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Effects of output coupler reflectivity on the performance of a linear cavity Brillouin/erbium fiber laser

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Abstract. The effect of output coupler reflectivity (or output coupling ratio) on the performance of a linear cavity Brillouin/erbium fiber laser (BEFL) is demonstrated. The operating wavelength, output laser power and number of channels vary with changes in the coupling ratio in the linear cavity system. The optimum BEFL operation is obtained with an output coupling of 40%, i.e., 60% of the laser power is allowed to oscillate in the cavity. A stable laser comb consisting of up to 40 channels with line spacings of approximately 0.09 nm are obtained at the Brillouin pump and 980 nm pump with powers of 2.5 mW and 100 mW, respectively. The linear cavity BEFL has the potential to be used in inexpensive wavelength division multiplexing system.

Keywords. Stimulated Brillouin scattering process; coupling ratio; linear cavity; multi-wavelength Brillouin/erbium fiber laser; Brillouin/erbium fiber laser.

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1. Introduction

Wavelength division multiplexing (WDM) is an effective and powerful means to increase the total information bit rate transmitted over long range communication links. Multi-wavelength sources are important components for WDM systems. There has been increased research efforts in erbium-doped fiber laser (EDFL) as fiber lasers have several advantages over semiconductor laser, such as inherent compatibility with single mode optical fiber networks, high conversion efficiencies, low insertion losses, ease of construction and low production cost. However, one of the main challenges of EDFLs is to achieve stable multi-wavelength lasing with small wavelength spacing at room temperature because the homogeneous line broadening in the erbium-doped fiber (EDF) leads to cross-gain saturation and wavelength competition. The homogeneous line broadening can be suppressed by cooling the

EDF in liquid nitrogen, but the technique is not suitable for practical applications because of the complexity and bulkiness of the system [1].

Alternatively, another promising multi-wavelength fiber laser system is based on a Brillouin/erbium fiber laser (BEFL) which uses the nonlinear effect in single-mode fibers (SMF). The BEFL is capable of generating channels with a constant dense spacing of about 10 GHz (0.08 nm) at room temperature, offering higher channel densities up to 10 times as compared to the 100 GHz spacing in current systems [2]. Various approaches such as ring cavities and seed Brillouin signal feedback systems have been studied in order to generate multi-wavelength BEFL [3–5].

In this paper, a linear cavity BEFL is proposed, in which 40 channels with line spacing of approximately 0.09 nm are obtained at the 1564 nm region. When compared to the ring cavity, BEFL is simpler as Brillouin signal is not used as an input signal. The effect of the coupling ratio on the performance of a linear cavity BEFL is also investigated as the coupling ratio plays an important role in determining the operating wavelength, the number of generated Brillouin-Stokes and the output power of the BEFL.

2. Experimental set-up

Figure 1 shows the experimental set-up for the linear cavity BEFL. An EDF of 14 m length with an Er^{3+} ion concentration of 440 ppm and cut-off wavelength of 962 nm is used in the system. The EDF is forward pumped through a WDM coupler by a 100 mW, 980 nm laser diode and two optical circulators, C2 and C3 (with port-to-port losses of 0.5 dB) are placed at both ends of the laser cavity to act as a fiber loop mirror. A narrow linewidth signal from an external cavity tunable laser source (TLS) is used as the Brillouin pump (BP) in the system. The TLS can be tuned from 1520 nm to 1620 nm with the maximum output power of 7 dBm. A circulator, C1, is used in conjunction with the coupler to inject the BP into the SMF and to couple the BEFL output.

The BP wavelength close to the peak gain wavelength of the EDF laser is injected into the SMF and the stimulated Brillouin scattering in SMF generates a Stokes-shifted signal in the opposite direction of the BP. The SBS is generated from the interaction between the pump light, a backscattered Brillouin Stokes and

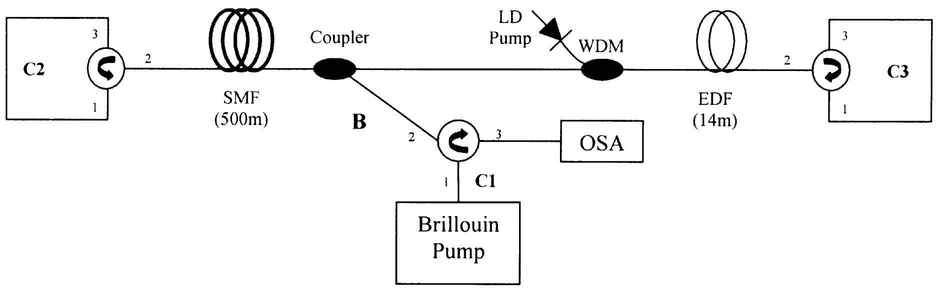

Figure 1. Experimental set-up of BEFL.

an acoustic wave. Due to the electrostriction, an acoustic wave is generated with an acoustic velocity V_A in the glass. Coupling with the acoustic wave causes the backscattered Stokes to downshift through the Doppler shift. The Stokes frequency ν_B has now shifted in the backward direction and is given by $\nu_B = (2nV_A)/\lambda_p$, where λ_p is the pump wavelength and n is the refractive index of SMF.

In the linear cavity BEFL system, the laser propagates through the EDF twice per oscillation trip. The first shifted Stokes signal propagates in the opposite direction to the BP and is amplified by the EDF before it is reflected back by the optical circulator C3. The reflected signal will be amplified again by the EDF before it goes through the SMF and reaches the optical circulator C2 to complete one oscillation. The oscillation continues till the first Brillouin Stoke reaches the threshold required to generate a second Stokes which is shifted further with a frequency ν_B relative to the first Stokes signal. The double-pass through the EDF reduces the effective cavity loss and enhances the laser performance. Compared with the ring cavity system [3–5], the linear cavity BEFL system does not require an extra feedback loop to generate a multiple wavelength Stokes. There is also no optical isolator in the cavity to prevent injection locking of the BP wavelength. Thus, the BP wavelength is not eliminated in the system and is shown in the spectrum as the line with the highest peak power.

The output of the laser is coupled out using a coupler in conjunction with an optical circulator, C1. An optical spectrum analysis (OSA) of 0.015 nm resolution is used for measurement. The effects of varying the input/output coupler ratio on the BEFL performance have been investigated in this experiment.

3. Result and discussion

Figure 2 shows the BEFL output comb against wavelength with various coupling ratios. The pump power at 980 nm is fixed at 100 mW, while the operating wavelength is a function of the length of the EDF and the cavity loss in the BEFL system. Varying the coupler ratio will subject the resonant cavity to experience different values of cavity loss, thus determining the amount of light that is injected as the BP and the amount of light that is allowed to oscillate in the cavity. Here, R is defined as a percentage of port B and is used to indicate the coupling ratio. Higher values of R increase the cavity loss, which in turn permits lower amounts of light to oscillate in the cavity and consequently results in the shifting of the laser wavelength to a shorter wavelength as shown in figure 2. This is attributed to the system which requires a higher pump power to achieve higher gain and overcome the loss to enable Stokes generation. The choice of the laser wavelength is dependent on the emission and the absorption cross-section of the EDF, which peaks at around 1530 nm. Therefore, the BEFL comb wavelength shifts to this region of operation, which has a higher gain. The BEFL operates at around 1564 nm, which coincides with the operating wavelength of the free-running EDF laser (without Brillouin pump). Lasing occurs at 1564 nm region and is due to the absorption of 1530 nm photons by the EDF to be emitted at around 1564 nm.

Figure 3 illustrates the number of Brillouin Stokes and the 1st Brillouin Stokes peak power at various coupler ratios, R. The Brillouin and 980 nm pump powers

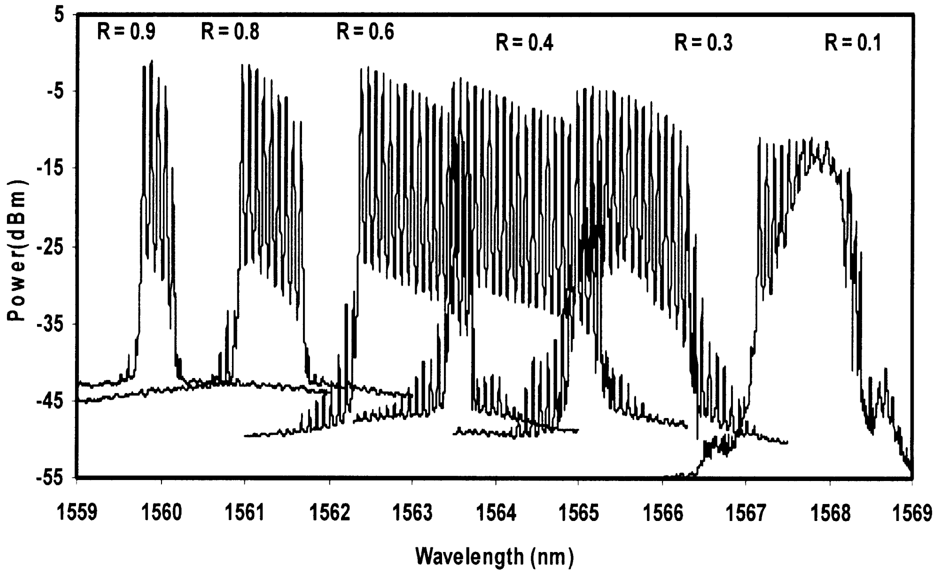

Figure 2. BEFL spectrum at various coupling ratios.

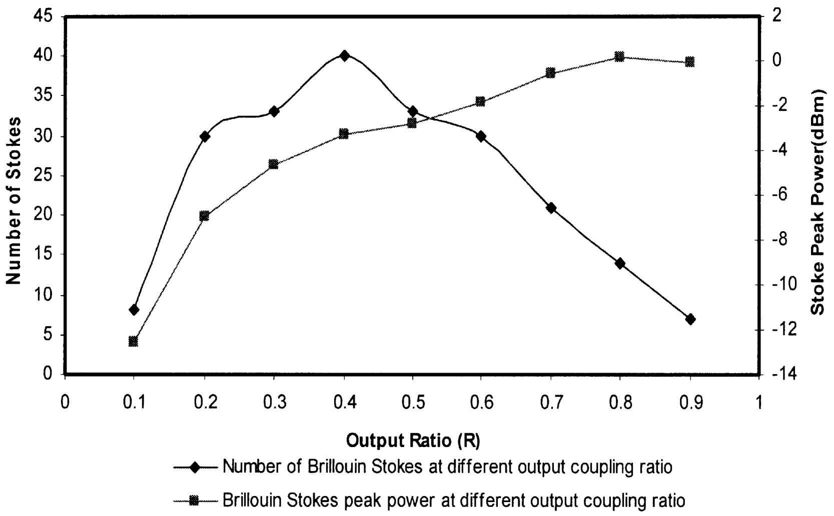

Figure 3. Brillouin Stokes peak power and number of Brillouin Stokes at different output ratios.

are fixed at 2.5 mW and 100 mW, respectively. Increasing the laser cavity loss not only shifts the operating wavelength to a shorter wavelength but also increases the output power of the laser as shown in figure 3. For instance, at the highest R of 0.9, the output power obtained is about 0 dBm, and is 12 dB higher as compared with the case of R equals 0.1. The number of Stokes also increases as

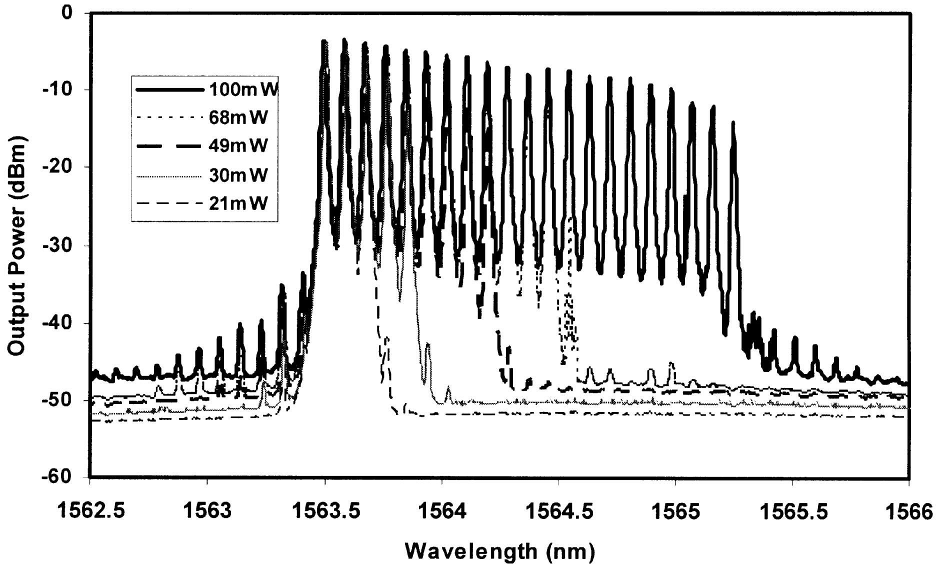

Figure 4. The BEFL spectra at various pump powers for $R = 0.4$.

the overall BEFL power increases. However, a very high output power reduces the mode competition, affecting the number of Stokes in the system. Reduced mode competition will allow only a small number of modes to survive and thus limits the number of Stokes. Therefore, the optimum coupler ratio R is obtained at 0.4, which provides the highest number of channels as shown in figures 2 and 3. Up to 40 channels are obtained with maximum peak powers of approximately −3.5 dBm. The optimum coupling ratio of 0.4 is for the selected Brillouin pump and 980 nm pump powers of 2.5 mW and 100 mW, respectively and is dependent on these pump powers.

Figure 4 shows the spectra of BEFL at various pump powers when the coupling ratio is set at 0.4. The BP wavelength, BP and 980 nm pump powers were fixed at 1563.5 nm, 2.5 mW and 100 mW respectively. As shown in the figure, the total output power corresponding to the number of the generated lines increases with 980 nm pump power. At 980 nm pump power of 100 mW, up to 40 lines of BEFL are produced with a maximum output power of −3.5 dBm around 1563.6 nm. A flat output power is also observed particularly in the first few lines due to the BP power being almost similar to the generated Stokes power in these lines. The simultaneous laser lines are separated by 0.09 nm due to the homogeneous nature of EDF gain and SBS effect. This interspacing depends on the BP wavelength, the acoustic velocity in the glass and the refractive index of SMF. The 3 dB bandwidth of each line is measured to be approximately 0.02 nm, and is limited by the OSA resolution ($\Delta\lambda \approx 0.015$ nm). The multi-line generation in the BEFL system also involves anti-Stokes scattering lines as shown in figure 4. The anti-Stokes lines arise due to the bi-directional operation and four-wave mixing process in the SMF. The spectrum was scanned 10 times continuously at maximum 980 nm pump power and with R of 0.4.

4. Conclusion

The effect of coupling ratio on the performance of a linear cavity BEFL is investigated. The coupler ratio affects the operating wavelength, power and number of lines of the output laser comb. The optimum BEFL operation is obtained with a center wavelength at around 1564 nm by allowing 60% ($R = 0.4$) of the laser power to oscillate in the cavity. The stable and strong BEFL comb of up to 40 lines is produced at BP and 980 nm pump powers of 2.5 mW and 100 mW, respectively. These results indicate that the linear cavity BEFL has high potential in applications for future inexpensive DWDM communication systems.

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