Investigation on characteristics of self-organization in Mach-Zehnder erbium-doped fiber laser cavity

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The characteristics of coherent coupling in Mach-Zehnder erbium-doped fiber laser cavity are experimentally studied. By virtue of a seemly controlling of length difference between two interferometric arms, the obtained comb-like spectrum of interferometer resonator with a period of 0.06 nm commendably agrees with the theory of self-organization coherence. The coherent output exits from the output mirror of a fiber Bragg grating with 4.5% reflectivity. A high coherent combining efficiency of 94% is obtained. Investigation on characteristics of the leak power opens out self-organization mechanism in Mach-Zehnder composite cavity.

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Coherent combination of multiple fiber lasers and amplifiers has attracted considerable attention[1−8]. Based on the master oscillator power amplifier (MOPA) system, coherent combining was realized with complex phase controlling[7,8]. Self-organization (or self-adjust) method in composite cavity needs not additional phase controlling[1−6]. In Refs. [1—3] two fiber Bragg gratings (FBGs) were used as cavity mirrors and wavelength selectors. It was necessary to tuning the FBGs to obtain the same wavelength lasing in two branch arms. In Refs. [4,5] coherent output was obtained from the fiber facet port in Mach-Zehnder laser cavity. In these conditions insuring good quality of facet port was very important.

In this letter, one 3-dB fiber loop mirror (FLM) and a FBG are introduced in Mach-Zehnder erbium-doped fiber laser cavity. The coherent output emits from the output mirror of the FBG with 4.5% reflectivity. A high coherent combining efficiency of 94% is obtained. The coherent output laser with high beam quality may be used as a good master oscillator in high-power amplifier system, and the study of the inherence of the self-organization will be helpful to laser interference research and optical fiber sensors[9].

The principle of self-organization interference of composite cavity is based on both the property of lasers ensuring operation on modes of lowest losses[10], and the use of an interferometric resonator configuration[4]. The typical cavities are adopted in Michelson and Mach-Zehnder lasers. Figure 1(a) shows the configuration of Mach-Zehnder erbium-doped fiber laser (MZEDFL). It consists of two independent erbium-doped fiber lasers which are pumped by two pigtailed laser diodes (LDs) emitting at 980 nm with a power ranged from 0 to 90 mW. Each of the high-concentrated erbium-doped fibers has lengths of ~ 4.6 m corresponding to almost complete pump absorption. The composite laser cavity is formed by the common 3-dB FLM offering reflectivity with almost 100% at a broad bandwidth and a common FBG with reflectivity of 4.5% at 1559.78 nm. The two arms of the active interferometer are spliced to a standard 50:50 coupler. A polarization controller (PC) is inserted into one branch arm for the sake of optimizing the combining efficiency and intra-cavity losses. Only one FBG is used for wavelength selection in order that the two branch arms emit the same wavelength laser which can finely conform to the coherent condition. Another output port is spliced to an isolator and acts as the MZEDFL's leak port. An optical spectrum analyzer (OSA) with 0.05-nm resolution measures the optical spectrum of the laser and a power meter is used to measure the laser powers.

The Mach-Zehnder interferometer without active medium acts as a spectral periodic filter of period $\Delta\nu = c/\Delta L$. When the active medium is put into the interferometric arm, the interferometer can be used as a resonator and a wavelength selector. The coupled modes emit from the Mach-Zehnder composite cavity. Output of the longitudinal modes of the independent erbium-doped fiber lasers and the coupled super-modes of MZEDFL are theoretically analyzed, as shown in Fig. 2.

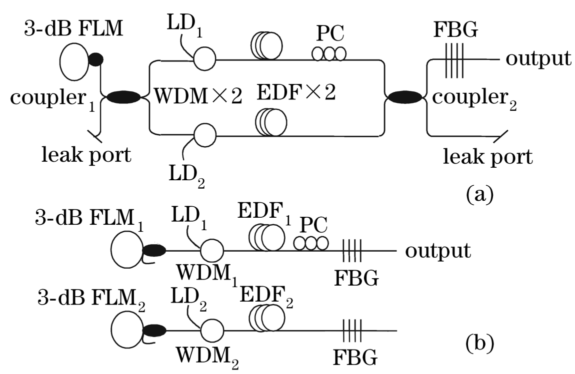

Fig. 1. (a) Experimental setup of the Mach-Zehnder erbium-doped fiber laser; (b) two independent erbium-doped fiber lasers.

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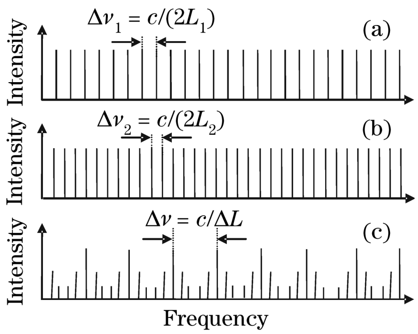

Fig. 2. (a), (b) Theoretical longitudinal modes spacing ($\Delta\nu_1$, $\Delta\nu_2$) of two independent lasers; (c) theoretical coupled super-modes spacing ($\Delta\nu$) of MZEDFL (c: velocity of light in vacuum; L_1, L_2: effective cavity lengths of two independent lasers; ΔL: effective length difference between two branch arms, $\Delta L = |L_1 - L_2|$).

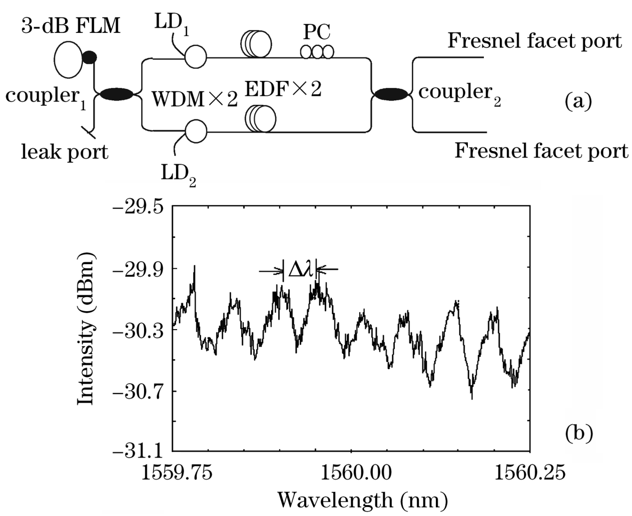

Fig. 3. (a) Experimental setup of measuring the interferometric spectrum; (b) the measured comb-like interferometric spectrum.

The length difference is controlled as 4 cm and less than the coherence length of the independent lasers (coherence length: $L_c = \lambda^2/\Delta\lambda_{FWHM}$; λ: the center wavelength of the FBG, $\Delta\lambda_{FWHM}$: 3-dB bandwidth of the independent lasers). We predict the frequency spacing of coupled super-modes to be $\Delta\nu = c/\Delta L = 7.5$ GHz. The interferometric spectrum shown in Fig. 3(b) is measured from the Fresnel facet port in Fig. 3(a). From the interferometric spectrum, $\Delta\lambda$ of 0.06 nm is obtained. Based on the relationship between $\Delta\lambda$ and $\Delta\nu$ ($\Delta\nu = c\Delta\lambda/\lambda^2$). $\Delta\nu$ of 7.4 GHz is experimentally demonstrated, which is in fairly good agreement with the predicted spacing.

The PC plates are rotated at optimum state when MZEDFL operates. By virtue of the seemly controlling of length difference between two arms, the maximal coherent output power (P_{coh}) reaches 34.7 mW while LD pump powers are 90 mW×2. The leak power (P_{leak}) from the isolator is only 0.6 mW. Output powers of two independent lasers are 18.1 mW (P_1) and 18.8 mW (P_2), respectively. High coherent combining efficiency of 94% is achieved [coherent combining efficiency: $\eta = P_{coh}/(P_1 + P_2)$]. Figure 4 shows the typical spectra of coherent output and independent laser output. The 3-dB bandwidth of the coherent spectrum is narrower than that of the spectrum of independent laser, which denotes the de-coupled mode suppression properties of self-organization. The peak values of the intensity are 15.30 dBm and 8.20 dBm respectively, which corresponds to different output power.

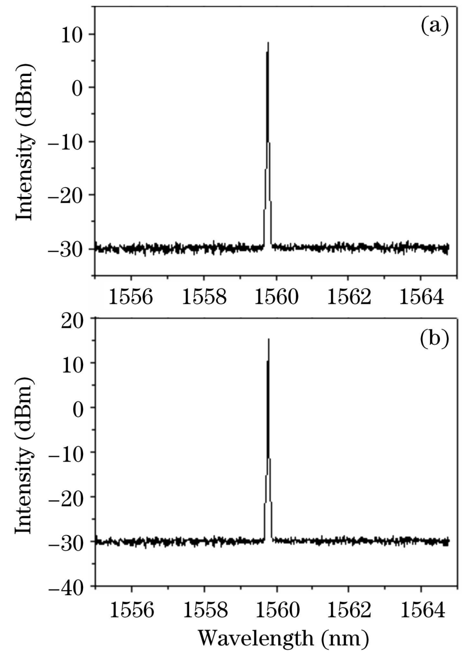

Fig. 4. Optical spectra of (a) independent laser and (b) the coherent output of MZEDFL.

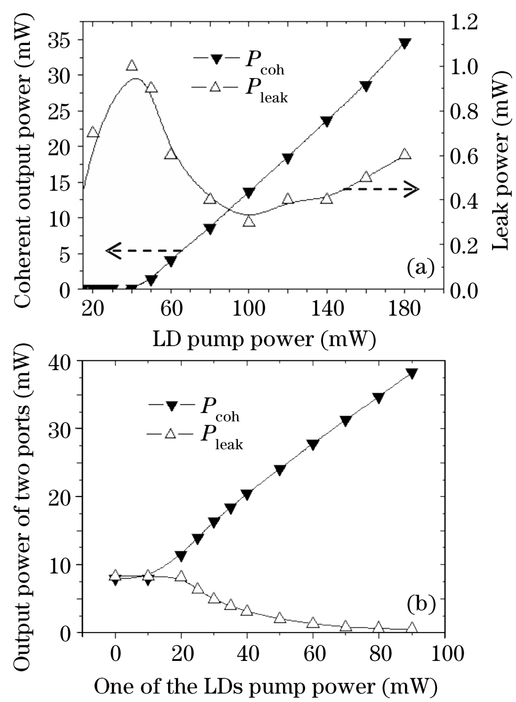

Fig. 5. (a) Coherent output power and leak power versus pump power; left axis for P_{coh}, right axis for P_{leak}; (b) output powers of composite cavity versus one of the LDs pump power and the other LD pump power is fixed at 90 mW.

Coherent output power and leak power versus pump power are shown in Fig. 5(a). The threshold pump value and the slope efficiency of P_{coh} are ~ 40 mW and 24.8%, respectively. As two LDs pump powers increase synchronously, the coherent output power is nearly linear to the pump power. But characteristics of the leak power versus pump power are distinct. When the pump value is lower than threshold, the leak power increases with the pump power, if the pump power higher than threshold, the leak power decreases with the pump power in the beginning, and then, increases slightly.

Characteristics of the leak power can be understood with laser oscillation theory and self-organization theory. If the pump power is lower than threshold, there is no steady oscillation in cavity, the power of amplified spontaneous emission (ASE) exits from the isolator and increases with the pump power. Steady oscillation is formed as the pump power is higher than threshold, lasing modes experienced lowest losses in two arms exit from the FBG, and thus, constructive interference occurs. So, destructive interference occurs at the other port with the isolator, which causes the leak power decreases quickly. As pump power increases, gain medium would operate in saturation region[11], the remained pump power makes the leak power increase slightly, as shown in Fig. 5(a). Figure 5(b) shows the outputs of the composite cavity versus one of the LDs pump power as the other LD power is fixed at 90 mW. When one of the LDs is pump-blocked and the other is fixed at 90 mW, output power of two ports is almost equal. As the LD is unblocked, and pump power increases, coherent output power increases quickly and leak power decreases, as shown in Fig. 5(b). We experimentally demonstrate that constructive interference occurs at the FBG and destructive interference occurs at the isolator, which is in good agreement with the theory of mode discrimination in composite cavity[10].

In conclusion, characteristics of coherent coupling in a Mach-Zehnder erbium-doped fiber laser cavity are experimentally demonstrated. By virtue of the seemly controlling of length difference between two interferometric arms, the comb-like spectrum of interferometer resonator with a period of 0.06 nm commendably agrees with the theory of self-organization coherence. The coherent output exits from the output mirror of a fiber Bragg grating with 4.5% reflectivity. A high coherent combining efficiency of 94% is obtained. Investigation on characteristics of the leak power opens out self-organization mechanism in Mach-Zehnder composite cavity. The study of the inherence of the self-organization will be helpful to laser interference research.

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References

1. V. A. Kozlov, J. Hern'andez-Cordero, and T. F. Morse, Opt. Lett. **24,** 1814 (1999).
2. T. B. Simpson, A. Gavrielides, and P. Peterson, Opt. Express **10,** 1060 (2002).
3. A. Shirakawa, T. Saitou, T. Sekiguchi, and K. Ueda, Opt. Express **10,** 1167 (2002).
4. D. Sabourdy, V. Kermène, A. Desfarges-Berthelemot, L. Lefort, and A. Barthélém, Opt. Express **11,** 87 (2003).
5. S. Chen, Y. Li, and K. Lu, Opt. Express **13,** 7878 (2005).
6. F. Liu, X. Jia, Y. Liu, S. Yuan, and X. Dong, Chin. Phys. Lett. **24,** 929 (2007).
7. J. Hou, R. Xiao, Z. Jiang, X. Cheng, B. Shu, J. Cheng, and Z. Liu, Chin. Phys. Lett. **22,** 2273 (2005).
8. J. Hou and R. Xiao, Chin. Phys. Lett. **23,** 3288 (2006).
9. M. Song, B. Zhao, and X. Zhang, Chin. Opt. Lett. **3,** 271 (2005).
10. W. W. Rigrod, IEEE J. Quantum. Electron. **6,** 9 (1970).
11. Y. Liu, X. Feng, L. Li, Y. Li, S. Yuan, G. Kai, Y. Li, and X. Dong, Chin. Phys. Lett. **22,** 343 (2005).