Widely tunable short-infrared thulium and holmium doped fluorozirconate waveguide chip lasers

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Abstract: We report widely tunable (≈260 nm) Tm^{3+} and Ho^{3+} doped fluorozirconate (ZBLAN) glass waveguide extended cavity lasers with close to diffraction limited beam quality (M^2≈1.3). The waveguides are based on ultrafast laser inscribed depressed claddings. A Ti:sapphire laser pumped Tm^{3+}-doped chip laser continuously tunes from 1725 nm to 1975 nm, and a Tm^{3+}-sensitized Tm^{3+}:Ho^{3+} chip laser displays tuning across both ions evidenced by a red enhanced tuning range of 1810 to 2053 nm. We also demonstrate a compact 790 nm diode laser pumped Tm^{3+}-doped chip laser which tunes from 1750 nm to 1998 nm at a 14% incident slope efficiency, and a beam quality of M^2≈1.2 for a large mode-area waveguide with 70 µm core diameter.

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1. Introduction

Optically pumped waveguide lasers with compact dimensions (<10s of mm’s) and high efficiency are well suited for integration into established electronic form-factors (such as integrated circuits) and electronics assemblies with their engineered wave-guiding properties enhancing solid-state laser characteristics [1]; thus providing advantages over diode lasers. While compact and widely tunable external cavity diode lasers [2] are available that cover regions in the visible and short-infrared spectral regions, they have limited mode-hope free tuning ranges, low average and peak-power, micron-scale active cross-sections, and produce astigmatic non-circular beams. On the other hand, in the short-infrared spectral region rare-earth doped fiber lasers achieve broad tuning ranges [3–5] with close to diffraction limited beams, and are capable of operation at power levels > 10 Watts [6,7]. However achieving a compact fiber laser packaging footprint is challenging due to the long fiber lengths needed, minimum fiber bending radius required, and need for mechanical support to the fiber splices.

As an alternative to diode and fiber lasers, rare-earth doped waveguide lasers possess moderate power (~100s of mWs); broad fluorescence bands; diffraction-limited beam-quality [8,9]; an optical axis defined by the waveguide; and long upper-state lifetimes allowing high energy storage. If wide and continuous tunability is important, rare-earth doped glasses have a broader and smoother fluorescence spectra than crystal hosts due to the broad stark splitting of the rare earth ions in amorphous glass hosts. The Stark broadening depends on the magnitude of local electric fields which in a glass is not site specific, as the rare-earth ions are located at random positions within the disordered structure of glass. In contrast, crystals have more discrete phonon-broadened transitions [10]. The wide emission bandwidth of Stark-broadened rare-earth electronic transitions in glass waveguide lasers is also enhanced due to

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the high population inversions achieved in these core-pumped devices, thus reducing ground state absorption at short wavelengths.

The widely tunable waveguide chip lasers we report here are based on ultrafast laser inscribed channel waveguides in thulium and holmium doped fluorozirconate (ZBLAN) glass that operate in the 1.7 to 2.1 µm spectral region. They have high efficiencies, and produce circularly symmetric outputs of high beam quality [11–13]. A specific characteristic of depressed cladding ZBLAN waveguide lasers is the ability to tailor the leaky mode waveguide diameter, thus allowing large waveguide mode areas that enable high peak-power operation (> 1 kW) [12]. These chip lasers are well suited to operation as master oscillators owing to high beam-quality, symmetrical beam shape, and the high-Q cavities are less susceptible to feedback and damage from amplifiers, and they possess larger active volumes compared to diode lasers.

Widely tunable laser sources near 2 µm are vital for applications including molecular spectroscopy, remote sensing, surgery, free space communications, materials processing, and defence. The 2 µm thulium band has recently been flagged as a candidate for future optical communication [14], and thus the development of alternate waveguide oscillators and amplifiers will be relevant.

Two micron class thulium waveguide lasers have matured rapidly in the last few years [10–13,15], with the increasing maturity of ultrafast laser inscription (ULI) [16–18], and liquid phase epitaxy [8,10]. Tunable 2 µm channel waveguide lasers reported include van Dalfensen *et al.* [8] who reported a Ti:sapphire pumped Tm^{3+} doped monoclinic double tungstate crystal waveguide laser with 130 nm of tuning covering 1810 nm to 1940 nm. Wide tunability of a Cr:ZnSe external cavity waveguide laser has also been reported with a tuning range of 2077 nm to 2777 nm [19]. For comparison, reports of tunable solid-state diode laser pumped bulk Tm^{3+} crystalline lasers include a 245 nm tuning range (1849-2059 nm) in $Tm:BaY_2F_8$ with watt level output [20], and a $Tm:GdLiF_4$ tunable across 228 nm (1826-2054 nm) [21]. It is significant that in both these reported bulk lasers, no reference was made to beam-quality, implying further cavity engineering is required to achieve diffraction limited beam-quality and high beam-pointing stability due to the variable thermal-lensing and beam-steering, respectably. This is a significant differentiator from fundamental-mode waveguide lasers which possess intrinsic lowest-order mode beam-quality, and pointing stability defined by the waveguide.

Here we report a 790 nm Ti:sapphire pumped thulium (1.9 mol %) waveguide laser which continuously tunes from 1725 nm to 1975 nm. Incident slope efficiency is 8%, and close to diffraction limited beam quality with a measured $M^2 \approx 1.3$. A thulium (1.9 mol % TmF_3) sensitized holmium (0.5 mol % HoF_3) waveguide laser achieves continuous tuning across the emission spectrum of both dopant ions and covers 1810 nm to 2050 nm. In a second series of experiments a more practical and compact diode-laser pumped configuration is demonstrated; the thulium doped chip is pumped by two polarisation-combined single-emitter 790 nm diode lasers. The L = 12 mm chip has a larger waveguide area (70 µm diameter channel), and achieves a slope efficiency of 14%, power of 60 mW, continuous tuning range of over 250 nm (1740-1998 nm) and possesses a measured beam quality of $M_{x,y}^2 \approx 1.13$, 1.24.

2. Experimental layout

The waveguide laser architecture is based on ultrafast laser inscribed refractive index modifications in ZBLAN bulk glass to create a low-loss depressed-cladding (for a complete description see [12]). The ULI process uses 50 fs pulses from a 5.1 MHz repetition rate Ti:sapphire oscillator to create 'rods' of reduced refractive index ($\Delta n \approx -0.001$) [22] that can be built up over multiple passes to form an annular cladding around an unmodified core as shown in the inset to Fig. 1. The chip writing time is < 30 minutes. The resultant low-loss waveguide (≈0.4 ± 0.2 dB/cm; measured by conducting a Findlay Clay analysis of the measured laser thresholds as a function of output-coupling [12]) has been used to demonstrate

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chip-sized devices incorporating thulium and holmium ions for highly efficient laser emission at 1.9 µm [11], 2.1 µm [13], and 2.9 µm [23], respectively.

The two different ZBLAN samples used in this work were all fabricated in house, starting as 50 g ingots of 1.9 mol % TmF_3:ZBLAN or 1.96 mol % TmF_3 and 0.22 mol % HoF_3:ZBLAN. Dicing and chip preparation were conducted in-house and has been described previously [12].

To operate the extended cavity end-pumped configuration (shown in Fig. 1(a)), the pump-end of the waveguide chips have a dielectric coating that is highly reflecting (HR) at the laser wavelength, λ_L~1.75-2.1 µm, and highly transmitting (HT) at the λ_p = 790 nm pump wavelength. The intra-cavity ends are anti-reflection (AR) coated for λ_L and λ_p. An AR coated f = 20 mm lens is used to provide cavity stability, and out-coupling is provided by a planar T = 23% broadband output coupler (OC). To excite the 1.9 µm Tm^{3+} and Tm^{3+} sensitised 1.9 µm Ho^{3+} transitions, we pump the chips at 790 nm into the $^3F_4$ level, where it induces a neighboring ground state Tm^{3+} to cross-relax into the upper $^3H_4$ laser level.

For the tuning demonstration we chose a Littrow configuration due to ease of alignment and wide tuning capability. Figure 1(b) illustrates the cavity for the tuning experiments where the 600 lines/ mm grating (blazed at 1.6 µm) replaced the OC, and was oriented in the Littrow condition so that the 1st-order diffracted light was reflected back into the standing wave cavity. The 0th-order diffracted light provided cavity out-coupling. The aluminum coated grating was specified to have an absolute diffraction efficiency of ≈91% for light polarised perpendicular to the grooves, and < 40% for parallel polarised light. The drawback of Littrow tuning is that the direction of the output beam is a function of wavelength. However a modified Littrow [24], or Littman Metcalf configuration can be used where the output direction is conserved when wavelength tuning the laser [25].

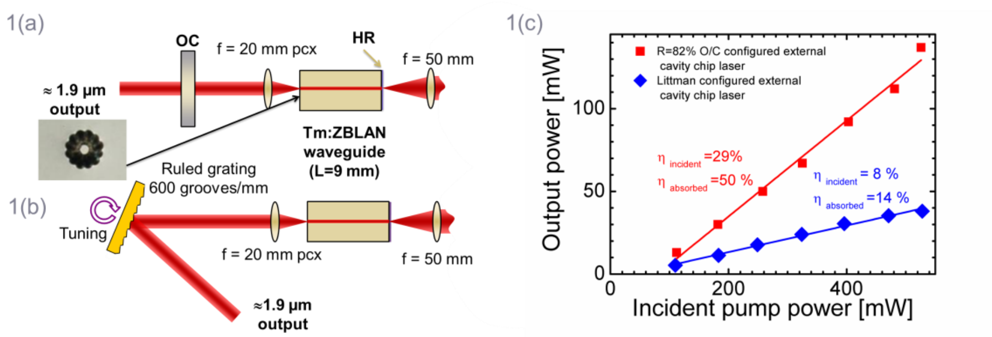

Fig. 1. (a): Tm:ZBLAN waveguide laser configured for external cavity operation using an output coupler mirror. Figure 1(b). A Littrow configured cavity containing a diffraction grating. Inset: A microscope end view of the depressed cladding waveguide. Figure 1c. Measured slope efficiency for the Ti:sapphire pumped external cavity Tm:ZBLAN laser and Littrow configured external cavity laser.

3. Ti-sapphire pumped Tm^{3+} waveguide chip laser

In the first series of experiments, a CW 790 nm Ti:sapphire laser (P = 600 mW) was used to pump the L = 9 mm chips (Tm:ZBLAN and Tm,Ho:ZBLAN). Each chip had 15 waveguides inscribed with core diameters ranging from 15 to 45 µm. To launch the Ti:sapphire into the waveguides, a f = 50 mm lens focused the beam to a spot size of ~29 µm with a numerical aperture (NA) of < 0.05. For these external cavity configurations described in sections 3 and 4, the largest 45 µm waveguide was used.

The lasing slope efficiency of the extended cavity (see Fig. 1(a)) Ti:sapphire pumped Tm:ZBLAN laser is plotted in Fig. 1(c). The incident slope efficiency when using a R = 77% OC mirror was 29%, with a threshold of ~75 mW. If the pump absorption (α = 5.1 dB/cm) for

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this short chip waveguide is taken into account, the internal slope efficiency is improved to ≈50%. Beam quality was measured at M^2≈1.3, for the largest 45 µm diameter waveguide.

By replacing the OC with the 1.6 µm blazed diffraction grating (attached to a 3-axis kinematic mirror mount, see Fig. 1(b)), the measured slope efficiency is shown in Fig. 1(b), and was ≈8% for incident power, and ≈14% for absorbed power. For this demonstration the pump was not double-passed through the gain chip. When rotating the grating in the horizontal plane the laser tuned continuously from 1730 nm to 1975 nm (245 nm) across the thulium fluorescence, as shown Fig. 2(a). The shortest wavelength achieved was set by a combination of the HR chip-coating reflectivity falling, decreasing gain, and increasing ground state absorption. The beam quality was measured at M^2~1.3, with a near-field beam-profile shown in the inset to Fig. 2(a). A slight ellipticity along the diffraction direction of the grating was present in the near-field beam with the $1/e^2$ beam diameter being 1.2 x 1.0 mm (horizontal and vertical, respectively). No side modes were found in the output spectrum, which had a FWHM linewidth across the tuning range varying between 0.4 and 0.2 nm, with a typical spectrum shown in Fig. 2(b) (Yokogawa AQ6375). The 140 pm spaced fringes correspond to the parallel end-faces of the L = 9 mm chip acting as a Fabry-Pérot etalon. Laser efficiency was improved by double-passing the pump light, which was accomplished by butting a 790 nm HR mirror (HT@1.9 µm) to the end of the waveguide. In this configuration the maximum power achieved from the Littrow cavity was 132 mW, however increased intra-cavity losses reduced the tuning range to 220 nm.

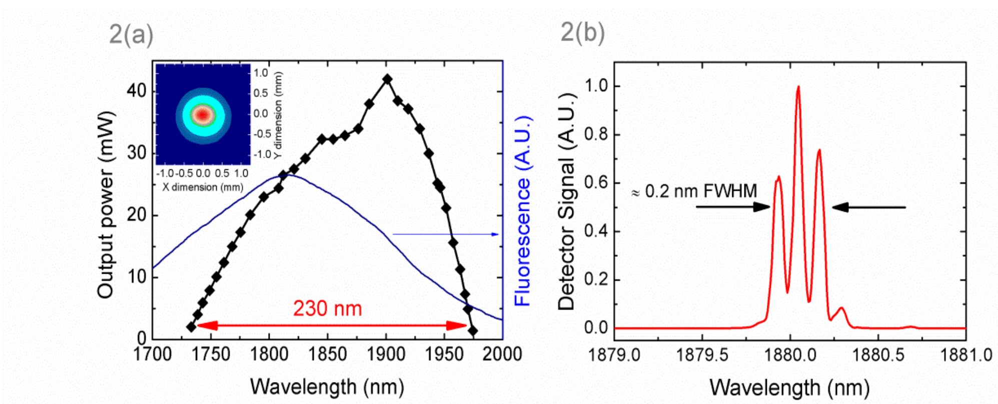

Fig. 2. (a). Measured tuning range of the Tm:ZBLAN chip with the thulium fluorescence spectrum overlaid. Fig. 2(b). A typical lineshape of the Littrow configured cavity. The fringes correspond to the L = 9 mm waveguide chip acting as a Fabry-Pérot etalon.

4. Ti-sapphire pumped Tm: Ho ZBLAN chip laser

The efficiency of the Tm^{3+} sensitized Ho^{3+} ZBLAN chip laser [13] was found to be lower than the Tm:ZBLAN chip laser. To increase the laser gain we configured the Littrow cavity to double-pass the pump by butting the 790 nm HR mirror to the end of the chip as shown in Fig. 3(a). Even with this double-passed pump configuration the tuning range was limited due to a high laser threshold attributable to low feedback from the grating. To further mitigate the low gain, a R = 77% OC was aligned prior to the grating to increase cavity feedback. In this configuration the laser achieved up to 25 mW output. With this configuration, single line continuously tunable output from 1810 to 2050 nm was achieved as shown in Fig. 3(b). Individual spectra recorded across the tuning range are shown in Fig. 3(c). The tuning range of the Tm,Ho:ZBLAN waveguide laser is substantially red-shifted compared to Tm:ZBLAN, and it is apparent that the tuning range covers the overlapped thulium and holmium

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emissions. At wavelengths longer than 2000 nm, the Tm^{3+} gain would be too low to support laser operation (as seen by the Tm^{3+} only doped chip and the fluorescence spectrum shown in Fig. 2(a)), and the emission here corresponds to holmium emission. The longest wavelength we achieved was 2050 nm, and at this wavelength the grating feedback was not sufficient to suppress the thulium emission dominating near 1890 nm. The short wavelength limit was 1820 nm where the laser could not reach threshold. The holmium emission achieved at >2000 nm from this co-doped system demonstrates non-radiative energy transfer from the excited thulium ions to the holmium ions, which then undergo stimulated emission. The continuous tunability in this co-doped system is consistent with the tuning behavior reported for a thulium holmium co-doped silica fiber laser [5].

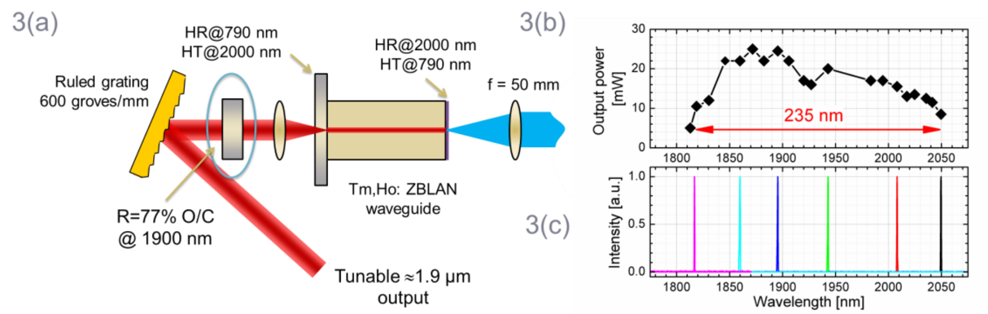

Fig. 3. (a). Modified Littrow external cavity Tm,Ho:ZBLAN waveguide laser using a R = 77% OC intra-cavity for additional cavity feedback. Fig. 3(b). Tuning curve for the Tm,Ho:ZBLAN waveguide laser. Fig. 3(c). Representative spectra across the tuning curve.

5. Diode-laser pumped Tm:ZBLAN chip laser

A more practical, elegant, and compact option for pumping the Tm^{3+} waveguide laser is to use single-emitter diode lasers. For this demonstration two in-house collimated $\lambda \approx 791$ nm P = 330 mW diode lasers are combined by a polarizer, and focused into the waveguide by a f = 50 mm lens as shown in Fig. 4. No optical isolation was used and care was taken to ensure feedback to the diodes was minimized. For this configuration we used a 1.9 mol % TmF_3 doped ZBLAN chip with L = 12 mm with the input end of the chip coated with a broadband HR@1.9 µm coating, and the other-end AR coated for 1.9 µm. Cavity stability was provided by an AR coated f = 50 mm plano-convex lens. As this was not an achromat lens, the lens spacing from the chip had to be adjusted across the tuning range due to the glass lens dispersion.

To characterise the external cavity operation of this configuration a R = 77% OC was substituted for the diffraction grating, and slope efficiency measured. Single transverse mode operation was observed across the available waveguide core diameters (15 µm – 70 µm). The highest efficiency operation we observed was for the largest waveguide. As this requires the lowest pump-brightness, coupling into this pump channel relaxed the pump beam-quality constraints and beam overlap requirements for the non circular and astigmatic diode laser beams. For all work reported here we used the largest 70 µm waveguide. The incident slope efficiency (Fig. 5(a)) for the 70 µm waveguide was ≈37%, at a relatively high threshold of 265 mW, which we attribute to the large pump volume, and therefore low intra-cavity intensity of this quasi 3-level transition. The calculated internal slope efficiency was 54%.

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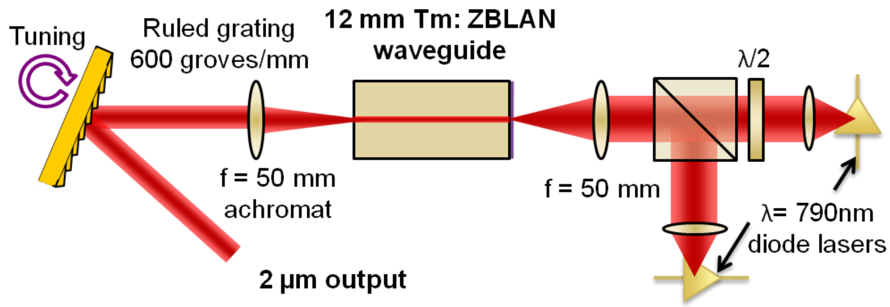

Fig. 4. Schematic of the twin 790nm diode-laser pumped Tm:ZBLAN waveguide laser.

When the OC was replaced by the Littrow-configured diffraction grating the incident laser slope efficiency was measured to be 14%, with up to 60 mW output power achieved at the peak gain wavelength near 1905 nm. The internal slope efficiency was calculated to be 19%. The tuning behavior for this Littrow-configured cavity was found to be continuous over 253 nm range with the output power shown as a function of wavelength in Fig. 5(b); the tuning range covers 1745 nm to 1998 nm. A typical spectrum of the tuned output is shown in Fig. 6(a), and has a FWHM of ≈0.4 nm, with the 92 pm (7.84 GHz) modulation on the spectral lineshape due to the chip acting as a Fabry-Pérot etalon. The longer wavelength 'redder' operation of this diode laser pumped chip compared to the L = 9 mm chip is attributable to the L = 12 mm 3-level gain chip suffering increased ground state absorption due to the reduced population inversion along the waveguide.

The beam quality of the diode laser pumped Littrow-cavity configured chip laser was single transverse mode with a Gaussian beam shape. The good beam quality was confirmed by a measurement of the beam quality as shown in Fig. 6(b), with M^2 = 1.23 in the horizontal (tuning) plane and M^2 = 1.14 in the vertical plane.

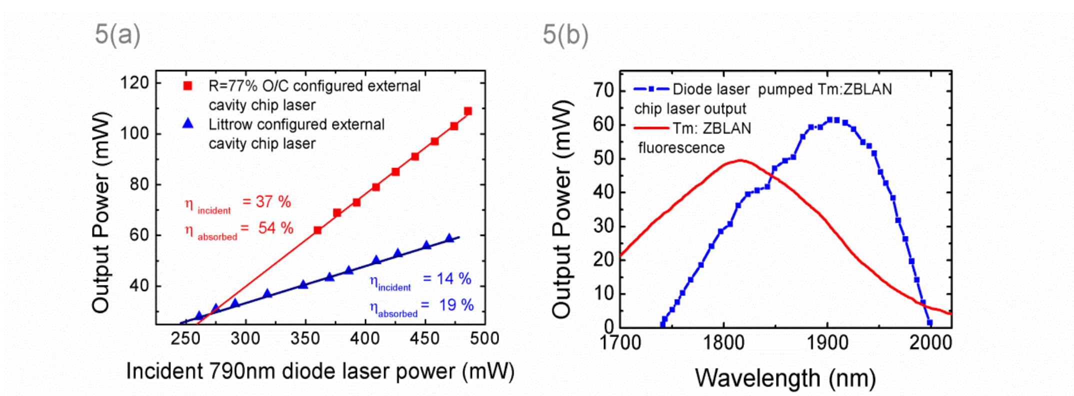

Fig. 5. (a). Slope efficiencies of the laser diode pumped L = 12 mm Tm: ZBLAN waveguide laser configured for external operation using either a R = 77% OC or a 600 lines/mm diffraction grating. Fig. 5(b). Measured tuning range of the Littrow configured Tm:ZBLAN laser for an incident pump power of 475 mW. For reference the fluorescence emission of Tm:ZBLAN is overlaid.

6. Discussion and conclusions

The time-averaged linewidth of 0.2 nm we report (16.6 GHz or 0.55 cm^{-1}) is too wide in order to perform gas phase molecular absorption spectroscopy. The etalon induced structure on the time-averaged spectral lineshape (shown in Fig. 6(a)) is indicative of spectral instability (i.e. a weakly competing cavity [26]), thus the instantaneous linewidth is expected to be narrower, and we predict that by angle polishing the AR coated end of the waveguide, the time-averaged bandwidth will substantially reduce. In addition a Littman-Metcalf configured cavity [25] will provide a narrower linewidth. The trade-off for this configuration is higher intra-cavity losses as the light is diffracted twice off the diffraction grating per resonator roundtrip, thereby incurring a higher laser threshold. To further narrow the linewidth for either configuration a diffraction grating with higher dispersion can be used. By shortening the cavity, and using a narrow-bandwidth volume Bragg holographic grating, there is also the potential for the laser to operate on a single longitudinal mode [27].

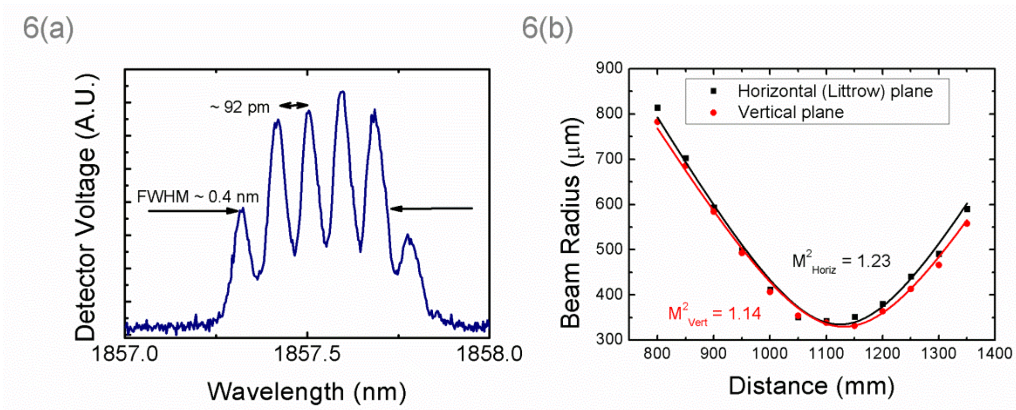

Fig. 6. (a). Time-averaged spectrum of the tuned output of the Littrow configured extended cavity chip laser. Fig. 6(b). Measured beam quality (M^2) of the Littrow configured extended cavity chip laser.

We expect we could achieve increased tuning range further into the infrared by use of a cavity with a birefringent element for wavelength tuning. This would allow a higher cavity Q (ie. less output coupling) thus allowing the lower-gain long wavelength thulium and holmium emissions to reach threshold. We also expect to be able to substantially improve performance by optimising the thulium concentration to enhance efficiency via cross-relaxation, thulium to holmium dopant ratio, chip lengths, and optical coatings.

The best efficiency we achieved for a Littrow configured laser cavity was in the diode-pumped configuration. This efficiency is an improvement over the Ti:sapphire pumping which we attribute to the longer chip length (12 mm cf. 9 mm). This result indicates that despite the beam quality of the combined diode lasers being inferior to the Ti:sapphire, a larger waveguide can be used to mitigate the effect of a less bright pump source. Unfortunately the L = 9 mm thulium ZBLAN chip was not available for a direct measurement of the diode-laser pumped efficiency.

In conclusion, the wavelength tunability we have achieved with the ZBLAN waveguide chip lasers are comparable to bulkier fiber-laser designs. These ZBLAN waveguide lasers feature low thresholds which have allowed us to demonstrate efficient operation using low-power single-emitter diode-laser pumps. Our wide tuning range of 1745 to 1998 nm for the 790 nm diode laser pumped Tm:ZBLAN laser covers an interesting spectroscopic region, and combined with the 60 mW of power and intrinsic close-to-diffraction limited beam quality ($M^2 \approx 1.3$) of fundamental mode waveguide lasers, this type of waveguide laser should have application for molecular spectroscopy, or as a master oscillator. We have also demonstrated that by the addition of holmium, the tuning range of the thulium sensitized ZBLAN chip laser can be extended up to 2050 nm.

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