Spectral characteristics of a regenerative semiconductor optical amplifier mutually injection locked with a Fabry–Perot laser diode

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The anomalous injection locking of a traveling-wave semiconductor optical amplifier (SOA) and a fiber-pigtailed Fabry–Perot laser diode (FPLD) linked with single-mode and improved side-mode suppression ratio output is demonstrated. We achieve this injection locking by driving the FPLD slightly below threshold and by feedback injecting the FPLD with fractional output of a closed-loop SOA. The SOA–FPLD link lases in a single FPLD longitudinal mode with a reduced linewidth of 0.013 nm and a maximum side-mode-suppressing ratio of 39.7 dB. A precise 3-dB linewidth of 45–50 MHz is also observed from the self-homodyne mode-beating spectrum. The optimized feedback-injecting power for the FPLD is ~2% of the SOA–FPLD linked output power of >400 μW. The variations in output power and in peak wavelength are not more than 0.54% and 0.06%, respectively. The injection-locked SOA–FPLD link is insensitive to the temperature fluctuation within ±0.25 °C. © 2004 Optical Society of America

OCIS codes: 140.4480, 140.2020, 140.3520.

1. Introduction

Injection-locked laser technology was demonstrated by Stover and Steier[1] to provide a clear physical picture of the oscillator dynamics between master and slave He–Ne lasers.[2] Some important phenomena such as bistability, bifurcation, and the period-doubling route to chaos were previously predicted and observed from injection-locking theories.[3–6] Such techniques have subsequently been applied to a variety of laser systems to ensure narrow linewidth,[7–9] single-mode operation,[10] or both. Versatile mutually injection-locked lasers, such as a fiber laser with a distributed-feedback semiconductor laser[11,12] and such as two distributed-feedback laser diodes,[13] have been reported that provide a simple and effective method for mode selection, wavelength synchronization, linewidth reduction, and side-mode suppression. Recently, much research has focused on the generation of single-mode Fabry–Perot laser diodes (FPLDs) with high side-mode-suppression ratios (SMSRs). For example, Chow and Shu have demonstrated two mutually injection-seeded, short-pulse FPLDs with a SMSR and a linewidth of ~20 dB and 0.47 nm, respectively.[14] However, we are aware of few studies of semiconductor optical amplifier (SOAs) linked with other laser sources. In this Letter we propose injection locking of a SOA with a FPLD to produce single-mode output with a high SMSR and a better signal-to-noise ratio (SNR). The effect of a FPLD-driven current on the output power, the mode linewidth, and the SMSR of a SOA is discussed.

2. Experiment and Theory

The injection-locked SOA–FPLD link is illustrated in Fig. 1. We implemented the SOA–FPLD link by connecting a commercially available, fiber-pigtailed traveling-wave SOA and a FPLD at a central wavelength of 1300 nm with two directional couplers. The output of the SOA is attenuated to inject the FPLD from which the feedback-injected FPLD output is subsequently coupled through an in-line polarization controller (PC) into the SOA. The in-line polarization controllers adjust both the feedback-injected power and the polarization of the feedback into the FPLD and the SOA. Output coupler OC1 couples 90% of the output from the FPLD into the SOA via output coupler OC2 with a coupling ratio of 50/50;

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Received 15 April 2003; revised manuscript received 21 August 2003; accepted 23 September 2003.
0003-6935/04/010153-07$15.00/0

65% of the SOA output is feedback injected into the FPLD via coupler OC3 with a 20% coupling ratio. The residual 80% output of OC3 is connected to OC2 to ensure lasing of the SOA. The 35% power of the SOA–FPLD link is coupled out by coupler OC4 for monitoring. The free-running SOA, with a saturation gain of 20 dB, is operated at a driving current of 100 mA, which results in an output power of >1 mW. The longitudinal mode spacing of the free-running SOA without a closed-loop fiber ring is 0.48 nm. After the SOA has connected with the fiber ring, the entire cavity length of the closed-loop SOA is approximately 14 m, which corresponds to a longitudinal mode spacing of 14 MHz (or 4.1 pm). The 3-dB linewidth of a longitudinal mode in the SOA lasing in a free-running mode is 0.042 nm. The threshold current and the mode spacing of the free-running FPLD at 24 °C are ~11 mA and ~0.76 nm, respectively. With the FPLD operating just below threshold and feedback injecting below 2% of the SOA power, the SOA–FPLD link lases at a FPLD longitudinal mode with reduced linewidth, improved SMSR, and better SNR. In principle, the feedback from the SOA and the cavity loss of the FPLD cancel each other to help in selecting single-longitudinal-mode lasing in the FPLD. The feedback injection from the FPLD to the SOA results in injection locking of a SOA–FPLD link, whose lasing mode and linewidth are dominated by the FPLD. Precise control of the feedback power suppresses the other side modes in the FPLD and the SOA during gain competition. The SMSR and the SNR of the SOA can be significantly improved by use of this injection-locking scheme.

Solving the rate equations that describe the principal and secondary modes of the FPLD during feedback injection from a regenerative SOA (closed loop by a fiber ring) permits the linewidth-reduction and side-mode-suppression effect of the FPLD to be achieved in an injection-locked SOA–FPLD link as shown in Fig. 1. The rate equations for these two modes in the FPLD are written as

$$\frac{\mathrm{d}}{\mathrm{d}t}[E_2 \exp(-i\omega t)] = [\tfrac{1}{2}(G_2 - \Gamma_2)]E_2 \exp(-i\omega t) + (\tfrac{1}{2}\rho_3\xi_3\Gamma_3)E_3 \exp[-i(\omega t - \theta)] + \frac{G_2 h\omega n_{sp}}{2\pi T_R}, \quad (1)$$

$$\frac{d}{\mathrm{d}t}[E_1 \exp(-i\omega t)] = [\tfrac{1}{2}(G_1 - \Gamma_1)]E_1 \exp(-i\omega t) + (\tfrac{1}{2}\rho_3\xi_3\Gamma_3)E_3 \exp[-i(\omega t - \theta)] + \frac{G_1 h\omega n_{sp}}{2\pi T_R}, \quad (2)$$

where G_1 and G_2 denote the gain coefficients, $G_1 h\omega n_{sp}/2\pi T_R$ and $G_2 h\omega n_{sp}/2\pi T_R$ are their corresponding spontaneous-emission noises, and $T_R = 2Ln/c$ denotes as the photon lifetime. The loss coefficients are written as Γ_1 and Γ_2, where $\Gamma_x = -[\ln(R_{\mathrm{eff},x})/2L]$ and L is the cavity length of the FPLD. The intensity-related rate equations can also be found by substitution of parameter I for E, as in the following equations. A feedback-seeding term from the SOA with its electric field denoted E_3 has been added to both equations. The intensity-related rate equations that result when parameter I is substituted for E, $I = EE^* = |E|^2$, and

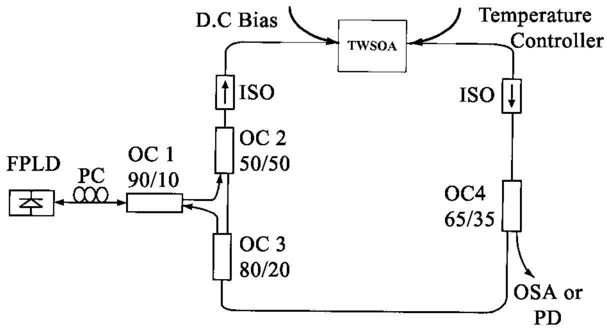

Fig. 1. Schematic of the injection-locked SOA–FPLD link: ISO, isolator; OSA, optical spectrum analyzer; PD, photodiode; other abbreviations defined in text.

$$\frac{\mathrm{d}I}{\mathrm{d}t} = \frac{d}{\mathrm{d}t}(EE^*) = E\frac{\mathrm{d}}{\mathrm{d}t}(E^*) + E^*\frac{d}{\mathrm{d}t}(E)$$

are

$$\frac{\mathrm{d}}{\mathrm{d}t}(I_1) = (G_1 - \Gamma_1)I_1 + \rho_1\xi_1\Gamma_1 I_1 + \frac{G_1 h\omega n_{sp}}{2\pi T_R} = (G_1 - \Gamma_1{}')I_1 + \frac{G_1 h\omega n_{sp}}{2\pi T_R}, \quad (3)$$

$$\frac{\mathrm{d}}{\mathrm{d}t}(I_2) = (G_2 - \Gamma_2)I_2 + \rho_2\xi_2\Gamma_2 I_2 + \frac{G_2 h\omega n_{sp}}{2\pi T_R} = (G_2 - \Gamma_2{}')I_2 + \frac{G_2 h\omega n_{sp}}{2\pi T_R}, \quad (4)$$

Equations (3) and (4) were simplified because only the intensities at λ_1 and λ_2 of the feedback injection from the SOA can contribute to the FPLD lasing modes. The steady-state SMSR of the FPLD with external seeding from SOA is expressed as

$$\mathrm{SMSR} = \frac{I_1}{I_2} = \frac{G_1}{(\Gamma_1{}' - G_1)} \times \frac{(\Gamma_2{}' - G_2)}{G_2} = \frac{G_1/\{1 + [I_1/I_S(1)]\}}{\Gamma_1{}' - \{G_1/[1 + I_1/I_S(1)]\}} \times \frac{\Gamma_2{}' - \{G_1[1 + I_1/I_S(2)]\}}{G_1/[1 + I_1/I_S(2)]}, \quad (5)$$

where saturation intensity $I_S(x) = I_x[\Gamma_x I_x/(I_x + hf/T_R)]/\{G_1 - [\Gamma_x I_x/(I_x + hf/T_R)]\}$ is the same for the principal and the secondary modes. Assuming that the gain of the FPLD is relatively comparable with the loss of FPLD cavity at below-threshold operation and that the output power of the FPLD is ~0.1 mW during feedback injection of the SOA, the SMSR of the FPLD (I_1/I_2) can thus be described as a function of the ratio of loss coefficients

$$\frac{I_1}{I_2} = \frac{C_1(\Gamma_2' - C_2\Gamma_1')}{\Gamma_1'} = \frac{C_1(1 - C_2\Gamma_1'/\Gamma_2')}{\Gamma_1'/\Gamma_2'} = \frac{C_1[1 - C_2 \ln(R_{\text{eff},1}')/\ln(R_{\text{eff},2}')]}{\ln(R_{\text{eff},1}')/\ln(R_{\text{eff},2}')}. \quad (6)$$

Therefore the SMSR of the FPLD under conditions of feedback injection can be plotted with Γ_2 taken as a constant. It is obvious that the SMSR of the FPLD can be as much as 50 dB if the loss of the principal mode is far smaller than that of the side mode (i.e., if Γ_1/Γ_2 is infinitely small). Alternatively, the SMSR can also be described as a function of the reflectivity change (ΔR) in the FPLD induced by feedback injection from the SOA. This description incorporates the effect of feedback seeding on the improvement of the SMSR of the FPLD.

The linewidth reduction of the FPLD with feedback seeding from an SOA can also be evaluated. The transmission intensity of the principal mode in the FPLD under the Fabry–Perot etalon effect is written as

$$I_1 = I_0 \frac{T_1^2}{(1 - R_1G_1)^2} \frac{G_1}{1 + [4R_1G_1/(1 - R_1G_1)^2]\sin^2 \frac{\Delta}{2}}. \quad (7)$$

The spectral linewidth of the FPLD lasing mode at 3-dB decay under the influence of feedback injection from the SOA can be obtained as

$$\Delta\lambda = \frac{\lambda_0^2}{2\pi nL} \frac{\lfloor 1 - R_{\text{eff},1}'G_1 \rfloor}{\sqrt{R_{\text{eff},1}'}\sqrt{G_1}} = \frac{\lambda_0^2}{2\pi nL} \frac{[1 - (R_1 + \Delta R)G_1]}{\sqrt{(R_1 + \Delta R)}\sqrt{G_1}}. \quad (8)$$

The linewidth of the SOA–FPLD can thus be plotted as a function of the change in reflectivity (ΔR) of the FPLD that is due to the feedback seeding from SOA. When the FPLD is operated nearly at threshold, it can be seen from Fig. 2 that the linewidth of the SOA–FPLD link can be reduced to one tenth of its original value as the change in reflectivity increases to 0.2–0.5. Although high-gain and high-feedback injection could further reduce the linewidth of the SOA–FPLD link, such operations may also lead to multimode lasing of the FPLD and therefore degrade the SMSR.

3. Results and Discussion

The amplified spontaneous-emission spectrum of a free-running SOA operating at 28 °C is shown in Fig. 3, which exhibits linewidths of ~43.9 and ~86.8 nm at rates of decay of 3 and 10 dB, respectively. In comparison, the lasing spectral linewidth of the free-running FPLD operated slightly above threshold is ~4.9 nm, in which a single-longitudinal-mode linewidth is 0.025 nm. Driving the closed-loop SOA at 65 mA or greater dramatically shrinks the lasing spectrum closed-loop SOA–FPLD link, as shown in Fig. 3. This requires a FPLD-driven current of 10.6 mA, which is just 4% below the lasing threshold. Because the FPLD is operated near the lasing regime, there is still a gain competition among the amplified spontaneous-emission modes inside the FPLD. At this stage, even small intracavity feedback power can efficiently lead to the survival of one FPLD mode in a cavity according to the feedback-injection model, because the single-FPLD-longitudinal-mode seeding eventually suppresses the lasing of other modes. The broadband amplified spontaneous-emission spectrum from SOA feedback is injected into the FPLD, which favors one of two FPLD longitudinal modes competing and surviving after round-trip amplifica-

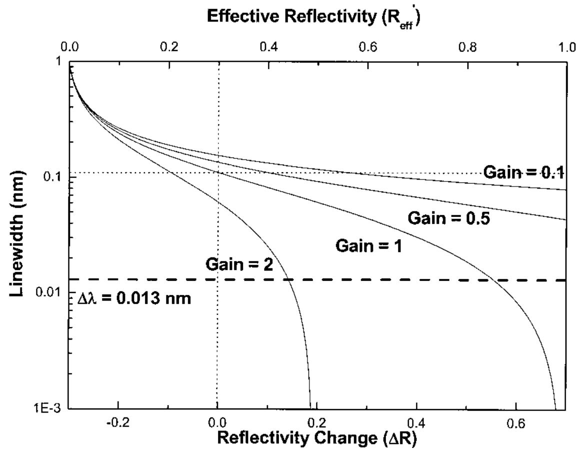

Fig. 2. Theoretically simulated linewidth at 3-dB decay as a function of effective reflectivity (R_{eff}) and reflectivity change (ΔR) for four gain conditions.

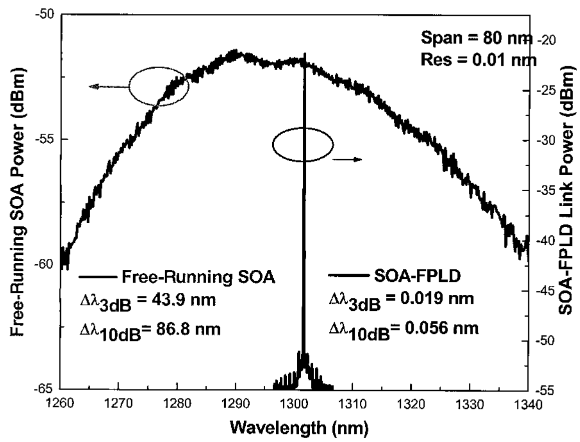

Fig. 3. Measured spectra of a free-running SOA and of an injection-locked SOA–FPLD link.

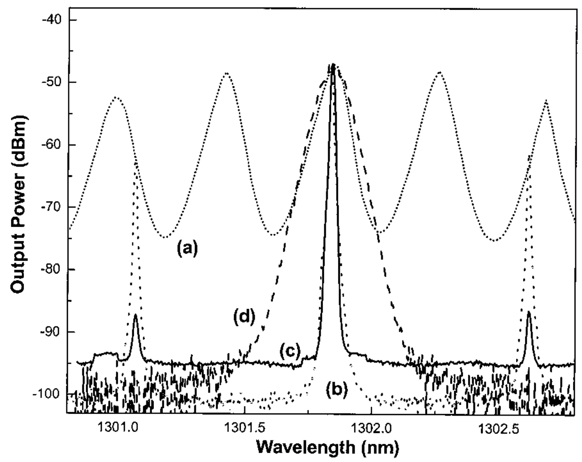

Fig. 4. Lasing spectra of (a) a free-running SOA, (b) a free-running FPLD, (c) an optically bandpass filtered SOAFL, and (d) an injection-locked SOA–FPLD link.

tion in the FPLD cavity. This mode then dominates the lasing of the SOA–FPLD link. In Fig. 4 the spectral analysis illustrates that only one FPLD-dominated longitudinal mode is lasing in the SOA–FPLD link because of the mutual injection-locking effect. Fitting the lasing line shape with a Gaussian function (shown in Fig. 5) yields lasing linewidths of the SOA–FPLD link for decay rates of 3, 10, and 20 dB of 0.013, 0.027, and 0.042 nm, respectively, which are much narrower than those of a free-running SOA, as listed in Table 1. In addition, the linewidth of the SOA–FPLD link is further characterized by self-homodyne mode-beating spectroscopy. The output of an injection-locked SOA–FPLD link is sent to a commercially available Mach–Zehnder-type fiber-optic interferometer (Hewlett-Packard Model HP11980A) and a high-speed photodetector (Newfocus 1014). The measured single-sided band linewidths at 3-dB-, 10-dB-, and 20-dB decay are only 45–50, 75–80, and 110–120 MHz, respectively, far

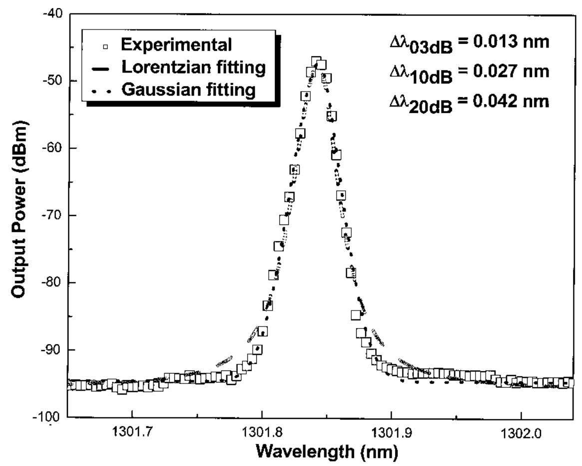

Fig. 5. Line shape and linewidth at rates of decay of 3, 10, and 20 dB of a SOA–FPLD link fitted by Gaussian and Lorentzian functions.

Table 1. Comparisons of Output Performance of an FPLD and a SOA in Various Laser Geometries

Laser Geometry	3-dB Linewidth (nm)	10-dB Linewidth (nm)	SNR (dB)	SMSR (dB)
Free-running FPLD	0.025	0.032	43	<10
Free-running SOA	0.042	0.138	27	<3
OBPF filtered SOA	0.084	0.180	51	<3
SOA–FPLD link	0.013	0.027	40	>30 (39.7 maximum)

smaller than those of the same system measured by a commercial optical spectrum analyzer (because of its systematic limit in a wavelength resolution bandwidth). The linewidth of the proposed SOA–FPLD link is still beyond that of a distributed-feedback laser diode (DFBLD), which is comparable with the commercially available wavelength-tunable laser (for example, in the Hewlett-Packard Model HP8168F laser, $\Delta\lambda$ in coherent mode 50–500 MHz) and is already sufficient for testing of wavelength-division multiplexing or dense-wavelength-division multiplexing modules.

Obviously, the linewidth, the SMSR, and the SNR of the SOA were greatly improved after the SOA was injection locked with the FPLD, and the most significant contribution of injection locking the SOA with the FPLD is single-longitudinal-mode selection of the linked device. The linewidths of a free-running FPLD, a free-running SOA, a SOA connected to an intracavity optical bandpass filter, and a SOA–FPLD link at 3-dB decay are approximately 0.025, 0.042, 0.084, and 0.013 nm, respectively. Furthermore, the SNR of the free-running SOA is also enhanced, from 27 to 40 dB, in the SOA–FPLD link. Note that the 3-dB filtering bandwidth of the commercial optical bandpass filter ($\Delta\lambda = 0.36$ nm) is larger than that of the FPLD cavity. Such a comparison thus facilitates a promising and cost-effective approach to generation of linewidth-reduced SOA output by use of the mutual injection-locking technique. The highest SNR (as much as 51 dB) can be obtained by use of an intracavity optical bandpass filter inside the free-running SOA ring laser, which still exhibits a relatively broadened linewidth after filtering. In particular, the SMSR of either the FPLD or the SOA is improved to >30 dB when mutual injection locking is achieved. Figure 6 depicts the measured SMSR and the linewidth of the SOA–FPLD link relative to the driven current of the FPLD. As the biased current of the FPLD increased from 8 to 10.6 mA, the SMSR of the SOA–FPLD link gradually increased from 17 to 30.3 dB, at which point the linewidth shrank significantly. We further compare the SMSR performance of the proposed SOA–FPLD link with another system that consists of the injection-locked link of a gain-switched FPLD and an erbium-doped fiber amplified FPLD. The maximum SMSR is better than 33 dB over a wide wavelength-tuning range of 19 nm.[15] In our case, the maximum (but not stationary) SMSR obtained was 39.7 dB. Even

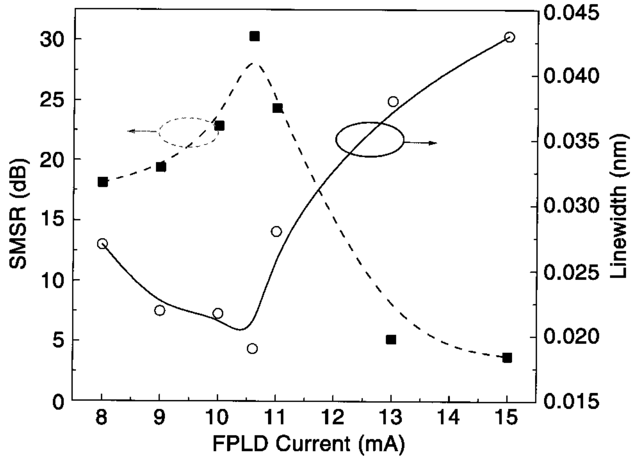

Fig. 6. SMSR and linewidth of a SOA–FPLD link at several driven currents of a FPLD.

in the worst case (without fine adjustment), the SMSR can be larger than 30.3 dB. As the biased current of the FPLD further increased to above threshold, the other side modes of the SOA adjacent to the longitudinal modes of the FPLD inevitably increased, leading to degradation of the linewidth and the SMSR of the SOA–FPLD link. In the worst case, both the 3-dB linewidth and the SMSR recovered to become comparable with those of a free-running SOA. Figure 7 shows the SNR and the peak power of the single-mode SOA–FPLD link as a function of FPLD-driven current. As the biased current of the FPLD increased to just below threshold, the SNR was enhanced to its highest value of 40.3 dB. Afterward, the SNR of the SOA–FPLD link gradually degraded to be the same as that of a free-running SOA. In comparison, the maximum SNR of two mutually injection-locked FPLDs[15] in a gain-switching scheme is estimated to be ~43 dB. The injection-locked SOA–FPLD link exhibits a slightly lower SNR (~40.3 dB) because the noise of the SOA is greater than that of the FPLD.

The degraded lasing spectra of the SOA–FPLD link

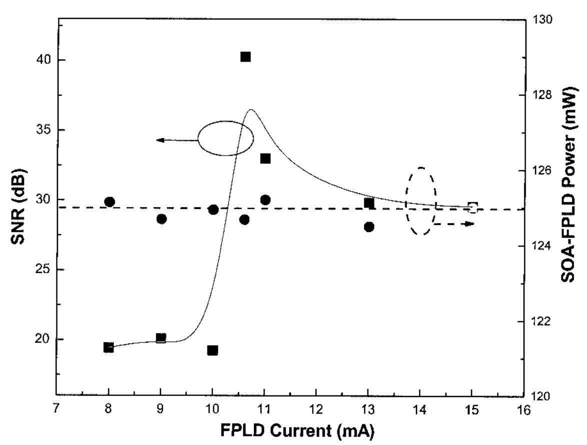

Fig. 7. SNR and output power at several driven currents of a FPLD.

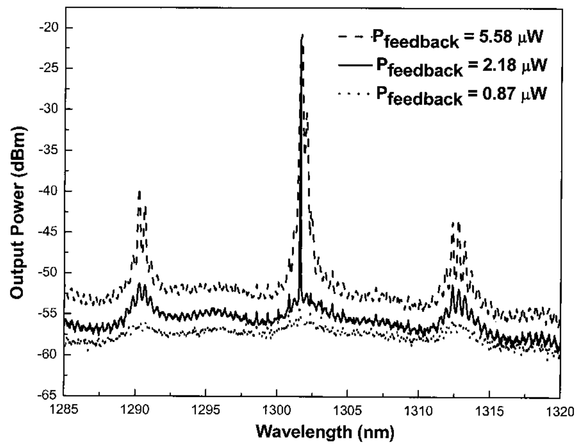

Fig. 8. Lasing spectra of a SOA–FPLD link at three feedback powers of a FPLD.

when the feedback power of the FPLD was increased are shown in Fig. 8. However, when the bias current of SOA was beyond threshold, the SMSR decreased. This effect is due to the increase in the feedback-injecting power for the FPLD at larger SOA output. The optimized feedback-injecting power for the FPLD to attain single-mode lasing in the SOA–FPLD link is 2.5 μW for an output power from the SOA–FPLD link of ~400 μW. At higher feedback powers, the growth of longitudinal modes from the SOA ring cavity not only broadens the central mode of such link but also helps lasing of the longitudinal modes in the FPLD cavity. The result is an eventual decrease in both the SMSR and the SNR of the SOA–FPLD link. Precise control of the temperature of the SOA is also important in our experiment. As the temperature was detuned from 30 °C to 15 °C, the FPLD under a constant driving current changed from spontaneous emitting to lasing mode, which led to a breakup of the injection-locking mechanism in the SOA–FPLD link. The lasing spectra of the SOA–FPLD link at different FPLD temperatures are shown in Fig. 9. The gain of the SOA is insufficient to overcome the cavity loss of the FPLD at higher temperatures because the threshold current of FPLD is increased. On the contrary, a decrease in FPLD temperature degrades single-mode performance as a result of reduction of the FPLD threshold current. Nonetheless, we also observed that the injection locking of the SOA–FPLD link can be recovered at any temperature and lasing at a fixed wavelength (with tiny deviation) by fine tuning of the FPLD-driven current. This corroborates the significant contribution of the FPLD to linewidth reduction and side-mode suppression of the SOA–FPLD link. The long-term variations of the peak power and the wavelength of the single-mode SOA–FPLD link are within 0.54% and 0.06%, respectively. The injection-locked SOA–FPLD link is relatively insensitive to temperature fluctuation within ±0.25 °C. Furthermore, the locking range of the injection-locked SOA–FPLD link has also been characterized

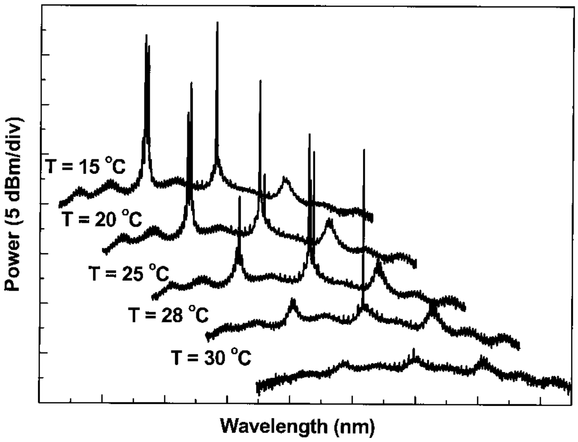

Fig. 9. Lasing spectra of a SOA–FPLD link at five temperatures of a FPLD.

by slight detuning of the temperature of the FPLD to achieve a wavelength shift between the free-running FPLD and the SOA. The tuning slope of the free-running FPLD wavelength as a function of temperature is approximately 0.12 nm/°C. It is difficult to initiate mutual injection locking when the detuning temperature is beyond ±0.05 °C, which corresponds to a locking range for the injection-locked SOA–FPLD link of approximately 6 pm (or ±750 MHz). The mutual injection-locking mechanism is less pronounced when the frequency difference between longitudinal modes of the SOA and the FPLD exceeds this value. The mode-hopping phenomenon with wavelength increments of 0.76 nm (equivalent to the free spectral range of a free-running FPLD) can be observed in the SOA–FPLD link only when the FPLD-driven current is well beyond threshold value.

Mutual injection locking of a DFBLD and an erbium-doped fiber laser (EDFL) has been previously reported.[11] In the beginning, these two lasers are individually lasing in free-running mode. Feedback injecting the DFBLD and the EDFL with precisely controlled power forces the lasers to synchronize their wavelengths with each other. Moreover, the lasing mode of the injection-locked DFBLD–EDFL link is dominated by the DFBLD; however, both the mode linewidth and the SMSR of the DFBLD and the EDFL are greatly improved by mutual injection locking. The mutual injection-locking behavior of the proposed SOA–FPLD link is slightly different from that of the DFBLD–EDFL link. The lasing modes of the SOA–FPLD link change abruptly at different driven currents of the FPLD. As the driven current is adjusted far below threshold, such a link lases in multiple SOA longitudinal modes. As the driven current is tuned close to threshold value within deviation of 10%, the SOA-FPLD link lases in a cavity-selected FPLD longitudinal mode. As the driving current exceeds threshold, the multimode FPLD dominates the lasing spectrum of the SOA–FPLD link. The narrowest linewidth of such a link can be observed when the FPLD is driven at just below threshold. This condition is achieved by precise control of the feedback-injecting power from the SOA to the FPLD, which helps in selecting one of the longitudinal modes in the FPLD cavity. Afterward, the FPLD feedback injects the SOA and forces it to oscillate synchronously. Such an operation finally gives rise to mutual injection locking of the SOA and the FPLD. It is worth noting that one can observe single-FPLD-longitudinal-mode lasing of the SOA–FPLD link with a slightly reduced linewidth only by setting the FPLD to be driven below threshold. Such an operation is also the greatest difference between the SOA–FPLD link and the EDFL–DFBLD link mentioned above. Fine tuning of the feedback-injecting power into the FPLD is the key to maintaining and stabilizing the single-FPLD-longitudinal-mode lasing performance of the SOA–FPLD link.

4. Conclusions

In conclusion, we have demonstrated a novel approach to obtaining single-mode output with high SMSR in an injection-locked SOA–FPLD link. To help in selecting the strongest mode from the gain spectrum of the FPLD for lasing in a SOA ring cavity, we bias the fiber-pigtailed FPLD at 11 mA (just below threshold) with an operating temperature of 24 °C. Such a scheme successfully links the amplification characteristic of a typical SOA ring cavity with the mode-selecting and tuning capability of the FPLD. A reduced linewidth of ~0.013 nm and a maximum SMSR of 39.7 dB were observed in an injection-locked SOA–FPLD link. By using self-heterodyne mode-beating spectral analysis, we determined the 3-dB linewidth of the SOA–FPLD link precisely as <50 MHz. With this technique, the narrow-linewidth SOA–FPLD link can provide an average power of as much as 400 μW with a fluctuation of less than 0.54%. Such an injection-locked SOA–FPLD link further exhibits the advantages of lower cost, simpler design, and more-compact size than conventional high SMSR lasers.

This study was supported in part by the National Science Council of the Republic of China under grant NSC91-2215-E-009-039.

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