420 fs Pulses from an Ultrafast Laser Inscribed Waveguide Laser Utilizing a Carbon Nanotube Saturable Absorber

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Abstract: We report the generation of 420 fs pulses of 1.56 μm light from a mode-locked ultrafast laser inscribed Er-doped waveguide laser. Passive mode-locking was achieved using a carbon nanotube saturable absorber.

OCIS codes: (130.3120) Integrated optics devices; (140.3500) Lasers, erbium; (140.3390) Laser materials processing

1. Introduction

The use of ultrafast lasers for inscribing structural modifications in transparent materials is currently attracting considerable research attention [1]. One application area of ultrafast laser inscription (ULI) that has attracted particular attention is the fabrication of active optical waveguide devices such as waveguide amplifiers [2, 3], and waveguide lasers [4, 5]. Given the success of ULI in these areas, there is now a drive to push the boundaries of what can be achieved. A number of groups are now working to increase output powers, demonstrate new wavelengths and pulsed operation using Q-switching and mode-locking techniques. To date however, there has only been one report of successful mode-locking of a ULI fabricated waveguide laser [4], and the authors were only able to demonstrate 1.6 ps pulses due to the low round trip net gain of their laser cavity. Here we report the generation of femtosecond pulses from a mode-locked ULI fabricated waveguide laser. This demonstration has been enabled by the realization of a high-gain ULI fabricated Er-doped bismuthate glass waveguide amplifier [3], and the use of a well developed carbon nanotube (CNT) saturable absorber [6-10].

2. Waveguide amplifier development

The glass substrate used in this study was an Er-doped bismuthate glass containing > 70 wt. % Bi_2O_3 and doped with 0.63 wt. %. Er. The glass was supplied by AGC in Japan. Waveguides were inscribed using a custom designed, variable repetition-rate master-oscillator power-amplifier (MOPA) ultrafast fiber laser system supplied by Fianium Ltd. For this work, the repetition-rate of the laser was set to 500 kHz and the pulse duration was measured to be ≈ 350 fs, full-width at half maximum. The central wavelength of the laser radiation was 1064 nm and the polarization was adjusted to be circular. The pulse train was focused into the sample using a 0.4 NA aspheric lens and the sample was translated through the focus using computer controlled x-y-z air-bearing stages (Aerotech). The waveguide cross section was controlled using the multiscan fabrication technique [3]. As a consequence, each waveguide was fabricated using 20 scans of the substrate through the laser focus, with each scan separated by 0.4 μm in the axis perpendicular to both the waveguide axis and the laser beam propagation axis. The optimum waveguide was inscribed using 133 nJ pulses and a translation speed of 1.0 $mm.s^{-1}$. After inscription, the sample was ground and polished at an angle of 3.0° to the waveguide axis, in order to reduce back-reflections. The final waveguide length was 87.0 mm.

Prior to constructing a laser cavity, the performance of the optimum waveguide was characterized. When two sections of 980/1550 nm wavelength division multiplexer (WDM) coupler fiber were butt-coupled to the waveguide facets (using index matching gel to reduce Fresnel reflections) the waveguide amplifier exhibited a background insertion loss of 4.2 dB, measured outside the Er-ion absorption band at 1620 nm, and a polarization dependent loss of ≈ 0.3 dB at 1533 nm. When pumped with ≈ 1.0 W of 980 nm light, the waveguide amplifier exhibited a peak fiber-to-fiber net gain of ≈ 16.0 dB at 1533.0 nm, and greater than 10.0 dB of net gain from 1527 nm to 1563 nm.

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3. Mode-locked waveguide laser construction and operation

A fiber ring cavity was constructed around the Er-doped bismuthate waveguide amplifier, as shown in Fig. 1(a). The optical isolator ensures unidirectional operation, thus reducing instabilities caused by reflections. Mode-locking is initiated by a CNT-polymer composite saturable absorber, which is sandwiched between 2 FC/PC fiber connectors. Output coupling is achieved using a broadband 90:10 fused fiber coupler. The pump light is delivered to the waveguide amplifier via two fused fiber wavelength division multiplexers (WDMs).

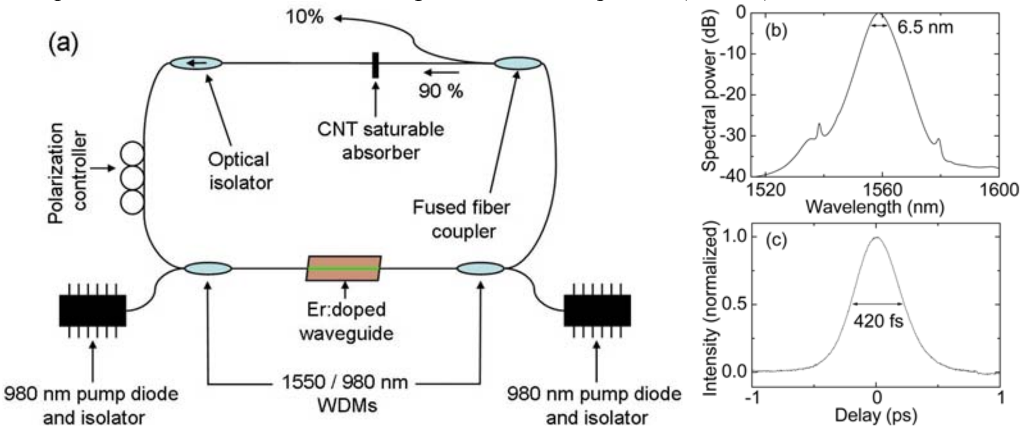

Figure 1 (a) Schematic diagram of the mode-locked waveguide laser cavity. (b) Optical spectrum of the mode-locked laser output (c) An autocorrelation of the output from the mode-locked laser assuming a $sech^2$ pulse shape.

Continuous wave (CW) oscillation started upon the application of 220 mW of counter-propagating pump power and 70 mW of co-propagating pump power. Self–starting single-pulse mode-locking initiated when the co-propagating pump was increased to 80 mw, with no Q-switching instabilities observed. The average output power increased with co-propagating pump power up to 0.5 mW of mode-locked output for 105 mW of co-propagating and 220 mW counter-propagating pump power. Although considerably more pump power was available, we did not attempt to exceed the 0.5 mW output power to avoid damage to the CNT-polymer composite. Fig. 1(b) plots the output optical spectrum with central wavelength ≈ 1560 nm and full-width at half maximum bandwidth of 6.5 nm. As shown in Fig. 1(c), an autocorrelation measurement yielded a pulse duration of 420 fs, assuming a $sech^2$ temporal profile, close to the bandwidth limit of 395 fs. A fast photo-diode and RF spectrum analyzer confirmed pulsing at a repetition rate of 39 MHz.

4. Conclusions

We have demonstrated a ULI fabricated, mode-locked waveguide laser producing 420 fs pulses with a full-width at half maximum spectral width of 6.5 nm. We believe this work will pave the way to compact, high-efficiency and high repetition-rate mode-locked lasers using the two novel technologies of ULI and CNT based saturable absorbers.

5. References

[1] K. M. Davis et al., "Writing waveguides in glass with a femtosecond laser," Opt. Lett. **21**, 1729-1731 (1996)
[2] G. Della Valle, et al., "C-band waveguide amplifier produced by femtosecond laser writing," Opt. Express **13**, 5976-5982 (2005)
[3] R. R. Thomson et al. " Ultrafast Laser Inscription of a High Gain Er-doped Bismuthate Glass Waveguide Amplifier," in *Advanced Solid-State Photonics*, OSA Technical Digest Series (CD) (Optical Society of America, 2010), paper AWB7.
[4] G. Della Valle et al., "Passive mode locking by carbon nanotubes in a femtosecond laser written waveguide laser," Appl. Phys. Lett. **89**, 231115 (2006)
[5] F. M. Bain et al., "Ultrafast laser inscribed Yb:KGd$(WO_4)_2$ and Yb:KY$(WO_4)_2$ channel waveguide lasers," Opt. Express **17**, 22417-22422 (2009)
[6] F. Wang et al., "Wideband-tuneable, nanotube mode-locked, fibre laser," Nat. Nanotechnol. **3**, 738-742 (2008).
[7] V. Scardaci et al., "Carbon Nanotube Polycarbonate Composites for Ultrafast Lasers." Adv. Mater. **20**, 4040-4043 (2008).
[8] E. J. R. Kelleher et al., "Nanosecond-pulse fiber lasers mode-locked with nanotubes," Appl. Phys. Lett. **95**, 111108 (2009).
[9] Z. Sun et al., "L-band ultrafast fiber laser mode locked by carbon nanotubes." Appl. Phys. Lett. **93**, 061114 (2008).
[10] T. Hasan et al., "Nanotube-Polymer Composites for Ultrafast Photonics," Adv. Mater. **21**, 3874-3899 (2009).

6. Acknowledgements

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