



A Ti: Sapphire Planar Waveguide Laser Grown by Pulsed Laser Deposition.

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Abstract

This paper documents the lasing performance of a waveguiding layer of Ti:sapphire, of ~12 μ m thickness, grown by pulsed laser deposition from a 0.12 wt % Ti₂O₃ Ti:sapphire single crystal target onto an undoped z-cut sapphire substrate. Lasing around 800nm is observed, when the waveguide layer is pumped by an argon ion laser, running on all blue green lines, with an absorbed power threshold of 0.56W using high reflectivity (R>98%) mirrors. Using a 5% pump duty cycle and a T = 35% output coupler, a slope efficiency of 26% with respect to absorbed power is obtained, giving quasi-CW output powers in excess of 350mW.

Ti: sapphire is a very useful solid state laser material as its vibronic nature leads to large gain bandwidths. The degree of tunability achievable (~650nm-1100nm) coupled with its excellent mechanical strength, high optical quality and good thermal conductivity have led to its widespread use in applications ranging from spectroscopy through prototyping to LIDAR. The major limitations in CW operation, have been the high pump power density required to achieve efficient lasing and the fact that the peak absorption is situated in the blue-green (~500nm). This requires the use of expensive pump lasers such as argon ion, doubled Nd:YAG, copper vapour or dye lasers.

Effort has therefore been directed towards waveguide fabrication in this material since the simultaneous pump and signal beam confinement leads to average spot sizes impossible to achieve in the bulk, with an associated reduction in lasing threshold. The requirement therefore is to grow waveguide layers of high crystal quality, low scattering loss and correct Ti valence state which would allow the use of miniature solid state pump sources.

Alternative routes to mode confinement also include the single crystal fibre geometry, as produced by the laser heated pedestal growth technique. These have exhibited pulsed operation¹ but true CW lasing has been precluded by strong re-absorption at the lasing wavelength due to the poor crystal quality achieved. The diameters involved (~350 μ m) also mean that there is in fact little improvement in beam confinement over bulk. Other waveguide fabrication techniques for this material, such as ion beam implantation² and thermal in-diffusion of the active ion into undoped substrates, can result in disruption of the crystal lattice, although lasing has recently been reported in a channel fabricated by this latter technique.³

We have already detailed the growth of Ti: sapphire layers on undoped z-cut oriented sapphire substrates, measuring 10x10x0.3 mm³, by the pulsed laser deposition technique⁴. Ion beam channelling studies have shown that the as-grown layers have excellent crystalline properties, better than annealed undoped sapphire, together with a significant degree of Ti incorporation into the lattice. This paper documents the subsequent realisation of a waveguide laser from one such sample.

The materials growth, undertaken at FO.R.T.H., involved ablation of a single crystal Ti: sapphire target of 0.12 wt % Ti_2O_3 using a KrF excimer (Lambda Physik LPX200 operating at 25Hz with 500mJ per pulse) focussed to an energy density of $\approx 4\text{J cm}^{-2}$. The vacuum chamber was evacuated to a base pressure of 1.6×10^{-5} mBar, then back-filled with argon to maintain a pressure of $\sim 3 \times 10^{-4}$ mBar during the deposition. The substrate was maintained at a temperature of $\sim 975^\circ\text{C}$ using a 100W CO_2 laser (Synrad 57-1-28W) over the 1 hour deposition time.

After deposition the average layer thickness was found to be $12.3\mu\text{m}$ using a Tencor alpha-step 2000 surface profiler. Particle induced X-ray excitation (PIXE) has shown that $>80\%$ of the Ti can be transferred from the target to the layer under these growth conditions⁵. Assuming therefore that the sample had a doping level equivalent to ~ 0.1 wt % Ti_2O_3 it was cut and optically polished to a length of 3.8 mm, to correspond roughly to the calculated pump absorption length of $\sim 3.4\text{mm}$ determined using an absorption cross-section value of $\sigma_a = 9.3 \times 10^{-20} \text{ cm}^2$ for the π polarisation at 490nm⁶, and suitably weighted to take account of both argon ion pumping lines at 488nm and 514nm. PIXE was not applied directly to samples used for lasing, since it is destructive to the fluorescence properties of the guide.

The lasing characteristics were then examined using an argon ion laser (Spectra Physics, 2020-05) as the pump source, operating on all lines, with 488nm and 514nm wavelengths predominant. The light was passed through an optical chopper and launched into the guiding layer using a x6.3 microscope objective. The laser cavity was formed initially using two plane dielectric mirrors with high reflectivity coatings on thin glass substrates. These had $R > 98\%$ over the range 765nm-805nm and transmission of $\sim 92\%$ at the pump wavelengths. These were initially butted onto the guide end faces using the surface tension of drops of Fluorinert FC-70 fluorinated oil, placed between guide and mirror, to ensure good parallelism. The mirrors were then more securely attached by glueing the mirror edges to the exposed ends of the sample. The excess Fluorinert was then allowed to evaporate before the experiments were performed. The chopper was set to a duty cycle of 5% to prevent any laser induced damage to the mirrors.

The fluorescence output power was detected using a small area Si photodiode and displayed on an oscilloscope. Lasing was observed with 1.01W incident on the launch objective, corresponding to an absorbed power of 0.56W. With these mirrors the lasing peak occurred spontaneously anywhere within the range 740nm to 830nm where the mirrors were still highly reflective and was highly dependent upon the launch conditions. The absorbed power was calculated from the incident power by measuring the product of the launch, L , and single pass absorption, A ⁷. This is done by comparing the total transmitted pump power obtained when launching into the guide, to that transmitted when the pump is focussed directly through the substrate. The spatial modes just above threshold were examined by imaging the guide exit face onto a Spiricon Beam Analyser (Model no LBA 100) using a x10 microscope objective. Both signal and pump were approximately Gaussian in the x, confined, and y, unconfined, planes, with radii $\omega_{sx} = 4.7\mu\text{m}$, $\omega_{sy} = 28\mu\text{m}$ for the signal and $\omega_{px} = 2.5\mu\text{m}$, $\omega_{py} = 68\mu\text{m}$ for the pump. The absorbed pump power at threshold for high reflectors can be expressed in the form⁸

$$P_{th} = \frac{hc}{\lambda_{pump}} \frac{\delta}{\tau_{fl} \eta_q \sigma_e} \frac{1}{2l J} \quad (1)$$

where h is Planck's constant, c is the speed of light, δ is the round trip loss, l is the laser cavity length, λ_{pump} is the pump wavelength, τ_{fl} is the fluorescence lifetime, η_{q} is the quantum efficiency, σ_{e} is the stimulated emission cross section and J is the integral of the product of the normalised pump and signal distributions over the cavity volume. Calculating J from the observed mode profiles (assuming the signal is collimated and the pump is diverging in the unconfined plane) and taking values of $\tau_{\text{fl}}=3.2\mu\text{s}$, $\eta_{\text{q}}=0.8$ at room temperature, $\sigma_{\text{e}}=3.65\times 10^{-19}\text{ cm}^2$ as representative of those available in the literature⁹⁻¹⁴ allows a figure of 1.8dB/cm for the single pass loss to be deduced. One of the drawbacks of the pulsed laser deposition (PLD) process is that small solid particulates and molten droplets may be ejected from the target and incorporated into the film. These act as scattering centres and they are probably responsible for the high scattering loss value. However this trial sample has not yet been graded for particulate count and subsequent inspection may show that an alternative better sample is available. This value is also likely to be an upper limit since both τ_{fl} and η_{q} decrease with increasing temperature^{9,10}, the latter falling to 0.68 by 325K, so any pump induced temperature increase would serve to decrease this loss estimate.

The output high reflectivity mirror was then replaced with one of average 5% transmission across the peak of the gain. However, the Fresnel reflection from the back face of the mirror substrate (which was approximately 160 μm thick) caused it to act as an etalon. This was also observed when the mirror was placed in a spectrophotometer to verify its transmission. Calculations show that the output mirror transmission varies between 3.3% and 7.5% as a function of wavelength, with a period of $\sim 1.3\text{ nm}$. If the variation in the air gap between mirror surface, and the guide exit face is also taken into consideration, then the degree of output coupling at any given wavelength may vary between 2% and 13%, assuming no significant divergence of the signal mode over these small etalon distances. In practice the pump spot was translated along the guide to obtain the lowest threshold possible so output coupling values close to the lower extreme are most likely. Lasing was achieved with this configuration at an absorbed power of 0.72W.

The lasing spectrum obtained in this instance was always centred around 808nm which corresponded roughly to the peak reflectivity of the output coupler. This was recorded using an OMA 2000 triple grating spectrometer (EG&G Princeton Applied Research Model 1471A). This is shown in Figure 1, where it can be seen that although the spectrometer has insufficient resolution to observe individual cavity modes, the intervals between the peaks in the envelope shown correspond to those expected from the mirror substrate etalon. It was also observed, by inserting a range of 10nm bandwidth notch filters into the output beam path, that mode hopping was occurring between these etalon modes, the spectrum appearing continuous due to the long integration time of the detector. The output power was recorded with a thermal optical power meter, taking into account the 5% chopper duty cycle. It was also confirmed using a Si photodiode which had been previously calibrated against an 803nm laser diode. This result is shown in Figure 2(a). Running quasi-CW with this duty cycle the slope

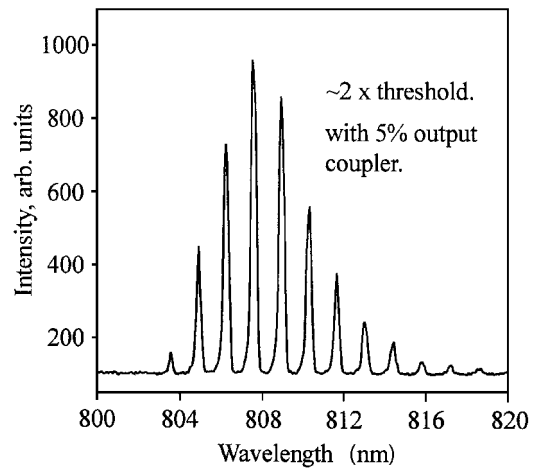


Figure 1. The lasing spectrum obtained from the waveguide well above threshold showing modulation due to the etalon modes of the output coupling mirror.

efficiency with respect to absorbed power was found to be 4%, giving rise to a maximum output power of 108mW for an absorbed power of 3.7W .

The chopper was then removed and the laser was operated fully CW up to an output power of 73mW . This gave results entirely equivalent to those already obtained quasi-CW over the range of input powers examined, provided that the sample was convectively cooled to offset the additional extra heating and the launch was re-adjusted to compensate for the heating effects on the entrance mirror. No attempt was made to quantify actual operating temperatures however. The laser was run in this mode for 40 minutes with no degradation in performance or sample damage. The laser was not run above 73mW in this instance solely due to likelihood of mirror damage.

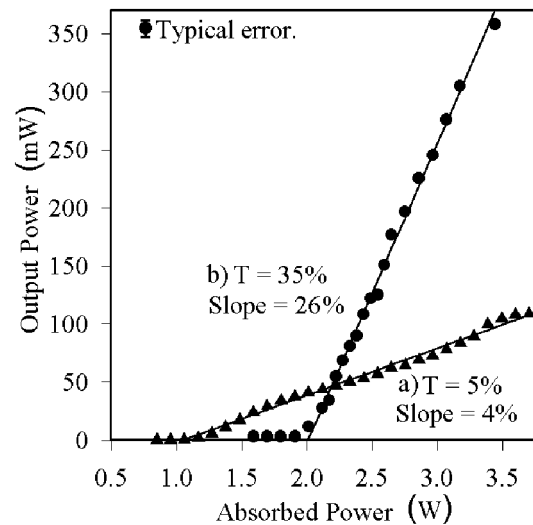


Figure 2. Output power characteristics for two output couplers: a) with 5% nominal transmission, b) with 35% nominal transmission.

The output coupler was then replaced by one of higher average transmission, $T=35\%$, in order to achieve a higher output power. The pump beam was again tracked across the input face of the guide to find the position of lowest threshold and output coupling, though the effective mirror reflectivity was again uncertain due to the etalon effects. A chopped pump with a 5% duty cycle was again employed to guard against possible mirror damage. The onset of lasing was observed at a wavelength of $\sim 802\text{nm}$ at an absorbed power threshold of 1.64W and a slope efficiency of 26% with respect to absorbed power was achieved, leading to a maximum average quasi-CW output power of 357mW for 3.44W of absorbed power, as shown in Figure 2(b) .

This work demonstrates that PLD is becoming directly competitive with the other more established methods of making waveguide lasers and optical films in general. That laser quality films of Ti: sapphire can be produced, an area where the traditional methods have failed, shows that PLD is at least complimentary to these techniques. Output powers and threshold levels, that compare well with the bulk material have been obtained. Further work is underway to improve this result by improving the mode overlap. This involves the use of cylindrical focussing and further optimisation of layer thickness. CW Laser operation at room temperature has rarely been obtained in transition metal doped waveguides of any type or material, and it is therefore anticipated that this technique will also lend itself to the growth of other tunable waveguide sources in such materials.

Future work will include adjusting the substrate temperature during growth to obtain single mode variable index guides and further reduce losses. It is also intended to explore means by which these guides can be tuned controllably, either by growing or manufacturing channels (for which a range of tuning schemes already exist) or by fabricating grating overlays on the planar guides.

Acknowledgements

The authors would like to thank Tom Brown, Dave Shepherd and Toby Warburton of the crystal waveguide laser group at the ORC, and Jaymin Amin of Corning N.Y. for their technical advice. AAA and LMBH wish to acknowledge the Engineering and Physical Sciences Research Council (EPSRC) for their financial support. This work has been supported by EPSRC via grant no. GR/L28722, by the Czech grant agency (GACR) via grant no 102/96/0429 and by the European Union through the framework of the DG XII Large installations Plan : Ultraviolet Laser Facility at FO.R.T.H-I.E.S.L.

References

1. L.Whu, A.Wang, J.Wu, L.Weil, G.Zhu, S.Ying. *Electron Lett* **31** 1151 (1995).
2. P.D.Townsend, P.J.Chandler, R.A.Wood, L.Zhang, J.McCallum, C.W.McHargue. *Electron Lett.* **26** 1193 (1990).
3. L.M.B.Hickey, A.A.Anderson, J.S.Wilkinson. Addendum to Proc 8th Europ. Conf. on Int. Opt. (1997), PD6 pp1-4.
4. A.A.Anderson, R.W.Eason, M.Jelinek, C.Grivas, D.Lane, K.Rogers, L.M.B.Hickey, C.Fotakis. *Thin Solid Films*, **300**, 68, (1997).
5. A.A.Anderson, R.W.Eason, M.Jelinek, L.M.B.Hickey, C.Grivas, C.Fotakis, K.Rogers, D.Lane. Proc. Conf. Lasers and Electro-optics Europe, paper CtuG8 p79 (1996)
6. R.L.Aggerwal, A.Sanchez, R.E.Fahey, A.J.Strauss. *Appl Phys Lett* **48** 1345 (1986).
7. D.Pelenc, B.Chambaz, I.Chartier, B.Ferrand, C.Wyon, D.P.Sheperd, D.C.Hanna, A.C.Large, A.C.Tropper. *Opt Comms* **115** 491 (1995)
8. M.J.F.Digonnet, C.J.Gaeta . *Appl Opt* **24** 333 (1985)
9. P.Albers, E.Stark, G.Huber, *J Opt Soc Am B* **3** 134 (1986)
10. P.F. Moulton, *J Opt Soc Am B* **3** 125 (1986)
11. A.Sanchez, A.J.Strauss, R.L.Aggarwal, R.E.Fahey, *IEEE J Quantum Electron* **24** 995 (1988)
12. M.Birnbaum, A.J.Pertica, *J Opt Soc Am B* **4** 1434 (1987)
13. W.R.Rapoport, C.P. Khatak, *Appl Opt* **27** 2677 (1988)
14. G.F.Albrecht, J.M.Eggleston, J.J.Ewing, *Opt Comms* **52** 401 (1985)