Single-transverse-mode Ti:sapphire rib waveguide laser

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Abstract: Laser operation of Ti:sapphire rib waveguides fabricated using photolithography and ion beam etching in pulsed laser deposited layers is reported. Polarized laser emission was observed at 792.5 nm with an absorbed pump power threshold of 265 mW, which is more than a factor of 2 lower in comparison to their planar counterparts. Measured beam propagation factors M_x^2 and M_y^2 of 1.3 and 1.2, respectively, indicated single-transverse-mode emission. A quasi-cw output power of 27 mW for an absorbed pump power of 1W and a slope efficiency of 5.3% were obtained using an output coupler of 4.6% transmission with a pump duty cycle of 8%.

OCIS codes: (230.7380) Waveguides, channeled; (140.3570) Lasers, single-mode; (130.2790) Guided waves; (310.1860) Deposition and fabrication.

References and links

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1. Introduction

Ti:sapphire is an established material and particularly attractive as a laser medium, because it offers a widely tunable output (650-1100nm) [1] and also exhibits a wide absorption band (400-650 nm). However, an adverse consequence of this wide tunability is a low peak emission cross section, which combined with a short fluorescence lifetime, necessitates high pump power densities to achieve efficient CW lasing. The undesirable prerequisite of high pump power levels can be overcome to a certain extent by adopting a planar or channel waveguide geometry. Channel waveguides in particular are characterized by lower laser thresholds than their planar counterparts due to the additional lateral confinement and excellent overlap between the laser and pump modes provided that the rib fabrication process does not introduce any additional losses over those present in the planar waveguide. Thresholds of the order of a few tens of mW would allow use of inexpensive pump sources such as frequency-doubled solid-state lasers and blue-green diodes.

Compact fluorescence and laser devices based on Ti:sapphire in channel geometries are particularly interesting for applications in optical coherence tomography (OCT) [2] due to their high brightness and potential to provide fully diffraction-limited, near circular, single-mode beams which would allow integration with OCT fiber interferometric arrangements [3]. Moreover, a combination of Ti:sapphire channel waveguides with semiconductor saturable absorber mirrors (SESAM) and saturable Bragg reflector (SBR) technologies would open up the possibility to develop a compact, portable, broadly tunable laser with the potential to produce high-repetition-rate mode-locked pulses. Such a source would be ideal for use in a range of applications such as photobiology, photomedicine, communications and particularly in OCT because the attributes of high-intensity pulses combined with the low average power and large bandwidth allow study of live cells/tissues with high longitudinal resolution [4].

Pulsed laser deposition (PLD) has proven to be a reliable technique for the growth of waveguiding films of various laser host materials and to be suitable for tailoring the concentration and valence state of dopants in the films. Control of the valence state of the incorporated titanium dopant in the layers is of particular importance in order to avoid adverse effects such as parasitic absorption and subsequent limitations in the waveguide laser performance due to the presence of tetravalent titanium (Ti^{4+}) [5]. To date, we have already demonstrated laser operation of PLD grown Ti:sapphire planar waveguides [6]. The latter had a degree of crystal perfection and dopant levels comparable with commercial bulk targets and the incorporated titanium was substitutional for the Al^{3+} in the correct lattice position [7]. Development of Ti:sapphire waveguide lasers has also been reported via titanium indiffusion. This approach has lead to observation of pump-power thresholds as low as 210±40 mW. However, those channel waveguide lasers were characterized by low slope efficiencies, typically in the order of ~0.1% [8]. In this paper we report on the laser operation of Ti:sapphire rib waveguides fabricated using PLD, followed by photolithography and ion beam etching.

2. Rib-waveguide fabrication

Ti:sapphire films were grown on (0001) “z-cut” oriented sapphire substrates by PLD from a single crystal Ti:sapphire target of 0.12 wt% Ti_2O_3. Ablation was provided by a KrF excimer laser (248 nm, repetition rate 25 Hz, pulse duration ~20 ns) focused to an energy density of ~4 J/cm^2 on the target. During growth the substrates were positioned at a distance of 4 cm away from the target material and held at a temperature of ~975°C by a raster scanned 50 W CO_2 laser. The deposited films had a thickness of ~12 μm, a doping level of approximately 0.1-wt% in Ti_2O_3 and were single crystalline with excellent crystalline quality [7].

For rib waveguide fabrication, the top surface of the PLD-grown Ti:sapphire planar waveguide was coated by a 10 μm thick negative photoresist (SU-8, Microchem) layer, which was then photolithographically patterned using a chromium mask and irradiation from a UV lamp. Following development, lines of photoresist were left on the sample surface. A 500 V neutralized Ar^+ beam with an ion current density of 0.9 mA/cm^2 was subsequently used to

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etch the exposed and the shielded parts of the waveguide. As a result, 8 arrays each containing 20 ribs with depth 3.5 μm and widths varying from 10 to 24 μm separated by 20 and 60 μm were produced. Following etching all the photoresist remnants were completely removed from the top of the guides by ultrasonic cleaning in an acetone bath and then a 5 μm thick sapphire clad layer was deposited by PLD to reduce scattering losses. Finally the end faces of the sample were cut and polished to a length of 5 mm to an optical quality finish. The structures resulting from the above procedure are shown in the inset in Fig. 1.

3. Waveguide laser results

The laser performance of the rib waveguides was investigated using an extended cavity configuration as shown in Fig. 1. This arrangement has the potential to allow introduction of

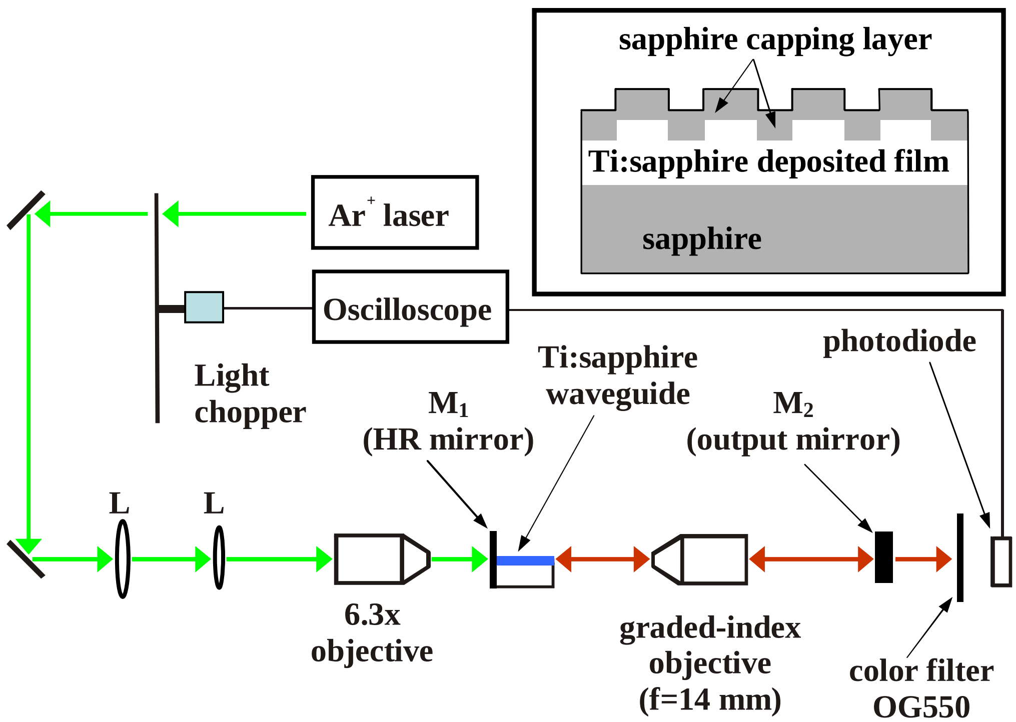

Fig. 1. Experimental configuration for the investigation of the rib waveguide lasers. The laser cavity is formed by the mirrors M_1 and M_2. The geometry of the resulting structure after the fabrication process is shown in the inset.

intracavity elements for modulation or tuning. The output from an argon-ion laser operating on all visible lines was used as a pump beam and was launched into individual rib waveguides using a microscope objective with a magnification of x6.3. Before launching, the pump beam passed through an optical chopper operating with a 8% duty cycle to avoid any mirror damage via the pump irradiation. To form the cavity a lightweight thin mirror (M_1) with reflectivity R_1 of 99.4% and transmission of 86% at the lasing and pump wavelengths, respectively, was attached at the in-coupling face of the sample, initially using the surface tension of a small amount of fluorinated liquid and then by securely gluing its edges at the exposed parts of the face. Guided light from the waveguide was collimated by the graded-index objective with a focal length f = 14 mm before propagating towards the out-coupling mirror (M_2). To reduce loss a single antireflection layer of MgF_2 (refractive index n = 1.38)

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with a thickness of 143 nm was thermally evaporated on the out-coupling face. A set of two mirrors with transmission values T_2 of 0.8% (HR mirror) and 4.6% at the laser wavelength, were successively used as output couplers. Guided light coupled out from the cavity was detected by a photodiode and displayed on an oscilloscope after having passed through a filter to block any residual transmitted pump irradiation. Laser action was obtained for all the ribs investigated.

Despite the use of intra-cavity optics, lasing was observed at an absorbed pump power threshold of 265 mW for ribs with width 10 μm when the HR mirror (T_2 = 0.8%) was used as an output coupler, which is a reduction by a factor of >2 in comparison to the monolithic but not overclad planar laser counterpart for which the threshold was 560 mW [6]. The absorbed pump power was calculated from the incident power by measuring the product of the launch efficiency, L, and the single-pass absorption, A. This was achieved by comparison of the total transmitted pump power obtained when launching the pump beam into the guide with that transmitted when the pump is focused directly through the substrate [9]. A further reduction in threshold could be realized by directly coating the waveguide face with mirrors reflective at the lasing wavelength. For absorbed pump powers up to 300 mW the chopper was removed and the laser was operated in a CW mode without observing any difference in the output characteristics. However, CW operation has not been attempted for higher pump powers as this can damage the in-coupling mirror. The laser output efficiency was investigated using a mirror with a transmission of 4.6% as an output coupler. This configuration led to an increase in the lasing threshold from 265 to 315 mW. Lasing occurred at 792.5 nm and a spectrum recorded by a spectrum analyzer at an absorbed pump power of 350 mW is shown in Fig. 2.

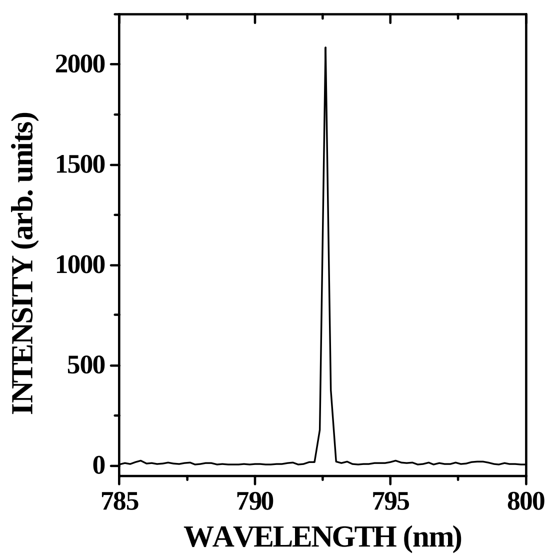

Fig. 2. Lasing spectrum originating from a Ti:sapphire rib waveguide for an absorbed pump power of 350 mW. The structure was 3.5 μm and 10 μm in height and width, respectively.

Figure 3 summarizes the laser output characteristics as a function of the input power using the T_2 = 4.6% output coupler and a duty cycle of 8%. A slope efficiency of 5.3% with respect to the absorbed pump power was obtained and a quasi-CW output power of 27 mW was measured for an absorbed pump power of 1 W. The value for the slope efficiency is higher than that obtained from the planar version of this waveguide (4%), [6] indicating that the fabricated structure has a propagation loss that is certainly not greater than that of its monolithic, but not overclad planar counterpart.

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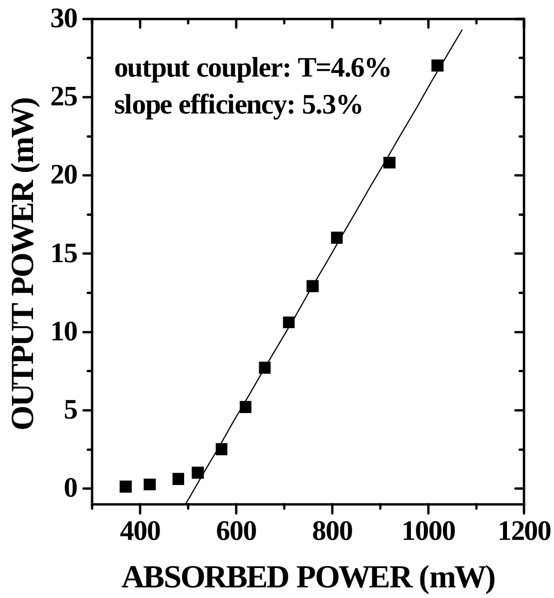

Fig. 3. Output power from a rib waveguide laser with height and width of 3.5 µm and 10 µm, respectively, as a function of the absorbed power for an output coupler with a 4.6% transmission at the lasing wavelength

As expected, the laser output was found to be π-polarized due to the larger emission cross section of the waveguide for the π compared to the σ polarization. Observation of the pump and lasing modes was performed by imaging the output beams onto a CCD camera. The experimentally recorded laser mode profile originating from a rib of width 10 µm for an absorbed pump power of 350 mW is shown in Fig. 4. The dimensions ($1/e^2$ intensity radius) of the lasing mode in Fig. 4 were W_{lx} = 3.5 µm by W_{ly} = 3.1 µm, while those of the pump mode were W_{px} = 3.3 µm by W_{py} = 2.5 µm. The profile indicates that the guides are suitable for producing a strong optical confinement and single-mode output.

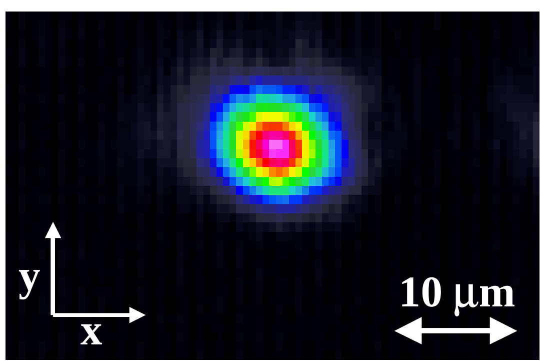

Fig. 4. Laser mode profile obtained from a Ti:sapphire rib waveguide of height 3.5 µm and width 10 µm using a 4.6 % output coupler at an absorbed power of 350 mW.

Measurements of the beam propagation factors (M^2) were performed with a Coherent Modemaster beam propagation analyzer, showing near-diffraction-limited output with values of 1.3 and 1.2 for the horizontal and vertical plane axes, respectively. However, ribs with widths above 20 μm were found to support at least two modes in the horizontal plane.

Evaluation of propagation loss in the laser device was obtained via calculations involving the slope efficiency (η). An estimate for the expected slope efficiency can be made following an analysis that incorporates effects of transverse mode profiles on the slope efficiency in longitudinally pumped lasers [10]. According to the proposed model η is given by:

$$\eta = \eta_q \frac{\lambda_p}{\lambda_l} \cdot \frac{-\ln(R_2)}{-\ln(R_1 \cdot R_2) + 2 \cdot l \cdot a_L} \cdot \eta_{pl} \tag{1}$$

where η_q is the pump quantum efficiency (assumed to be 1, so that for every pump photon one laser photon is produced) λ_l =792.5 nm is the laser and λ_p = 514 nm the pump wavelength (emission at the strongest line was assumed), R_1 and R_2 correspond to the reflectivities of the input and output mirrors for the lasing wavelength, α_L is the propagation attenuation coefficient, l is the length of the laser medium. The term η_{pl} in (1) is a parameter that contains the overlap of the pump with the laser beam and is given by the relation:

$$\eta_{pl} = \frac{W_{lx} \cdot W_{ly} \cdot (2W_{px}^2 + W_{lx}^2)^{1/2} \cdot (2W_{py}^2 + W_{ly}^2)^{1/2}}{(W_{px}^2 + W_{lx}^2) \cdot (W_{py}^2 + W_{ly}^2)} \tag{2}$$

where W_{lx}, W_{ly}, W_{px}, W_{py} refer to the 1/e^2 intensity radii for the laser and pump modes in the horizontal and vertical planes respectively. Given the known spot sizes and assuming that all the loss is due to the waveguide attenuation from Eq. (1) for η=5.3%, R_1=0.994 and R_2=0.954 we obtain an upper limit of <1.7 dB/cm^{-1} for the propagation loss which is comparable to that obtained for the unclad planar host (1.8 dB/cm) [6]. Although the sapphire cladding layer is expected to suppress to a certain extent the propagation loss, the value obtained for the ribs also includes losses originating from possible non-perpendicularity of the channel to the mirror at the input face, the out-coupling objective in the cavity, the AR coated end-face and the launching of the feedback beam back into the waveguide. This indicates that the rib fabrication process does not contribute any significant extra loss, which has also been confirmed with non-lasing loss measurements of these structures [11] using the self-pumped phase conjugation technique [11, 12].

4. Summary

In summary, Ti:sapphire rib waveguides fabricated by PLD followed by photolithography and ion beam etching show single transverse mode laser emission. To increase the integration capability of the device an approach to be followed in future development is to directly coat the mirrors on the end faces of the waveguide. With a view to increase the spectral bandwidth of the laser source and in turn obtain the high longitudinal resolution required by OCT applications current work concentrates on the demonstration of mode-locked operation of a Ti:sapphire rib waveguide laser using both SESAM and SBR devices capable to produce ultra-short pulses. As a first step towards this goal, we intend to investigate the dispersion management necessary for the final ultrashort pulse laser by implementing an external cavity geometry waveguide resonator. On this occasion the tunability of the waveguide will also be studied. Also work is in progress towards the development of amplified spontaneous emission (ASE) sources from the rib structures with minimization of the narrowing in the spectral bandwidth of their fluorescence emission.

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