In-band pumped low threshold Ti:Tm:LiNbO$_3$ waveguide laser

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***Abstract*—The first in-band pumped Ti:Tm:LiNbO$_3$ waveguide laser emitting at 1890nm is reported. A special cavity enables pumping at 1650nm with a threshold of 4mW, a slope efficiency of 11% and up to 4.5mW output power.**

Keywords-integrated optics; waveguide; laser; lithium niobate; thulium.

I. INTRODUCTION

Thulium (Tm) based lasers utilizing the $^3F_4 \rightarrow {}^3H_6$ radiative transition find applications in spectroscopy, medicine, remote sensing and material processing. Lasing action from a variety of Tm doped crystals has been reported in the literature [1]. Tm:LiNbO$_3$ (LN) lasers pumped at 795 nm ($^3H_6 \rightarrow {}^3H_4$ transition) were already demonstrated both in bulk [2] and waveguide geometries [3, 4]. Here we report the first demonstration of a Fabry-Pérot type Ti:Tm:LN waveguide laser in-band pumped at 1650 nm and operating near 1890 nm emission wavelength. This is the longest emission wavelength from a Tm:LN laser reported so far. The Tm-doped waveguide structure is similar to that successfully employed as waveguide quantum memory recently [5].

II. LASER FABRICATION

A. *Tm Diffusion Doping and Waveguide Fabrication*

0.5 mm thick Z-cut wafers of undoped optical grade congruent lithium niobate were Tm-doped near the +Z-surface before waveguide fabrication. A vacuum deposited Tm layer of 32 nm thickness was in-diffused at 1130 ^{0}C during 150 hours in an argon-atmosphere followed by a post treatment in oxygen (1 hour). The diffusion profile was determined by secondary neutral mass spectroscopy. The maximum Tm concentration (at the surface) is 1.25 x 10^{20} cm^{-3}; the Tm penetration depth ($d_{1/e}$) is 9 µm. Afterwards, photolithographically defined, 6.5 µm wide, 104 nm thick Ti stripes were deposited on the Tm-doped sample and in-diffused at 1060 ^{0}C for 9.6 hours. In this way optical channel guides were formed in the 30 mm long sample; they are single mode structures for wavelengths > 1500 nm.

B. *Cavity Formation*

The laser cavity was formed by two special dielectric multilayer mirrors, vacuum-deposited on the end faces of the Ti:Tm:LN waveguide. The pump coupler (PC) mirror has a high reflectivity (R > 90 %) at wavelengths > 1800 nm, but a high transmission (T > 90 %) at the 1650 nm (pump) wavelength. The output coupler (OC) mirror has a high reflectivity (R > 95%) at both, pump and laser wavelengths, enabling in this way double pass pumping. The calculated finesse of the cavity at 1890 nm is 32, assuming 0.1 dB/cm propagation losses (see discussion below).

III. EXPERIMENTAL RESULTS

A. *Waveguide Characterization*

The waveguide propagation losses due to scattering are 0.3 dB/cm measured for TE polarization at 1505 nm [6]. They decrease at longer wavelengths to ~ 0.1 dB/cm at 1900 nm. The mode distributions were measured as well. For example, the full width at half maximum of the TE mode at 1650 nm is 7.8 µm x 5.8 µm.

The absorption and fluorescence characteristics of Ti:Tm:LiNbO$_3$ channel guides, fabricated in the same way as described above, are presented in Fig.1 together with the energy level scheme exploited. The strong absorption band around 1650 nm enables efficient in-band pumping (see also inset of Fig.1). Several maxima in the fluorescence spectrum indicate a potential laser emission at ~1760 nm, ~1800 nm and ~1850 nm for free running devices as already demonstrated in the past by pumping at ~795 nm [3, 4]. Emission at longer wavelengths is reported for the first time in this contribution.

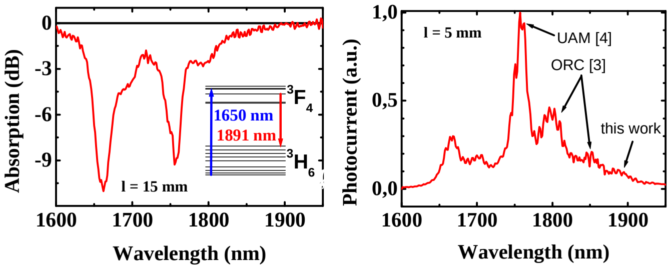

Figure 1. Measured TE absorption (left; l = 15 mm) and fluorescence (right; l = 5 mm) spectra of Ti:Tm:LiNbO$_3$ channel guides of length l for 1600 nm < λ < 1900 nm together with the corresponding energy level scheme of Tm-ions.

B. *Laser Power Characteristics*

Using a 1650 nm pump, laser emission was only found around 1890 nm in TE polarization independent on the pump polarization. Fig. 2 presents the recorded power characteristics. Lasing was found to set in at 6 mW of incident pump power corresponding to ~ 4 mW of coupled pump power only. With increasing pump power the spectrum of the pump laser shifts to somewhat longer emission wavelengths resulting in an even better pump absorption (see also Fig. 1). The result is a slightly increasing slope efficiency up to 11% at ~50 mW incident pump power. The output power of up to 4.5 mW (limited by the available pump power) was stable over time. Both, maximum output power and slope efficiency surpass the results reported so far for Tm:LN waveguide lasers [3, 4] by a factor of 7 and 11, respectively. Moreover, the laser threshold is lower by more than an order of magnitude.

The power characteristics have also been modeled using the commercial software RP Fiber Power. As input parameters the measured data discussed above and absorption and emission cross sections from the literature [7] were used.

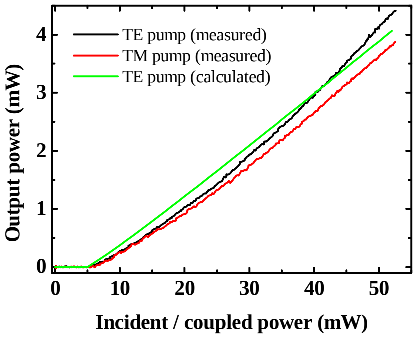

Figure 2. Power characteristics of the Ti:Tm:$LiNbO_3$ waveguide laser for TE polarized emission: output power at 1890 nm emission wavelength versus incident (experiment) and coupled (simulation) pump power at 1650 nm.

C. *Relaxation Oscillations*

When investigating the time dependence of the laser output, nearly undamped relaxation oscillations were observed as pulses of 84 kHz repetition frequency (pump power dependent) with a duty cycle of a few percent. An example – presented as RF-spectrum of the electrical photodiode output – is shown in Fig. 3. The relaxation oscillations could be suppressed by feedback controlled pumping as described in [8].

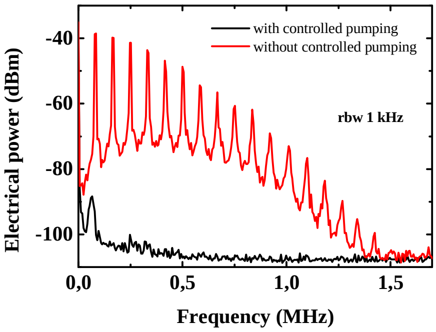

Figure 3. Relaxation oscillations of the laser output, displayed as RF-spectrum of the electrical output of the photodiode without (red) and with (black) feedback controlled optical pumping (here: 14 mW pump power).

D. *Laser Emission Spectra*

Laser emission spectra were measured with a spectrometer of 0.25 nm resolution. Irrespective of the pump polarization, the emission was found to be near 1890 nm and TE polarized with a spectral envelope of a few nanometers (see Fig. 4). However, the fine structure of the laser spectra changed from scan to scan and was also found to be pump power dependent.

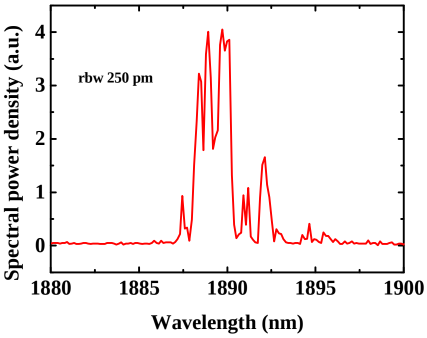

Figure 4. TE polarized laser emission spectrum for operation with 32 mW of incident pump power (1650 nm; TE polarised).

IV. CONCLUSIONS

The first in-band pumped Ti:Tm:$LiNbO_3$ waveguide laser was developed. The laser is pumped at 1650 nm and has a remarkably low threshold of ~ 4 mW coupled pump power only. Its emission wavelength is 1890 nm with a spectral width of a few nanometers. The laser output is TE polarized for both pump polarizations. We expect that appropriate spectral filtering yields stable single mode emission. If the filtering is tunable, the broad wavelength range 1750 nm $< \lambda <$ 1920 nm might be accessible. Moreover, simulation results indicate several possibilities for a further optimization of the device with respect to threshold, slope efficiency and output power.

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