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Mode-Locked sub 200 fs laser pulses from an Er-Yb-Ce ZBLAN Waveguide Laser

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ABSTRACT: Passively mode-locked sub 200 fs pulses are generated from Er-Yb co-doped ZBLAN waveguide laser using a semiconductor saturable absorber mirror repetition rates of up to 533 MHz. At 156 MHz and 1556 nm central wavelength, the chip laser operates with a broad 25 nm bandwidth. The waveguides were written in the Er-Yb co-doped ZBLAN glass by using ultrafast laser inscription.

Over the past few decades, sources of ultrafast laser pulses have progressed from complex and specialized systems to compact and robust tabletop instruments. Because of the high peak-powers and broad spectrum, ultrafast lasers are applicable to emerging applications such as telecommunication [1, 2], frequency combs [3, 4] and high-speed digitization [5].

To enable instruments powered by ultra-fast lasers to be suitable for use outside the laboratory, new designs for portable and robust ultrafast lasers are required. An important but underrepresented regime is ultra-short pulses with high repetition rates (0.1 to 2 GHz) in various spectral domains with high-peak powers along with compact and reliable architectures [5-8].

We have previously reported a new compact waveguide laser architecture, where ultra-fast laser (ULI) inscribed waveguides are written into chips of rare-earth doped fluorozirconate glass. By tailoring the rare-earth dopant and waveguide design we have achieved efficient laser operation throughout the near to short-wave infrared spectral domain, covering 1.1, 1.5, 1.9, 2.1 and 2.9 μm [9-14], and demonstrated extended laser tuning ranges of up to 253 nm for thulium doped ZBLAN. By combining this wavelength flexibility, broad gain bandwidths, and the intrinsic large mode-area of these depressed-cladding guiding structures, the essential requirements are met to realise a compact laser geometry that is ideal for mode-locked applications and covers specific bands across the 1-3 μm spectral domain. In this paper, we present characteristics of a mode-locked laser that demonstrates proof of principle for this wavelength flexible architecture. Specifically, we have achieved passive ultrafast mode-locked operation based on Erbium doped Fluorozirconate glass [15] with ULI large mode-area waveguides (50 μm diameter).

Erbium has been used as the preferred dopant in different host materials to generate ultrafast mode-locked pulses ranging from several picoseconds to ~100 fs in the 1.5 μm wavelength domain [16-20]. Generally, in the 1.5 μm band, the existing mode-locked lasers available to cover the 100 MHz to multi-GHz repetition rate are solid-state laser designs with short laser cavities (L ~ < 0.5 m). However, the requirement for robust single transverse mode operation of solid-state lasers to ensure mode-locking is challenging due to high sensitivity to cavity and mirror alignment, power dependent

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thermal lensing, and the precise overlap of the pumped gain region and the resonator mode.

The guided-wave confinement of fiber like structures in the bulk gain media solves these alignment issues of unguided solid-state lasers. While 'all fiber' lasers are desirable for their compact and reliable design, their high gain, low Q-factor, and high-nonlinearity due to tight light confinement (mode area ~ 0.5×10^{-6} cm^2) over an extended distance leads to enhanced non-linear effects such as self-phase modulation (SPM) [21] and require dispersion compensation [16].

Recently, we reported a widely tunable (~100 nm) Er-Yb-Ce doped fluoro-zirconate waveguide laser [9] with relatively large mode-area (~ 11×10^{-6} cm^2). The wide and flat gain profile of Er^{3+} in ZBLAN glass combined with large mode-area waveguides make them promising candidates for peak-power scalable ultrafast laser devices.

In this paper, we demonstrate a passively mode-locked Er-Yb-Ce: ZBLAN chip laser oscillator. This waveguide-based laser generates sub 200 fs transform-limited pulses at 156 MHz repetition rate with a 25 nm spectral bandwidth. This is the widest bandwidth and shortest pulses achieved in a passively mode-locked planar waveguide laser.

Initial numerical simulations of this mode-locked laser operating in the normal dispersion regime (ZBLAN has a zero dispersion λ of 1.6 μm [22]) suggest that the large mode-locked bandwidth results from the efficient use of the gain spectrum of erbium, instead of spectral broadening from nonlinear effects as reported earlier in Er^{3+} doped fibre lasers [24]. This is conceptually significant since this design takes the advantages of guided laser geometry without the nonlinear effects, which allows scaling up of the pump power for maximum use of the erbium gain bandwidth.

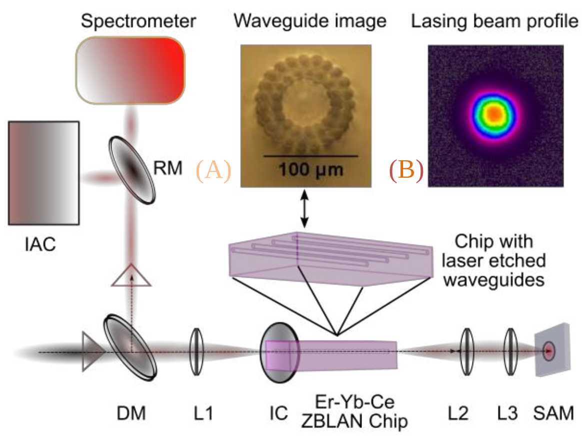

Figure 1. Schematic of the passively mode-locked ultrafast Er-Yb-Ce-ZBLAN waveguide laser. DM: Dichroic Mirror, L_1: F = 30 mm, IC: Input coupler (R_{1550} = 95%); L_2: F = 25 mm; L_3: (F = 4.5 mm); SAM: Semiconductor based Saturable Absorber; RM: retractable mirror to get intensity autocorrelation traces; optical spectrum and rf spectrum. Inset (A) image of the laser etched waveguide with double-ring structure (waveguide diameter ~ 50 μm) and (B) nearfield beam-profile of the mode-locked laser output.

The glass substrate is Er^{3+} and Yb^{3+} co-doped (0.5 mol. % Er^{3+} and 2 mol. % Yb^{3+}) ZBLAN glass. Cerium (5 mol. %) is added to increase the branching ratio from the Er^{3+} $^4I_{11/2}$ pump level to the laser upper state $^4I_{13/2}$ [23]. Fluorozirconate glasses such as ZBLAN have high transparency from the UV to ~ 4 μm [22]. Combined with high rare-earth solubility and low phonon energies they make excellent candidates for compact and efficient waveguide lasers. Depressed cladding waveguides are directly inscribed in the glass substrate (length = 13 mm) by ultrafast laser pulse inscription (5 MHz, < 250 fs, λ = 520 nm), produced from a frequency-doubled laser (IMRA, DE0210). Further details about the ZBLAN waveguides and ultrafast laser inscription methods can be found in previously published work [14].

The experimental setup is shown in Fig. 1. A fiber-coupled diode laser (Thorlabs, model # BL976-PAG900) is used as the pump. The pump beam is focussed into the ZBLAN waveguide by an achromatic lens (L_1, Focal length (F) = 30mm) through an input/output coupler (IC, R=95%). To set the repetition rate, the laser oscillator cavity length could be easily varied between ~ 0.1 to 1.0 m by using two lenses in a relay configuration of L_2 (AR coated achromatic lens with F = 30 mm) and lens L_3 (F = 4.5 mm) to re-image the mode onto the SAM (BATOP Gmbh, SAM-1550-15-12ps-4). The mode-locked output is reflected out of the beam path by the dichroic mirror (DM) and passes through a combination of half-wave plate (HWPL) and polarization beam-splitter (PBSL) to get the autocorrelation trace and spectrum. The spectrum of the mode-locked pulses is recorded by using an optical spectrum analyser (MS9470A, Anritsu Corp.). The experimental auto-correlation trace of the mode-locked pulses was obtained by using an APE Pulse Check auto-correlator (A.P.E. Angewandte Physik & Elektronic GmbH).

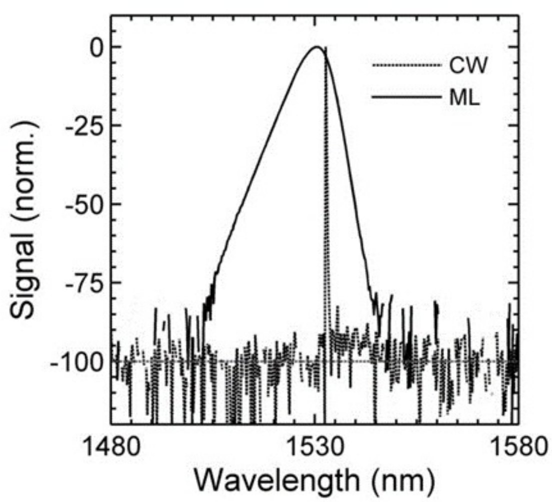

Figure 2. Measured spectral emission of the erbium chip laser when operating in continuous wave (dotted line) and passively mode-locked mode (solid line).

Fig. 2 shows the spectra of the passively mode-locked laser oscillator in an extended cavity (distance between IC and SAM ~ 96 cm) at 156 MHz repetition rate. The dotted line represents the spectrum when the oscillator is running in a CW mode and the solid line shows the mode-locked spectrum.

When the pump power (λ_{pump} = 976 nm) was further increased, we observed a broader spectral profile from this passively mode-locked oscillator. Fig. 3 (A-B) shows the experimentally observed optical spectrum and auto-correlation trace of the mode-locked output respectively at 156 MHz repetition rate at a higher pump power. Up to ~ 5 mW of mode-locked output power was achieved in this configuration. The FWHM of the spectral output measured from Fig. 3 (A) is $\Delta\lambda_{fwhm}$ = 25 nm. Fig. 3 (B) (red-solid line), shows the Fourier transform of the mode-locked spectrum. There is a perfect match between experimentally observed autocorrelation trace (Fig. 3 (B) solid line, black) and the Fourier transform (Fig. 3 (B) solid red line) of the mode-locked spectrum. It is evident from this close fit that the waveguide laser oscillator generates transform-limited pulses. As $Sech^2$ pulse shapes are extensively used to describe mode-locked pulses, we used a typical fit function [29] $f(t) = \frac{\text{sech}^4\left(\frac{t}{2.4445T}\right)}{3T}$, where T = pulse-width when f(t) is decreased by $1/e^2$, to measure the pulse-width from the experimentally observed autocorrelation trace as shown in Fig. 3 (B). The dashed-line (blue) in Fig. 3 (B) shows the f(t) fit to the envelope of the experimental data (solid, black). From the fit, the autocorrelation width (τ_p^{AC}) was estimated to be 277 fs by using τ_p^{AC} = 2.720T. It results in a pulse-width of $\tau_p^{\exp}$ = 180 fs.

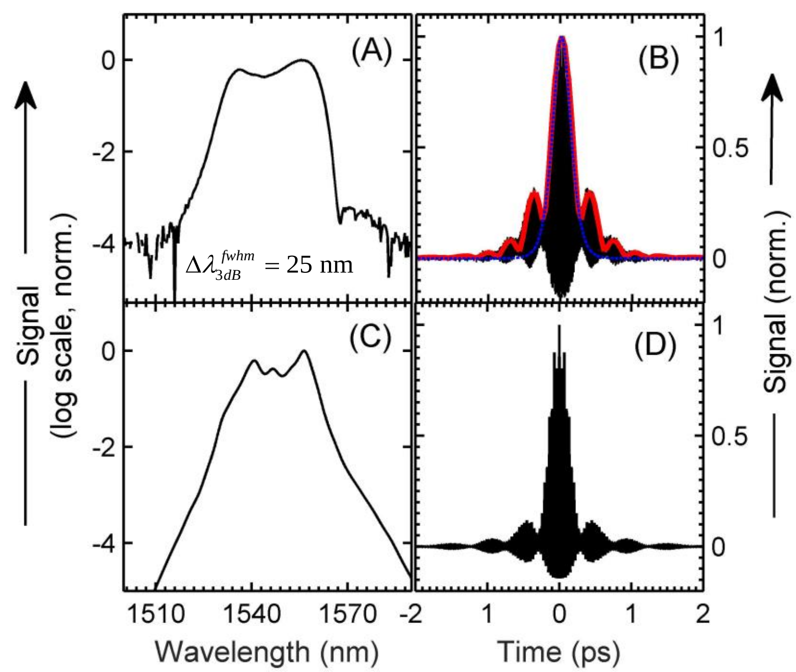

Figure 3. Mode-locked output of the Er-Yb-ZBLAN waveguide oscillator at 156 MHz repetition rate. Experimentally observed mode-locked (A) spectrum with $\Delta\lambda_{fwhm\ (3dB)}$ = 25 nm bandwidth and (B) auto-correlation trace (black, solid line), Fourier transform of the mode-locked spectrum (red, dashed line) and f(t) fit (blue, dotted line) to the autocorrelation trace indicates τ_p=180 fs. Exact match between the experimentally observed auto-correlation and the Fourier transform of the observed mode-locked spectrum suggests transform-limited pulse generation. To explore the origins of the broad spectral output, a Ginzberg-Landau equation was used, (C) shows the simulated mode-locked spectrum and (D) simulated auto-correlation trace from the numerical model.

We now consider the origin of the broad mode-locked spectrum. The RF spectrum of the mode-locked pulses is shown in Fig. 4. This data supports single mode-locked pulse operation and therefore negates the origin of broad spectrum from multiple-pulse operation within the oscillator cavity.

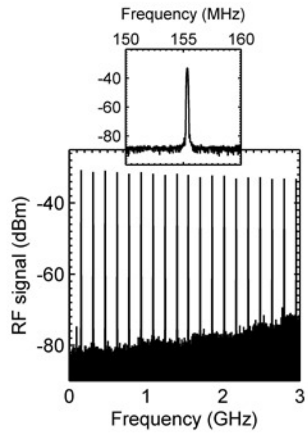

Fig. 4. RF spectrum of mode-locked pulses (RBW = 100 kHz). Inset shows the zoomed-in RF spectrum indicating single-pulse operation.

The observed spectrum is not enhanced by nonlinear processes either since the waveguide area is approximately ~ 20 × 10^{-6} cm^2, which leads to an estimated nonlinear coefficient of $\gamma = \frac{2\pi}{\lambda}\frac{n_2}{A_{eff}} \approx 10^{-4}$ W/m at λ = 1.55 μm for a nonlinear ZBLAN refractive index of 1.5 × 10^{-20}. For a waveguide length of 13 mm and ~2 kW intra-cavity peak intensity a negligible roundtrip nonlinear phase change of 0.0003 π radians is estimated. The exact match between the Fourier transform of the mode-locked spectrum and the experimentally observed autocorrelation trace (Fig. 3 (B)) also supports this insignificant phase contribution.

The dispersion of the ZBLAN waveguide is estimated to be low at ~ 7.4 fs^2/mm at 1550 nm by using the Sellmeier equation. The waveguide dispersion is assumed close to the material dispersion due to the large mode area. Therefore, we conclude that multiple-pulse operation, non-linear effects such as SPM and higher order dispersion effects do not have significant contributions to generate broad spectral output. To explore the origins of this broadband spectral profile, we used a numerical model based on the Ginzburg-Landau equation. The results from numerical simulations are shown in Fig. 3 (C) and (D) and represent the simulated mode-locked spectrum and the simulated auto-correlation trace respectively. Based on the numerical solution to the Ginzburg-Landau equation, which qualitatively agrees with experimental results, the wide and flat gain profile of Er^{3+} in ZBLAN glass accounts for the observed broad spectral output of the mode-locked pulses.

By shortening this mode-locked laser cavity, we have also achieved stable mode-locked operation at 533 MHz and 1.3 GHz. The autocorrelation trace of the mode-locked pulses at 533 MHz repetition rate is shown in Fig. 5. The solid (black) line represents the experimentally observed autocorrelation trace and the dotted line (red) shows the f(t) fit to the experimental data. The inset in Fig. 5 shows the mode-locked spectral output. Based on the f(t) fit function, at 533 MHz repetition rate, we obtained a pulse-width of 416 fs.

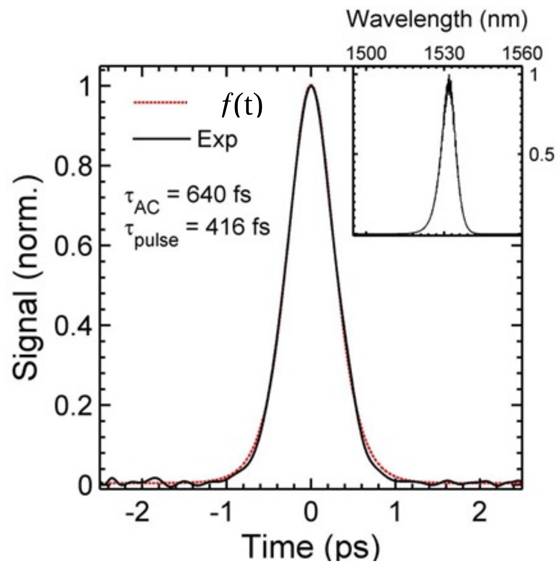

Fig. 5. Experimentally observed autocorrelation trace (solid, black) of the passively mode-locked oscillator at a repetition rate of 533 MHz.The dotted (red) line represents the *f*(t) fit to the experimental data that suggests the mode-locked pulse-width of 416 fs. Inset in the figure shows the spectrum of the mode-locked pulses.

Conclusions

We demonstrate a passively mode-locked Er-Yb-ZBLAN waveguide laser oscillator using a semiconductor saturable absorber. This waveguide oscillator produces mode-locked pulses with 25 nm bandwidth utilizing the wide gain bandwidth of erbium. To the best of our knowledge, this is the first experimental evidence to support more than 10 nm spectral bandwidth (FWHM) in a passively mode-locked waveguide laser. With modest efficiency improvements of the cavity, the cavity will be able to exploit the broader erbium bandwidth, and be able to achieve sub 100 fs pulses.

The performance of this mode-locked design should be directly transferrable to chip lasers that can be optimised to operate on a range of rare-earth transitions covering the near to short-wave infrared (1-3 μm) spectral domain. This ultrafast oscillator design is power scalable to multi-GHz repetition rate with direct applications in telecommunication, metrology and for the defence industry. We are targeting peak-power scaling of SESAM mode-locked TDLs to the multi kW regime with sub-100-fs pulse durations for high repetition rate compact frequency comb applications and non-linear frequency conversion.

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