Mode Beating Noise Reduction of Mutually Injection-Locked Erbium-Doped Fiber Laser and Laser Diode Link

Yu-Huang Lin and Gong-Ru Lin

***Abstract*—We report a mutually injection-locked Erbium-doped fiber amplifier (or laser) and Fabry–Pérot laser diode link (EDFA-FPLD or EDFL-FPLD) for single longitudinal mode lasing with linewidth of 0.012 nm and sidemode suppression ratio of 42 dB. The 3-dB linewidths of <20 MHz and 350 kHz for the EDFL-FPLD and EDFA-FPLD links, respectively, are reported using interferometric determination. The mode-beating noise can be completely eliminated in the EDFA-FPLD link.**

***Index Terms*—Mutual injection locking, Fabry–Pérot laser diode, Erbium-doped fiber amplifier (EDFA).**

THE PHYSICAL aspects of injection-locked semiconductor or fiber laser have been studied extensively [1]–[7]. In particular, the mutual injection-locking technology has attracted considerable interest [2], [4], [5], [7]. Recently, a Fabry–Pérot laser diode (FPLD) feedback seeded by a fiber Bragg grating has been demonstrated with a sidemode suppression ratio (SMSR) of up to 42 dB [8]. A mutually injection-locked Erbium-doped fiber laser (EDFL)-FPLD link was also reported, which can be lasing at a selected FPLD longitudinal mode with linewidth of <0.017 nm and SMSR of up to 50 dB [9]. Nonetheless, the lasing spectrum of the mutually injection-locked EDFL-FPLD link still includes significant beating noises due to dense longitudinal modes of long-cavity EDFL. The beating noise inevitably limits the application of the narrow-linewidth EDFL-FPLD link. Not long ago, an intracavity semiconductor optical amplifier-based high-pass filtering technology has emerged to suppress the beating noises of EDFL [10], [11]. This work demonstrates a simple approach to simultaneously achieve linewidth reduction, SMSR improvement, and mode-beating noise suppression of an Erbium-doped fiber amplifier (EDFA)-FPLD link by feedback seeding the FPLD with an EDFA in open-loop configuration.

A bidirectionally pumped commercial EDFA module with maximum output of 23 dBm is employed to build up the EDFL-FPLD or EDFA-FPLD link, as illustrated in Fig. 1. The wavelength, threshold current, and longitudinal mode spacing of the free-running FPLD at 35 °C are 1560 nm, 13 mA, and 1.2 nm, respectively. The EDFL-FPLD is constructed using an FPLD and a close-loop EDFA which functions as an EDFL.

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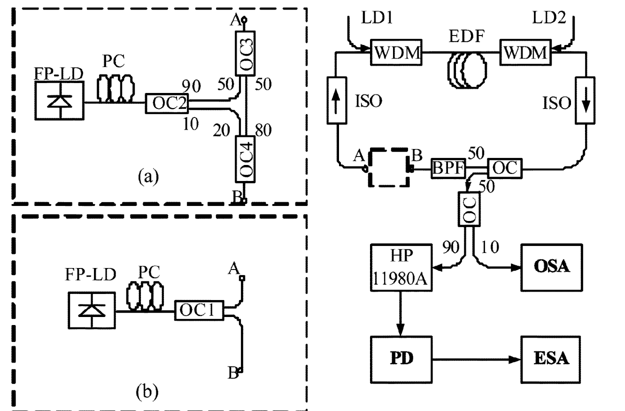

Fig. 1. Block diagrams of (a) an EDFL-FPLD link and (b) an EDFA-FPLD link.

The EDFA-FPLD link denotes a similar system, however, the EDFA is not close-loop. The latter design excludes the lasing of EDFL longitudinal modes in the former EDFL-FPLD link. In the EDFL-FPLD link [9], a 20% output of the EDFL with intracavity optical bandpass filter (OBPF) is employed to externally seed the FPLD, as shown in Fig. 1(a). This setup introduces an additional loss of about 1.1 dB. The OC2 (90 : 10) coupler avoids the over-seeding of the FPLD and minimizes the insertion loss of the EDFL-FPLD link. The OC3 (with a 50% coupling ratio) combines the other output of EDFL and FPLD to form the EDFL-FPLD link. The length of the EDFL ring cavity is 45 m, producing a longitudinal mode spacing of 4.4 MHz. In the EDFA-FPLD link displayed in Fig. 1(b), the filtered amplified spontaneous emission (ASE) from the EDFA is injected into the FPLD. The adding of an intracavity OBPF avoids the lasing of FPLD sidemodes, which somewhat suppress the beating noise in the EDFA-FPLD link. To measure the actual linewidth and the mode-beating noise, the self-heterodyne beating spectra of the EDFL-FPLD and EDFA-FPLD links are monitored by an electrical spectrum analyzer in connecting with an interferometer and a high-gain photodetector.

The lasing spectrum of the EDFL-FPLD link is relatively broadened when the FPLD is driven at well below threshold. The lasing linewidth gradually narrows as the mode-selecting capability of the FPLD is initiated at larger biases. To operate the EDFL at single FPLD longitudinal-mode and high SMSR, the feedback-injected FPLD must be biased at near-threshold. The lasing linewidth is minimized as only one of the FPLD longitu-

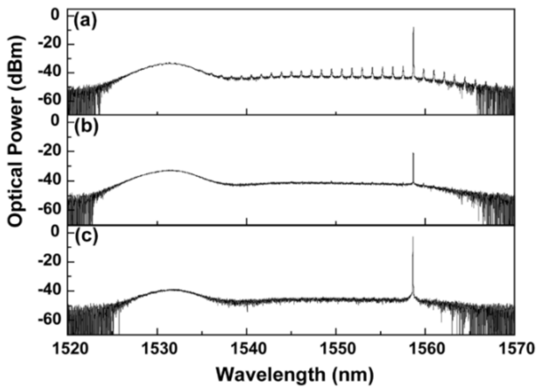

Fig. 2. Optical spectra of mutually injection-locked EDFA-FPLD link with different feedback injecting power (a) 0.37, (b) 4.5, and (c) 5.4 mW.

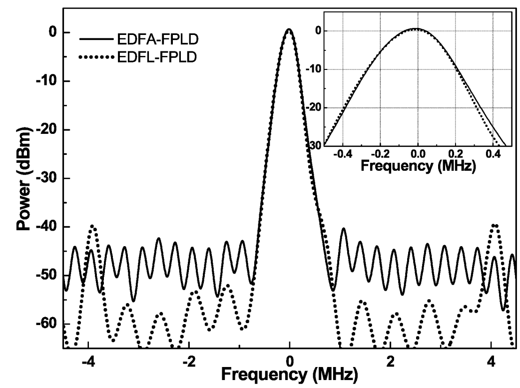

Fig. 3. Mode-beating spectra of the EDFL-FPLD and EDFA-FPLD links measured by interferometer.

dinal modes survives in the EDFL-FPLD link. This is attributed to the combined effects of gain-profile filtering and mutual injection-locking [11]. Since the partial output of EDFA is filtered and then feedback injected into the FPLD, the EDFA-FPLD link output with an SMSR exceeding 40 dB is easily achievable. The SMSR can be optimized by selecting the appropriate coupler ratio of the EDFA-FPLD link. When the FPLD is injected by the filtered ASE from EDFA (with power of 0.37 mW), the other longitudinal modes of FPLD grow up to compete the gain with the principle mode. This causes a degraded SMSR of only 23 dB, as shown in Fig. 2(a). Although the single-mode lasing occurs when the feedback injecting power increases to 4.5 mW, the SMSR is as low as 25 dB. The coupling ratio of OC1 and the mutual injecting power are then adjusted to improve the SMSR of the EDFA-FPLD link. The highest SMSR of 42 dB is obtained with a mutual injection power of 5.4 mW [see Fig. 2(c)], and the 3-dB linewidth of the EDFA-FPLD link is reduced to 0.016 nm. Notably, the linewidth of the mutually injection-locked EDFA-FPLD link can be as small as 0.012 nm, which is, however, achieved by high-power seeding the unbiased FPLD at a cost of worse SMSR.

In fact, the feedback injection of the FPLD from the filtered EDFA is equivalent to the increase in the end-face reflectivity of the FPLD, which reduces the linewidth and improves the SMSR in the mutually injection-locked EDFA-FPLD link. These results have also been theoretically interpreted. In principle, the SMSR (defined as the power ratio of the principal to sidemode, I_1/I_2) of the EDFA-FPLD link can be expressed as a function of change (ΔR) in reflectivity (R) [10]

$$\frac{I_1}{I_2} = \frac{C_1(\Gamma_2' - C_2\Gamma_1')}{\Gamma_1'} = \frac{C_1(1 - C_2\Gamma_1'/\Gamma_2')}{\Gamma_1'/\Gamma_2'} = \frac{C_1[1 - C_2 \ln(R_1 + \Delta R)/\ln(R_2)]}{\ln(R_1 + \Delta R)/\ln(R_2)} \quad (1)$$

where C_1 and C_2 are constants, Γ_1' and Γ_2' are effective loss coefficients, and R_1 and R_2 are reflectivity for principle and sidemodes in FPLD. The ΔR is the change in reflectivity of FPLD due to feedback injection. Assuming that the original reflectivity of the principal and the sidemodes are almost identical, and that the change in reflectivity of the principal mode is more pronounced than that of the sidemode under a feedback seeding situation. On the other hand, the linewidth of the EDFA-FPLD can also be obtained by considering the Fabry–Pérot etalon effect of FPLD. The 3-dB linewidth of the EDFA-FPLD link can also be plotted as a function of the effective reflectivity of FPLD by using the following formula [10]:

$$\Delta\lambda = \frac{\lambda_0^2}{2\pi n L}\frac{\lfloor 1 - R'_{\text{eff},1}G_1 \rfloor}{\sqrt{R'_{\text{eff},1}}\sqrt{G_1}} = \frac{\lambda_0^2}{2\pi n L}\frac{[1-(R_1+\Delta R)G_1]}{\sqrt{(R_1+\Delta R)}\sqrt{G_1}} \quad (2)$$

where λ_0 is the central wavelength, n is the refractive index, L is the length of FPLD cavity, and $R'_{\text{eff},1}$ and G_1 are the effective reflectivity and gain coefficient of the principle mode in FPLD with feedback injection, respectively. When the mutual injection-locking of the EDFA-FPLD link is achieved, the effective reflectivity of FPLD changes into $R'_{\text{eff},1} \equiv R_1 + \Delta R$. Hence, we can plot the linewidth as a function of either the effective reflectivity $(R'_{\text{eff},1})$ or the change in reflectivity (ΔR). The reduction on the linewidth is more pronounced as the gain of FPLD increases. Nonetheless, the linewidth and the SMSR of the EDFA-FPLD link can only be optimized at the specified gain and change in reflectivity of FPLD.

The mode-beating spectra of EDFL-FPLD and EDFA-FPLD links are compared using a self-heterodyne optoelectronic interferometer, as shown in Fig. 3. Although the optimum SMSR of 48 dB can be obtained from the mutually injection-locked EDFL-FPLD link, the sidemodes and the mode-beating noises remain observable in the lasing spectrum, as shown in Fig. 4(a). Even the FPLD sidemodes are eliminated in the OBPF-filtered EDFL-FPLD spectrum, the mode-beating noises from the longitudinal modes of the long EDFL ring cavity still survives, as shown in Fig. 4(b). In Table I, the characteristics of the free-running EDFL, the OBPF-filtered EDFL, the conventional EDFL-FPLD link, and the newly proposed EDFA-FPLD link are summarized. Obviously, the free-running EDFL exhibits a relatively wide lasing spectrum. The 3-dB linewidth of the OBPF filtered EDFL is reduced to 0.034 nm. Meanwhile, the OBPF-filtered EDFA-FPLD link can further reduce the linewidth to 0.012 nm (even better than that of EDFL-FPLD link). In comparison, the measured linewidth at 10-dB decay of the OPBF filtered EDFA-FPLD link and EDFL-FPLD link are 0.03 and 0.05 nm, respectively. The mode-beating spectral analysis reveals that the actual linewidths of the mutually injection-locked EDFL-FPLD link at 3-, 10-, and 20-dB decay are only 20, 39, and 80 MHz,

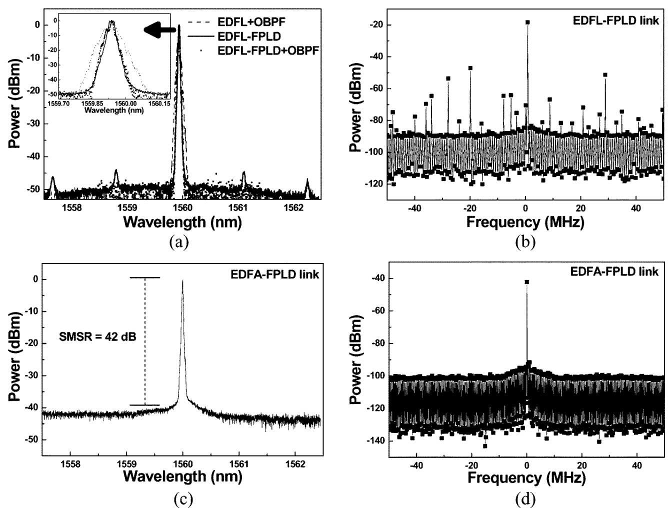

Fig. 4. (a) Lasing and (b) mode-beating spectra of EDFL-FPLD links with and without OBPF; (c) lasing and (d) mode-beating spectra of EDFA-FPLD link.

TABLE I
3-dB LINEWIDTH ($\Delta\lambda$), SMSR, AND REQUIRED INJECTION POWER FOR DIFFERENT LASER CONFIGURATIONS

Configurations	Injection (mW)	Linewidth (nm)	SMSR (dB)
EDFL Free-running	--	1.015	36
OBPF filtered EDFL	--	0.034	45
EDFL-FPLD Link	8.63	0.017	48
EDFA-FPLD Link	0.37	0.018	23
EDFA-FPLD Link	4.5	0.018	25
EDFA-FPLD Link	5.4	0.012	42

respectively. The EDFL-FPLD link exhibits a larger linewidth even at a higher feedback injecting power, which is attributed to the interference of enormous longitudinal modes in the EDFL cavity [see Fig. 4(b)]. In contrast, the EDFA-FPLD is design specifically to eliminate the sidemodes and mode-beating noise of the EDFL-FPLD link, as shown in Fig. 3. These two configurations differ in that the EDFA is not based on a close-loop regime. In this case, there are no resonant cavity modes generating in the EDFA, only the spontaneous emission from FPLD is amplified by the EDFA and feedback injected into the FPLD after OBPF filtering. Without these EDFL cavity modes, the EDFA-FPLD link can reach an ultranarrow and clean spectrum under injecting condition, as illustrated in Fig. 4(c) and (d). Adding an intracavity OBPF in the EDFA-FPLD link helps the elimination of FPLD sidemodes, while using the open-loop EDFA avoids the EDFL longitudinal modes. This eventually results in a distributed feedback LD-like spectrum lasing from EDFA-FPLD link with optimized Lorentzian linewidth of about 350 kHz (see Fig. 3). This design has enhanced the overall performances of the EDFA-FPLD link compared to the previous EDFL-FPLD link, which also corroborates the niche of amplified feedback seeding in the mutual injection-locking system. For ultranarrow bandpass filtering and beating-noise suppression, the use of FPLD in the EDFA is, thus, straightforward.

In conclusion, this work compares the linewidth, SMSR, and mode-beating noise characteristics of the mutually injection-locked EDFL-FPLD and EDFA-FPLD links. To select the strongest FPLD mode lasing in the EDFA-FPLD link, the FPLD must be biased at just below the threshold condition. The sidemode in the EDFA-FPLD link can be completely suppressed through mutual injection-locking, intracavity OBPF, and active FPLD filtering. The narrowest 3-dB linewidth of 0.012 nm and comparable SMSR of 42 dB in an EDFA-FPLD link is obtained under a feedback injecting power of 5.4 mW, lower than that required for an EDFL-FPLD link. The proposed EDFA-FPLD link exhibits a better beating noise suppression performance as compared to the EDFL-FPLD link.

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