Passive, Stable and Order-Adjustable SBS Q-Switching Fiber Laser *

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We propose a new method to separate different orders of an all-fiber passive Q-switching stimulated Brillouin scattering (SBS) laser. We use two fiber Bragg gratings connected by two circulators for the filtering. We obtain a stabilized pulse laser and measure the pulse width of different orders. The first order of SBS has a central wavelength of 1549.75 nm, an average output power of 9 mW, and a pulse width of 400 ns. The pulse width of SBS is reduced by the higher-order signals with the larger fluctuations.

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In recent years, pulse fiber lasers had already attracted wide interests because of their great potential for many applications in remote sensing, nonlinear optical components, laser material processing and supercontinuum generation.[1–4] Q-switching is one of the most important techniques for the generation of pulses on timescales from nanoseconds to microseconds, and it can be divided into two types, active Q-switching, and passive Q-switching. However, to achieve active Q-switching, a modulator is needed, which gives rise to extra cost and structural complexity. Because devices with low cost and compact structure are highly advantageous, this issue has received a great deal of attention.

Stimulated Brillouin scattering (SBS) is an effective approach for obtaining high-power Q-switching pulse lasers.[5–8] Compared with Q-switching with saturable absorbers,[9–12] all-fiber laser structures have better beam quality and the potential of better stability. Furthermore, with SBS in our structure, this design does not require additional Q-switching components. A unique passive Q-switching through the cooperative effect of SBS and Rayleigh backscattering (RS) has been studied after its first demonstration by Fotiadi in 1998. This approach has many advantages including low threshold, low pulse width and high peak power.[13–19] However, similar to other SBS Q-switching techniques, it also shows the problem of pulse width and repetitive frequency instability.[7,8,15] It has been shown theoretically and experimentally that the fluctuation arises from the thermal noise occurring in the Brillouin scattering process.[15,16,18]

The SBS process has the ability to compress a pulse into a narrower pulse in a gain system,[16,20,21] therefore a sufficiently narrow Q-switching pulse can be obtained through a high-order SBS process. However, high-order SBS generation is accompanied by more random thermal noise, which leads to the fluctuation of periods and intensity of SBS pulse.

Previous studies have already used several active methods for control of fluctuation. In 2003, using pulsed pump and hybrid Q-switching, Fan *et al.* stabilized the repetition frequency to be the same as the pump frequency.[22] In 2009, using the external injection to control the gain of the cavity, Pan *et al.* reduced the variance of the repetition rate to approximately 1%.[19]

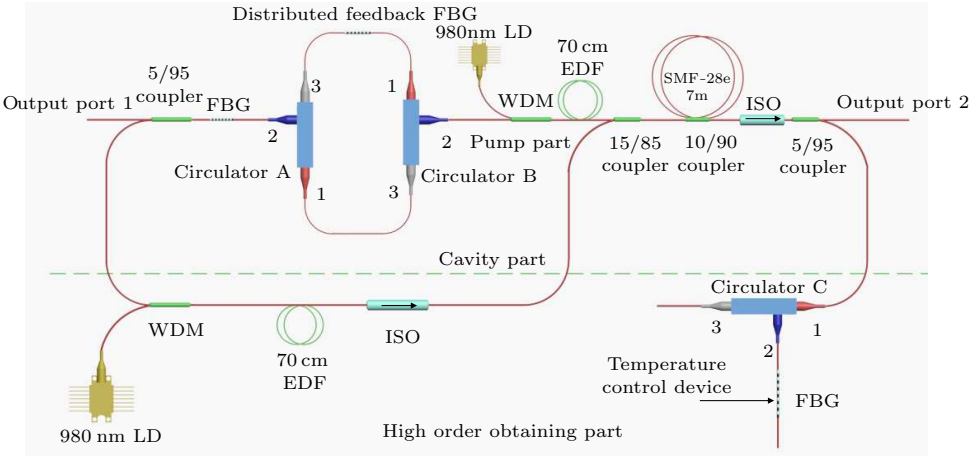

Fig. 1. The schematic diagram of the SBS Q-switching fiber laser.

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In this Letter, we describe a passive, stable, and adjustable order SBS Q-switching fiber laser. Using a dual circulator and controlling the gain of the self-injection, we separate different orders of SBS, obtaining a pulse train with fluctuations of the pulse energy, and a repetitive frequency of less than 10%. We also show that the pulse width of the Brillouin laser decreases as the order increases.

A schematic diagram of the SBS Q-switching laser is shown in Fig. 1. Based on the roles of the laser components, we can divide the diagram into three parts: the pump part, the resonant cavity, and the high-order obtaining part.

The pump part contains a 70-cm-long EDF (Liekki-Er110) with an absorption of 110 dB/m at a wavelength of 1550 nm. The EDF is pumped by a 980 nm laser diode (LD) with the maximum power of 450 mW accompanied by a 980/1550 nm WDM.

One side of the resonant cavity component uses the structure of two circulators, a fiber Bragg grating (FBG), and a distributed feedback fiber Bragg grating (DFB). The FBG has a central reflection wavelength of 1549.67 nm, with a bandwidth of 0.1 nm and a reflectivity of 95%; the DFB has a central transmission wavelength of 1549.67 nm, identical to the FBG's reflection wavelength, and a 0.01 nm transmission window. The contrast between the transmission spectrum of the DFB and the reflection spectrum of the FBG is shown in Fig. 2.

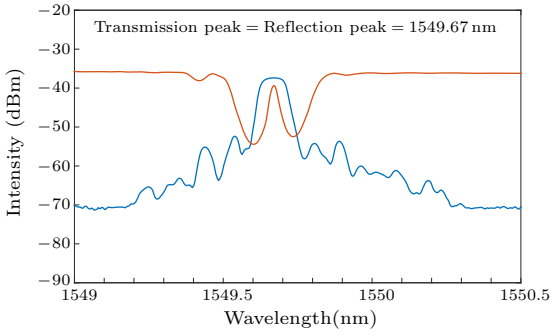

Fig. 2. Both the transmission spectrum of the DFB and the reflection spectrum of the FBG show a peak at 1549.67 nm.

The circulators, DFB and FBG, are connected according to Fig. 1. When the light travels from port 2 of circulator B, it will arrive to port 1 of circulator A, and then to port 2 and FBG. The selected wavelength will be reflected and go back to DFB, where the wavelength range will be secondly narrowed. Thus only the 0.01 nm spectral width of the laser satisfying the wavelength conditions can be reflected back.

Another side of the resonant cavity part uses an interference ring. The interference ring was made by connecting the same side of a 10/90 coupler and adding the SMF-28e fiber to make a length of 7 m. The RS effect occurs when the light passes the interference ring, which acts as the cavity mirror.

Two 5/95 couplers are placed at the end of both cavity sides for measuring the pulse and the spectrum.

The high-order obtaining part contains the same set of devices as the pump part, and it is used as the gain of self-injection. A 15/85 coupler is used to connect the self-injection into the cavity and an isolator prevents the light from entering the cavity. At the end of the cavity, port 2 of circulator C connects to an FBG with a spectral width of 0.1 nm, and this fiber grate is placed in the temperature control device. Thus different orders of SBS can be separated.

The spectrometer (AQ6317B) has a minimum resolution of 0.01 nm, and an oscilloscope (Lecroy 640Zi) with an optical bandwidth of 40 GHz is used for analysis.

Firstly, we start the pump of the gain part 1, and the output spectra of the wavelength selecting part (output port 1) under different pump powers are shown in Fig. 3.

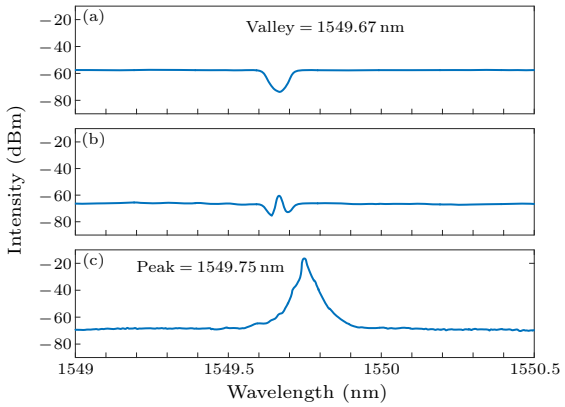

Fig. 3. The optical spectra of output port 1 under different pump powers: (a) 50 mW; (b) 150 mW; and (c) 300 mW.

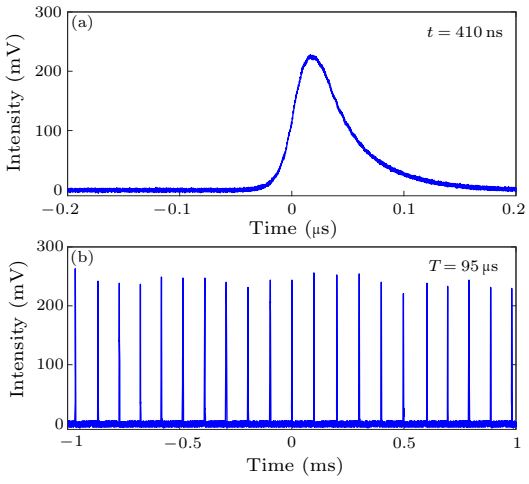

Fig. 4. Oscilloscope trace of the Q-switching SBS laser single pulse (a) and pulse train (b). Here t represents the pulse width and T the pulse period.

When the power is 50 mW, no spectral peak is observed in the output. When the power rises to 150 mW, a small oscillatory peak is observed in the reflection band. When the pump power reaches 300 mW, the peak becomes obvious. The signal is measured with a 10 GHz photo detector and a 4 GHz digital os-

cilloscope. The Q-switching pulse has the power of 9 mW, a pulse width of 400 ns, a pulse period of 100 μs and a peak power of 2.25 W. The fluctuations of both the pulse cycle and pulse strength are less than 10%, as shown in Fig. 4.

This phenomenon can be explained based on the optical path. When RS occurs, it goes back to the wavelength selecting part, and returns with a wavelength range of approximately 0.01 nm. After the pulse is amplified and reaches the threshold, SBS occurs, leading to a 0.08 nm blue shift of the wavelength. This will stop the reflection at the wavelength selecting part and allow the pulse to pass straight through. Therefore, only one order of SBS is generated in one period. Figure 5 shows the spectrum of output port 2. The 0.08 nm wavelength difference between peaks 1 and 2 represents the blue shift caused by SBS.

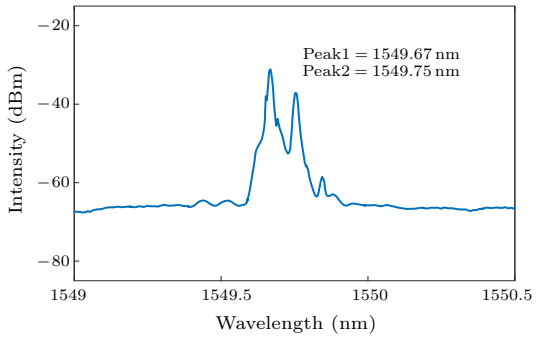

Fig. 5. Optical spectrum of output port 2. The two peaks represent RS and 1st-order SBS, respectively.

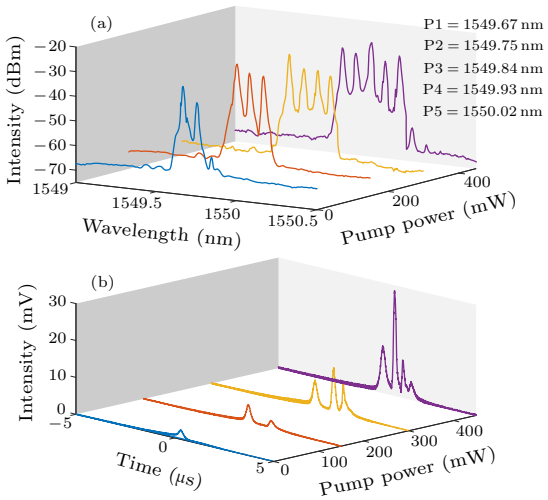

Fig. 6. Spectrum (a) and oscilloscope trace (b) of high order SBS pulse under different pump powers.

Next, we keep the power of pump 1 at the threshold level and gradually increase the power of pump 2. Pulse shape and spectrum of the light are measured at output port 2, as shown in Fig. 6.

The number of peaks changes with pump 2 power, and at first, only two peaks representing RS and SBS can be observed. When the power of pump 2 rises to 150 mW, 3 peaks and 2 pulses are observed in the spectrum and in the oscilloscope trace, respectively. When the power of pump 2 rise to 300 mW, the number of peaks in the spectrum increases to 4 and the number of pulse peaks increases to 3. Finally, when the power of pump 2 reaches 450 mW, 5 peaks and 4 pulses are observed in the spectrum and 4 in the oscilloscope trace, respectively. The wavelength differences between the two adjacent nearby spectrum peaks are all 0.08 nm.

When the SBS occurs, a 0.08 nm blue shift is observed, which makes the wavelength selecting part invalid, and the SBS laser is amplified by the gain part and coupled back to the resonant part. When we raise the pump power and the intensity reaches the threshold, the second order SBS occurs, thereby giving rise to an additional 0.08 nm blue shift. Thus a new peak is formed in the spectrum, and a new pulse exists. If we continue to increase the pump power, the second order signal passes the wavelength selecting part, is amplified, and coupled it then reaches the threshold; additionally, a third order SBS may exist. Thus more spectral peaks and pulses are observed at a higher pump power.

We can use the order separating part to separate each single order of SBS from the other orders.

Using a water bath to heat the fiber grate in the order separating part, we keep the reflection wavelength of the fiber grate exactly the same as the 2nd- and 3rd-order wavelengths. We measure the pulse shape and spectrum, and the results are shown in Fig. 7.

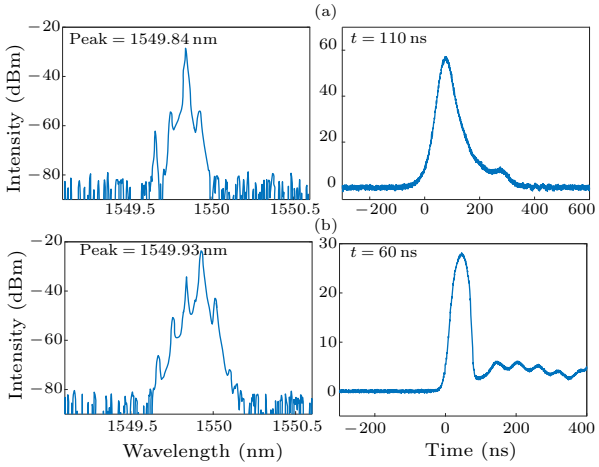

Fig. 7. The spectrum and pulse shape of the 2nd (a) and 3rd (b) order SBS.

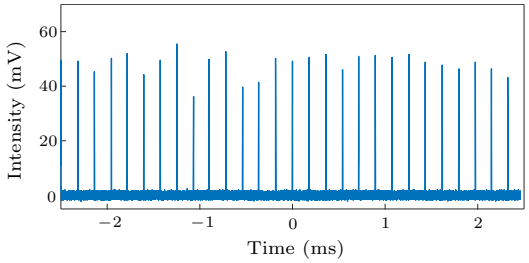

Fig. 8. The oscilloscope trace of the 2nd-order SBS pulse train.

As shown in the figure, a higher order SBS has a

smaller pulse width than the first order SBS, but they are not as stable as the first SBS. Figure 8 shows the pulse sequence of the second order SBS, which displays the fluctuation of approximately 40%.

In conclusion, we have separated different orders of SBS and obtained a stable SBS Q-switching laser using two fiber Bragg gratings connected by two circulators. Here the 1st order SBS pulse is the most stable with the 400 ns pulse width and the fluctuations of pulse energy and repetitive frequency of less than 10%, while the higher order SBS has a narrower pulse width, and its stability decreases.

References

[1] Shangguan M J, Xia H Y, Wang C, Qiu J W, Shentu G L, Zhang Q, Dou X K and Pan J W 2016 *Opt. Express* **24** 19322
[2] Luo Z C, Liu M, Liu H, Zheng X W, Luo A P, Zhao C J, Zhang H, Wen S C and Xu W C 2013 *Opt. Lett.* **38** 5212
[3] Weber R, Graf T, Berger P, Onuseit V, Wiedenmann M, Freitag C and Feuer A 2014 *Opt. Express* **22** 11312
[4] Rigaud P, Van de Walle A, Hanna M, Forget N, Guichard F, Zaouter Y, Guesmi K, Druon F and Georges P 2016 *Opt. Express* **24** 26494
[5] Eichler H J, Menzel R and Schumann D 1992 *Appl. Opt.* **31** 5038
[6] Tang Y L, Li X H and Wang Q J 2013 *Opt. Lett.* **38** 5474
[7] Hu M, He B, Liu H, Yang Y F, Zheng Y, Chen X L, Zhang L and Zhou J 2014 *J. Lightwave Technol.* **32** 2510
[8] Xu Z W, Luo X, Yang L Y, Peng J G, Li H Q and Li J Y 2017 *Appl. Opt.* **56** 4971
[9] Canbaz F, Yorulmaz I and Sennaroglu A 2017 *Opt. Lett.* **42** 1656
[10] Wu L, Li D C, Zhao S Z, Yang K J, Li X Y, Wang R and Liu J 2015 *Opt. Express* **23** 15469
[11] Chen Y, Lin Y, Zou Y, Luo Z D and Huang Y D 2012 *Opt. Express* **20** 9940
[12] Li X H, Chen X W, Han W J, Kong W J and Liu J H 2014 *Chin. Phys. Lett.* **31** 124202
[13] Chernikov S V, Zhu Y, Taylor J R and Gapontsev V P 1997 *Opt. Lett.* **22** 298
[14] Fotiadi A A and Kiyan R V 1998 *Opt. Lett.* **23** 1805
[15] Fotiadi A A, Deparis O, Kiyan R V, Chernikov S and Ikiades A 2001 *Proceedings Volume 4354, Laser Optics 2000: Semiconductor Lasers and Optical Communication* (Russian Federation: St. Petersburg) p 125
[16] Fotiadi A A, Mégret P and Blondel M 2004 *Opt. Lett.* **29** 1078
[17] Fotiadi A A and Mégret P 2006 *Opt. Lett.* **31** 1621
[18] Preda C E, Fotiadi A A and Mégret P 2012 *Opt. Express* **20** 5783
[19] Pan Z Q, Li M, Ye Q, Cai H W, Fang Z J and Qu R H 2009 *Opt. Express* **17** 3124
[20] Li H P and Ogusu K 1999 *Jpn. J. Appl. Phys.* **38** 6309
[21] Li H P and Ogusu K 2001 *J. Opt. Soc. Am.* B **18** 93
[22] Fan Y X, Lu F Y, Hu S L, Lu K C, Wang H J, Zhang G Y and Dong X Y 2003 *Opt. Lett.* **28** 537