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# Carbon nanotubes mode-lock a laser-written waveguide laser

**Giuseppe Della Valle, Roberto Osellame, Giulio Cerullo, Paolo Laporta, Uwe Morgner, Aleksey G. Rozhin, and Andrea C. Ferrari**

*Femtosecond laser writing and films of carbon nanotubes combine to create a 1.5μm mode-locked waveguide laser that provides 1.6ps pulses.*

Recently, great effort has been devoted to developing waveguide lasers able to provide ultrashort light pulses because of their inherent simplicity and compactness compared with fiber lasers.[1,2] Because erbium:ytterbium (Er:Yb)-doped glass waveguides can generate large gains (2–4dB/cm) over short lengths, they can be used to make lasers with compact cavities and high repetition rates. Such lasers will provide inexpensive low-noise light sources for applications in optical communications, in optically sampled analog-to-digital converters,[3] and in arbitrary optical waveform synthesis.[4]

The technique of passive mode locking that employs semiconductor saturable-absorber mirrors is widely used to generate picosecond and femtosecond laser pulses.[5] Recently, however, a new technology for making saturable absorbers has emerged, based on carbon nanotubes (CNTs). CNTs show strong and tunable saturable absorption in the near IR and ultrashort recovery time.[6] They also can be cheaply assembled into polymer composites and easily integrated into optical fiber communication systems. We have made a femtosecond-laser-written waveguide laser that operates in the very stable passive mode-locking regime by means of an innovative saturable absorber based on CNTs.

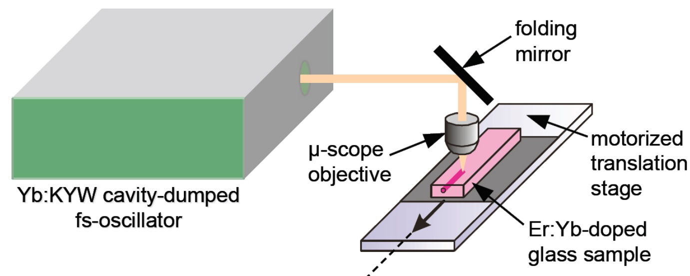


***Figure 1.*** *The writing system for waveguide manufacturing holds the beam from the laser steady while a translation stage moves the glass sample. Yb:KYW: Ytterbium-doped potassium yttrium tungstate. Er:Yb: Erbium:ytterbium.*

**Active waveguide and the CNT mode locker**

We used an innovative diode-pumped femtosecond oscillator, operating at a wavelength of 1040nm with a 350fs pulse duration to write the waveguide in an Er:Yb-doped phosphate glass (2% wt. of $Er_2O_3$ and 4% wt. of $Yb_2O_3$).[7] A high-numerical-aperture objective focuses the femtosecond pulses inside the glass. We implemented a transverse writing configuration in which motorized stages translated the sample perpendicular to the laser beam at 50–100μm/s (see Figure 1). We adopted an optimized set of writing parameters (885kHz repetition rate, 250nJ energy per pulse) to fabricate a 36mm-long waveguide. Insertion losses from this waveguide to standard telecommunications fibers were as low as 1.9dB.

CNTs are produced by laser ablation.[8] We used high-power ultrasonication to disperse purified CNTs in water with sodium dodecylbenzene sulfonate as a surfactant. The residual CNT bundles are removed by microfiltration, and the resulting solution is then mixed with polyvinyl alcohol (PVA) and dried at room temperature to obtain a 50μm-thick freestanding film. The film has a broad absorbance spectrum around 1.5μm—as shown in Figure 2(a)—with a 0.36 peak (i.e., 1.52dB absorption, of which 0.6dB is saturable), a laser damage threshold $>600MW/cm^2$, a saturation intensity of $\sim 80MW/cm^2$, and a recovery time shorter than 1ps. By sandwiching such a film between two FC- or PC-style connectors with index-matching fluid at both fiber ends, we packaged a fiber-pigtailed CNT-PVA mode locker: see Figure 2(b).

**The mode-locked waveguide laser cavity**

Figure 3 shows a schematic of the mode-locked waveguide laser in a ring cavity configuration that incorporates both the 36mm-long active waveguide and the fiber-pigtailed CNT-PVA

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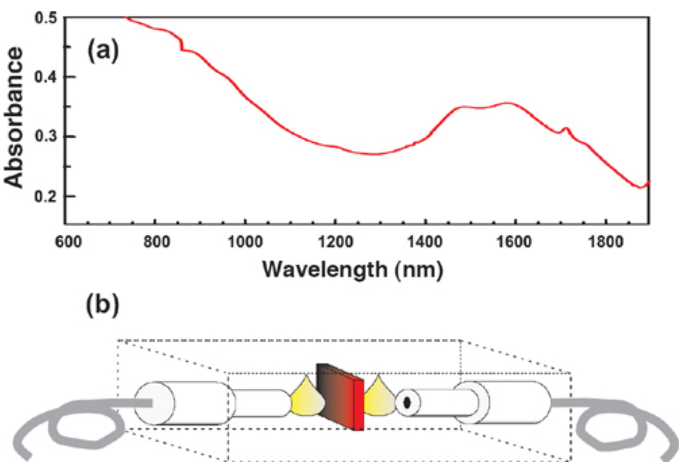


*Figure 2. (a) Absorbance spectrum of the carbon nanotube (CNT) film peaks near 1.5µm. (b) A freestanding film of CNTs (red) is sandwiched between fiber connectors with index-matching fluid (yellow) to create a fiber-pigtailed mode locker.*

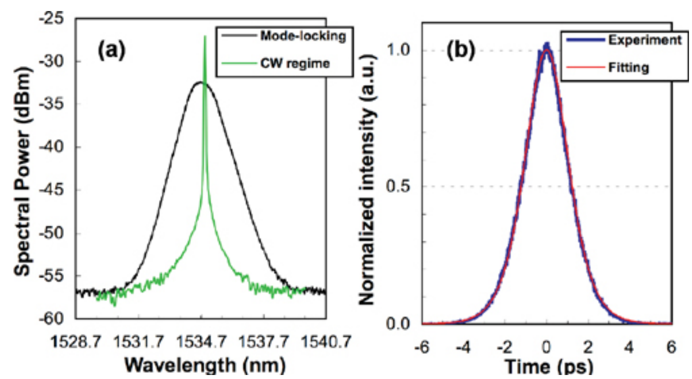


*Figure 4. (a) Laser output spectrum in continuous wave (CW) and mode-locking regimes. (b) Autocorrelation trace of the mode-locking pulse.*

mode locker.[9] Two 976nm laser diodes, which provide a total of 480mW incident power, are coupled to the waveguide in a bi-propagating pumping scheme by wavelength division multiplexers (WDMs). Previous gain measurements on this sample, performed at 1.5µm, showed a net gain in the whole C-band, with a 7.3dB peak value at 1535nm for an incident pump power of 460mW. Five percent of the intracavity radiation is coupled out of the ring resonator. Unidirectionality of light propagation in the ring is imposed by an optical isolator.

Figure 4(a) shows the laser output spectrum. Continuous-wave (CW) laser action starts at 450mW incident pump power, and self-starting single-pulse stable mode locking is observed just above the laser threshold. The laser central wavelength in the mode-locking regime is 1535nm, with an oscillating bandwidth (at –3dB) of 1.6nm. Using an autocorrelator, we estimated the pulse duration to be about 1.6ps, resulting in a time bandwidth product of 0.329, which provides fairly good agreement with the 0.315 value for transform-limited sech (hyperbolic secant)$^2$ pulses. The repetition rate of this cavity was 16.7MHz, but a much higher repetition rate can be obtained using a linear cavity in which the saturable absorber is placed directly on the waveguide facet. As an example, according to the saturation intensity of the nanotube absorber, 1GHz operation could be feasible with an intracavity average power of about 100mW. Such a power level was already demonstrated in similar waveguide lasers operated in CW.[7]

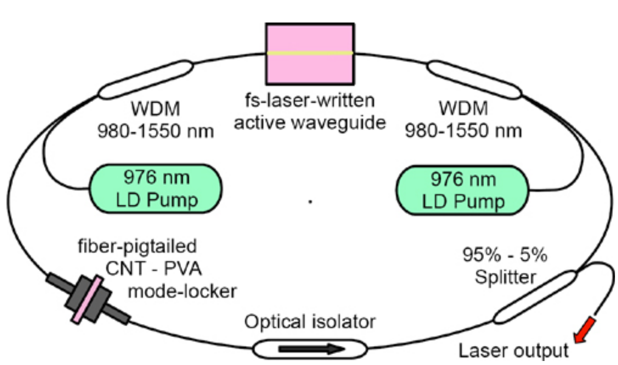


*Figure 3. Experimental setup of the mode-locked waveguide laser uses two laser diodes (LDs) to pump the waveguide. WDM: Wavelength-division multiplexer. CNT-PVA: CNTs mixed with polyvinyl alcohol.*

**Conclusion**

We demonstrated passive mode locking of a femtosecond-laser-written waveguide laser by using a saturable absorber based on CNTs. Our work expands the capability of femtosecond laser writing for manufacturing 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 gigahertz repetition rates.

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