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A *Q*-switched multi-wavelength Brillouin erbium fiber laser with a single-walled carbon nanotube saturable absorber

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Abstract

A *Q*-switched multi-wavelength Brillouin erbium fiber laser (MWBEFL) is demonstrated using a single-walled carbon nanotube–polyethylene oxide (SWCNT–PEO) saturable absorber (SA). The SA is fabricated by cutting off a small part of the developed SWCNT–PEO film and sandwiching it in between two FC/PC (fiber connector/physical contact) fiber connectors. Multi-wavelength combs with ten lasing lines and spacing of 0.158 nm are obtained by the use of 2 km long dispersion compensating fiber as the Brillouin gain medium and a four-port circulator to isolate and circulate the odd-order Stokes signals. *Q*-switched pulse trains with a repetition rate of 105.2 kHz and a pulse width of 0.996 μs are obtained in the proposed MWBEFL at a 1480 nm pump power of 120 mW and a Brillouin pump power of 5.4 dBm.

1. Introduction

Q-switched fiber lasers are generally used for generating high energy pulses at relatively low repetition rates [1–5]. They can be constructed by active [2] or passive techniques [3]. Compared to those fabricated using the active technique, passively *Q*-switched fiber lasers are advantageous in terms of compactness, simplicity, and flexibility in design [4, 5]. They have been intensively investigated using different kinds of saturable absorbers (SAs) such as transition metal-doped crystals [6] and semiconductor saturable absorber mirrors (SESAMs) [7]. However, these SAs are complex and expensive to fabricate. Furthermore, their incompatibility with many optical fibers limits their widespread application. Recently, single-walled carbon nanotubes (SWCNTs) have been discovered to show promising potential in mode locked fiber laser systems due to their intrinsic saturable absorption properties, ultrafast recovery time and wide absorption wavelength bandwidth [8, 9].

On the other hand, many works have also been reported on multi-wavelength fiber laser, with the aim of catering to the needs of many applications, especially as regards dense wavelength division multiplexing (DWDM) [10, 11]. Stimulated Brillouin scattering (SBS) is one of the main techniques used to generate multi-wavelength laser combs as it offers advantages such as narrow linewidth, low threshold, directional sensitivity of the SBS gain etc [12, 13]. To date, many works have been reported on multi-wavelength Brillouin fiber lasers (BFLs), which produce a wavelength comb with a constant spacing of 0.08 nm [14, 15]. However, channel spacing of 0.08 nm is not practical for DWDM applications, as it is difficult to demultiplex the channels at the receiver end. Therefore, many works on multi-wavelength BFLs with double Brillouin spacing (DBS) of around 0.16 nm have also been reported [16].

In this paper, a *Q*-switched multi-wavelength Brillouin erbium fiber laser (BEFL) is demonstrated, based on SWCNT-based SA. It uses a four-port circulator to discriminate between the odd-order and even-order Stokes signals, and thus allows comb spectrum generation with DBS. An erbium gain is used to assist in the comb generation while *Q*-switching is achieved by inserting a thin film of SWCNT–polyethylene oxide (SWCNT–PEO) polymer composite into the ring cavity by sandwiching it in between two FC/PC fiber connectors.

2. Fabrication of SWCNT saturable absorber and the experimental setup

Dispersion of SWCNTs was achieved, ultrasonically aided by sodium dodecyl sulfate (SDS) solution. 250 mg of SWCNTs were added to 400 ml SDS solution in deionized water at 1% concentration before being sonicated for 30 min at 50 W. The solution was centrifuged at 1000 rpm to remove large particles of undispersed CNTs to obtain a dispersed suspension that is stable for weeks. SWCNT–PEO composite was fabricated by adding 1.8 ml dispersed SWCNT suspension containing 1.125 mg of solid SWCNTs into a solution of 1 g PEO (average molecular weight: 1 × 106 g mol^{-1}) in deionized water and thoroughly mixed. The SWCNT–PEO composite was cast onto a glass Petri dish and kept in a vacuum oven at 60 °C for 48 h, to form a thin film thickness of around 50 µm. The SA is fabricated by cutting off a small part of the prepared film (2 × 2 mm^2) and sandwiching it in between two FC/PC fiber connectors, after depositing index-matching gel onto the fiber ends.

Figure 1 shows the experimental setup for the proposed MWBEFL, which consists of a piece of erbium-doped fiber (EDF), which is pumped by a 1480 nm laser diode via a wavelength division multiplexer, an optical circulator, two couplers, and a piece of 2 km long dispersion compensating fiber (DCF) and an SWCNT–PEO SA. The EDF is 4.5 m long with an erbium concentration of 2000 ppm, cutoff wavelength of 910 nm, pump absorption rate of 24 dB m^{-1} at 980 nm and dispersion coefficient of −21.64 ps nm^{-1} km^{-1} at $\lambda = 1550$ nm. A four-port circulator is used to discriminate between the odd-order and even-order Stokes signals and at the same time to ensure unidirectional operation of light. The BP (Brillouin pump) from an external cavity tunable laser source is injected into the EDF loop via a 3 dB coupler. The amplified BP is then sent into the DCF from port 1 through port 2 of the optical circulator to generate backward-propagating SBS. The backward-propagating SBS oscillates inside the DCF loop to generate the first Stokes signal once the BP power exceeds its threshold. The first Stokes signal is re-injected into the other end of the DCF in a counter-clockwise direction to act as a BP to generate the next Stokes signal. The newly generated Stokes signal propagates in a clockwise direction, and thus it oscillates and gets amplified in both loops, generating newer Stokes signals in an opposite direction. The cascading process continues to generate multi-wavelength lasing. In the DCF loop, the odd-order Stokes lines are blocked by the circulator and the even-order Stokes lines are allowed to oscillate and build up their intensity. A portion of the oscillating light inside the EDF loop is extracted from the laser system using another 3 dB coupler. The dispersion coefficient for the DCF is −107 ps nm^{-1} km^{-1}. The output spectrum is characterized by an optical spectrum analyzer with a resolution of 0.015 nm. The temporal characteristics of the MWBEFL output were monitored using a combination of a photo-detector and a real time oscilloscope.

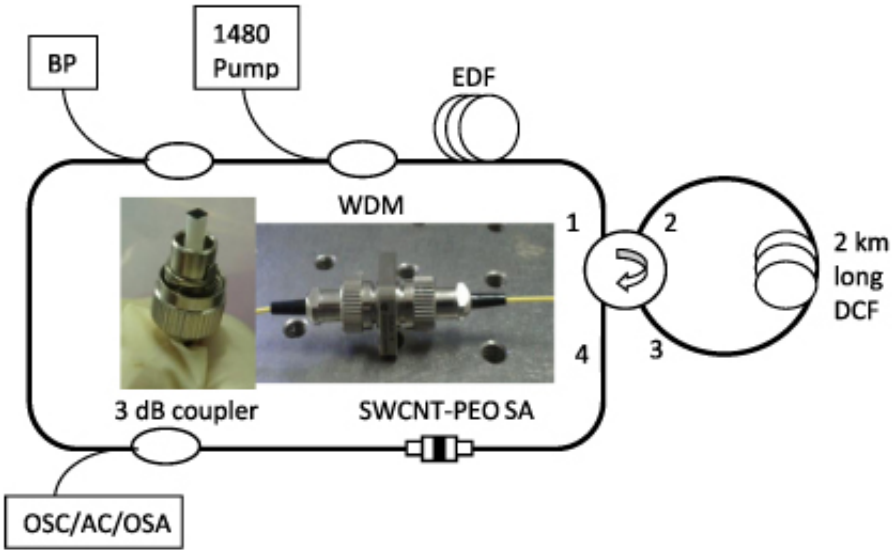

Figure 1. Experimental setup of the proposed *Q*-switched device.

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3. Results and discussion

Figure 2 shows the output spectrum of the MWBEFL when the BP power and wavelength are set at 5.8 dBm and 1565 nm, respectively. In the experiment, the 1480 nm pump power is fixed at 120 mW. The BP wavelength is set to coincide with the peak lasing of the EDF loop without the BP to assist in Brillouin Stokes signal generation. As can be seen, ten lasing lines are obtained with a constant spacing of 0.158 nm and an optical signal to noise ratio (OSNR) higher than 10 dB, due to the cascaded Brillouin effect. The anti-Stokes lines are also observed at wavelengths shorter than the BP one, which occurs when the various Stokes waves interact with the pump wave through the four-wave mixing process. It is observed that the peak power of subsequent Stokes signals is always lower than that of the previous Stokes signals because these subsequent Stokes signals are generated from the previous Stokes signals. The highest peak power of −3.9 dBm is observed at 1565.158 nm, which corresponds to the second Brillouin Stokes signal.

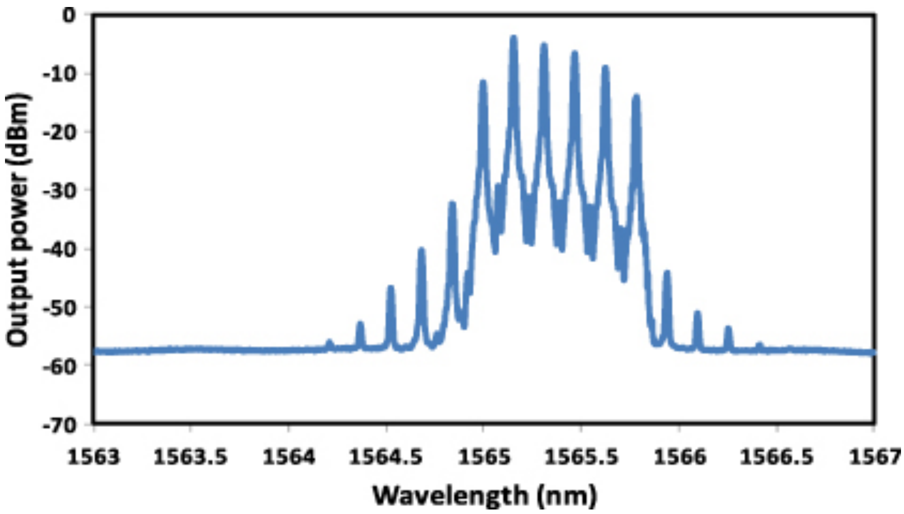

Figure 2. Output spectrum of the MWBEFL with a double Brillouin spacing.

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The temporal characteristic of the laser is measured by using a photo-detector and an oscilloscope. A *Q*-switching behavior is observed at the 1480 nm pump power of 120 mW. The temporal characteristic of the laser is also investigated without the injection of the BP. Without the BP, the proposed laser operates as a long cavity EDF laser with a random lasing. When the laser diode pump power is gradually increased to around 98 mW, stable *Q*-switching pulse can be observed for both lasers with and without the BP. Figures 3(a) and (b) show the oscilloscope trace of the MWBEFL without and with the BP, respectively. In the experiment, the BP and 1480 nm pump power are fixed at 5.4 dBm and 120 mW, respectively. Both figures indicate a stable pulsing behavior, which is mainly due to the growth of SBS that causes a series of avalanche processes leading to a *Q*-switching effect.

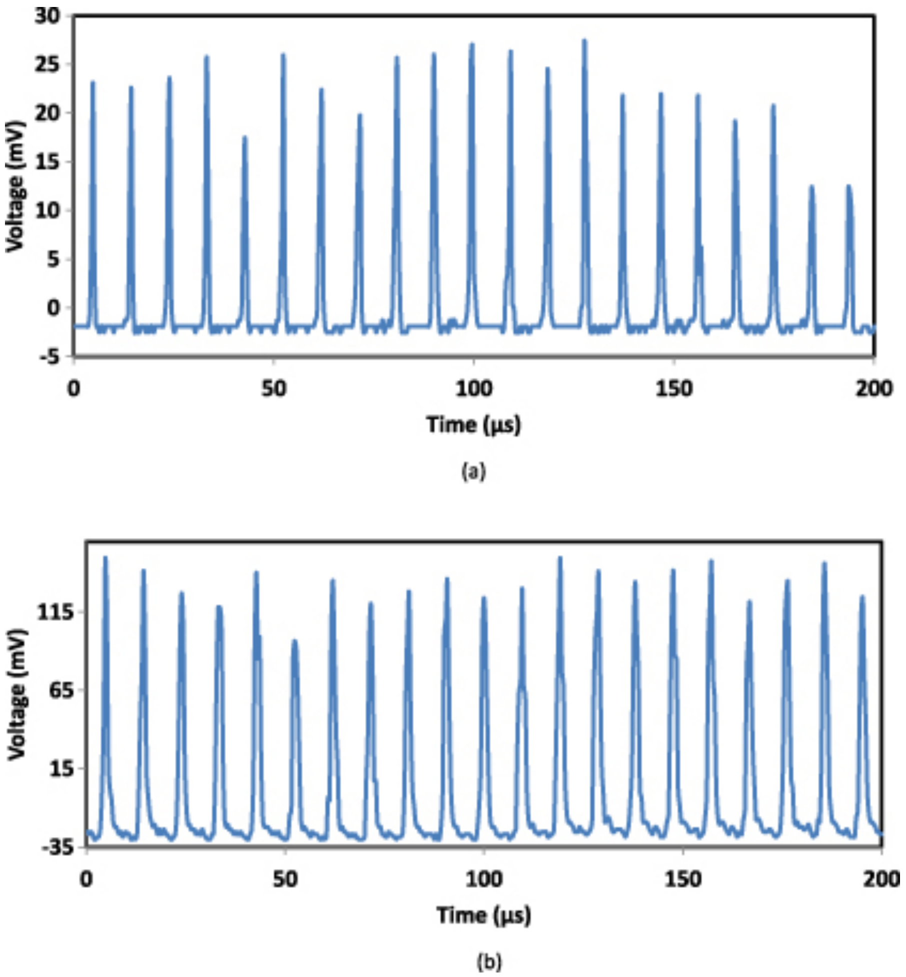

Figure 3. Output pulses train from the *Q*-switched lasers (a) without and (b) with the BP.

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The repetition rates of the pulsed laser are obtained at 102.5 kHz and 105.2 kHz without and with the BP, respectively. The corresponding pulse widths are 1.060 and 0.996 µs. The repetition rates and pulse widths for the two lasers are almost the same due to the similarity in cavity length. With the BP, the laser operates in multi-wavelength mode, while only a random single-wavelength operation is achieved without the BP. These results show that the SWCNT–PEO saturable absorber can serve as a passive *Q*-switch inside the BEFL resonator for generating multi-wavelength pulses with DBS. The proposed BEFL is capable of producing *Q*-switched pulses, which has many potential applications such as in super-continuum generation.

4. Conclusion

A *Q*-switched MWBEFL is successfully demonstrated using an SWCNT–PEO SA. The SA is obtained by sandwiching the developed SWCNT–PEO film in between two FC/PC fiber connectors after depositing index-matching gel onto the fiber ends. The proposed laser generates a multi-wavelength comb with ten lasing lines with spacing of 0.158 nm using 2 km long DCF as the Bragg grating mirror in conjunction with a figure-of-eight configuration with a four-port circulator. *Q*-switched pulse trains with a repetition rate of 105.2 kHz and a pulse width of 0.996 µs are also achieved at the 1480 nm pump power of 120 mW and BP power of 5.4 dBm.

References

[1]
Skorczakowski M et al 2010 Mid-infrared Q-switched Er:YAG laser for medical applications Laser Phys. Lett. ***7*** *498–504* IOPscience

[2]
Andrés M V, Cruz J L, Díez A, Pérez-Millán P and Delgado-Pinar M 2008 Actively Q-switched all-fiber lasers Laser Phys. Lett. ***5*** *93–9* IOPscience

[3]
Garnov S V et al 2007 Passive mode-locking with carbon nanotube saturable absorber in Nd:GdVO4 and Nd:Y0.9Gd0.1VO4 lasers operating at 1.34 μm Laser Phys. Lett. ***4*** *648–51* IOPscience

[4]
Yap Y K, De La Rue R M, Pua C H, Harun S W and Ahmad H 2012 Graphene-based Q-switched pulsed fiber laser in a linear configuration Chin. Opt. Lett. ***10*** *041405* CrossRef

[5]
Kurkov A S 2011 Q-switched all-fiber lasers with saturable absorbers Laser Phys. Lett. ***8*** *335–42* IOPscience

[6]
Pan L, Utkin I and Fedosejevs R 2007 Passively Q-switched ytterbium doped double-clad fiber laser with a Cr^{4+}:YAG saturable absorber IEEE Photon. Technol. Lett. ***19*** *1979–81* CrossRef

[7]
Huang J Y, Huang W C, Zhuang W Z, Su K W, Chen Y F and Huang K F 2009 High-pulse-energy, passively Q-switched Yb-doped fiber laser with AlGaInAs quantum wells as a saturable absorber Opt. Lett. ***34*** *2360–2* CrossRef

[8]
Zhou D P, Wei L, Dong B and Liu W K 2010 Tunable passively Q-switched erbium-doped fiber laser with carbon nanotubes as a saturable absorber IEEE Photon. Technol. Lett. ***22*** *9–11* CrossRef

[9]
Luo A, Luo Z and Xu W 2011 Switchable dual-wavelength passively mode-locked fiber ring laser using SESAM and cascaded fiber Bragg gratings Laser Phys. ***21*** *395–8* CrossRef

[10]
Shahabuddin N S, Ahmad H, Yusoff Z and Harun S W 2012 Spacing switchable multiwavelength fiber laser based on nonlinear polarization rotation and Brillouin scattering in photonic crystal fiber IEEE Photon. J. ***4*** *34–8* CrossRef

[11]
Liu Y G, Dong X, Shum P, Yuan S, Kai G and Dong X 2006 Stable room-temperature multi-wavelength lasing realization in ordinary erbium-doped fiber loop lasers Opt. Express ***14*** *9293–8* CrossRef

[12]
Shahi S, Harun S W and Ahmad H 2009 Multi-wavelength Brillouin fiber laser using Brillouin–Rayleigh scatterings in distributed Raman amplifier Laser Phys. Lett. ***6*** *737–9* IOPscience

[13]
Harun S W, Shirazi M R and Ahmad H 2007 Multiple wavelength Brillouin fiber laser from injection of intense signal light Laser Phys. Lett. ***4*** *678–80* IOPscience

[14]
Shahi S, Harun S W and Ahmad H 2009 Multi-wavelength Brillouin fiber laser using a holey fiber and a bismuth-oxide based erbium-doped fiber Laser Phys. Lett. ***6*** *454–7* IOPscience

[15]
Shahabuddin N S, Ahmad H, Yusoff Z and Harun S W 2012 Spacing-switchable multiwavelength fiber laser based on nonlinear polarization rotation and Brillouin scattering in photonic crystal fiber IEEE Photon. J. ***4*** *34–8* CrossRef
[16]
Ahmad B A, Al-Alimi A W, Abas A F, Harun S W and Mahdi M A 2012 Stable double spacing multiwavelength Brillouin erbium doped fiber laser based on highly nonlinear fiber Laser Phys. ***22*** *977–81* CrossRef

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