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Discussion

Dual-wavelength passively Q-switched Erbium doped fiber laser based on an SWNT saturable absorber

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ABSTRACT

We report a dual-wavelength, all-fiber, passively Q-switched Erbium doped fiber laser based on a single-wall carbon nanotube saturable absorber. By just varying the pump power to balance the peaks of the Erbium doped fiber gain spectra in the cavity, the laser can operate in the dual-wavelength Q-switching regime without intracavity spectral filters or modulation elements. Our experimental results show that the fiber laser can simultaneously generate Q-switched microsecond pulses at ~1532 nm and ~1558 nm, which have the same repetition rate of tens of kHz and around 0.5 nJ pulse energies. Our scheme is quite simple to implement at a low cost.

1. Introduction

Q-switching technology has been widely studied to generate high-energy, short laser pulses, with a wide range of applications from metal cutting, microfabrication and range finding to medical treatment. Traditionally, active Q-switching methods using optical modulation devices, such as acousto-optic modulators [1,2] and electro-optic modulators [3,4] are the most widely adopted schemes in Q-switched lasers. Due to the presence of the modulators and other bulk devices in the cavity, the configurations of the widely-used, actively Q-switched solid-state lasers are often relatively complicated. With the increasing popularity and performance improvement of fiber lasers, Q-switched Erbium-doped-fiber (EDF) lasers have attracted more and more attention, which could have advantages in their size, weight and cost [5,6]. On the other hand, in contrast to the actively Q-switching schemes, the passively Q-switching techniques based on saturable absorbers (SAs) could have additional advantages such as simplicity and compactness. Various SAs including the metal doped crystals [7,8], quantum-well semiconductor devices [9], and the metal doped fibers [10,11] have been investigated and could play an important role in the characteristics of the Q-switched lasers. SAs based on the single-wall carbon nanotube (SWNT) materials have emerged as another attractive choice [12–14], and they could be easily compatible with an all-fiber cavity configuration.

Both the emission spectrum of the gain fiber and the absorption spectrum of SWNT are rather broad, compared to the bandwidth of a Q-switched output, so it is possible to realize passively Q-switched Erbium-doped fiber lasers at different wavelengths. Wavelength-tunable Q-switched Erbium-doped fiber lasers have been reported by using fiber Bragg gratings, Fabry–Perot (F–P) filters or other tunable filters in the cavity [15–17].

On the other hand, the multi-wavelength Q-switched lasers, which can simultaneously generate synchronized Q-switched pulse trains at different center wavelengths, can be useful in airborne Lidar, terahertz generation, multiphoton dissociation of molecules and other nonlinear optics or sensing applications [18]. Very recently, by using the birefringence-induced filtering effect, a dual-wavelength Q-switched EDF laser with a graphene saturable absorber has been reported [19]. Leveraging the spectral gain peaks of the Yb-doped fiber wavelength, the dual-wavelength passively Q-switching operation has been demonstrated around 1 μm wavelength, which uses Cr^{4+}:YAG as the saturable absorber [20]. Based on the broad absorption spectrum of SWNT, dual-wavelength Q-switched lasers are also possible to be realized with this kind of low-cost, fiber-compatible saturable absorbers.

In this paper, based on a SWNT saturable absorber, without using any spectra filtering effect or modulation elements in the cavity, we experimentally demonstrate an all-fiber, passively

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Q-switched EDF laser, which can simultaneously generate two pulse trains at different wavelengths over 25 nm apart. Generation of the dual-wavelength output is based on the spectral gain profile of the EDF that could possess two peaks under certain pump and signal conditions determined by the intracavity loss [21].

2. Experimental setup

The configuration of the EDF ring laser with an SWNT SA is shown in Fig. 1. A 4.7-m long piece of EDF (INO Er105) acts as the gain medium with an absorption coefficient of 6.1 dB/m at 1530 nm and 4.7 dB/m at 980 nm. It is pumped by a 980 nm laser through a 980/1550 wavelength-division multiplexer (WDM). An optical isolator follows the output section of the EDF to maintain the unidirectional propagation of the light, and a polarization controller (PC) is used to adjust the state of polarization. The light is coupled out of the cavity by an 80/20 fiber coupler. 80% of the light is coupled back into the cavity, and the 20% port is used as the laser output. The total length of the single mode fiber (SMF) in the cavity is about 3.1 m. The total loss of the cavity at 1554 nm is ~10.1 dB (excluding the absorption of EDF). The output pulse trains are passed through a four-channel demultiplexer filter with the center wavelengths of 1532.6 nm, 1540.6 nm, 1550.1 nm and 1558.2 nm (the filtering bandwidth is around 7 nm for every channel), which has an insertion loss of ~1.1 dB. We note that there is no device with large birefringence or polarization dependence in the cavity and little birefringence-induced-filtering effect is observed in our setup.

SWNT/polyimide (PI) polymer is used as a material for the saturable absorber. Our SWNT is fabricated by the chemical vapor deposition (CVD) method and PI is used as the composite matrix owing to its high glass-transition temperature and good environmental stability. The doping concentration of SWNT and polyimide (PI) is ~1 wt%. A piece of the polymer film with a thickness of 58 μm is sandwiched between two FC/PC ferrules. The modulation depth of the material's saturable absorption has been characterized as 1.9% [21,22], and the recovery time of SWNT's ultrafast nonlinear optical responses is believed to be ~1 ps [23]. Yet, we note that, in the much slower Q-switched regime, the performance of the mode-locker could vary. The mode-locker has an optical insertion loss of 8.6 dB at the wavelength of 1554 nm, partially because of the high doping concentration, and exhibits relatively good tolerance to the thermal damage. The optical loss includes the absorption of the saturable absorber layer itself and the misalignment between the two ferrules caused by the insertion of the saturable absorber. Because of the comparatively high loss of the absorber, the EDF is relatively less saturated compared to similar cavity configurations.

The optical spectrum of the laser output is measured by an optical spectrum analyzer (Agilent 86142B). The pulse trains are detected by a real-time oscilloscope (Agilent Infiniium MS07054A) through a photodetector.

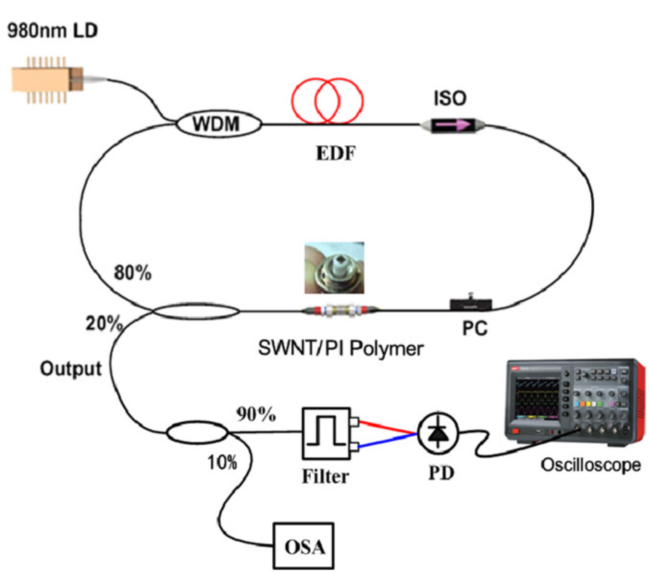

Fig. 1. Schematic representation of the experimental setup.

3. Experimental results and discussions

At the above level of optical loss in the cavity, the change in the pump power can significantly alter the gain spectrum shape of the EDF. The dependence of output spectra on the pump power is shown in Fig. 2. When the pump power is relatively low (e.g. at 28 mW), the gain around the 1558 nm wavelength is significantly larger than that at the 1532 nm window. The laser begins to Q-switch at 1558 nm when the pump power gets higher. As the pump level increases, it is also observed that the gain around 1532 nm increases much faster than that at 1558 nm. Therefore, under certain pump powers, EDF can possess two gain peaks that have nearly the same magnitude, one near 1532 nm and the other near 1558 nm [24], which could enable dual-wavelength Q-switching (DWQS) operation of the laser.

On the other hand, while the laser begins to Q-switch at 1558 nm, the output has repetition rates of several kHz (depending on the pump power) and μs pulse-durations. When the pump is further increased to 62 mW, the Q-switching operation at ~1532 nm can also be achieved. The corresponding repetition rate and pulse-duration of the output at that wavelength is 32.3 kHz and ~6 μs, respectively. Meanwhile, the other gain peak at ~1558 nm is still in the Q-switched mode, and dual-wavelength Q-switched (DWQS) operation is realized. Stable dual-wavelength Q-switched mode can be maintained within the pump power range of 62–120 mW.

Fig. 3 shows the pulse traces measured by the oscilloscope at three different pump powers as the outputs at different wavelengths are connected to the scope consecutively. The amplitudes of the traces are normalized to better reveal and compare the detailed characteristics of the dual-wavelength pulse trains. The pulses at the two wavelengths have the same repetition rate, and, as the pump power increases, both repetition rates increase.

The pulse repetition rate and pulsewidth of the Q-switched lasers are shown in Fig. 4 at varying pump powers. Similar to many other passively Q-switched lasers, the repetition rate is closely related to the pump level: the higher the pump power, the

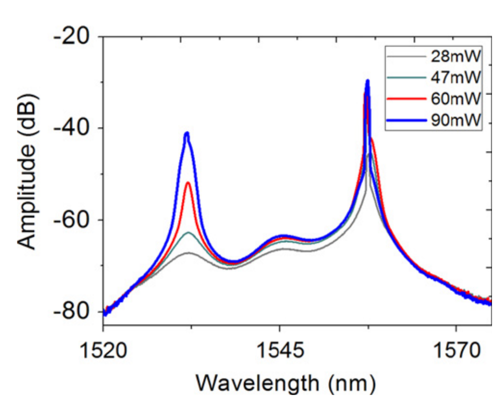

Fig. 2. Spectra of the laser under different pump powers.

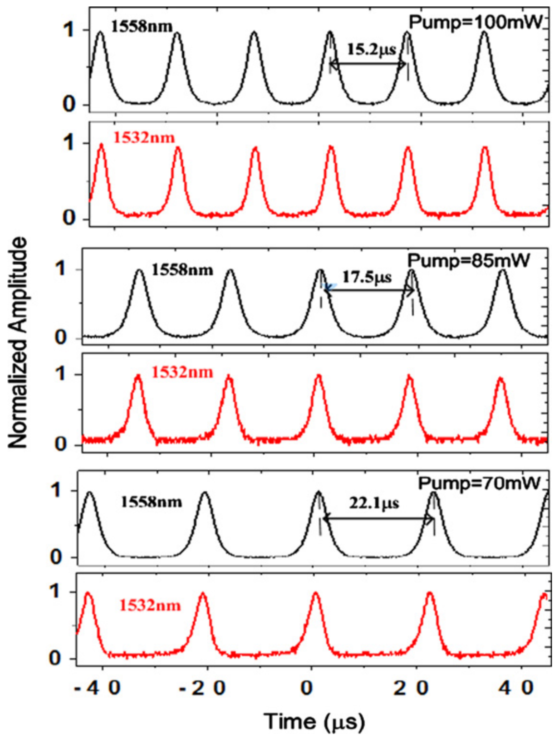

Fig. 3. The oscilloscope trace in the DWQS (1558 nm and 1532 nm) operation at different pump levels.

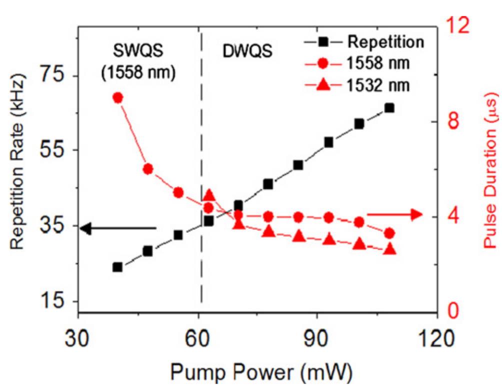

Fig. 4. Repetition rate and pulse duration as a function of pump power at the single-wavelength and dual-wavelength Q-switched mode.

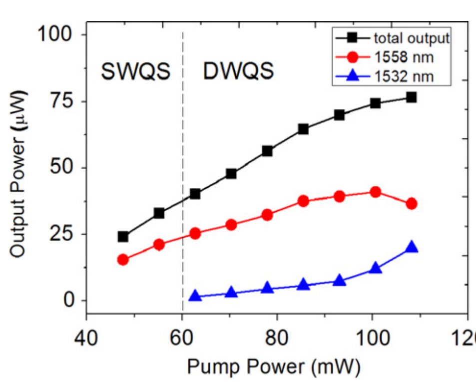

Fig. 5. Dependences of total output power (before bandpass filter), 1558 nm, and 1532 nm power on pump power.

higher the repetition rate is. That is because high pump power leads to a shorter time for the inversion number of the gain medium to reach the threshold. Repetition rates from 23.8 kHz to 66.2 kHz can be achieved, when the pump power is increased from 36 mW to 108 mW. As indicated in the previous work [14], the long pulse duration of ∼μs is due to the long cavity lifetime related to the long length of the cavity, which can be reduced by decreasing the cavity length with a highly doped Erbium fiber or other more compact components. In our experiment, we observe that the pulse durations of these two pulse trains at different center wavelengths are somewhat different. The pulses at 1532 nm are typically slightly shorter than those at 1558 nm. Within the above pump power range, the pulsewidth at 1558 nm is initially relatively long (∼9 μs) under the single-wavelength Q-switched (SWQS) regime, which quickly drops as the pump power increases. It can be further reduced to ∼3.3 μs at the highest pump power. On the other hand, the pulse duration at 1532 nm is between ∼4.8 μs and ∼2.6 μs. The differences may be related to the different absorption and emission parameters at the two wavelengths as the ground- and excited-state populations vary [20].

Because of the slightly higher gain at that wavelength window, the pulses at ∼1558 nm have higher energy in the cavity, compared to those at 1532 nm, whereas the power of the latter rises faster at the larger pump powers, which is shown in Fig. 5. The total power shown in the figure is measured before the optical filter, and the powers at two wavelengths are measured after the filter. While both output powers initially increase, when the pump power is larger than 100 mW, the power of the pulses at ∼1558 nm begins to drop, and the pulses at ∼1532 nm rise. This is due to the fact that under high pump powers, the increase in the gain at ∼1532 nm is more significant while that at 1558 nm is relatively reduced. We note that the energy distribution of the two pulses can be further adjusted by introducing extra controlled optical loss in the cavity, as that can also influence the gain tilt of the EDF [21]. While current output powers at both wavelengths are relatively low, it is limited by the damage threshold of the SA. Further increase in the output power could be enabled by the development of SAs with higher thermal damage threshold, such as SWNTs hosted in SiO_2 matrix or other material [14], and would facilitate more potential applications. Further boosting the power with an optical amplifier is a feasible solution to those application demanding even higher pulse energies.

4. Conclusions

In this paper, we demonstrate a dual-wavelength Q-switched Erbium doped fiber laser based on an SWNT saturable absorber. By simply tuning the pump power, dual-wavelength (∼1558 nm and ∼1532 nm), nanojoule Q-switched pulses are obtained. It could find applications where multiple synchronized short optical pulses are needed. Considering the all-fiber structure, simple realization and low cost, it is expected that more attractive applications could be realized using such multi-wavelength Q-switched short pulse lasers.

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