10GHz Short-Cavity Fiber Pulsed Lasers Passively Mode-locked using Carbon Nanotubes

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Abstract: *A fiber pulsed laser with a 1cm cavity length and a 10GHz fundamental repetition-rate is demonstrated using a carbon nanotube-based mode-locker deposited within the laser cavity. This is the shortest fiber mode-locked laser ever reported to date.*

Introduction

Passively mode-locked fiber lasers are attractive alternative to semiconductor-based pulse sources. The long upper-state lifetime of rare-earth-doped fibers and the thermal stability of silica fibers help to reduce laser noise and timing jitters. Fiber compatibility of an all-fiber pulse source will also reduce coupling loss and improve overall power efficiency. The nonlinearity and dispersion properties of the fiber cavity can also be designed and managed for effective pulse shaping for the generation of transform-limited optical pulses. However, one major drawback of fiber pulsed lasers is their relatively long laser cavity in the order of ten's of meters to hundred's of meters, due to the length required for the rare-earth doped fiber gain medium and the lack of a miniature fiber-compatible mode-locker. Higher doping concentration is limited by clustering-induced up-conversion and quenching effects. Standard mode-locking mechanism such as nonlinear loop mirrors, nonlinear polarization evolution requires long length of fibers. On the other hand, semiconductor-based mode-locking mirrors (SBR, SESAM etc.) need free-space optics, which increases cavity length. "Telecom-class" repetition rates in the order of 10GHz will require a fiber laser cavity length of 1cm or shorter. One way to overcome this limitation is to operate a fiber pulsed laser is higher harmonics of its fundamental repetition rate[1]. However harmonically mode-locked lasers with multiple pulses in the cavity have issues such as supermodes and pulse-to-pulse jitter, which will require complex mode suppression and jitter control mechanisms rendering it bulky in size and costly. An elegant solution, in theory, will be to make a 1-cm-short fiber laser cavity, together with a fiber compatible laser mode-locker, operating in a fundamental mode. This have not yet been demonstrated so far due to the extremely stringent constrain in fitting a fiber gain medium and a mode-locker, all within a 1cm cavity length.

Short-cavity fiber Fabry-Perot CW lasers have previously been demonstrated using high-gain Erbium-Ytterbium (Er:Yb) co-doped fibers for single-wavelength [2][3] and multi-wavelength [4] lasing operations. Recently, a single-walled carbon nanotube-based saturable absorber called "Saturable Absorber Incorporating NanoTube" (SAINT) as demonstrated for optical noise suppression of ultrafast optical pulses in the picosecond regime[5]. Subsequently, the first passively mode-locked fiber lasers using SAINT as a mode-locker was demonstrated [6], as well as the first Q-switched laser using SAINT as a Q-switch [7]. In order to avoid confusion, the device which possesses properties optimized for ultra-fast laser mode-locking will be referred to as a MINT, Mode-locker Incorporating NanoTubes. MINT offers many advantages including an ultra-fast recovery time (<1ps) and a simple fabrication process. MINT can also be fabricated directly onto a cleaved fiber end [8] to give a miniaturized, fiber compatible device. We have successfully demonstrated a 2cm-long mode-locked Fabry-Perot laser operating at a fundamental frequency of 5GHz with a pulsewidth of 0.68ps using highly-doped Er:Yb fibers in combination with a MINT[9].

Here, we present a "telecom-class" mode-locked fiber laser operating at record high fundamental repetition rate of 10GHz. The laser cavity length, including the Er:Yb gain fiber and the mode-locker (MINT) is as short as 1cm. This is the shortest cavity length and the highest fundamental repetition rate ever achieved in a passively mode-locked fiber lasers.

Experimental Setup

The schematic of the passively mode-locked fiber laser is depicted in Fig.1. A 1cm-long Er:Yb fiber with an absorption of 100dB/m at 1535nm and 2400dB/m at 976nm, is used as the laser gain medium. High-reflection (HR) mirrors of >99% are deposited on polished ends of two fiber ferrules. The 1cm Er:Yb gain fiber is placed in a 1cm-long ferrule with one end bonded to one of the HR fiber ferrule mirrors which has an end fiber pigtail spliced to a 1550/980 wavelength-division multiplexed (WDM) coupler. The laser is pumped with a 980nm laser diode (LD) through the WDM coupler, and the laser output is taken from the 1550 port of the WDM coupler as shown in Fig. 1.

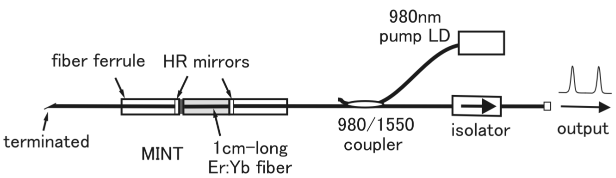

Fig. 1: Schematic of the 10GHz mode-locked fiber laser.

An isolator is spliced to the output port to prevent back-reflection into the laser cavity. The other end of the laser cavity was butted against the other HR fiber ferrule mirror with a layer of MINT deposited and sandwiched between the laser ferrule surface and the HR mirror ferrule. The end fiber pigtail of this HR fiber ferrule is terminated to prevent back-reflection. The MINT layer has a thickness of <200nm and an estimated absorption of <0.3dB at 1550nm. The MINT was fabricated using commercially available single-walled carbon nanotubes after special purification process to achieve the properties required for laser mode-locking purposes. Its absorption range covers from 1450nm to 2000nm. Fig. 2 shows the FE-SEM image of the carbon nanotube bundles in the MINT device. Since the 1cm-length of Er:Yb fiber has an absorption of only 1dB at 1535nm, and therefore a low expected gain, it is important to keep the MINT absorption at a low level in order to satisfy laser operating condition.

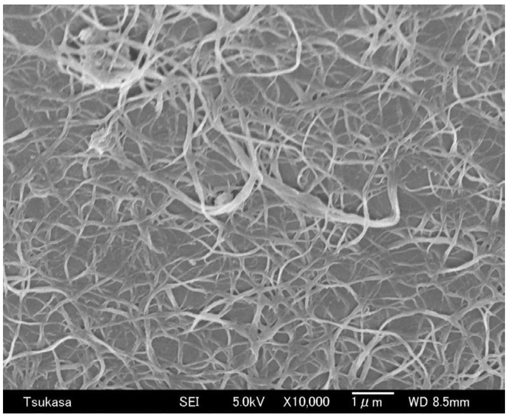

Fig. 2: FE-SEM image of MINT composition.

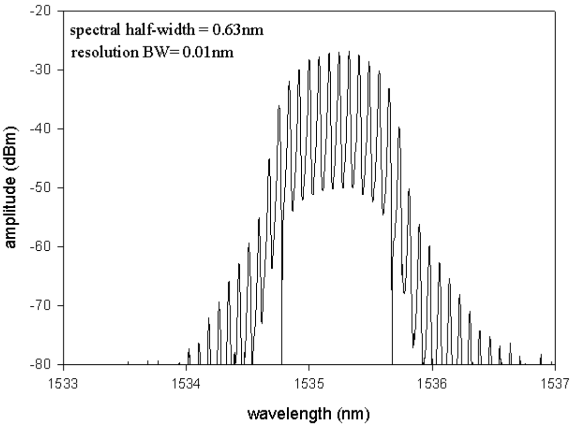

Fig. 3: Output optical spectrum of the fiber laser.

Results and Discussion

The laser starts to mode-lock at a pump power of ~25mW, producing pulses at a fundamental repetition rate of 10.4GHz with a relatively low output power of –22dBm. When the pump power is raised to 70mW, the output power is increased to –17dBm. The output optical spectrum of the laser is shown in Fig. 3. The spectral width is measured to be ~0.63nm and the spectral mode-spacing of ~0.08nm is clearly observable. A fundamental repetition rate, of 10.42GHz, is measured using a fast photo-detector and an RF spectrum analyzer (Fig. 4). The autocorrelation trace of the output pulses and a Gaussian-profile fitting are shown in Fig. 5. An inferred pulsewidth of 6.2 ps is measured from the autocorrelation trace, which give a time-bandwidth product of 0.488, very close to the transform limited Gaussian time-bandwidth product of 0.441.

Although the laser is operating at a relatively low output power, due to the limited pump absorption of the 1cm length of Er:Yb gain fiber. One solution is to add a length of doped fiber to the other output end of the laser, and utilizes the unabsorbed pump power for post-amplification of the output pulse. Another solution is to use gain fiber with an even higher doping levels.

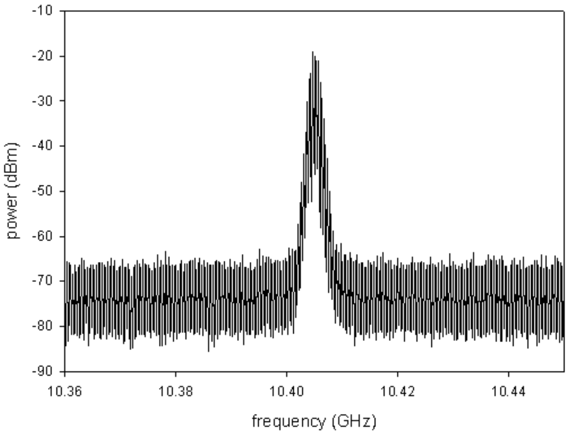

Fig. 4: RF spectrum of the output pulses at 10.42GHz.

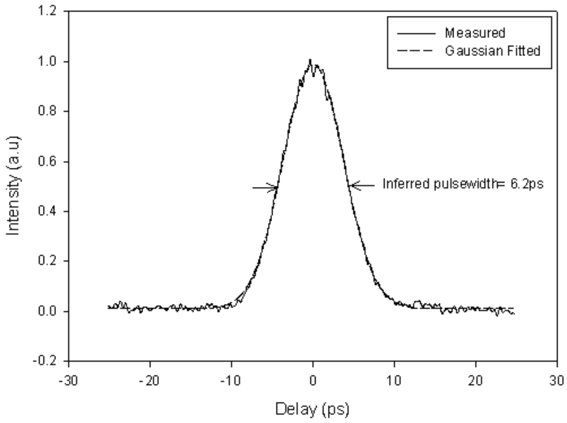

Fig. 5: Autocorrelation trace of the output pulses.

Conclusion

We have presented a passively mode-locked fiber laser operating at a record high fundamental repetition rate of 10.42GHz, with a very short laser cavity of 1cm. This is achieved by using highly-doped Er:Yb gain and a novel carbon nanotube-based mode-locker, which can be deposited as a thin-film between the gain gain fiber and the cavity reflecting mirror in an elegant all-fiber-ferrule configuration. This enables the realization of a simple and compact fiber mode-locked pulsed laser operating in the telecom-class repetition-rate. Furthermore, the simplicity and low fabrication cost of this device makes it a practical pulse source which could finally place fiber pulsed lasers on a competing ground with semiconductor pulsed sources.

References

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