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Tunable multiwavelength narrow linewidth Brillouin erbium fiber laser based on Rayleigh backscattering

Xiaorui Wang,[a] Yanfu Yang,[a,*] Meng Liu,[b] and Yong Yao[a]
[a]Harbin Institute of Technology, College of Electronic and Information Engineering, Shenzhen Graduate School, University Town, Nanshan District, Shenzhen 518055, China
[b]Nanyang Technological University, School of Electrical and Electronic Engineering, 50 Nanyang Avenue, Singapore City 639798, Singapore

Abstract. A Rayleigh backscattering (RBS) assisted Brillouin erbium fiber laser scheme with multiwavelength narrow linewidth output is proposed and investigated experimentally. The stimulated Brillouin scattering and RBS take place at two conventional single-mode fibers (SMFs), respectively. RBS is used as a mechanism to compress the linewidth of each Stokes component, and it has been realized and maximized in conventional SMF by optimizing injection power of Stokes light through adjusting variable optical attenuator (VOA). By adjusting VOA attenuation, the laser can obtain three wavelengths output with 3 dB linewidth less than 2 KHz for each wavelength, or six wavelengths output with 3 dB linewidth less than 5 KHz. [DOI: 10.1117/1.OE.55.6.066106]

Keywords: optics; lasers; scattering; fiber lasers.

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1 Introduction

Stimulated Brillouin scattering (SBS) is a prominent nonlinear effect in an optical fiber. It can be simply described as an interaction among optical pump, acoustic wave, and Stokes wave. The frequency down-shifting property of Stokes light [around 10 GHz in single-mode fiber (SMF)] make SBS a beneficial effect employed in multiwavelength fiber lasers.[1] In a multiwavelength Brillouin fiber laser, the linewidth of single Stokes light is typically >10 MHz, which is limited by two kinds of mechanisms. First, the linewidth of Stokes light is mainly determined by phonon lifetime in fiber core with relationship $\Delta\upsilon = 1/2\pi T$, where $\Delta\upsilon$ is the linewidth of Stokes light and T is the phonon lifetime.[2] Second, the longitudinal fiber core dopant concentration nonuniformity[3] and the mechanical strain variation along the fiber[4] can also contribute to Stokes light spectrum broadening. Several methods have been proposed to compress the linewidth of the Stokes light, such as employing an unpumped erbium doped fiber (EDF) as a saturable absorber,[5] using uniform fiber Bragg grating written in EDF as an autotracking filter,[6] and employing short-length chalcogenide waveguide[7] or highly nonlinear fiber[8] as a Brillouin gain medium.

Rayleigh backscattering (RBS) caused by density nonuniformity in the fiber core area is another important effect in SMF, and usually its scattering coefficient is lower than that of SBS by two orders.[9] Recently, RBS has been proved to be an alternative mechanism to compress the linewidth of fiber laser output.[10–19] Various laser structures combining RBS with fiber Bragg grating[10,11] or a bandpass filter,[12,13] as wavelength selection components have been proposed to achieve single-wavelength narrow linewidth output. In our previous work, by combining RBS with two cascaded fiber Bragg gratings, dual-wavelength narrow linewidth laser output is realized,[14] and similar experimental results are also recently reported by Zhu et al.,[15] which proved that RBS can be used as a linewidth narrowing mechanism in multiwavelength circumstances. By combining SBS with RBS, Fotiadi and Kiyan[16] first experimentally observed narrow linewidth (≈100 KHz) Stokes light caused by RBS light accumulation in a section of special fiber with a high RBS coefficient. Similar narrow linewidth Stokes light was also reported by Pang et al.[17] by employing a section of special cascaded fiber or nonuniform fiber[18,19] as an RBS medium. However, limited by laser structure, these reported Brillouin lasers have only one Stokes component output, and the specially designed RBS fibers are complex in fabrication.

Considering the backscattering performance of SMF is sensitive to the power of injected light, conventional SMF can be used as an RBS medium in the case that the injected light power is optimized. In this paper, we report an RBS assisted multiwavelength narrow linewidth Brillouin erbium fiber laser. Conventional 20 km SMF with variable optical attenuator (VOA) placed before it is employed as an RBS medium. By adjusting the VOA attenuation, the light power injected into 20 km SMF can be optimized to maximize RBS light. The laser can realize three wavelengths output with the linewidth both <2 kHz and the extinction ratio >40 dB, or six wavelengths output with the linewidth both <5 kHz and the extinction ratio around 30 dB. This makes the laser promising to be used as a light source in many fields, such as optical communication and optical sensing.

2 Experimental Setup and Principles

The experimental setup is shown in Fig. 1. The laser structure consists of a main cavity in which SBS and RBS happen at two different fibers, respectively, and an RBS cavity for collecting RBS light. In the main cavity, a commercial tunable laser source (TLS) with the linewidth of 150 kHz is used as the Brillouin pump. Its output is injected to 25 km SMF, which acts as the Brillouin gain medium, and a Faraday rotation mirror is used to reflect the Brillouin pump and Stokes

*Address all correspondence to: Yanfu Yang, E-mail: yangyanfu@hotmail.com

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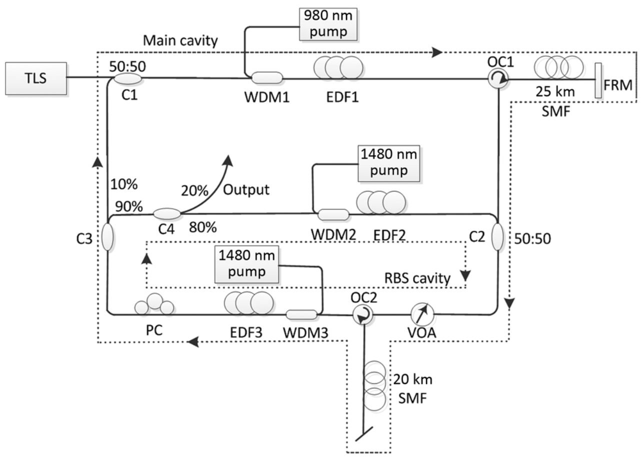

Fig. 1 Experimental setup of RBS assisted Brillouin erbium fiber laser. TLS, tunable laser source; VOA, variable optical attenuator; C1 through C4, optical couplers; WDM1, 980/1550 nm wavelength division multiplexer; WDMs 2 and 3, 1480/1550 nm wavelength division multiplexers; EDF, erbium doped fiber; OC, optical circulator; PC, polarization controller; SMF, single-mode fiber; FRM, Faraday rotation mirror.

light back to the cavity. The 10 m EDF1 pumped by 980 nm laser provides gain for both the Brillouin pump and multiple Stokes lights. Another 20 km SMF with one end buried in refractive index matched liquid is used as the RBS gain medium. The 15 m EDF3 pumped by 1480 nm laser is employed to compensate the intensity loss caused by low RBS coefficient (≈0.025% in 20 km SMF). The distributed RBS on 20 km SMF can be considered as the frequency selection mechanism[16–19] to compress linewidth of the injected light. However, the scattering coefficient of RBS is extremely lower than that of SBS and the RBS light would be sharply suppressed if SBS happens. Thus, VOA is necessary to adjust light power launched into 20 km SMF. As a result, the optimized injection power, which is lower than the SBS threshold and meanwhile as high as possible to collect more RBS light, can be obtained. The principle of multiple Stokes lights output can be described as follows. First, the Brillouin pump is amplified by EDF1 and injected to 25 km SMF in which SBS happens. Considering the high injection power and the high SBS transmission coefficient of 25 km SMF, the first-order Stokes light backscattered out from 25 km SMF can have very high power. Then the first-order Stokes light is injected to 20 km SMF, and SBS happens at 20 km SMF for the high injection power. Then the second-order Stokes light is backscattered out from 20 km SMF and starts traveling around the RBS cavity. EDF2 and EDF3 provide gain for the second-order Stokes light circling in the RBS cavity. With proper VOA attenuation, RBS happens at 20 km SMF for the injected second-order Stokes light, and meanwhile, SBS happens for the injected first-order Stokes light. After multiple round trips, the second-order Stokes lasing can be built up in the RBS cavity. At coupler 3, 10% second-order Stokes lasing is split into the main cavity, then is amplified by EDF1, and injected to 25 km SMF in which SBS happens. Then the third-order Stokes light can be backscattered out from 25 km SMF and injected to 20 km SMF in which RBS happens. Then the third-order Stokes light, which is backscattered out from 20 km SMF, starts traveling around the RBS cavity and becomes lasing light. Similarly, other higher-order Stokes components can be excited by SBS in 25 km SMF in the main cavity and be collected by the RBS cavity for successful lasing. The linewidth for each Stokes component circling in the RBS cavity can be compressed with the help of RBS light accumulation.

Figure 2 shows the pre-experimental setup for measuring backscattering light including both RBS and SBS components of 20 km SMF with different launched power. The output power of the TLS is adjusted by VOA and then injected to 20 km SMF with a fiber end buried in refractive index matched liquid. The backscattered light is first amplified by a low-noise EDF amplifier, and then partly (10%) detected by an optical spectrum analyzer and partly (90%) sent to a Mach–Zehnder interferometer (MZI) for linewidth measurement with the self-heterodyne method.[20] On one arm of the MZI, an acoustic optic modulator is employed to generate 80 MHz frequency shift. With the time delay of 92 km SMF on the other arm, the frequency resolution of the linewidth measurement setup is calculated to be ∼1.1 kHz. The output light of MZI is detected by a photodetector with a bandwidth of 350 MHz. Then the detected signal is observed by an electric spectrum analyzer with a bandwidth of 1 GHz. It is noted that this linewidth measurement setup is also used for analyzing the characteristics of the laser output in Fig. 1.

3 Experimental Results and Discussion

With the setup presented in Fig. 2, the optical spectrum of backscattered light under different injection power is measured, as shown in Fig. 3(a). The corresponding radio frequency (RF) spectrum is shown in Fig. 3(b). As we can see from Fig. 3(a), with the injection power increased from −3.02 to 12.71 dBm, the power of RBS light first increases and reaches a peak value, and then sharply decreases when the SBS light gradually increases and becomes dominant. Under the injection power of 9.33 dBm, the RBS and SBS components of backscattered light have almost the same power. The corresponding RF spectrum is typical Brillouin gain spectrum with a narrow linewidth peak at the central position. A similar RF spectrum has also been reported by Pang et al.[17] However, with the injection power of 5.78 dBm, only narrow linewidth wavelength is found in the RF spectrum for RBS dominant output, and with injection power of 12.71 dBm, only the typical Brillouin gain spectrum is found for the SBS dominant output. This indicates that the narrow linewidth component in the RF spectrum results from RBS light and the wide Brillouin spectrum is related to the SBS component. This conclusion is furthermore confirmed by employing an ultra-narrow (≈1 GHz) bandpass tunable filter (TF) to filter out the RBS component and SBS component from backscattered light in case of 9.33 dBm pump power, as shown in Fig. 3(c). The corresponding RF spectrums are shown in Fig. 3(d). The above characterization results indicate that the SBS has a wide gain spectrum, and the RBS component can be maximized with optimized injection power. Thus, the injection power for RBS gain fiber must be controlled with VOA, as mentioned above.

In the following, the operation characteristics of the experiment setup in Fig. 1 is investigated. With the VOA attenuation around 5.2 dB, three Stokes wavelengths with the linewidth less than 2 kHz are observed. The TLS is set to be

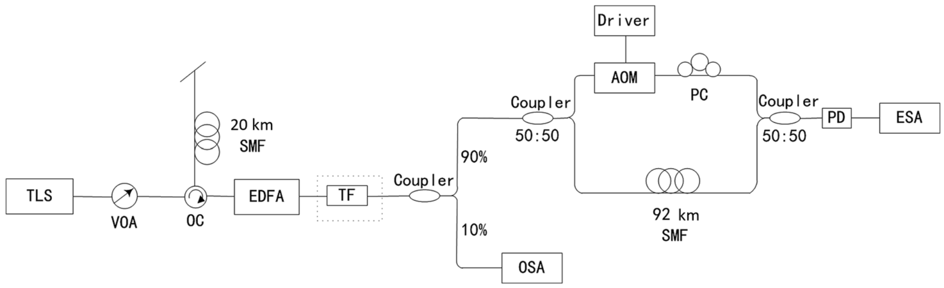

Fig. 2 The experimental setup for backscattering measurement. TF, tunable filter; OSA, optical spectrum analyzer; AOM, acoustic optic modulator; PD, photodetector; ESA, electric spectrum analyzer.

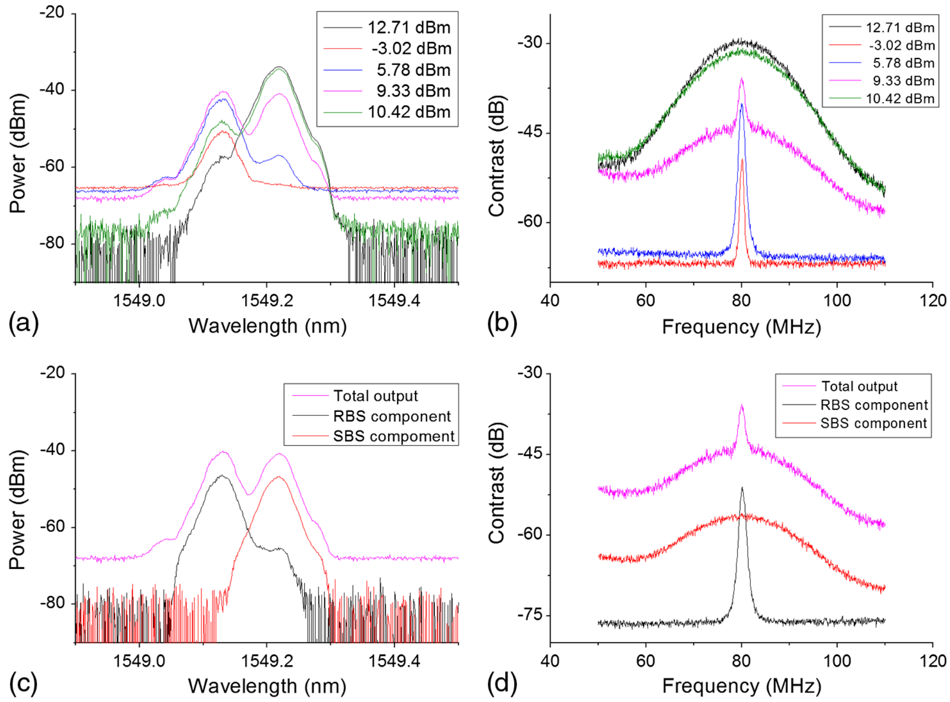

Fig. 3 Optical and RF spectrums of backscattered light of 20 km SMF with different injection power: (a) optical spectrum, (b) RF spectrum of (a), (c) optical spectrum of SBS and RBS power equally output light, and filtered output lights, and (d) RF spectrum of (c).

1549.13 nm on wavelength and 9.1 mW on output power. The pump powers of EDFs 1, 2, and 3 are set to be 356, 523, and 425 mW, respectively. The spectrums of the total output light and three respective Stokes components filtered by TF are shown in Fig. 4. Clearly, the second- to fourth-order Stokes components with the wavelengths of 1549.308, 1549.398, and 1549.486 nm are filtered out, respectively. The low power of the first-order Stokes component indicates that SBS happened at 20 km SMF for the first-order Stokes as mentioned before; thus, the power of RBS light is sharply suppressed. The output power of the laser is measured to be 5.6 mW, corresponding to 0.43% optical conversion efficiency for the laser.

Figures 5(a)–5(c) show the observed RF spectrums of the second- to fourth-order Stokes light with 560 kHz resolution bandwidth (RBW), respectively. In each Stokes component, the RF spectrum is typically a narrow peak on the top of the pedestal induced by Brillouin gain spectrum. The narrow spectrum peak is formed of RBS light accumulation through multiple round trips in the RBS cavity. The typical Brillouin gain spectrum comes from SBS gain. Thus, the contrast of

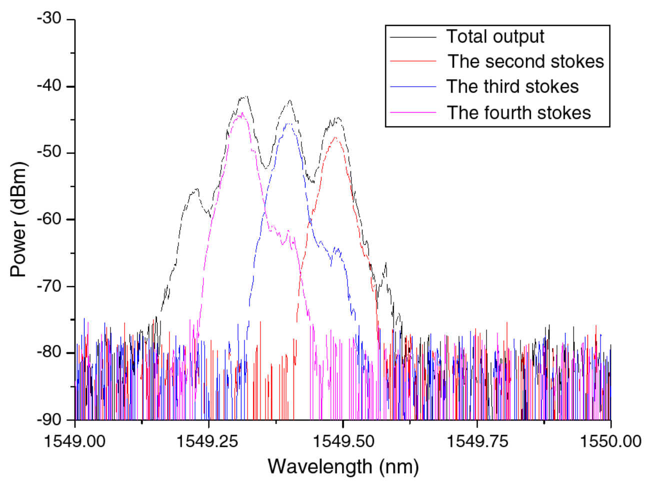

Fig. 4 Optical spectrum of multiple Stokes and second- to fourth-order filtered out Stokes.

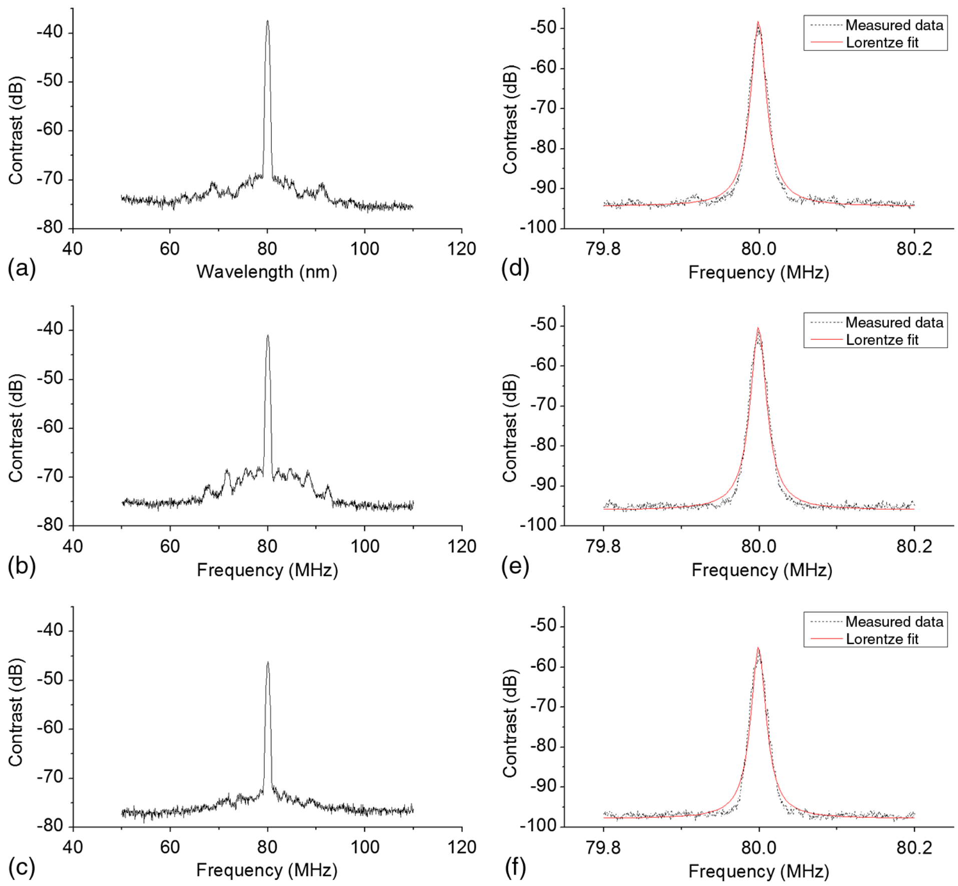

Fig. 5 RF spectrums of the second- to fourth-order Stokes. (a) through (c) RF spectrums of the second- to fourth-order Stokes with 560 kHz RBW. (d) through (f) RF spectrums of the second- to fourth-order Stokes with 3.9 kHz RBW.

the central narrow peak and the pedestal is determined by relative strength of RBS light accumulation and SBS gain. Figures 5(d)–5(f) show the RF spectrums of the central narrow wavelength with RBW of 3.9 kHz for the second- to fourth-order Stokes lights. The respective 20 dB linewidths are measured to be 22.6, 23.9, and 23.5 KHz, corresponding to 3 dB linewidths of 1.13, 1.20, and 1.18 KHz assuming Lorentzian spectral profile. The contrast ratios between the peak and the pedestal are 46.0, 45.3, and 42.5 dB, respectively.

The linewidth compression performance of RBS is related to its random distributed scattering property, which has been theoretically and experimentally investigated.[18,19] The RBS is caused by nonuniformity of the refractive index in the fiber core, and the Rayleigh scattering centers are randomly distributed along the fiber with random scattering coefficients. At the injection end of the fiber, the back-propagation light is formed by coherent superposition of lights backscattered by different scattering centers along the fiber. For different wavelengths within the injection light spectrum, the effective RBS coefficient, which is defined as coherent superposition light amplitude divided by injection light amplitude, can be different, and the resonant wavelength with dominant effective RBS coefficient can be selected out for successful lasing. The linewidth of selected out wavelength is narrower than the whole injection light spectrum. Another mechanism related to RBS-based linewidth compression is the property that the intensity of RBS light is proportional to the inverse fourth power of its wavelength.[11] The wavelengths at the front edge of the injection light spectrum have a lower RBS coefficient compared with the wavelengths at central positions; thus, the front edge of the RBS light spectrum can be suppressed, and after multiple round trips of front edge suppression, the spectrum narrowing can be achieved. In our experiment, all these mentioned mechanisms can help for forming the linewidth narrowing property of RBS.

In the following, the influence of VOA on the laser output characteristics, including the number of Stokes components, the linewidth, and contrast of the measured electrical spectrum for single Stokes component, are investigated in detail. The VOA employed in the experiment can adjust loss for both the main cavity and RBS cavity and the launched power into 20 km SMF. Figure 6(a) shows the RF spectrums of the second-order Stokes light with RBW of 560 KHz and with the VOA attenuations of 0.3, 1.9, 3.14, 5.22, 8.09, and 10.6 dB, respectively. Figure 6(b) shows the corresponding RF spectrums with 9.1 kHz RBW. The dependence of linewidth and contrast on the VOA attenuation for the second-order Stokes is shown in Fig. 6(c). When the attenuation increases from 0.3 to 10.6 dB, the linewidth first decreases from 2.71 to 1.363 kHz and then increases extremely slightly. Meanwhile, it is also observed that the number of Stokes components decreases from 6 to 1 along with the attenuation increasing. The contrast has the maximum value of 47.9 dB with the attenuation of 5.22 dB. The linewidth and contrast variation as a function of the attenuation can

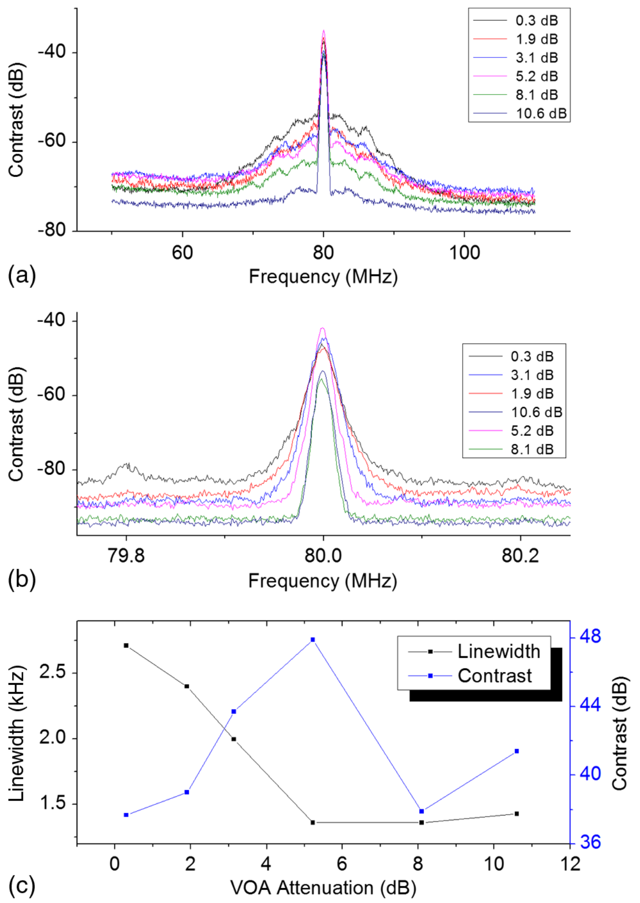

Fig. 6 (a) RF spectrum of second-order Stokes light with different VOA attenuation and RBW of 560 kHz and (b) with RBW of 9.1 KHz. (c) The linewidth and contrast of second-order Stokes with different VOA attenuation.

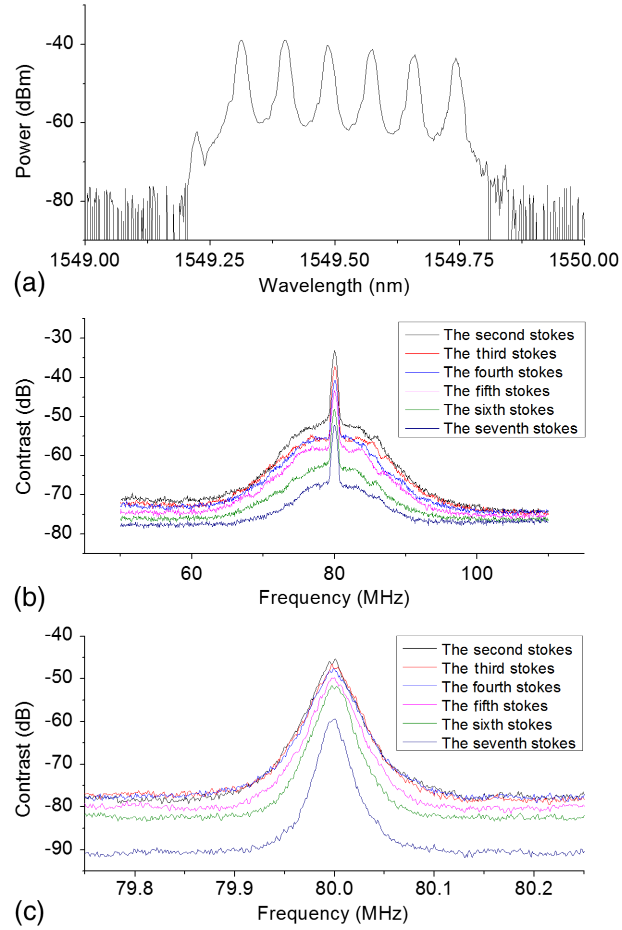

Fig. 7 Optical spectrum and RF spectrum of the second- to seventh-order Stokes light with VOA attenuation <0.3 dB: (a) optical spectrum, (b) RF spectrum with 560 kHz RBW and (c) RF spectrum with 9.1 kHz RBW.

be explained as follows: with the attenuation decrease, the power launched into 20 km SMF increases. In the beginning, the injected optical power is lower than the SBS threshold and consequently the backscattered light is RBS dominant. The RBS light increases with the increase of injection light power; thus, the linewidth of Stokes light decreases and the contrast increases. However, once the launched power exceeds the SBS threshold, the injected light will be mostly backscattered by SBS, and the RBS light decreases. Thus, the linewidth of Stokes light slightly increases and the contrast decreases. Similar relative proportion variation of RBS and SBS components in backscattering light of SMF has been shown in the pre-experiment in Fig. 3. Figure 7 presents the optical spectrum and RF spectrum of the laser output with the minimal VOA attenuation (<0.3 dB). Clearly, six narrow linewidth Stokes components are obtained with the 3 dB linewidths of 4.48, 4.61, 4.86, 4.32, 3.70, and 3.10 kHz, respectively. With different light power and same VOA attenuation, the intensity of RBS light at 20 km SMF for the six Stokes components can be different; thus, their linewidths are slightly different. The contrast between the peak and the pedestal for them are 32.1, 30.1, 29.6, 30.3, 31.3, and 30.7 dB, respectively.

In order to further confirm the role of distributed RBS in linewidth narrowing, a Faraday rotation mirror (FRM) is added to the end of the 20 km SMF replacing refractive index matched liquid. The RF spectrums of the second-order Stokes light with different VOA attenuations are shown in Fig. 8. The RF spectrums are the style of Brillouin gain spectrum and no narrow spectrum peaks are present. With the

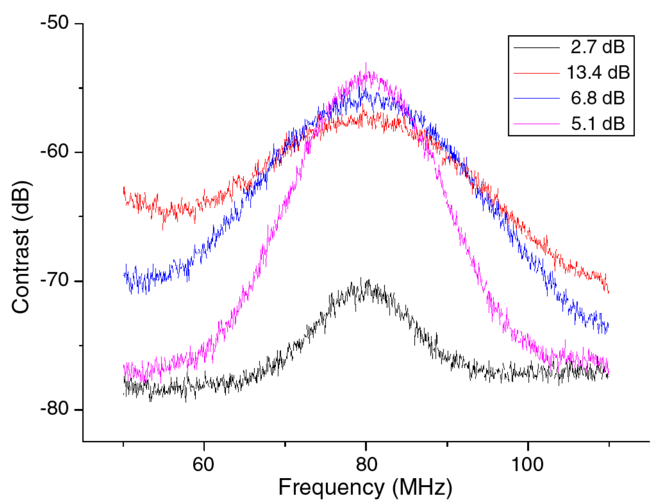

Fig. 8 RF spectrum of the second-order Stokes with 560 kHz RBW and different VOA attenuation, and with FRM placed at the end of 20 km SMF.

FRM at the end of 20 km SMF, the RBS light was buried in the light reflected by FRM and the light backscattered by SBS; thus, no RBS light related narrow spectrum peaks are found. In our experiment, within gain spectrum of EDF, the wavelength of multiple stokes light is determined by seed Brillouin pump which is provided by TLS, so the output wavelengths of the laser can be adjusted by adjusting the output wavelength of TLS.

4 Conclusion

In conclusion, an RBS-assisted Brillouin erbium fiber laser with multiple wavelengths narrow linewidth output is proposed and experimentally investigated. RBS and SBS take place at two different conventional SMFs, respectively. RBS is used as a mechanism to compress the linewidth for each Stokes component, and it has been realized and maximized in conventional SMF by optimizing injection power of Stokes light through adjusting VOA placed before SMF. Three wavelengths output with the 3 dB linewidths of 1.13, 1.20, and 1.18 kHz, respectively, and with the extinction ratios of 46.0, 45.3, and 42.5 dB, respectively, are realized under optimized VOA attenuation. Six wavelengths output with the linewidth less than 5 kHz and the extinction ratio around 30 dB are also obtained under less attenuation.

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Xiaorui Wang is a postgraduate student at Shenzhen Graduate School, Harbin Institute of Technology, China. His recent research field lies in fiber lasers.

Yanfu Yang is an associate professor at Shenzhen Graduate School, Harbin Institute of Technology, China. He received his PhD from Tsinghua University in 2007. From 2007 to 2011, he was with the Photonic Research Center at Hong Kong Polytechnic University as a postdoctoral research fellow. His current research interests include ultrahigh-speed optical fiber transmission system and advanced fiber lasers.

Meng Liu is a current PhD student at Nanyang Technological University, Singapore. His recent research fields lie in fiber optics and fiber lasers.

Yong Yao is a professor at Shenzhen Graduate School, Harbin Institute of Technology, China. He received his BS degree in optoelectronics and his MS degree in physical electronics from Harbin Institute of Technology, Harbin, China, in 1986 and 1989, respectively, and his PhD in optics from South China Normal University, Guangzhou, China, in 2002. His research interests include optoelectronics, and optics detection and measurement.