Single-longitudinal-mode operation of a grating-based fiber-ring laser using self-injection feedback

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A fiber Bragg grating– (FBG–) based fiber-ring laser that utilizes the transmitted light of the FBG as self-injection feedback for single-longitudinal-mode (SLM) oscillation is proposed and demonstrated. This laser is simply constructed by means of feeding back the transmitted light of the FBG and is coupled into the main ring cavity through an optical coupler. The self-injection feedback is the key to ensuring SLM laser oscillation. The SLM operation principle is discussed in detail, and a SLM laser with output power of 6.6 dBm, an optical signal-to-noise ratio of 57 dB at 1549.19 nm, and a short-term linewidth of 3.5 kHz is reported.

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Single-longitudinal-mode (SLM) erbium-doped fiber lasers (EFL's) have potential applications in optical communications, CATV systems, fiber sensors, and spectroscopy. Among these EFL's, the unidirectional ring-cavity configuration,[1,2] which can potentially offer more output power with low relative intensity noise, has been extensively studied. Because of the required intracavity components and connecting fibers, a rather long cavity length (always several tens of meters) of the fiber-ring laser is unavoidable and brings out an enormous number (10^5–10^6) of densely spaced longitudinal modes lying beneath the erbium gain curve. To achieve SLM operation, researchers have proposed several techniques for EFL's, such as integrating two cascaded Fabry–Perot filters of widely different free spectral ranges (FSR's) into the ring cavity,[1,2] employing a compound ring resonator composed of a dual-coupler fiber ring and a tunable bandpass filter,[3] using twisted erbium-doped fibers and a fiber-type half-wave plate to control the cavity,[4,5] and inserting a passive multiple ring cavity into the main cavity as a mode filter.[6]

In this Letter an EFL that utilizes the transmitted light of a fiber Bragg grating (FBG) as self-injection feedback for SLM oscillation is proposed and demonstrated. The laser is simply constructed by means of feeding back the transmitted light of the FBG and is coupled into the main ring cavity (MRC) through an optical coupler. This self-injection feedback provides longitudinal-mode restriction and ensures SLM laser oscillation.

Figure 1 shows the structure of the FBG-based fiber laser, with self-injection provided by feeding back of the transmitted light of the FBG. This fiber laser obviously has two ring cavities: a MRC and a secondary ring cavity. The main ring cavity is formed by loop paths L_0 and L_1 and is linked to the secondary ring cavity, in which the light travels along paths L_0 and L_2. Loop path L_2 denotes the feedback path, in which the transmitted light of the FBG passes through a polarization controller, an optical delay line, and a variable optical attenuator and is combined with the reflected light from the FBG by an optical coupler. According to Ref. 7, the optical waves in each ring cavity should be in phase with the original wave after one complete turn, and the two phase conditions corresponding to the two ring paths can be written as

$$\beta(L_0 + L_1) + \phi_r = 2m\pi\,, \qquad (1)$$

$$\beta(L_0 + L_2) + \phi_t + \pi/2 = 2n\pi\,, \qquad (2)$$

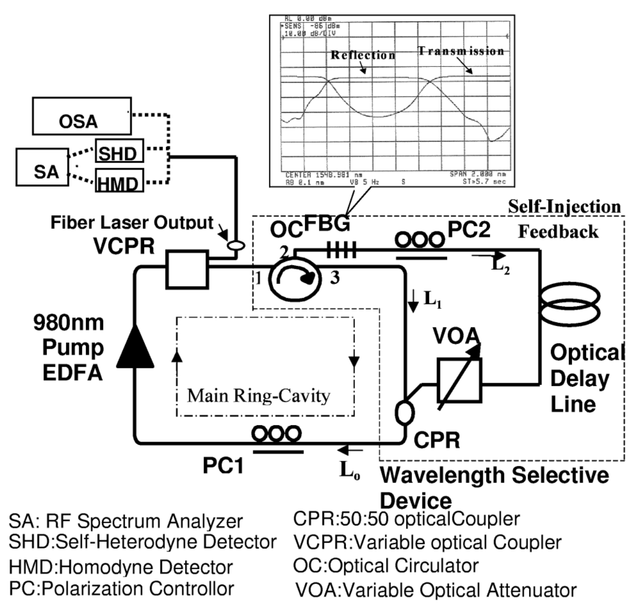

Fig. 1. FBG-based fiber-ring laser with self-injection feedback for SLM operation: proposed configuration and experimental setup. OSA, optical spectrum analyzer; EDFA, erbium-doped fiber amplifier.

where β is the propagation constant, ϕ_r is the phase of the reflection from the FBG, $\phi_t = \phi_r - \pi/2$ is the phase of the transmission through the FBG, and m and n are positive integers. If the length of L_0 is roughly several tens of meters, the delay time (approximately several hundred picoseconds) of the FBG can be neglected. For each ring, the FSR is inversely proportional to its length, and so the effective FSR of this two-ring cavity is the least common multiple number of FSR's of the MRC and the secondary ring cavities. The maximum selectively occurs at an optical frequency that simultaneously satisfies the above phase conditions.

The FBG with transmitted light feedback forms a wavelength-selective device in the fiber-ring cavity. When the phase conditions are satisfied and the excess loss of the optical coupler is negligible, the effective intensity transmissivity T of the wavelength-selective device is given by

$$T = \mathrm{IL}_{12}\mathrm{IL}_{23}(1-\kappa_c)|\rho|^2 + \mathrm{IL}_{12}\mathrm{IL}_{\mathrm{PC}}\mathrm{IL}_{\mathrm{VOA}}\kappa_c|1-\rho|^2 + 2[{\mathrm{IL}_{12}}^2\mathrm{IL}_{23}\mathrm{IL}_{\mathrm{PC}}\mathrm{IL}_{\mathrm{VOA}}\kappa_c(1-\kappa_c)]^{1/2}|\rho||1-\rho|, \tag{3}$$

where ρ is the amplitude reflection coefficient of the FBG[8]; κ_c is the intensity coupling coefficient of the optical coupler; IL_{12} and IL_{23} are the intensity losses from port 1 to port 2 and from port 2 to port 3, respectively, for the optical circulator; and $\mathrm{IL}_{\mathrm{PC}}$ and $\mathrm{IL}_{\mathrm{VOA}}$ are the intensity losses of the polarization controller and the variable optical attenuator, respectively. The second and third terms on the right-hand side of Eq. (3) indicate the frequency-dependent components that are due to the feedback effect. Normally, ρ is close to 1 when the light frequency is within the reflective band of the FBG and decreases to 0 when the light frequency is near the band edge of the FBG. Therefore the feedback-induced components are significant only for the light frequency operated near the band edge of the FBG and are proportional to $\mathrm{IL}_{\mathrm{VOA}}$ and $\sqrt{\mathrm{IL}_{\mathrm{VOA}}}$. Thus the optical frequency of the maximal T is located within the band edge of the FBG and is determined by $\mathrm{IL}_{\mathrm{VOA}}$. For the parameters $\kappa_c = 50\%$, $N = 10{,}000$, $\mathrm{IL}_{\mathrm{PC}} = 0$ dB, $\mathrm{IL}_{12} = \mathrm{IL}_{23} = 1$ dB, and $\kappa L = 8$, intensity transmissivity T versus detuning $-\Delta f$ for $\mathrm{IL}_{\mathrm{VOA}} = 0, 5, 10, \infty$ dB is shown in Fig. 2. The detuning, which has maximal T, is expected as a function of $\mathrm{IL}_{\mathrm{VOA}}$ and is shown in Fig. 3. Larger values of $\mathrm{IL}_{\mathrm{VOA}}$ will decrease the detuning of maximal T. According to the analysis above, the laser mode oscillates only at an optical frequency that simultaneously satisfies the phase conditions given by Eqs. (1) and (2) and provides maximal T. By use of the self-injection technique and choice of proper path lengths of L_0, L_1, and L_2, SLM operation of the fiber-ring laser can be achieved.

The proposed configuration and experimental setup of EFL with self-injection feedback are shown in Fig. 1. The MRC is composed of a 980-nm-pumped erbium-doped fiber amplifier with a saturated output power of 12 dBm, a variable optical coupler, an optical circulator, a reflective FBG, a polarization controller, and a 50:50 optical coupler. The FBG, with a 3-dB bandwidth of 0.8 nm (~100 GHz) and a reflectivity of >99% at 1548.8 nm, determines the lasing wavelength of the EFL. The transmitted light of the FBG passes a polarization controller, an optical delay line, and a variable optical attenuator and is coupled into the MRC by a 50:50 optical coupler.

In the experiments the path length ($L_0 + L_1$) of the MRC is ~80 m, which corresponds to a 2.5-MHz FSR, and the path length ($L_0 + L_2$) of the secondary ring cavity is 86 or 100 m (corresponding to FSR's of 2.3 or 2 MHz). Therefore the effective FSR's of the EFL with self-injection feedback are calculated to be approximately 230 and 10 MHz for $L_0 + L_2$ of 86 and 100 m, respectively. We first adjust the polarization controller in the MRC to obtain the lasing wavelength near the long-wavelength edge of the FBG without adding the self-injection feedback (i.e., $\mathrm{IL}_{\mathrm{VOA}} = \infty$ dB). Then we adjust the attenuation loss ($\mathrm{IL}_{\mathrm{VOA}}$) of the variable attenuator and measure the lasing wavelength of the EFL by use of an optical spectrum analyzer. The measured laser output spectrum is shown in the inset of Fig. 2 for $\mathrm{IL}_{\mathrm{VOA}} = 5, 10, \infty$ dB. The measured lasing detuning ($-\Delta f$) versus attenuation loss is shown in Fig. 3. The lasing detuning

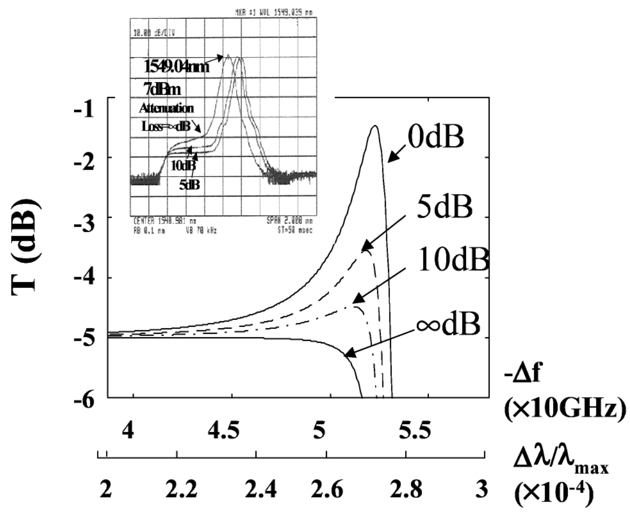

Fig. 2. Intensity transmissivity T of the FBG with transmitted light feedback versus detuning $-\Delta f$ for different optical attenuator losses $\mathrm{IL}_{\mathrm{VOA}}$. Inset, measured optical spectrum of the fiber laser for the same $\mathrm{IL}_{\mathrm{VOA}}$ values.

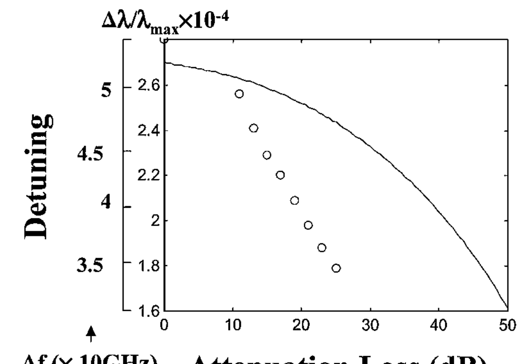

Fig. 3. Calculated detuning of (solid curve) maximal T and (open circles) measured lasing detuning versus the loss of the optical attenuator.

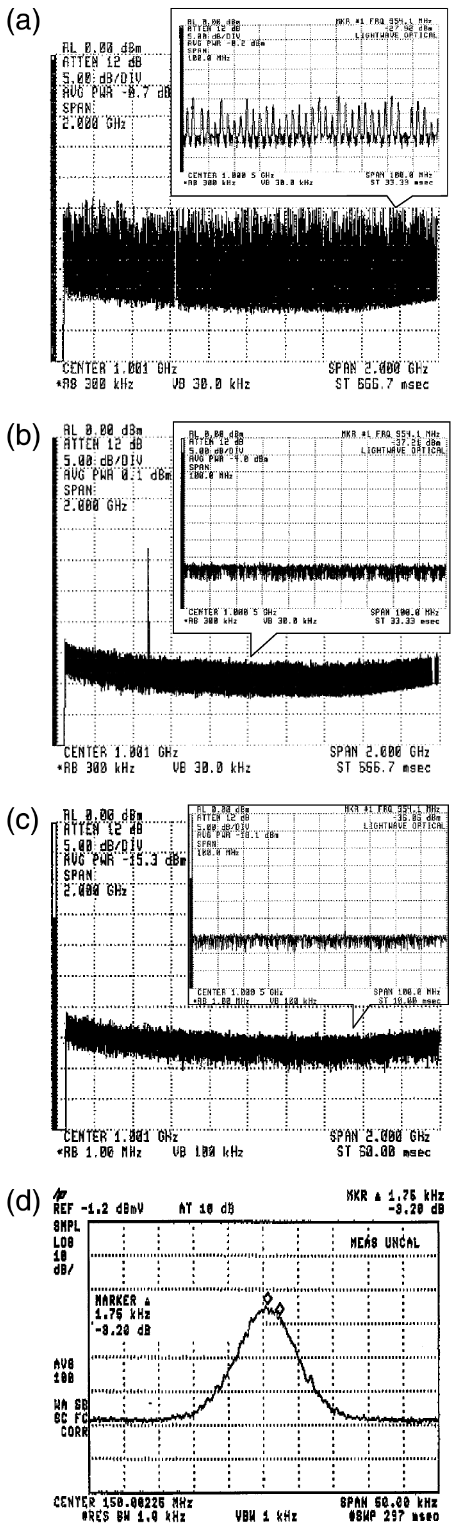

Fig. 4. Detected homodyne frequency spectrum of the fiber laser (a) without self-injection feedback operation, (b) with self-injection feedback of $L_0 + L_2 = 100$ m and $IL_{VOA} = 10$ dB, and (c) with self-injection feedback of $L_0 + L_2 = 86$ m and $IL_{VOA} = 10$ dB. (d) Linewidth of the fiber laser with self-injection feedback of $L_0 + L_2 = 86$ m and $IL_{VOA} = 10$ dB, as measured by the delayed self-heterodyne method.

decreases with increasing attenuation loss and has the same decreasing trend with the calculated detuning of the maximal intensity transmissivity. The difference between the measured and the calculated results possible is due to the polarization alignment and to the discrimination between the apodized FBG used in our experiment and the uniform FBG in our calculation. When $IL_{VOA} = \infty$ dB, the output power of the EFL is ~7 dBm, with an optical signal-to-noise ratio of >57 dB at 1549.04 nm. When $L_0 + L_2 = 86$ m and $IL_{VOA} = 10$ dB, the output of the EFL is decreased by only 0.4 dB (i.e., the output is 6.6 dBm), with an optical signal-to-noise ratio of >57 dB at a lasing wavelength of 1549.19 nm. Next we measure the electrical frequency spectrum of the EFL by use of the self-homodyne detection method. As shown in Fig. 4(a), the electrical frequency spectrum of the EFL without addition of self-injection feedback is very noisy and unstable owing to mode hopping. After addition of self-injection feedback of $L_0 + L_2 = 100$ m and $IL_{VOA} = 10$ dB, spectral noise is significantly reduced, as shown in Fig. 4(b). If self-injection feedback of $L_0 + L_2 = 80$ m and $IL_{VOA} = 10$ dB is added, a pure EFL spectrum is observed [Fig. 4(c)], and stable SLM operation is achieved. As shown in Fig. 4(d), the measured short-term linewidth of the EFL, which has self-injection feedback of $L_0 + L_2 = 86$ m and $IL_{VOA} = 10$ dB, is found by use of the delayed self-heterodyne method to be 3.5 kHz.

In conclusion, we have presented a single-longitudinal-mode erbium-doped fiber laser that utilizes the transmitted light of a FBG as self-injection feedback for SLM oscillation. This SLM operation principle was discussed in detail, and a SLM laser with an output power of 6.6 dBm, an optical signal-to-noise ratio of 57 dB at 1549.19 nm, and a short-term linewidth of ~3.5 kHz was reported.

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