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PAPER

Experimental Study of Lasing Characteristics of Brillouin/Erbium Optical Fiber Laser

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SUMMARY A lasing charactrization of a Brillouin/erbium optical fiber laser (BEFL) is experimentally discussed. In the BEFL, an erbium-doped fiber amplifier (EDFA) is incorporated into the Brillouin laser resonator to enhance small Brillouin gain, which makes the configuration of the Brillouin laser resonator easy and flexible. The experimental results show that the output power of the BEFL has a threshold against the Brillouin pump power, and above the Brillouin threshold, the output power increases linearly with the EDFA pump power. The BEFL threshold decreases with increasing the length of the optical fiber in the laser resonator used as a Brillouin gain medium. The BEFL oscillates in a stable single longitudinal mode because the bandwidth of the Brillouin gain profile is very narrow (~ 30 MHz). The relative intensity noise (RIN) and the spectral lineshape were measured. The noise floor level decreases with increasing the EDFA pump power, and the full-width at half maximum of the BEFL was measured to be about 8 kHz.

key words: *optical fiber, stimulated Brillouin scattering, fiber laser, nonlinear fiber optics*

1. Introduction

Stimulated Brillouin scattering (SBS) is a nonlinear process arising from resonant interaction between intense single-frequency laser light (called the Brillouin pump) and acoustic waves in an optical fiber, and a backward propagating lightwave (Stokes wave) is generated at the frequency of about 10 GHz lower than that of the Brillouin pump in 1.55 μm wavelength region. The SBS gives optical gain in an optical fiber, and can be utilized to fiber amplifiers/lasers and microwave signal generators [1]–[3]. The bandwidth of the Brillouin gain is, however, about 30–50 MHz [4], and then the SBS cannot be used as the optical amplifier in the optical fiber communication system because of high-speed data transmission of more than 10 GHz. The useful application of the SBS is the Brillouin fiber laser because stable single-frequency oscillation is expected from the narrow bandwidth.

The drawback of the Brillouin fiber laser is that a high finess optical resonator should be configured because of small optical gain of the Brillouin gain. Recently, a Brillouin fiber laser combined with an erbium-doped optical fiber amplifier, a Brillouin/erbium fiber laser (BEFL), was proposed and demonstrated [5]–[7]. In the BEFL, an erbium-doped fiber amplifier (EDFA) is incorporated into the laser cavity to enhance small Brillouin gain. As a result, the high-finess laser cavity is not required and the configuration of the laser cavity becomes easy and flexible.

In this paper, we present experimental results about the oscillating characteristics and the intensity noise properties of the BEFL. Previous reports on the BEFL are mainly focused on the lasing power, the spectral linewidth, and the multi-wavelength operation, and no experimental result is, to our knowledge, reported on the intensity noise property. Hence the main purpose of the paper is to make clear the intensity noise property of the BEFL. In Sect. 2, we briefly describe the operation principle of the BEFL. In Sect. 3, we show the experimental results such as the lasing threshold, the optical power and the optical spectrum. The measured intensity noise properties and the spectral linewidth are shown in Sects. 4 and 5, respectively, and in Sect. 6, we summarize our results.

2. Configuration

Figure 1 shows the configuration of the BEFL. The BEFL resonator consists of a 10 m-long erbium-doped fiber (EDF) pumped by a 1.48 μm laser through a WDM coupler (WDM-FC), an optical isolator, a single-mode fiber (SMF) which acts as a gain medium for the Brillouin gain, and a 3 dB fiber coupler (FC-B). The optical isolator is used to block the Brillouin pump and to realize an uni-travelling laser resonator for the Brillouin scattering light. No polarization controller and no phase compensator were used in the laser resonator. The EDF and the WDM-FC are spliced, and the other fiber components are connected by FC/PC connectors. A tunable semiconductor laser (spectral linewidth is about 400 kHz), followed by the fiber amplifier, was used as the Brillouin pump (BP) laser. When the BP is injected into

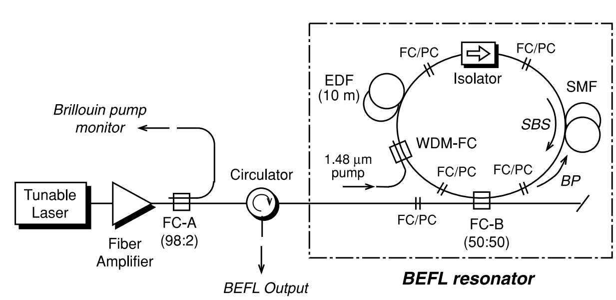

Fig. 1 Configuration of Brillouin/erbium fiber laser (BEFL).

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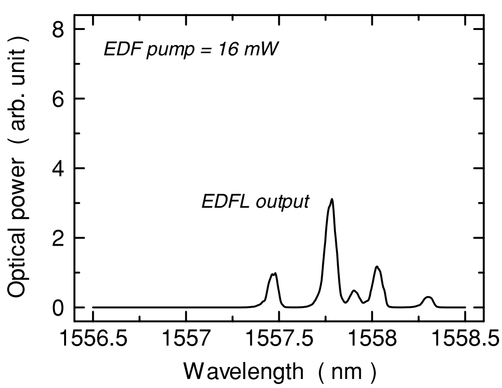
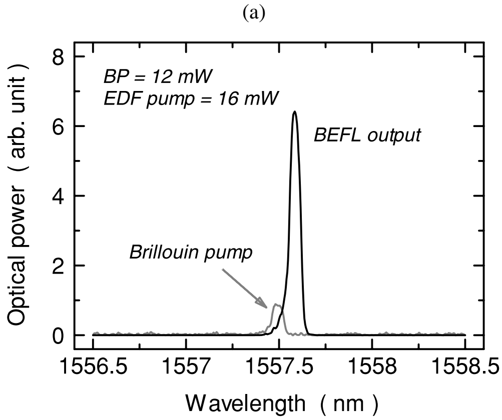
the BEFL resonator, a backward Brillouin scattering light is generated at a Stokes-shifted frequency from the BP frequency. The small Brillouin gain is enhanced by pumping the EDF in the BEFL resonator, and then the Brillouin gain can easily overcome the resonator loss. As a result, the Brillouin laser oscillation occurs.

3. Lasing Spectrum and Optical Output

Figure 2 shows the measured lasing spectrum of (a) the free-running erbium-doped fiber laser (EDFL), and (b) the BEFL along with the spectrum of the Brillouin pump, measured by an optical spectrum analyzer. The resolution bandwidth of the optical spectrum analyzer is 0.064 nm. The length of the SMF in the BEFL resonator is 140 m, and the total cavity length is about 160 m. The resultant free spetral range of the BEFL resonator is about 1.3 MHz. The EDF pump power is 16 mW. The free-running EDFL, which means no Brillouin pump is injected, exhibits multi-mode lasing spectrum. Figure 2(b) shows the lasing spectrum of the BEFL with 12 mW of the Brillouin pump power, which means the Brillouin pump is injected into the EDFL operating as is shown in Fig. 2(a). The lasing spectrum exhibits single-mode oscillation, and its wavelength is about 0.1 nm longer than that of the Brillouin pump. The wavelength shift of +0.1 nm corresponds to the optical frequency shift of −10 GHz (down shift) for 1.55 μm wavelength region, and therefore the lasing spectrum shown in Fig. 2(b) is caused by the Brillouin scattering.



(a)



(b)

Fig. 2 Lasing spectrum of (a) the free-running EDFL, and (b) the BEFL, measured by an optical spectrum analyzer.

Figure 3 shows the fine lasing spectrum of the BEFL measured by a Fabry-Perot interferometer (FPI) with the Finess of 175 and the free spectral range (FSR) of 2 GHz. The Brillouin pump power is 12 mW, and the EDF pump power is 16 mW. The BEFL oscillates in a single longitudinal mode, and no mode-hopping was observed for several tens minutes. The stable oscillation is achieved due to the narrow bandwidth of the Brillouin gain profile of typically 30 MHz, which is equivalent to insert an optical bandpass filter with 30 MHz bandwidth.

Figure 4 shows the measured lasing power against the Brillouin pump power when the SMF in the BEFL resonator is (a) 140 m and (b) 630 m. The BEFL has a threshold against the Brillouin pump and the threshold decreases with increasing the length of the SMF because the Brillouin gain increases with increasing the length of the SMF. Above the threshold Brillouin pump power, the output power is almost constant when the length of the SMF is 140 m, and the output power gradually increases with increasing the Brillouin pump power when the length of the SMF is 630 m. The output power also increases with increasing the EDF pump power.

Figure 5 shows the output power against the EDF pump power. The closed circles are the output power when the SMF resonator in the BEFL is 140 m, and the open squares are the output power when the SMF in the BEFL resonator is 630 m. The output power linearly increases with increasing the EDF pump power. From Figs. 4 and 5, we can say that the output power of the BEFL is primary dominated by the EDF pump power. The abrupt increase in the output power shown in Fig. 4 is due to the optical gain of the EDF in the BEFL resonator, and the gradual increase in the output power above the Brillouin threshold shown in Fig. 4 is due to the Brillouin optical gain.

Figure 6 shows the measured threshold Brillouin pump power against the length of the SMF in the BEFL resonator. The closed circles are the measured threshold Bril-

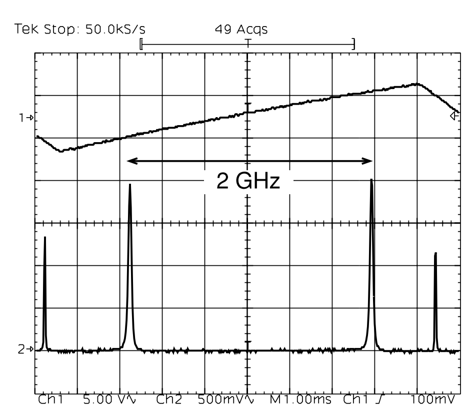


Fig. 3 Fine lasing spectrum of the BEFL measured by a Fabry-Perot interferometer with the FSR of 2 GHz and the Finess of 175. The Brillouin pump power is 12 mW, and the EDF pump power is 16 mW.

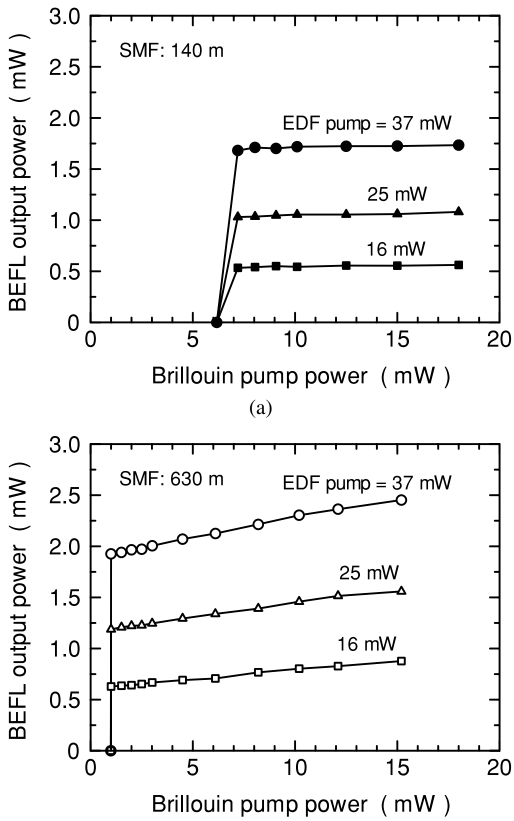


Fig. 4 Output power of the BEFL against the Brillouin pump power when the SMF in the BEFL resonator is (a) 140 m and (b) 630 m.

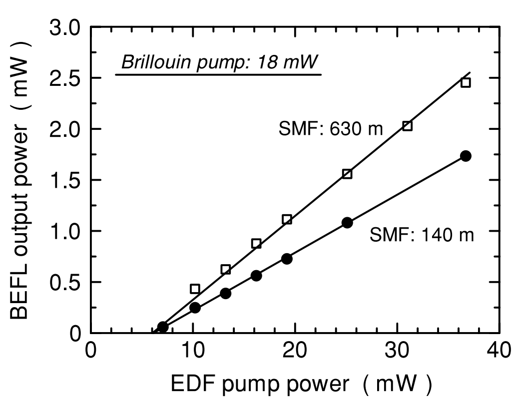


Fig. 5 Output power of the BEFL against the EDF pump power.

louin pump power when the linewidth of the Brilloun pump laser was 400 kHz. The Brillouin threshold decreases with increasing the length of the SMF because the Brillouin gain linearly increases with the length of the SMF. The cross in Fig. 6 is the measured threshold Brillouin pump power when the linewidth of the Brillouin pump laser was about 40 MHz, showing the increased threshold Brillouin pump power. Generally, the Brillouin gain g_B and the threshold Brillouin pump power for the SBS, P_C, are expressed as [8], [9];

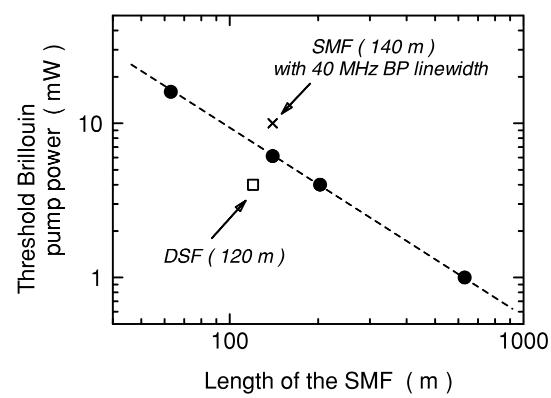


Fig. 6 Threshold Brillouin pump power against the length of the SMF in the BEFL resonator.

$$g_B = \frac{\Delta\nu_B}{\Delta\nu_B + \Delta\nu_p} g_{B0} \tag{1}$$

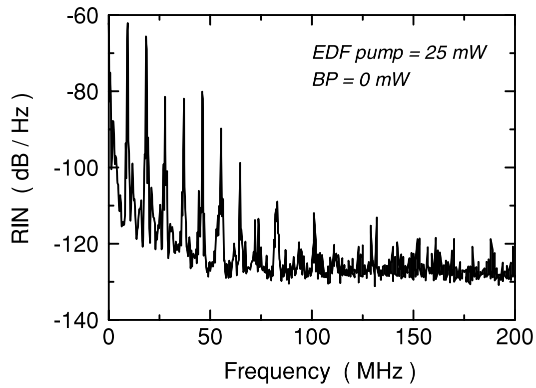
$$P_C = \frac{21 A_{eff}}{g_B L_{eff}} \tag{2}$$

$$L_{eff} = \frac{1 - \exp(-\alpha_p L)}{\alpha_p} \tag{3}$$

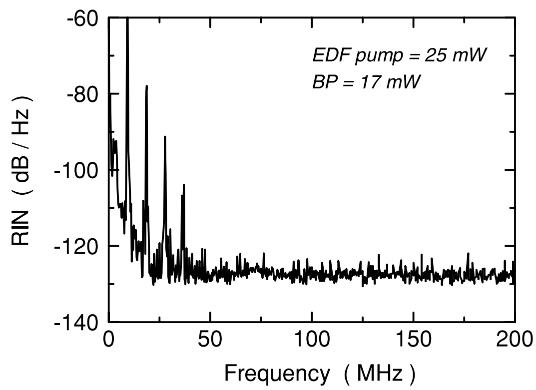
where g_{B0} is the maximum Brillouin gain, $\Delta\nu_B$ and $\Delta\nu_p$ are the bandwidth of the Brillouin gain and the spectral linewidth of the Brillouin pump, respectively, A_{eff} is the effective core area of the fiber, L_{eff} is the effective interaction length, α_p is the loss of the fiber for the Brillouin pump, and L is the fiber length. From the equations, the Brillouin gain decreases and the threshold Brillouin pump power increases with increasing the linewidth of the Brillouin pump laser, resulting in the increased threshold Brillouin pump power. In Fig. 6, the open square is the measured Brillouin threshold when a dispersion-shifted optical fiber (DSF: 120 m) was used in stead of the SMF, showing the lower threshold Brillouin pump power than the case when the SMF was used. The refractive index of the core in the DSF is higher than that in the SMF, and then the effective core area is smaller than that of the SMF to maintain single-mode propagation. The decreased A_{eff} gives decreased SBS threshold P_C from Eq. (2), and as a result, the threshold Brillouin pump power is lowered.

4. Intensity Noise Spectrum

Figure 7 shows the measured intensity noise spectrum of the BEFL. The EDF pump power is 25 mW, and the Brillouin pump power is (a) 0 mW and (b) 17 mW. The resolution bandwidth of the spectrum analyzer is 100 kHz. The length of the SMF in the BEFL resonator is 140 m, and the total cavity length is about 160 m. The resultant free spetral range of the BEFL resonator is about 1.3 MHz. Peak signals are observed in the noise spectrum and the separation is 9.3 MHz. Since the free-spectral range of the BEFL resonator is about 1.3 MHz, the observed peak signals are not the longitudinal modes of the BEFL. The free-spectral range of 9.3 MHz corresponds to the resonator length of 11 m in a

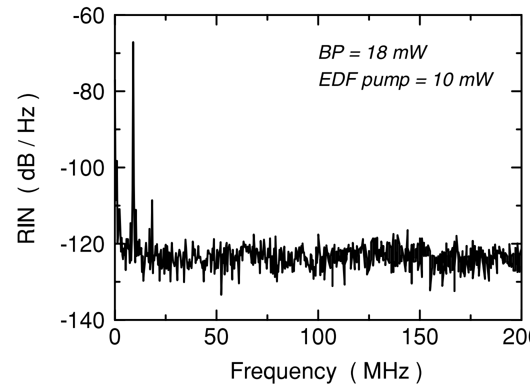


(a) Brillouin pump: 0 mW.

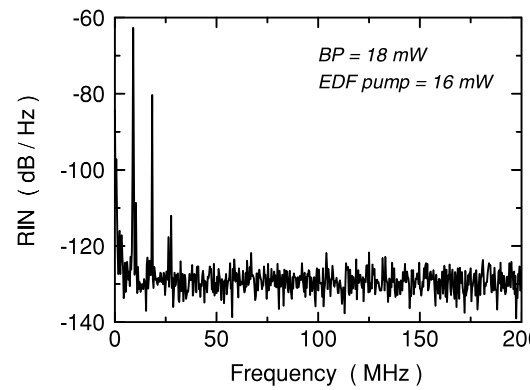


(b) Brillouin pump: 17 mW.

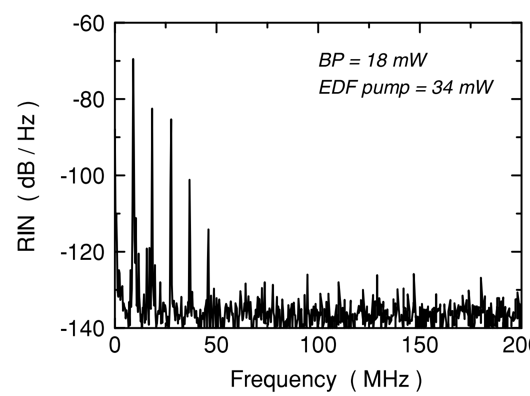
Fig. 7 Measured RIN of the BEFL. The length of the SMF in the BEFL resonator is 140 m, and the EDF pump power is 25 mW.



(a) EDF pump: 10 mW.



(b) EDF pump: 16 mW.



(c) EDF pump: 34 mW.

Fig. 8 Measured RIN of the BEFL. The length of the SMF in the BEFL resonator is 140 m, and the Brillouin pump power is 18 mW.

fiber Fabry-Perot resonator, and then the observed peak signals are generated from unwanted reflections at the FC/PC connectors of the EDF and the WDM-FC in the BEFL resonator. No peak signals are expected in the intensity noise spectrum if unwanted reflections are eliminated. When no Brillouin pump is injected, the peaks exists in 0–100 MHz frequency range as is shown in Fig. 7(a). When the Brillouin pump is injected, the number of the peaks decreases and the peaks exist below 50 MHz frequency range. The is due to the Brillouin gain. The total gain profile of the BEFL is given by multiplication of the profiles of the EDF gain and the Brillouin gain, and the bandwidth of the Brillouin gain is typically 30 MHz, which is narrower than the bandwidth of the EDF gain. The spectrum shown in Fig. 7(b) is equivalent to multiply a low-pass filter whose bandwidth is given by the bandwidth of the Brillouin gain. We can also find out that the noise floor level is unchanged with the Brillouin pump power.

Figure 8 shows the measured intensity noise spectrum of the BEFL for the different EDF pump power. The Brillouin pump power was 18 mW. The number of the peak signal separated by 9.3 MHz increases with increasing the EDF pump power because of the increased Brillouin gain. The noise floor level decreases with increasing the EDF pump power. The noise floor level against the EDF pump power is plotted in Fig. 9. The noise floor level is estimated from the RIN spectrum in 150–200 MHz frequency range. The noise floor level apparently decreases with the EDF pump power. The noise floor level is almost the same with the that of the EDFL, which means no Brillouin pump is injected into the BEFL. This means that the intensity noise level is determined by the EDFL, and the low-noise BEFL can be obtained by reducing the intensity noise of the EDFL.

5. Spectrum Lineshape

Figure 10 shows the measured spectral lineshape for (a) the Brillouin pump and (b) the BEFL when the Brillouin pump power and the EDF pump power are 15 mW and 31 mW, re-

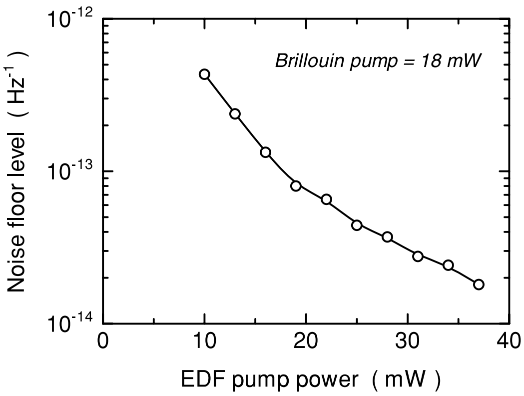


Fig. 9 Measured noise floor level in the RIN spectrum against the EDF pump power.

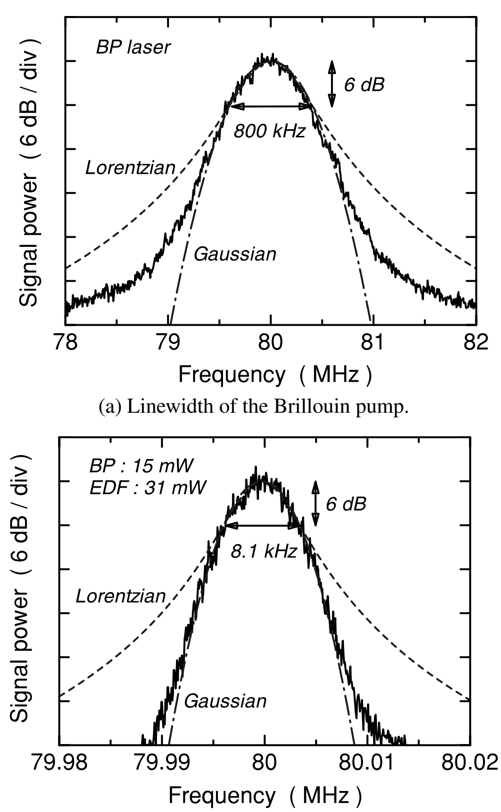


Fig. 10 Measured spectral linewidth of BEFL. The length of the SMF in the BEFL resonator is 140 m. The dashed line is Lorentzian profile and the dash-dot-dash line is Gaussian profile.

spectively. The length of the SMF in the BEFL resonator is 140 m. The spectral lineshape was measured by the delayed self-heterodyne method with 5 km fiber delay line, which gives about 20 kHz linewidth resolution. The resolution bandwidth and the sweep time of the spectrum analyzer were 300 Hz and 1.2 s, respectively. The lineshape of the beat spectrum for the Brillouin pump is close to Gaussian profile and its FWHM (Full Width at Half Maximum) is 800 kHz. The lineshape of the beat spectrum for the BEFL

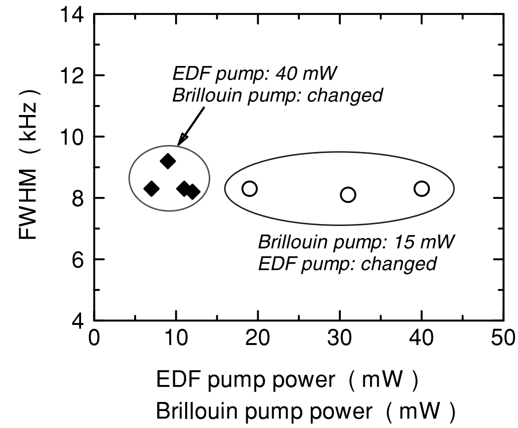


Fig. 11 Measured FWHM of the BEFL for various values of the EDF pump and the Brillouin pump powers. The length of the SMF in the BEFL resonator is 140 m.

is also Gaussian-like and its FWHM is 8.1 kHz. Figure 11 shows the measured FHWM of the BEFL for various values of the EDF pump and the Brillouin pump powers. The close diamonds show the FWHM against the Brillouin pump power when the EDF pump power was 40 mW, and the open circles show the FHWM against the EDF pump power when the Brillouin pump power was 15 mW. The FWHM is almost contant irrespective of the EDF pump power and the Brillouin pump power.

Although we cannot exactly estimate the spectral linewdith of the BEFL because the measured beat spectrum is narrower than the linewidth resolution of the system, the BEFL is expected to be highly coherent light source with kHz or sub-kHz spectral linewidth.

6. Conclusions

We have experimentally discussed the lasing characteristics of a Brillouin/erbium optical fiber laser (BEFL). The experimental results show that the output power of the BEFL has a threshold against the Brillouin pump power, and above the Brillouin threshold, the output power increases linearly with the EDF pump power. The threshold Brillouin pump power decreases with increasing the length of the optical fiber in the laser resonator used as a Brillouin gain medium because of larger Brillouin optical gain for longer optical fiber. The Brillouin threshold also decreases when a DSF is used as the Brillouin gain medium, and increases when the linewidth of the Brillouin pump laser increases. The BEFL oscillates in a stable single longitudinal mode because the bandwidth of the Brillouin gain profile is very narrow (~ 30 MHz).

In the intensity noise spectrum, many peak signals due to unwanted reflection in the BEFL resonator are observed, and the number of the peak signals decreases by the Brillouin pump because of narrow gain bandwidth of the Brillouin gain. The noise floor level is independent of the Brillouin pump power, and decreases with increasing the EDF pump power. The spectral lineshape of the BEFL was measured by the delayed self-heterodyne method. The FWHM is estimated to be about 8 kHz, and is independent of the Brillouin pump power and the EDF pump power.

The BEFL can be used as a light source in interferometric sensor systems which need highly coherent laser source, for example, resonator fiber-optic gyroscopes. The wavelength tunability of the BEFL was also reported in [7] and the tuning range is about 3 nm by changing the wavelength of the Brillouin pump laser. Highly coherent and tunable characteristics of the BEFL can be used as a laser source in high resolution spectroscopy and frequency-modulated continuous-wave (FMCW) sensing system.

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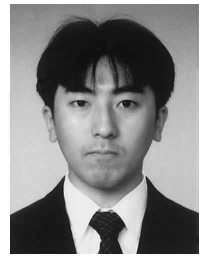

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