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Improved Q-Switching pulse Performance in Multi-Wavelength Brillouin-Erbium Doped Fiber Laser

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ABSTRACT

Employing a highly nonlinear, 4.5-meter-long Erbium-doped fiber (EDF) as the hybrid gain medium, a self-Q-switched laser produced the Q-Switched pulses in multiwavelength. The laser's repetition rate could be adjusted between 15.46 and 57.31 kHz, and its center operating wavelength was approximately 1594 nm. A multi-wavelength Brillouin Erbium fibre laser (BEFL) operating in the L-band was successfully activated using stimulated Brillouin scattering (SBS). By varying the input pump power within the range of 64.8 mW to 259.4 mW, the pulse width can be controlled from 16.14 to 8.50 µs using less than 156.4 mW of pump power. The SBS-based Q-switched laser showed exceptional stability with a maximal pulse energy of 84.10 nJ, and the fundamental radio frequency signal-to-noise ratio (SNR) reached a high of 70.45 dB. Notably, no actual saturable absorber components were used in this experiment, making it the first successful implementation of a BEFL with multi-wavelength output that is Q-switched using SBS.

1. Introduction

In the last few years, multi-wavelength fiber lasers offer many advantages, including low cost, high beam quality, and excellent heat dissipation properties, and have gained significant importance in various fields in recent years. Due to its potential uses in optical communication systems, dense wavelength division multiplexing (DWDM), optical fibre sensing, optical instrument testing, and microwave photonics, erbium-doped fibre lasers (EDFLs) are of great interest [1, 2].

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Several techniques have been suggested and shown to reduce mode competition in EDF, including nonlinear effects like stimulated Brillouin scattering (SBS), nonlinear polarization rotation (NPR), and four-wave mixing (FWM) [3-5].

Multi-wavelength fibre lasers are adaptable and can be used in a variety of applications such as spectroscopy, optical sensing, microwave photonics, and optical communication [6].

Stimulated Brillouin scattering (SBS) is a nonlinear phenomenon that produces a down-shifted Stokes signal by consuming pump energy when a certain threshold is surpassed [7]. An acoustic wave is produced through the interaction between the pump wave and a nonlinear material while obeying momentum and energy conservation. SBS-based multi-wavelength lasers have received considerable attention, and the magnitude of the Brillouin shift differs for different fiber types [8]. In the 1550 nm region, for example, silica-based single-mode fibers (SMFs) have an estimated Brillouin shift of 10 GHz or 0.08 nm [9, 10].

With optical gains in both the normal 1550 nm band (C-band) and the long wavelength band (L-band, 1570–1620 nm), EDFs have garnered attention for their potential to take advantage of the available bandwidth in optical fibers [11, 12]. In recent years, the L-band has gained popularity, leading to several studies on L-band EDF amplifiers (EDFAs) and fiber lasers (EDFLs), as well as numerous successful transmission experiments in the L-band [13, 14].

Q-switched EDFLs have numerous applications in fields such as telecommunications, sensing, and medicine, making them a compelling choice [15]. However, there is a need for better performance, such as higher pulse energy, and designing new Q-switched fiber lasers is imperative [16, 17]. Q-switched laser operation can be achieved using active or passive Q-switching technique [18, 19]. In Q-switched fiber lasers, the stochastic stimulated Brillouin scattering (SBS) process within the laser cavity is the main factor contributing to pulse jitter [20, 21].

Recent reports suggest that SBS-induced pulses can be generated in EDFLs. This phenomenon is attributed to the operation of rare-earth-doped fiber lasers with Q-switching modes, which often accompanies laser power exceeding the relatively low SBS threshold in single-mode fiber.

2. Methodology and Experimental Setup

The Q-switched multi-wavelength EDFL was created using an all-fiber ring arrangement, as shown in Figure 1. The active medium chosen was the Fiber core I-25 Erbium doped fiber (EDF), with an Erbium-ion concentration of 2200 ppm, due to its strong nonlinearity. The EDF has a mode-field diameter of 6 m, a numerical aperture of 0.24, 950 nm cut-off wavelength, and core absorption of 90 dB/m at 980 nm. The EDF length of 4.5 m was chosen to offer enough nonlinear and linear gain for the Brillouin Erbium fibre laser (BEFL), and it effectively absorbs pump light along its entire length. The fiber is believed to contain 12500 weight ppm of Erbium ions. The laser cavity has an overall length of 10.22 m, with a 980 nm laser diode that back-pumps the HB-EDF and EDF through a 980/1550 nm wavelength division multiplexer (WDM). An 80/20 output coupler is used to tap the laser output, which can be used for subsequent monitoring or application. Inside the laser cavity, a polarization-insensitive optical isolator is used to assure unidirectional transmission and prevent bidirectional transmission.

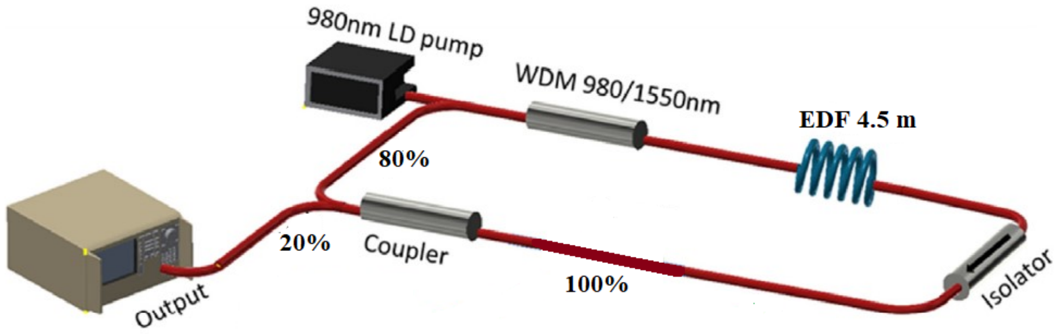

Fig. 1. Q-switch multi-wavelength BEFL configuration

By boosting the Brillouin signal and decreasing the threshold for stimulated Brillouin scattering (SBS) with an intra-cavity Erbium-doped fibre amplifier, the Brillouin fibre laser (BFL) generates and oscillates the Stokes wave (EDFA). All optical parts are directly spliced into the cavity to reduce cavity loss. With the help of an optical spectrum analyzer (OSA) with a resolution of 0.015 nm, the spectral characteristics of the laser output are identified. A digital oscilloscope and a radio frequency (RF) spectrum analyzer operating at 7.8 GHz are used to measure the repetition rate and stability of the Q-switched laser, respectively. The power meter and its power head measure the average laser output power, and a fast photodetector converts the measurement into an electrical signal.

3. Results

3.1 Output Optical Spectrum

We initially kept an eye on the BEFL's optical spectrum while its pump power was gradually increased. The results of this experiment at three different pump powers (59.1 mW, 107.7 mW, and 156.4 mW) are presented in Figure 2. Even with a modest pump power of 64.8 mW, using a channel spacing of 0.08 nm, we were successful in developing a Brillouin laser with several wavelengths. Several wavelengths could be produced by combining nonlinear Brillouin gain with linear EDF gain, which is a uniform phenomenon. As the pump power increased, the number and intensity of both Stokes and anti-Stokes lines increased. At a pump power of 156.4 mW, we obtained an optical comb with a minimum of 50 Stokes and anti-Stokes lines with identical spacing. The optical comb in Figure 2 shifted slightly towards shorter wavelengths as the pump power increased. When the pump power was increased from 64.8 mW to 259.4 mW, the peak wavelength changed from 1694.04 nm to 1593.86 nm. This shift, which also occurred at shorter wavelengths with the rise in power, is a result of EDF income. The wavelength comb of the anti-Stokes was shifted towards the blue end of the spectrum as a result, generating the subsequent Stokes at a shorter wavelength.

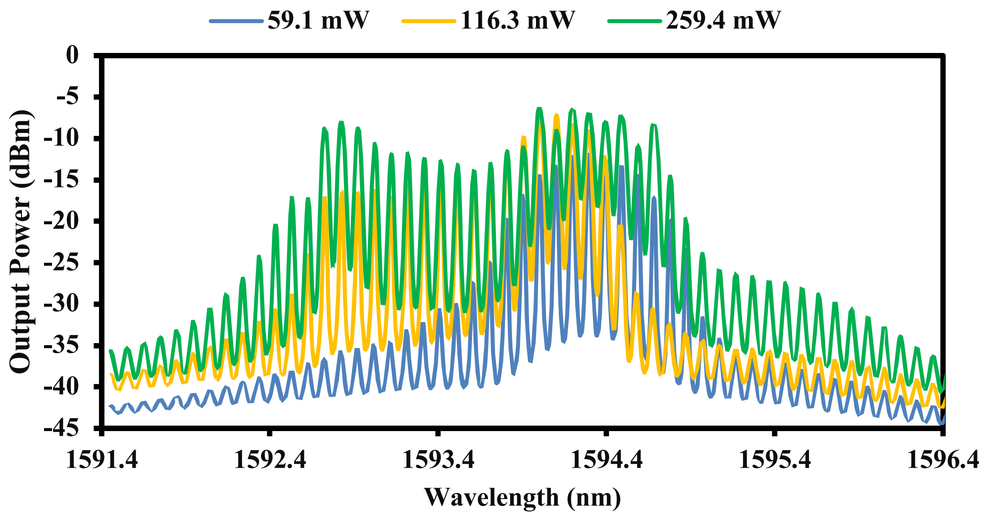

Fig. 2. depicts the output spectrum combs and measured output pulse trains of the BEFL under various pump power conditions

A high-speed sensor and a digital oscilloscope were utilised to study the time-related properties of the BEFL, and a series of pulses was detected when the pump power reached 64.8 mW. This event happens as a result of the ring structure's nonlinear self-Q-switching process. Because of the inherent instability in relaxation oscillation, an increase in SBS in the BEFL cavity causes a chain reaction of avalanche events, resulting in the SQS effect. As the 980 nm pump was tuned, During the power range of 64.8 mW to 162.3 mW, a dependable and long-lasting Q-switched pulse train was generated. 3.2 A strong and reliable pulse train using a Q-switch.

Figure 3 and Figure 4 shows the illustrate the oscilloscope trace of the laser under maximum pump power. The regularity of SQS pulsing increases as well as the pulse repetition rate with the increase of pump power. The pulse-to-pulse period decreases from 16.14 µs to 8.5 µs, which corresponds to an increase in repetition rate from 15.46 kHz to 57.31 kHz, as pump power is increased from 64.8 mW to 162.3 mW. An active EDF with a high level of inversion can indeed be emitted as Q-switched pulses because of the low Q-factor that the SBS process in the EDFL cavity causes. It is worth noting that the Q-switched pulse generation disappears as the pump power is increased beyond 162.3 mW, and the comb generation process stabilizes.

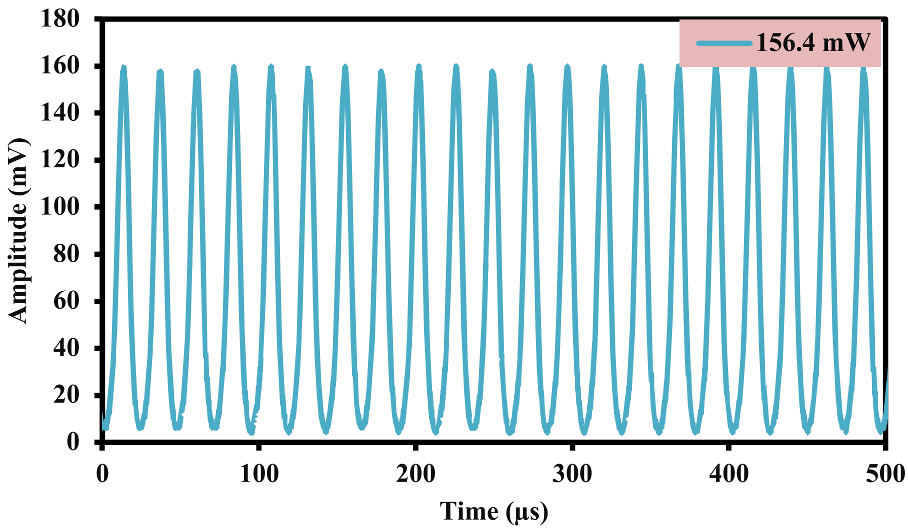

Fig. 3. Measured the output of pulse trains for the maximum pump power 156.4 mW

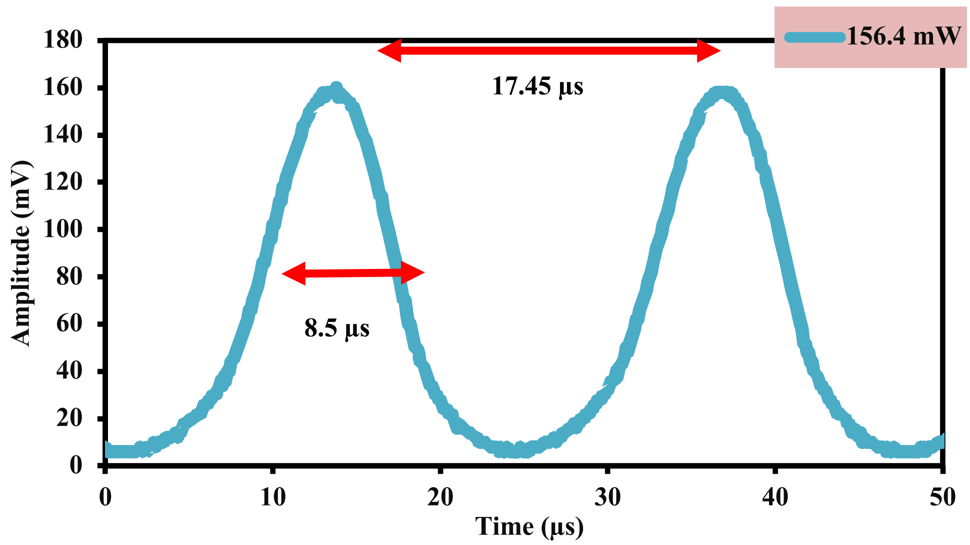

Fig. 4. Measured the highest period and repetition rate for one single pulse

3.2 The RF Spectrum Absorption

The RF spectrum is displayed in Figure 5, with a pump power of 162.3 mW. The fundamental RF peak, operating at 57.31 kHz, matches the oscilloscope data. Increasing the pump power is observed to increase the SNR, with a measurement of 70.45 dB at 156.4 mW. A high SNR above 50 dB suggests the Q-switched laser is very stable. Furthermore, the laser generated a stable pulse train with significantly low noise fluctuation, Justifying the suggested SBS-based Q-switched laser's stability and viability.

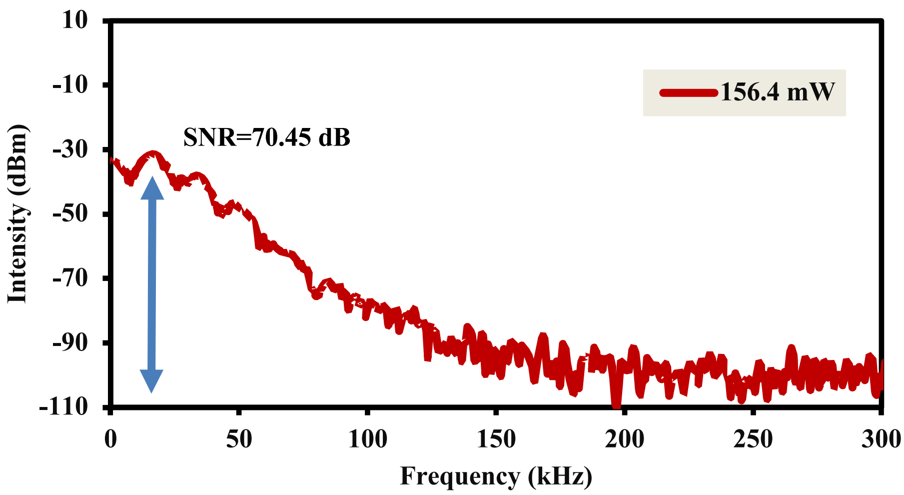

Fig. 5. RF spectrum under the maximum 156.4 mW pump power

The cavity quality (Q)-factor of an erbium-doped fibre laser (EDFL) is low due to the stimulated Brillouin scattering (SBS) mechanism. As a result, the active EDF can achieve a high level of inversion, which is subsequently released as a Q-switched pulse. When 980 nm light is supplied into the EDF, population inversion in the gain medium commences, culminating in laser production via stimulated emission. Due to the BFL fundamental competition between gain and loss in the ring cavity, the basic Brillouin laser develops slowly. Since there is strong enough feedback supplied by the ring cavity and the substantial gain produced by SBS, many Stokes waves are created at the SBS threshold. Because of the high gain and temporal jitter imposed by the stochastic nature of the SBS process, these Stokes waves fluctuate in the laser cavity, boosting the inverse population and producing a pulse. Ultimately, a huge Stokes wave pulse of many orders is generated.

Figure 6 shows how pulse width and repetition rate fluctuate as input pump power varies. As the pump power increases from 64.8 mW to 162.3 mW, the pulse width reduces to 8.5 s, while the repetition rate increases accordingly from 15.46 kHz to 57.31 kHz. The connection between single pulse energy, average output power, and incident pump power is depicted in Figure 7. Both single pulse energy and average output power increase constantly as pump power increases. The highest possible pulse energy is 84.1 nJ, while the highest possible output power is 4.82 mW. As the pump power exceeds 162.3 mW, the Q-switched pulses become unstable and disappear.

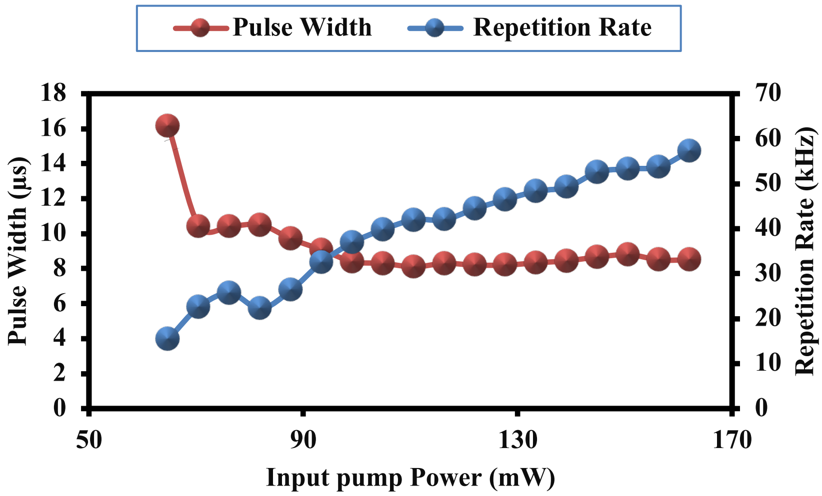

Fig. 6. Pulse width and repetition rate of the laser respond

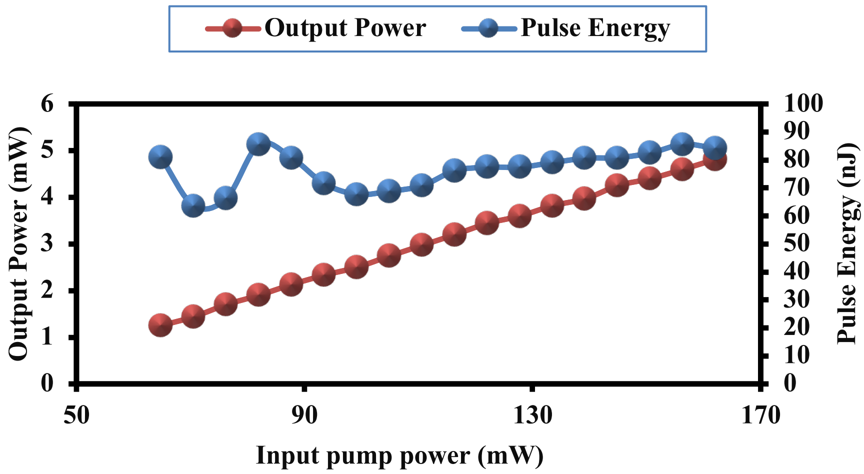

Fig. 7. Output power and pulse energy of the laser respond

4. Conclusions

The stochastic character of the SBS process allowed for the successful demonstration of a self-Q-switched multiwavelength BEFL. By adjusting the pump power to between 64.8 mW and 156.4 mW, we were able to produce brief pulses at a frequency ranging from 15.46 kHz to 57.31 kHz, with a central wavelength of approximately 1594 nm. The laser's highest pulse energy and shortest pulse width were 84.1 nJ and 8.5 µs, respectively. The SNR of the fundamental was up to 70.45 dB, indicating stable operation of the output pulses. This achievement could be a starting point for further SBS research, particularly for the development of cost-effective and widely available Q-switched lasers.

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