Passive mode locking by carbon nanotubes in a femtosecond laser written waveguide laser

Giuseppe Della Valle,[a] Roberto Osellame, Gianluca Galzerano, Nicola Chiodo, Giulio Cerullo, Paolo Laporta, and Orazio Svelto
Istituto di Fotonica e Nanotecnologie-CNR, ULTRAS-INFM-CNR, Dipartimento di Fisica, Politecnico di Milano, Piazza Leonardo da Vinci, 32, 20133 Milan, Italy

Uwe Morgner
Institut für Quantenoptik, University of Hannover, Welfengarten 1, Hannover D-30167, Germany

A. G. Rozhin, V. Scardaci, and A. C. Ferrari
Engineering Department, Cambridge University, 9 JJ Thompson Avenue, Cambridge CB3 0FA, United Kingdom

(Received 11 July 2006; accepted 29 October 2006; published online 7 December 2006)

The authors report on the first demonstration of mode locking in an active waveguide laser manufactured by femtosecond laser writing. The active waveguide is fabricated in an Er–Yb-doped phosphate glass, and the mode locker is a fiber-pigtailed saturable absorber device based on single-wall carbon nanotubes specially designed to efficiently operate at 1.5 μm. Transform-limited 1.6 ps pulses were observed in a ring laser cavity configuration. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2403912]

Recently, a great effort has been devoted to passive mode locking of waveguide lasers, because of their inherent simplicity and compactness with respect to fiber lasers.[1,2] Er–Yb-doped glass waveguides can, in fact, generate large gains (2–4 dB/cm) over short lengths, thus allowing compact cavities and high repetition rate operation without the need of harmonic mode locking with its associated instabilities. Such lasers will provide low-noise and inexpensive light sources for applications in optical communications, optically sampled analog-to-digital converters,[3] and in spectral line-by-line pulse shaping for arbitrary optical wave form synthesis.[4]

An innovative technology for fabrication of optical waveguides is the direct writing by femtosecond laser pulses.[5] This is a simple and low cost technique that avoids any photolithographic process and allows three-dimensional fabrication. In the last few years, the quality of femtosecond laser written waveguides has shown a substantial improvement, culminating in the demonstration of a cw waveguide laser.[6] The next challenge consists in short pulse generation and passive mode locking using saturable absorbers appears to be the most promising solution.[7]

Classically, semiconductor saturable absorber mirrors are employed for passive mode locking of lasers.[8] Recently, a new technology based on carbon nanotubes (CNTs) has emerged as an alternative for the realization of saturable absorbers. CNTs show strong saturable absorption with ultrafast recovery,[9] polarization insensitivity, and high optical damage threshold;[10] in addition, the possibility to tune their band gap in the near IR spectral range by selecting the appropriate diameter distribution makes them attractive for applications as photonic switches.[11] Finally, they can be easily and cheaply assembled into polymer composites, allowing their integration into optical fiber communication systems. These characteristics make them ideally suited as saturable absorbers.[12] In this letter we report on the first demonstration of a mode-locked laser based on a femtosecond laser written waveguide. The laser operates at 1.5 μm and passive mode locking is obtained by means of a specially designed CNT saturable absorber, providing 1.6 ps transform-limited pulses at 16.7 MHz repetition rate.

Direct waveguide writing is accomplished by a diode-pumped cavity-dumped femtosecond Yb:KYW oscillator, operating at 1040 nm wavelength,[13] with 885 kHz repetition rate, 250 nJ pulse energy, and 350 fs pulse duration. The substrate is a commercial phosphate glass (QX from Kigre, Inc.) doped with 2 wt % of Er_2O_3 and 4 wt % of Yb_2O_3. A very high numerical aperture objective (100× oil immersion, 1.4 numerical aperture) is used to focus the femtosecond pulses 170 μm inside the glass. A transverse writing configuration, i.e., with the sample translated in a direction perpendicular to the laser beam, is implemented with motorized stages at a translation speed of 50 μm/s. Both end facets of the waveguides are polished after laser inscription. The writing parameters are optimized to obtain the best waveguide performance in terms of insertion losses.

The 36-mm-long waveguide employed in this work shows insertion losses of 1.9 dB when coupled to standard single mode fibers. The losses were measured at 1600 nm wavelength, outside the erbium absorption band. From near-field measurements of waveguide and fiber modes, the coupling losses are estimated to be ~0.25 dB/facet, and, consequently, propagation losses are evaluated to be of the order of 0.4 dB/cm. Previous gain measurements performed at 1.5 μm (Ref. 14) showed net gain in the whole *C* band, with 7.3 dB peak value at 1535 nm for an incident pump power of 460 mW.

Figure 1 shows a schematic of the mode-locked waveguide laser in a ring cavity configuration. Two 976 nm laser diodes, providing 480 mW total incident power, are coupled to the waveguide in a bipropagating pumping scheme by means of wavelength division multiplexers (WDMs). A broadband fiber coupler is used to couple 5% of the intrac-

[a]Electronic mail: giuseppe.dellavalle@polimi.it

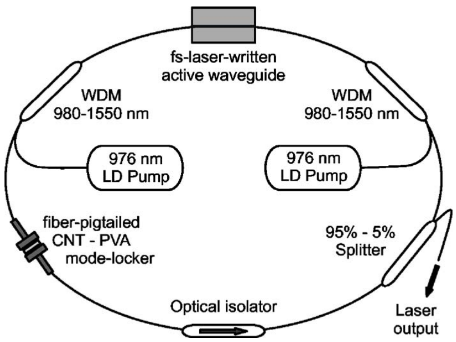

FIG. 1. Schematic setup of the ring laser cavity configuration.

avity radiation out of the ring resonator. Unidirectionality of the ring is imposed by an optical isolator, which also prevents mode-locking instabilities caused by back reflections. An index matching fluid is applied between the waveguide and fiber end facets, thus preventing Fabry-Pérot filtering effects, which could reduce the oscillating bandwidth. The mode locker is a single-wall CNT-spolymer film saturable absorber, packaged by sandwiching the film in the fiber-pigtailed FC/PC connector with index matching fluid at both fiber ends (see Fig. 1). The CNTs are produced by laser ablation.[15] High-power ultrasonication (Bioruptor, Diagenode) is utilized to disperse purified CNTs in water by using sodium dodecylbenzene sulphonate surfactant. The residual CNT bundles are removed by microfiltration. The resulting solution is then mixed with polyvinyl alcohol (PVA) and dried at room temperature to obtain a freestanding film with a thickness of $\sim 50\ \mu$m. The absorbance spectrum of the film is shown in Fig. 2: it has a broadband centered at $\sim 1.5\ \mu$m, with peak absorbance of about 0.36 (corresponding to 1.52 dB absorption, of which 0.6 dB is saturable). Such film has high laser damage threshold (more than 600 MW/cm^2) and a saturation intensity of about 80 MW/cm^2. A recovery time lower than 1 ps is reported for CNT-polymide composites.[9]

Figure 3(a) shows the laser output spectrum recorded with an optical spectrum analyzer (0.1 nm resolution bandwidth). Continuous wave laser action starts at 450 mW incident pump power. Self-starting single-pulse stable mode locking is observed just above laser threshold. No self-*Q*-switching instabilities are observed and the mode-locking regime is stable for several hours. The laser output power is measured to be ~ 0.1 mW. Such a low value is due to the relatively high insertion losses along the ring cavity. In addition to the CNT-PVA film absorption, the packaging of the

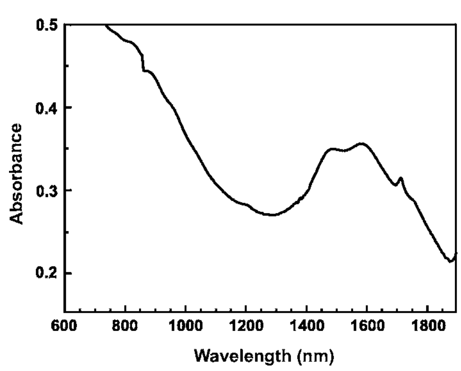

FIG. 2. Optical absorbance of the CNT-PVA film.

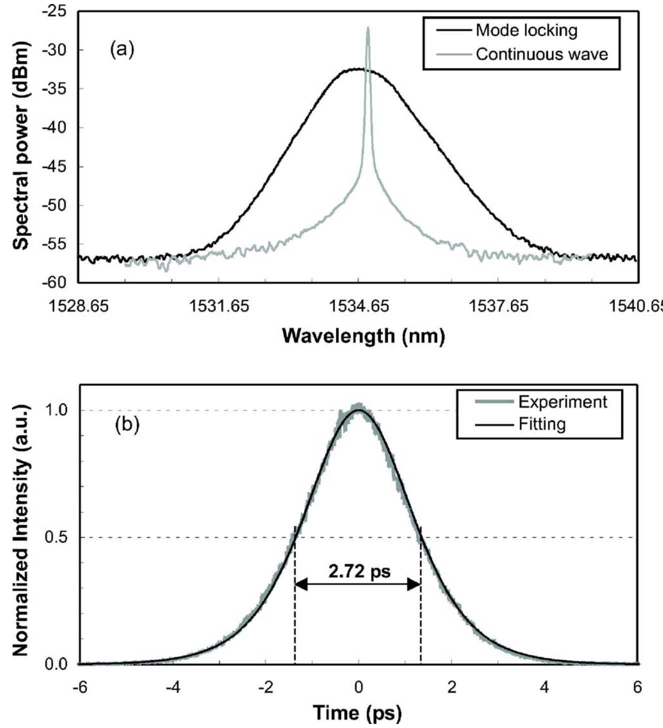

FIG. 3. (a) Laser output spectrum in continuous wave and mode-locking regimes. (b) Autocorrelation trace of the mode-locking pulse.

fiber-pigtailed mode locker is responsible for 2.8 dB extra losses, bringing the measured nonsaturated insertion loss to about 4.3 dB. Taking into account WDMs and optical isolator insertion losses (1.7 dB), and cavity output coupling (0.22 dB), the overall ring cavity losses amount to 6.2 dB, rather close to the net gain obtained in the waveguide.

The laser central wavelength in the mode-locking regime is 1535 nm, and the full width at half maximum (FWHM) is 1.6 nm, corresponding to $\Delta\nu = 204$ GHz. The pulse shape was investigated by a noncollinear autocorrelator, and the pulse autocorrelation trace is reported in Fig. 3(b). The experimental trace is well fitted considering a sech^2 pulse as expected from saturable absorber passive mode-locking theory.[7] The autocorrelation trace FWHM was measured to be 2.72 ps, corresponding to a pulse duration $\Delta\tau = 1.76$ ps. Taking into account the dispersion introduced by the 6 m standard single mode fiber connecting the laser to the autocorrelator (16 ps $nm^{-1}\ km^{-1}$), the pulse duration at the output of the laser is $\Delta\tau_p = 1.60$ ps, resulting in a time bandwidth product $\Delta\tau_p \Delta\nu = 0.329$, in fairly good agreement with the 0.315 value for transform-limited sech^2 pulses. The pulse duration is in good agreement with that calculated from soliton mode-locking theory considering that the overall intracavity dispersion amounts to $-0.12\ ps^2$.[7] The repetition rate of the current cavity is 16.74 MHz. Note that a much higher repetition rate can be obtained using a linear cavity configuration where the saturable absorber is directly placed on the waveguide facet. As an example, according to the saturation intensity of the nanotube absorber, 1 GHz operation could be feasible with an intracavity average power of about 100 mW. Such a power level was already demonstrated in similar waveguide lasers operated in cw.[6]

To investigate the stability of the pulse train, we measured the radio-frequency spectrum of the pulses around the eighth harmonic of the repetition rate (133.89 MHz) by

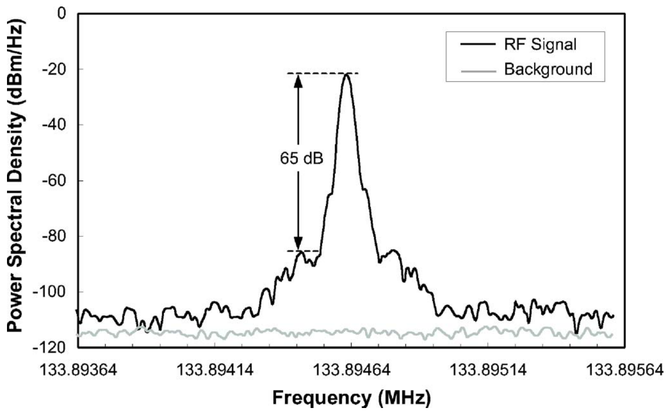

FIG. 4. rf spectrum of the mode-locking pulses measured at around the eighth harmonic of the repetition rate. Resolution bandwidth is 18 Hz; jitter measurement bandwidth is 700 Hz.

means of a fast photodiode (250 MHz bandwidth) connected to an electrical spectrum analyzer. Figure 4 shows the signal spectrum together with the noise background due to photodetector thermal noise. A carrier-to-noise ratio of 65 dB indicates a low relative timing jitter $\Delta t/T$ (with T being the train period); following the method reported in Ref. 16 we estimated $\Delta t/T \simeq 3\times 10^{-4}$, corresponding to a jitter $\Delta t = 19$ ps.

In conclusion, we demonstrated passive mode locking of a waveguide laser manufactured by direct femtosecond laser writing using a specially designed fiber-pigtailed CNT-PVA saturable absorber. Our work expands the capability of femtosecond laser writing towards manufacturing of complex photonic devices. An upgraded version of this technology, whereby a CNT absorber is incorporated into a monolithic laser structure, could provide very compact mode-locked laser sources with repetition rates in the 1–3 GHz range. Moreover, by reducing intracavity losses and optimizing dispersion, it should be possible to exploit the whole Er gain bandwidth and achieve femtosecond operation.

The authors wish to thank G. Lanzani for useful discussion. Three of the authors (A.G.R., V.S., and A.C.F.) acknowledge funding from EPSRC Grant No. GR/S97613/01 and from Advance Nanotech Inc. A.C.F. acknowledges funding from The Royal Society and from The Leverhulme Trust. U.M. acknowledges support from the European Community Access to research infrastructure action, contract R113-CT-2003-506350 (Centre for Ultrafast Science and Biomedical Optics).

[1] E. R. Thoen, E. M. Koontz, D. J. Jones, D. Barbier, F. X. Kaertner, E. P. Ippen, and L. A. Kolodziejski, IEEE Photonics Technol. Lett. **12**, 149 (2000).
[2] J. B. Schlager, B. E. Callicoatt, R. P. Mirin, N. A. Sanford, D. J. Jones, and J. Ye, Opt. Lett. **28**, 2411 (2003).
[3] P. W. Juodawlkis, J. C. Twichell, G. E. Betts, J. J. Hargreaves, R. D. Younger, J. L. Wassermann, F. J. O'Donnell, K. J. Ray, and R. C. Williamson, IEEE Trans. Microwave Theory Tech. **49**, 1840 (2001).
[4] Z. Jiang, D. S. Seo, D. E. Leaird, and A. M. Weiner, Opt. Lett. **30**, 1557 (2005).
[5] K. M. Davis, K. Miura, N. Sugimoto, and K. Hirao, Opt. Lett. **21**, 1729 (1996).
[6] R. Osellame, N. Chiodo, G. Della Valle, G. Cerullo, R. Ramponi, P. Laporta, A. Killi, U. Morgner, and O. Svelto, IEEE J. Sel. Top. Quantum Electron. **12**, 277 (2006).
[7] F. X. Kaertner, J. Aus der Au, and U. Keller, IEEE J. Sel. Top. Quantum Electron. **4**, 159 (1998).
[8] U. Keller, Nature (London) **424**, 831 (2003).
[9] Y.-C. Chen, N. R. Raravikar, L. S. Shadler, P. M. Ajayan, Y.-P. Zhao, T.-M. Lu, G.-C. Wang, and X.-C. Zhang, Appl. Phys. Lett. **81**, 975 (2002).
[10] A. G. Rozhin, Y. Sakakibara, H. Kaktaura, S. Matsuzaki, K. Ishida, Y. Achiba, and M. Tokumoto, Chem. Phys. Lett. **405**, 288 (2005).
[11] H. Kataura, Y. Kumazawa, Y. Maniwa, I. Umezu, S. Suzuki, Y. Ohtsuka, and Y. Achiba, Synth. Met. **103**, 2555 (1999).
[12] T. R. Schibli, K. Minoshima, H. Kataura, E. Itoga, N. Minami, S. Kazaoui, K. Miyashita, M. Tokumoto, and Y. Sakakibara, Opt. Express **13**, 8025 (2005).
[13] R. Osellame, N. Chiodo, G. Della Valle, S. Taccheo, R. Ramponi, G. Cerullo, A. Killi, U. Morgner, M. Lederer, and D. Kopf, Opt. Lett. **29**, 1900 (2004).
[14] G. Della Valle, R. Osellame, N. Chiodo, S. Taccheo, G. Cerullo, P. Laporta, A. Killi, U. Morgner, M. Lederer, and D. Kopf, Opt. Express **13**, 5976 (2005).
[15] S. Lebedkin, P. Schweiss, B. Renker, S. Malik, F. Hennrich, M. Neumaier, C. Stoermer, and M. M. Kappes, Carbon **40**, 417 (2000).
[16] D. von der Linde, Appl. Phys. B: Photophys. Laser Chem. **39**, 201 (1986).