CHARACTERISATION OF TI:DIFFUSED CHANNEL WAVEGUIDES IN SAPPHIRE

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Abstract
The development of Ti:diffused channel waveguides in sapphire is demonstrated and their characteristics discussed with a view to the development of a Ti:sapphire waveguide laser.

Introduction
The development of a Ti:sapphire waveguide laser would have significant impact as a versatile, compact source in portable instrumentation for applications in sensing and spectroscopy. In the bulk configuration the Ti:sapphire laser is one of the best known solid state lasers with an output whose wavelength is continuously tunable over 400nm in the red and near infra-red. Confinement of both the pump and signal in a waveguide geometry would, assuming low propagation losses, significantly reduce the required pump power threshold, opening the way for the use of a directly butted solid state laser as a pump source. Other advantages of the waveguide geometry include the potential for monolithic integration of tuning and wavelength selection components which would significantly enhance the ease of use.

Recently, significant progress towards the realization of a Ti:sapphire waveguide laser by diffusion doping has been reported. At a temperature just below the melting point of sapphire, Ti has been introduced to significant depths in a time scale of hours, with the spectroscopy of the diffused region identical to that of a high quality bulk doped laser crystal[1]. Furthermore, the diffusion doping of sapphire with Ti has been observed to increase the local refractive index and lead to the formation of single mode slab waveguides at λ=633nm[2]. Here we report the development of channel waveguides in sapphire at a significantly lower temperature than previously reported, discuss properties of both the diffusion and the resultant waveguides and offer a projection of the expected lasing performance.

Fabrication
Channel waveguides were realised by diffusing from a photolithographically patterned thin film diffusion source, as follows. A mask defining a series of stripes was transferred onto the polished surface of a sapphire wafer oriented perpendicular to the c-axis, using a standard lift-off technique. The stripes ranged from 3μm to 16μm wide, stepping 1μm in width and spaced by 100μm and are identified by reference to the initial width of the mask opening (3μm, 7μm etc.). A thin film diffusion source was deposited by thermal evaporation from a $Ti_2 0_3$ powder in a partial oxygen atmosphere. The diffusion was carried out in a carbon resistance furnace in an inert argon atmosphere; fabrication conditions specific to the sample, discussed in this paper (S114), are given in the table below. Following the diffusion, opposite end faces are polished to high optical quality in preparation for a series of characterisation procedures.

Table 1 Summary of fabrication conditions

Sample Identity	Source Thickness	Diffusion Temperature	Diffusion Time	Heating and Cooling Cycles
S114	114±10nm	1750±30°C	1 hour	Heat over 27mins; Rapid cool (<10mins)

__Characterisation - (i) Spatial distribution of diffused Ti__

The extent of diffusion from the patterned source was characterized by a fluorescence imaging technique, in which the spatial distribution of diffused, fluorescent Ti at the polished end face is imaged onto a digitizing vidicon camera. A resolution of ±2μm may be achieved with careful alignment and quantitative data may be obtained by comparison with the fluorescent yield from a standard bulk doped sample. This technique is only sensitive to Ti^{3+} incorporated substitutionally on the Al^{3+} lattice.

Figure 1 illustrates some of the characteristics of the Ti^{3+} distribution following a diffusion from a patterned source. This shows clearly that the peak Ti^{3+} concentration incorporated decreases with stripe width, indicating that the diffusion source has been depleted during the diffusion. It is also interesting to note the high concentrations of Ti^{3+} incorporated. Typically, high quality bulk doped Ti:sapphire laser crystals are doped at a level less than 0.1wt% Ti_2O_3 in Al_2O_3. The 10% error bars indicate the error in the quantitative comparison with the standard sample, although larger errors may arise from inaccuracies in the spatial positioning with respect to the initial stripe source.

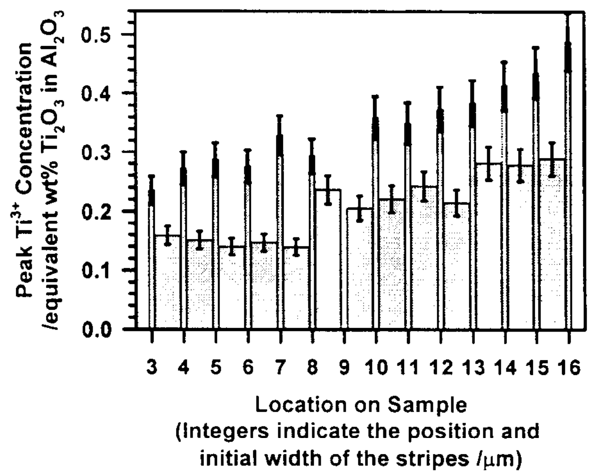

Figure 1 Peak diffused fluorescent Ti^{3-} concentration measured both beneath and midway between the original stripe locations.

Figure 1 also illustrates that the concentration of Ti^{3+} incorporated in a region midway between the stripes is not negligible, indicating that a strong lateral movement of Ti^{3+} from the stripe source has occurred. In each case this is sufficiently advanced to form a continuous Ti-rich region between the initial location of the stripes. The diffusion coefficient that would describe such a movement is significantly greater than that describing the depth diffusion. Such lateral diffusion has implications for the development of high quality channel waveguides since, in many instances, the continuum of Ti diffused into the region in between the initial stripes is sufficient to support a waveguide. The occurrence of a slab waveguide at the pump wavelength would significantly increase the threshold in a waveguide laser.

In the case of the better known Ti-diffused $LiNbO_3$ waveguides, an anisotropy in the diffusion kinetics has been reported[3][4] and debated[5], although the degree of anisotropy reported is significantly less than that observed here. However, it is likely that the diffusion of Ti into sapphire would follow a similar path to that reported for Ti into $LiNbO_3$, with the initial formation of a intermediary compound which then acts as the diffusion source[6] and the local defect structure playing a major role in the progression of the reaction and the diffusion kinetics. Further investigation is required in order to understand the mechanisms responsible for the rapid lateral diffusion observed and enable the fabrication of optimized waveguide devices by the diffusion of Ti in sapphire.

Characterisation - (ii) Channel Waveguide Properties

Figures 2 and 3 illustrate properties of the channel waveguides. Figure 2 shows spectral attenuation for the channels diffused from the 3μm, 7μm 11μm and 15μm stripes. All show a strong absorption in the blue-green corresponding to the characteristic absorption band of Ti^{3+} in sapphire. The strength of the absorptions corresponds to an average modal concentration of 0.2-0.3wt% which is in agreement with the high Ti^{3+} concentrations illustrated in Figure 1. The rapidly rising losses at the longer wavelengths illustrate the increasing waveguide propagation losses as they approach cut-off. As expected, the waveguides diffused from the broadest stripes cut-off at longer wavelengths.

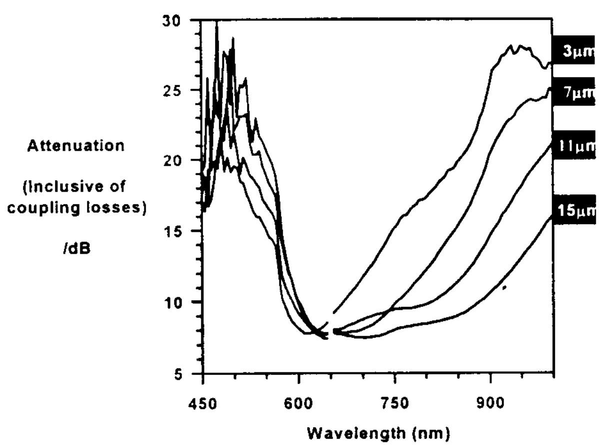

Figure 2 Spectral attenuation of channel waveguides (TM polarization). The attenuation is inclusive of input and output coupling losses; the device length is 5.5mm.

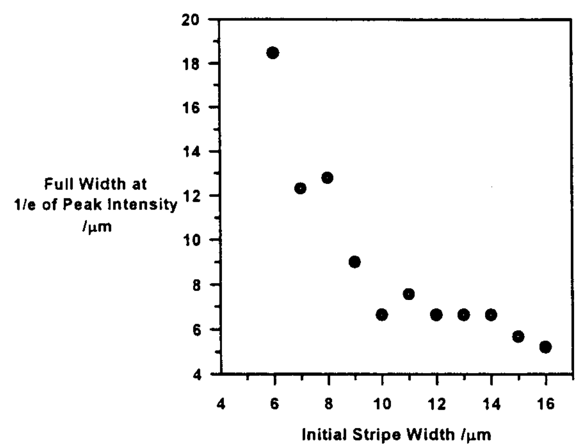

Figure 3 Channel waveguide modal properties in the depth dimension at λ = 800nm as a function of initial stripe width (TM polarization).

The cause of the small increase in waveguide losses around 750nm has not been identified, however this may be due to a change in input coupling losses. An alternative interpretation suggests absorption losses due to the presence of Ti^{4+} which is known to interact with a substitutionally incorporated Ti^{3+} to give rise to a broad absorption in the near infra-red, peaking around 800nm[7]. The presence of any so-called Ti^{3+}-Ti^{4+} pairs and the associated residual absorption which overlaps the gain band would be detrimental to the lasing performance. Further work is underway to establish the origin of this feature.

Waveguide modes were exited via prism coupling and figure 3 illustrates the mode sizes measured in the depth dimension at a wavelength of 800nm, near the peak of the gain band. Clearly the narrower stripes are cut-off at this wavelength whilst the broader stripes remain well confined, which is in good agreement with the spectral attenuation measurements.

Example of the modal intensity profiles are given in figure 4, in which the TM_{00} mode profiles are illustrated at λ=488nm and λ=800nm, prospective pump and lasing wavelengths respectively.

The asymmetry of the mode profile is clear and the 2:1 aspect ratio is typical of the channel waveguides. The noise in the lower contour plot is due to fluctuations in laser power during the measurement.

Prospective Lasing Performance
Considering the dimensions of the waveguide modes illustrated in figure 4 and assuming a 0.2wt% average modal concentration, it is projected that a waveguide laser based on this system would have a threshold of the order of tens of mW using 95% reflective mirrors and assuming minimal losses. The occurrence of significant waveguide propagation or reabsorption losses would increase the required pump power, although enhancement of the lateral confinement would enable a further reduction in the threshold pump power.

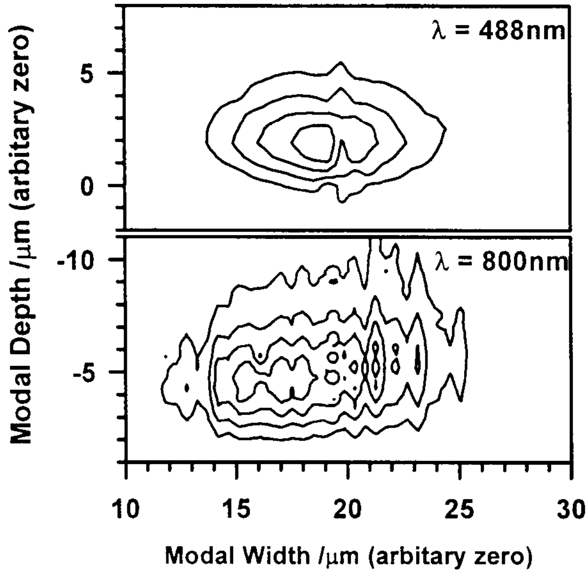

Figure 4 TM_{00} mode profiles for the 11μm channel waveguide at λ = 488nm and λ=800nm.

Summary
In summary, the development of Ti-diffused channel waveguides in sapphire has been demonstrated. High concentrations of Ti^{3+} have been incorporated and a significant lateral spread from the stripe source has been observed. Waveguide spectral attenuation measurements illustrate the characteristic broad absorption in the blue-green and waveguides diffused from the broadest stripes are observed to cut off in the near infra-red. The channel waveguides show a highly asymmetric profile and initial calculations indicate that a pump power threshold of the order of the order of tens of mW is attainable. These results represent a significant step towards the realization of a miniature Ti:sapphire waveguide laser.

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