A single-mode and highly side-mode-suppressed 1.55-μm Fabry–Perot laser diode (FPLD) is achieved by feedback injection with an erbium-doped fiber laser (EDFL). For selection of the strongest longitudinal mode from the gain spectrum of the FPLD for lasing in the EDFL, the FPLD is operated at just below the threshold condition and is feedback injected by 0.02% of the EDFL output power. The lasing mode and center wavelength of the proposed single-mode FPLD source are decided by cross-correlated gain profiles of the EDFL and the FPLD; however, the effect of FPLD injection modes is found to be more pronounced. The optimized lasing linewidth (system limitation) and side-mode suppression ratio of 0.01 nm and >49 dB are obtained, which are far better than those of a FPLD at free-running condition. The worst linewidths at 3- and 10-dB decay are observed to be at approximately 0.016 and 0.05 nm, respectively. Linear wavelength tuning of as much as 4.5 nm (from 1558.7 to 1563.2 nm) by adjustment of the temperature of the FPLD from 10 °C to 40 °C at just below threshold is reported. The wavelength-tuning slope is approximately 0.14 nm/°C under temperature accuracy of 0.1 °C. © 2003 Optical Society of America

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higher than 40 dB over a tuning range of 11.5 nm
were generated from the self-seeding FPLD. None-
theless, this technique still relies on the use of a
tunable linearly chirped fiber Bragg grating to
provide wavelength-selective feedback and output
filtering functions. Alternatively, the fast and wide-
range wavelength tuning of the FPLD can be
implemented via the provision of optical feedback
to a self-seeded laser diode that also acts as an ac-
tive Fabry–Perot filter. Wavelength selection is realized
by one’s electrically tuning the comblike spectral re-
sponse of such an ordinary FPLD biased below its
threshold, a stepwise wavelength tuning over a range
of 9–11 nm with a SMSR from 13 to 22 dB throughout
the range.5–7 In particular, the power penalty re-
sulting during the self-seeding-induced mode-
selecting process is another disadvantage.

2. Experiment

To resolve the predicament of the power dissipation
and the finite SMSR performance of the self-seeded
FPLD-based filtering technique, we demonstrate a
new approach for generating a high-power, single-
mode, and ultrahigh SMSR FPLD by using a free-
running EDFL and feedback-injecting techniques in
this paper. The EDFL is formed by the self-
feedback of a commercial fiber-pigtailed FPLD; they are connected to each other by use of
optical couplers with predetermined power-splitting
century, and longitudinal

to the EDFL facilitates in selection of one longitudinal
mode with improved SMSR lasing in the FPLD,
which then is feedback injected to EDFL to obtain a
linewidth-reduced output. Under the precise con-
trol on the feedback power of approximately 12.4 μW,
the optimized linewidth-reduction performance is ob-
served while the other side modes in either the FPLD
or the EDFL are greatly suppressed during the gain
competition process.

3. Results and Discussions

A. Spectral Analysis

One obtains the best narrow-linewidth operation of
the EDFL and FPLD’s link by driving the FPLD at
just below threshold, as shown in Fig. 2. As the
partial output of the EDFL feedback injects into the
FPLD, the FPLD-filtered EDFL’s lasing spectrum
with a SMSR of >48 dB is observed, and the mea-
sured spectral linewidths are 0.016 and 0.05 nm at 3-
and 10-dB decay, respectively. As observed in our
experiment, the measured SMSR is enhanced by
nearly 10 dB as the wavelength resolution of the
optical spectrum analyzer is improved from 0.1 to
0.01 nm. The higher wavelength resolution results
in an averaging over a smaller resolution band to
obtain the peak signal, which not only shrinks the
measured spectral line but also improves the SMSR

Fig. 1. Experimental setup of the narrow-linewidth FPLD-
filtered EDFL. PC, polarization controller; OC, optical coupler;
PD, photodetector; OSA, optical spectrum analyzer; WDM, wave-
length division multiplexing coupler.
level (as well as accuracy). Note that the typical longitudinal mode linewidth of the FPLD at a free-running scheme is still large as compared with that of the FPLD-filtered EDFL (see the inset of Fig. 2). One can clearly observe that the lasing peak of the FPLD-filtered EDFL matches well with the peak mode in the free-running FPLD spectrum. Because the filtering ability of the FPLD to the EDFL is less decisive when operated at below or well above the threshold condition, the EDFL is thus lasing at self-seeding or multi-FPLD modes. In contrast, the EDFL acts rather like a closed-loop amplifier (or slave laser) for the FPLD in the latter case. The FPLD becomes nearly transparent as it is biased close to the threshold current. This leads to the amplification of a broadband spontaneous-emission-limited spectrum of the FPLD in the EDFL ring cavity. After several round trips, one of the amplified longitudinal modes within the correlated gain profiles of the EDFL and the FPLD eventually overcomes the loss of the intracavity FPLD operated at the just-below-threshold condition, which then dominates the lasing wavelength of the FPLD as well as the EDFL. Although the use of a circulator instead of three couplers can achieve a comparable SMSR, it cannot make EDFA lase because the feedback of the EDFA is directly injected into the FPLD cavity but not to the EDFA itself. This eventually results in a broadened lasing spectrum, as shown in Fig. 3. The feedback injection of the EDFA to both the FPLD and the EDFA itself is mandatory to the linewidth-reduction effect of the proposed system. The coupler-based system thus facilitates the lasing of the EDFA and the reduction of its spectral linewidth feedback into the FPLD, which helps in reducing the cross-correlated gain profile of the FPLD and lasing the FPLD at a narrower linewidth. In comparison with the circulator-based system, the use of couplers further benefits from the flexibility of tuning the feedback-injection ratio to the FPLD and the EDFA. Moreover, the circulating function can also be simulated by the coupler scheme when the connection between OC2 and OC3 is opened (the feedback from the FPLD through OC3 to the EDFL is interrupted by the optical isolator). The reduction in the number of the lasing modes of the external cavity relies strictly on shortening the external cavity length; for example, a linear cavity EDFL might be one of the potential candidates to meet this demand. However, the shortened cavity inevitably increases the mode spacing and the mode linewidth in the meantime. An alternative way is to use a distributed feedback laser diode instead of a FPLD as the active filter, which, however, is less cost effective.

B. Power Stability and Wavelength Tunability

The power-current characteristics of the free-running FPLD operated at 35 °C, the free-running EDFA’s output power, and the EDFL with an intracavity feedback-injection-controlled FPLD that functions as an intracavity optical bandpass filter are shown in Fig. 4. It can be seen that the FPLD-filtered EDFL has already been lasing with output power of 60 mW even though the FPLD is unbiased. In comparison,
the output power of the FPLD-filtered EDFL is as much as 46.5 mW, which corresponds to an insertion loss of 1.1 dB. It is found that the power stability of the EDFL is superior, which exhibits very low fluctuation (of approximately 1%) even though the driven current of the FPLD changes. The residual variation is mainly attributed to the slightly red-shifted gain peak of the FPLD and the less-flattened EDFA gain profile. The varied spectra of the EDFL, controlled by the intracavity feedback-injected FPLD driven at different current conditions (below, near, and above the threshold current) and a constant operating temperature (35 °C), are illustrated in Fig. 5. It is found that the output spectrum is slightly broadened and the SMSR is greatly degraded owing to the amplification of the side modes when the FPLD is driven at higher currents above threshold. The mode numbers of the EDFL ring cavity also abruptly increases as the bias current of the FPLD increases. These results can clearly be interpreted to mean that the peak wavelength among these modes is still predominated by the cross-correlated gain profiles of the EDFL and the FPLD; however, the effect of the FPLD is more pronounced. One striking feature of our proposed scheme is for one to operate the EDFL at single FPLD mode with a high SMSR regime by driving the feedback-injected FPLD at near-threshold current. When the FPLD is operated at a nearly lasing regime, the broadband spectrum of the FPLD reveals that there is still a competition between cavity modes resulting from spontaneous emissions. At this stage, even a small intracavity feedback power can efficiently lead to a single mode that can be sustained in the cavity, which eventually suppresses the other lasing modes of the EDFL. Mode selection is therefore achieved by one’s fine tuning the power and polarization of the feedback light from the EDFL cavity. The drift in the peak wavelength of the principle lasing mode in the FPLD-filtered EDFL under an increasing FPLD current is negligible in that the EDFL and the FPLD are injection locked to each other. The SMSR of the FPLD-filtered EDFL spectrum can still be maintained at 40 dB or greater at the driven current of the FPLD, ranging from 9.5 to 12 mA, as shown in Fig. 6. The narrow-linewidth generation can be achieved only when the FPLD is driven at below-threshold current within a 20% deviation, whereas the other side mode arises when the current of the FPLD exceeds the threshold current. It is found that such a high SMSR decreases dramatically as the FPLD’s driven current becomes equivalent to or slightly higher than the threshold value.

The temporal stability of the peak wavelength and the output power of the FPLD-filtered EDFL is shown in Fig. 7. It is found that the variation in the peak wavelength is ±0.05 nm. The peak wavelength of the system is highly stable without mechanical or environmental disturbance. The long-term power stability of the EDFL output has been monitored. The maximum fluctuation of the 60% coupling output power (27.2 mW) is 0.03 mW or ΔP/P = 1.18 × 10⁻³ with a measuring speed of 100 Hz. If we further use a high-speed detector and a digital multimeter (New Focus, 1014, and Hewlett

Fig. 5. Measured spectra of the EDFL with the feedback-injection FPLD biased at different current conditions.

Fig. 6. Evolution of the SMSR of the FPLD-filtered EDFL at different FPLD currents.

Fig. 7. Stability in peak wavelength of the FPLD-filtered EDFL and the long-term FPLD-filtered EDFL output power.
Packard, HP34401A) with a data-acquisition speed of 1 ms, the measured power fluctuation is only $4.4 \times 10^{-3}$. The long-term drift in output power of the FPLD-filtered EDFL measured from OC4 (35%) is below 0.2% within 2.5 h. These results can clearly be interpreted to mean that the proposed FPLD-filtered EDFL system could probably exhibit a narrow linewidth, actually, a single-FPLD-mode lasing spectrum, which is already beyond the systematic resolution. On the other hand, although a maximum SMSR of greater than 50 dB in transient (−10 min) is obtained, a slightly decayed but relatively stable SMSR of 49 dB at a measuring duration of 1 h or longer is preferred. Experimental results also reveal that the increase in the driven current (or decrease in operating temperature) of the FPLD may not only lead to the growth of other FPLD modes and the broadening of the spectral linewidth but also cause a red shift in the lasing spectrum. At last, the temperature-dependent wavelength output of the FPLD and the output power stability of the FPLD-filtered EDFL at different temperatures are shown in Fig. 8. One may obtain the linear wavelength tuning by simply changing the FPLD temperature from 10 °C to 40 °C but maintaining its bias current at just below threshold (from 16 to 20 mA). Under this condition, the output wavelength of the FPLD-filtered EDFL linearly increases from 1558.7 to 1563.2 nm. This corresponds to a wavelength-tuning sensitivity of approximately 0.14 nm/°C. Although the SMSR of the EDFL output at different FPLD temperatures is unavailable to keep as a constant, the best SMSR of the regenerative EDFA with a FPLD filter operated at 40 °C can still be as high as 24 dB. Figure 9 illustrated the output measured of the FPLD-filtered EDFL at temperatures from 10 °C to 40 °C at 5 °C increments. The modes of the FPLD are found to red shift while the temperature of the FPLD increases. As the temperature decreases from 40 °C to 10 °C, the FPLD changes from spontaneous emitting to lasing mode under the constant driven current of the FPLD, which leads to a breakup of the injection locking between the FPLD and the EDFL. The degraded lasing spectra at different temperatures that are individually contributed by the EDFL and FPLD can be observed. Nonetheless, we have also observed that the FPLD’s filtering capability can be recovered, and lasing at a desired wavelength (with tiny deviation) occurs via fine tuning of the FPLD’s driven current to below threshold at certain temperatures. The SMSR of the FPLD-filtered EDFL at different FPLD temperatures have been measured and shown in Fig. 10. As the FPLD is controlled at a temperature far from room temperature, the output spectrum with decreasing SMSR is observed. This is mainly attributed to the instability of the temperature-controlled performance of the FPLD at lower- and higher-temperature regions. The FPLD has been shown to exhibit a distinguished contribution to the linewidth reduction and side-mode suppression of the EDFL, at a cost, however, of a nearly 20% additional cavity loss.
4. Conclusions

In conclusion, we demonstrate a novel approach for obtaining narrow-linewidth or single-FPLD-mode lasing in the EDFL with a high SMSR by adding a FPLD into the EDFL cavity (connected by commercial optical couplers) and feedback injecting the FPLD with part of the EDFL output via a polarization controller. For selection of the strongest mode from the gain spectrum of the FPLD for lasing in the EDFL ring cavity, the FPLD biased at just below the threshold condition with an operating temperature of 35 °C also functions as an active optical bandpass filter. The lasing wavelength is controlled by gain profiles of both the EDFL and the FPLD; however, the effect of FPLD injection modes is found to be more pronounced. Such a scheme successfully links the high-gain amplification characteristics of a typical EDFL ring cavity and the mode-selecting and the wavelength-tuning capabilities of the FPLD. With this technique, the narrowest 3- and 10-dB spectral widths and the highest SMSR are 0.016 nm, 0.05 nm, and 49 dB, respectively. Such a FPLD-filtered EDFL provides average output power as great as 46.5 mW. The fluctuation in the peak wavelength and the output power are less than 0.2 nm and within 0.2%, respectively. The value of the SMSR abruptly decreases as the driven current of the FPLD increases beyond threshold. Linear wavelength tuning of >4.5 nm (from 1558.7 to 1563.2 nm) by adjustment of the temperature of the FPLD from 10 °C to 40 °C at just below threshold is reported. The wavelength-tuning performance of the FPLD-injected linewidth-reduced EDFL system implemented by control of the temperature of the FPLD with an accuracy to 0.1 °C is also reported. Such a system essentially benefits from advantages such as simple design, compactness, and cost effectiveness as compared with the conventional single-mode and wavelength-tunable lasers.

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