# Investigation of Q-Switching Characteristics in Single- and Double-Spacing Multi-Wavelength Brillouin Erbium Fiber Laser

A multi-wavelength Brillouin erbium fiber laser (BEFL) with a Q-switching characteristic is demonstrated using a piece of non-zero dispersion shifted fiber (NZ-DSF) as a Brillouin gain medium (BGM) in conjunction with relaxation oscillation technique. The performance of the multi-wavelength short pulse generation is investigated for two different BEFL configurations for single and double Brillouin spacing outputs. The Q-switched BEFL generates a pulse train with repetition rates of 10.36 and 20.41 kHz whose corresponding pulse widths are 13.21 and 3.84 μs for the single and double Brillouin spacing outputs, respectively. The self-starting pulses are obtained within a low 1480-nm pump power region at a slightly higher power than the lasing threshold power. This pulse laser based on stimulated Brillouin scattering (SBS) is fairly stable at room temperature.

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## SECTION 1
## INTRODUCTION

All-fiber Q-switched fiber lasers are of great interest for numerous applications such as marking, industrial micromachining, dermatology, and dentistry [1], [2]. Various techniques have been proposed to achieve Q-switching with high energy, high peak power, and short pulse emission [3], [4], [5]. The pulse duration of the Q-switched pulses generated by these techniques ranges from hundreds of nanoseconds to several tens of microseconds due to the long resonator lengths of typical fiber lasers. Recently, there have been reports on the use of stimulated Brillouin scattering (SBS) as a distributed passive Q-switching mechanism to generate short pulses that are much shorter than the resonator lengths [5], [6], [7], [8], [9], [10]. Unlike the conventional Q-switched fiber lasers, where the pulse duration is proportional to the photon lifetime in the resonator, the short pulses generated by SBS do not depend on the photon lifetime in the resonator but rather on the dynamics of the nonlinear process. For instance, Fan *et al.* [6] demonstrated a hybrid Q-switched ytterbium fiber laser with pulse duration of 5 ns by exploiting pulsed pump light and SBS of the gain fiber. More recently, Loranger *et al.* [10] proposed generating phase-locked pulses in the picosecond regime by using SBS. Two systems with two different repetition frequencies, 10.87 GHz and 21.74 GHz, corresponding to the SBS natural frequency in single mode fiber have been demonstrated in this paper.

Likewise, SBS based multi-wavelength lasers or Brillouin fiber lasers (BFLs) have also attracted considerable interest for various applications in dense wavelength division multiplexing (DWDM), fiber optic sensing, microwave photonics, and spectroscopy [11], [12]. To date, many works have been reported on multi-wavelength BFLs, which produce a wavelength comb with a constant spacing of 0.08 nm [13]. 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 strategies have been put forward to widen the channel spacing to facilitate demultiplexing. For an efficient multi-wavelength generation, a relatively long Brillouin gain medium (BGM) and high pump power are necessary to achieve sufficient gain to compensate for cavity loss and to achieve the threshold power for Brillouin Stokes generation. To meet these requirements, Brillouin erbium fiber laser (BEFL) is devised in which erbium-doped fiber (EDF) is added in the cavity to provide an additional gain to assist in the Stokes generation. A BEFL with a quasi-periodic pulsation characteristic was reported based on a linear configuration with a single Brillouin spacing (BS) [12]. Recently, multi-wavelength BEFLs with double BS of around 0.16 nm have also been reported [14].

In this paper, Q-switched multi-wavelength BEFL is demonstrated using a piece of non-zero dispersion shifted fiber (NZ-DSF) as a BGM in conjunction with relaxation oscillation technique [15]. The performance of the multi-wavelength short pulse generation from two different BEFLs configurations is investigated for single and double BS outputs. The passive Q-switching through the relaxation oscillation technique is a self-starting process that does not require an intra-cavity modulator. It is observed that microsecond pulses in kHz range can be achieved by pumping the EDF within a low pump power range, which is slightly higher than the lasing threshold power. Compared with the previous work by Loranger *et al.* [10], the repetition rate of the proposed multi-wavelength Q-switched BEFL is determined by the cavity length instead of the SBS natural frequency.

## SECTION 2
## Experimental Setup

The Q-switching characteristics of two configurations of multi-wavelength BEFL as illustrated in Fig. 1 are investigated. Fig. 1(a) and (b) shows the BEFL setup with a single BS and double BS output, respectively. Both configurations use a 4.5 m long EDF and a 10 km long NZ-DSF as the gain media. The EDF has an erbium concentration of 2000 ppm, cutoff wavelength of 910 nm, pump absorption coefficient of 24 dB/m at 980 nm, and a dispersion coefficient of −21.64 ps/nm·km at $\lambda = 1550\ \mathrm{nm}$. It is pumped by a 1480-nm laser diode via a wavelength division multiplexer (WDM) to provide a linear gain in the 1550 nm region. The NZ-DSF has a dispersion coefficient of 6.7 $\mathrm{ps/nm \cdot km}$ at $\lambda = 1550\ \mathrm{nm}$. The Brillouin pump (BP) from an external cavity continuous wave tunable laser source is injected into the EDF loop via a 3 dB coupler. The amplified BP is then sent into the NZ-DSF from port 1 through port 2 of the optical circulator to generate backward-propagating SBS. In the first BEFL with a single BS of Fig. 1(a), an optical circulator is used at the output end of the NZ-DSF to act as a mirror and allow a double propagation of the pump and Brillouin Stokes in the gain medium before it is routed into the ring resonator via port 3. Ports 3 and 1 of this circulator are connected together to enable the injected signal from port 2 to be reflected back into the same port. The backward-propagating SBS will oscillate inside the resonator to generate the first Stokes once the BP power exceeds its threshold. The first Stokes signal is then re-injected into the NZ-DCF to act as a BP to generate the next Stokes. The cascading process continues to generate multi-wavelength comb spectrum with a single BS output. Polarization controller (PC) is used in Fig. 1(a) to adjust the polarization state of the light in the cavity, which can induce the intra-cavity filtering effect in the fiber laser.

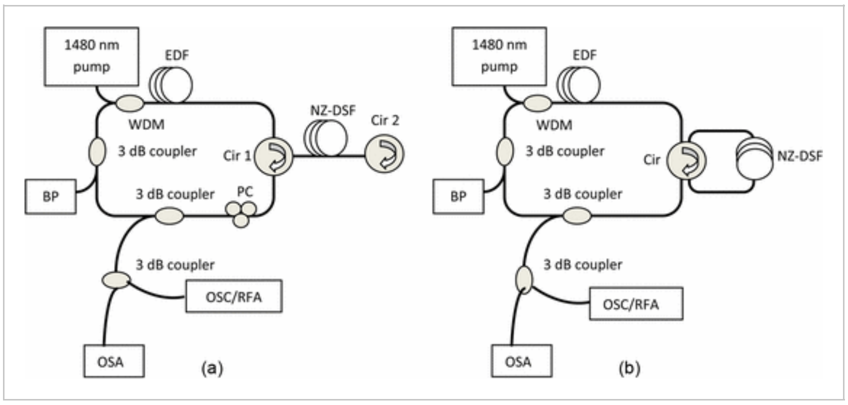


**Fig. 1.** Experimental set-up of the proposed multi-wavelength BEFL configured with (a) single BS and (b) double BS.

In the second BEFL of Fig. 1(b) for double BS, a four-port circulator is used to discriminate the odd and even order Stokes signals and, at the same time, to ensure unidirectional propagation of light. The backward-propagating SBS oscillates inside the NZ-DSF loop to generate the first Stokes once the BP power exceeds its threshold. The first Stokes signal is re-injected into the other end of the NZ-DSF in a counterclockwise direction to act as a BP to generate the next Stokes. The newly generated Stokes propagates in clockwise direction and gets amplified in both loops to generate newer Stokes in the opposite direction. The cascading process continues to generate multi-wavelength lasing whereby the odd-order Stokes lines in the NZ-DSF loop are blocked by the circulator, whereas the even-order Stokes lines are allowed to oscillate and build-up their intensity. Two 3 dB couplers are used to tap out the output from both setups so that its characteristics can be measured by an optical spectrum analyzer (OSA), oscilloscope (OSC), and radio frequency analyzer (RFA).

The temporal characteristic could be observed in both lasers when the first Stokes is generated at pump power of 27 mW and 24 mW for single- and double-spacing configurations, respectively. This is attributed to the nonlinear self-pulsing mechanism, which causes an inherent instability in relaxation oscillation. The growth of SBS in the BEFL cavity causes a series of avalanche processes leading to Q-switching. The instability is still present as the EDF is pumped at low power of up to 46 mW and 35 mW for BEFLs configured with single- and double-spacing multi-wavelength comb, respectively. As the pump power is increased further, the comb generation process stabilizes, and the pulse generation disappears.

## SECTION 3
## Results and Discussion

Fig. 2 shows the output spectra of the BEFL with a single BS at three different 1480 nm pump powers; 27 mW, 40 mW, and 121 mW. In the experiment, the BP power and wavelength are fixed at 5.4 dBm and 1563 nm, respectively. The BP wavelength is set to coincide with the peak lasing of the resonator without the BP to assist in Brillouin Stokes generation. A comb of lines is generated due to the cascaded Brillouin effect if the threshold condition is met. It is observed that a stable first Stokes is generated at 1480 nm pump power of around 26 mW. As shown in Fig. 2, the number of lines increases with the pump power. For instance, a total of 20 lasing lines are observed at 1480 nm pump power of 121 mW with a signal to noise ratio (SNR) higher than 10 dB. With a lower pump power of 40 mW, only 6 lines are obtained. This shows that the higher 1480 nm pump power provides a higher erbium gain to assist in generating more lasing lines. The higher gain boosts up a higher order Brillouin Stokes to reach their SBS threshold for oscillation in the cavity. The anti-Stokes lines are also observed at wavelengths shorter than the BP, which occurs due to four-wave mixing (FWM) effect. FWM is a nonlinear process where various Stokes waves interact with the pump wave to produce new wavelengths with lower power. The channel spacing between each consecutive Stokes and anti-Stokes line is constant at 0.086 nm as shown in Fig. 2.

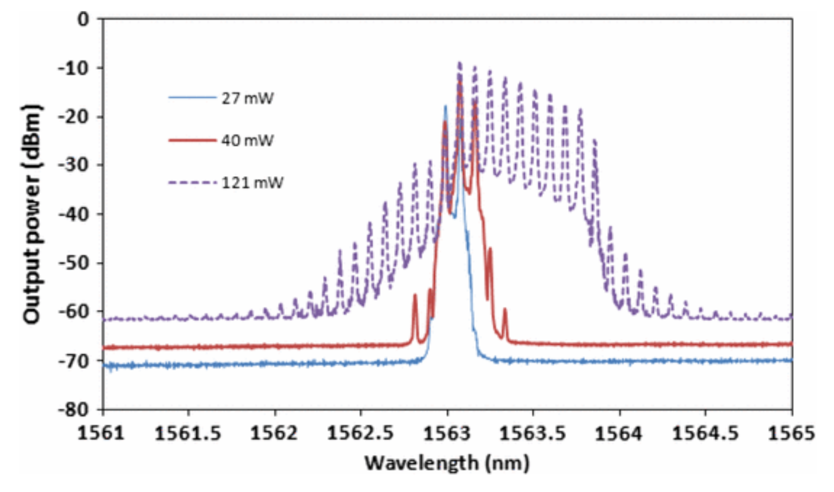


**Fig. 2.** Output spectra of the BEFL configured with a single BS at various 1480 nm pump power when the BP power is fixed at 5.4 dBm.

The temporal characteristics of the multi-wavelength BEFL are also investigated as shown in Fig. 3. A stable Q-switching behavior is observed as the 1480 nm pump power is set within 27 mW to 46 mW. Fig. 3(a) shows the oscilloscope trace of the laser, which indicates a constant peak to peak spacing of 96.5 $\mu s$. The generated pulses are slightly unstable due to SBS noise. In the experiment, the BP and 1480 nm pump power is fixed at 5.4 dBm and 40 mW, respectively. This Q-switching or pulsing behavior is due to the relaxation oscillation, a natural trait of fiber laser, which occurs around the laser threshold as the SBS grows. Physically, the origin of relaxation oscillation can be explained as follows: rapid growth of the Stokes power near the input end of the fiber depletes the pump. This reduces the gain until the depleted portion of the pump passes through of the fiber. The gain then builds up, and process repeats itself. In other word, the relaxation oscillation and instabilities happen due to the gain, which reacts too slowly to the light field and the stimulated lifetime, which is too long compared with the cavity decay time. The repetition rate and pulse width of the pulsed laser are obtained at 10.36 kHz and 13.21 $\mu s$, respectively. Fig. 3(b) shows the radio frequency (RF) spectrum of the Q-switched fiber laser, which reveals the repetition rate of 10.36 kHz. As seen, the SNR is observed to be more than 25 dB, which indicates that the pulsing behavior is stable. The pulse energy of the output Q-switched laser varies from 3.87 nJ to 20.78 nJ as the 1480 nm pump power is increased from 27 mW to 46 mW.

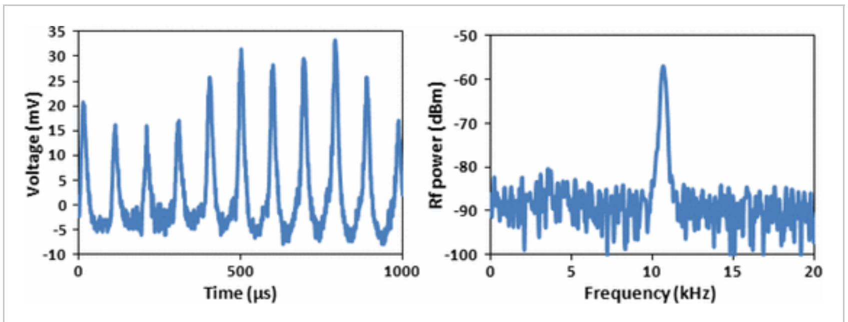


**Fig. 3.** Temporal characteristic of the proposed multi-wavelength Q-switched BEFL with a channel spacing of 0.086 nm. (a) Oscilloscope trace. (b) RF spectrum.

Fig. 4 shows the output spectrum of the proposed Q-switched BEFL configured with a double BS at different 1480 nm pump powers. In the experiment, the BP power and wavelength are fixed at 5.4 dBm and 1565 nm, respectively. As seen in the figure, 16 multi-wavelength lasing lines are observed with an OSNR higher than 10 dB at the maximum pump power of 121 mW. The spacing between two consecutive Stokes' is ascertained at 0.173 nm. It is observed that the peak power of subsequent Stokes is always lower than that of the previous Stokes because these subsequent Stokes are generated from the previous Stokes. The highest peak power of −3.4 dBm is observed at 1565.17 nm, which corresponds to the second Brillouin Stokes. At lower pump power of 35 mW and 24 mW, the number of lines is reduced to 13 and 5 lines, respectively.

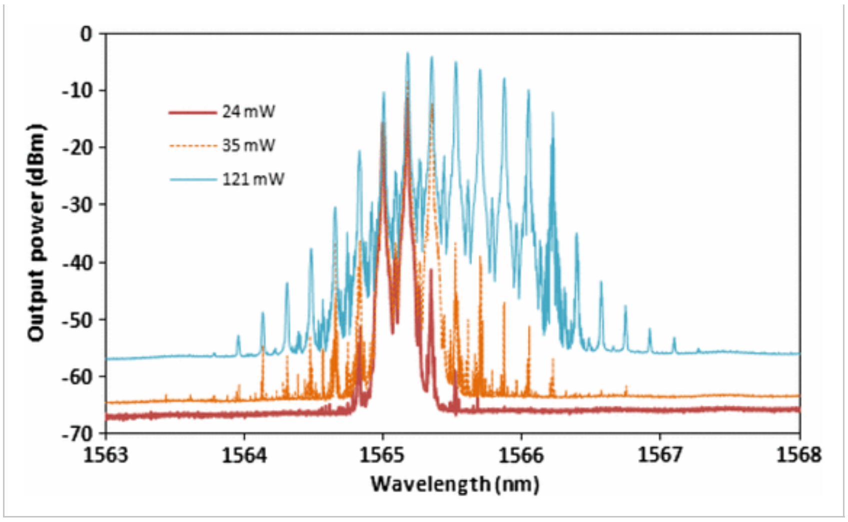


**Fig. 4.** Output spectra of the BEFL configured with a double BS at various 1480 nm pump power when the BP power is fixed at 5.4 dBm.

Fig. 5 shows the Q-switching characteristic of the BEFL configured with double BS, where a portion of the output is fed into oscilloscope and RF spectrum analyzer after the optical to electrical conversion by a fast photo-detector. A stable pulsing characteristic is only obtained as the 1480 nm pump power is fixed within 24 mW to 35 mW, which is slightly higher than the lasing threshold of the BEFL. Fig. 5(a) shows the oscilloscope trace of the laser when the BP and 1480 nm pump power is fixed at 5.4 dBm and 35 mW, respectively. As seen, the repetition rate and pulse width of the laser are obtained at 20.41 kHz and 3.84 $\mu s$, respectively. The SBS provides a strong feedback in the laser cavity in the form of a short SBS relaxation oscillation pulse, which is equivalent to an increase of the cavity's Q-factor during a short period of time and leads to a pulse generation. As the 1480 nm pump power is increased above 35 mW, the pulse train becomes unstable and gradually disappears. This is attributed to the higher pump power, which allows the peak output power to rise, which enhances both SBS and spontaneous emission noise that perturbs and fluctuates the output pulse.

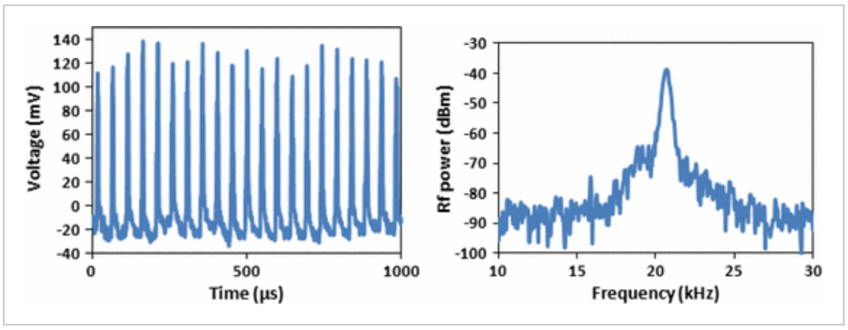


**Fig. 5.** Temporal characteristic of the proposed multi-wavelength Q-switched BEFL with a channel spacing of 0.173 nm. (a) Oscilloscope trace. (b) RF spectrum.

It is also observed that the repetition rate of the pulse with single BS is half of that of pulses with double BS. This is attributed to the total travelling distance of the single BS, which has longer cavity, wherein the Q-switched pulses propagate twice through the NZ-DSF in the configuration. The pulse is also broader in the first BEFL configured with a single BS due to the double propagation of the pulses through the NZ-DSF, which increases the cavity dispersion. The output frequency spectrum is analyzed with the RF spectrum analyzer as shown in Fig. 5(b). The SNR obtained is more than 30 dB, which confirms the stability of the pulses. However, the obtained SNR is still lower compared to those from other Q-switching techniques based on saturable absorber [16], which has an SNR of more than 40 dB. Further investigation is required to optimize the stability of the SBS based Q-switched lasers so that they can be used for real applications. The pulses from the BEFL with double BS are observed to be more stable compared to the ones from the BEFL with a single BS, as their output spectrum exhibits a better peak power and SNR for each line. Even though both BEFLs produce multiple Stokes, the breakup of the pulse continuity is not observed due to an excellent phase locking between SBS orders. It is also observed that the energy of pulses with double BS can be increased from 7.44 nJ to 16.52 nJ by varying the 1480 nm pump power from 24 mW to 35 mW. No pulsing characteristic is observed without the BP in both configurations of single and double BS. This indicates that the Q-switched laser output is due to the SBS.

## SECTION 4
## CONCLUSION

Two multi-wavelength BEFLs with pulsing characteristics have been demonstrated and compared using an NZ-DSF as the BGM. The Q-switching has been obtained when the EDF is pumped within a small range of power, which is slightly higher than the lasing threshold of the laser. For instance, the Q-switching of the first BEFL, which is configured with a single BS of 0.086 nm, commences as the pump power is set within 27 mW to 46 mW due to the relaxation oscillation and instabilities, which occur right after the lasing threshold. This is caused by the gain, which reacts too slowly to the light field, and the stimulated lifetime, which is too long compared with the cavity decay time. The Q-switched BEFL generates a pulse train with repetition rates of 10.36 kHz and pulse width of 13.21 $\mu\text{s}$ as the 1480 nm pump and BP are fixed at 40 mW and 5.4 dBm, respectively. For the second BEFL with a double BS of 0.173 nm, the repetition rate and pulse width are obtained at 20.41 kHz and 3.84 $\mu\text{s}$, respectively. The SNR obtained is more than 25 dB for both BEFLs, which confirms the stability of the pulses.

## FOOTNOTES

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## KEYWORDS

**INSPEC: Controlled Indexing**

Q-switching, fibre lasers, optical fibre dispersion, optical pulse generation, optical pumping, stimulated Brillouin scattering

**INSPEC: Non-Controlled Indexing**

BEFL, BGM, Brillouin gain medium, Brillouin spacing, NZ-DSF, Q-switching, double-spacing multiwavelength Brillouin erbium fiber laser, frequency 10.36 kHz, frequency 20.41 kHz, lasing threshold power, multiwavelength short pulse generation, nonzero dispersion shifted fiber, pump power region, relaxation oscillation, self-starting pulses, single-spacing fiber laser, stimulated Brillouin scattering, temperature 293 K to 298 K

**Authors Keywords**

Q-switching, multi-wavelength laser, stimulated Brillouin scattering (SBS)

## CORRECTIONS

None