Theory and Experiments of a Mode-Beating Noise-Suppressed and Mutually Injection-Locked Fabry–Perot Laser Diode and Erbium-Doped Fiber Amplifier Link

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***Abstract*—By using Fabry–Perot laser diode (FPLD) as a resonant ultranarrow bandpass filter in an Erbium-doped fiber amplifier or laser (EDFA or EDFL), the theory and experiment for side-mode suppression and linewidth reduction of mutually injection-locked EDFL–FPLD and EDFA–FPLD links are demonstrated. Based on the amplified feedback injection loop, the 3-dB linewidth of 3.4 MHz for the EDFA–FPLD link is determined by using self-heterodyne interferometric spectral analysis. The EDFA–FPLD link exhibits a nearly mode-beating noise-free performance as compared to the EDFL–FPLD link. This is due to the release of the resonant cavity configuration in the EDFL–FPLD link at a cost of slightly lower side-mode suppression ratio ($\sim$42 dB). The maximum output power of the EFDA–FPLD link is 20 mW under an FPLD input power of 0.1 mW.**

***Index Terms*—Erbium-doped fiber amplifier, Fabry–Perot laser diode, linewidth, mode beating noise, mutual injection locking, side-mode suppression ratio.**

I. INTRODUCTION

THE mutually injection-locked semiconductor or fiber laser has received substantial attention [1]–[3] since it can produce a single longitudinal mode lasing with higher side-mode suppression ratio (SMSR) for potential applications in the optical data communications. In principle, the injection locking laser systems strictly rely on external seeding or self-feedback injection of a continuous-wave (CW) laser to achieve single mode and pulsed generation. Previously, a sampled grating distributed Bragg reflector laser CW lasing with SMSR of 30–50 dB and wide tuning range of 62 nm has been achieved [4]. In a subsequent experiment, a distributed feedback laser (DFB) laser and Erbium-doped fiber laser were mutually injection locked with each other to achieve singly longitudinal-mode lasing, where the linewidth of the DFB laser is reduced to below 1.5 MHz [5]. On the other hand, various self-seeding and external seeding schemes were emerged to suppress the multimode spacing spectrum of a gain-switched Fabry–Perot laser diode (FPLD) [6], which enables single wavelength and wavelength-tunable operation of the FPLD pulses [7], [8]. In particular, the gain-switched FPLD is injected by the wavelength element from an external tunable laser source, and the single-mode optical pulses can be achieved when the injected wavelength coincides with one of the gain-switched FPLD modes. Later, a dc-biased FPLD together with fiber Bragg grating recently developed as the external-injection seeding source due to the high cost of the commonly used CW tunable laser source. However, the SMSR can be up to 42 dB but the wavelength tuning range is still narrow (about 11.5 nm) [9].

More recently, the mutual injection locking of an EDFL–FPLD link by low-level feedback injecting the fiber-pigtailed FPLD with an EDFL adapted from a commercial EDFA module was reported [10]. With the FPLD operating at just below its threshold condition (within 10% range), the EDFL–FPLD link can be lasing at a selected FPLD longitudinal mode with reduced linewidth of $<$0.017 nm and an improved SMSR of up to 50 dB [11]. Nonetheless, the lasing spectrum of the mutually injection-locked EDFL–FPLD link still includes many beating noises, which are produced by the dense longitudinal modes of EDFL with mode spacing of 4 MHz. Such a strong beating noise in the narrow-linewidth EDFL–FPLD link puts severe limitations on its applications of the optical communication. To overcome this, Xu *et al.* have proposed to use a semiconductor optical amplifier in the laser cavity, which acts as a high-pass filter to suppress the beating noises in EDFL [12].

In this paper, we theoretically and experimentally analyze the linewidth reduction and SMSR improvement of an EDFL–FPLD link and EDFA–FPLD links by feedback seeding the FPLD using the EDFA in close- and open-loop configurations, respectively. The FPLD acts as a mode selector and an ultranarrow bandpass filter in such links. The optimized mutually injection-locking condition of the EDFA–FPLD link using an open-loop EDFA are compared with that using a close-loop EDFA (or EDFL) in previous demonstration. The performances of both configurations are discussed. We further demonstrate a side-mode elimination and mode-beating noise suppressing scheme by using an optical bandpass filter in the EDFA–FPLD link.

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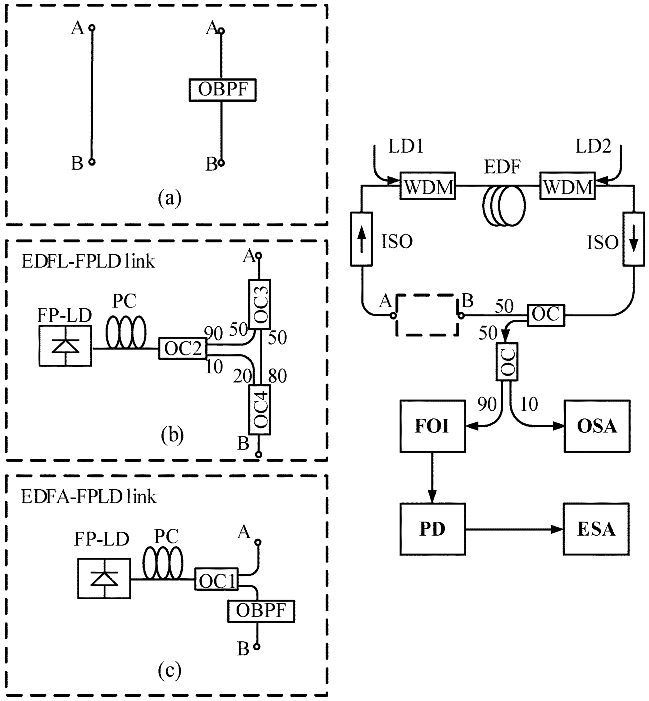


Fig. 1. Block diagrams of experimental setup. (a) Free-running EDFL without or with the OBPF. (b) Configuration for an EDFL–FPLD link. (c) Configuration for an EDFA–FPLD link. PC: polarization controller; OC: optical coupler; OBPF: optical bandpass filter; WDM: wavelength division multiplexing; EDF: erbium-doped fiber; ISO: isolator; FOI: fiber-optic interferometer; PD: photo-detector; OSA: optical spectrum analyzer; ESA: electric spectrum analyzer.

II. EXPERIMENTAL

Prior to building up the EDFA–FPLD or EDFL–FPLD link, a bi-directionally 980 nm-pumped commercial Erbium-Doped Fiber Amplifier (EDFA) module with maximum output of 23 dBm is close-loop to form Erbium-Doped Fiber Laser (EDFL), as shown in Fig. 1(a). The EDFL–FPLD is constructed by using an FPLD in connection with a close-loop EDFA which functions as an EDFL with longitudinal mode spacing of only 4.4 MHz, as shown in Fig. 1(b). On the other hand, the EDFA–FPLD link denotes a similar system, in which the EDFA is not close-loop, as shown in Fig. 1(c). This design eliminates the generation and lasing of the EDFL longitudinal modes in the former EDFL–FPLD link. The EDFA–FPLD link is implemented only by use of optical couplers (OCs) with predetermined power splitting ratios, and in-line polarization controller (PC). Such a design excludes the use of other expansive components such as optical circulators, fiber Bragg gratings, DBR or DFBLDs. The wavelength, threshold current, and longitudinal mode spacing of the free-running FPLD at 35 °C are about 1560 nm, 12 mA, and 1.2 nm, respectively. Two different mutual injection-locking links (EDFL–FPLD and EDFA–FPLD) are investigated in our experiments. In the EDFL–FPLD link [11] shown in Fig. 1(b), a 20% output from the EDFL is employed to externally seed the FPLD. This introduces an additional loss of about 1.1 dB. The OC2 (90:10) coupler avoids over-seeding of the FPLD and facilitates the smallest insertion loss of the FPLD when injecting into the EDFL. The OC3 with 50:50 coupling ratio combines the injection from FPLD and the 80% EDFL output to close-loop the EDFL. The length of the EDFL ring cavity is 45 m, which gives rise to a longitudinal mode spacing of 4.4 MHz (calculated by c/nL). Although this arrangement achieves the optimal SMSR, it still suffers the disadvantage of beating noises due to the longitudinal modes of EDFL. Alternatively, the EDFA–FPLD link is proposed as an amplified feedback seeding scheme. This implementation is slightly different from the EDFL–FPLD link, in which an EDFA is not regeneratively feedback by itself, as shown in Fig. 1(c). In the EDFA–FPLD link, the filtered ASE of EDFA feedback-injects into the FPLD after passing through a commercially available optical bandpass filter (OBPF). The bandwidths of the OBPF at 3 and 10 dB decay are 1.38 and 2.94 nm, which are measured by using a gain-clamped EDFA based broadband amplified spontaneous emission source. The OBPF inserted between the FPLD and EDFA avoids the feedback injection of amplified FPLD side modes (although they are small as compared to the principle lasing mode) from EDFA to FPLD. This also helps the suppression of the beating noise in EDFA–FPLD link. By setting the constant temperature and current of the FPLD as 35 °C and 10 mA, the coupling ratio of OC1 was varied to obtain the single-mode lasing with optimized SMSR in the EDFA–FPLD link. Between the FPLD and the EDFL (or EDFA), an in-line PC is employed to fine tune the power injected into the FPLD. The FPLD is then controlled at just below threshold condition, and the feedback injected power from the EDFL or EDFA is carefully adjusted. The feedback from EDFL (or EDFA) and the cavity-loss of FPLD compromise to facilitate one longitudinal mode with improved SMSR lasing in FPLD. The output of FPLD then feedback injects the EDFL or EDFA to obtain a linewidth-reduced output each link. The optimized linewidth reduction is observed under the precise control on the feedback power for FPLD, while the other side-modes in EDFL–FPLD or EDFA–FPLD link are greatly suppressed during the gain competition process. The output of an EDFL–FPLD or EDFA–FPLD link is monitored by optical spectrum analyzer (OSA, Advantest Q8384) with 0.01-nm resolution and optical power meter (ILX Lightwave, OMM-6810B) with an OC of 90:10 coupling ratio. To measure the actual linewidth and the mode-beating noise, the self-heterodyne beating spectral output of the EDFL–FPLD or EDFA–FPLD link is monitored by electrical spectrum analyzer (ESA, Agilent HP8565E) in connection with an interferometer (Agilent HP11980A) and a high-gain optical receiver (BCP 320A), as shown in Fig. 1.

III. THEORETICAL SIMULATION OF SMSR AND LINEWIDTH

The principle of mutual injection locking of the EDFA–FPLD (or EDFL–FPLD) has been elucidated in more detail. The FPLD is initially operated at below threshold condition, which is subsequently forced to be lasing by the feedback injection from EDFA (or EDFL). The FPLD is an intracavity component since the EDFA (or EDFL) and the FPLD are mutually injection locked to each other in the current setup (with a simplified block diagram shown in Fig. 2). The lasing mode is decided by the FPLD instead of the EDFA (or EDFL).

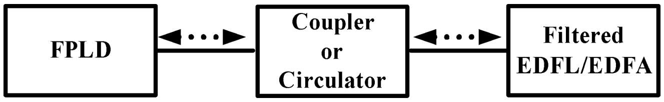


Fig. 2. Mutually injection seeding scheme between FPLD and filtered EDFL (or EDFA).

Remarkably, the linewidth and side-mode suppressing ratio of the EDFA–FPLD (or EDFL–FPLD) link is smaller than that of a single FPLD at free-running condition. First of all, the SMSR of the FPLD without the feedback seeding from EDFA (or EDFL) is theoretically discussed. The optical fields of the principle and secondary (the largest side-mode) modes in the FPLD are denoted as E_1 and E_2, and the time-dependent rate equation of the FPLD can be written as [13]

$$\frac{d}{dt}\left[E_1 \exp(-j\omega t)\right] = \left[\frac{1}{2}(G_1 - \Gamma_1)\right] E_1 \exp(-j\omega t) + \frac{G_1 h\omega n_{sp}}{2\pi T_R} \tag{1}$$

$$\frac{d}{dt}\left[E_2 \exp(-j\omega t)\right] = \left[\frac{1}{2}(G_2 - \Gamma_2)\right] E_2 \exp(-j\omega t) + \frac{G_2 h\omega n_{sp}}{2\pi T_R}. \tag{2}$$

In these equations, the index j defines each parameter for the principle ($j = 1$), the secondary ($j = 2$, the largest side-mode), and the external (or feedback) injection mode ($j = 3$). The w is the angular frequency, G_j is the gain coefficient, Γ_j is the loss coefficients, h is the Planck's constant, n_{sp} is the photon number of spontaneous emission, and T_R is the photon lifetime. The terms of $(G_1 h\omega n_{sp})/(2\pi T_R)$ and $(G_2 h\omega n_{sp})/(2\pi T_R)$ are the corresponding spontaneous emission noises. Moreover, G_1 and G_2 are expressed as

$$G_1 = \frac{g_{\text{linear}1}}{1 + \frac{I_1}{I_S(1)}} \tag{3}$$

$$G_2 = \frac{g_{\text{linear}2}}{1 + \frac{I_2}{I_S(2)}} \tag{4}$$

where $G_{\text{linear}j}$ is the linear gain coefficient, I_j is the optical intensity, and $I_{\text{s}}(j)$ is the saturation intensity. In addition, Γ_j is defined by

$$\Gamma_j = -\frac{\ln(R_{\text{eff},j})}{2L} \tag{5}$$

where L is the cavity length of the FPLD, and $R_{\text{eff},j}$ is the effective reflectivity. The intensity-related rate equations can also be given by substituting parameter E with I using the following equations

$$I = E \cdot E^* = |E|^2 \tag{6}$$

$$\frac{dI}{dt} = \frac{d}{dt}[E \cdot E^*] = E \cdot \frac{d}{dt}[E^*] + E^* \cdot \frac{d}{dt}[E]. \tag{7}$$

In this case, (1) and (2) become

$$\frac{d}{dt}[I_1] = (G_1 - \Gamma_1)I_1 + \frac{G_1 h\omega n_{sp}}{2\pi T_R} \tag{8}$$

$$\frac{d}{dt}[I_2] = (G_2 - \Gamma_2)I_2 + \frac{G_2 h\omega n_{sp}}{2\pi T_R}. \tag{9}$$

Under thermal equilibrium, the mode intensity is stable and not temporally fluctuated, and we have

$$\frac{d}{dt}[I_1] = (G_1 - \Gamma_1)I_1 + \frac{G_1 h\omega n_{sp}}{2\pi T_R} = 0 \tag{10}$$

$$\frac{d}{dt}[I_2] = (G_2 - \Gamma_2)I_2 + \frac{G_2 h\omega n_{sp}}{2\pi T_R} = 0. \tag{11}$$

We consider a simple model for the mutually injection-locked EDFA–FPLD (or EDFL–FPLD) link as illustrated in Fig. 2, in which two of the independent laser sources are injection locking each other via an optical coupler or circulator. When the FPLD is feedback seeded by an EDFA or EDFL source of filtered lasing lineshape, (1) and (2) can be rewritten as

$$\frac{d}{dt}\left\{E_1 \exp(-i\omega t)\right\} = \left[\frac{1}{2}(G_1 - \Gamma_1)\right] E_1 \exp(-i\omega t) + \left[\frac{1}{2}\rho_3 \xi_3 \Gamma_3\right] E_3 \exp\left[-i(\omega t - \theta)\right] + \frac{G_1 h\omega n_{sp}}{2\pi T_R} \tag{12}$$

$$\frac{d}{dt}\left\{E_2 \exp(-i\omega t)\right\} = \left[\frac{1}{2}(G_2 - \Gamma_2)\right] E_2 \exp(-i\omega t) + \left[\frac{1}{2}\rho_3 \xi_3 \Gamma_3\right] E_3 \exp\left[-i(\omega t - \theta)\right] + \frac{G_2 h\omega n_{sp}}{2\pi T_R} 3 \tag{13}$$

where E_3 and Γ_3 are the optical field and loss coefficient for feedback injection. ρ_3 is the propagation loss. ξ_3 is the differential quantum efficiency for the light emitted from the laser to the grating output coupler. θ is the phase delay. It is seen that the feedback seeding term $[(1/2)\rho_3\xi_3\Gamma_3]E_3 \exp[-i(\omega t - \theta)]$ form the EDFA (or EDFL) has been added to the above equations. The intensity-related rate equations of two modes in FPLD are expressed as

$$\frac{d}{dt}[I_1] = (G_1 - \Gamma_1)I_1 + \rho_3 \xi_3 \Gamma_3 I_3 + \frac{G_1 h\omega n_{sp}}{2\pi T_R} \tag{14}$$

$$\frac{d}{dt}[I_2] = (G_2 - \Gamma_2)I_2 + \rho_3 \xi_3 \Gamma_3 I_3 + \frac{G_2 h\omega n_{sp}}{2\pi T_R}. \tag{15}$$

If only the intensities of λ_1 the central wavelength of principle mode) and λ_2 (the central wavelength of secondary mode) in the feedback injection can contribute to the FPLD lasing modes at same wavelength, (14) and (15) can be simplified as

$$\frac{d}{dt}[I_1] = (G_1 - \Gamma_1)I_1 + \rho_1 \xi_1 \Gamma_1 I_1 + \frac{G_1 h\omega n_{sp}}{2\pi T_R} \tag{16}$$

$$\frac{d}{dt}[I_2] = (G_2 - \Gamma_2)I_2 + \rho_2 \xi_2 \Gamma_2 I_2 + \frac{G_2 h\omega n_{sp}}{2\pi T_R}. \tag{17}$$

By setting and $(1 - \rho_1\xi_1)\Gamma_1 = \Gamma_1'$ and $(1 - \rho_2\xi_2)\Gamma_2 = \Gamma_2'$, we have

$$\frac{d}{dt}[I_1] = \left[G_1 - (1 - \rho_1\xi_1)\Gamma_1\right] I_1 + \frac{G_1 h\omega n_{sp}}{2\pi T_R} = \left[G_1 - \Gamma_1'\right] I_1 + \frac{G_1 h\omega n_{sp}}{2\pi T_R} \tag{18}$$

$$\frac{d}{dt}[I_2] = \left[G_2 - (1 - \rho_2\xi_2)\Gamma_2\right] I_2 + \frac{G_2 h\omega n_{sp}}{2\pi T_R} = \left[G_2 - \Gamma_2'\right] I_2 + \frac{G_2 h\omega n_{sp}}{2\pi T_R}. \tag{19}$$

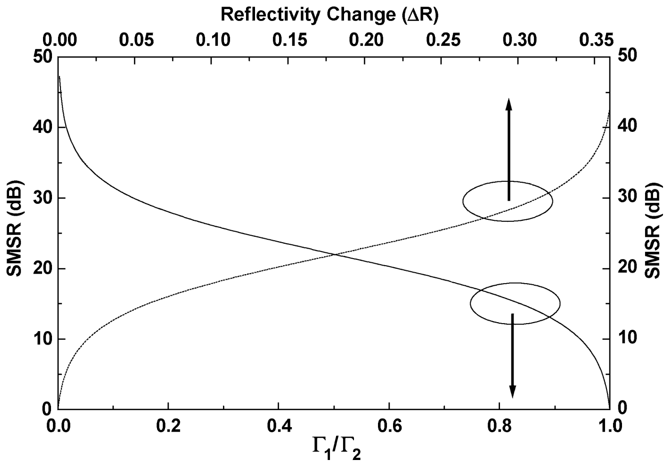


Fig. 3. Theoretically simulated SMSR of the mutually injection-locked EDFL–FPLD as function of reflectivity change (ΔR) and the ratio of loss coefficient (Γ_1/Γ_2).

Therefore, the SMSR of FPLD with feedback (or external) seeding from EDFA or EDFL can be expressed as

$$\mathrm{SMSR}=\frac{I_1}{I_2}=\frac{g_1}{(\Gamma_1'-g_1)}\times\frac{(\Gamma_2'-g_2)}{g_2}$$
$$=\frac{\frac{g_l}{\left(1+\frac{I_1}{I_{S(1)}}\right)}}{\Gamma_1'-\frac{g_l}{\left(1+\frac{I_1}{I_{S(1)}}\right)}}\times\frac{\Gamma_2'-\frac{g_l}{\left(1+\frac{I_1}{I_{S(2)}}\right)}}{\frac{g_l}{\left(1+\frac{I_1}{I_{S(2)}}\right)}} \tag{20}$$

where the saturation intensity I_S can be described as

$$I_S(x)=\frac{\left(I_x\times\frac{\Gamma_x I_x}{I_x+\frac{hf}{T_R}}\right)}{\left(g_l-\frac{\Gamma_x I_x}{I_x+\frac{hf}{T_R}}\right)}. \tag{21}$$

Assuming the saturation of the principle and side modes are equivalent (i.e., $\mathrm{I_s}(1)=\mathrm{I_s}(2)$), the gain of FPLD is relatively comparable to the loss of FPLD cavity at threshold condition, the output power of FPLD is about 0.1 mW under the feedback injection of EDFA or EDFL, the cavity length (L) is 250 μm, the refractive index (n) is 3.5, and the photon lifetime (T_R) is 5.8 ps. The SMSR, I_1/I_2, can, thus, be described as a function of the ratio of loss coefficients

$$\frac{I_1}{I_2}=\frac{C_1\left(\Gamma_2'-C_2\Gamma_1'\right)}{\Gamma_1'}$$
$$=\frac{C_1\left(1-\frac{C_2\Gamma_1'}{\Gamma_2'}\right)}{\frac{\Gamma_1'}{\Gamma_2'}}$$
$$=\frac{C_1\left[1-\frac{C_2\ln\left(R'_{\mathrm{eff},1}\right)}{\ln\left(R'_{\mathrm{eff},2}\right)}\right]}{\frac{\ln\left(R'_{\mathrm{eff},1}\right)}{\ln\left(R'_{\mathrm{eff},2}\right)}} \tag{22}$$

where C_1 and C_2 are constants.

Therefore, the SMSR of the FPLD under feedback injection condition (by taking Γ_2 as a constant) is shown in Fig. 3. It is obviously that the SMSR of FPLD can be up to 50 dB if the loss of the principle mode is far smaller than the side mode (i.e., Γ_1/Γ_2 is infinitely small). Therefore, the use of a self-feedback seeding for the FPLD (after passing through an external mode-selecting element) essentially helps to reduce the Γ_1/Γ_2 and to increase the SMSR of the mutually injection-locked EDFA–FPLD link.

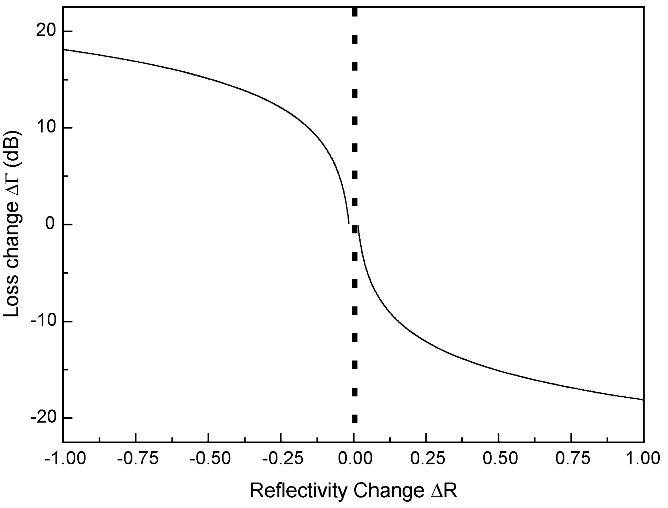


Fig. 4. Change of loss coefficient ($\Delta\Gamma$) as a function of reflectivity change (ΔR) under the mutual injection-locking condition.

In addition, the relationship between the loss coefficient Γ and the reflectivity R can be correlated each other by writing the following formula:

$$\Gamma_1=-\frac{\ln\left(R'_{\mathrm{eff},1}\right)}{2L} \tag{23}$$

$$\Gamma_2=-\frac{\ln\left(R'_{\mathrm{eff},2}\right)}{2L} \tag{24}$$

where $R'_{\mathrm{eff},j}$ denotes the effective reflectivity of the FPLD cavity under external feedback seeding from the EDFA or EDFL. Therefore, the change of loss coefficient for the FPLD can, thus, be expressed as

$$\Delta\Gamma=-\frac{\partial}{\partial R}\left[\frac{\ln\left(R'_{\mathrm{eff}}\right)}{2L}\right]\cdot\Delta R=-\frac{\Delta R}{2LR'_{\mathrm{eff}}}. \tag{25}$$

The variation in loss coefficient of FPLD as a function of reflectivity change due to the feeding seeding of EDFA or EDFL is plotted in Fig. 4.

Consequently, the SMSR of FPLD under feedback injection condition can be rewritten as a function of reflectivity change. The ratio of loss coefficients Γ_1'/Γ_2' can be represented as

$$\frac{\Gamma_1'}{\Gamma_2'}\Rightarrow\frac{\Gamma_1+\Delta\Gamma_1}{\Gamma_2+\Delta\Gamma_2}=\frac{\Gamma_1-\frac{\Delta R}{2LR_{\mathrm{eff},1}}}{\Gamma_2-\frac{\Delta R}{2LR_{\mathrm{eff},2}}}$$
$$=\frac{-\frac{\ln(R_{\mathrm{eff},1})}{2L}-\frac{\Delta R}{2LR_{\mathrm{eff},1}}}{-\frac{\ln(R_{\mathrm{eff},2})}{2L}-\frac{\Delta R}{2LR_{\mathrm{eff},2}}}$$
$$=\frac{-\frac{1}{2L}\left[\ln\left(R_{\mathrm{eff},1}+\frac{\Delta R_{\mathrm{eff},1}}{R_{\mathrm{eff},1}}\right)\right]}{-\frac{1}{2L}\left[\ln\left(R_{\mathrm{eff},2}+\frac{\Delta R_{\mathrm{eff},2}}{R_{\mathrm{eff},2}}\right)\right]}. \tag{26}$$

We assume that the effective reflectivity of the principle mode is equal to the largest side mode $R_{\mathrm{eff},1}\cong R_{\mathrm{eff},2}=((3.5-$

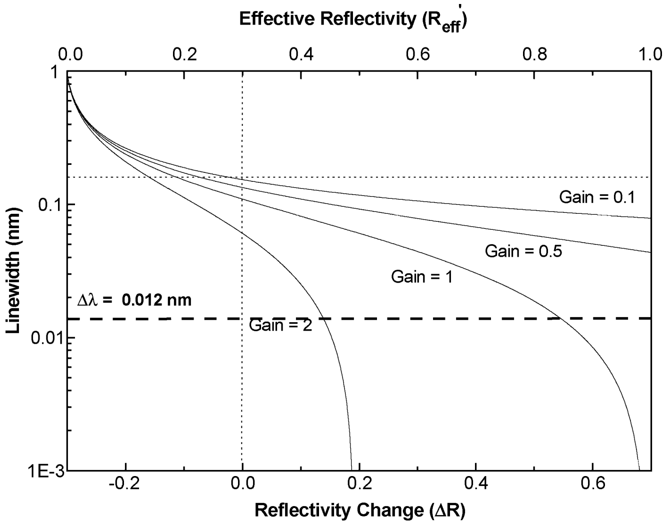


Fig. 5. Simulated linewidth of mutually injection-locked EDFL–FPLD link as a function of reflectivity change (ΔR).

$1)/(3.5+1))^2 = 0.31$ and the reflectivity change of the principle mode is far stronger to the largest side mode ($\Delta R_{\text{eff}.1} \gg \Delta R_{\text{eff},2} \approx 0$). Then (26) can be written as

$$\frac{\Gamma_1 + \Delta\Gamma_1}{\Gamma_2 + \Delta\Gamma_2} \cong \frac{\left[\ln\left(R_{\text{eff},1} + \frac{\Delta R_{\text{eff},1}}{R_{\text{eff},1}}\right)\right]}{[\ln(R_{\text{eff},2})]}. \tag{27}$$

Therefore, the SMSR of the FPLD as a function of reflectivity change due to the feedback seeding from EDFA (or EDFL) can also be obtained (see Fig. 3).

Furthermore, with the feedback seeding from EDFA or EDFL, the linewidth of the FPLD is also evaluated. If we consider the Fabry–Perot etalon effect of the FPLD, the 3-dB linewidth of the FPLD lasing mode spectrum can, thus, be described as

$$\Delta\lambda = \frac{\lambda_1^2}{2\pi n L}\frac{(1 - R_1 G_1)}{\sqrt{R_1}\sqrt{G_1}}. \tag{28}$$

If the effective reflectivity of FPLD is slightly changed due to external feedback seeding, this may give rise to a change in the longitudinal-mode linewidth of FPLD. That is

$$\Delta\lambda = \frac{\lambda_1^2}{2\pi n L}\frac{\left[1 - R'_{\text{eff},1}G_1\right]}{\sqrt{R'_{\text{eff},1}}\sqrt{G_1}} = \frac{\lambda_1^2}{2\pi n L}\frac{[1 - (R_1 + \Delta R)G_1]}{\sqrt{(R_1 + \Delta R)}\sqrt{G_1}}. \tag{29}$$

Thus, the simulated linewidth of the FPLD can also be plotted as a function of the change in reflectivity of the FPLD due to the feedback seeding of the EDFA or EDFL, as shown in Fig. 5. Therefore, the linewidth reduction and side-mode suppression of FPLD in the mutually injection-locked EDFA–FPLD link or EDFL–FPLD link can be understood through the theoretical modeling as shown above.

IV. RESULTS AND DISCUSSIONS

A. Free-Running FPLD and EDFL

In this experiment, the spectra and mode-beating noise characteristics of either the EDFL–FPLD or EDFA–FPLD link are compared with those of a commercial DFBLD (Panasonic LNFE03YBE4UP) with linewidth and SMSR of 0.5 MHz and 37.5 dB, respectively, as shown in Fig. 6(a) and (b). Without the mutual injection locked link, the lasing spectrum and the self-heterodyne mode-beating spectrum of a free-running FPLD (at above threshold current of 20 mA) are shown in Fig. 6(c) and 6(d). The free-running FPLD exhibits a relatively wide lasing spectrum with signal-to-noise ratio (SNR) of about 35 dB. The longitudinal-mode spacing, 3-dB linewidth, and SMSR of the free-running FPLD spectrum are 1.2 nm, at least 2 nm, and <2 dB, respectively. The linewidth of a single longitudinal mode in the free-running FPLD measured by an OSA is 0.02 nm, which is much broader than that of a DFBLD with negligible beating noise. On the other hand, the lasing spectrum of a free-running EDFL formed by a close-loop EDFA with 3-dB lasing linewidth and SNR of 1.015 nm and 20 dB is shown in Fig. 6(e). A broadened mode-beating noise spectrum has also been observed due to the interference among enormous longitudinal modes in the EDFL cavity, as shown in Fig. 6(f). The mode-beating spectrum of EDFL can extend up to several >100 GHz (corresponding to a 3-dB linewidth of 1.015 nm). When an OBPF is added into the EDFL ring cavity, the 3-dB linewidth of the free-running EDFL is further reduced to 0.034 nm, however, the mode-beating noises still exists (with a reduced bandwidth of >4 GHz). Nonetheless, both the free-running and the OBPF filtered EDFLs exhibit large mode-beating noises, which restrict their applications in practical fiber-optic communication networks.

B. EDFL–FPLD Link With Close-Loop EDFA

The lasing spectra of the EDFL–FPLD link driven by different currents (below, near, and above threshold current) at 35 °C are different, as illustrated in Fig. 7. The EDFL–FPLD link exhibits a relatively broadened spectrum when FPLD is biased well below threshold, the lasing linewidth gradually becomes narrow as the mode-selecting capability of the FPLD is initiated at larger biases. One striking feature of the proposed scheme is to operate the EDFL at single FPLD longitudinal-mode regime with high SMSR by driven the feedback-injected FPLD at near-threshold current. It is realized that when the FPLD is operated at nearly lasing regime, the broadband spectrum of the FPLD reveals that there is still a competition among the spontaneously emitted modes. At this stage, even a small intracavity feedback power can efficiently lead to single-mode survived in cavity, which eventually suppresses the other lasing modes of the EDFL. The mode-selection is therefore achieved by fine-tuning the power and polarization of the feedback light from the EDFL cavity. The lasing linewidth reaches a minimum when one of the FPLD longitudinal modes is selected by the EDFL–FPLD link due to the combined effects of gain profile filtering and mutual injection locking [11]. The SMSR of FPLD can be as high as 48 dB as the partial output of EDFL is filtered and then externally injected back into the FPLD. According to our simulation, the linewidth of a FPLD longitudinal mode in the EDFL–FPLD link can be further reduced by at least one order of magnitude, however, the SMSR of the EDFL–FPLD link is greatly degraded due to the amplification of the side-modes

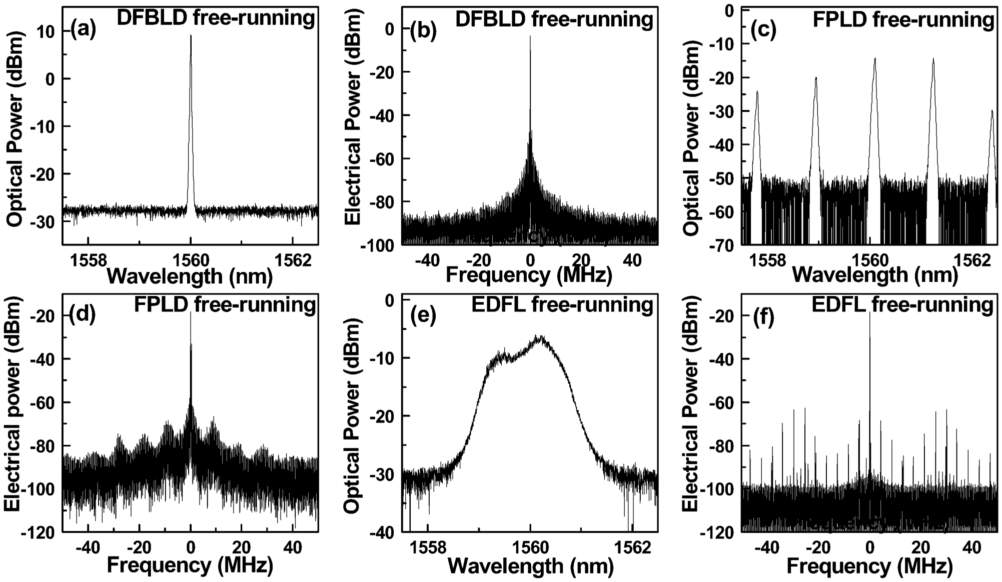


Fig. 6. Lasing and mode-beating spectra of (a)–(b) commercial DFBLD, (c)–(d) CW lasing FPLD, and (e)–(f) Free-running EDFL, respectively.

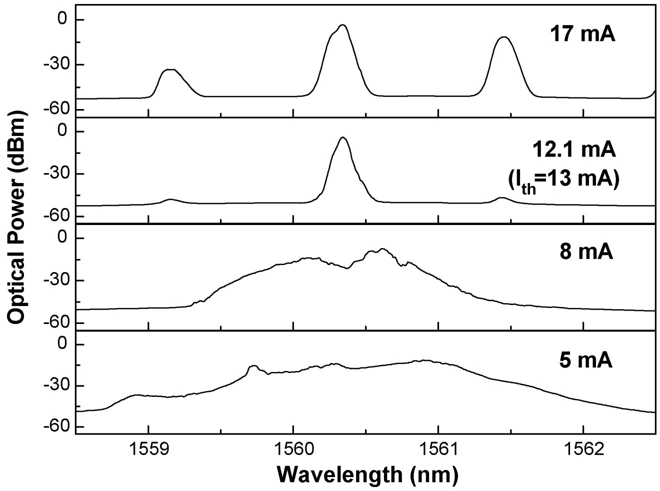


Fig. 7. Lasing spectra of a mutually injection-locked EDFL–FPLD link with the FPLD at different biased currents.

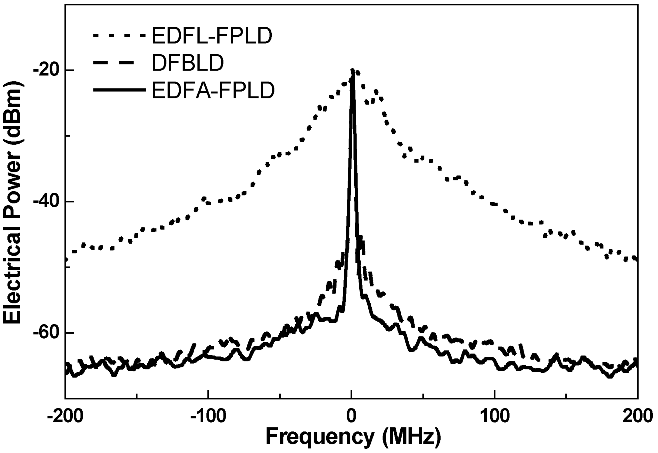


Fig. 8. Comparison on the mode-beating spectra of DFBLD, mutually injection-locked EDFL–FPLD link, and EDFA–FPLD link.

when FPLD is driven at higher currents above threshold. The mode numbers of the EDFL ring cavity also abruptly increases as the bias current of FPLD arises. The peak wavelength is still dominated by the cross-correlated gain profile of the EDFL and FPLD, while the effect of FPLD is more pronounced. The drift in peak wavelength of the principle lasing mode in the FPLD filtered EDFL under increasing FPLD current is negligible since the EDFL and the FPLD are injection locked to each other. Similarly, the beating noise with 4.4-MHz spectral spacing resulting from the EDFL ring cavity cannot be suppressed in such configuration, as shown in Fig. 11(b). By measuring the linewidth of such an EDFL–FPLD link in a self-heterodyne optoelectronic interferometric spectrometer (with microwave spectrum analyzer), the exact lasing spectrum of DFBLD and EDFL–FPLD link are compared (see Fig. 8). The measured 3-dB spectral linewidths of DFBLD and EDFL–FPLD link are 3.4 and 19 MHz, respectively. The overall relative intensity noise (RIN) of the DFBLD (thermal and shot noises of the measurement included) rapidly decays to −145-dBm/Hz background at frequency beyond 50 MHz. The RIN of EDFL–FPLD link linearly decreases from −80 dBm/Hz to background within 300-MHz bandwidth.

C. EDFA–FPLD Link With Open-Loop EDFA

In order to eliminate the side modes and the mode-beating noise of the EDFL–FPLD link, an EDFA–FPLD link is proposed. The difference between these two configurations is that the EDFA is not constructed in close-loop regime. In this case, there are no resonant cavity modes generating by the EDFA, which only amplifies the spontaneous emission from FPLD and feedback seeds into the FPLD after filtering. The best SMSR can be obtained by setting the FPLD at 35 °C and just below threshold driving condition and selecting the appropriate coupler ratio (OC1) of the EDFA–FPLD link. Fig. 9 shows the optical spectra of EDFA–FPLD link with different coupling ratios of OC1. When FPLD is injected by the filtered ASE from EDFA with power of 0.37 mW (using OC1 with coupling ratio

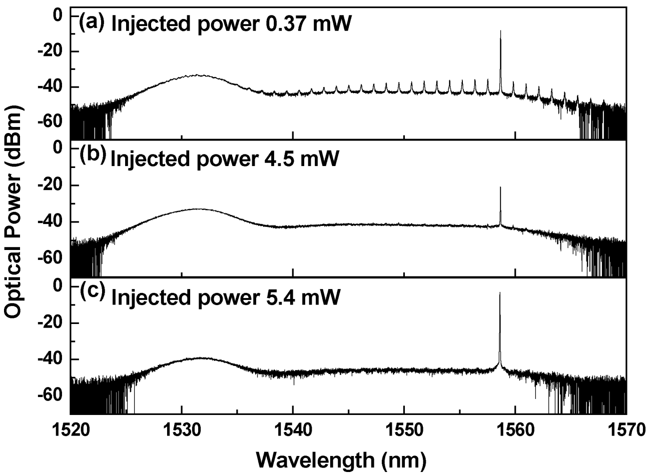


Fig. 9. Optical spectra of mutually injection-locked EDFA–FPLD link with different coupling schemes. (a) 5% EDFA feedback injects into the FPLD. (b) 95% EDFA feedback injects into the FPLD. (c) 50% EDFA feedback injects into the FPLD.

of 5%), it is seen that the other longitudinal modes of FPLD are growing up to be competitive with the principle mode. This eventually leads to a bad SMSR of only 23 dB, as shown in Fig. 9(a). To improve this, the coupling ratio of OC1 and the mutual injecting power for the FPLD in Fig. 1(c) is adjusted. Although there is only the dominant mode lasing under the strong mutual injection, the SMSR is still 25 dB as the feedback injecting power increases to 4.5 mW (using OC1 with coupling ratio of 95%), as shown in Fig. 9(b). The highest SMSR of 42 dB [see Fig. 9(c)] is obtained with a mutual injection power of 5.4 mW (using a 50% coupling ratio in this scheme), where the corresponding 3-dB linewidth of the EDFA–FPLD link is reduced to 0.016 nm. Note that the minimum linewidth of the mutually injection-locked EDFA–FPLD link ever obtained is as small as 0.012 nm, which is achieved by high-power seeding the unbiased FPLD at a cost of worse SMSR. The 3-dB spectral linewidth of EDFA–FPLD link measured by interferometeric method is comparable with that of a DFBLD (see Fig. 8). In comparison with the EDFL–FPLD link, the EDFA–FPLD link not only suppresses beating noise but also reduces the 3-dB linewidth by almost one order of magnitude. In fact, the feedback injection from the filtered EDFA is equivalent to an increase on the end-face reflectivity of FPLD, which inevitably leads to the reduction of linewidth and the improvement of SMSR in mutually injection-locked EDFA–FPLD link. These results have also been confirmed by our simulation, as shown in Fig. 3 and 5. To compare, the lasing spectra of the free-running EDFL, the OBPF filtered EDFL, the EDFL–FPLD link, and EDFA–FPLD link are illustrated in Fig. 10. Obviously, the free-running EDFL exhibits a relatively wide-band lasing spectrum. The 3-dB linewidth of the OBPF filtered EDFL is reduced to 0.034 nm. The OBPF filtered EDFA–FPLD link can further reduce the linewidth to 0.012 nm, which is even better than that of EDFL–FPLD link. Furthermore, the measured spectral linewidths of the OPBF filtered EDFA–FPLD link and EDFL–FPLD link are 0.03 and 0.05 nm at 10-dB decay, respectively. The characteristic parameters of the aforementioned systems are listed in Table I.

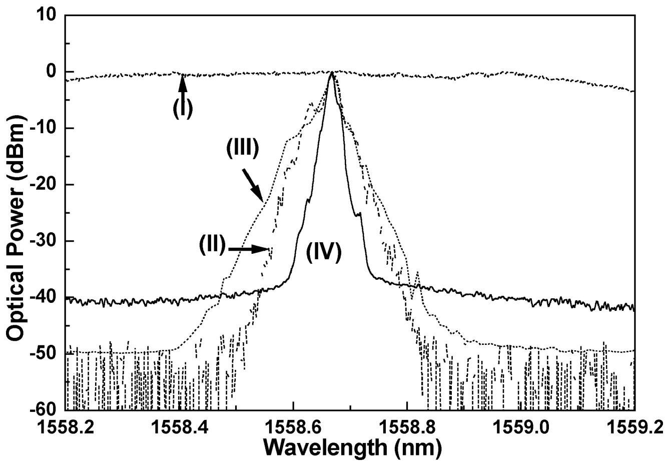


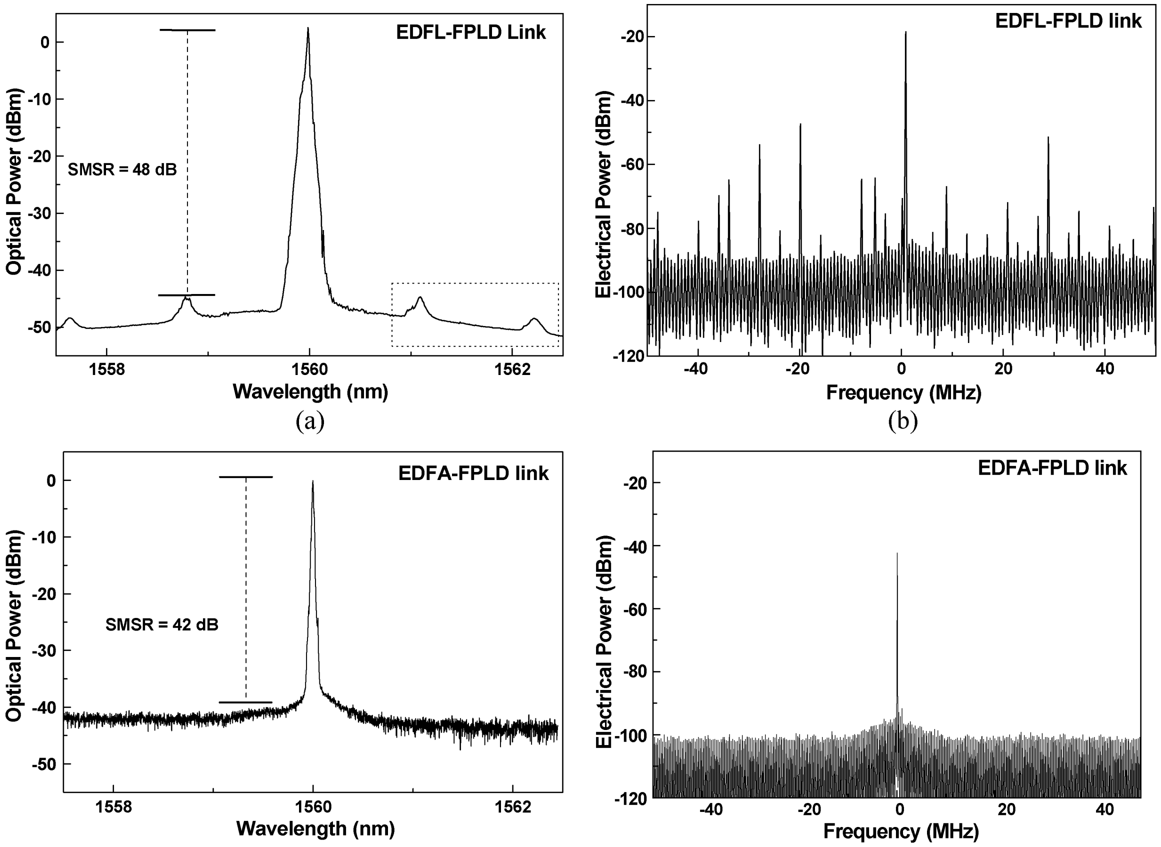
Fig. 10. Lasing spectra of (I) free-running EDFL, (II) OBPF filtered EDFL, (III) mutually injection-locked EDFL–FPLD link, and (IV) mutually injection-locked EDFA–FPLD link.

TABLE I
THE 3-dB LINEWIDTHS ($\Delta\lambda$), SMSR, AND REQUIRED INJECTING POWER FOR THE FPLD AT DIFFERENT LASER CONFIGURATIONS

Configurations	Injection (mW)	Linewidth (MHz)	SMSR (dB)
EDFL Free-running		1.27×10^5 (or 1.015 nm)	36
OBPF filtered EDFL		4.25×10^3 (or 0.034 nm)	45
DFBLD		3.4	~40
EDFL-FPLD Link	8.63	19	48
EDFA-FPLD Link	0.37	3.4	23
EDFA-FPLD Link	4.5	3.4	25
EDFA-FPLD Link	5.4	3.4	42

D. *Discussion*

Even at a higher feedback injecting power, the EDFL–FPLD link still exhibits a larger linewidth, which is attributed to the interference of enormous longitudinal modes in the EDFL cavity with free spectral range of about 4.4 MHz. Without these modes, the EDFA–FPLD link can reach a smaller linewidth and nearly mode-beating noise-free lasing spectrum at low-feedback injecting condition. Although the best SMSR of up to 48 dB can be obtained from the mutually injection-locked EDFL–FPLD link, the side-modes are still observable in the lasing spectrum, as shown in Fig. 11(a). Such a configuration inevitably increases the mode-beating noises [see Fig. 11(b)]. In contrast, the side-modes are completely eliminated in the mutually injection-locked EDFA–FPLD link [see Fig. 11(c)], and a nearly clean mode-beating spectrum can be observed in Fig. 11(d). The adding of intracavity OBPF in the EDFA–FPLD helps the elimination of FPLD side-modes, while the use of open-loop EDFA avoids the EDFL longitudinal modes. In addition, the FPLD is operated at just below threshold current in our experiment, corresponding to an output power of below



(a) (b)

(c) (d)

Fig. 11. Lasing and mode-beating spectra of (a)-(b) EDFL–FPLD and (c)-(d) EDFA–FPLD links.

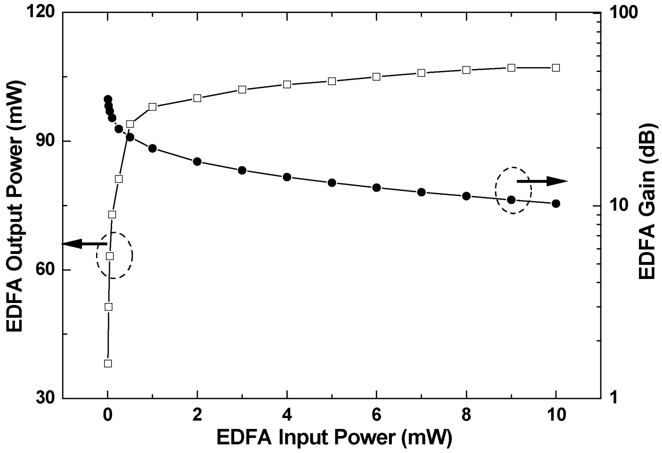


Fig. 12. Output power and gain characteristics of EDFA at different input powers.

0.1 mW. Although the EDFA can provide very large gain for such a small input signal (see Fig. 12), the maximum output power of the EFDA-FPLD link is still limited at 20 mW. Since the insertion loss of the 50% output coupler added into the EDFA–FPLD link is about 3.3 dB, and the output of the EDFA–FPLD link is further attenuated by 10 dB (coupling ratio of 10%, as shown Fig. 1). In comparison, the maximum output power of a commercial DFB laser diode can be 10–40 mW. To enlarge the output power of the EDFA–FPLD link, the use of an FPLD with larger output power is mandatory. With these ameliorations, a DFBLD-like performance of the EDFA–FPLD link can be obtained. This design has already improved the overall performances of previous demonstration (the EDFL–FPLD link), which also corroborates the niche of amplified feedback seeding in mutual injection-locking laser system for linewidth reduction and SMSR enhancement. The use of FPLD in the EDFA for ultranarrow bandpass filtering and beating-noise suppression is, thus, straightforward.

V. CONCLUSION

We theoretically analyze the effect of feedback seeding power for FPLD on the linewidth, SMSR, and mode-beating noise characteristics of a mutually injection-locked EDFL–FPLD or EDFA–FPLD link. The SMSR and 3-dB linewidth of such link as a function of feedback power dependent reflectivity change are simulated. By comparing the EDFL–FPLD link with the EDFA–FPLD link, it is fount that the side-mode in the EDFA–FPLD link can be entirely suppressed due to the effects of mutual injection-locking, intracavity OBPF and active FPLD filtering. To help selecting the strongest mode from the gain-spectrum of FPLD lasing in the EDFA–FPLD link, the FPLD must be biased at just below threshold condition. The narrowest 3-dB linewidth of 3.4 MHz and comparable SMSR of 42 dB in an EDFA–FPLD link are obtained under a feedback injecting power of 5.4 mW. Furthermore, the EDFA–FPLD link exhibits a better beating noise suppression performance as compared to the EDFL–FPLD link. The maximum output power of the current EFDA-FPLD link is limited at 20 mW, and the improvement relies on the use of an FPLD with larger output power. With the improved mutual injection-locking scheme, a mode-beating noise-free single-mode and high-SMSR EDFA–FPLD link is primarily demonstrated, which has a comparable performance with commercial DFBLD sources.

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