A high-efficiency Brillouin fiber ring laser

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A high-efficiency Brillouin fiber ring laser is demonstrated using the standard single-mode fiber. The laser exhibits a 3.6-mW threshold. The output power is 22 mW with 40-mW pump power, and the maximum optical-to-optical efficiency is 55%. The output is single wavelength with a 3-dB linewidth of 5 MHz, and the interval of center frequency between the laser and the pump light is 11 GHz (0.088 nm). It is shown that the stimulated Brillouin scattering threshold of ring resonator is lower and the energy transfer efficiency is higher than those in fiber.

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Stimulated Brillouin scattering (SBS) is one of the most dominant nonlinear effects in various media. It is well known that optical fibers are particularly suitable media for SBS study. The threshold power of SBS is the lowest of all the nonlinear effects in single-mode fibers (SMFs). Although SBS is detrimental for coherent optical communication systems[1,2], it has applications in Brillouin fiber lasers[3−9], optical delay lines[10], fiber sensors[11], and phase conjugations[12]. In recent years, SBS fiber ring lasers have attracted considerable interest because of their advantages of ultra-narrow linewidth and low threshold power.

Shirazi *et al.* proposed a new configuration for a Brillouin fiber laser (BFL) using components similar to a conventional but with a higher output power[6]. In this letter, we make a basal research on Brillouin fiber ring laser using the similar configuration with a high output power. By using a pump with narrower linewidth, a shorter length of fiber, and a polarization controller (PC), we get a high-efficiency BFL.

The process of SBS can be described classically as a nonlinear interaction between the pump and Stokes fields through an acoustic wave. The pump field generates an acoustic wave through the process of electrostriction. The acoustic wave in turn modulates the refractive index of the medium. This pump-induced index grating scatters the pump light through Bragg diffraction. The scattered light is downshifted in frequency because of the Doppler shift associated with a grating moving at an acoustic velocity ν_A. In a SMF, the only relevant directions are the forward and backward directions. Commonly the forward SBS is ignored, and only the backward one is considered. The Brillouin frequency shift is given by

$$\nu_B = \Omega_B/2\pi = 2n\nu_A/\lambda_p, \qquad (1)$$

where λ_p is the wavelength of the pump power and n is the modal index at the pump wavelength. If ν_A= 5.96 km/s and n= 1.45, whose values appropriate for silica fibers, $\nu_B \approx 11.1$ GHz at λ_p= 1.55 μm.

Generally, both the ring cavity and the Fabry-Perot cavity can be used for making Brillouin fiber lasers. However, higher-order Stokes lines are generated through cascaded SBS in BFL consisting of a Fabry-Perot cavity, which is very useful to dense wavelength division multiplexing (DWDM) telecommunication systems. Most BFLs use a ring cavity to avoid the generation of multiple Stokes lines through cascaded SBS.

In this letter, the configuration in Ref. [6] for a BFL is used. The experimental setup for the BFL is shown in Fig. 1. The ring resonator consists of a circulator, a 3-km-long G.652 SMF, a 3-dB coupler, an isolator (ISO), and a PC. The Brillouin pump was a distributed feedback (DFB) laser diode with a linewidth of approximately 1 MHz and a maximum power of 40 mW. The output was measured with an AQ6970 optical spectra analyzer (OSA) of Yokogawa. The narrow-linewidth Brillouin pump was injected directly into the SMF through the circulator in a clockwise direction. The generated backward-propagating SBS oscillated inside the resonator in anti-clockwise direction to generate the Brillouin laser. The isolator was used to prevent the pump from forming a transmitting loop and prevent higher order Stokes lines. The PC can keep the state of Stokes lines maintaining resonance with the eigenstate of polarization existing in the ring resonator. Adjusting the PC would affect the experimental results. There is a linear relationship between the pump power and the driving current. Thus by tuning up the current, the pump power can be increased or decreased. The magnitude of drive current expresses the magnitude of pump light power.

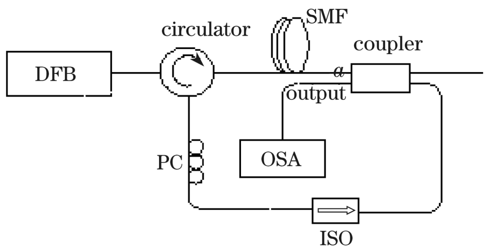

Fig. 1. Experimental setup of Brillouin fiber ring laser.

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Figure 2 shows the output spectra of the proposed Brillouin fiber ring laser under different pump powers. In the experiment, the 3-dB coupler allowed half of the light to oscillate in the cavity and the other half to couple out as output. This configuration generates a Brillouin laser which is at a wavelength 0.088 nm longer than the Brillouin pump. Under a low pump power, the anti-Stokes lines are also observed. Stokes resonance is generated when the driving current of pump is 35 mA. The driving current was varied from 30 to 300 mA. The generated peak power was observed to increase as the current increased, which was attributed to the increment of Brillouin gain with pump power. The measured 3-dB linewidth of Stokes output was less than 0.02 nm, limited by the OSA resolution of 0.02 nm. This value cannot manifest the real linewidth of the Brillouin fiber ring laser which has a several tens of megabertz gain linewidth limitation.

The real 3-dB linewidth of the Brillouin fiber ring laser was measured by the short fiber delayed self-heterodyne based narrow linewidth analyzer sample[13]. The linewidth of the Brillouin fiber ring laser strongly depended on the linewidth of the Brillouin pump, based on the theoretical analysis performed by Debut *et al.*[14] A simple analytical relation connecting the Brillouin laser linewidth $\Delta\nu_{\text{Stokes}}$ and the pump laser linewidth $\Delta\nu_{\text{pump}}$ is given by

$$\Delta\nu_{\text{Stokes}} = \Delta\nu_{\text{pump}} \Big/ \left(1 + \frac{\gamma_{\text{A}}}{\Gamma_{\text{C}}}\right), \qquad (2)$$

where $\gamma_{\text{A}} = \pi\Delta\nu_{\text{B}}$ and $\Gamma_{\text{C}} = -c\ln R/nL$ are the damping rate of the acoustic wave and the cavity loss rate, respectively, $\Delta\nu_{\text{B}}$ is the full-width at half-maximum (FWHM) of Brillouin gain curve, C is the velocity of light, R is the amplitude feedback parameter characterizing the ring cavity, L is the length of the resonator loop. The output frequency spectrum is shown in Fig. 3. The spectral linewidth of the Brillouin fiber ring laser was measured to be around about 5 MHz, wider than the pump light linewidth measured to be about 1 MHz. The result can be explained by the fact that the Brillouin pump is not stable because of the instability of drive source. The laser frequency of the Brillouin fiber ring laser output follows the frequency fluctuation of its pump laser; the stabilized Brillouin fiber ring laser suffers from fast frequency modulation, which results in the broadening of Brillouin output[11].

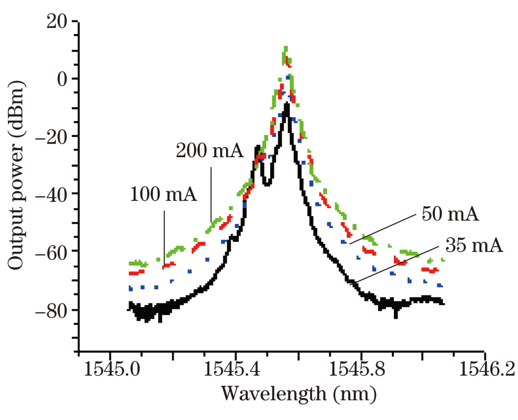

Fig. 2. Output spectra of fiber ring laser under different pump powers.

The higher Brillouin pump power generates a higher reflectivity of SBS. When the length of the fiber is set, the higher the Brillouin pump power is, the easier the establishment of the acoustic optical grating is, and the Stokes lines are accumulated rapidly. The coupling interaction is also strengthened. However, when the pump power reaches a definite level, the optical-to-optical efficiency is not changed obviously with the Brillouin pump power. We can believe that the definite level is the optimal power and this value is strongly depending on the fiber length.

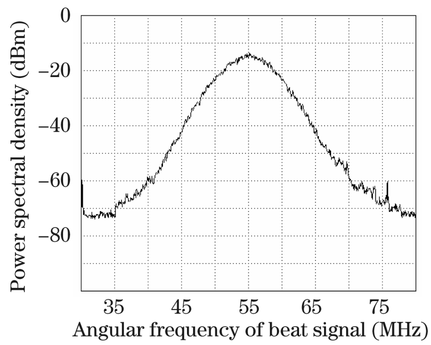

Fig. 3. Spectrum using laser linewidth measurement.

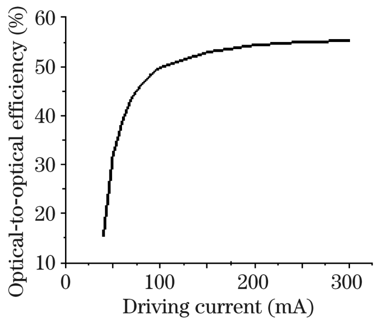

Fig. 4. Relationship between optical-to-optical efficiency and driving current.

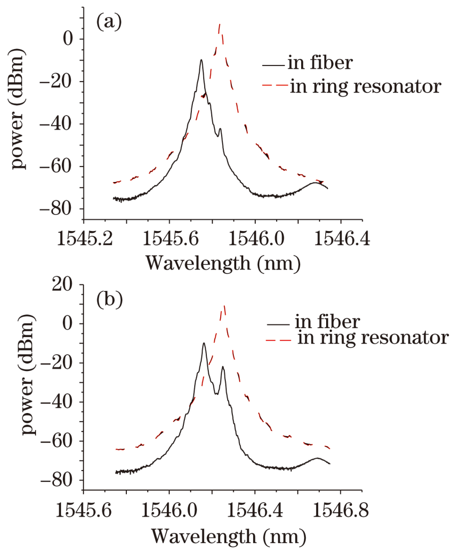

Fig. 5. Comparison of SBS between in ring laser and in fiber. The driving currents are (a) 100 and (b) 200 mA, respectively.

Figure 4 shows the optical-to-optical efficiency of the Brillouin fiber ring laser at different pump powers. When the driving current is less than 100 mA, the optical-to-optical efficiency grows almost linearly with the pump strength. But it maintains stable when the driving current exceeds 100 mA. In the experiment, the maximum of the optical-to-optical efficiency was 55% with 300-mA driving current. The output power was 22 mW measured with a power meter.

Hill *et al.* have demonstrated and proved that the feedback loop could decrease the threshold of SBS in 1976[15]. Because the lower threshold and the selective amplification of resonator, the transfer efficiency from pump light to Stokes light was improved. In order to eliminate the effect of the loop feedback caused by the coupler, we cut the ring cavity at point a (see Fig. 1). We compare the results of this configuration (i.e., in fiber) with those in the ring cavity, as shown in Fig. 5. It is demonstrated that the threshold of SBS is lower and the transfer efficiency is higher in the ring resonator.

In conclusion, we studied the high-efficiency Brillouin fiber ring laser elementarily. This Brillouin fiber ring laser exhibited a 3.6-mW threshold. The output power was 22 mW with 40-mW pump power, and the optical-to-optical efficiency was 55%. The 3-dB linewidth was about 5 MHz. The ring cavity has a lower SBS threshold and a higher transfer efficiency than a fiber.

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