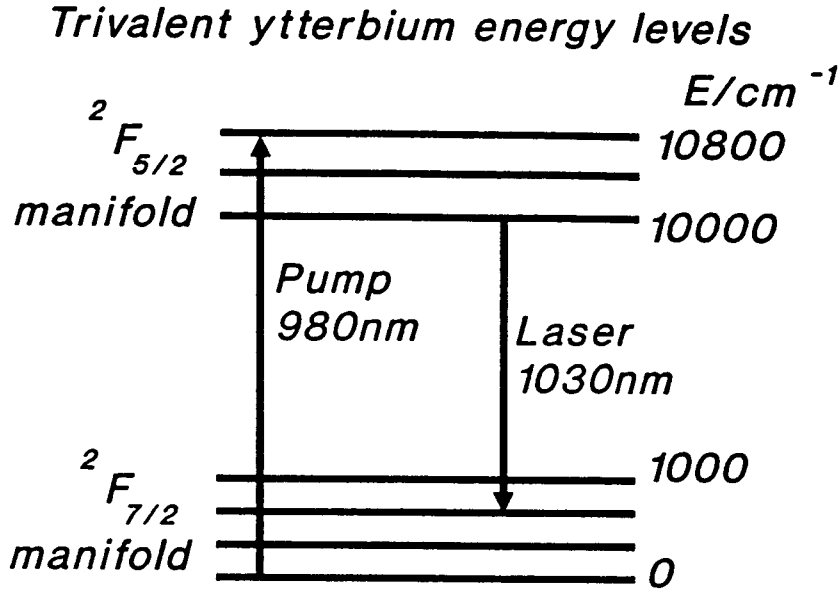

Figure 1

DOPING AND WAVEGUIDE FABRICATION

The diffusion of ions into a substrate can be described by the general diffusion equation(1) [7]:

$$b^2 = 4Dt \quad (1)$$

where b is the diffusion depth into the substrate, t is the diffusion time and

$$D = D_o\exp(-T_o/T) \quad (2)$$

is the diffusion coefficient for Yb^{3+} at a temperature T. The diffusion depth and concentration can be controlled by choosing an appropriate combination of diffusion time, temperature and film thickness. The doping level achievable is limited by the maximum solubility of the ion at that temperature. The resulting diffusion ion concentration profile can be described by a complementary error function with a maximum at the surface[8].

A 7nm layer of Yb metal was deposited on half of the sample using an Edwards evaporation coater. Half of the sample was left undoped to allow fabrication of undoped Ti channels for comparison with the doped channels. The sample was then placed in a tube furnace on a silica boat at 1050°C for 164 hours; a wet (1.5ml water/hour) oxygen atmosphere was maintained by passing the input oxygen through a water bubbler at 1l/min. The wet atmosphere was introduced to slow the outdiffusion of Li_2O from the surface of the $LiNbO_3$, which would otherwise result in an increase in the extraordinary refractive index and hence a planar waveguide for π polarised light. After the rare-earth diffusion a photoresist mask was made,

upon which 50nm of titanium metal was evaporated. The sample was then soaked in acetone to dissolve away the photoresist, revealing a set of 4 to 16μm wide Y-oriented Ti stripes. The titanium metal was then diffused for 9 hours at 1050°C in the same wet oxygen atmosphere. Finally the crystals were end polished perpendicular to the resulting channels to allow efficient end coupling of the pump laser light.

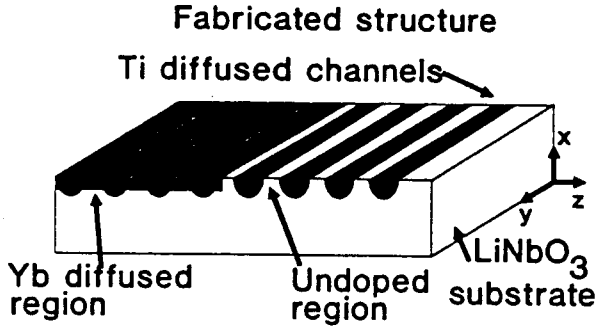

Figure 2

Absorption spectra were taken with the apparatus shown in figure 3. White light was Passed through a Thermo Jarrell Ash monochromator. The light was then fed into the waveguide, as shown, and the resulting transmitted light imaged on a Si diode detector connected to a pre-amp and Stanford SR-510 lockin amplifier. A background correction was then made by recording the output of an undoped titanium channel over the same wavelength range. Polarised spectra were obtained by placing a broadband Glan-Taylor polarising cube in front of the detector. Fluorescence measurements were made by pumping the waveguide with a mechanically chopped Ti:sapphire laser tuned to 956nm. The output from the waveguide was then passed through a monochromator, and the light from the monochromator was then focused onto a Si diode detector. Again polarised spectra were obtained by passing the fluorescence through a Glan-Taylor polarising cube. Fluorescence lifetimes were also taken with this apparatus, except that the detector output was displayed on a digital oscilloscope. When the pump was blocked by the chopper the resulting fluorescence decay could be seen on the oscilloscope. The fluorescence lifetime was deduced from the shape of the decay curve.

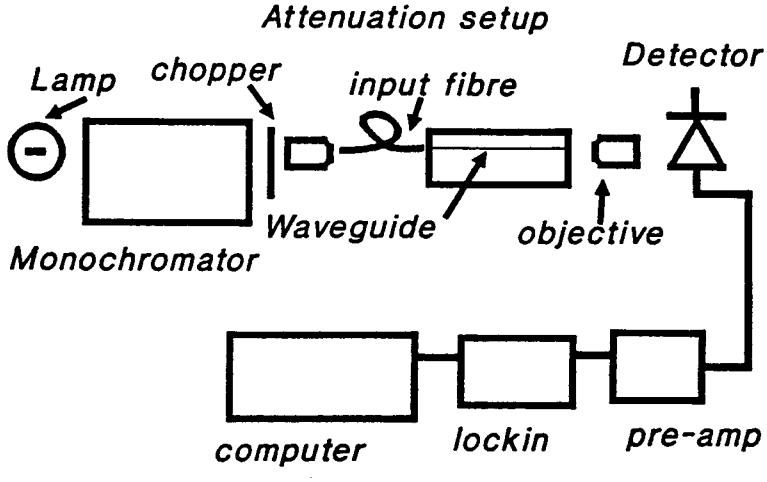

Figure 3

RESULTS AND DISCUSSION

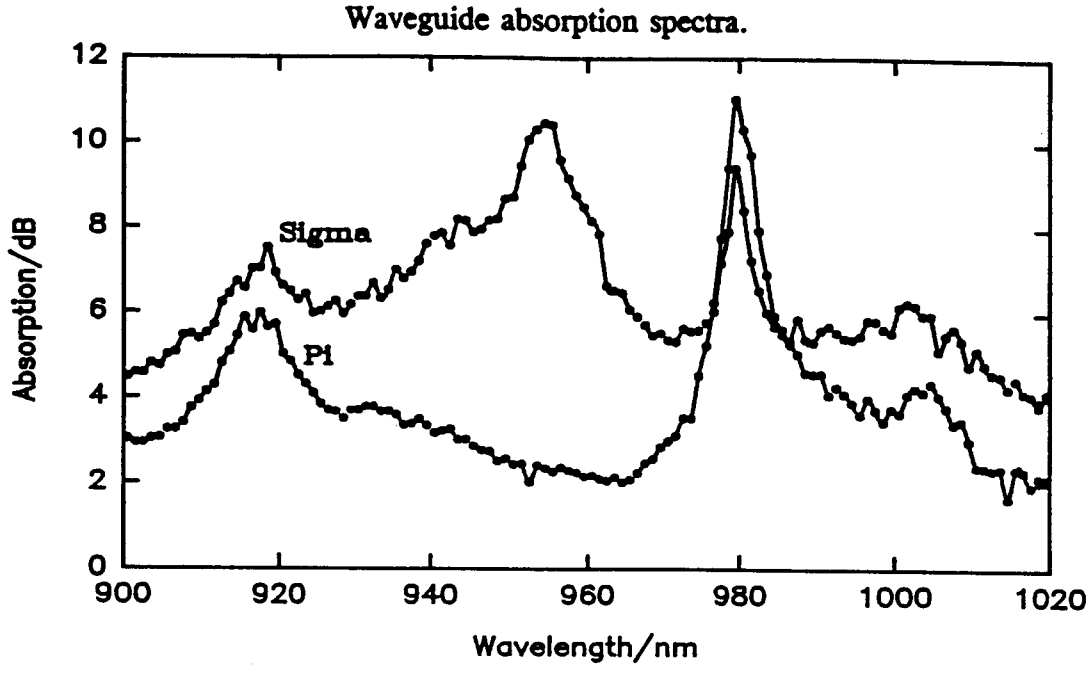

Figure 4.

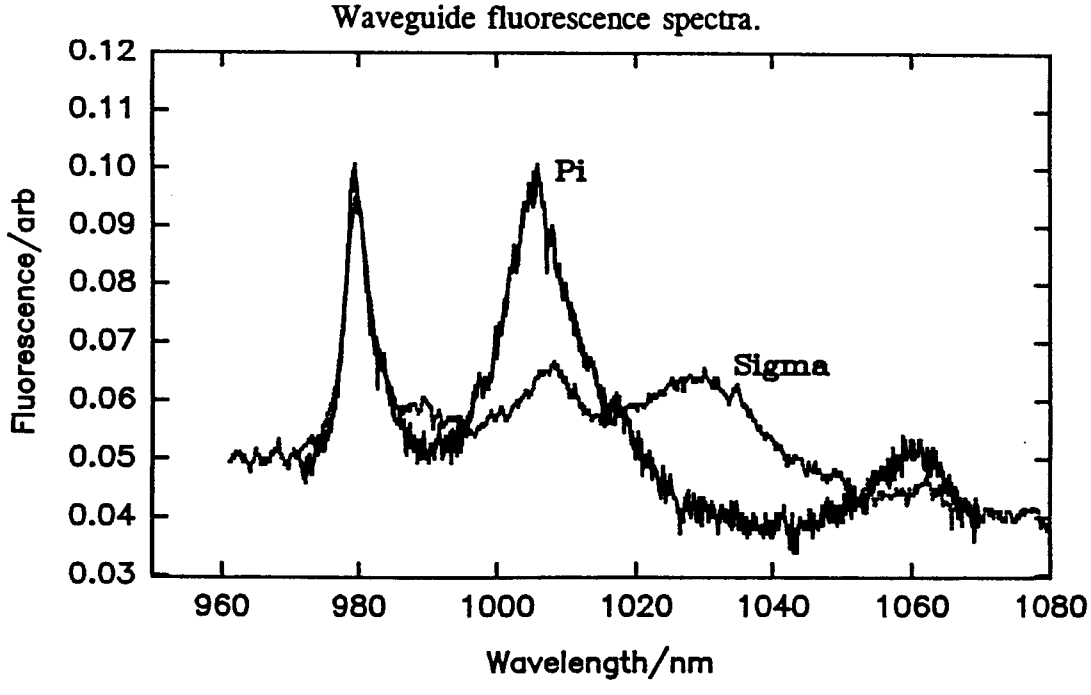

Figure 5

Waveguide Yb:Ti:$LiNbO_3$ absorption spectra for σ-and π-polarised light can be seen in figure 4 above. Three main absorptions, at around 918, 956 and 980nm were observed, and appear to be coincident with those seen in Czochralski-grown bulk doped Yb:$LiNbO_3$[9].The 956nm peak is revealed to be σ-polarised only, whereas the 918 and 980nm absorptions are seen in both σ- and π-polarisations. Polarised fluorescence was observed at 980, 1005, 1030 and 1060nm as shown in figure 5. σ- and π-polarised light was seen at both 980 and 1005nm, and σ-polarised fluorescence seen at 1030nm. The 1060nm emission was π-polarised. From this spectroscopic data an energy level diagram was deduced and is shown in figure 6 below.

Energy levels of diffused Yb^{3+} in Ti:$LiNbO_3$ waveguides

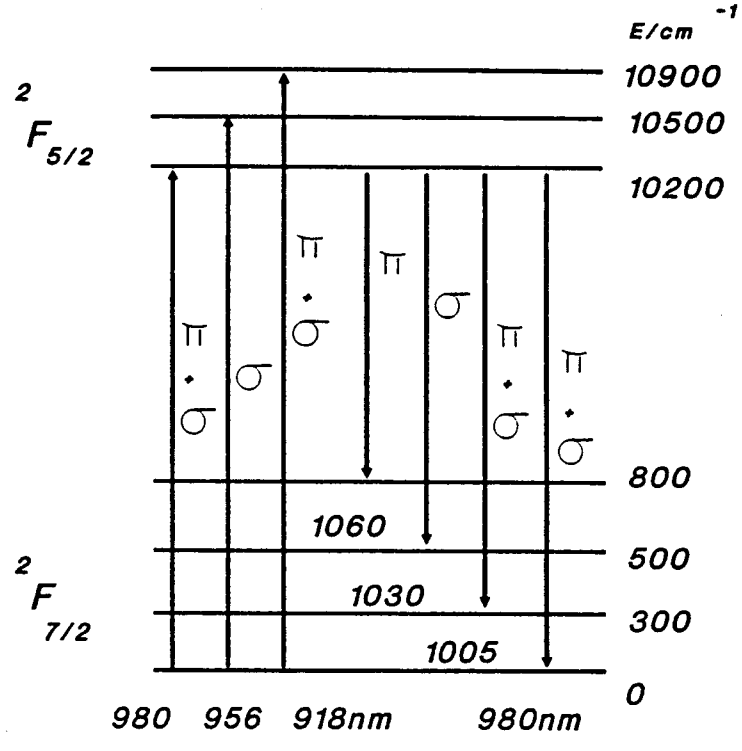

Figure 6

The fluorescence lifetime was found to be around 1ms a figure typical of noncentrosymmetric oxides[10]. Low signal levels, however, prevented us from estimating the lifetime to a higher degree of accuracy. Good agreement was found for the observed polarisations of the absorption and fluorescence and those predicted by group theory. The selection rules of a Yb^{3+} ion in a C_{3v} symmetry lattice site suggest that Yb occupies a Li^+ or Nb^{5+} position, and it is expected to substitute the latter site since other rare earths in $LiNbO_3$ are reported to occupy this position[8].

In a first attempt to obtain lasing, light from a Ti:sapphire laser tuned to 956nm was coupled into a waveguide with a x10 microscope objective. This preliminary experiment was unsuccessful, probably as a consequence of the high($\sim$2 $dBcm^{-1}$)propagation losses seen in both doped and undoped waveguides, high end losses and only modest levels of gain in the doped waveguides resulting from the quite low ($\sim 2.5 \times 10^{19}$ cm^{-3})Yb^{3+} dopant level. The high loss is thought mainly to be due to the poor initial optical quality of the $LiNbO_3$ used. Also further losses were induced by the pump laser via the photorefractive effect-a light induced nonuniform change in the refractive index of the waveguide. This was reduced by heating the substrate to

>150°C so as to anneal the light induced space charge responsible for the photorefractive loss. Surface defects, which have been a major loss factor in some of our past indiffused $LiNbO_3$ wafers, were thought to contribute only a very minor loss in this sample as the surface had low numbers of defects when compared to samples diffused in dry oxygen in the same apparatus. The waveguide processing resulted in a well-confined single mode at the pump and fluorescence wavelengths for σ-polarised light. The spot size for this mode, which is defined as the radial distance from the peak intensity in the guide to the point at which the intensity had fallen to $1/e^2$ of this value, was calculated from the output beam divergence, and this was measured on a Big-sky beam profiler. At 950nm the mode had a spot size of 4μm horizontally and 5μm vertically, and at 1030nm the spot size of the mode was 4μm horizontally and 4μm vertically. The π polarised light was found to couple readily from the titanium channel into the lithium outdiffused planar guide which led to very high losses for this polarisation.

SUMMARY AND CONCLUSIONS

Yb^{3+}-diffused $LiNbO_3$ has been prepared and studied in titanium diffused channel waveguides and was found to be spectroscopically similar to Czochralski-grown bulk-doped Yb^{3+}:$LiNbO_3$. Yb^{3+} was determined to exist in a C_{3v} symmetry site in the waveguide structure, and hence probably exists in the Nb^{5+} position as do other rare earths in $LiNbO_3$. The titanium diffused channels produced a well confined single mode output for σ-polarised light whilst the π-polarised light was coupled into the Li^+-outdiffused planar layer. Laser action was prevented by a combination of the poor optical quality of the $LiNbO_3$ used and the modest levels of gain available from the low Ytterbium concentration present in the guide. Work is currently underway in superior quality substrate material with higher Yb^{3+} doping levels from which lasing is expected.

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