Observation of Harmonics in a Uni-Directional Mode-Locked Fiber Laser Incorporating a Carbon Nanotube Saturable Absorber

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Abstract

The relationship between peak power, pump power, pulse width, spectral width, and repetition frequency with respect to the various harmonics was studied in a uni-directional mode-locked fiber laser incorporating a carbon nanotube saturable absorber. The saturable absorber, which was designed to work at 1550 nm, was composed of 0.8-nm-diameter carbon nanotubes. This laser produced a fundamental frequency of 11.23 MHz, of which the harmonics were multiples. By varying the pump power, an increasing linear relationship developed between repetition frequency and harmonic. We also observed a decreasing linear relationship between spectral width and peak power with the harmonic.

Introduction

Carbon nanotubes exhibit many interesting physical, electrical, thermal, and optical properties. Recently, an interest in their optical properties has made them the point of interest for mode-locked lasers. Due to their fast recovery times, nonlinear absorption of light intensity, and relatively easy fabrication, these nanosized carbon tubes make for a suitable saturable absorber in fiber lasers [1-3]. Coupled with harmonic mode locking, the equal spacing of pulses within the laser cavity, these lasers can be used in optical communication systems for ultra fast data transfer [4-6]. In this experiment, we studied the characteristics of harmonics in a passively mode-locked fiber laser with a carbon nanotube saturable absorber (CNSA).

Experimental Procedure

A uni-directional ring laser cavity was designed with components and measurements as labeled in Figure 1. A fiber pigtailed 980 nm diode (capable of > 100 mW output) was used to pump the 4 meter long erbium doped fiber (EDF). An isolator (> 30 dB isolation) was put in the cavity to ensure uni-directional lasing. A 15 meter long standard single mode fiber was used to compensate the dispersion. The laser was coupled out the cavity through an 88/12 coupler. The carbon nanotube saturable absorber was provided from SouthWest Nanotechnologies and consisted of 0.8-nm-diameter carbon nanotubes. Through the laser output, we utilized a spectrum analyzer to measure the spectrum and spectral width. A digital oscilloscope was used to measure the repetition frequency and to estimate the peak power.

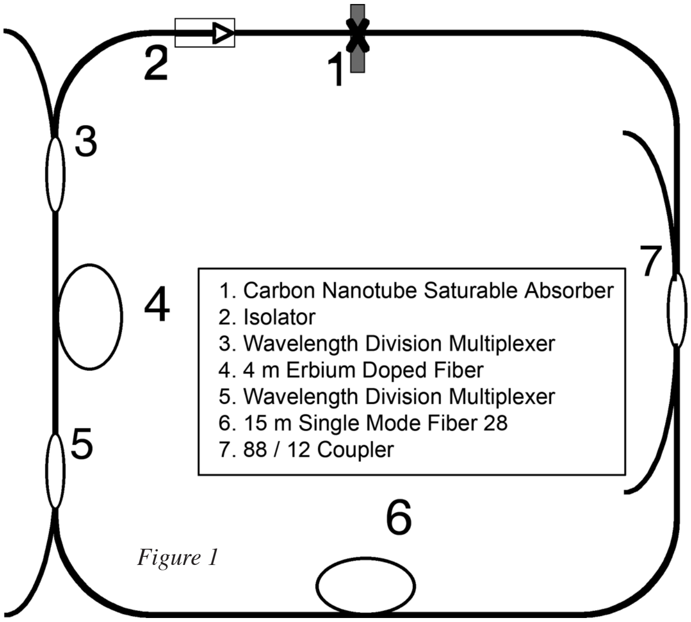

Figure 1

Results

This mode-locked laser operated at a fundamental frequency of 11.23 MHz, of which the harmonics were multiples. Depending on the pump power, the laser operated at different harmonics (up to 14^{th}), see Figure 2. It is almost a linear relationship between the pump power and order of harmonics.

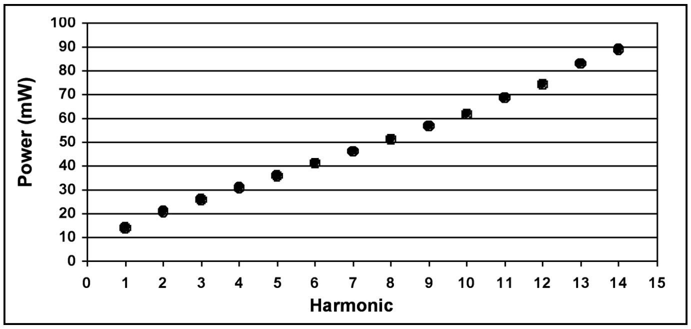

Figure 2

This is the first time that such stable and controllable harmonics have been observed in experiments in such fiber lasers.

To verify that pulses from our laser were from the mode-locked operation instead of another mechanism, like oscillation relaxation or Q-switching, pulse width measurement of the laser was attempted. Although we were not able to determine the actual pulse width from an auto-correlation measurement, we did use the spectrum analyzer to have a preliminary study of the pulse width. The 3-dB widths of the spectra were about 15-16 nm (see Figure 3), depending on the order of harmonics at which the laser was operating.

Directly from $\Delta \nu \times \Delta t \approx 1$ and $\Delta\nu/\nu = \Delta\lambda/\lambda$, it was easy to estimate the pulse width was on the order of 500 fs, which was much smaller than expected for oscillation relaxation or Q-switching. From Figure 3, it was also observed that the overall spectral width decreased (implying the pulse width increased) with increasing harmonics, which has also been observed by other researchers.

Finally, peak powers at different harmonics were measured (see Figure 4). The majority of the data followed a trend of declining as the harmonic increased, which has also been observed by other researchers. However a small section of data developed a trend of slightly increasing as the harmonic increased. This was more than likely due to a change in the digital oscilloscope's settings while the data was being taken.

Conclusion

We have demonstrated harmonic mode-locking in a fiber laser incorporating carbon nanotubes. For the first time, it has been demonstrated that reliable harmonics can be tuned by changing the pump power of the laser. Spectral width has been measured to estimate the actual pulse width of the laser.

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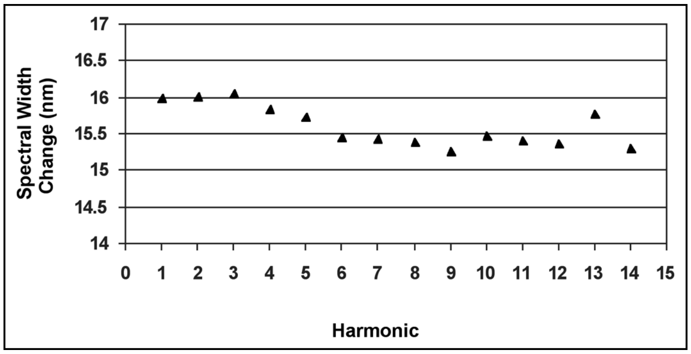

Figure 3

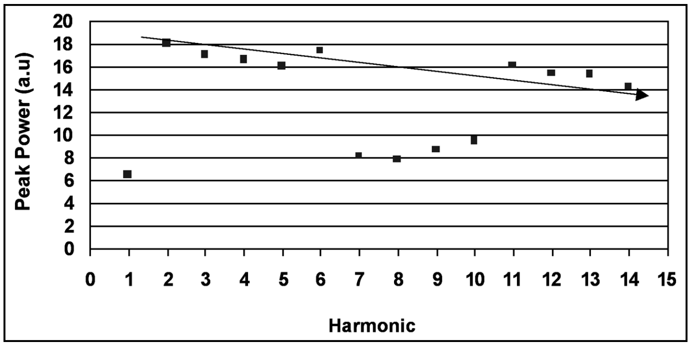

Figure 4