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Spectroscopy of high index contrast Yb:Ta_2O_5 waveguides for lasing applications

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Abstract. Ytterbium-doped waveguides are required for compact integrated lasers and Yb-doped Ta_2O_5 is a promising candidate material. The design, fabrication and spectroscopic characterisation of Yb:Ta_2O_5 rib waveguides are described. The peak absorption cross-section was measured to be 2.75×10^{-20} cm^2 at 975 nm. The emission spectrum was found to have a fluorescence emission peak at a wavelength of 976 nm with a peak cross-section of 2.9×10^{-20} cm^2 and a second broad fluorescence band spanning from 990 nm to 1090 nm. The excited-state life time was measured to be 260 μs.

1. Introduction

Yb-doped optical materials have found widespread application for lasers emitting at wavelengths near 1 μm in bulk, disk and fiber configurations. Their main attractive properties include broad absorption near 0.98 μm, long excited-state lifetime, and broadband gain bandwidth operation. Lasing in Er-doped [1] and Yb-doped [2] alumina and Nd-doped [3] and Er-doped [4] tantalum pentoxide (Ta_2O_5) have been demonstrated, and here we explore the suitability of Ta_2O_5 as a waveguide host for Yb ions. Ta_2O_5 is a promising material for mass-producible, multifunctional, integrated photonic circuits on silicon, exhibiting excellent mechanical, electrical and thermal properties and good compatibility with complementary-metal–oxide–semiconductor (CMOS) technologies [5]. Its high refractive index ($n \approx 2.124$ at $\lambda \approx 980$ nm) [6] allows high index contrast between the silica waveguide cladding and core, providing for low-loss, tight bend radii thereby enabling the development of compact photonic circuits due to the strong confinement of the optical modes. As well as Ta_2O_5 excelling as host for rare-earth ions, it also provides a large third-order nonlinearity ($n_2 \approx 7.25\text{x}10^{-19}$ m^2/W at $\lambda \approx 980$ nm) [7] for all-optical processing.

In this work, the design and fabrication of 2.5 wt% Yb_2O_3 doped Ta_2O_5 rib waveguides on silicon using magnetron sputtering, photolithography and argon ion beam milling is presented. The spectroscopic properties of Yb^{3+} ions in Ta_2O_5 such as the absorption cross section (σ_{abs}), emission cross-section (σ_{em}), fluorescence spectrum and radiative lifetime were measured and currently the waveguides are being optimised for the realisation of compact waveguide lasers.

2. Channel waveguide design

Rib waveguides in Ta_2O_5 were designed to give single mode operation for wavelengths between 970 nm and 1100 nm, to cover the signal and pump wavelengths associated with typical Yb-doped materials. Waveguides were designed to be fabricated on oxidised silicon wafers and to have a silica cladding for symmetry and high index contrast, allowing tight modal confinement. A rib waveguide approach, as shown in figure 1, was adopted to allow single mode operation of channels with various widths to be readily fabricated using conventional photolithography, to maximise pump-signal overlap and to minimise waveguide loss resulting from any sidewall roughness. The rib height was chosen to be 1µm to ensure good confinement of the modes within the core and the initial design was selected using the approach of Soref et al. [8] and the waveguide properties fully determined using finite element analysis. While an etch depth of up to 500 nm could be used and still maintain monomode operation, an etch depth of 150 nm was chosen as a compromise between modal spotsize and loss due to sidewall roughness, leaving the outer slab thickness at 850 nm. With these constraints, waveguides with widths below 1.9 µm, readily achieved by conventional photolithography, were predicted to be monomode at a wavelength of 970 nm.

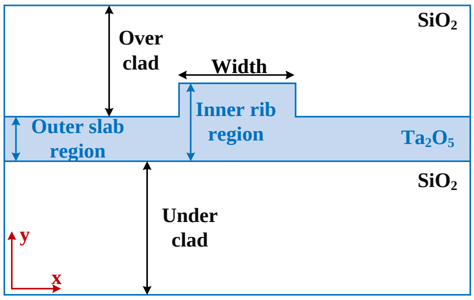

Figure 1. Cross-section of etched rib waveguide design

3. Fabrication of Yb:Ta_2O_5 waveguides

A 1 µm thick layer of Yb:Ta_2O_5, using RF magnetron sputter deposition system from a 150 mm wide circular powder-pressed Ta_2O_5 target doped with 2.5 wt.% of ytterbium oxide (~$6.2x10^{20}$ Yb atoms/cm^3) onto a 4 inch silicon substrate having a 2.5 µm thick thermally-grown silica overlayer. The deposition was performed in a vacuum chamber which had been pumped to a base pressure of 10^{-8} Torr. During the deposition process the chamber was filled with a mixture of oxygen and argon gases at flow rate of 5 sccm and 20 sccm, while the substrate was kept at a constant temperature of 200 °C and magnetron power of 300 W. The chamber was maintained at a pressure of 10 mTorr. These conditions are based on previous optimisation for Ta_2O_5 hosting erbium ions for 1.5µm emission to provide the lowest optical loss with an acceptable deposition rate [9]. Rib waveguides were realised using conventional photolithography and argon ion beam milling (IBM) to produce the waveguide design described in Section 2. Strips of photoresist of widths varying from 1 to 10 µm were defined in positive photoresist spun onto the deposited Yb:Ta_2O_5 film. The Yb:Ta_2O_5 film was then etched by 150 nm using an OIPT Ion Fab 300 Plus ion beam etch and deposition system. After etching and the removal of excess photoresist the wafer was immersed in a solution of 30% aqueous potassium hydroxide (KOH) at a temperature of 55 °C for 20 minutes to reduce surface roughness [9] introduced during the etching process. To reduce any oxygen deficiency and stresses introduced during the sputtering and etching processes the wafer was then annealed for two hours at 600 °C, with the furnace temperature ramped up at a rate of 3 °C per minute and ramped down at a rate of 2 °C per minute to room temperature [9].

To protect the waveguide layer from external influences and to create a symmetrical waveguide system, a 2 µm silica overcladding was deposited onto the patterned Yb:Ta_2O_5 film. The silica was sputtered using the same RF magnetron sputtering system used for the Yb:Ta_2O_5 layer. After the silica deposition, the wafer was again annealed at 600 °C to reduce oxygen deficiency and release the stresses introduced during the deposition process. To characterise the waveguides for their spectroscopic properties the wafer was diced and the end-facets were polished to optical quality.

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4. Characterisation of spectral properties of Yb:Ta_2O_5

This section presents the procedures for determining spectral characteristics of the Yb:Ta_2O_5 waveguides such as the excited state lifetime, and the absorption and emission spectra, and the results obtained, leading to the deduced absorption and emission cross-sections. The excited-state lifetime and the absorption and emission cross-sections will enable the design of an efficient waveguide laser. These measurements were performed taking into account the effects of the waveguide configuration such as waveguide loss, the material/mode overlap factor and the potential for significant amplified spontaneous emission.

4.1. Absorption spectrum

The measurement of the absorption spectrum of the ytterbium ions in Ta_2O_5 was carried out to determine the absorption cross-section at the pump wavelength near 980nm. In a 3 mm long waveguide the spectrum was obtained by end-coupling broadband (700 – 1700 nm) white light from a tungsten halogen lamp into the polished end-facet of a waveguide using a monomode fibre. Light emerging from the waveguide was captured using a multi-mode fiber and fed into an optical spectrum analyser (OSA). Measurements were made with and without the device in place in order to quantify the spectral insertion loss, including coupling loss, propagation loss and Yb ion absorption.

The resulting spectrum is shown in figure 2a, where two prominent absorption bands of ytterbium at 935 and 975 nm are clearly visible. The peak absorption cross-section for ytterbium ions in Ta_2O_5 in the pump band occurred at 975 nm was calculated to be 2.75x10-20 cm^2, using an estimated concentration of the Ytterbium ions in the Ta_2O_5 of 6.2x1020 cm^{-3}, assuming that the composition of the film is the same as that of the sputtering target.

4.2. Fluorescence spectrum

The fluorescence spectrum for the Yb-doped Ta_2O_5 was captured using an experimental setup consisting of a 971 nm fiber Bragg grating-stabilised laser source butt-coupled via a single-mode fiber into an end-facet of a waveguide. The collection of the fluorescence was achieved using a multimode fiber positioned above the waveguide close to the input, and fed directly into an OSA. An estimate of the emission cross-section was deduced from the absorption cross-section using McCumber analysis [10, 11]. The accuracy of the deduced cross-section is poor at longer wavelengths due to the noise in the absorption spectrum and the nature of the McCumber transform, but is acceptable close to 977 nm, where the emission cross-section was estimated to be $\sigma_{em} = 2.90 \pm 0.73$ x10^{-20} cm^2. This was used as a scaling factor to plot the emission cross-section spectrum from the fluorescence spectrum, as shown in figure 2b. The sharp peak at 971nm is due to pump radiation scattered by the waveguide.

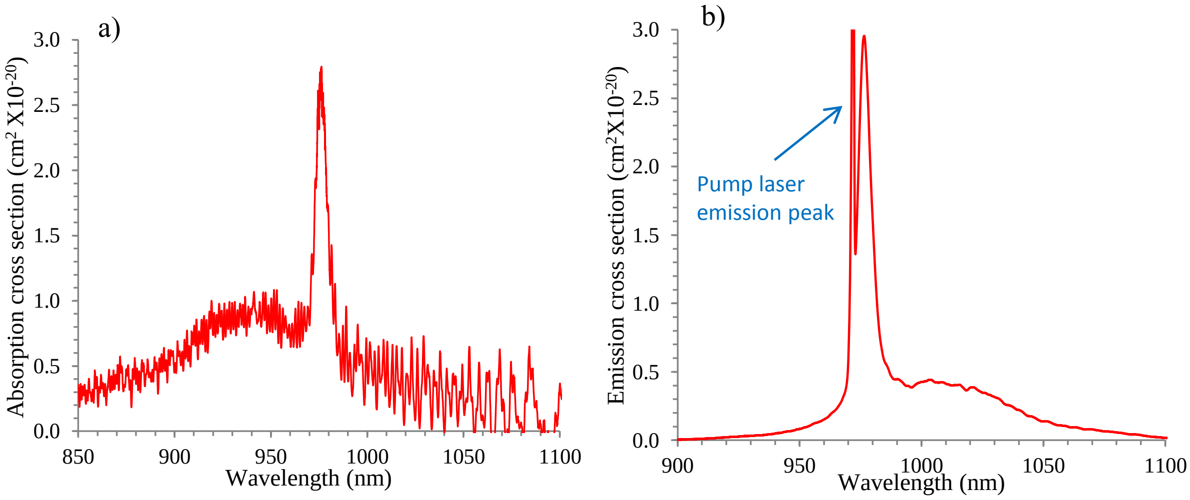

Figure 2a) Yb:Ta_2O_5 absorption cross-section spectrum **b)** Yb:Ta_2O_5 emission cross-section spectrum

4.3. Excited-state lifetime
The fluorescence lifetime was measured from a 10.8 mm long Yb:Ta_2O_5 waveguide sample from the same wafer as that used for the absorption and fluorescence characterisation. Light from the 971 nm pump laser diode was chopped at 200Hz using a mechanical chopper and focused into an end-facet of an Yb:Ta_2O_5 waveguide, with the pump power kept minimal to avoid significant amplified spontaneous emission (ASE). The light from the output of waveguide was passed through a set of long pass filters with a cut-off wavelength of 1 μm to eliminate the pump wavelength. The resulting fluorescence power was then detected using a silicon photodetector and amplifier connected to an oscilloscope. The time resolution of the system was approximately 20 μs and the lifetime was found to be 260 ± 30 μs.

5. Conclusion
In conclusion, we have studied the spectroscopic properties of Yb:Ta_2O_5 as a new material for waveguide laser applications, and determined the absorption and emission cross-sections and the excited-state lifetime. CMOS-compatible fabrication technology was used to realise rib waveguides on silicon substrates which operated in a single mode for wavelengths ranging between 970 nm and 1100 nm for waveguide widths smaller than 1.9 μm. The peak absorption cross-section was measured to be 2.75×10^{-20} cm^2 at 975 nm. The emission spectrum was found to comprise a sharp peak at a wavelength of 976 nm, with a peak emission cross-section of 2.9×10^{-20} cm^2, and a second broad peak which spanned from 990nm to 1090 nm. The upper state life time was measured to be 260 ± 30 μs. Yb:Ta_2O_5 shows promise as a material system for the development of advanced compact lasers with monolithically integrated components to add functionality. Optical structures such as ring resonators can be formed in this material system, exploiting the high index contrast, and nonlinear components for switching or modelocking can be realised, exploiting the high third order nonlinearity of tantalum pentoxide. Efforts are underway to demonstrate a mode-locked Yb:Ta_2O_5 waveguide laser.

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