Nd:Ta_2O_5 Rib Waveguide Lasers

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Abstract

Ta_2O_5 waveguides offer great potential for high-density active photonic crystal circuits and their combination with rare-earth dopants for active devices is of interest for increasing their potential functionality. To this end, neodymium-doped Ta_2O_5 rib waveguide lasers have been fabricated on an oxidized silicon wafer by RF sputtering and argon ion-beam milling and the first laser action in this material has been demonstrated. Lasing was observed at wavelengths between 1060nm and 1080nm and an absorbed pump power threshold of 87mW was obtained.

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Tantalum pentoxide is a promising candidate material for advanced photonic crystal waveguide devices, as it has a high refractive index (n>2) allowing large index contrast,[1] low absorption over a wide wavelength region,[2] large third-order nonlinearity,[3] significant photosensitivity,[4] and high optical damage threshold.[5] Rare-earth doped Ta_2O_5 waveguide films have the potential to provide compact sources and amplifiers for a wide range of applications in telecommunications and elsewhere. High index materials offer advantages for making compact waveguides with small effective area, enabling low-threshold lasing and the exploitation of nonlinear effects at low power. The incorporation of photonic crystals in these waveguides would offer greater functionality through engineering of the emission wavelengths. The high laser damage threshold of Ta_2O_5 further broadens its application to the generation and processing of ultra-short high-peak power optical pulses. However, high index contrast also makes the realization of low-loss waveguides a significant technological challenge. Er- and Pr-doped Ta_2O_5 waveguides have been realised by deposition on SiO_2 substrates followed by ion-implantation, and their losses and luminescence properties studied.[6,7] However, to date there have been no reports on Nd-doped Ta_2O_5, or of lasing in rare-earth-doped Ta_2O_5, although the growth and absorption and fluorescence spectra of $NdTa_7O_{19}$ crystals has been reported with a view to realising solid-state lasers.[8] The extensive IR transparency of Ta_2O_5 is a result of low maximum phonon energy (<900cm^{-1})[9] compared with silicate glasses, which is also very important for the realisation of many efficient rare-earth-doped devices. In addition to their promising optical properties, Ta_2O_5 films have low toxicity, very good thermal and mechanical properties and excellent compatibility with silicon technology, being widely used for high-k gate dielectrics.[10] This compatibility with silicon processing renders Ta_2O_5 waveguides an appropriate choice for mass-manufacturable low-cost integrated optical devices in future systems. In this letter, we present the fabrication and operation of neodymium-doped Ta_2O_5 rib waveguide lasers for the first time.

Two microns of thermal oxide were grown on a silicon wafer at a temperature of 1100°C in an oxygen atmosphere. A 3μm thick neodymium-doped Ta_2O_5 film was then deposited on this wafer by RF sputtering from a Ta_2O_5 target doped with 0.5wt% Nd_2O_3 (~1.5×10^{26} Nd ions/m^3) in an oxygen/argon atmosphere. The pressure during sputtering was 35mTorr, and the flow rates of argon and oxygen were 16 and 6 sccm, respectively. Rib waveguides were then formed by patterning the wafer with "stripes" of photoresist of widths ranging from 2μm to 20μm, and then argon ion beam milling the exposed tantalum pentoxide by 1μm in depth to create ribs of height 3μm surrounded by slab waveguide regions of thickness 2μm. The waveguides were then sawn and end-polished to provide waveguides of length 5.5mm, taking care to ensure that the end faces were perpendicular to the rib waveguides. Monomode waveguides at a wavelength of 1.06μm could be realised with much smaller dimensions, but this large waveguide design was chosen to ease end-fire coupling of the pump, reduce the effects of edge rounding and divergence of the lasing mode at the end facets and hence reduce mirror butt-coupling loss, and to limit the impact of edge and surface roughness upon waveguide propagation loss. The samples were then annealed in an oxygen atmosphere at 520°C for 60 hours to reduce propagation loss due to oxygen defects without causing crystallization of the film.[11]

Measurements were made on the waveguides before attachment of mirrors to the end faces in order to estimate coupling efficiency, propagation loss and Nd absorption length. Light from a Ti:sapphire laser tuned to 700nm, well away from the Nd absorptions at 740nm and 800nm, was end-fire coupled into each waveguide using a ×10 microscope objective lens, which was found to yield the best coupling efficiency across a broad range of waveguide widths. The waveguide showing greatest output power, which had a rib width of 19±0.5 μm, was selected for subsequent measurements. The maximum waveguide transmittance was measured to be 37%, once Fresnel reflections were taken into account, representing a combined coupling and propagation loss of 4.3dB at λ=700nm. The transmittance of the same waveguide was measured again with the Ti:sapphire laser tuned onto the Nd absorption at 800nm. The absorption showed evidence of saturation for incident pump powers above 400mW. The absorption at low pump powers was found to be 79%, after extraction of the coupling and propagation losses which are assumed to be the same at 700nm and 800nm. This absorption corresponds to a 1/e absorption length of ~3mm, which is comparable with other materials doped with 0.5wt% Nd_2O_3.[12] A detailed study of the spectroscopy of Nd: Ta_2O_5 will be reported elsewhere.[13]

A laser resonator was formed by butting plane mirrors to the end faces of the waveguides with the aid of a thin film of Fluorinert liquid (FC-70) for adhesion. The pump input mirror had a reflectivity of >99.9% at λ = 1.06μm and a transmittance of 87% at λ = 800nm; output couplers with reflectivities between 40% and 100% were used. The laser performance was assessed by end-fire coupling light from the Ti:sapphire pump source into the waveguides as before. The output was collected with a ×10 microscope objective lens and directed onto a power meter or spectrum analyzer as required. An RG1000 filter was used to block the unabsorbed pump light after the laser. A typical laser characteristic is shown in Figure 1, for the laser with an output mirror reflectivity of 91%. The absorbed pump power has been calculated assuming a pump launch efficiency of 42% with respect to the pump power incident upon the launch objective, taking into account input mirror transmission, and a waveguide propagation loss of 2dB/cm, to be discussed further below. The absorbed pump power threshold in this case is ~120mW, and the slope efficiency is 1.0%.

To explore the laser behaviour further and to obtain an independent estimate of the waveguide losses, the pump power threshold was measured as a function of output mirror reflectivity for four mirror reflectivities between 40% and >99.9%. A Findlay-Clay analysis was then carried out to determine the round-trip cavity losses.[14] The threshold pump power incident upon the input objective lens, corrected for the previously measured saturation of the absorption, is plotted against the natural logarithm of the output mirror reflectivity in Figure 2, with a line of best fit. The intercept on the *–ln(R)* axis represents the cavity round-trip loss exponent L, which is approximately 0.5. While the uncertainty in this measurement is rather high due to the small number of data points, this corresponds to a propagation loss of 2 dB/cm at the lasing wavelength at $\lambda \approx 1.06\mu m$, which is consistent with our estimate from the transmission measurements at $\lambda = 700nm$. Losses in neodymium-doped Ta_2O_5 slab waveguides realised in a similar way have been found to be 0.7±0.2 dB/cm,[13] showing that edge roughness of a rib waveguide is likely to have caused a significant increase in loss. Furthermore, similar undoped rib waveguides have been shown to have a loss of 1.6dB/cm at $\lambda = 1550nm$,[15] which is consistent with a loss of 2dB/cm at this shorter wavelength. Assuming a coupling loss of 3dB and a propagation loss of 2dB/cm, the lowest threshold observed, of 260mW incident upon the input objective lens, corresponds to a launched pump power threshold of 109mW and an absorbed pump power threshold of 87mW.

The expected slope efficiency is given by: $$\eta = \eta_q \eta_{ol} \frac{\lambda_s}{\lambda_p} . \frac{-\ln R}{-\ln R + L}$$

where λ_s is the laser wavelength, λ_p is the pump wavelength, η_q is the quantum efficiency, η_{ol} is the pump/signal overlap factor,[16] R is the output mirror reflectivity and L is the additional cavity round trip loss. If η_q and η_{ol} were unity, then a best-case slope efficiency of $\eta \approx 12\%$ would be expected with the 91% reflectivity output mirror. The reasons for the low measured slope efficiency are unknown at present, but may include a quantum efficiency substantially lower than unity, a lower than unity overlap factor, or an underestimate of cavity round-trip losses.

The lasing spectrum was investigated by directing the laser output onto an optical spectrum analyzer. Lasing was found to occur at many wavelengths between 1060nm and 1080nm, and a typical lasing spectrum is shown in Figure 3 for a launched pump power of 300 mW. Lasing over this large range of wavelengths is a result of the broad fluorescence bandwidth typical of neodymium in amorphous hosts, combined with the use of resonator mirrors with broadband reflectivity.

In summary, Nd-doped Ta_2O_5 rib waveguide lasers have been realised for the first time, demonstrating the first laser in this material system. Incorporation of multiple rare-earths and photonic crystal waveguides would allow implementation of multi-wavelength sources on a single chip. The lowest absorbed pump power threshold was found to be 87mW but this may be reduced by lowering the waveguide losses through further development of the fabrication processes, using narrower channels with smaller modal spotsizes, and optimization of the Nd concentration and cavity length. Further spectroscopic studies are underway to explore methods of improving the slope efficiency, and photonic crystal mirrors are being fabricated. Ta_2O_5 is a versatile material for high-contrast high-density optical waveguide circuits and this demonstration of gain opens up routes to new active circuit applications.

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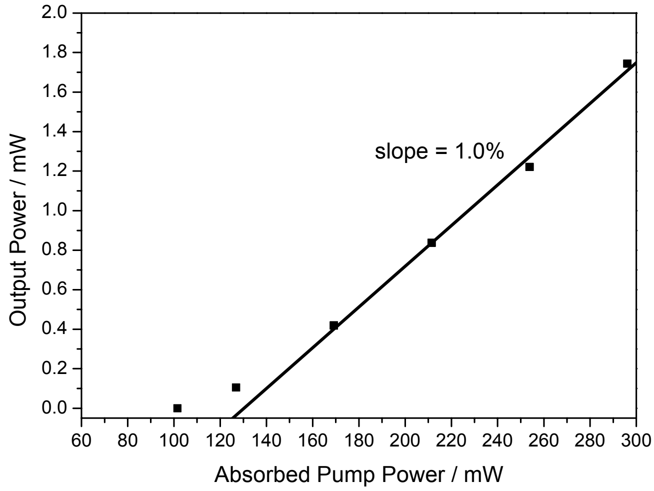
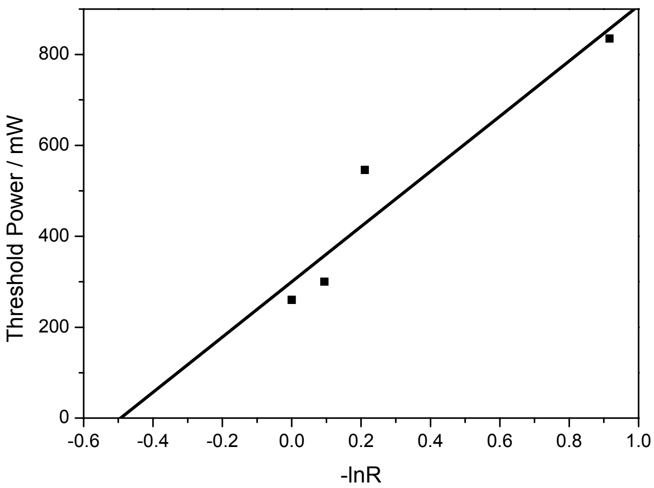
Figure Captions

FIG. 1 Output power against absorbed pump power for the laser with a 91% output mirror.

FIG. 2 Findlay-Clay plot of the threshold pump power incident on the launch objective against output mirror reflectivity, for a rib waveguide of width 18μm.

FIG. 3 Typical lasing spectrum for the 18μm wide rib waveguide laser at a pump power of 300mW.


slope = 1.0%
Output Power / mW
Absorbed Pump Power / mW
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
60 80 100 120 140 160 180 200 220 240 260 280 300


Threshold Power / mW
800
600
400
200
0
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
-lnR

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