$Er:Ta_2O_5$ waveguide optimization & spectroscopy

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Abstract. *The optimization of erbium-doped Ta_2O_5 thin film waveguides deposited by magnetron sputtering is described. Background losses below 0.4dB/cm have been obtained before post-annealing. A broad photoluminescence spectrum centered at 1534nm is obtained, and the photoluminescence power and fluorescence lifetime increase with post-annealing, yielding promising results for compact amplifiers.*

1. Introduction

Optical amplifiers are key components in optical telecommunications and in fully-integrated optical systems. Erbium doped materials are of particular importance in optical communications technology, due to their excellent performance as gain media for amplifiers and lasers at the telecommunications wavelength of 1.5 microns. Low-cost, compact erbium doped waveguide amplifiers (EDWAs) are essential for local-loop optical systems, and fully-functional densely integrated planar lightwave circuits (PLCs) will rely upon gain as electronic integrated circuits do at present. Erbium-doped high index contrast materials have generated great interest [1-4], and will allow strong confinement of light, ultra compact photonic devices, and non-linear processes at moderate power levels. Tantala (Ta_2O_5) has already been used as a host for rare earth ions [5-7], with lasing being achieved only in $Nd:Ta_2O_5$ to date [5]. This, combined with high refractive index (>2.0), moderate phonon energy for high radiative efficiency [8], a large third order non-linearity [9], and high photosensitivity [10], makes it an ideal material for realising multifunctional PLCs. In this paper, the deposition and optimisation of erbium-doped Ta_2O_5 ($Er:Ta_2O_5$) thin films using magnetron sputtering is presented. The photoluminescence and fluorescence lifetime characterisation of these $Er:Ta_2O_5$ films annealed at different temperatures are also presented to evaluate this material's potential as a high index contrast host for erbium and as an EDWA.

2. Waveguide fabrication & characterization

Slab waveguides were fabricated by magnetron sputter deposition of a powder pressed, $Er:Ta_2O_5$ target onto an oxidised silicon substrate (oxide thickness ~ 2.1 μm). The target was doped with 1 wt. % of Er_2O_3 (~2.5 x 10^{-20} ions/cm^3). The deposition was carried out in a vacuum chamber pumped to a base pressure of 10^{-8} Torr and backfilled with an $Ar:O_2$ ambient. In order to obtain high-quality as-deposited films, substrate temperature, magnetron power and O_2 gas flow rate were optimised to yield low-loss films. The deposition rate was determined by measuring the film thickness for various sputtering times, using a stylus profilometer. Figure 1a shows the thickness plotted against time, for the deposition conditions optimised below, with the average deposition rate found to be ~ 2 nm.min^{-1}.

The slab waveguide losses were measured at 633nm (He-Ne laser) by prism coupling and measuring the propagation decay length. The losses were estimated at several different places on a sample to check the homogeneity of the sample, and averaged. The optical loss variation with substrate temperature is shown in Figure 1b. The sample sputtered at 200^{o}C gave the lowest losses (~0.4 dB/cm), so this was chosen as the optimum substrate temperature. Losses are expected to be substantially lower at wavelengths near 1550nm.

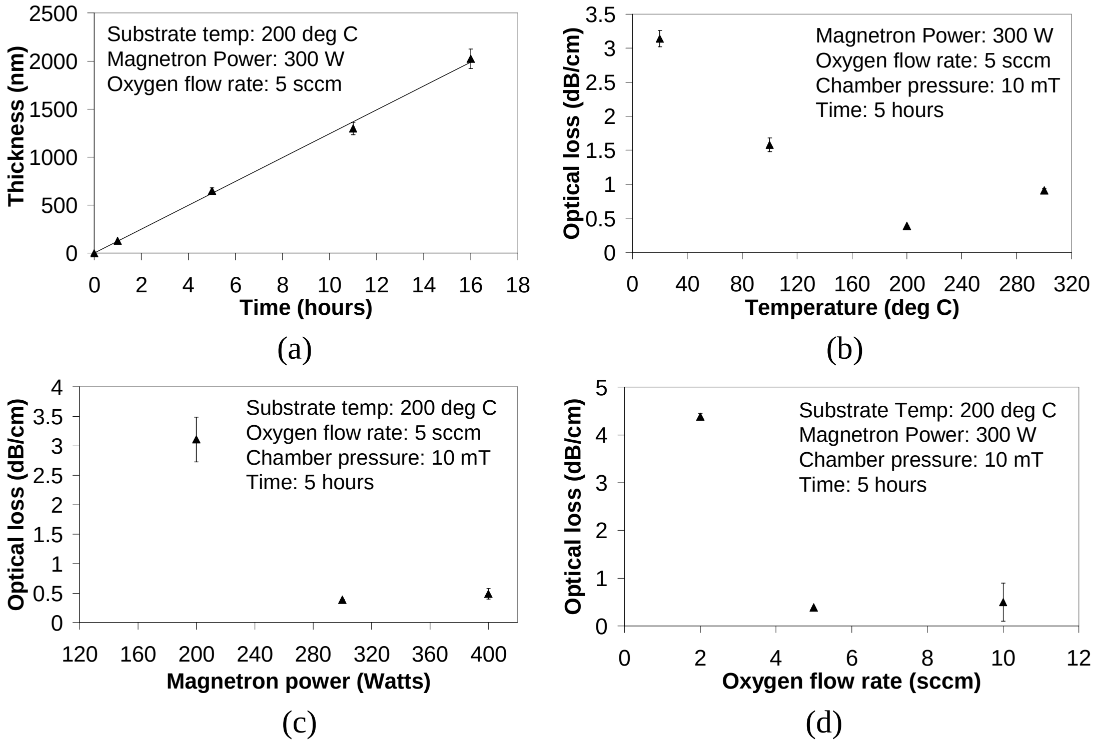


Fig 1 Er:Ta_2O_5 waveguide optimization a) Er:Ta_2O_5 deposition rate. b) Loss vs. substrate temperature, c) Loss vs. magnetron power, and d) Loss vs. oxygen flow rate.

Figure 1c shows the variation of optical loss with magnetron power, with low loss being achieved at 300W. Argon is used to start and maintain the plasma discharge and thus its flow rate is not critical, but the oxygen flow rate plays an important role in achieving low loss films as shown in figure 1d. With the increase in the O_2 flow rate, the film approaches its stoichiometric composition and hence lowest possible loss, but a further increase will lead to increased oxidisation of the target surface and an unacceptably low deposition rate. For our samples, a flow rate of 5sccm achieved the lowest loss value and a reasonable deposition rate. Ellipsometry measurements were performed on the sputtered Er:Ta_2O_5 samples to determine the thin film refractive index at various wavelengths in the visible region. Figure 2 shows the results for the fully optimized Er:Ta_2O_5 film.

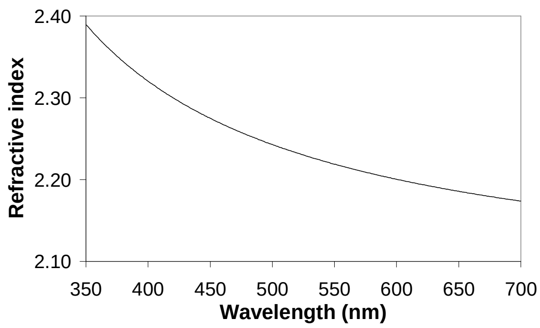
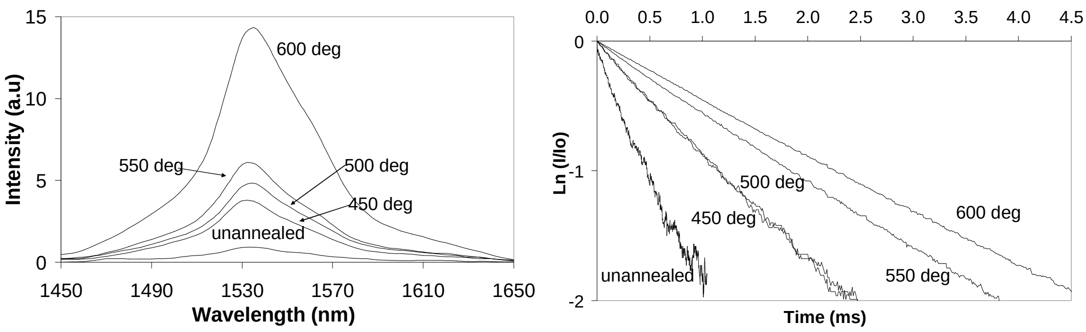


Fig 2.Refractive index of magnetron sputtered Er:Ta_2O_5 in the visible wavelength region.

2. Photoluminescence characterization

Photoluminescence measurements were performed at room temperature by pumping erbium ions into their $^4I_{11/2}$ level using a Ti:Sapphire laser emitting at 980nm. The thickness of the sample was approximately 2 microns. The power density was of the order of $1kW/cm^2$ (180mW total power), and was chopped at 25Hz. The luminescence was collected perpendicular to the sample, sent to a 30cm focal monochromator, and detected with an InGaAs photodiode through a lock-in amplifier. The resolution of the spectra was 10nm. Lifetime measurements were also performed with 0.2ms resolution.The photoluminescence spectra of annealed and non-annealed magnetron sputtered $Er:Ta_2O_5$ samples are shown in Figure 3a. Four samples were annealed at 450,500,550 and 600°C, respectively, in a tube furnace for one hour in oxygen. Higher temperatures were not employed as annealing above 600°C is expected to result in a lossy polycrystalline film [11].



(a) (b)

Fig 3 a) Photoluminescence spectra (bottom: unannealed, topmost: 600 °C) and b) Luminescence decay (leftmost: unannealed, rightmost: 600 °C) for annealed and unannealed samples.

The emission spectra correspond to the transition between the $^4I_{13/2}$- $^4I_{15/2}$ levels of the Er^{3+} ion and peak at 1534nm. The bandwidth of the spectrum (FWHM) was measured to be 50nm which is substantially broader than those obtained from non-telluride glasses (~30nm) [12] and comparable to high index contrast hosts such as telluride glasses (n~2.1, 65nm) [13] and alumina (n~1.69, 55nm) [14] and shows potential for broadband applications. The photoluminescence intensity increases with annealing temperature to about 14 times that of the unannealed sample, at 600°C. The luminescence lifetime of the erbium ions is shown in Figure 3b and was found to increase from 0.53ms for the as-deposited sample to 2.4ms for the sample annealed at 600°C, where I/I_o is the intensity normalized with respect to the maximum intensity. The relationship between the intensity and lifetime can be explained in terms of the decrease in the non radiative decay rate when annealed at higher temperatures. The 2.4ms lifetime decay is smaller than those obtained from non-telluride glasses (10-15ms) [12] and alumina (6ms) [14] but comparable to high refractive index hosts such as telluride glasses (3.5ms) [15] and zirconia (n~2.04, 1.8ms) [2].

3. Conclusions

The deposition of $Er:Ta_2O_5$ by magnetron sputtering has been optimized to yield low loss slab waveguides (<0.4 dB/cm at 633nm) without annealing and losses can be expected to reduce further upon annealing at high temperatures, and with use at longer wavelengths. The refractive index of the thin film was determined over the wavelength range from 350nm to 700nm. A relatively broad photoluminescence spectrum

(FWHM~50nm) peaking at 1534nm was obtained, and a luminescence lifetime of 2.4ms was measured for the erbium ions in the Er:Ta_2O_5 film for optimised sputtering and annealing conditions. The results obtained for the losses and radiative lifetime are promising, for realizing erbium-doped integrated amplifier/laser and multifunctional photonic circuits based on Er:Ta_2O_5.

4. Acknowledgements

The authors would like to thank Neil Sessions, David A. Sager and Dr G. Senthil Murugan for their invaluable help and advice on optimising the sputtering process.

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