Switchable, dual-wavelength passively mode-locked ultrafast fiber laser based on a single-wall carbon nanotube modelocker and intracavity loss tuning

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Abstract: We demonstrate a dual-wavelength passively mode-locked soliton fiber laser based on the single-wall carbon nanotube saturable absorber. By using a simple scheme of adjusting the intracavity loss, the gain profile of the erbium-doped fiber laser is effectively controlled. Besides operating at a single wavelength, the laser is able to simultaneously generate sub-picosecond pulses at both ~1532 and 1557 nm wavelength. The mode-locking wavelength can also be quickly switched from one wavelength to the other by changing the intracavity loss with a tunable attenuator.

OCIS codes: (320.7090) Ultrafast lasers; (140.3510) Lasers, fiber; (160.4236) Nanomaterials.

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1. Introduction

Single-wall carbon nanotube (SWNT) has been demonstrated to possess very large and ultrafast nonlinear optical responses [1], which render it an attractive alternative to ultrashort pulse applications. Various saturable absorbers (SA) based on SWNT films, SWNT-doped polymer and, even, SWNT solutions have been widely studied for passively mode-locked lasers [2–5]. Because of the tunability of its saturable absorption wavelength by varying the SWNT's diameter, mode locked lasers based on SWNT SA's had been realized over a wavelength range between 1 μm and 2 μm [5–11]. Even a same SWNT saturable absorber device can be used in different laser configurations to operate at different wavelengths over a large wavelength span [12–14], due to the relatively large SWNT diameter distribution and its resultant broadband saturable absorption spectrum. Furthermore, a tunable SWNT-based mode locked fiber laser had been demonstrated with a tunable filter in the laser cavity [15].

In stead of generating its output at one center wavelength, multi-wavelength ultrafast lasers can simultaneously yield pulse trains at different center wavelengths. They have attracted much interest as the ultrashort pulse laser technologies progress, and could find applications in optical sensing, optical signal processing, component characterization, and optical communications. While many of the multi-wavelength pulse lasers are actively mode-locked [16–18], their passively mode-locked counterparts are capable of generating much shorter pulses. Experimental observations of multi-wavelength output have been realized in fiber ring cavities mode-locked by the nonlinear polarization rotation technique [19,20]. Semiconductor-saturable-absorber-mirror-based mode-locked lasers had also been demonstrated to realize multi-wavelength dissipative soliton operation [21]. In these previously studied passively mode-locked laser configurations, the output wavelengths are selected by optical filtering in the cavity (such as birefringence-induced spectral filtering) [20,21] or by external injection locking [22], and in most cases the spacing between the wavelengths are relatively several nanometers.

In this paper, we demonstrate a dual-wavelength passively mode locked fiber soliton laser incorporating a SWNT modelocker. A very simple scheme of controlling the gain tilt of the erbium-doped fiber (EDF) in the cavity is realized through cavity loss tuning. Instead of using optical filtering techniques, the operating status and the output wavelength(s) of the laser can

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be controlled by adjusting an attenuator in the fiber ring. Compared with its semiconductor counterparts, the broad mode-locking bandwidth and sub-picosecond response time of the SWNT device can be leveraged, and stable and switchable dual-wavelength output is achieved at the wavelengths more than 25 nm apart in the 1550 nm wavelength window.

2. Experimental setup

Our experimental setup, as shown in Fig. 1, consists of an Erbium-doped fiber ring laser with an SWNT modelocker. A 980 nm laser is used as the pump source. The pump light is coupled into a 4.5-meter-long piece of EDF (INO Er105) using a 980/1550 wavelength-division multiplexer (WDM). The EDF has a nominal absorption coefficient of 6.1 dB/m at 1530 nm. An optical isolator is placed at the output of the forward-pumped EDF to ensure the unidirectional propagation of the light in the cavity. A polarization controller (PC) is used to adjust the state of polarization. A programmable optical tunable attenuator (JDS MAPA + 23) with a 1-dB insertion loss is used to adjust the cavity loss. A section of standard single mode fiber (SMF) is placed into the cavity to ensure the anomalous average dispersion and, thus, the soliton operating regime of the laser. The overall length of the SMF in the cavity, including all the pigtails of various components, is ~18.3 m. A 90/10 fiber coupler is used as the output coupler with 90% of the light coupled back to the cavity and 10% used as laser output.

In contrast to other studied multi-wavelength passively mode-locked fiber lasers, the control of the lasing wavelength and switching between the single-wavelength and dual-wavelength operation is not realized by optical filtering in our configuration. Utilizing the well-known gain spectral profile of the EDF [23] that can possess two peaks under certain pump and signal conditions, the attenuator is used to tune the intracavity loss condition. The gain tilt of the EDF under a constant pump power is changed accordingly, as different intracavity loss/gain distributions result in changes in the inversion condition of the EDF. When the cavity loss is low, the EDF is more saturated so that the gain around 1560 nm can be larger. When the loss is increased, the peak of the EDF's gain can shift to 1530 nm. When the gains at the two peaks, one near the 1530 nm to one near 1560nm, are similar, dual-wavelength operation of the laser could occur.

The modelocker consists of a piece of SWNT/polyimide (PI) polymer sandwiched between two FC/PC ferrules. The SWNT used is fabricated by the chemical vapor deposition (CVD) method and has a nominal diameter around 1 nm. The SWNT is first ultrasonicated in H_2SO_4/HNO_3 (3:1) and then in the dimethyl formamide (DMF) solvent, before the SWNT suspension is mixed with a DMF solution of polyimide resin (from Sigmal). PI is chosen as the composite matrix for its high glass-transition temperature, low optical loss, and good environmental stability. The mixture is sonicated to obtain a uniform composite solution, and then is baked in an oven to completely remove the solvent and to obtain a free-standing film. The doping concentration is ~1 w.t.%, and the uniformity of the dispersion is good upon optical inspection with relatively low aggregations considering the high SWNT concentration. Its optical characteristics can be found in [24]. The film is 45 μm thick and the modelocker has an optical insertion loss of 2.3 dB at the wavelength of 1.554 μm.

The optical spectrum of the laser output is measured by an optical spectrum analyzer (Agilent 86142B). The temporal pulse shape is measured by a home-built intensity autocorrelator. The pulse trains are detected by a real-time oscilloscope (Agilent Infiniium MS07054A, 500-MHz) through a 1-GHz photodetector (New Focus 1611), whose RF spectrum is measured by an Agilent N9320B spectrum analyzer.

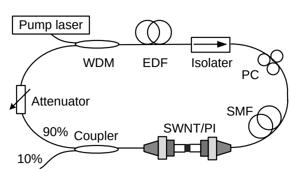

Fig. 1. Schematic of the experimental setup.

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3. Experimental results and discussions

3.1 Single-wavelength mode-locking

We first demonstrate and study the single-wavelength mode-locking operation of the laser at the two wavelengths. When we set the attenuation of the tunable attenuator to be 0 dB, the measured total loss of the cavity at 1.554 μm is ~6.13 dB considering the insertion losses of the components' (excluding the absorption of EDF). The EDF shows a gain peak near the 1560 nm under such a condition. Similarly to other previously demonstrated soliton fiber lasers, by varying the pump level, the laser can operate under a CW condition, single-pulse mode-locked condition and multi-pulse mode-locked condition, sequentially. Figure 2(a) shows the output power and the operation status under different pump powers. The CW pump threshold is ~7 mW with a lasing wavelength at ~1558.7 nm. Mode locking can be realized at the pump power higher than ~9 mW through slightly perturbing the laser cavity. The self-starting mode-locking of the laser is also possible and its threshold is ~23 mW. The repetition rate of the pulse train is ~9.09 MHz under the single-pulse condition, matching the round-trip time of the cavity. When the pump power goes even higher, multiple pulses occur within each round-trip time, as what commonly happens to this kind of lasers.

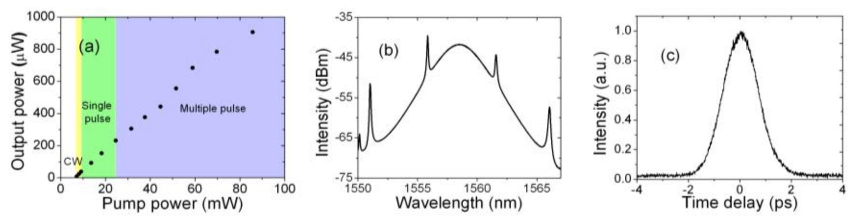

Fig. 2. (a) Output power and operating status of the laser vs. the pump power, when the attenuator is set at 0 dB. (b) Optical spectrum and (c) autocorrelation trace of the laser output centered at 1558.5 nm when the pump power is 16.4 mW.

The optical spectrum and the autocorrelation trace of the pulses are shown in Fig. 2(b) and Fig. 2(c), when the pump power is 16.4 mW. The output power is measured to be 130 μW under that stable single-pulse state. The spectrum is centered at 1558.5 nm with a full-width half-maximum (FWHM) bandwidth of ~3.0 nm. The measured autocorrelation trace has a FWHM width of 1.6 ps, and the pulse width is estimated to be 1.04 ps if a sech^2-shape pulse is assumed. The measure time-bandwidth product is 0.39, which is somewhat larger than the transform limit due to some residual chirp. The expected, compressed pulse width is 0.85 ps.

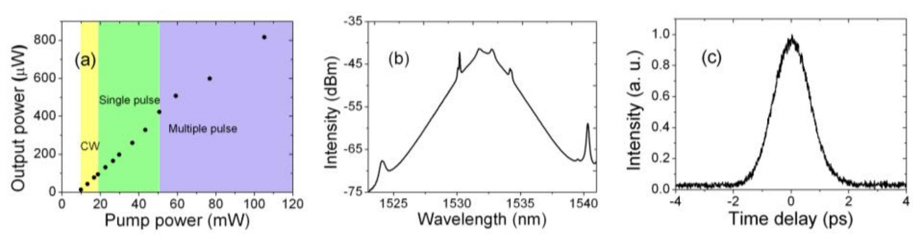

Fig. 3. (a) Output power and operating status of the laser vs. the pump power, when the attenuator is set at 3 dB. (b) Optical spectrum and (c) autocorrelation trace of the laser output centered at 1532.2 nm when the pump power is 19.8 mW.

Then, we increase the attenuation of the tunable attenuator to 3.0 dB and the total loss of the cavity is increased to ~9.13 dB. The center wavelength of the laser is shifted to the other gain peak wavelength of the EDF at ~1532 nm. As shown in Fig. 3(a), certain other characteristics of the laser also change as the intracavity loss is increased. The CW pump threshold is increased to 9.5 mW. The single pulse mode locking state can be achieved when the pump power is increased to ~20 mW by slightly perturbing the cavity. The mode-locking also can self-start when the pump power is above 45 mW. Due to the larger cavity loss, these

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numbers are significantly larger than those when the center wavelength is ~1558 nm. The slope of the output power vs. the pump power is also reduced in Fig. 3(a). The measured optical spectrum and autocorrelation trace when the pump power is 19.8 mW and the output power is 105 μW are shown in Fig. 3(b) and Fig. 3(c). The center wavelength is 1532.2 nm and the bandwidth at FWHM is ~2.7 nm. The measured pulsewidth is about 0.96 ps and the time-bandwidth product is 0.33.

3.2 Dual-wavelength mode-locking

Based on the above observations, it is clear that, by adjusting the intracavity loss, it is possible to reach a point that both the above two gain peaks have nearly equal magnitude. Under such a condition, the dual-wavelength lasing could be possible. In our setup, such a condition can be realized when the tunable attenuator is set to around 2.2 dB. The fiber laser first emits CW light at both 1532 and 1557 nm when the pump power is cranked up from zero. The output spectrum shows narrow CW peaks near the 1532 and 1557 nm region when the pump power is 32.8 mW(see Fig. 4(a)). One can see that the spectral peaks at these two wavelengths have roughly the same height now. Through slightly perturbing the cavity, dual-wavelength mode-locking can occur. The measured mode locking optical spectrum is also shown in Fig. 4(a). The mode locked laser emits two pulse trains at different center wavelengths. The center wavelengths are 1532.2 nm and 1557.3 nm, and the spectral widths are ~3.3 nm and ~3.8 nm, respectively. The total output power is 248 μW, comparable to the single wavelength case. Figure 4(b) shows the measured RF spectrum of the pulse trains. The repetition rates of the pulse trains' at two wavelengths are actually slightly different, due to the group velocity dispersion of the fiber cavity. From the spectrum analyzer's results, the pulses at 1532.2 nm have a repetition rate of 9.090312 MHz, and the 1557.3 nm pulses have a 9.089842 MHz rate. The difference in their repetition rates is 470Hz. If the dispersion parameter of EDF is roughly estimated to be ~-6.5 ps/km/nm based on similar previously reported numbers, which may not be accurate, the repetition difference would be ~580 Hz, close to the experimental results. The observed temporal oscilloscope trace, when triggered by the 1557.3 nm pulses (shown in Fig. 4(c)), also illustrates the above frequency difference, showing the pulses at 1532.2 nm 'drifts' in the time domain relative to the pulses at 1557.3 nm. It also shows that the two kinds of pulses have somewhat different amplitudes, i.e. pulse energies.

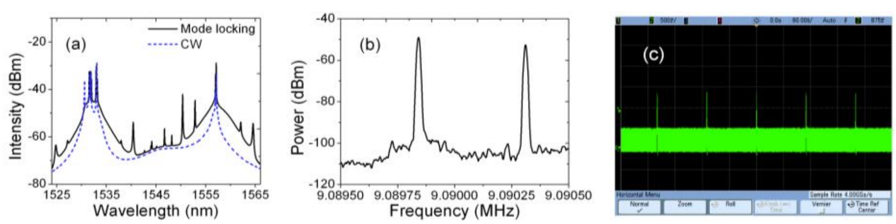

Fig. 4. (a) Output optical spectrum at the dual-wavelength CW and dual-wavelength mode-locked state, when the pump power is 32.8 mW; (b) the corresponding RF spectrum; (c) the corresponding oscilloscope trace.

We also measure the autocorrelation trace of the pulses at two wavelengths separately. The above dual-wavelength output is filtered with bandpass filters with 1528.5 nm to 1536.5 nm pass band and 1554.2 nm to 1562.2 nm pass band, respectively. As shown in Figs. 5(a) and 5(b), the pulse widths of the pulses at 1532.2 nm and 1557.3 nm are 0.99 ps and 0.95 ps, and their time-bandwidth products are 0.41 and 0.45, respectively, which are close to the results under the single-wavelength conditions. We note that these results are measured under very low average powers (several tens of μW) due to the loss of the filter so that the autocorrelation results are noisier.

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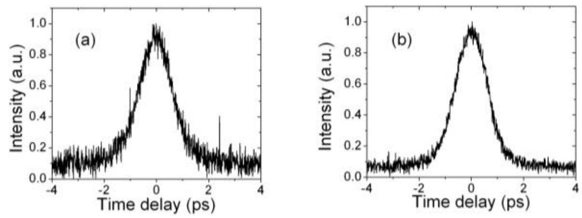

Fig. 5. The autocorrelation trace of (a) 1532.2 nm pulse and (b) 1557.3 nm pulse.

3.3 Switchable mode locking operations

Based on the above results, it is expected that the operating condition of the laser can be simply switched through changing the cavity loss. The process is demonstrated here. Here the pump power is set at 46 mW, which is larger than the self-start threshold for both 1532nm and 1557nm mode locking. When the automated tunable attenuator (whose tuning time is ~190 ms) is adjusted from 0 dB to 3 dB, the mode-locked output at 1557 nm disappears, and, after a short period of transition period, the 1532 nm pulse output builds up (shown in Fig. 6(a)). The length of the ‘gap’ is ~1.3 s for this measurement, which varies somewhat from time to time because of the random pulse build-up process in the cavity. Vice versa, when the tunable attenuator is switched from 3 dB to 0 dB, the mode locking wavelength is changed from 1532 nm to 1557 nm (shown in Fig. 6(b)). However, the transition time is much shorter, in this case ~130 ms. The difference in the transition speed is because of the lower self-start pump power at 1557 nm.

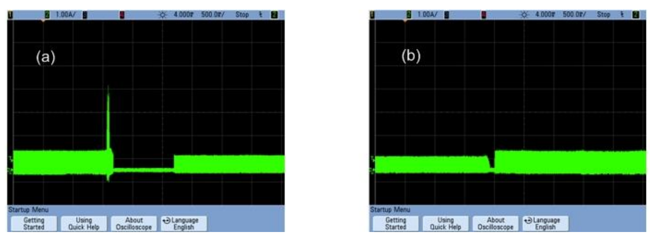

Fig. 6. The oscilloscope trace when mode locking wavelength changes from (a) 1557 nm to 1532 nm and (b)1532 nm to 1557 nm.

4. Conclusions

In this paper, we demonstrate a switchable dual-wavelength mode-locked fiber laser based on SWNT saturable absorber. Sub-picosecond outputs at two wavelengths that are ~25 nm apart can be realized by simply tuning the intracavity loss. Considering the wide mode-locking bandwidth of the SWNT device, it is expected that multi-wavelength pulse lasers covering larger wavelength ranges and with more attractive features could be realized using such devices.

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