Er^{3+} Active $Yb^{3+}Ce^{3+}$ Co-Doped Fluorozirconate Guided-Wave Chip Lasers

David G. Lancaster, Yahua Li, Yuwen Duan, Simon Gross, Michael W. Withford, and Tanya M. Monro

***Abstract*— We report efficient 1.55-μm laser operation in a waveguide chip laser femtosecond-laser inscribed in bulk fluorozirconate glass. The ternary doped glass is composed of erbium as the active laser ion, ytterbium sensitizer, and cerium to enhance the branching ratio from the pump to the erbium upper laser state. We have achieved slope efficiencies up to 25%, with a low 100-mW threshold. To meet diverse application requirements, we also report the wide tunability of 1507–1593 nm, and large single-transverse-mode Gaussian beam-output from the 55 μm diameter waveguides.**

***Index Terms*— WG laser, erbium, ultra-fast laser inscription, infrared.**

I. Introduction

ERBIUM doped waveguide (WG) lasers (EDWLs) operating in the eyesafe and telecommunication band near 1.55 μm have application in optical communications, laser radar, spectroscopy, and signal processing. These applications require low-cost, respectable efficiency, compactness, and most importantly a WG fabrication technique flexible enough to allow new designs to be conveniently realized. Ultra-fast laser inscription (ULI) of WGs into bulk substrates is a rapidly maturing technique that allows custom three-dimensional WG geometries to be imprinted [1] into rare-earth (RE) doped substrates. If erbium-doped ULI WGs are to be performance competitive with high performing ion-exchange fabricated WG devices, the challenge is identifying a host glass with sufficient gain that can be UL inscribed with low-loss WGs. We report here a contender based on fluorozirconate glass that we propose can be used as a building block for 'on-chip' micro-photonics circuits and enhance the philosophy of low-cost, and micro form-factors for convenient integration into miniature systems.

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The highest performing devices in the 1.55 μm infrared band (or more conveniently, the C-band which covers 1530-1565 nm) are planar WG glass lasers formed by ion exchange fabrication in ytterbium sensitized erbium-doped phosphate glasses (Schott IOG-1). In 2000, a 28 % slope efficiency and P=170 mW 1540 nm laser was reported [2]. This was improved upon in 2008 by a P=160 mW, 46 % slope efficiency laser [3]. The core diameters of these ion exchanged WGs ranged from 3 to 8 μm diameter for fundamental mode operation which has the benefit of achieving high pump saturation (or inversion) of the 3-level erbium transition, but limits peak-power scaling.

Lasers based on ULI WGs in phosphate glasses have to-date reported lower efficiencies than ion exchanged phosphate produced WGs. For instance 21 % slope efficiency was reported in [4]. This lower efficiency has been attributed to ion migration effects occurring in the ULI modified WG core [5]. Other ULI C-band emitting WG lasers (see [6] for a comprehensive review), include Oxyfluoride silicate glass at 0.005 % efficiency [7], and bismuthate achieving 1.25 mW of mode-locked laser output [8].

We report here a flexible approach to large diameter WG laser gain modules (up to 55 μm diameter with robust single transverse mode operation), specifically lasers in the 'eyesafe' spectral region with ULI fabricated depressed-cladding WGs in erbium doped fluorozirconate glasses. Our primary motivation is compact planar-laser devices capable of energy storage for short-pulse laser and amplifier operation. These investigations demonstrate a reasonable efficiency from large mode-area WGs to allow scaling to high peak-powers. As a first step towards this goal we report general laser characteristics for this ternary-doped fluorozirconate glass containing ULI WGs.

II. Background

There have been no reports of erbium doped fluorozirconate glass WG lasers in the 1.5 μm band. Early investigations of erbium doped fluoride glass [9] indicated a wide gain bandwidth, could be highly doped, and long upper-state lifetimes (~9.4 ms) due to low phonon energy. However, only 1480-nm pumping was feasible. Pumping erbium fluorozirconate at 980 nm suffers from excited state absorption (ESA) due to high lying metastable states, and thus only a low excited-state population can be achieved in the 1550 nm transition upper level ($^4I_{13/2}$). The ESA results in green fluorescence emitted from 980 nm pumped Erbium ZBLAN fibers.

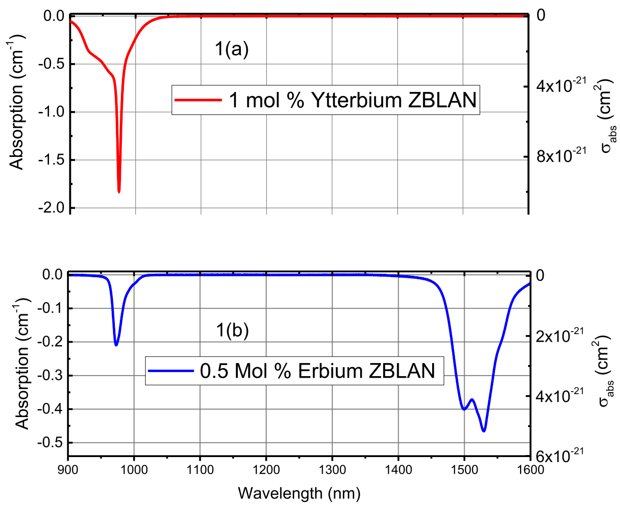

Fig. 1. Measured absorption in units of dB/cm and measured absorption cross-section (σ_{abs}) for a) 1 mol % Ytterbium doped ZBLAN, b) 0.5 mol % Erbium doped ZBLAN bulk glass.

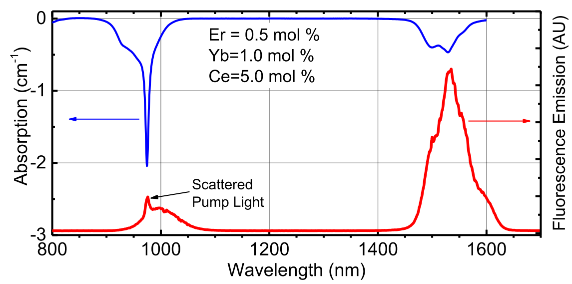

Fig. 2. Measured absorption in units of cm^{-1} of erbium ytterbium cerium doped ZBLAN (0.5 mol % erbium, 1.0 mol % ytterbium, 5.0 mol % cerium). The measured fluorescence emission spectrum for this composition is also shown.

In 1999 [10] it was reported that the addition of cerium (up to 6 mol %) to erbium doped ZBLAN improved the branching ratio (a spectroscopic investigation) from the erbium $^4I_{11/2}$ to $^4I_{13/2}$ from 0.20 to 0.95. Subsequently, a ZBLAN fiber laser (L=25 cm) containing 5 mol % Ce^{3+} and 0.5 mol % Er^{3+} achieved efficient laser operation at 1.54 μm with incident slope efficiencies of ~27 % [10].

To overcome the low absorption cross-section of erbium at 976 nm, ytterbium is routinely used as a sensitizer. Fig. 1(a) and 1(b) shows the measured absorption and absorption cross-sections (σ_a) for singly doped 1.0 mol % Yb^{3+} and 0.5 mol % Er^{3+} ZBLAN glasses (Cary 5000, Agilent). The low Er^{3+} absorption of ~0.2 cm^{-1} at 976 nm (for 0.5 mol %) is impractical for short WG lasers, however 1 mol % Yb^{3+} results in 1.8 cm^{-1} absorption at 976 nm.

Fig. 2 shows the absorption characteristics for a ternary doped 0.5 mol % Er^{3+} and 1.0 mol % Yb^{3+}, and 5.0 mol % Ce^{3+} spectroscopic glass sample with a combined Er^{3+} + Yb^{3+} absorption of ~2 cm^{-1} at 976 nm.

The measured fluorescence for 976 nm excitation of a 0.5 mol % Er^{3+}, 1 mol % Yb^{3+} spectroscopic sample recorded using a spectrophotometer (Edinburgh Instruments, FLS980) is also shown in Fig. 2. The broad fluorescence emission from the $^4I_{11/2}$ state to the ground manifold centered at ~1535 nm is highlighted. As can be seen the fluorescence is co-incident with the strong ground state absorption, indicating that high Er^{3+} inversion is required to overcome the ground state absorption.

A spectroscopic study of this ternary doped ZBLAN [12], reported that the 1.5 μm fluorescence (for fixed Er^{3+} concentration) was strongly dependent on the Yb^{3+} concentration. Thus an aim of this letter was to investigate the laser efficiency as a fn. of the Yb^{3+} sensitizer. Due to a large parameter space for this ternary rare-earth doped glass, as well as the multi-step cycles required for processing doped glass billets into laser suitable WG chips, we limited our investigation to an active ion concentration of 0.5 mol % Er^{3+}, with either 0.5 mol % or 1.5 mol % Yb^{3+}. The Ce^{3+} concentration was set to 5.0 mol %.

III. Experimental Configuration

For glass ingots with > 6 mol % RE the glass quality was compromised by regions containing crystals due to the high RE doping. To reduce the overall lanthanide concentration no additional lanthanum was incorporated into the glass. In contrast previous ZBLAN billets we have fabricated with low RE concentration (< 3 mol %) are generally free of crystals (highly dependent on raw material quality). The 50 g glass for one of the ingots has a nominal composition (in mol. %) of 51 ZrF_4 − 19 BaF_3 − 1.5 YbF_3 − 0.5 ErF_3 − 5 CeF_3 -3 AlF_3 − 19 NaF. They are prepared in a glovebox purged with dry N_2 (≤10 ppmv water) using commercially available raw materials (anhydrous fluorides) of 99.9 % or higher purity.

The Yb^{3+} concentrations in the two chips are 0.5 and 1.5 mol %, with WG lengths of 28.14 mm and 14.5 mm, respectively. Based on these lengths and RE concentrations, the calculated small-signal pump absorption of the 0.5 and 1.5 mol % Yb^{3+} are: ~15 dB (97 %) and 21 dB (99 %), respectively. However, the measured pump absorption at maximum incident pump power (540 mW) is significantly lower at 65 % and 81 %, respectively, indicating strong Yb^{3+} ground state depletion for these core-pumped lasers. The low conc. Yb^{3+}-doped chip was longer to achieve reasonable pump absorption, however the length of each chip was not optimised.

The process steps to fabricate the chips are glass ingot casting, dicing, surface polishing to allow the transverse ULI of the WGs, grinding back of the WG ends (by ~500 μm), optical polishing of the WG end-faces, followed by application of anti-reflection coatings at the pump and laser wavelengths. The WG laser architecture is based on ultrafast laser inscribed refractive index modifications in ZBLAN bulk glass to create a low-loss depressed-cladding. The ULI process uses ~50 fs pulses from a 5.1 MHz repetition rate Ti:sapphire oscillator to create 'rods' of reduced refractive index ($\Delta n \sim -0.001$) that can be built up over multiple passes to form an annular cladding around an unmodified core as shown in the inset to Fig. 3. The detailed characteristics of the WG inscription process are described in [13].

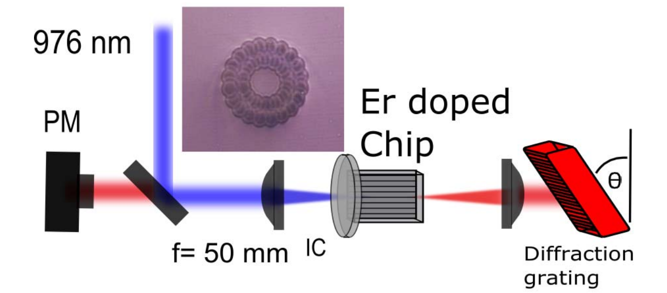

Fig. 3. Modified Littrow tuning configuration. IC: Input Coupler; PM: Power Meter. Inset: End-view of a waveguide, WG core diam. is ~ 34 μm.

The written WG diameters range from 16-55 μm diameters, with the light confined by the ULI written depressed cladding regions of ~ 32 μm surrounding the unmodified core. A 700 mW single-mode fibre coupled 974 nm diode laser pumps the WG cores via two AR-coated relay lenses (f=11 and f=50 mm aspheric lenses) to allow numerical aperture (NA) matching of the HI1060 fiber and chip WGs (NA of chip WGs was measured at ~0.04 ± 0.01).

The laser resonator for free-running continuous-wave output experiments used bulk mirrors (diam=12.5 mm) physically butted to each end of the AR coated chips.

To demonstrate the wavelength tunability, a modified Littman grating tuning configuration is used as shown schematically in Fig. 3. This layout has the advantage over a standard Littman geometry of the output beam being co-linear (counter-propagating) with the incident pump beam and not relying on the out-coupling provided by the angle dependent 0^{th}-order grating reflection. The tunable laser cavity is composed of an AR coated collimating lens (f=30 mm) followed by a 300 lines/mm diffraction grating blazed at 1.7 μm, oriented to reflect the first-order diffracted beam back into the WG. Tuning is achieved by rotating the angle of the grating in the horizontal plane.

IV. Experiments

To provide a performance comparison, slope-efficiencies were collected for the free-running monolithic-cavity configured 0.5 and 1.5 mol % doped Yb^{3+} chips (same Er^{3+} and Ce^{3+}).

Measured slope efficiency of the chip lasers with 1.5 mol % and 0.5 mol % Yb^{3+} concentrations are shown in Fig.4 and Fig. 5, respectively (for a range of output couplers). The best performance of each chip was achieved for WG diams. of ~ 38 ± 2 μm. This is consistent with the pump spot being ~ 35 μm diam. ($1/e^2$). Both the incident slope-efficiency and the absorbed power slope-efficiencies are shown to allow a more meaningful comparison due to the differing absorptions of each chip. For each laser 95 %, 90 %, and 80 % reflectance output-couplers (OCs) were used. Unabsorbed pump light through the chip laser was measured directly using filters to discriminate against the laser emission. Single-transverse-mode WG laser operation was observed during all experiments reported here, consistent with our previous reports of M^2 ~1.1 for Tm^{3+} doped chip lasers at 1.9 μm [14].

The 1.5 mol % Yb^{3+} chip has a threshold of ~ 90 mW for the 90 % R OC. The slope eff. as a fn. of incident pump is 17.6 to 20 %, as shown in Fig. 4a. If the slope efficiencies are considered as a fn. of absorbed power (Fig. 4b), they improve to ~25 %. Free running wavelengths for this chip ranged from 1558 to 1568 nm (95 % OC), indicating that a high Er^{3+} inversion is obtained.

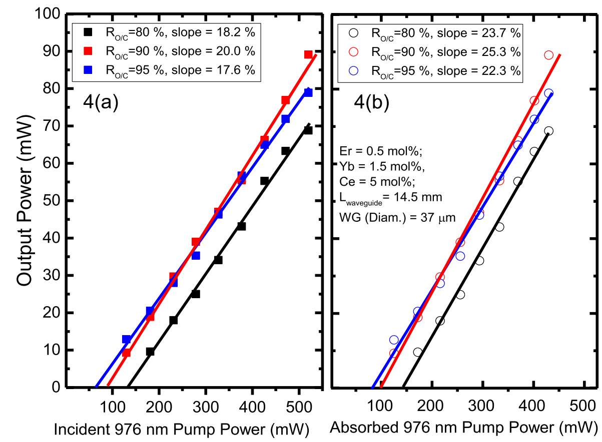

Fig. 4. Measured laser slope efficiencies of the 0.5 mol % Er^{3+}:1.5 mol % Yb^{3+}:5 mol % Ce^{3+}doped ZBLAN chip laser, L =14.5 mm. (a) fn. of incident 976 nm pump, and (b) fn. of absorbed 976 nm pump.

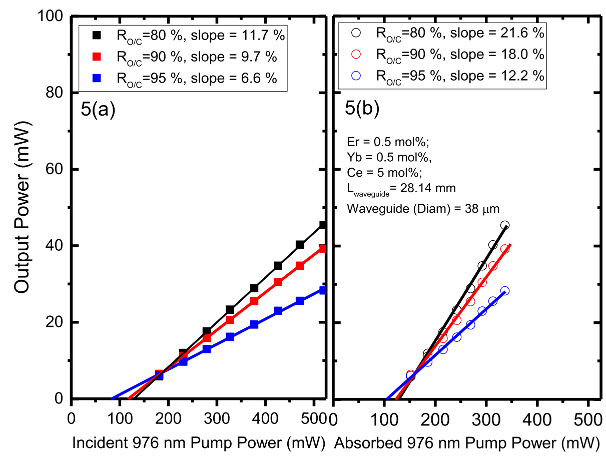

Fig. 5. Measured laser slope efficiencies of the 0.5 mol % Er^{3+}:0.5 mol % Yb^{3+}:5 mol % Ce^{3+} doped ZBLAN chip, L =28.4 mm. (a) as a fn. of incident 976 nm pump, and (b) as a fn. of absorbed 976 nm pump.

Slope efficiency of the 0.5 mol % Yb^{3+} chip reaches ~12 % for the 80 % output coupler (Fig. 5a), and due to the low saturated absorption of the chip at maximum pump power this increases substantially to ~22 % as a fn. of absorbed pump power (Fig. 5b). Maximum output power measured was 55 mW for 510 mW incident pump. Laser threshold is OC dependent as expected and ranges from 90 to 130 mW. Free running wavelengths for this laser ranged from 1560 nm up to 1587 nm (95 % OC). This is substantially red-shifted compared to peak-gain thus implying a low Er^{3+} inversion was achieved for this lower Yb^{3+} concentration, and likely inefficient energy transfer from Yb^{3+} to the Er^{3+}.

Figure 6 details the tuning range of the 1.5 mol % Yb^{3+}: 0.5 mol % Er^{3+} ZBLAN chip when configured in the modified Littman cavity configuration. Slope efficiency is lower at 5 % than monolithic operation (gain center), which is partly due to

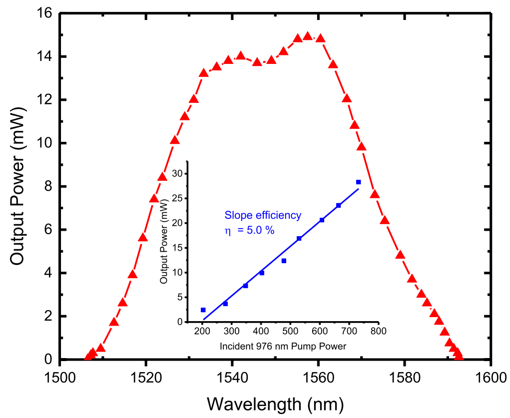

Fig. 6. Measured laser tuning performance of the erbium ytterbium cerium doped ZBLAN (0.5 mol % Er, 1.5 mol % Yb, 5.0 mol % Ce). The laser used a modified Littrow cavity as shown in Fig. 3.

use of a tarnished diffraction grating, as well as additional losses due to the grating also out-coupling the 0^{th} order light (power of this rejected beam was not measured). The tuning experiments reported in Fig. 6 were conducted for an incident power of 550 mW. The tuning range achieved is 1507 nm to 1593 nm, with the tuning being smooth and continuous, and no evidence observed of spectral instability or wavelength jumps. Beam quality was at all times observed to be single transverse mode.

V. Discussion

A particular challenge in comparing WG devices with differing Yb^{3+} sensitizer concentrations are that the WG lengths for efficient laser operation will not be equal. Thus the low concentration 0.5 mol % Yb^{3+} chip is ~1.52× longer than the high concentration 1.5 mol % Yb^{3+} chip. This will introduce additional round-trip losses in the chips which we estimate at 0.73 dB and 1.4 dB (for the L=14.5 mm, L=28.14 mm chips, respectively) based on loss measurements we have made at ~1400 nm (using a commercial supercontinuum and acousto-optic spectral filter) of 0.25 ± 0.05 dB/cm from comparable Er^{3+} doped WG chips. Thus the higher-doped short Yb^{3+} chip's higher performance, cannot be simply attributed to the higher Yb^{3+} concentration, and the reduced round trip loss must also be considered. Hence care needs to be taken in interpreting the slope efficiency data.

Perhaps the most significant result we report that supports the advantage of higher Yb^{3+} doping is that the higher Yb^{3+} sensitized sample lases at shorter wavelengths (1558-1568 nm), compared to the lower Yb^{3+} sample (1560-1587 nm), indicating that higher Er^{3+} inversion is achieved in the former. This is consistent with improved energy transfer between the Yb^{3+} to Er^{3+} ions, when higher Yb^{3+} concentrations are used.

Numerical rate-equation modelling is required to optimize this laser; the challenge is the lack of availability of spectroscopic constants (including non-radiative transfer coefficients between ions, ETU and ESA coefficients). Hence detailed spectroscopic investigations will be required to optimize this ternary doped laser system, thus allowing a comprehensive rate equation approach to be developed.

VI. Summary and Conclusion

We report here laser characteristics for erbium, ytterbium, cerium doped fluorozirconate glass, and demonstrate that efficient (>25 % slope efficiency) laser operation can be achieved in fs-laser inscribed WGs. We conclude that higher concentrations of Yb^{3+} are desirable to enhance the efficiency of the laser, and that short WG lengths are also desirable to reduce cavity loss due to WG propagation losses. We also demonstrate a wide tuning range for this laser, indicating its potential for short-pulse mode-locked operation. Thus while this ternary doped glass is not optimized, the performance we report here compares well with any ULI WG lasers operating in the C-band, with the benefit of a significantly larger mode-area, yet robust single transverse-mode operation, which is critical for peak-power scaling.

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