320 fs pulse generation from an ultrafast laser inscribed waveguide laser mode-locked by a nanotube saturable absorber

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Ultrafast laser inscription is used to fabricate the gain element for a mode-locked Er-doped bismuthate glass waveguide laser. Mode-locking is initiated and stabilized by the use of a single wall carbon nanotube saturable absorber. The waveguide laser produces 320 fs pulses at 1.56 μm with a pulse repetition rate of 40 MHz and average output power of 1.25 mW. © *2010 American Institute of Physics*. [doi:10.1063/1.3486177]

The research and development of Er-doped waveguide lasers is receiving great interest.[1–3] Waveguide-based devices such as these can offer increasing levels of integration with ever decreasing footprints, in contrast to more established optical fiber-based devices.[1] Ultrafast laser inscription (ULI) is a highly flexible waveguide fabrication technique that uses focused ultrashort pulses of sub-bandgap light to directly write waveguides inside a substrate material.[4] ULI is now readily applicable to a range of amorphous and crystalline materials including laser glasses.[5–11]

References 5–9 presented the early results on Er-doped ULI waveguide lasers. Reference 5 demonstrated a laser incorporating a ULI device as the gain element in a fiber cavity, while Reference 6 mode-locked a ULI fabricated waveguide laser. Reference 7 reported a single longitudinal mode laser using a pair of narrow-bandwidth fiber Bragg gratings (FBG) either side of a ULI fabricated gain element.[7] Reference 8 went on to transfer this approach to an Er-doped oxyfluoride silicate glass, thereby achieving lasing from a ULI device in a non-phosphate glass. Reference 9 increased the level of integration, eliminating the requirement for additional FBGs or mirrors, by inscribing a Bragg grating directly into the gain medium, producing a monolithic distributed feedback (DFB) waveguide laser.

In addition to the work on ULI in amorphous materials, a number of groups have also used this technique to fabricate waveguides in crystalline gain media. Reference 10 reported a neodymium doped yttrium aluminum garnet (Nd:YAG) ceramic waveguide laser with a 60% slope efficiency, which relied on the Fresnel reflections from the ceramic/air boundary to provide the optical feedback. More recently, Reference 11 demonstrated laser action from ULI fabricated waveguides in $Yb:KGd(WO_4)_2$ and $Yb:KY(WO_4)_2$.

Single wall carbon nanotubes (SWNTs)[12–22] and graphene[12,13] are promising saturable absorbers (SAs) for mode-locking fiber,[12–17] waveguide,[6] solid-state,[23] and semiconductor lasers.[24] They have several advantages over the more established semiconducting SA mirrors (SESAMs), including low saturation fluence, ultrafast recovery time, wavelength tunablity, and ease of fabrication, with no need for complex processes, such as molecular beam epitaxy and ion implantation[22–24]

Here, we present ultrafast pulse generation from a mode-locked Er-doped waveguide laser fabricated using ULI. Our waveguide laser is mode-locked using SWNTs and produces 320 fs pulses with 1.25 mW average power.

The glass substrate material is an Er-doped bismuthate glass (Er-BG) containing in excess of 70 wt % Bi_2O_3 and doped with 0.63 wt % Er (Asahi Glass Co., Japan). Bismuthate glass is selected as the waveguide substrate, because it can be highly doped with Er-ions, thus it can provide high gain efficiency[25] and its wide-band emission spectrum favors ultrafast pulse generation.[26] Waveguides are inscribed in the 90 mm sample of the Er-BG using a custom designed, variable repetition-rate master-oscillator power-amplifier (MOPA) ultrafast fiber laser system (Fianium Ltd, UK). For this work, the repetition rate of the laser is set to 500 kHz and the pulse duration measured to be ≈350 fs at the full width at half maximum (FWHM). The central wavelength of the inscription laser is 1064 nm and the polarization is adjusted to be circular. The pulse train is focused to a spot ≈200 μm below the surface of the Er-BG sample using a 0.4 NA aspheric lens. The sample is translated through the focus in the axis perpendicular to the laser propagation direction using computer controlled Aerotech x-y-z air-bearing stages. The waveguide cross-section is controlled using the multiscan fabrication technique.[8] Consequently, the waveguide is inscribed by translating the material through the laser focus 20 times, with each scan separated by 0.4 μm in the axis perpendicular to both the waveguide and the laser beam propagation axes. The waveguide we use here is inscribed with a laser pulse energy of 133 nJ and a sample translation speed of 1.0 $mm\cdot s^{-1}$. After inscription, the sample is ground and polished at a 3.0° angle to reduce back-reflections, resulting in a final waveguide length of 87 mm.

The passive and active properties of the inscribed waveguide were investigated extensively.[26] When coupled to OFS Clearlight 980 16 high numerical aperture coupler fiber, the waveguide exhibits a fiber-to-fiber insertion loss of 4.0 dB at 1618 nm, outside the Er^{3+}-ion absorption band. This consists of a ≈0.9 dB per facet coupling loss and a ≈2.0 dB propagation loss. The polarization dependent loss of the waveguide (with no pump applied) is 0.3 dB at 1533 nm. Upon

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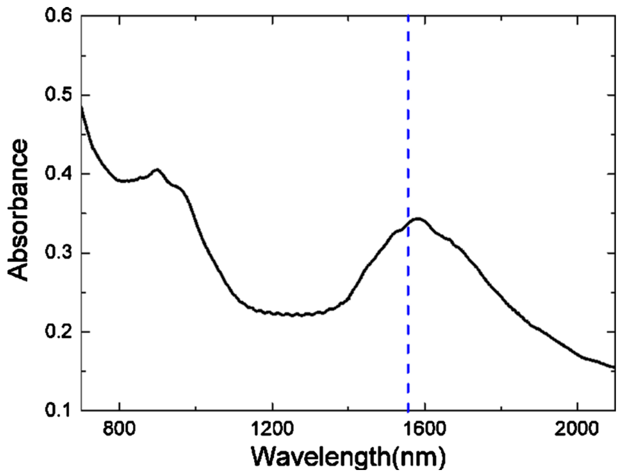

FIG. 1. (Color online) Absorption spectrum of the SWNT composite. The operation wavelength is indicated by a dashed vertical line.

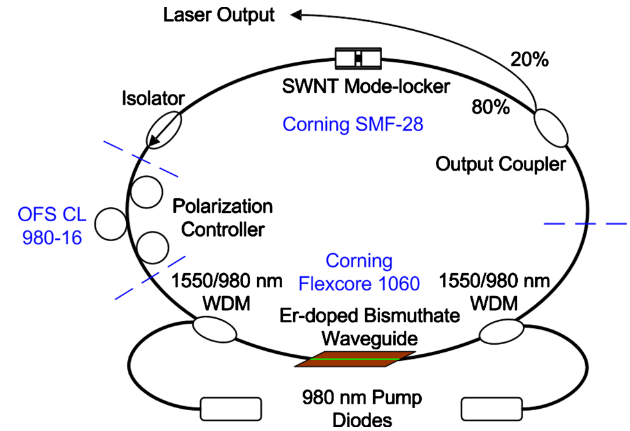

FIG. 2. (Color online) Schematic of the mode-locked laser, with fiber type for each section. WDM denotes wavelength division multiplexer.

the application of ≈1.0 W of 980 nm pump, the amplifier displays a peak fiber-to-fiber net gain of 16.0 dB at 1533 nm, with a polarization dependence of 0.6 dB. Net gain is observed from 1505 to 1565 nm with over 9.0 dB net gain across the optical communication C-band, from 1530 to 1565 nm.

For photonic applications, SWNT-polymer composite fabrication through nonaqueous dispersion is important to avoid moisture absorption by the host polymer.[15,18,27] Here, the preparation of the SWNT-based SA first involves exfoliation of the SWNT bundles (0.05 wt %) by strong ultrasonication (Branson 450A, 20 kHz) in ortho-dichlorobenzene (o-DCB). The SWNTs are grown by laser ablation[28] and purified.[29] The diameter distribution is controlled by changing the growth temperature.[28] Poly-3-hexylthiophene polymer (0.06 wt %) is used as the dispersant to prevent reaggregation. After ultrasonication, large unexfoliated bundles and catalyst particles are removed by ultracentrifugation in a Beckman Coulter Optima Max E centrifuge at 800 000 g for 3 h. The upper 90% of the supernatant is then collected, filtered through a 1 μm glass fiber filter (Millipore) and then sonicated with 120 mg of polycarbonate pellet (Apec 1600) for 1 h. Polycarbonate is used as a host polymer due to its high transparency at 1.5 μm.[15] The mixture is then drop-cast in a petri dish and left in a vacuum chamber at room temperature. Slow evaporation of o-DCB results in 30 μm thick SWNT composites. The absorption peak of the SWNT composite is ≈1600 nm, as shown in Fig. 1, corresponding to the first optical transition in semiconducting tubes.[30]

A fiber ring cavity is constructed around the Er-BG waveguide amplifier, as shown in Fig. 2. The optical isolator ensures unidirectional operation. Mode-locking is initiated and stabilized by the SWNT based SA sandwiched between two fiber connectors with physical contact (FC/PC). Output coupling is achieved using a broadband 80:20 fused fiber coupler (JDS uniphase), placed before the SWNT-SA, helping to reduce the average power reaching the SA. The pump light is delivered to the waveguide amplifier via two fused fiber wavelength division multiplexers (WDMs). The cavity also contains 239 cm of Corning SMF-28, 112 cm of Corning Flexcore 1060, 152 cm of OFS Clearlight 980 16 and the 87 mm Er-doped bismuthate waveguide. The linear dispersions of these components at 1560 nm are estimated by their manufacturers to be 17.9 ps/nm·km, 8.0 ps/nm·km, −1.0 ps/nm·km, and −120 ps/nm·km, respectively,[31–34] resulting in a net cavity dispersion of 40±2 fs/nm (−0.051 ps^2). This anomalous net cavity dispersion enables soliton mode-locking.

Under the application of 130 mW of co-propagating and 220 mW of counter-propagating 980 nm pump light, the laser produces an average mode-locked output power of 1.25 mW. A fast photodiode and RF spectrum analyzer confirm a 40 MHz pulse repetition frequency, corresponding to a 31 pJ pulse energy, with no Q-switching instabilities observed. The laser output is coupled into an autocorrelator with the intracavity fiber polarization controller adjusted to minimize the duration of the pulses. Fig. 3 plots an interferometric autocorrelation, and the inferred intensity autocorrelation. From Fig. 3, a 320 fs FWHM pulse duration is deduced, assuming a $Sech^2$ temporal pulse profile, consistent with soliton mode locking stabilized by a SA. Autocorrelations taken over the period of the study shows no change in pulse duration. The peak wavelength of the laser radiation is 1560 nm with a spectral FWHM of 8.9 nm, yielding a time bandwidth product (TBP) of 0.351. This is close to the 0.315 TBP expected for transform limited $Sech^2$ pulses. The small discrepancy between theoretical and experimentally measured TBPs can be accounted for by dispersion from the ≈0.8 m length of SMF-28 between the cavity and the autocorrelator.

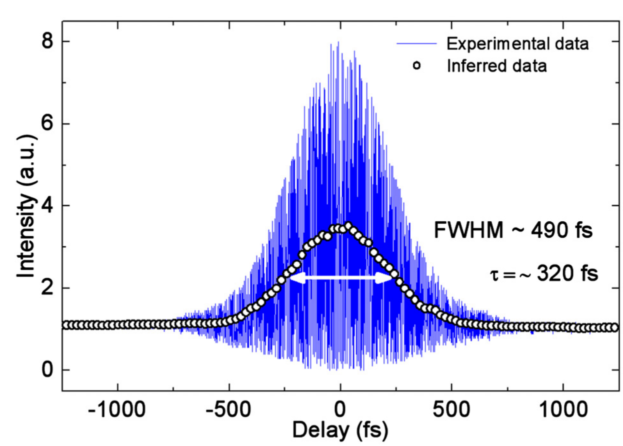

FIG. 3. (Color online) Interferometric autocorrelation (line) and the inferred intensity autocorrelation (circles) of the laser output.

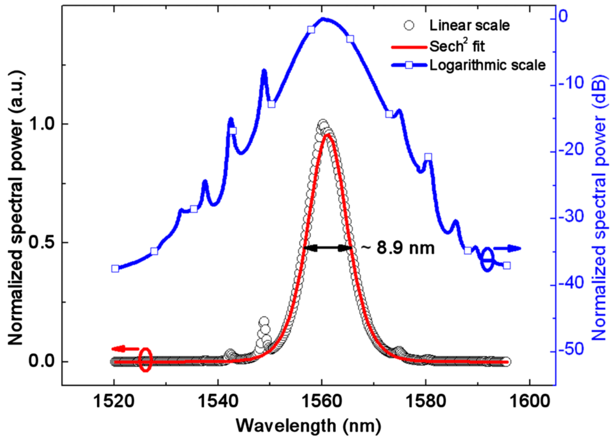

FIG. 4. (Color online) Optical spectra of the output from the laser in a logarithmic scale (squares), and in a linear scale (circles) with the Sech[2] fit (line). The Sech[2] curve is fitted with the sidebands masked.

Strong spectral sidebands are visible in the optical spectrum produced by the laser, Fig. 4. These result from the loss, gain, and dispersion characteristics of the cavity components shedding dispersive waves from the soliton-like cavity pulse.[35,36] Over multiple round trips the components of the dispersive wave resonant with the soliton-like pulse can be enhanced. This phase-matching between the dispersive wave and the nondispersive pulse allows us to estimate the total cavity dispersion based on the offset of the spectral sidebands.[37] Assuming the pulse is bandwidth-limited within the cavity, and ignoring any dispersive terms above the second order, the total dispersion is estimated to be 42 ± 2 fs/nm (0.054 ps^2), in excellent agreement with the cavity dispersion calculated from the characteristics of the optical fibers and substrate given by the manufacturers.[31–34]

In conclusion, we demonstrated subpicosecond pulsed operation of a passively mode-locked waveguide laser fabricated using ULI. Self-starting, single pulse mode-locking was facilitated by the use of a SWNT-SA. The laser produces 320 fs pulses at 1.56 μm at a repetition rate of 40 MHz. The maximum average output power is 1.25 mW. This work, in combination with the ever increasing fabrication capabilities of ULI, will pave the way for low cost, robust, high repetition rate ultrafast laser sources required for spectrometry, and future generation telecoms networks.

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