

Fabrication of Sub-micron High Refractive Index Tantalum Pentoxide Waveguides for Optical Propulsion of Microparticles

Balpreet Singh Ahluwalia, Ananth Z. Subramanian, Olav Gaute Hellesø, Nicolas M. B. Perney, Neil P. Sessions and James S. Wilkinson

Abstract— Design, fabrication and optimization of Tantalum Pentoxide (Ta_2O_5) waveguides to obtain low-loss guidance at a wavelength of 1070 nm are reported. The high-refractive index contrast ($\Delta n \sim 0.65$, compared to silicon oxide) of Ta_2O_5 allows strong confinement of light in waveguides of sub-micron thickness (200 nm), with enhanced intensity in the evanescent field. We have employed the strong evanescent field from the waveguide to propel micro-particles with higher velocity than previously reported. An optical propelling velocity of 50 $\mu\text{m/s}$ was obtained for 8 μm polystyrene particles with guided power of only 20 mW.

Index Terms— Optical waveguides, Optical device fabrication, Optical strip waveguides, Integrated optics

I. INTRODUCTION

The high refractive index of Ta_2O_5 renders it suitable for application to making dense and compact photonics circuits, and it is a good host for rare-earth ions to achieve optical gain [1]. Optical non-linear behaviour like supercontinuum generation and self-phase modulation in Ta_2O_5 waveguides has been reported, suggesting its good stability and high damage threshold limits [2]. A high refractive index contrast allows strong confinement of light and by fabricating waveguides of sub-micron thickness (150-200 nm), the intensity of the evanescent field may be maximised [3]. This combination will find usage for applications requiring high evanescent field like optical propelling of micro-particles [4-8]. The conventional waveguide materials used for micro-propulsion can be classified as, a) low refractive index contrast (Δn) (≤ 0.04) Cs^+ or K^+ ion-exchanged waveguides [4]; b) medium Δn (~ 0.10) SU-8 (an epoxy-based negative photoresist) polymer waveguides [5]; c) high Δn (~ 0.52) silicon nitride (Si_3N_4) waveguides [6]. High Δn waveguides imparts higher optical forces for micro-particle propelling as compared to low Δn waveguides. In this paper, we report fabrication, optimization and characterization of high

refractive index Ta_2O_5 waveguide for micro-propulsion of particles with higher velocities than previously reported ($\sim 50 \mu\text{m/s}$). Ta_2O_5 has a refractive index of approximately 2.10 at 1064 nm, yielding a core/substrate Δn of 0.65 on silica, while Si_3N_4 has a refractive index of 1.97 yielding a Δn of 0.52. Optimization of the fabrication steps is crucial to obtain Ta_2O_5 waveguides with low propagation losses ($\sim 1 \text{ dB/cm}$ at 1070 nm) resulting in optical propelling of micro-particle with high velocity. The distinct advantage of Ta_2O_5 over Si_3N_4 is its higher damage threshold and absence of prominent absorption peaks over broad range of wavelengths (600-1700 nm), making them suitable for applications requiring high power.

II. DESIGN AND FABRICATION OPTIMIZATION

Ta_2O_5 waveguides with thickness between 150-250 nm were reported to generate high intensity in the evanescent fields [3]. Strip waveguides of 200 nm thickness and width ($1 < w < 10 \mu\text{m}$) were fabricated. Ta_2O_5 was deposited using magnetron sputtering on an oxidised silicon substrate (oxide thickness 5 μm). In order to have optically good as-deposited films of sub-micron thickness ($\sim 200 \text{ nm}$) it is necessary to optimise the sputtering conditions. The parameters optimised for the deposition were the substrate temperature, magnetron power and the oxygen gas flow rate. The optimum sputtering conditions were obtained at 200°C substrate temperature, magnetron power of 300 W and O_2 and Ar flow rates of 5 and 20 sccm respectively. This process yielded a propagation loss of 0.4 dB/cm for slab waveguides at a wavelength of 633 nm, without annealing. The refractive index of the deposited Ta_2O_5 slab waveguides was found to be 2.1 ± 0.02 at a wavelength of 1064 nm, using ellipsometry. Conventional photolithography followed by argon ion-beam milling was employed to realize the waveguides. It was found that ion-beam milling at an angle of 45 degrees reduced the side-wall roughness of channel waveguides considerably as compared to the conventional zero degree angle. The side wall roughness was observed using scanning electron microscope. Finally, the samples were treated with plasma-ashing for 10 minutes to remove remaining photo-resist to yield smooth waveguide walls.

III. LOSS MEASUREMENT AND CHARACTERIZATION

Loss measurements on the fabricated waveguides yielded an insertion loss (sum of propagation and coupling losses) in the

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Authors: - Balpreet Ahluwalia and Olav Gaute Hellesø are with the Department of Physics and Technology, University of Tromsø, Norway (corresponding author) e-mail: balpreet@phys.uit.no

Authors: - Ananth Z. Subramanian, Nicolas M. B. Perney, Neil P. Sessions and James S. Wilkinson are with Optoelectronics Research Centre, University of Southampton, Southampton, UK

range of 25-35 dB for unannealed samples. The large losses observed were mainly due to the propagation loss of the unannealed samples. In order to reduce the losses, samples were annealed from 450°C to 600°C in oxygen in a tube furnace for 2-5 hours, as shown in Fig. 1. Higher temperatures were not employed as annealing above 600 °C is reported to result in a lossy polycrystalline film [9]. The lowest loss was obtained for samples annealed at 600 °C for 5 hours with a ramp rate of 3 °C/min. Annealing helps to remove stress built up in the waveguides during the fabrication processes and reduces losses by filling oxygen deficiencies. Annealing reduced the propagation loss to around 1 dB/cm (determined by cut-back method).

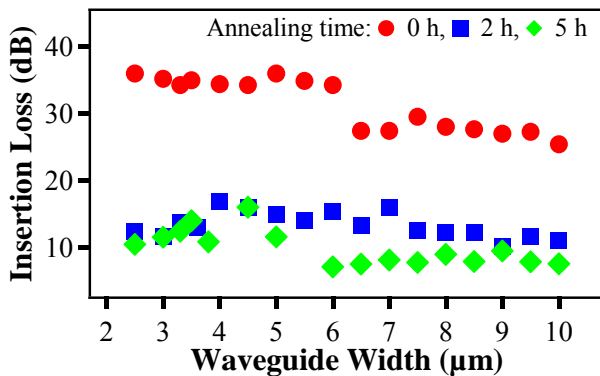


Figure 1: Influence of annealing on insertion loss for 3 cm long Ta_2O_5 waveguides with varying width.

To ensure that the waveguide does not have intrinsic absorption peaks at the wavelength of interest (1070 nm) we performed white light absorption measurements on a thicker rib waveguide sample as shown in Fig. 2. Light from a tungsten halogen lamp (600-1700 nm) was coupled, using a fiber specified as single mode at 1550 nm, to a 4 cm long rib waveguide (2.72 μm thick and etched down to 1 μm). The partially-etched rib waveguide sample was used for spectral measurements, which allows efficient coupling to optical fibre and a measurable transmission spectrum from the white light source. It is evident from Fig. 2 that there are no prominent absorption peaks over 600-1700 nm wavelength range. Ta_2O_5 waveguides are thus suitable for higher power regime where absorption losses lead to significant heating and thus to fluidic instabilities and potentially destruction of the waveguide like in case of silicon nitride discussed below.

We compared the damage threshold for Ta_2O_5 waveguides with those of Si_3N_4 waveguides. Both Si_3N_4 and Ta_2O_5 waveguides have almost identical Δn (refractive index contrast), possessing similar optical properties like power in the evanescent field and optical losses. The output power from both the waveguides (of identical dimensions 200 nm thick and 5 μm wide) was recorded while increasing the input power. As the input power was increased, the output from the Si_3N_4 waveguide saturated, resulting in catastrophic failure of the waveguide, visible as black strip along waveguide as shown in the inset of Fig. 3. The catastrophic failure of Si_3N_4 waveguides was repeatable at input power of around 1 W. In

contrast to this, the Ta_2O_5 waveguide showed no signs of damage and increased absorption, even at input powers up to 2W, nor did we observe increased fluctuations in output power at these high powers, implying that heating was not an issue. A probable reason for the catastrophic failure of the Si_3N_4 waveguides at high powers is the absorption caused by the second overtone of N-H (nitrogen-hydrogen) bonds which peaks at 1.060 μm . Absorption by the first overtone of N-H bonds at 1.51 μm is a known problem in Si_3N_4 waveguides [10-11].

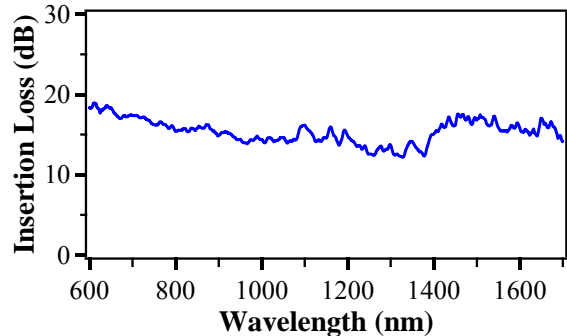


Figure 2: White light absorption spectrum of Ta_2O_5 waveguides.

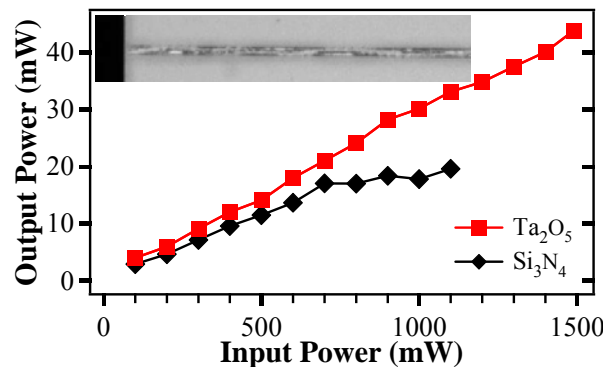


Figure 3: Comparison of damage threshold for Ta_2O_5 and Si_3N_4 waveguides, inset shows the burnt Si_3N_4 waveguide for input power ~ 1 W.

IV. OPTICAL GUIDING OF MICRO-PARTICLES

Optimized low-loss waveguides were employed for optical guiding experiments. A 5 W Ytterbium fiber laser at 1070 nm and an IR coated objective lens (80X, 0.9 N.A, Nacet) was used. A microscope with 10X objective lens and cooled CCD (charge coupled device) camera were employed to capture images. Polystyrene particles (refractive index 1.59) of diameter 8 μm were used in the experiment. Submicron thick Ta_2O_5 waveguide with low propagation loss generates evanescent beam with high intensity for fast propulsion of micro-particles. Figure 4(a-d) shows optical guiding of 8 μm particles (highlighted by the circle) on a 200 nm thick and ~ 8 μm wide waveguide. The arrow on Fig. 4(a) shows the propagation direction of light. Linear dependency of the optical propulsion velocity with the input power is shown in

Figure 5. With an input power of 700mW and output power (guided power) of only 20mW the optical propulsion velocity achieved was 50 $\mu\text{m/s}$. The optical propulsion velocity was determined by taking the average velocity of the same micro-particle at different locations over the waveguide. To the best of our knowledge, the optical guiding velocity obtained by Ta_2O_5 waveguides is the highest reported so far for micro-particles. Microparticles of other diameters (3-10 μm) were also propelled successfully on these waveguides and showed similar dependence of velocity upon diameter to that reported earlier for low Δn waveguides [4], but with larger absolute velocities. Table 1 compares Ta_2O_5 results with other optical guiding velocity (*Vel.*) reported in the literature [4-7] for different particle diameter (*Dia.*) for given input (P_{in}) and output (P_{out}) power. For tapered fibre even with output power of 400 mW, the guiding velocity is limited to 15 $\mu\text{m/s}$. Compared to Si_3N_4 (high Δn waveguide) there is significant improvement of the propelling velocity with Ta_2O_5 .

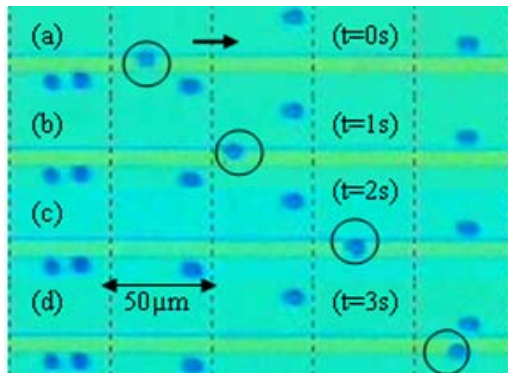


Figure 4: Optical propulsion of 8 μm micro-particles.

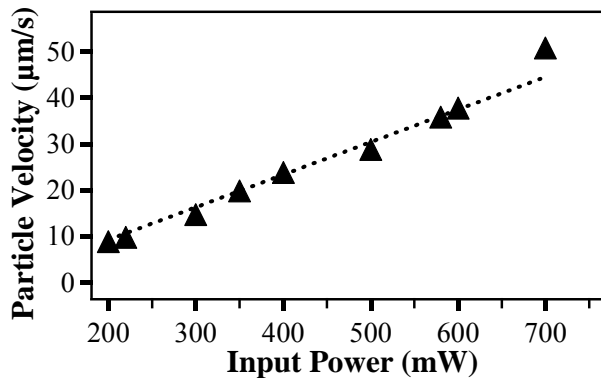


Figure 5: Optical propulsion velocity of 8 μm particle with the input power over waveguide of width $\sim 8 \mu\text{m}$.

Waveguide	Vel. ($\mu\text{m/s}$)	P_{in} (mW)	P_{out} (mW)	Dia. (μm)	Width (μm)	Thickness (μm)
Cs+ Ion [4]	33	870	?	10	2.5	2
Si_3N_4 [6]	15	?	20	2	2	0.2
SU-8 [5]	28	?	53	23	2.8	0.560
Fiber [7]	15	500	400	3	~ 0.95	0.95
Ta_2O_5	50	600	20	8	8	0.2

Table 1 Comparison of propulsion velocity of micro-particles

V. CONCLUSION

The optimization and fabrication of low-loss, sub-micron dimension high-index contrast Ta_2O_5 waveguide for micro-particle propulsion has been demonstrated. The waveguides were found to be stable for high power applications with no significant absorption peaks over a large range of wavelengths. Thus biosensors based on Ta_2O_5 waveguide and micro-fluidics will find usage in micro-particle and cell guiding and sorting applications.

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REFERENCES

- [1] B. Unal, M.C. Netti, M.A. Hassan, P.J. Ayliffe, M.D.B. Charlton, F. Lahoz, N.M.B. Perney, D.P. Shepherd, C.Y. Tai, J.S. Wilkinson and G.J. Parker, "Neodymium doped tantalum pentoxide waveguide lasers," IEEE J. Quantum Electron. vol. 41, pp. 1565-1573, Dec. 2005.
- [2] John D. Mills, Tipsuda Chaipiboonwong, William S. Brocklesby, Martin D. B. Charlton, Caterina Netti and Majd E. Zoorob, Jeremy J. Baumberg, "Group velocity measurement using spectral interference in near-field scanning optical microscopy", Appl. Phys. Letts., vol. 89, pp. 051101 1-3, July 2006.
- [3] Gert L. Duveneck, Andreas P. Abel, Martin A. Bopp, Gerhard M. Kresbach, Markus Ehrat, "Planar waveguides for ultra-high sensitivity of the analysis of nucleic acids", Anal. Chim. Acta, vol. 469 pp. 49-61, Jan. 2002.
- [4] K. Grujic, O. G. Hellesø, J. S. Wilkinson and J. P. Hole, "Optical propulsion of microspheres along a channel waveguide produced by Cs+ ion-exchange in glass," Opt. Commun. vol. 239, pp. 227-235, July 2004.
- [5] Bradley S. Schmidt, Allen H. J. Yang, David Erickson, and Michal Lipson, "Optofluidic trapping and transport on solid core waveguides within a microfluidic device", Opt. Exp. vol. 15, pp. 14322-14334, Oct. 2007.
- [6] S. Gaugiran, S. Gétin, G. Colas, A. Fuchs, F. Chatelain, J. Dérouard, and J.M. Fedeli, "Optical manipulation of microparticles and cells on silicon nitride waveguides," Opt. Exp., vol.13, pp.6956-6963, Sept. 2005.
- [7] G. Brambilla, G. Senthil Murugan, J. S. Wilkinson, and D. J. Richardson, "Optical manipulation of microspheres along a subwavelength optical wire", Opt. Letts., vol. 32, pp. 3041-3043, Oct. 2007.
- [8] Allen H. J. Yang, Sean D. Moore, Bradley S. Schmidt, Matthew Klug, Michal Lipson & David Erickson, "Optical manipulation of nanoparticles and biomolecules in sub-wavelength slot waveguides", Nature vol. 457, 71-75, Jan. 2009.
- [9] P.C. Joshi and M.W. Cole, "Influence of postdeposition annealing on the enhanced structural and electrical properties of amorphous and crystalline Ta_2O_5 thin films for dynamic random access memory applications," J. Appl. Phys., vol. 86, pp. 871-880, July 1999.
- [10] F. Ay, A. Aydinli, "Comparative investigation of hydrogen bonding in silicon based PECVD grown dielectrics for optical waveguides", Optical Materials, vol. 26, pp. 33-46, Jan. 2004.
- [11] Kerstin Wörhoff, Paul V. Lambeck, and Alfred Driessen, "Design, tolerance analysis, and fabrication of silicon oxynitride based planar optical waveguides for communication devices", J. Lightwave Technol. J. of Light. Tech. vol. 17, pp. 1401-1407, Aug. 1999.