320 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 sub-picosecond modelocked pulses from an ultrafast laser inscribed Er-doped waveguide laser. 320 fs pulses at a repetition rate of 40 MHz and energy of 31 pJ were facilitated via passive modelocking by a carbon nanotube saturable absorber.**

Keywords-component; waveguide devices; ultrafast optics

I. INTRODUCTION

The intensities attainable in the focal region of tightly focused ultrafast lasers can be used to locally modify the structure of transparent materials. These structural changes manifest themselves in a variety of ways, one example of which may be a refractive index modification. This refractive index modification can be used to inscribe optical waveguides by translating the material through the focus [1]. This technique is known as ultrafast laser inscription (ULI). ULI is attracting considerable research interest, one particularly exciting area of which is the development of active optical devices, including waveguide amplifiers [2,3] and waveguide lasers [4,5].

The emphasis of many research groups now is in the optimization of these devices, increasing the output powers and range of wavelengths over which they operate. There is also an interest in developing Q-switched and mode-locked waveguide lasers. To date there has been only one successful report of a ULI-fabricated mode-locked waveguide laser [4]. This laser produced 1.6 ps pulses, however the round trip net gain of the cavity was insufficient for femtosecond pulse generation. Here we report on a high gain ULI fabricated Er-doped bismuthate glass waveguide amplifier used in conjunction with a carbon nanotube (CNT) saturable absorber for the generation of 320 fs pulses.

II. 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. 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 (FWHM). 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 cross section of the waveguide was controlled using the multiscan fabrication technique [3] with each waveguide fabricated using 20 scans of the substrate through the laser focus, with each scan separated by 0.4 μm. The optimum waveguide was inscribed using 133 nJ pulses and a translation speed of 1.0 $mm.s^{-1}$. To reduce back reflections the sample was ground and polished at an angle of 3.0° to the waveguide axis, leaving the final waveguide 87.0 mm long.

Prior to constructing a laser cavity, the performance of the optimum waveguide was characterized. The passive performance was assessed by measuring the fiber-to-fiber insertion loss outside the Er^{3+} absorption band at a wavelength of 1618 nm. The waveguide exhibited a background insertion loss of 4.0 dB when coupled to OFS Clearlight 980-16 coupler fiber. 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.

III. 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. The pump light is delivered to the waveguide amplifier via two fused fiber wavelength division multiplexers (WDMs). Mode-locking is initiated by a well developed CNT-polymer composite saturable absorber [6-10], which is sandwiched between 2 FC/PC fiber connectors. The optical isolator ensures unidirectional operation, reducing instabilities caused by reflections. Output coupling is achieved using a broadband 80:20 fused fiber directional coupler.

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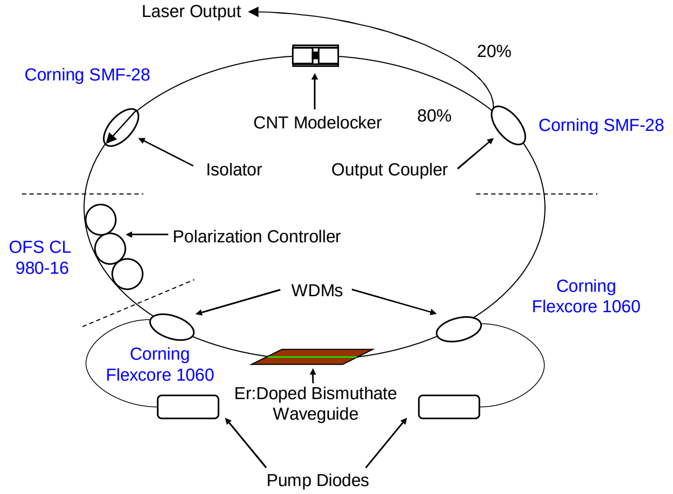

Figure 1. Schematic of the modelocked waveguide laser cavity

Under application of 130 mW of co-propagating and 220 mW of counter-propagating pump, the laser produced an average output power of 1.25 mW. A fast photodiode and RF spectrum analyzer confirmed a pulse repetition frequency of 40 MHz with no Q-switch instabilities observed. Greater pump power was available but previous studies had shown degradation of the polymer host of the saturable absorber for average powers greater than 5 mW. The laser output was coupled into a non-linear autocorrelator and the fiber polarization controller adjusted to minimize the duration of the pulse. Fig. 2 is a plot of the interferometric autocorrelation with the inferred intensity autocorrelation. From Fig.2, a pulse duration of 320 fs FWHM is derived assuming a $Sech^2$ temporal pulse profile consistent with soliton modelocking stabilized by a saturable absorber. Figure 3 plots the optical spectrum of the laser radiation, the central wavelength was 1560 nm with a spectral FWHM of 8.9 nm yielding a time bandwidth product of 0.351 close to the 0.315 expected for transform limited $sech^2$ pulses. The discrepancy can be accounted for by dispersion from the ~0.8 m piece of SMF-28 between the cavity and the autocorrelator.

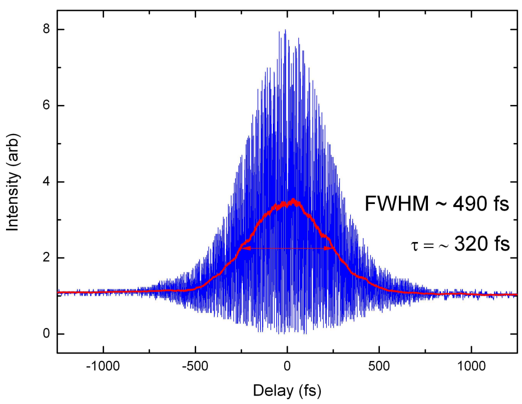

Figure 2. An interferometric autocorrelation of the output from the laser (Blue), with inferred intensity autocorrelation (Red).

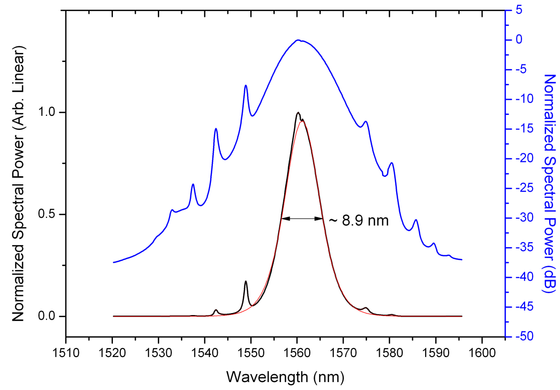

Figure 3. Optical spectrum of the modelocked waveguide laser, linear (Black) with $Sech^2$ fit (Red), and logarithmic (Blue).

IV. Conclusions

We have demonstrated a ULI fabricated, mode-locked waveguide laser producing 320 fs pulses with a FWHM spectral width of 8.9 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.

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