Performance of Ar^+ -Milled Ti:Sapphire Rib Waveguides as Single Transverse-Mode Broadband Fluorescence Sources

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Abstract—Rib waveguides have been fabricated in pulsed-laser-deposited Ti:sapphire layers using photolithographic patterning and subsequent Ar^+ -beam milling. Fluorescence output powers up to 300 μW have been observed from the ribs following excitation by a 3-W multiline argon laser. Mode intensity profiles show high optical confinement and the measured beam propagation factors M_x^2 and M_y^2 of 1.12 and 1.16, respectively, indicate single transverse-mode fluorescence emission. Loss measurements using the self-pumped phase conjugation technique have yielded comparable values (1.7 dB/cm) for the ribs and the unstructured planar waveguide counterparts. The combination of optimum modal properties and strong optical confinement, together with sufficient levels of fluorescence output, make the single-mode Ti:sapphire rib waveguides a very interesting candidate as a fluorescence source for optical coherence tomography applications.

Index Terms—Ion beam applications, laser ablation, lithography, loss measurement, optical tomography, optical waveguides, rib waveguides.

I. INTRODUCTION

OPTICAL coherence tomography (OCT) is an interferometric imaging technique, which provides cross sectional images of diffusive media, such as biological tissue, with high longitudinal and transverse spatial resolutions. There are three general requirements for the light source used for OCT in biological imaging: 1) emission in the near infrared to ensure adequate penetration of the light in the tissue; 2) a large spectral bandwidth to ensure a short coherence length and, therefore, improved longitudinal resolution; and 3) high irradiance to achieve a wide dynamic range and detection sensitivity for imaging weakly backscattering structures in the tissue [1], [2]. Typical light sources for OCT for medical applications are edge light-emitting diodes (ELED) and superluminescent diodes (SLD), offering a longitudinal resolution of

~ 10 – 15 and 15 – 30 μm , respectively, which is inadequate for subcellular imaging. Approximately 2 - μm resolution has been demonstrated using a Ti:sapphire bulk fluorescent emitter [3] and slow *in vivo* scanning can be performed in this way [4]. However, these sources are insufficient for fast-scanning OCT due to their low brightness. Recently, femtosecond Ti:sapphire lasers have been introduced as large-bandwidth high-brightness light sources offering a longitudinal resolution of ~ 1 μm [5].

In an attempt to develop light sources which combine high spectral power density, large bandwidth, and high spatial coherence, together with compactness and simplicity, we report here an investigation of the waveguiding characteristics of rib waveguide structures fabricated by Ar^+ -beam milling in Ti:sapphire films grown by pulsed laser deposition (PLD). The latter has been proven a reliable technique for the growth of waveguiding films of various laser host materials. Lasing has so far been observed in PLD grown Nd:Gd₃Ga₅O₁₂ [6], [7] and Ti:sapphire planar guides [8]. Recently, these Ti:sapphire waveguides have also demonstrated their suitability as broadband luminescence sources with a bandwidth that is applicable to the investigation of biotissue, and output powers sufficient to be considered for integration in existing OCT interferometric setups [9].

Rib waveguides show a number of advantages over their unstructured planar film counterparts such as lower threshold for laser structures, due to the lateral confinement of both the pump and laser modes, and improved efficiency provided that the rib fabrication process does not itself introduce any additional loss. Furthermore, their capability of providing a fully diffraction-limited, near-circular, single-mode beam makes them suitable for low loss coupling with components such as the fiber optic interferometers used in OCT systems. Fluorescence emission from a Ti:sapphire channel waveguide has previously been reported for ribs fabricated by reactive ion etching (RIE) [10]. Despite the multimode nature of the fluorescence output ($M_x^2 = 5.5$ – 9 and $M_y^2 = 2.3$ – 2.9), its coupling efficiency to a single-mode fiber was already an order of magnitude higher than that from a planar guide.

This paper reports the substantial improvement in the modal properties and the fluorescence output for ribs patterned by Ar^+ -beam milling as characterized by the single-mode emission and the almost five-times higher output powers than the previously reported RIE-fabricated counterparts [10]. Additionally, we have assessed the fabrication technique in terms of its potential to have minimum contribution to background

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Fig. 1. Schematic of the rib fabrication steps in Ti:sapphire films. (a) Application of a negative photoresist on top of a Ti:sapphire layer by spin coating. (b) Exposure to UV light (mask aligner). (c) Development to produce stripped patterns of photoresist with a rib shape. (d) Ion beam milling to etch the uncovered Ti:sapphire surfaces. (e) Removal of the photoresist remnants to obtain rib structures. The inset shows details of the resulting structures.

propagation loss in the host film by performing loss measurements using the self-pumped phase conjugation (SPPC) technique [11]. Finally, we have investigated the possibility to obtain higher fluorescence output using amplified spontaneous emission as well as laser action.

II. EXPERIMENTAL DETAILS

A. Fabrication Techniques

Depositions were performed in a stainless steel vacuum chamber, which was evacuated down to a base pressure of 5×10^{-6} mbar. Films were grown by pulsed laser ablation of a single crystal Ti:sapphire target of 0.12 wt% Ti_2O_3 in a background argon atmosphere of 3×10^{-4} mbar. Ablation was provided by a KrF excimer laser (Lambda Physik, LPX 200, 248 nm, pulse duration ~ 20 ns) operated at 25 Hz, and focused to an energy density of $\sim 4 \text{ J/cm}^2$ on the target. Films were deposited on sapphire (100) substrates positioned at a distance of 4 cm away from the target material. All films employed for the investigation were grown at substrate temperatures of $\sim 975^\circ\text{C}$ and had a thickness of $\sim 11 \mu\text{m}$. To localize the substrate heating and to prevent contamination through desorption from the walls of the deposition chamber, a 100 W CO_2 laser (Synrad 57-1-28 W) was used as a heating source. This heating technique has already been implemented successfully in PLD [12], [13].

The rib waveguide fabrication is illustrated in Fig. 1. In the first step, a $10\text{-}\mu\text{m}$ -thick layer of negative photoresist (SU-8,

Fig. 2. Optical microscope picture of: (a) the polished end-face of a Ti:sapphire rib waveguide and (b) top view of the same structure.

Microchem) was applied on the top of the PLD-grown Ti:sapphire waveguide [Fig. 1(a)] and then was photolithography patterned using a chromium mask and irradiation from a UV lamp [Fig. 1(b) and (c)]. Prior to the coating procedure, the sample had been dehydrated by maintaining it at a temperature of 80°C for 10 min. Subsequently, the sample was mounted on a rotating holder and Ar^+ -beam milling was used [Fig. 1(d)] to etch the exposed parts of the waveguide to produce an array of $5\text{-}\mu\text{m}$ deep Ti:sapphire ribs with widths w varying from 6 to $16 \mu\text{m}$ separated by $100 \mu\text{m}$ [Fig. 1(e)]. As shown in the inset in Fig. 1, the ribs had a trapezoidal profile. The width at the top of the structure d was 60% of the corresponding value w at the base for the $w = 14 \mu\text{m}$ rib, which is also used for our simulations in Section II-B. The etch rate of the Ti:sapphire and the SU-8 photoresist using a 500-V neutralized Ar^+ beam with an ion density of 0.9 mA/cm^2 in a background pressure 2×10^{-6} mbar and at an exposure angle of 40° were 13 and 24 nm/min respectively. The exposure angle in the milling process has an impact on the width ratio (d/w) in a way that higher angles lead to more inclined side faces. Following Ar^+ milling, all the photoresist remnants were completely removed from the top of the guide by ultrasonic cleaning in an acetone bath. After all the fabrication steps had been completed, the end faces of the sample were polished to an optical finish to optimize the in- and out-coupling procedures. Fig. 2 shows optical microscope pictures of a typical profile and a top view of one of the resulting guides.

B. Loss Measurements and Transmission Characteristics

Nondestructive propagation loss measurements for the 5.2-mm-long rib waveguides were performed via the SPPC method [11] using the experimental arrangement shown in Fig. 3. The output from a Ti:sapphire laser (Spectra Physics, Model 3900S) operating at 720 nm was launched into the

Fig. 3. Experimental arrangement for loss measurements via self-pumped phase conjugation.

rib waveguides and then coupled out using two microscope objectives with a magnification of $\times 6.3$ and $\times 20$, respectively. This short Ti:sapphire wavelength was chosen so that the combination of output power and operating wavelength provided optimal crystal response in terms of intensity and build-up time of the phase conjugated signal. To optimize the coupling efficiency for the Ti:sapphire laser, the beam was shaped to an aspect ratio of 2.5:1 to adequately fit that of the modes of the guide using a cylindrical lens telescope, (L1 and L2, focal lengths $f = 25$ cm and 10 cm respectively). The outcoupled waveguide mode was phase conjugated via SPPC from a nominally undoped BaTiO₃ crystal and the retro-reflected beam was thereby automatically coupled back into the waveguide without any launch losses other than the Fresnel reflections. Using the standard total internal reflection (TIR) geometry [14] the BaTiO₃ crystal was mounted on a rotation-translation stage so that the crystal response could be optimized by varying the transverse position of the beam input and the angle of incidence. An aperture was positioned at the exit face of the sample to ensure that only the rib waveguide mode underwent phase conjugate reflection. Two 1° wedged beam splitters (WBS1, 2) and two photodiodes (PD1, 2) connected to a lock-in amplifier respectively were used to monitor the incident as well as the phase-conjugate signal before and after its passing through the rib waveguides. Modulation for the signal, which was fed to the lock-in amplifier, was provided by a mechanical chopper positioned between the wedged beam splitter (WBS2) and the crystal. With this configuration, the SPPC signal was distinguished from all other reflections resulting from the optical elements and more importantly the waveguide faces. The power of the incident beam at the BaTiO₃ crystal input face was 11.4 mW and had a diameter of ~ 1.5 mm as it entered the crystal. The maximum steady-state reflectivity was found to be 47% of the input intensity at an incident angle of 42° with respect to the normal to the crystal surface and at a transverse position of $x = 2$ mm on the 5.7-mm-wide crystal face. The build-up time of the reflected signal was ~ 3 min. The waveguide loss in decibels per unit length α was therefore derived from the following equation:

$$\alpha = \left(\frac{1}{L}\right) \cdot 10 \cdot \log_{10} \left[\left(\frac{1}{K}\right) \cdot \left(\frac{PD1}{PD2}\right) \right] \quad (1)$$

where L is the length of the rib waveguide and K is the transmission factor which includes all power losses due to the op-

tical elements and the Fresnel reflection from the coupling and decoupling faces of the waveguide. It is given by

$$K = \left(\frac{T_{BS2}}{R_{BS2}}\right) \cdot (R_{BS1}) \cdot (T_{O1}) \cdot (T_{O2}) \cdot (T_{FR})^2 \quad (2)$$

where R_{BS1} and R_{BS2} are the reflection coefficients for the wedged beam splitters WBS1 and WBS2, respectively, T_{BS2} stands for the transmission coefficient for the beam splitter WBS2, T_{O1} and T_{O2} represent the transmission coefficients for the coupling and decoupling objective respectively, and T_{FR} is the Fresnel transmission coefficient at the waveguide-air interface. T_{FR} is given by the equation

$$T_{FR} = 1 - \left[\frac{(1-n)}{(1+n)} \right]^2 \quad (3)$$

where n is the refractive index of the waveguiding material. For Ti:sapphire ($n = 1.76$), the Fresnel transmission coefficient is 0.93. After having determined K by measuring the terms in (2), we measured the ratio PD1/PD2 as described above, and thereby evaluated the waveguide loss from (1). The propagation loss for the rib waveguide was 1.7 ± 0.1 dB/cm, with reproducibility within an error of 5% for a set of five measurements. Comparison between this value and the one obtained for the Ti:sapphire planar waveguide host [8] leads to the conclusion that the loss level remains essentially unchanged after the rib fabrication process. We further note that no dependence of the loss on the size of the ribs was observed over the range of values between 9 and 16 μm . Ribs with widths smaller than 9 μm have shown higher losses (≥ 5 dB/cm) due to imperfections in the fabrication process arising from the photolithographic patterning.

The throughput of the Ti:sapphire laser beam from a 5- μm -deep rib waveguide with a width w of 14 μm , which was on top of a 5- μm -thick Ti:sapphire film, was imaged onto a CCD camera. The experimentally recorded profile, shown in [Fig. 4(a)] along with the calculated mode profile at 800 nm [Fig. 4(b)], was Gaussian in the horizontal and nearly Gaussian in the vertical plane of the guide. The asymmetry in the vertical direction is due to the asymmetric refractive index profile in this axis. From the size of the image on the CCD camera, a spot size of $3.6 \times 5.8 \mu\text{m}^2$ has been calculated for the guided mode, which is in good agreement with the simulated fundamental mode intensity profile shown in Fig. 4(b). The simulation, which was performed using a software package from Kymata Software using the finite-difference method, suggests that the guide supports only one mode and this also agrees with the

Fig. 4. (a) Mode intensity profiles of the out-coupled light for 100-mW in-coupled power from a Ti:sapphire laser operating at 800 nm. The 5- μm -deep rib structure had a width w of 14 μm and was on top of a 5- μm -thick Ti:sapphire film. (b) Simulated fundamental mode intensity profile for a Ti:sapphire rib structure with the same dimensions.

experimental observation. We have assumed an increase in the refractive index $\Delta n = 3.7 \times 10^{-4}$ for the Ti:sapphire film compared to the sapphire substrate, which corresponds to a Ti concentration of 0.1-wt%. This value of doping level was inferred by taking into account that the Ti:sapphire crystal target used for the PLD experiments had a concentration of 0.12-wt% in Ti_2O_3 , and is entirely consistent with the results from the Particle-Induced X-ray Excitation (PIXE) investigation [8], which has shown that $\sim 80\%$ of the Ti can be transferred from the target to the PLD layer under the growth conditions described in Section II-A. The single transverse-mode nature of the outcoupled beam was also confirmed by measuring the beam propagation factors (M^2) with a Coherent Modemaster beam propagation analyzer, with values of 1.03 and 1.09, respectively, for the parallel and the perpendicular directions with respect to the waveguide plane. It should be noted that this does not prove that the guide only supports one transverse mode, as single-mode propagation in a multimode guide is possible. However, it is certainly consistent with a single-mode guide. A stronger test of the single-mode nature of the guide will be given by looking at the fluorescent output, as this will be coupled to all the supported modes.

C. Fluorescence Characteristics

The fluorescence characteristics were examined with an argon laser as the pump source (Coherent, Model Innova 70)

Fig. 5. Fluorescence emission profiles measured at the exit face of a Ti:sapphire rib waveguide with a depth of 5 μm and widths w of: (a) 10, (b) 14, and (c) 16 μm . The thickness of the Ti:sapphire underlying layer was 5 μm .

operating on all lines. The fluorescence emission, which was collected from the exit face of the guide, was imaged on the CCD camera after having passed through an OG 550 filter to block the residual transmitted pump irradiation. It was then masked by an aperture to ensure that only the fluorescence from the rib guide itself and not from the planar region between the ribs, was measured. The experimentally recorded intensity profiles of the fluorescence (without the aperture) originating from ribs with a height of 5 μm and widths w varying from 10 to 16 μm are shown in [Fig. 5]. The profiles indicate that the guides are suitable for producing strong optical confinement. Measurements of the beam propagation factors show diffraction limited output with values of 1.12 and 1.16, respectively, for the parallel and the perpendicular directions with respect to the waveguide plane. This is essential to ensure efficient coupling to the fiber-optic interferometric arrangements used in OCT systems. The strong optical confinement of the fluorescence emission also indicates the potential for fabrication of closely spaced (in the order of a few tens of micrometers) multiple ribs on the same substrates.

Fig. 6 shows the fluorescence output power from waveguides with different widths as a function of the input power. The maximum output powers were 283 μW ($w = 16 \mu\text{m}$), 243 μW ($w = 14 \mu\text{m}$) and 181 μW ($w = 10 \mu\text{m}$), and the corresponding slope efficiencies were 9.5×10^{-5} , 8.1×10^{-5} , and 6.2×10^{-5} .

To make a rough prediction of the theoretical fluorescence power as a function of the pumping power and the rib size, we

Fig. 6. Fluorescence power as a function of pump power from an Ar^+ laser for 5- μm -deep ribs with a width at the bottom of: (●) 16, (□) 14, and (▲) 10 μm . The full line refers to the calculated fluorescence output for a rib with a width of 16 μm , the dashed line to 14 μm , and the dotted one to 10 μm . For the calculations, we assume 5- μm -deep ribs.

follow a plane-wave analysis accounting for depletion of the absorbing level as outlined in [15]. We assume a four-level system with population in either the emitting level or in the ground state. The population density n_2 in the emitting level will vary along the propagation direction y of the guide, and so we define a length integrated population density given by

$$N_2 = \int_0^L n_2(y) dy \quad (4)$$

where L is the length of the waveguide. The fraction of input pump power that is absorbed in the waveguide is

$$F_A = 1 - e^{\sigma_p(N_2 - n_0 L)} \quad (5)$$

where $\sigma_p = 6 \times 10^{-20} \text{ cm}^2$ is the absorption cross section for π polarization at 515 nm [19], and $n_0 = 2.6 \times 10^{-19} / \text{cm}^3$ corresponds to the total dopant density of Ti and was obtained by assuming that the sample had a doping level equivalent to 0.1-wt% Ti. The excitation rate induced by the pump beam is then given by the expression

$$R_{\text{ex}} = \frac{P_p \cdot \eta_{\text{del}}}{h \cdot v_p} \cdot \left[1 - e^{\sigma_p(N_2 - n_0 L)} \right] \quad (6)$$

where P_p is the pump laser input power, h is Planck's constant, v_p is the frequency of the pump irradiation, and η_{del} is the delivery efficiency of the pump into the guide and accounts for the launch efficiency as well as for losses originating from the optics delivery system to the guide. The parameter η_{del} is strongly dependent on the size of the guides and the measured values for ribs with a width w of 10, 14, and 16 μm were, correspondingly,

0.46, 0.6, and 0.69 for our optical setup. The rate of de-excitation due to the spontaneous emission is:

$$R_{\text{de-ex}} = \frac{N_2 \cdot A}{\tau} \quad (7)$$

where A is the cross-sectional area of the pumped region and $\tau = 3.2 \mu\text{s}$ [16] is the excited-state lifetime (we neglect non-radiative lifetime quenching with increasing temperature owing to sample heating under laser pumping). Assuming steady-state conditions, we set the rate of excitation of the Ti^{3+} ions in (6) equal to de-excitation rate in (7). The resulting expression allows us to calculate N_2 and subsequently the total fluorescence power P_{tot} as a function of input power. The latter is deduced from

$$P_{\text{tot}} = N_2 \cdot \frac{A \cdot h \cdot v_l}{\tau} \quad (8)$$

where v_l is the frequency of the fluorescence output, which we take as the value at the centre of the fluorescence spectrum at $v_l = 3.75 \times 10^{14} \text{ Hz}$. The fraction of the total fluorescence power that is captured by the numerical aperture (NA) of the waveguide, and therefore provides useful guided output P_{fl} , is given by [17]

$$P_{\text{fl}} = P_{\text{tot}} \cdot \frac{\Omega}{4 \cdot \pi} \quad (9)$$

where Ω is the solid angle captured by the waveguide NA and is given by

$$\Omega = \frac{\pi \cdot \theta^2}{n^2} \quad (10)$$

where n is the refractive index of the waveguide and θ is the divergence of the waveguide output and is related to the NA by

$$NA = \sin \theta \cong \theta. \quad (11)$$

As an estimate of θ , and hence the effective NA of our rib guides, we take the divergence of the smallest mode-size obtained (77 mrad). The lines in Fig. 6 represent the fluorescence power as calculated from (9) as a function of input pump power for rib structures of various widths w . We observe that fluorescence output levels for ribs with different size derived by our basic model calculations are in agreement with the experimental results. The curvature of the theoretical lines, which is more evident for the smaller in size ribs, is due to saturation of the absorption in the guide, although this effect was not clearly observed experimentally over the investigated pump energy range.

Measurements of the fluorescence power have also been performed with a mirror of high reflectivity at the emission wavelength range of the guide and a transmission of 86% for the pump beam butted to the incoupling face of the guide. This configuration leads to an increase of $\sim 46\%$ in the emitted fluorescence power, which results from the back reflection of the counter propagating luminescence. Thus, as shown in Fig. 7, for a rib with a width w of 14 μm , the maximum output power increases from 243 to 350 μW , and the corresponding slope efficiencies from 8.1×10^{-5} to 1.2×10^{-4} .

Fig. 7. Fluorescence output as a function of pump power from an Ar^+ laser for 5- μm -deep ribs with a width at the bottom of 14 μm with (●) and without (□) incoupling mirror.

III. CONCLUSIONS

In summary, rib waveguides based on PLD-grown Ti:sapphire thin films have been fabricated by Ar^+ milling. Mode-intensity profiles and fluorescence output power measurements have shown that the specific waveguide geometry leads to a strong optical confinement and maintains the fluorescence output efficiency at reasonable levels compared to their thin-film counterparts. Furthermore, nondestructive loss measurements using the self-pumped phase conjugation technique have shown that the additional fabrication steps required to obtain the rib waveguides do not significantly increase the value of propagation loss compared to the background loss level of other PLD-grown Ti:sapphire thin films which were between 1.6 and 1.8 dB/cm. The optimum modal properties, high fluorescence output, and its compactness make it a suitable fluorescence source for integration with fiber-optic OCT systems. Future work will concentrate on decreasing the background losses in the PLD-grown Ti:sapphire host film waveguides and as a consequence those in the rib structures, as well as on investigating the use of amplified spontaneous emission to increase the output power without too large a decrease in bandwidth. It is also interesting to note that, even with the current level of propagation losses, demonstration of laser action in a Ti:sapphire channel waveguide should be possible [8].

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