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Single-Longitudinal-Mode Brillouin/Erbium Fiber Laser With High Linewidth-Reduction Ratio

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Abstract—Saturable-absorber-based autotracking filter is incorporated for the first time in hybrid Brillouin/erbium fiber laser to achieve a single-longitudinal-mode operation. We experimentally demonstrate a linewidth-reduction ratio of 166 with a 150-m Brillouin gain media. At the same time, with the intracavity erbium-doped fiber amplifier (EDFA) to compensate the loss introduced by the mode-selection elements, Brillouin pump threshold is as low as 3 mW under 120 mW of 980-nm pump power and the maximum output power is 7 mW. Moreover, the autotracking filter also helps to suppress self-lasing and enables tuning range over the entire C-band.

Index Terms—Nonlinear fiber optics, optical fiber lasers, Brillouin lasers, linewidth reduction.

I. INTRODUCTION

BRILLOUIN fiber lasers have drawn much attention owing to their intrinsic narrow linewidth and applications in coherent communications, fiber sensing or optical spectrum analysis [1], [2]. For traditional Brillouin fiber lasers, long Brillouin gain media or critically coupled resonant cavities are usually required owing to the small Brillouin-gain coefficient ($\sim 10^{-11}$ m/W) [3]. However, both methods have their own shortcomings. With a long cavity, the mode spacing will be much smaller than the Brillouin gain bandwidth (~ 20 MHz), which will result in multi-mode operation. The single-longitudinal-mode operation of such long-cavity Brillouin laser was first demonstrated by Chen et al by incorporating unpumped erbium-doped fiber (EDF) loop inside the cavity [4]. However, the additional mode-selection element caused substantial loss, resulting in a Brillouin pump threshold as high as 40 mW and a maximum output power of only -20 dBm. On the other hand, a different class of Brillouin lasers utilize short cavities that are resonant for the Brillouin pump or for both the Brillouin pump and the Stokes wave (double resonant cavity, DRC) to lower down the pump threshold and achieve SLM operation. Ultra-narrow linewidth around 100 Hz has been demonstrated in such kind of lasers [5], [6]. A minor shortcoming of this technique is that much effort is required to carefully control either the

pump frequency or the cavity length to achieve the resonance. As a result, these lasers are usually operated on a fixed wavelength to maintain the resonance. Brillouin/erbium fiber lasers (BEFL) can eliminate the need for critically coupled resonant cavities by incorporating the EDFA gain inside the cavity [7]. They can easily operate with non-resonant cavities made of Brillouin gain media as short as several meters and can provide much larger output power [8], [9]. However, as we will demonstrate later, these short-cavity Brillouin lasers have limited linewidth-reduction ratio compared to those incorporating longer Brillouin media under the same power feedback ratio.

In order to overcome the dilemma in conventional single-longitudinal mode Brillouin lasers, here we introduce a novel BEFL that incorporates saturable-absorber-based auto-tracking filter and a sub-ring cavity to achieve SLM operation, which is the first time to the best of our knowledge that such mode-selection technique is applied to the BEFL. Much longer Brillouin gain media can be utilized to greatly enhance the linewidth-reduction ratio while still maintaining the SLM operation. Meanwhile, the loss introduced by the additional elements is compensated by the EDFA, thus low Brillouin pump threshold and adequate output power are achievable. Moreover, the auto-tracking filter also serves to suppress the self-lasing without incurring excessive loss to the Brillouin signal. Therefore, tunability over the entire C-band is achieved with lower Brillouin pump power.

II. THEORY OF LINEWIDTH REDUCTION

Theoretical and experimental study on the mechanism of linewidth reduction in Brillouin lasers [10], [11] has indicated that single-longitudinal-mode BEFL with long Brillouin gain media can be an effective tool for linewidth reduction. Based on the result of their numerical study, it has been revealed that the phase fluctuation of the Stokes wave, though strongly correlated to that of the pump wave, is greatly attenuated and smoothed through the process of SBS. It can be intuitively explained by noting that the phase diffusion of the pump laser is usually much slower than the response of the acoustic wave. Therefore, the phase of the acoustic wave can be treated as adiabatically following that of the pump wave. Owing to the phase matching condition in the SBS process, the phase fluctuation of the Stokes wave is thus much weaker than the pump wave. As the linewidth is fundamentally determined by the phase fluctuation, the linewidth-reduction ratio of the Brillouin laser can be described by Eq. (1). $\Delta\nu_s$ and $\Delta\nu_p$

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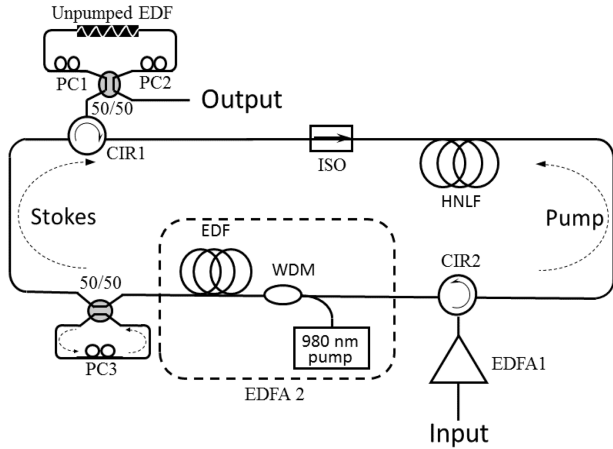


Fig. 1. Experimental setup. WDM, wavelength-division multiplexer; EDF, erbium-doped fiber; CIR, circulator; PC, polarization controller; ISO, isolator; HNLF, high nonlinear fiber.

represent the FWHM of the Brillouin signal and the Brillouin pump, respectively. $\gamma_A = \pi \Delta \nu_B$ and $\Gamma_c = -c \ln R / nL$ describe the acoustic damping ratio and the cavity loss ratio, respectively.

$$\Delta \nu_s = \frac{\Delta \nu_p}{\left(1 + \frac{\gamma_A}{\Gamma_c}\right)^2} \quad (1)$$

$\Delta \nu_B$ is the Brillouin gain bandwidth, n and L represent the refractive index and length of the Brillouin gain media and c is the speed of light. It is worth noting that, the physical meaning of R is the amplitude feedback ratio of the Stokes wave, which has been taken as the coupling ratio of the cavity in some papers.

One of the important implications of Eq. (1) is that, under the same power-feedback ratio, the linewidth-reduction ratio of the Brillouin laser is proportional to the length of the Brillouin gain media, therefore longer fiber is strongly preferable for linewidth reduction. This is why we believe the hybrid Brillouin/erbium fiber laser is an effective tool for linewidth reduction. Much longer Brillouin gain media can be utilized while maintaining the SLM operation with the assistance of intra-cavity mode-selection elements. At the same time, the loss introduced by the mode-selection elements can be compensated by the intra-cavity EDFA. It ensures a higher power-feedback ratio, which also contributes to a larger linewidth-reduction ratio according to the equation.

III. EXPERIMENTAL SETUP

The proposed configuration is shown in Fig.1. As a proof-of-concept experiment, we first used a narrow-linewidth tunable laser source (TLS) as input, which was amplified to generate the Brillouin pump. The Brillouin gain media was a 150-m highly-nonlinear dispersion-shifted fiber (HNL-DSF) with nonlinear coefficient of $30 \text{ W}^{-1} \text{ km}^{-1}$. An isolator was placed after the Brillouin gain media to eliminate the residual pump so that the cavity would not be injection-locked to the Brillouin pump. Meanwhile, a Stokes signal propagating in the opposite direction was generated from the Brillouin gain media, which would be amplified by the

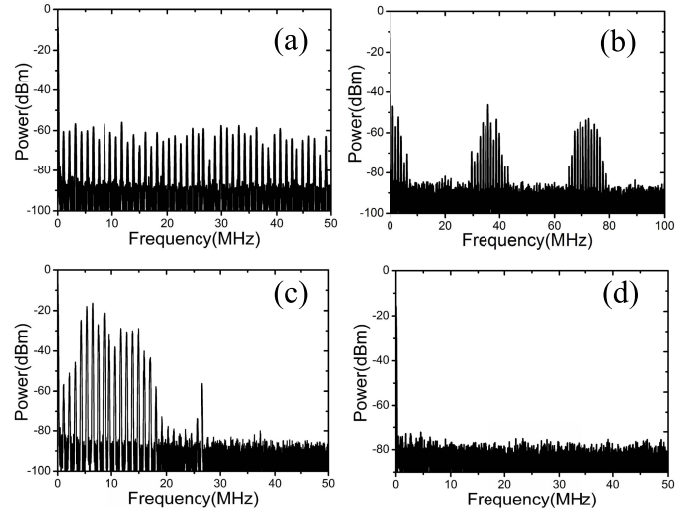


Fig. 2. Measured RF spectra (a) without the Brillouin gain and mode-selection elements. (b) Without Brillouin gain but with sub-ring cavity. (c) With Brillouin gain but without mode-selection elements. (d) With Brillouin gain and all mode-selection elements.

intra-cavity EDFA and start oscillating inside the cavity. In order to achieve SLM operation, two mode-selection elements were utilized. First, a sub-ring cavity made of a 50/50 coupler and a polarization controller (PC) was inserted to broaden the mode spacing. The following element was a Sagnac loop mirror that consisted of two PCs and a length of 4-m unpumped EDF in between. By properly controlling the state-of-polarization of the two counter-propagating lightwaves inside the loop mirror, an ultra-narrowband auto-tracking filter would be induced inside the EDF owing to the spatial-hole-burning effect [12]. The FWHM of the effective filtering by the combination of the auto-tracking filter and the sub-ring cavity was estimated to be less than 1.8 MHz, which was less than twice the free spectral range (FSR) of the cavity. Therefore, stable single-longitudinal-mode condition was well satisfied with the combination of these two mode-selection elements.

IV. GENERAL LASER PERFORMANCE

The effect of mode-selection was observed with a photodetector and an electrical spectrum analyzer under the condition of maximum pump power (Brillouin pump at 70 mW, 980-nm pump at 120 mW), as shown in Fig. 2. First, when two mode-selection elements were removed and the Brillouin pump was turned off, the cavity was just a normal erbium-doped fiber laser and the modes existed all over the observation range. The function of the sub-ring cavity is to partially broaden the mode spacing. As can be observed in Fig. 2(b) when we added the sub-ring cavity, there were only clusters of mode remained, whose distribution period was determined by the length of the sub-ring cavity. When the Brillouin pump was present without any mode-selection elements, the laser would be injection-locked to the Brillouin signal. For this reason, there were modes only within the Brillouin gain bandwidth (~ 20 MHz). After the sub-ring cavity and the auto-tracking filter were inserted, the SLM operation was achieved with side-mode suppression ratio (SMSR) over 50 dB. This ratio can be further improved if we decrease the output power, for

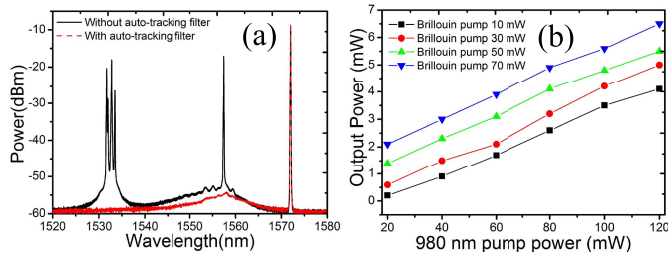


Fig. 3. (a) Self-lasing suppression effect of the auto-tracking filter. (b) Output power as function of 980 nm pump power under different Brillouin pump power.

the FWHM of the auto-tracking filter will be narrower with smaller refractive index change [13].

In addition to the side-mode-suppression effect, the auto-tracking filter also helps to suppress the self-lasing, which is a common problem of BEFL and will affect the tuning range when the Brillouin gain is small [14]. This effect was mostly obvious when the Brillouin pump was tuned to the margin of the C-band, as shown in Fig. 3(a), when the 980-nm pump power and Brillouin power were 100 mW and 30 mW, respectively. When the auto-tracking filter was replaced with the equivalent attenuation to maintain the same output power, predominant self-lasing modes appeared in the two spectral positions of EDFA gain peaks. However, when the auto-tracking filter was present, self-lasing was completely suppressed with Brillouin signal left undisturbed. This may be attributed to the following two reasons: first, as only coherent lightwave can form a standing wave inside the EDF, incoherent lightwave experience higher loss than the coherent oscillating mode [15]. Second, the absorption cross section of EDF is also larger at the two self-lasing wavelengths. Therefore, the threshold for self-lasing is raised and lower Brillouin pump power is required to suppress self-lasing.

Under the condition of SLM operation and maximum 980-nm pump power, the Brillouin pump threshold was as low as 3 mW despite the loss introduced by the mode-selection elements. The maximum output power was 7 mW when the Brillouin pump was also turned to maximum (70 mW). In Fig. 3(b), we characterized the output power as a function of 980nm pump power under different Brillouin pump power. The conversion efficiency between the 980 nm pump power and the Stokes light was about 4.5%, which can be further improved by optimizing the home-made intra-cavity EDFA. The conversion efficiency between the Brillouin pump and the Stokes light was about 3.3%. Even though it is still lower than the efficiency of Brillouin lasers with short resonant cavities, it is already much higher than that of 0.013% in the first long-cavity SLM Brillouin laser in [4] and the maximum output power is also greatly improved from 0.01 mW to 7 mW.

Under the condition of maximum output power, we characterized the wavelength tunability. As shown in Fig. 4, the laser could be tuned from 1535 nm to 1575nm without self-lasing. The current tunable range was limited by both the intra-cavity EDFA and the EDFA for Brillouin pump amplification, which are both C-band. However L-band tunability is also available by simply replacing current C-band EDFA with L-band ones,

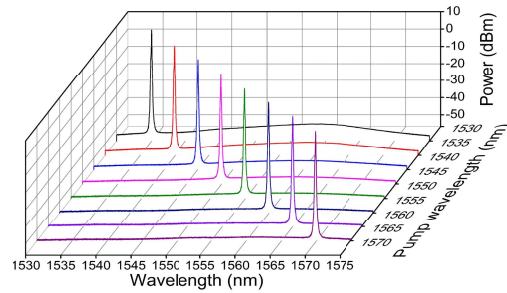


Fig. 4. Output spectra with pump wavelength tuned from 1535nm to 1575nm.

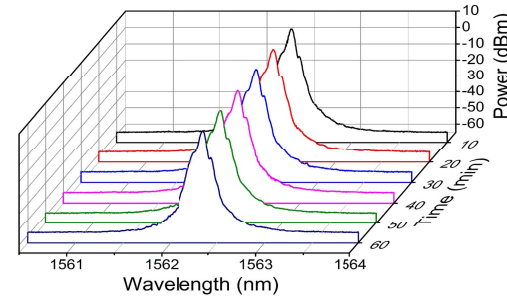


Fig. 5. Measured output spectra in every 10 minutes.

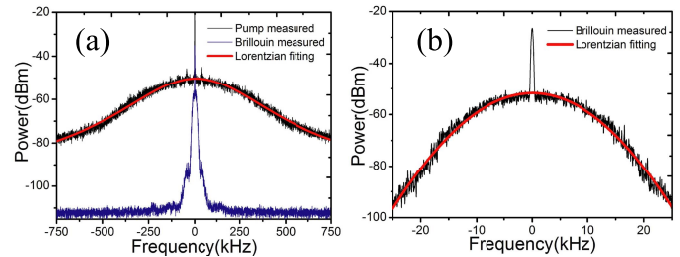


Fig. 6. Measured linewidth of (a) input and output. (b) Zoon-in view of Brillouin laser.

as the mode-selection technique we adopt completely accommodates L-band operation [16].

Fig. 5 shows the measured spectra recorded every 10 mins for over 60 mins with a sweeping speed of 2 Hz. We could observe no wavelength drifting in 60 mins and the average power was stable. Even though there existed some power fluctuation on short time scales that could not be captured by the optical spectrum analyzer, it can be stabilized by applying temperature control and vibration damping.

V. DISCUSSION OF LINEWIDTH REDUCTION

Also under the condition of maximum output power, a delayed self-homodyne detection using 25-km single-mode fiber (SMF) was then conducted to test the linewidth reduction effect. In order to avoid the effect of $1/f$ noise [17], we compared the 20-dB linewidth derived from the Lorentzian fitting. As shown in Fig. 6, the 20-dB linewidth of the input (pump laser) and the output (Brillouin laser) were about 500 kHz and 15 kHz, respectively, corresponding to a linewidth-reduction ratio of 33.3.

However, without any dedicated stabilizing measure with the environment, the influence of temperature and acoustic fluctuation will greatly broaden the output linewidth [18]. Therefore, the intrinsic linewidth may be much narrower.

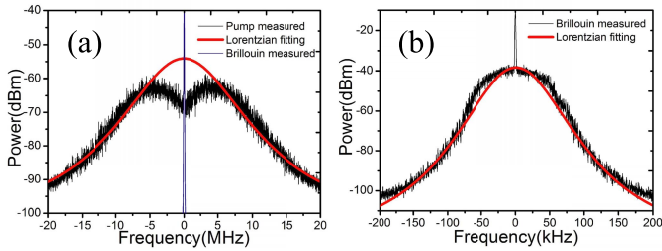


Fig. 7. Measured linewidth of (a) input and output using a broader pump. (b) Zoon-in view of Brillouin laser.

In order to minimize the influence of environment fluctuation and obtain more accurate linewidth-reduction ratio, we replaced the narrow-linewidth Brillouin pump with a broader one. The same pumping condition was adopted and the output power was almost the same. As shown in Fig. 7, the dip in the center of the pump spectrum might be attributed to lower conversion efficiency of the photodetector in the low frequency range. For the Brillouin signal, the $1/f$ noise in the low frequency range made the spectrum more Gaussian, whose influence was negligible as we deduced the linewidth 20 dB down from the peak. From the Lorentzian fitting, the 20-dB linewidth of the pump laser and the Brillouin laser were deduced to be 10MHz and 60 kHz, respectively, which corresponded to a linewidth-reduction ratio of 166. Apparently, the measured reduction ratio was greatly improved. However, there is still a substantial discrepancy compared with the theoretical results. Under the same condition, the power-feedback ratio of the Stokes signal was measured to be -9.5 dB. If we adopt the parameter of $\Delta\nu_B = 20$ MHz, $n = 1.4$ and $L = 150$ m in Eq. (1), the theoretical linewidth-reduction ratio is over 1000. Considering the influence of environment fluctuation and limited deviation in the linewidth measurement, we believe this discrepancy is reasonable as the theoretical model does not consider the intensity noise induced by the intra-cavity EDFA, which will broaden the intrinsic linewidth of the Stokes wave.

As a proof-of-concept experiment, the linewidth of the Stokes wave we obtained is not comparable to the ultra-narrow linewidth demonstrated in [5] and [6], as we did not apply any dedicated stabilizing measure with the environment. Nevertheless, it is worth noting that even as a sub-optimal prototype, the linewidth-reduction ratio of 166 is already much higher than the 37.5 in [5] and the 3 in [6]. A reduction ratio of 200 has been demonstrated in a conventional SLM Brillouin laser incorporating 600-m Brillouin gain media particularly for linewidth reduction [19], which is only slightly higher than our result even though we incorporated much shorter gain media (150 m). It should indicate a much higher achievable linewidth-reduction ratio, as our configuration can accommodate much longer Brillouin gain media if we adopt a higher-finesse sub-ring cavity.

VI. CONCLUSION

In summary, we presented a novel single-longitudinal-mode hybrid Brillouin/erbium fiber laser with high linewidth-reduction ratio. A sub-ring cavity and a saturable-absorber-based auto-tracking filter were utilized to achieve stable SLM

operation and an intra-cavity EDFA was incorporated to compensate the cavity loss. We experimentally demonstrated a linewidth-reduction ratio of 166, with even higher ratio to be expected by stabilizing the laser environment. Brillouin pump threshold is as low as 3 mW and the maximum output power is 7 mW. The wavelength tunability can cover the entire C-band and can be extended to L-band with self-lasing effectively suppressed by the auto-tracking filter.

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