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A 900nm Nd:Ti:$LiNbO_3$ waveguide laser.

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Abstract

The first laser operation of Nd^{3+} doped $LiNbO_3$ around 900nm is reported. An absorbed power threshold of 26mW was obtained when the device was pumped at 814nm. The design of the waveguide geometry to favour laser operation at this wavelength is demonstrated.

Neodymium-doped solid-state lasers which operate on transitions in the $^4F_{3/2}\rightarrow^4I_{9/2}$ band around 0.9μm are potentially interesting as compact sources for frequency doubling into the blue [1-2]. The challenge is to arrange sufficiently intense pumping for these quasi-three-level transitions which operate on the thermally-populated levels of the $^4F_{9/2}$ ground manifold, while at the same time suppressing lasing on the competing four-level $^4F_{3/2}\rightarrow^4I_{11/2}$ transition near 1.1μm which, under strong pumping, may exhibit an order of magnitude more gain. A waveguide resonator is particularly suited to such quasi-three-level transitions, as the reabsorption losses tend to dominate any propagation losses present from the guiding structure [3].

$LiNbO_3$ is an attractive choice as a host matrix for this transition by virtue of the straightforward techniques by which channel waveguide lasers can be fabricated [4-7]. There is currently keen interest in the periodic poling of $LiNbO_3$, which has been used to produce efficient quasi-phase-matched non-linear optical devices [1,8]. A self-frequency-doubled, compact, waveguide laser source is thus feasible in this material.

In this letter we demonstrate lasing behaviour around 0.9μm in a waveguide laser fabricated in $Nd:LiNbO_3$. We also discuss the use of the cut-off behaviour characteristic of diffused channel waveguides to control the wavelength dependent propagation losses and so eliminate the parasitic lasing of the 1.1μm transition. The performance of the lasers is severely curtailed by photorefractive effects which become stronger as the wavelength is reduced. It is clear, however, that the sensitivity of LiNbO3 to photorefractive damage can be reduced with appropriate MgO doping [5], periodic poling [9], annealed proton exchanged waveguides [10] or thermal annealing treatments [9] which could provide scope to improve the performance of the devices described.

The cleaned x-cut $LiNbO_3$ substrate was initially coated with an 8±2nm planar layer of Nd in an Edwards thermal evaporator. The sample was then heated to 1090°C for 240 hours in an O_2 atmosphere with a flow rate of 0.5l/min. This caused the Nd layer to diffuse into the $LiNbO_3$, resulting in a surface concentration of $\sim 10^{20}$ ions/cm^3 and a 1/e diffusion depth of 5.3μm as estimated from the data in reference [11]. In order to fabricate the waveguides, a layer of Ti was deposited on the sample and standard photolithographic techniques were used to realise stripes of various widths along the y-axis of the substrate. The sample was then heated in an O_2 atmosphere to 1005°C resulting in the indiffusion of the Ti to form channel waveguides.

The waveguide fabrication details are shown in table 1 for two samples labelled sample 1 and sample 2, used in this study. Sample 1 was fabricated using techniques for the fabrication of waveguides in Nd-doped $LiNbO_3$ we have used previously [12]. The waveguides fabricated in sample 2 which came from a separate wafer, were designed to manipulate the intrinsic cut-off behaviour of indiffused waveguides to produce high propagation losses around 1.1μm, whilst leaving the guides low loss at 0.9μm. In the discussion below, channels are referenced by the initial width of the Ti stripe from which they were formed.

In order to test the lasing behaviour of the samples, the crystals were polished to realise parallel endfaces and pumped using a cw Ti:Al_2O_3 laser at 814nm, the output from which could be rotated into either the σ or π polarisation. The light was end-launched into the waveguides using a X10 microscope objective. Optical feedback was provided either by the Fresnel reflections from the endfaces of the waveguide or by the attachment of thin mirrors to the endfaces using the surface tension of a thin layer of fluorinated liquid. Detection was provided either by the use of a large area Si detector or, where exact wavelength detection was required, an OMA 2000 scanning spectrometer.

Sample 1 was cut and polished to a length of 15mm and pumped with σ-polarised 814nm light. With feedback provided from the endfaces of the waveguide (~14% reflectivity), lasing was obtained at 1084nm. The output power was observed to be unstable due to photorefractive damage. When the pump beam was chopped at 90Hz with a 30:1 duty cycle, stable laser output was observed. The launch efficiency of the pump, measured by tuning the pump laser off the Nd absorption and assuming propagation losses of 0.4dB/cm, was found to be 56±7%. This enabled a slope efficiency of 52±6% with respect to launched pump power and a threshold of 18±2mW of launched pump power to be determined for the 1084nm transition in a 6μm waveguide.

In order to reduce reabsorption losses on the $^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition and encourage lasing around 900nm, sample 1 was cut down to a length of 6mm and repolished. A laser cavity was formed using mirrors with a high reflectivity (>99%) around 0.9μm and low reflectivity (≈14%) around 1.1μm. However even in these short length devices, the 14% residual reflectivity of the mirrors at 1.1μm was enough to make the guides lase at 1.084μm. No lasing was observed around 0.9μm. Sample 1 was then further reduced in length to 2mm. A cavity was formed using the same mirrors and the guide was pumped using a chopped 814nm beam in the π polarisation. Lasing was observed at 902nm in all of the waveguides. In some of the multimode guides simultaneous lasing was observed at several wavelengths, for reasons which are not yet fully understood. Figure 1 shows the spectrum of laser emission from a 10μm guide. Lasing peaks can be seen in this figure at 889nm, 902nm, 915nm and 927nm corresponding to transitions of the different Stark levels of the $^4I_{9/2}$ multiplet of the Nd $^{3+}$ion [13]. Under certain launch conditions lasing could be observed around 1.1μm in some waveguides. The 0.9μm lasing observed was very short-lived, typically lasting a few seconds due to severe photorefractive damage. When the guides were pumped with σ-polarised light, the lasing behaviour was slightly more stable allowing a launched pump power threshold of 52mW (~25mW absorbed power) to be measured for a 10μm wide guide lasing at 902nm. Even in this case however, the degradation of the lasing behaviour precluded other measurements of laser performance on this transition.

The photorefractive damage was such that lasing could not be restarted in a guide which had previously been damaged, even after an interval of 24 hours. Following the method of reference [14], a 3.5-hour anneal at 360°C with oxygen flowing at 0.5 l/min was carried out on sample 1 and whilst no permanent reduction in susceptibility to photorefractive induced damage was observed after this process, the guides could again be made to lase with an unstable performance similar to that obtained before.

The short length of sample 1, whilst reducing problems with parasitic lasing around 1.1μm, results in low pump absorption. Indeed, the absorption length in this sample, obtained from the measurement of the transmitted pump at low power, was found to be (4.1±0.2)mm and so high pump powers which further exacerbate photorefractive problems have been required. Sample 2 has been designed so that the waveguide geometry eliminates the parasitic lasing allowing longer crystal lengths to be used, thereby reducing the pump power requirements.

Fig 2 shows white light attenuation spectra in the range 800nm-1150nm of a sequence of 5 channel waveguides which increase in steps of 1μm from 2.9μm - 6.9μm. The spectra were measured using a standard white light setup as described in reference [15]. The measurement was made on a 4mm length of sample 2. The attenuation values include an undetermined coupling loss and so they are higher than the internal values of the propagation loss in this sample. Each curve shows the Nd absorption band around 814nm and absorption losses around 900nm as expected. Each curve also shows a large increase in loss with wavelength above a certain critical value. We interpret this as evidence for progressively weaker guidance of the mode as it approaches cut-off, an interpretation which is supported by the manner in which the onset of this loss shifts to shorter wavelength as the guide width is reduced. The two narrowest guides appear to show increased background losses far from cut-off, but this may be due only to decreased coupling efficiency.

The lasing experiments described for sample 1 were repeated for a 4mm length of sample 2 using a chopped, π-polarised pump beam and the same high reflecting 900nm mirrors. It was immediately apparent that a high level of photorefractive damage was being produced in this sample. By optimising the pump launch, it was possible to observe lasing around 900nm in guides with widths from 7.5μm-6.3μm. The lasing lasted for less than one second, and after the guides had 'flash' lased, no further lasing could be observed. However, no parasitic lasing around 1.1μm was observed at any stage using these waveguides and the 900nm mirrors. After subjecting the damaged guides to the annealing process described earlier, attempts were made to obtain lasing around 1.1μm using appropriate high reflectivity mirrors. Lasing behaviour was then observed in the 7.1μm wide waveguide alone. Again, the lasing was very short lived, lasting for less than one second.

The very high level of photorefractivity present in this sample has adversely affected the results obtained even compared to the results from sample 1. This is in line with other observations we have made where photorefractivity has been found to vary greatly from sample to sample. We have shown that no parasitic lasing occurs around 1.1μm when high reflectivity 900nm mirrors are used. Lasing around 1.1μm has been suppressed to such a degree that even with highly reflecting mirrors at this wavelength , it is very hard to observe, whereas it is relatively easy to obtain 900nm lasing, although it is very short lived.

In conclusion we have demonstrated lasing on the $^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition around 900nm in Nd-diffused Ti:$LiNbO_3$ for the first time to our knowledge. Four laser lines at 927nm, 915nm, 902nm and 889nm have been observed, corresponding to prominent features in the fluorescence spectrum of this transition. Parasitic lasing on the high-gain 1.1-μm transition has been shown to be a problem, which can be partially controlled by using wavelength selective mirrors and by restricting the length of the gain medium. This reduces both the gain at 1.1 μm and the reabsorption losses at 0.9 μm. These measures did not fully eliminate the parasitic lasing; moreover high pump powers were required by the short device in which pump absorption was incomplete, increasing the level of photorefractive damage in the sample and leading to unstable lasing characteristics.

An alternative method of eliminating the parasitic lasing, in which the intrinsic 'cut-off' loss spectrum of the waveguide was manipulated via the width of the channel, has been investigated.

White light loss spectra measured for sets of channels with incrementally varying widths illustrate that it is practical to introduce an excess propagation loss at 1.1 μm which more than compensates for the ground state reabsorption loss at 0.9 μm. Lasing results from these channels appear to confirm this measurement, although this sample exhibited a high level of photorefractive damage, making it impossible to infer propagation losses from the lasing characteristics.

The lasers we have described have been affected by photorefractive damage, and future work must first address this problem perhaps using the techniques described earlier. Periodic poling of such devices could then yield simple designs for monolithic, intracavity frequency doubled, channel waveguide lasers.

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Table Captions

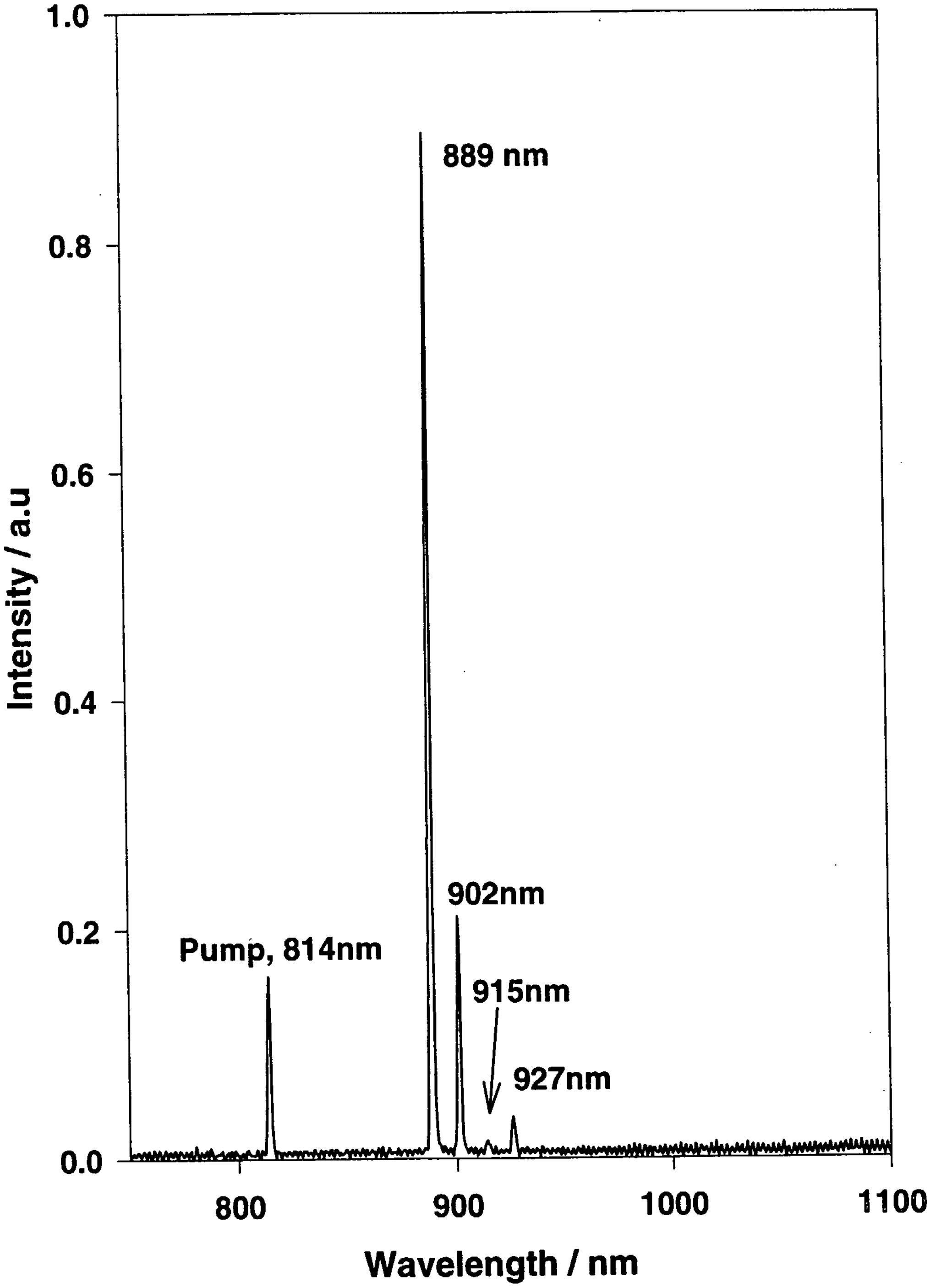
Table 1 Waveguide fabrication details for samples used in this study.

Sample	Channel Widths	Ti Depth	Indiffusion Time
1	3-16μm 1μm Steps	95nm	9 hours
2	1.5-7.5μm 0.2μm steps	41nm	6 hours

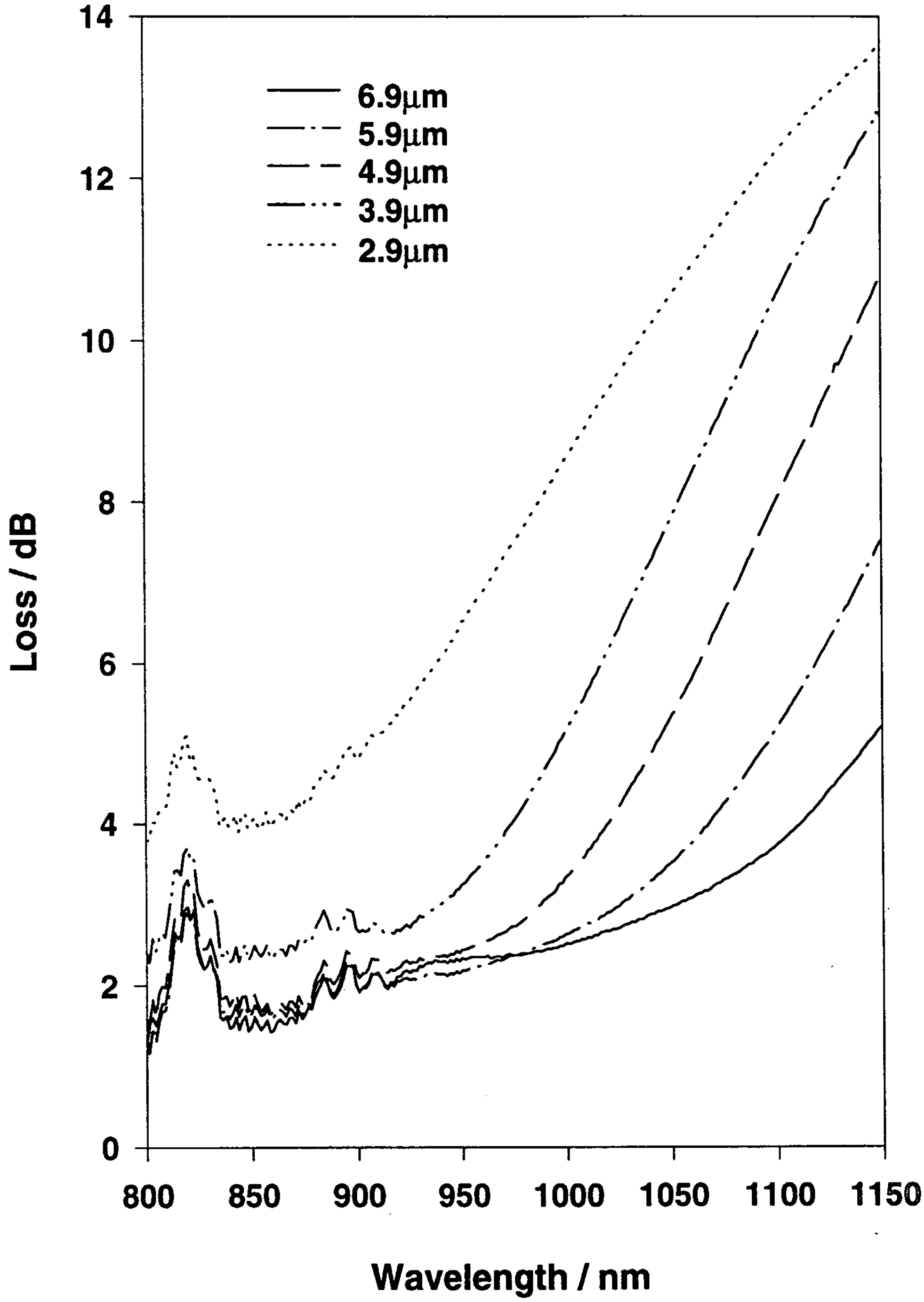
Figure Captions

Figure 1 Spectrum of output from a 2mm long, 10μm wide channel in sample 1 including lasing at four wavelengths and the unabsorbed pump. The laser resonator is formed by mirrors with a high reflectivity around 900nm butted to the endfaces.

Figure 2 Spectrum of total transmission loss in the 800nm - 1250nm region of channels in sample 2 with widths, 2.9, 3.9, 4.9, 5.9 and 6.9μm.



1.0
0.8
0.6
0.4
0.2
0.0
Intensity / a.u
889 nm
902nm
915nm
927nm
Pump, 814nm
800
900
1000
1100
Wavelength / nm



6.9µm
5.9µm
4.9µm
3.9µm
2.9µm
Loss / dB
Wavelength / nm
0
2
4
6
8
10
12
14
800
850
900
950
1000
1050
1100
1150