Sapphire Waveguide Lasers

James S. Wilkinson and Vasilis Apostolopoulos
Optoelectronics Research Centre, University of Southampton, Highfield, Southampton, Hampshire, SO17 1BJ, UK
Tel: +44 23 8059 2792 Fax: +44 23 8059 3149 E-mail: jsw@orc.soton.ac.uk

Louise M.B. Hickey
Southampton Photonics Inc., Phi House, Chisworth Science Park, Enterprise Road, Southampton, SO16 7NS, UK
Tel: +44 23 8076 6070 Fax: +44 23 8076 6311 E-mail: Louise.Hickey@southamptonphotonics.com

Abstract: The fabrication and operation of titanium-indiffused sapphire waveguide lasers with pump power thresholds of 210mW at 514.5nm are reported. Ga-indiffused sapphire waveguides for potential integration of passive and active devices for laser control are also described.
©2001 Optical Society of America

1. Introduction

The titanium sapphire laser is a versatile laboratory tool for spectroscopic applications, with a tuning range from 650nm to 1050nm [1], making it well suited to tunable short-pulse operation. Realisation of a Ti:sapphire waveguide laser on a chip promises low-threshold operation for ready pumping with solid-state sources, rendering it compatible with incorporation into compact spectroscopic instruments. Further, sapphire is a versatile substrate for the epitaxial growth of materials such as ZnO for electrical control of laser operation and silicon for realisation of electronic circuits and detectors. We have previously shown that titanium may be diffused into sapphire to give similar spectroscopic behavior to bulk-doped crystals [2], demonstrated waveguide fabrication by titanium diffusion in sapphire [3], and realised the first waveguide laser in Ti diffused sapphire [4]. In this paper, recent advances in which lasers with lower pump power thresholds were realised by optimising the device geometry are described. The fabrication of gallium-indiffused sapphire waveguides for potential integration of passive and active waveguide devices and independent optimisation of the optical properties of waveguide and gain medium is also outlined. The combination of Ga-diffused waveguides with Ti-diffused gain regions may lead to further reductions in pump power threshold and the realization of tunable line-narrowed waveguide lasers in sapphire.

2. Titanium-diffused waveguide laser fabrication and measurements

Waveguide lasers were fabricated by diffusing 270 ± 7nm thick, nominally 3μm wide, stripes of titanium oxide, deposited by thermal evaporation from Ti2O3 powder, into 10mm x 10mm c-cut sapphire wafers. Diffusion took place in an argon atmosphere at 1700 ± 60°C for a duration of 60 minutes plus approximately 10 minutes each for heating and cooling. The sample was cut and polished to yield a device 4mm long, and mirrors were attached to the polished endfaces. The mirrors had a transmission of 90% at 500nm and reflectivities of >98% at wavelengths between 760nm and 810nm. Transverse magnetic (TM) - polarised pump radiation from an argon ion laser operating at 514.5nm was chopped and end-fire coupled into a waveguide through the input mirror. The chopper operated to repeatedly pass pump radiation for 1ms and block it for 19ms, to reduce heating of the sample. Guided output radiation was collected with a microscope objective lens and unabsorbed pump radiation was separated from laser signals using a cold mirror with an edge at 700nm. Using appropriate filters the pump and signal radiation was measured using silicon photodetectors; the waveguide mode profiles were measured using a silicon CCD camera.

3. Laser performance

The waveguide laser signal output power is shown as a function of launched pump power in Figure 1 for two different channels. The launched pump power is estimated from the pump power at the output and the signal output power is averaged over 100 pump pulses for each pump power. The threshold pump power is 210 ± 10mW for both lasers and the slope efficiencies are approximately 0.06% for both lasers. Assuming that the quantum efficiency is 80% and taking the mirror transmission to be 2%, the round-trip loss is estimated as 12dB for both lasers. Deviations in linearity in the power characteristics are believed to be due to thermal effects. Laser spectra were measured for each laser. Emission was recorded between 780nm and 885nm for different pump powers and chopper duty cycles.
The mode intensity profiles for the laser mode and the pump mode for laser 1 were measured during lasing, and are shown in Figures 2a & b, respectively. The intensity profiles in Figure 2 are TM polarised and show fundamental mode operation with the signal mode having an approximate width of 10 μm and depth of 5 μm at full-width 1/e peak intensity. The pump mode is shown on the same scale and is substantially narrower; at wavelengths below 500 nm the waveguide supported more than one mode. White-light waveguide absorption measurements showed that the waveguides had an average titanium concentration equivalent to 0.13 ± 0.02 wt.% Ti₂O₃ in Al₂O₃ by comparison with published results for bulk crystals [4]. These measurements yielded no evidence of significant absorption due to Ti⁺, which causes absorption in the gain band and lowers the material figure of merit.

4. Gallium-indiffused waveguides

The index elevation, Δn, achieved for titanium concentrations appropriate for the realisation of efficient lasers is less than 10⁻³, resulting in large modal spot sizes and, consequently, non-optimum pump power thresholds. Further, the realisation of active integrated optical circuits with low-loss waveguide bends on a small chip requires a larger index change. Rare-earth diffusion in lithium niobate combined with titanium-diffused waveguides has led to a wide range of multi-functional waveguide laser devices [5]. In a similar way, it is expected that titanium and gallium may be combined in sapphire, as the active and waveguide ion respectively, leading to the fabrication of low-threshold broadly tunable waveguide lasers.

Gallium oxide films of thickness 50 nm were deposited from a Ga₂O₃ source onto c-cut sapphire substrates and annealed in argon at 1600°C for times of 1 and 4 hours, and the diffusion coefficient of Ga in sapphire was found to be (3.31±0.05) x 10⁻¹⁷ m²s⁻¹. Subsequently, waveguides were fabricated in four c-cut sapphire samples of dimensions 10mm x 10mm x 0.5mm by diffusion from unpatterned deposited films of gallium oxide in oxygen at 1600°C for 16 hours. Gallium oxide thicknesses of 60±5, 90±5, 130±7 and 200±10 nm were used. Using the measured diffusion coefficient these samples are expected to exhibit a diffusion depth, defined as 1/e of the peak concentration, of
2.8±0.3µm. Two parallel ends of each waveguide sample were polished to optical quality to allow end-face coupling of input radiation and near-field intensity profiles to be measured. The modal intensity profiles for the waveguides were measured using an argon ion laser operating at 488nm and a He-Ne laser at 633nm. Light was launched into the waveguide in the TE polarisation by coupling with a microscope objective lens or with a fibre. The light emerging from the waveguide was imaged on CCD camera using a microscope objective lens.

The samples with source thickness of 60, 85, 130nm showed no residue on the surface after the diffusion, indicating that all the gallium had diffused into the sapphire, in contrast to the sample with a source thickness of 200nm. The samples with the 60 and 85nm source thicknesses were monomode at both wavelengths.

![Graph showing mode size against source thickness](image)

Figure 3 shows the mode size of the fundamental mode at 488nm and 633nm as a function of gallium oxide source thickness for samples with source thickness between 60 and 130nm. It is clear that the mode size reduces with source thickness, and that a smaller mode size has been obtained than that for titanium diffused waveguides in sapphire. It is expected that the index change is approximately proportional to the concentration of the dopant, so that as the source film thickness increases the index change will also increase, resulting in a reduction of mode size for sufficiently shallow waveguides. Figure 3 confirms this expectation and the process yielded the anticipated small mode sizes. The maximum index elevation achieved is estimated to be 6x10⁻² using a simple waveguide model.

5. Conclusions

The lasers described in this paper show a considerable reduction in pump power threshold compared with the 1.2 W reported previously for Ti-diffused sapphire lasers [4]. However, the low slope efficiency indicates either that the quantum efficiency is low, or that the waveguide propagation losses or mirror coupling losses are high. Gallium-indiffused waveguides have been shown to yield reduced modal spotsize. Gallium and titanium indiffusion may potentially be combined to realise lasers, providing a route to active waveguide optimization for low propagation loss and low laser threshold. Work is in progress to study such co-doping, which will also allow reader integration of active and passive devices for tuning, to integrate wavelength selection devices, and to operate the lasers continuously (CW) with appropriate cooling.

6. References