Ytterbium-Doped Tantalum Pentoxide Waveguides: Spectroscopy for Compact Waveguide Lasers

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Abstract: Ytterbium-doped materials are common gain media in high-performance laser systems. In this work, the first spectroscopic investigation of ytterbium-doped tantalum pentoxide (Yb:Ta2O5) for compact waveguide laser applications is presented.

OCIS codes: (140.3615) Lasers, ytterbium; (230.7380) Waveguides, channeled

1. Introduction

Integrated channel waveguide solid-state lasers are key components in the quest for fully integrated optical circuits with advanced functionality such as tunability and pulsed operation. Ta_2O_5 has been selected as the host material for the realization of a compact, integrated ytterbium doped waveguide laser as it offers many important attributes such as good ability to host rare-earth ions, as demonstrated with erbium [1] and neodymium [2], a large third nonlinearity [3] and a high refractive index ($n \approx 2.124$ at $\lambda \approx 980$ nm) [4]. High index contrast between the waveguide cladding and core provides for low-loss tight bend radii enabling the development of compact and ultra-small photonic circuits due to the strong confinement of the optical modes, and offers the potential for 2-D photonic crystal operation.

Ta_2O_5 thin films also have excellent mechanical and thermal properties and have great compatibility with complementary-metal–oxide–semiconductor (CMOS) technologies making it an ideal candidate for mass producible integrated optical circuits.

In this work, we present for the first time the initial spectroscopic findings for $Yb{:}Ta_2O_5$ rib waveguides and quantify the absorption cross section and fluorescence spectrum for this $Yb{:}Ta_2O_5$ material.

2. Waveguide design and fabrication

Suitable dimensions for single mode (SM) operation of rib waveguides in tantalum pentoxide at a wavelength of 980 nm were determined using the method outlined in [5], and were confirmed using finite element modelling (COMSOL), Figure 1b. A 1µm rib height with an etch depth of 150 nm was predicted to yield SM operation at widths up to 1.9 µm, and a cross-sectional diagram of the waveguide design is shown in Figure 1a.

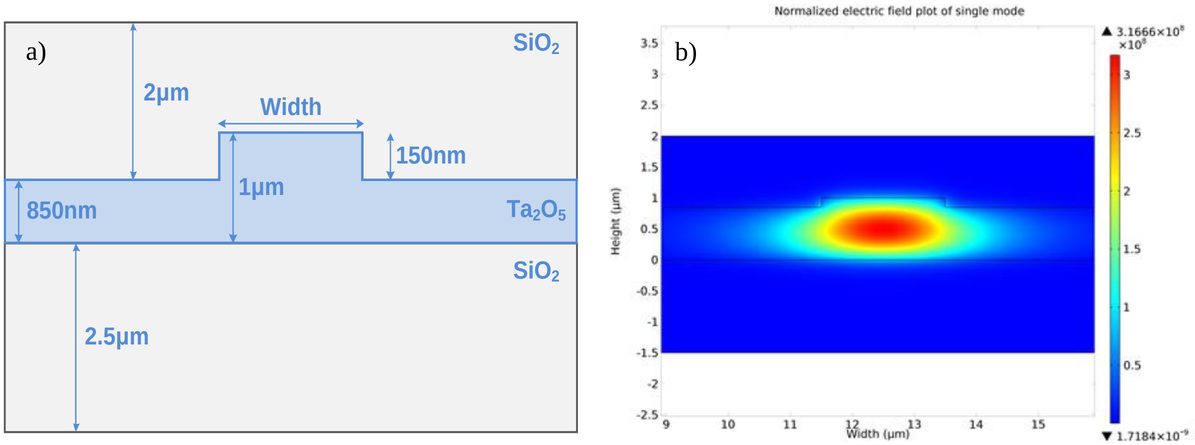

Figure 1a) Rib waveguide structure cross-section dimensions b) COMSOL simulation of a mode intensity profile of rib waveguide

$Yb{:}Ta_2O_5$ slab waveguides were fabricated by RF magnetron sputter deposition from a powder-pressed tantalum pentoxide target, doped with 2.5 wt% of ytterbium (~ $6.2\text{x}10^{20}$ atoms/cm^3) onto a silicon substrate with 2.5 µm pre-deposited silica layer. The $Yb{:}Ta_2O_5$ was deposited using conditions of 200 ^{o}C substrate temperature, 300 W of magnetron power, and 20 and 5 sccm of argon and oxygen gas flow. For the development of rib structures a combination of photolithography and argon ion beam milling (IBM) was used. The mask pattern used for photolithography consisted of straight channels of width varying from 1 to 10 µm in 0.2 µm steps, with 100 µm spacing. This defined the channel waveguide mask for the argon IBM process. After the rib structure was etched into the Yb:Ta_2O_5 film, a 2 µm of silica was deposited to encapsulate the waveguide core, producing a symmetrical channel waveguide.

3. Spectral characterization

Measurement of the absorption spectrum of a broad ytterbium-doped rib waveguide was performed to allow for the accurate determination of ytterbium absorption cross sections at the pump (~980 nm) wavelength. The absorption spectrum of the Yb:Ta_2O_5 was determined through broadband (700-1700 nm) white light measurements using light from a tungsten halogen lamp. The light from the lamp was coupled to a 3 mm long, end-facet polished Yb:Ta_2O_5 rib waveguide sample. The waveguide with the widest width was selected to ensure that the majority of the power travelled in the Yb:Ta_2O_5 core material rather than in the cladding, so that the absorption measurement was an accurate reflection of the Yb:Ta_2O_5 material. Light was coupled out of the waveguide using a multimode fiber into an optical spectrum analyzer (OSA).

The resulting spectrum is shown in Figure 2a, where the 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 and was calculated to be $2.75\text{x}10^{-20}$ cm^2, using an estimated concentration of the Ytterbium ions in the Ta_2O_5 (~$6.2\text{x}10^{20}$ cm^{-3}), that is assuming that the film composition is the same as the sputtering target concentration.

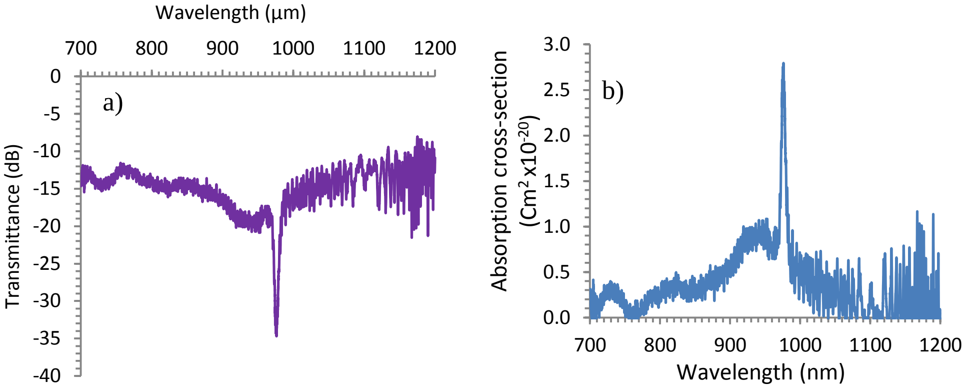

Figure 2a) Yb:Ta_2O_5 absorption spectrum b) Yb:Ta_2O_5 absorption cross-section

The fluorescence spectrum of the Yb:Ta_2O_5 waveguide was also obtained to quantify the peak emission wavelength and the bandwidth. The apparatus for measuring the fluorescence spectrum consisted of a 977 nm fiber Bragg grating laser source, fiber butt-coupled with a single mode fiber into end-facet of the Yb:Ta_2O_5 waveguide. Waveguides with widths below 2 µm were found to be single moded at 977nm. The output light was collected using a multi-mode fiber positioned vertically above the waveguide near the waveguide input, and this was fed into an Optical Spectrum Analyser (OSA). The resulting fluorescence spectrum is shown in Figure 3, along with the input pump power from the laser diode measure without a sample. From the collected spectrum it is evident that there are three interesting regions shown, the first region indicates fluorescence peaks at wavelengths of 972 nm and 976 nm at peak pump wavelength of 971 nm, while the second region shows broad fluorescence band between 900 nm and 1135 nm. The last significant region at a wavelength of 744 nm is the most unexpected of the three regions. This is because the wavelength 744 nm corresponding to a wavenumber of 13440.86 cm^{-1} is not evident in the Yb^{3+} energy level diagram. Similar emission of wavelength was also shown by Paschotta et al. [6], citing that this could be caused by Ge-O defects leading to the weak board-band fluorescence around 744 nm.

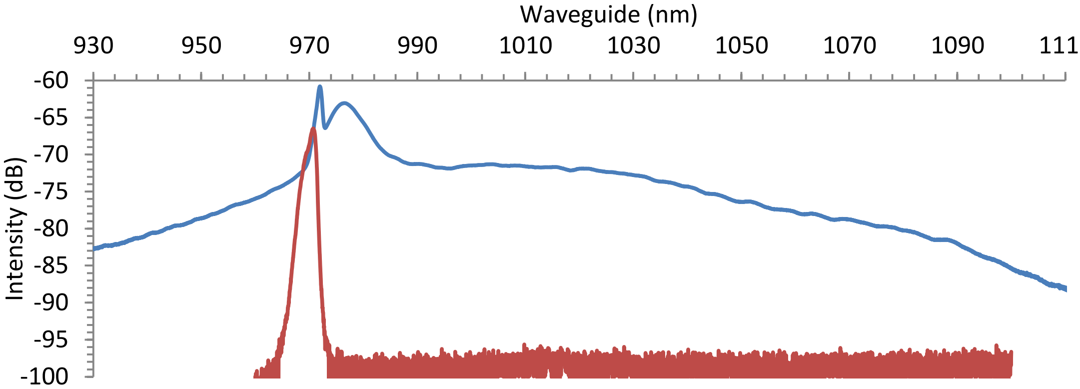

**Figure 3 Fluorescence Spectrum Yb:Ta_2O_5 waveguide:
blue spectrum of Yb:Ta_2O_5 fluorescence; red spectrum of pump source**

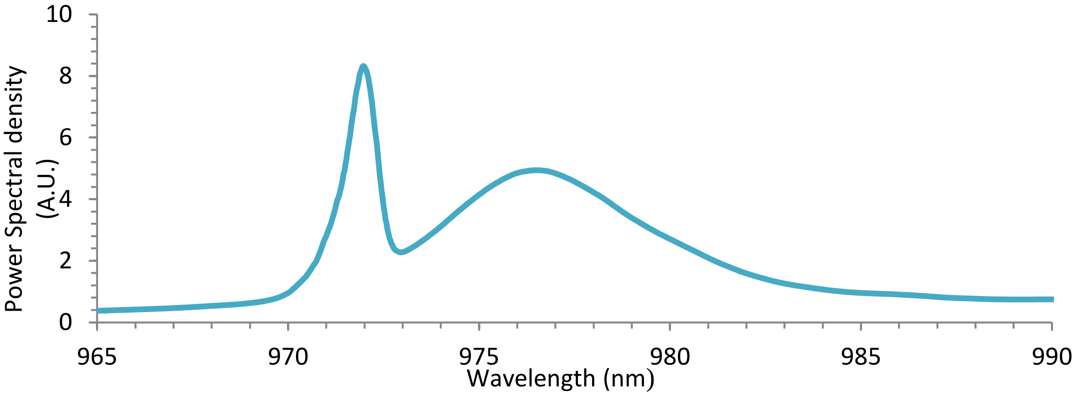

Figure 4 Fluorescence power density spectrum of Yb:Ta_2O_5

4. Conclusion

In conclusion, Yb:Ta_2O_5 waveguides operating in a single mode at a wavelength of 977nm for widths less than 2 µm were realised on silicon substrates and the absorption and fluorescence spectra obtained. The peak absorption cross-section was measured to be 2.75×10^{-20} cm^2 and the emission spectrum was found to be typical of Yb-doped materials in the wavelength region around 1 µm. This material system shows promise for advanced compact lasers with monolithically integrated components to add functionality, such as ring resonators exploiting the high index contrast and nonlinear components for switching, exploiting the high $\chi^{(3)}$ of tantala. The CMOS-compatible nature of the processes used to fabricate these waveguides offers a potential route to low-cost mass production of these lasers.

5. References

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