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Broadband bidirectional Brillouin–Raman random fiber laser with ultra-narrow linewidth

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We present a Brillouin–Raman random fiber laser (BRRFL) with full-open linear cavity structure to generate broadband Brillouin frequency comb (BFC) with double Brillouin-frequency-shift spacing. The incorporation of a regeneration portion consisting of an erbium-doped fiber and a single-mode fiber enables the generation of broadband BFC. The dynamics of broadband BFC generation changing with the pump power (EDF and Raman) and Brillouin pump (BP) wavelength are investigated in detail, respectively. Under suitable conditions, the bidirectional BRRFL proposed can produce a flat-amplitude BFC with 40.7-nm bandwidth ranging from 1531 nm to 1571.7 nm, and built-in 242-order Brillouin Stokes lines (BSLs) with double Brillouin-frequency-shift spacing. Moreover, the linewidth of single BSL is experimentally measured to be about 2.5 kHz. The broadband bidirectional narrow-linewidth BRRFL has great potential applications in optical communication, optical sensing, spectral measurement, and so on.

Keywords: random laser, fiber laser, stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS)

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1. Introduction

Multi-wavelength Brillouin random fiber laser with simple structure, narrow linewidth, independence of the resonant cavity and fixed reflector of conventional fiber lasers, holds great promise for applications in fiber optical communication, optical sensing, spectral measurement, and so on.[1,2] Due to the relatively small Brillouin gain and large random cavity loss, multi-wavelength Brillouin random fiber lasers relying on backward Rayleigh scattering (RS) in the fibers to form a randomly distributed feedback, usually need to combine stimulated Brillouin scattering (SBS) with rare-earth-doped fiber gain or stimulated Raman scattering (SRS) gain together to generate multi-wavelength outputs.[3,4] Unfortunately, Brillouin Er-doped or Yb-doped fiber multi-wavelength lasers are difficult to thoroughly inhibit the homogeneous broadening phenomenon and the Er-doped or Yb-doped fiber has restricted gain bandwidth. The output wavelength number and bandwidth from Brillouin Er-doped or Yb-doped fiber multi-wavelength lasers are rather limited.[5–7] Recently, Brillouin–Raman fiber lasers with narrow bandwidth of Brillouin gain and wide bandwidth of Raman amplification have been extensively investigated to address this problem.[8–12]

Since the random fiber laser based on RS-induced random distribution feedback, was proposed first by Turitsyn *et al.* in 2010,[13] SBS and SRS have been widely used to realize multi-wavelength fiber lasers with a large number of Brillouin Stokes lines (BSLs). In 2013, Wu *et al.* proposed a semi-open-cavity multi-wavelength Brillouin–Raman random fiber laser with a resonant cavity composed of a fiber ring mirror and randomly distributed Rayleigh backscattering in a 10-km-long dispersion-compensated fiber (DCF), generating 210 uniform BSLs within 16.8-nm bandwidth with a spacing of 0.08 nm.[14] At the same year, Wang *et al.* added a 50-km-long single-mode fiber (SMF) into Brillouin–Raman fiber laser to enhance RS effect, which reshapes the output spectrum.[15] A multi-wavelength output with a frequency interval of about 10 GHz and a bandwidth of 40 nm is achieved, when the power level and linewidth between Brillouin component of Stokes lines and Rayleigh component of Stokes lines gradually reach balance due to the narrowing effect of RS on the BSLs. In 2019, a multi-wavelength Brillouin–Raman fiber laser with a 51-nm-wide bandwidth was proposed and demonstrated, which is configured in a half-open cavity design with a variable optical attenuator to control and optimize the mirror reflectivity in the cavity.[16] In the following year, the same group replaced the variable optical attenuator with an arc-shaped optical fiber attenuator to control the mirror reflectivity, thereby suppressing gain competition among longitudinal cavity modes and obtaining almost the same bandwidth.[17] All above mentioned are half-open cavity structures with unidirectional output, which features a Brillouin comb with interval of a single Brillouin frequency shift.

A fully open cavity that brings in more complicated nonlinear effects, like bidirectional RS based random distributed feedback, SBS, and SRS, turns the generation of BSL comb into double Brillouin-frequency-shift output in bidirection. In

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2013, Mamdoohi *et al*. used DCF and bismuth-oxide erbium doped fiber as a hybrid gain medium to extend Raman gain, and obtained a multi-wavelength output with a frequency interval of about 20 GHz and a bandwidth of 28 nm based on RS feedback effect.[18] In 2018, Al-Alimi *et al*. adopted a micro-air cavity in the Brillouin–Raman fiber laser to control optical feedback and nonlinear competition in the fibers.[19] At high Raman power, the stronger RS enhanced the feedback mechanism of the Stokes lines, allowing a part of energy to transfer between the self-excited mode and the BSLs. As a result, a multi-wavelength output with a frequency interval of about 20 GHz and a bandwidth of 46.6 nm was obtained.[19] Recently, our group proposed the regeneration enhancement effect through incorporating a combination of erbium-doped fiber amplifier and SMF into one side of the Brillouin–Raman random fiber laser (BRRFL) in order to further enhance the performance of the BRRFL.[20] The side-mode suppression ratio (SSR) and the order number of generated Brillouin Stokes lines (BSLs) both show some improvements. But the performance is still limited, and the linewidth of single BSL has not been characterized.

In this paper, a multi-wavelength BRRFL with linear full-open cavity for bidirectional narrow-linewidth Brillouin frequency comb (BFC) generation is proposed and demonstrated. The effects of the pump power (erbium-doped fiber and Raman) and Brillouin pump wavelength on the broadband BFC generation are investigated in detail, respectively. A flat-amplitude Brillouin Stokes frequency comb with 40.7-nm bandwidth from 1531 nm to 1571.7 nm and built-in 242 orders BSLs with double Brillouin-frequency-shift spacing is obtained, benefited from the regeneration enhancement effect. The linewidth of single BSL is experimentally measured to be about 2.5 kHz by using delayed self-heterodyne technique.

2. Experimental setup and principle

Figure 1 shows the experimental setup of the BRRFL with a regeneration portion that we proposed, which has a full-open linear cavity configuration. A semiconductor tunable laser source (TLS) with an output power range from 7.6 dBm to 12.6 dBm acts as a Brillouin pump (BP) laser source to provide BP light, coupled into the cavity from port 1 of a 3-port circulator designated as Cir. Meanwhile, 1455-nm Raman pump (RP) laser light with maximum output power of 831.8 mW is mixed with the BP light and enters an 8.8-km-long DCF through a 1455-nm/1550-nm wavelength-division multiplexer (WDM). It is explained that this is a reflective WDM, which means that the RP light will be reflected backward after having entered WDM and will transmit to the right together with BP. In order to realize the regeneration enhancement effect of random lasing, a 1.3-m-long erbium-doped fiber (EDF) which is pumped by a 980-nm laser diode (LD) through a 1550-nm/980-nm WDM, and a coil of 10-km SMF are added and located at the right of the DCF. The linear cavity configuration takes an isolator (ISO) as the end to avoid the influence of Fresnel reflection, so as to ensure the generation of stable random lasing. At the both terminals (output 1 and output 2) of the linear cavity configuration, the optical spectra from both directions can be detected by optical spectrum analyzers (OSA, AQ-6370D) with a resolution of 0.02 nm.

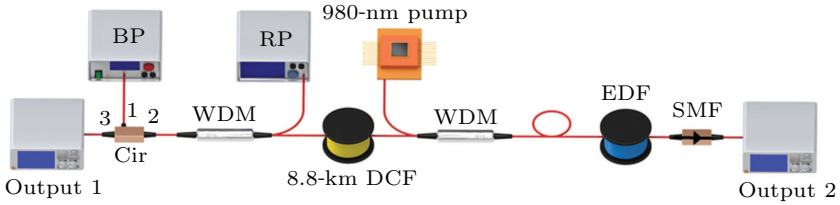


Fig. 1. Experimental setup of Brillouin–Raman random fiber laser with regeneration portion.

The mechanism of generating the BFC is to combine the enhanced synergistic nonlinearity with the regeneration portion, which can be described as follows: the 1550-nm BP light, which is injected into port 1 of Cir and output from port 2, integrates with the 1455-nm RP light. Both BP light and RP light transmit into DCF through a 1455-nm/1550-nm WDM. The BP light is amplified through distributed Raman amplification based on the SRS effect in DCF. Once the SBS threshold is reached, the generated first-order BSL will propagation backwards, opposite to the BP light. Similarly the first-order BSL is also amplified through distributed Raman amplification, and serves as a new pump to generate the second-order BSL which is propagated in the backward direction with respect to the first-order BSL. Simultaneously, the residual BP light and even order BSLs enter into 1550-nm/980-nm WDM through the right end of DCF. As they continue to be amplified in the EDF, the forward-propagated even-order BSLs will serve as new BP to stimulate higher order backward-propagated odd-order BSLs in the SMF as long as the next order SBS threshold is satisfied. Thus, all the processes that occur in the DCF with Raman amplification will recur in the SMF with EDF gain, which can be regarded as regeneration and enhancement of the former. Generally speaking, the lower-order BSLs act as the pump of the higher-order BSLs to produce more BSLs with higher order, and such a cascaded process will continue until the amplified BSLs of a certain order is limited by the

amplification efficiency and cannot reach the SBS threshold of the next order. That is, when the overall gain is not enough to offset its loss, the cascade stops. As a result, the residual BP light and all the even order BSLs output directly from output 2, while the backward-propagated odd order BSLs output from port 3 of the Cir together with the BP backward scattered through RS, realizing two BFCs output with double Brillouin-frequency-shift spacing from separated ends of the random cavity.

3. Results and discussion

During the experiment without the regeneration enhancement effect of random lasing, i.e., with the portion of EDF and SMF removed, it is observed that there always remains RP light in the output spectrum measured at output 2 after the cascaded BSLs have been magnified. In order to use the remained RP and provide more BSLs with double Brillouin-frequency-shift spacing, the combination of a 1.3-m-long EDF pumped by a 980-nm laser diode (LD) through a 1550-nm/980-nm WDM and a coil of 10-km SMF, is incorporated between the DCF and the isolator as a regeneration portion. Firstly, the effect of the regeneration portion is investigated, as the BP and RP power are set to 7.6 dBm and 831.8 mW respectively with a BP wavelength of 1563.2 nm. Figure 2(a) depicts the output BFCs of the BRRFL measured at output 2 under different 980-nm LD pump power. The leftmost wavelength line whose intensity is higher than other lines' is from the residual pump. It clearly shows that the BSL number of the output even-order BFC has an evident increase from no 980-nm LD pump power to 100-mW 980-nm LD pump power. But with the increase of 980-nm LD pump power from 100 mW to 350 mW, the number of attainable BSLdoes not increase significantly. It contributes to the gain bandwidth limitation and saturation effect, which makes the available number of output BSLs basically remain unchanged with higher 980-nm LD pump power. For clearer observation, an enlarged view of the marked section in Fig. 2(a) with all curves superimposed is shown in Fig. 2(b). Apparently, the output power of the even-order BFCs at output 2 shows a synchronous upward trend with the increase of 980-nm LD pump power from 0 mW to 350 mW, while the power of odd-order BFCs at output1 almost remains constant. At the same time, the amplitude flatness and the optical signal-to-noise ratio (OSNR) deteriorate to a certain degree. Thus, during the following experiment, the pump power of 980-nm LD is fixed at 100 mW.

Next, the effect of RP power on the output BFC is investigated. The BP wavelength is set to 1553 nm, and the 980-nm LD power and the BP power are set to 100 mW and 7.6 dBm respectively. The first-order BSL at output 1 is easily observed with the RP power increased to 446.7 mW. When the RP power is further increased to 501.2 mW, the second-order BSL emerges at output 1 as shown in Fig. 3(a). But there is a 19.46-dB power difference between the first order BSL and the second order BSL. Note that the observed second order BSL at output 1 is its RS component, since the propagation direction of the second order BSL is opposite to that of the first-order component (leftward). It also means that the rightward second order BSL is generated at output 2. The output spectra at output 2 under different RP power are measured as shown in Fig. 3(b). When the RP power is 602.6 mW in Fig. 3(b), the amplified Stokes lines are not enough to overcome the self-oscillation. Thus, the mixing of BSLs and the self-oscillation modes makes the output spectrum disordered slightly. When the RP power is further increased to 660.7 mW, the stable BFC with a bandwidth of 14.5 nm and an OSNR of 26.6 dB begins to appear. The bandwidth and the OSNR are both enhanced with the RP power increasing from 660.7 mW to 831.8 mW. This can be explained by the fact that the optical gain of BP and BSLs increase with the RP power rising. Consequently, BP and BSLs will get more energy from RP pump light, so that BP and BSLs will be amplified, increasing the output BSL orders and flattening the BFC as well. However, the power difference between adjacent BSLs decreases with the RP power continuously going up. This is because the RS component is also amplified. Meanwhile, the fourwave mixing (FWM) effect between BP and BSLs that propagate in the same direction is raised a little, resulting in the generation of some anti-Stokes light.

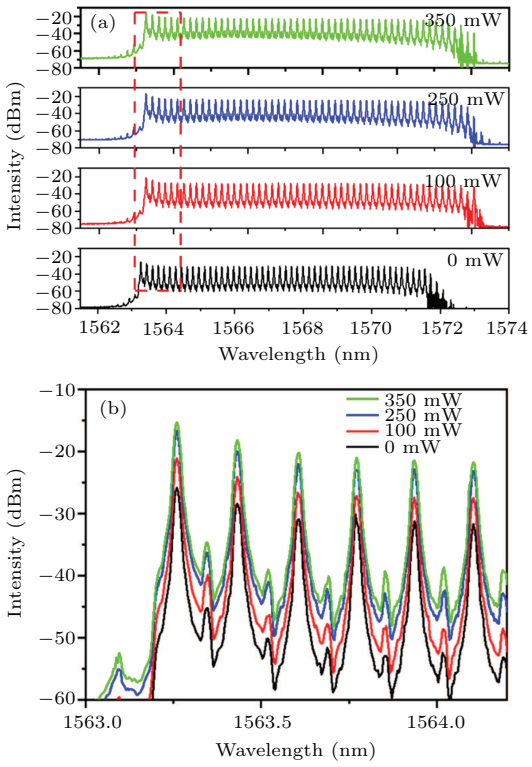


Fig. 2. (a) Output spectra from output 2 under different 980-nm LD pump powers, (b) enlargement of the parts marked in Fig. 2(a).

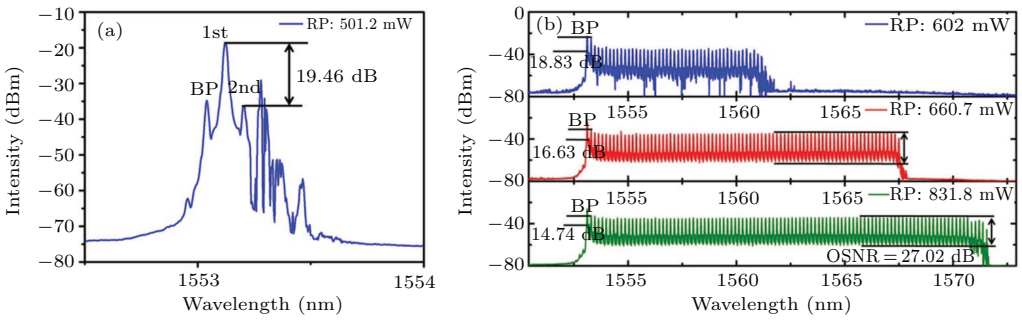


Fig. 3. (a) Output spectrum at output 1 under RP power of 501.2 mW, (b) output spectra at output 2 under different RP powers.

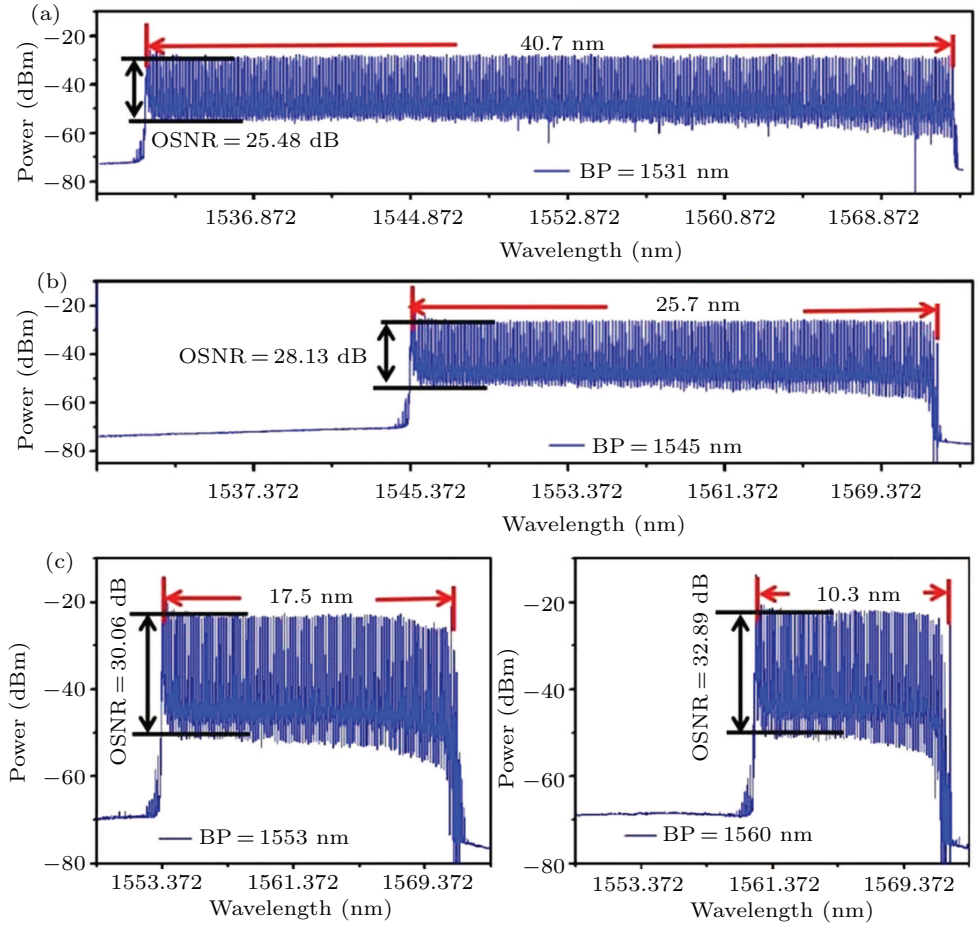


Fig. 4. Output spectra from output 1 at BP wavelength of (a) 1531 nm, (b) 1545 nm, (c) 1553 nm, and (d) 1560 nm, with BP, RP, and 980-nm LD power set to 7.6 dBm, 831.8 mW, and 100 mW, respectively.

In the following, the influence of the BP wavelength on the performance of BFC is investigated. Figure 4 shows the output BFC from output 2 in some selected BP wavelengths under 980-nm LD pump power 100 mW, RP power 831.8 mW, and BP power 7.6 dBm. Initially, the BP wavelength is fixed at the left of the Raman gain peak of 1531 nm (about 1553.3 nm), the output spectrum covers a wavelength range from 1531 nm to 1571.7 nm (40.7 nm), and obtains a maximum of 242 order Stokes lines output with a wavelength spacing of double Brillouin frequency shifts (~ 0.165 nm) as shown in Fig. 4(a). The OSNR is about 25.48 dB. When the BP wavelength is set be slightly close to the Raman gain peak at 1545 nm, a flatter BFC is obtained in a range of 1545 nm–1571.8 nm, and the OSNR rises to 28.13 dB as shown in Fig. 4(b). When the BP wavelength is 1553 nm near the Raman gain peak, an output spectrum with 1553 nm–1571.1 nm (18.1 nm) wavelength range and 104 Stokes lines is obtained as shown in Fig. 4(c). The OSNR turns to 30.06 dB. Figure 4(d) reveals the output spectrum at output 2 when BP wavelength is 1560 nm near the end of Raman gain. Only 65 order Stokes lines ranging from 1560 nm to 1570.9 nm (10.9 nm) can be observed, while the OSNR rises from 30.06 dB to 32.89 dB. Evidently, with the tuning of BP wavelength, the change of the output BFC is embodied in the bandwidth of cascaded BSLs and the fluctuation of output BSL number and OSNR. And with the increase of BP wavelength, the bandwidth of the output BFC

obtained at output 2 is gradually shortened, but the OSNR of the output BFC is improved. When the BP wavelength exceeds the Raman gain range, the BP and BSLs cannot be amplified enough to meet the SBS threshold, so that the output spectrum is mainly self-oscillation mode. Figure 4 reveals the trend of tunable range of BFC and its OSNR changing with BP wavelength. Within the Raman gain range, the shorter the BP wavelength, the wider the bandwidth of the BFC is, but the OSNR becomes poorer as well. On the contrary, increasing the BP wavelength will get less BSLs, but the OSNR of BFC will experience a gradual promotion obviously.

To highlight bidirectional operation of the random fiber laser, the obtained BFCs from output 1 and output 2 are shown in Fig. 5, when the RP power is 831.8 mW and 980-nm LD power is 100 mW with BP wavelength of 1535 nm. It is seen that the output BFCs exhibit 2.8-dB flat amplitude, comparable to the result reported previously. It is also indicated that under the same pumping condition, odd order BSLs from output 1 in Fig. 5(a) have a greater OSNR than even order BSLs output 2 in Fig. 5(b). This is because all even order BSLs have to pass through the EDF and SMF, which will introduce amplified spontaneous emission (ASE) noise and worsen the OSNR, while only part of odd order BSLs need to go through this process. Besides, the peak power difference between adjacent BSLs of odd order BFC is also superior to the even one, i.e., the peak power difference between odd orders of BSLs and Rayleigh components of even orders of BSLs for odd order BFC is larger than that for even order BFC. It is also due to the amplification role of the regeneration portion in the right. But it is worth noting that both two combs can realize the output of 225 cascade BSLs in a wide bandwidth, and have a clean-cut feature at the ends of the comb.

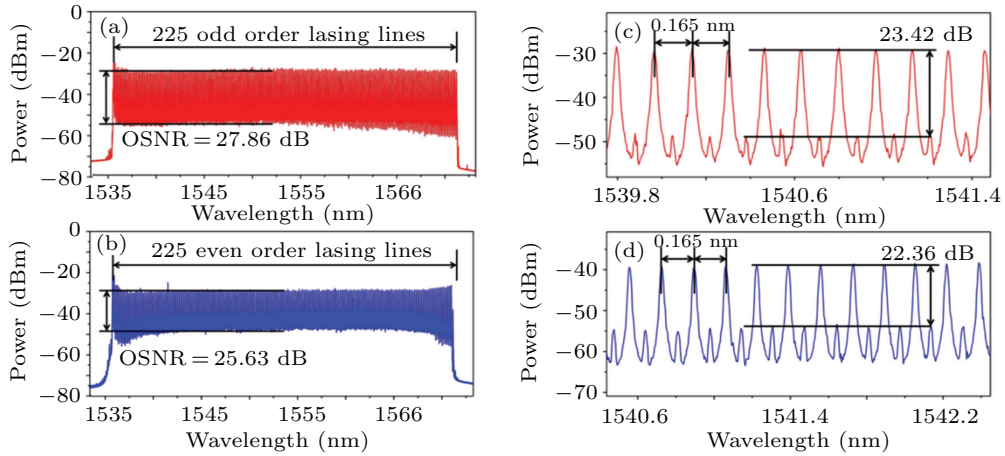


Fig. 5. BFC output from (a) output 1, (b) output 2, (c) detailed spectrum of (c) odd BSLs and (d) even BSLs.

The obtained BFC with a bandwidth of 40.7 nm is subject to the pumping condition of single-wavelength RP of 831.8 mW and 980-nm LD pump of 100 mW. On the contrast, the recorded Brillouin comb bandwidth is 57.2 nm, which is implemented through Raman gain engineering based on multi-wavelength RP scheme.[1] This scheme is cumbersome and costly with just passable results. For the case of single wavelength RP, a 46.6-nm BFC with 20-dB OSNR is produced at Raman power of 950 mW, through controlling the flatness in amplitude of BSLs by employing an air-gap outside of the cavity.[19] Although this is the widest bandwidth attained in multi-wavelength BRRFL incorporated a single-wavelength RP, the introduction of air-gap inevitably brings extra losses. By using a 50/50 coupler to divide 1000-mW RP power into two fiber-entry points, 212 flat amplitude channels with an average 27.5-dB OSNR were achieved,[9] which is less than our obtained 225 BSLs with 27.9-dB OSNR under single-wavelength RP of 831.8-mW and 980-nm LD pump of 100 mW. It is indicated the proposed regeneration portion scheme performs well in terms of pump efficiency.

The narrow linewidth is one of the advantages of Brillouin random fiber laser.[21–23] We use the non-zero delay self-heterodyne method based on acoustooptic modulator (AOM) to measure the linewidth of single BSL. The experimental setup for linewidth measurement is shown in Fig. 6(a). Since there is no narrow-band filter to filter out single BSL, an alternative method is adopted, that is, only the first-order BSL is excited. We set the BP power to 12.6 dBm and the RP power to 446.7 mW to just excite the first-order BSL. The first-order BSL to be measured is then divided into upper and lower channels through a 3-dB coupler. The upper branch passes through the 30-km SMF used as an optical fiber delay line. The lower branch passes through the AOM and the frequency is shifted by 80 MHz to avoid the influence of noise near the zero frequency. The upper and lower branches recombine at another 3-dB coupler and the beat radio frequency (RF) signal with a central frequency of 80 MHz is detected and measured by using a 15-GHz photo detector (PD) and an electrical spectrum analyzer (ESA). The obtained beat RF signal is shown in Fig. 6(b), with a video bandwidth of 1 Hz, resolution band-

width of 500 Hz, and the scanning bandwidth from 79.6 MHz to 80.4 MHz. It features a 3-dB linewidth of about 2.507 kHz, which is deduced from 20-dB bandwidth in order to reduce the noise influence. Based on this test system, we believe the linewidth of any order of BSL can be measured so long as a sufficiently narrow filter is added. And the magnitude order of the linewidth should be the same as that of the first order measured.

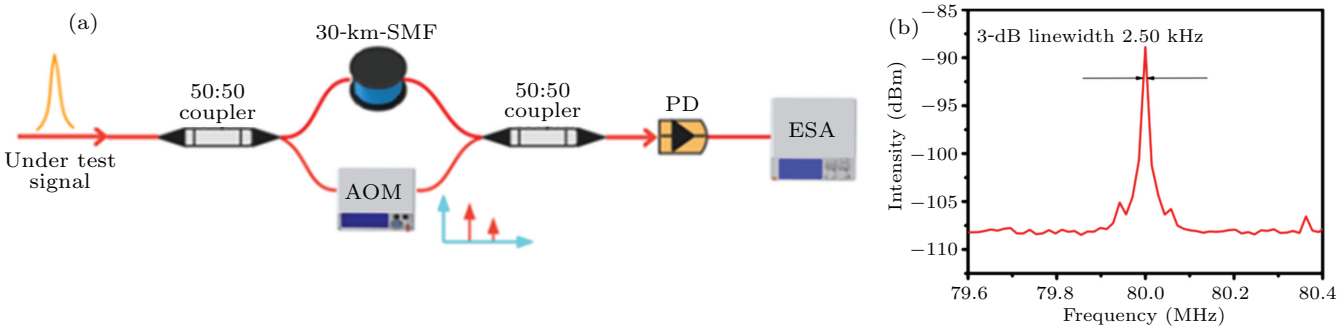


Fig. 6. (a) Experimental setup for linewidth measurement, (b) measured beat RF spectrum.

4. Conclusions

In summary, we obtained a broadband bidirectional Brillouin frequency comb from a multi-wavelength BRRFL in which the regeneration enhancing effect in a full-open linear cavity configuration is used. With the assistance of regeneration portion, the BRRFL we proposed shows advancement in not only the number of output BSLs, but also the excellent flatness of BFC with better OSNR, than those generated by conventional RFLs under the same pumping conditions. In the experiments, by adjusting the BP power to 7.6 dBm at 1531 nm, a wideband BFC of up to 242-order BSL with a wavelength spacing of double Brillouin frequency shift can be obtained. Moreover, the linewidth of single BSL is experimentally measured to be about 2.5 kHz. With the improved wideband BFC with better OSNR and its narrow linewidth, it has broad opportunities for promoting the applications in optical communication, microwave photonics, and optical sensing systems.

Acknowledgements

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