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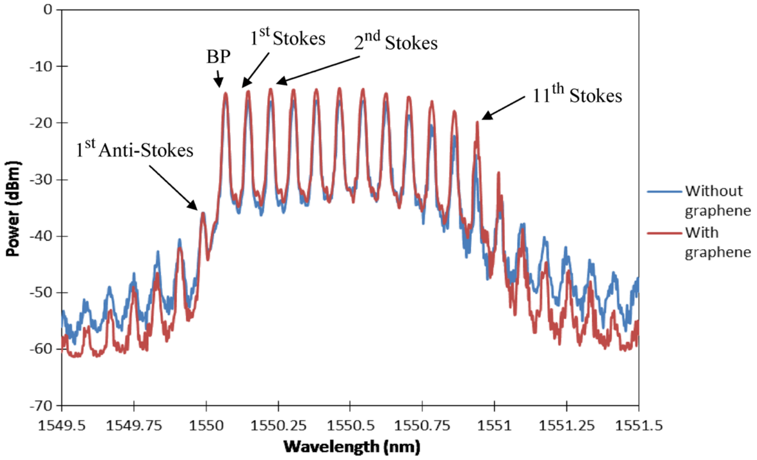

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Passively Q-Switched 11-Channel Stable Brillouin Erbium-Doped Fiber Laser With Graphene as the Saturable Absorber

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Abstract: A passively Q-switch Brillouin erbium-doped fiber laser (BEDFL) with 11 stable lasing wavelengths at peak power of -15 dBm between 1550.1 nm to 1551.0 nm, 1.67-μs pulsewidth, and repetition rate of 152.40 kHz is demonstrated. The proposed BEDFL uses a 7.7-km dispersion compensating fiber (DCF), assisted by an erbium-doped fiber amplifier (EDFA) to generate the multiwavelength output by stimulated Brillouin scattering. A graphene layer embedded in the laser cavity acts as a saturable absorber, allowing for Q-switched pulses.

Index Terms: Brillouin fiber laser, graphene, Q-Switch fiber laser.

1. Introduction

Research on multiwavelength fiber lasers (MWFLs) is a topic of contemporary interest due to potential applications in dense wavelength division multiplexed (DWDM) optical communication systems besides other attractive applications in areas as diverse as optical fiber sensors, optical metrology, photonics true-time-delay (TTD) beam-forming systems, and photonic component characterization [1]–[4]. Although there have been various approaches to realize MWFL, all-fiber Q-switched MWFL is an attractive platform for example to study supercontinuum generation and also for terahertz generation. Generally, for terahertz generation, multiwavelength lasers such as dual-wavelength lasers with closely spaced lines are required, either as a high-power continuous wave (CW) or pulse laser sources. An all-fiber Q-switched MWFL is reported in [5], which exploits an electronically scanned Fabry–Perot (FP) filter for Q-switching and wavelength selection. However, relatively high insertion loss and complexity involved in the system are issues that need to be addressed for their real-world utilization. Lately, the Q-switched operation in fiber laser by employing graphene as a saturable absorber (SA) is attracting a lot of attention [6]–[8] due to its unique properties like high electron mobility, low insertion loss, good optical transparency, zero band-gap energy, and ultrawide band tunability due to the linear dispersion of the Dirac electrons [9]. In addition, the saturation behavior, which is triggered by Pauli blocking [10], allows graphene to be a good SA. Application of graphene for obtaining a multiwavelength Q-switched fiber laser based on four-wave mixing (FWM) has been already demonstrated by Luo et al. [11] with a minimum pulse duration of 2.5 μs and maximum pulse repetition rate of 63.0 kHz. Another interesting approach for

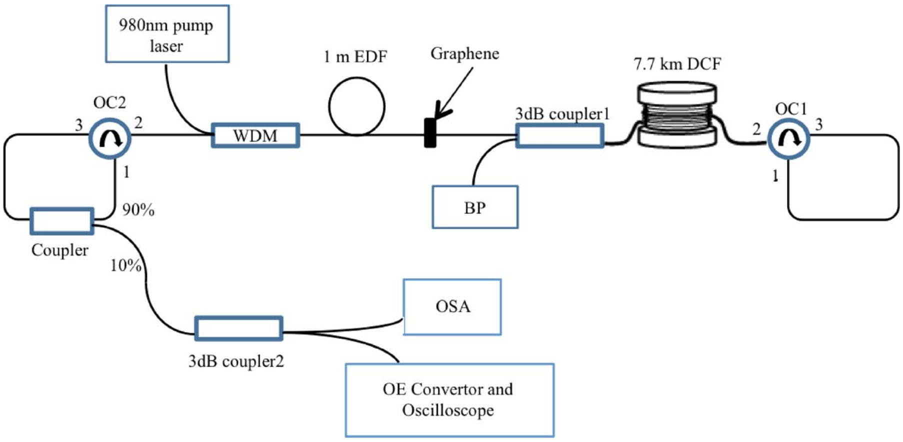

Fig. 1. Experimental setup of the graphene-based Q-switched multiwavelength BEDFL (WDM: wavelength-division multiplexer; EDF: erbium-doped fiber, BP: Brillouin Pump, DCF: dispersion compensated fiber, OC1, OC2: optical circulators; OSA: optical spectrum analyzer).

creating the pulsed multiwavelength fiber laser is based on stimulated Brillouin scattering (SBS) as it offers passive all-fiber solution, which has the potential to yield low-cost supercontinuum generation [12]. Besides that, the pulsed multiwavelength fiber laser based on SBS is compatible for nonlinear fiber application, provided that nanosecond pulses could be generated [13]. SBS-based multiwavelength fiber laser is usually formed by combining Brillouin with erbium-doped fiber (EDF) gains in tandem to form Brillouin erbium-doped fiber laser (BEDFL), by exploiting the broad-gain spectrum of the EDF [14].

In this paper, we investigate and demonstrate realization of pulsed output from a multiwavelength BEDFL by incorporating graphene as the SA for passive Q-switching. To the best of our knowledge, this is the first demonstration of a passively Q-switched BEDFL with graphene as the SA, which allows simultaneous control of the pulse repetition rate and the number of generated Brillouin Stokes' through variation in the pump power. Our results confirm utility of integrating graphene as SA in a BEDFL layout to yield a multiwavelength pulsed fiber laser. This MWFL can find application as a source for terahertz generation by filtering a two-wavelength output from the rest for mixing purposes.

2. Experimental Setup

Fig. 1 shows the experimental setup for the graphene-based Q-switched multiwavelength BEDFL that is constructed in a linear cavity geometry, with a pair of optical circulators connected at the end of both sides of the cavity.

The Q-switched multiwavelength BEDFL uses a 7.7-km dispersion compensating fiber (DCF) with an effective mode area (A_{eff}) of 15 μm^2 as the nonlinear medium for generating the multiwavelength output through the SBS process. A tunable laser source (TLS), giving an output power of 10.9 dBm at a wavelength of 1550.1 nm, is used as the BP and is injected into the linear cavity through a 3-dB coupler placed just before the 7.7-km DCF. The BP is used to generate the first Stokes wavelength in the DCF, which travels in the opposite direction of the BP towards the graphene layer and then towards a 1-m highly doped EDF (LIEKKI Er80-8/125), which has a mode field diameter of 9.5 μm at 1550 nm, as well as core absorption coefficients of 41 and 80 dB/m at 980 and 1530 nm, respectively. The EDF is pumped by a 980-nm laser diode through a wavelength division multiplexing (WDM) coupler, with the other port connected to Port 2 of the optical circulator OC2. Port 3 of OC2 is connected to Port 1 through a 90:10 optical coupler and acts as a “mirror” for the linear cavity. The 10% port of the optical coupler is connected to a 3-dB coupler, designated 3-dB coupler 2 in Fig. 1, and the outputs of the 3-dB coupler are connected to an optical spectrum analyzer (OSA) and an opto-electronic (OE) converter, together with an oscilloscope for the purpose of measuring pulse characteristics of the generated output. The other end of the DCF is connected to

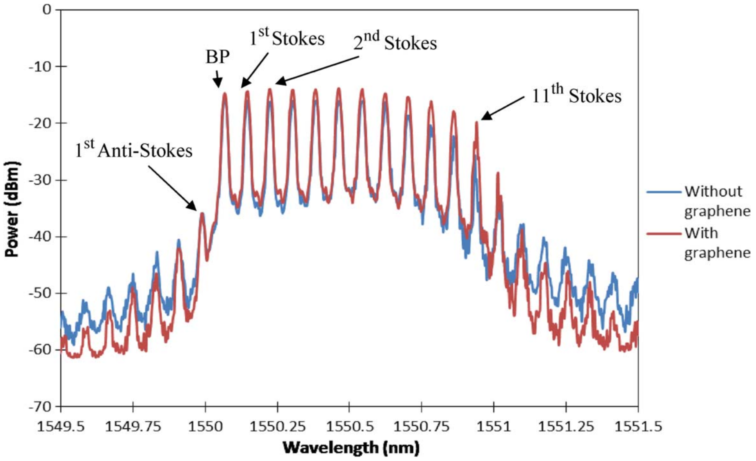

Fig. 2. Output spectrum of the multiwavelength BEDFL with and without graphene as an SA in the linear cavity configuration, showing the generation of Stokes and anti-Stokes lines as well as their output powers.

Port 2 of another optical circulator, OC1, which is routed by connecting Port 3 to Port 1 to act as the second “mirror” in the linear cavity. The working mechanism of the cavity can be divided into two cases, i.e., with and without graphene acting as an SA in the cavity. In the case of the cavity without the graphene, the BP moves from left to right into the DCF towards OC1. The first Stokes is generated in the DCF and moves from right to left, towards the EDF gain medium, and will be amplified before being reflected back by OC2 into the gain medium for further amplification. The first Stokes then travels back into the DCF to generate the second Stokes, which travels backwards towards OC2, and will be reflected into the gain medium and move towards the DCF. The BP, which is emitted from the DCF, will be reflected by OC1 and will travel from right to left into the DCF to generate the first Stokes that travels from left to right towards OC1 and will be reflected back into the DCF to generate the second Stokes and so forth. This power of the Stokes generated closely follows the gain spectrum of the EDF. The generation of Stokes lines will take place until the power of the preceding Stokes falls below the threshold power for generating further Stokes lines based on the SBS process. Anti-Stokes lines are also generated based on the FWM effect. This experimental measurement is repeated with the addition of the graphene layer in the cavity, as shown in Fig. 1. From the observation that will be discussed in the next section, the graphene layer aids in the output power of the generated Stokes lines, while at the same time giving the multiwavelength Q-switched output.

The graphene layer used in this paper is formed on the face of the fiber ferrule using the optical deposition technique, which has been described in detail in reference [15]. The setup consists of an amplified spontaneous emission (ASE) with an average power of 15 dBm that is injected into a pigtailed optical fiber, with the connector end immersed in the graphene solution. The graphene layer is formed through the induced process of thermophoresis, whereby the graphene layer will be automatically deposited onto the fiber ferrule. Basically, the formation of the graphene layer is based on the optical trapping and heat convection effects. After 30 min, the ferrule is lifted from the solution, and the excess solution is allowed to evaporate for 30 min. The graphene itself is obtained from Graphene Research Ltd. in the form of an aqueous solution consisting of graphene flakes with an average flake thickness of 0.35 nm (approximately one monolayer) and an average lateral particle size of $\sim$550 nm (150–3000) nm. The graphene flakes are suspended in a N-methyl Pyrrolidone solution, as in a similar case to that of [16] and [17].

3. Results and Discussion

Fig. 2 shows the output spectrum of the multiwavelength BEDFL with and without incorporation of graphene as an SA within its linear cavity. The BP power is set at 10.9 dBm and a wavelength of 1550.1 nm, while the 980-nm pump is operated at an optical output power of 267.25 mW.

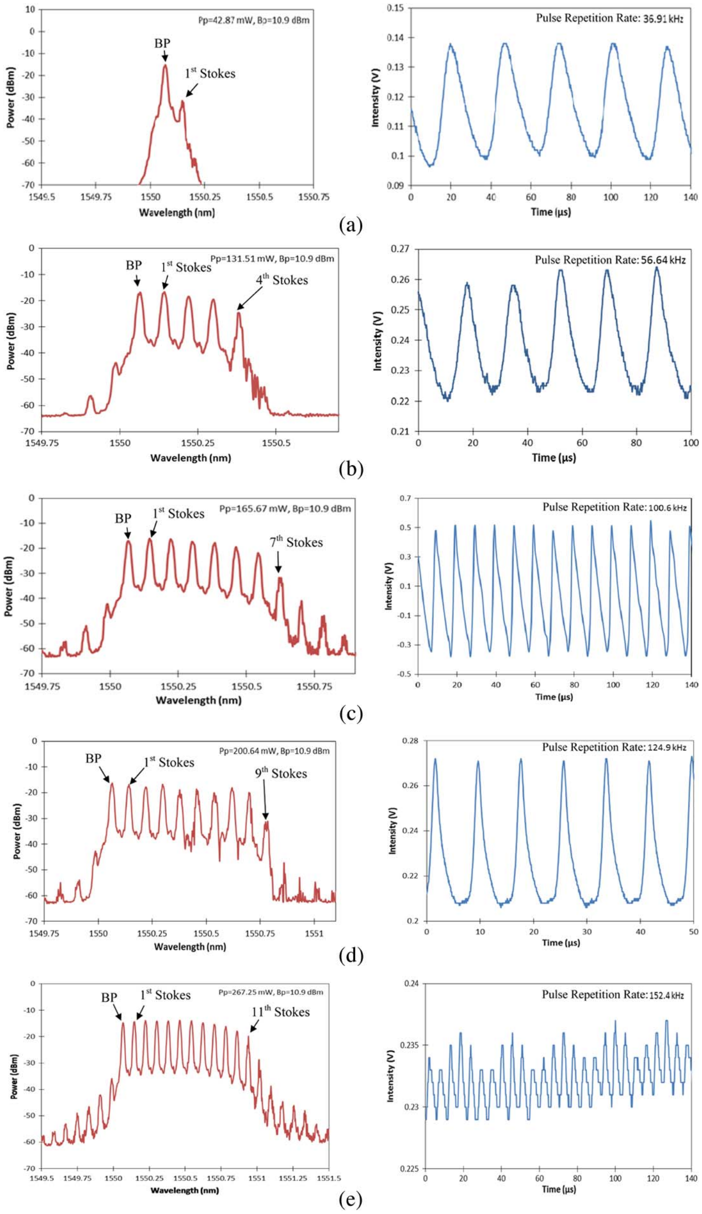

Fig. 3. Measured Stokes lines, pulse repetition rate and pulsewidth for different 980 pump powers. (a) *Left:* Observed optical spectrum as taken from the OSA which shows the BP as well as the first Stokes generated. *Right:* The generated Q-switched pulses as taken from the oscilloscope, giving a pulse repetition rate of 39.61 kHz and a pulsewidth of 12.17 μs. Both measurements are taken at a laser pump power to the EDF at 42.87 mW. (b) *Left:* Observed optical spectrum as taken from the OSA which shows the BP as well as the 1st, 2nd, 3rd and 4th Stokes generated. *Right:* The generated Q-switched pulses as taken from the oscilloscope, giving a pulse repetition rate of 56.64 kHz and a pulsewidth of 5.96 μs. Both measurements are taken at a laser pump power to the EDF at 131.51 mW. (c) *Left:* Observed optical spectrum as taken from the OSA which shows the BP as well as the 1st to 7th well defined Stokes, and 3 smaller Stokes generated. *Right:* The generated Q-switched pulses as taken from the oscilloscope, giving a pulse repetition rate of 100.60 kHz and a pulsewidth of 4.79 μs. Both measurements are taken at a laser pump power to the EDF at 165.67 mW. (d) *Left:* Observed optical spectrum as taken from the OSA which shows the BP as well as the 1st to 9th well defined Stokes. *Right:* The generated Q-switched pulses as taken from the oscilloscope, giving a pulse repetition rate of 124.90 kHz and a pulsewidth of 1.72 μs. Both measurements are taken at a laser pump power to the EDF at 200.64 mW. (e) *Left:* Observed optical spectrum as taken from the OSA which shows the BP as well as the 1st to 11th well defined Stokes. *Right:* The generated Q-switched pulses as taken from the oscilloscope, giving a pulse repetition rate of 152.40 kHz and a pulsewidth of 1.67 μs. Both measurements are taken at a laser pump power to the EDF at 267.25 mW.

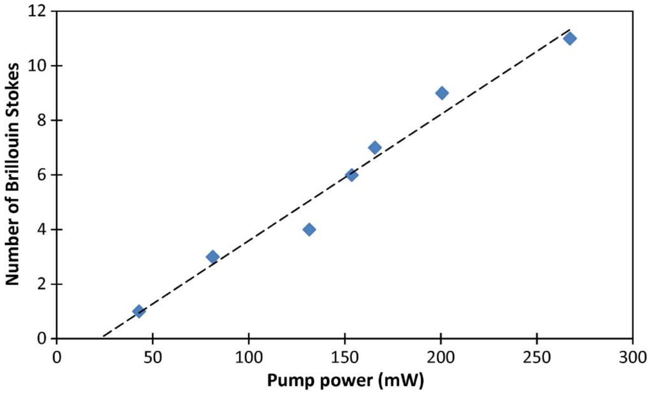

Fig. 4. Number of Stokes at different laser diode pump powers to the EDF.

Under these conditions, about 11 lasing wavelengths with flat and stable output powers of approximately −14 dBm are obtained, spanning from 1550.1 to 1550.9 nm. It can be observed from Fig. 2 that the BEDFL spectrum is similar for both cases, i.e., with and without graphene, although a higher output power is obtained when the graphene layer is present in the cavity. However, this is only valid for the first 12 Stokes, after which the system without graphene has a higher peak power. This is because, at the low gain area of the EDF, the output power is low, and therefore, there is some absorption occurring in the graphene layer, in turn lowering the output power. The same case can be made for the anti-Stokes, whereby the low gain area causes absorption by the graphene layer, in turn lowering the output power. The anti-Stokes that are generated are based on the FWM effect, whereby the first anti-Stokes arises from the interaction between the BP and the first Stokes. The second anti-Stokes results from the FWM interaction between the BP and the second Stokes, and this process continues, thus generating the anti-Stokes lines, as observed in the figure.

Fig. 3(a)–(e) shows the output spectrum taken from the OSA, as well as the corresponding pulses obtained from the OE converter, which is connected to a 500-MHz oscilloscope, showing the pulsewidth and repetition rate. The BP is kept constant at 1550.1 nm at a power of 10.9 dBm, while the EDF pump power is increased from 42.87 mW to 267.25 mW. In the case of the lowest pump power of 42.87 mW, as shown in Fig. 3(a), only a single Stokes line is generated at 1550.2 nm. At this point, the pulse repetition rate measured is about 36.91 kHz, with a pulsewidth of 12.17 μs. As the pump power is increased to 131.51 mW, as shown in Fig. 3(b), the number of Stokes lines obtained also increases to four lines with a power of approximately −20 dBm. The corresponding pulse generated has a repetition rate of 56.64 kHz and a pulsewidth of 5.96 μs. Fig. 3(c) shows the multiwavelength spectrum obtained at a pump power of 165.67 mW, which gives seven Stokes lines with a stable power of approximately −20 dBm, and pulses with a repetition rate of 100.60 kHz, as well as a pulsewidth of 4.79 μs. Further increase in the pump power to 200.64 mW also gives an increase in the number of Stokes lines generated, in this case giving nine Stokes with powers of within −20 dBm, as shown in Fig. 3(d). The Q-switched pulses obtained at this power have a repetition rate of 124.90 kHz and a pulsewidth of 1.72 μs. At the maximum available pump power of 267.25 mW, 11 Stokes lines are generated with a fairly flat top output power of about −15 dBm, although there are many other lines also generated but at lower peak powers. The corresponding pulses as observed from the oscilloscope have a repetition rate of 152.40 kHz and a pulsewidth of 1.67 μs, as shown in Fig. 3(e).

The fluctuations in the Y-axis of the right-hand graph of Fig. 3(e) could be attributed to the increase of the number of Stokes lines generated. Since the output port is common, some interactions are possible between the Stokes lines, which may cause fluctuations. As a summary, the number of Stokes lines generated against the 980-nm pump power to the EDF is shown in Fig. 4. From the figure, it can be seen that the number of Stokes lines increases almost linearly with increased pump power, from only one Stokes line at a pump power of 42.87 mW to 11 Stokes lines at the maximum pump power of 267.25 mW. Using the curve-fitting method, a simple correlation

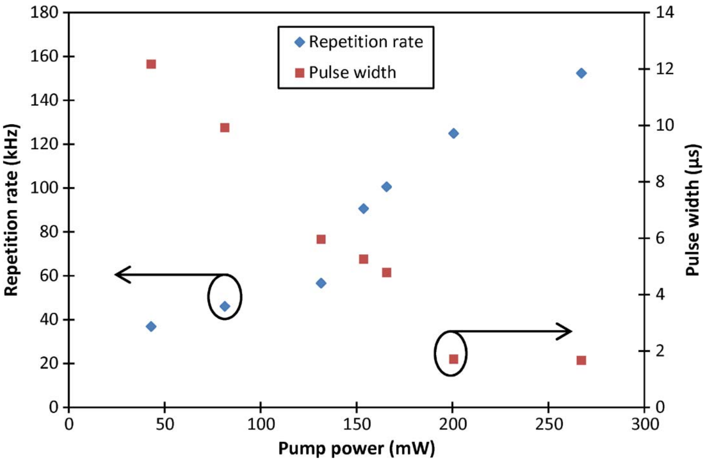

Fig. 5. Repetition rate and pulsewidth of the BEDFL for different laser diode pump powers to the EDF.

can be made, giving a slope efficiency of 0.0463 Stokes lines per mW. The gives new Stokes lines for every increase of about 25 mW in the pump power.

Fig. 5 shows the plot of the repetition rate and its pulsewidth of the pulses obtained from the BEDFL against the laser diode pump power to the EDF. Higher repetition rates are obtained as the pump power is increased, from a minimum value of 36.91 kHz at a pump power of 42.87 mW to a maximum repetition rate of 152.40 kHz at 267.25 mW. The repetition rate of the pulses obtained also increases almost linearly as the pump power is raised. The pulsewidth, on the other hand, is inversely proportional to the pump power, whereby the largest pulsewidth of 12.17 μs is obtained at the lowest pump power of 42.87 mW, while the smallest pulsewidth of 1.67 μs is obtained at the highest pump power of 267.25 mW.

The proposed BEDFL has potential application as a source for generating terahertz signals, whereby closely spaced lines are required and normally, for effective terahertz generation, a laser output with a tunable spacing operating in a pulse mode will be an advantage, given the necessary peak power. Although these lines are emitted simultaneously, with a channel spacing of 0.08 nm, which is due to the SBS effect, individual channels can be retrieved using an fiber Bragg grating (FBG) with a 3-dB reduced bandwidth as small as 0.04 nm [18]. Alternatively, the extraction of the wavelengths can also be accomplished using a phase-shift FBG with full width at half-maximum (FWHM) bandwidth of about 0.026 nm, which can be commercially acquired from companies such as O/E Land Inc. [19].

4. Conclusion

A Q-switched BEDFL using graphene as an SA has been proposed and demonstrated. The BEDFL uses a 7.7-km DCF and a conventionally pumped EDF in a linear cavity to generate Brillouin Stokes. Up to 11 Stokes wavelengths with a flat output of -15 dBm over a wavelength range of 1550.1 nm to 1551.0 nm are obtained at a BP power of 10.9 dBm and a maximum EDF pump power of 267.25 mW. By varying the laser diode pump power to the EDF, the pulsewidth and repetition rate can be varied, with a pulsewidth as small as 1.67 μs and a repetition rate as high as 152.40 kHz being obtained at the maximum laser diode pump power to the EDF. The proposed BEDFL can be used as a source for generating terahertz signals due to its ability to generate closely spaced lasing wavelengths in a pulse mode.

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