Tunable Single-Mode Fiber Laser with a Low-Cost Active Fabry-Perot Filter of Ultra-Narrow-Linewidth and High Side-Mode-Suppressing Ratio

Gong-Ru Lin* and Jung-Rung Wu**
* Institute of Electro-Optical Engineering, National Chiao Tung University
** Graduate Institute of Opto-Electronic Technology, National Taipei University of Technology

ABSTRACT

We demonstrate a novel approach for generating a narrow-linewidth and highly side-mode suppressed Erbium-doped fiber laser (EDFL) by combining it with an intracavity feedback-injected 1.55μm Fabry-Perot laser diode (FPLD) via optical couplers. To help selecting the strongest longitudinal mode from the gain-spectrum of FPLD for lasing in the EDF ring cavity, the intracavity FPLD is operated at just below threshold condition associated with an intracavity feedback optical power ratio of <1%. The lasing mode and center wavelength of the proposed EDFL source are decided by both the cross-correlated gain profile of EDFA and 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. The worst linewidth at 3-dB and 10-dB decay are observed to maintain at about 0.016 nm and 0.05 nm, respectively. Linear wavelength tuning of up to 6 nm (from 1551.5 nm to 1557.7 nm) by adjusting temperature of FPLD from 10 ℃ to 50 ℃ at just below threshold is reported. The wavelength-tuning slope is about 0.155 nm/℃ under temperature accuracy of 0.1 ℃.

Keywords: Erbium-doped fiber laser, narrow linewidth, single-mode, Fabry-Perot laser diode, feedback injection, side mode suppression ratio, wavelength-tunable

1. INTRODUCTION

The advent of advanced wavelength-division multiplexing (WDM) or dense WDM (DWDM) technology has raised up the practical need for wavelength-tunable lasers, since which offers the convenience in shifting optical channels and releases the requirements of a massive inventory of lasers at versatile wavelengths [1-2]. In addition, highly stable single-mode lasers with low noise performance at fixed wavelengths are also the promising optical transmitters or testing sources in traditional fiber-optic communication systems. For example, such laser sources can be achieved by fabricating a wavelength-tunable InGaAsP/InP multiple-λ/4-shifted distributed feedback (MQS-DFB) laser with three λ/4-shifts and five electrodes was fabricated. The current DFB laser diode technology has led to several records such as the stable single mode operation with an excellent SMSR of more than 40 dB, the continuous wavelength tuning range of 1.7 nm under constant output power mode, and the minimum spectral linewidth of 3MHz at an output power of 20mW [3]. Other completed lasers have further shown sidemode suppression ratios as high as 47dB and wavelength shifting sensitivity of 0.035nm/mA (or 4.5GHz/mA) [4]. Alternatively, narrow spectral linewidth lasing has also been demonstrated in thermally wavelength tunable super-structure-grating distributed Bragg reflector (SSG-DBR) laser diode incorporating with thin-film Pt heaters. Such device has a spectral linewidth of only 400 kHz with in a wide quasi-continuous tuning range of 40 nm under CW operation at room temperature [6].

On the other hand, some distinguished and cost-effective means for generation a wavelength-tunable single-mode laser pulses from a Fabry-Perot laser diode (FPLD) by self-seeding with low-level (about 0.2~6%) feedback power has

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*Corresponding Author. E-mail: grlin@cc.nctu.edu.tw; Phone: 886 3 5712121 ext. 56376; Fax: 886 3 5716631; Address: Institute of Electro-Optical Engineering, National Chiao Tung University, No. 1001, Ta Hsueh Rd., Chinchu, Taiwan 30050, R.O.C.

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previously reported. Such a cost-effective technique is reported to generate wavelength-tunable chirp-compensated single-mode pulses with a SMSR higher than 40 dB over a tuning range of 11.5 nm [7] based on self-seeding a Fabry–Perot laser diode (FPLD). This technique relies on the use of a tunable linearly-chirped fiber Bragg grating to provide wavelength-selective feedback, output filtering, and chirp compensation. The recent achievement for fast and wide-range wavelength tuning of (FPLD) relies on the provision of optical feedback to a self-seeded laser diode which also acts an active Fabry–Perot filter. Wavelength selection is realized by electrically tuning the comb-like spectral response of such an ordinary FPLD biased below its threshold, a stepwise wavelength tuning over a range of 9~11 nm with a sidemode suppression ratio of from 13~22 dB throughout the range [8-10]. Different approach has also been achieved by self-seeding a FPLD with a tunable linearly-Chirped fiber Bragg grating [11], however, these schemes are more complicated and not cost-effective.

Table I: The comparison in single-mode output characteristics of EDFL with different configurations

	SMSR	Output power	Wavelength tuning range	Spectral linewidth	Required components
SOA	>35dB	0.7 mW I=120mA	20nm	10 kHz	phase modulator
DFB laser	> 40 dB	20 mW	1.7 nm	3 MHz	Distributed Bragg grating
DBR laser	43 dB	1.5 mW	10 ^{0}C (17-27-^{0}C) - 0.013 nm/^{0}C	40 kHz	Distributed Bragg Reflector
Gain-switched LD	13 dB	50 mW	20nm	—	External grating
Self-injection seeded FPLD with grating	> 40 dB	21~34 μW	11.5 nm	—	FPLD and Fiber Bragg grating
Linear cavity single-mode EDFL	—	< 5 mW	—	< 47 kHz	Two mode selective Bragg grating reflectors
Ring cavity single-mode EDFL	> 35 dB	< 0.27 mW	—	—	Two high finesse FFP filters
Narrow-linewidth EDFL	> 49 dB	> 22 mW (65% coupler)	7 nm	< 3.48 GHz (OSA limited)	FPLD

Recently, with the fast evolution of Ebium-doped fiber lasers (EDFLs), narrow-linewidth and wavelength-tunable operation of such a high power optical source with wide gain spectrum has become an intriguing topic of researches. Previously, versatile optical filters like diffraction fiber Bragg grating, Fabry-Perot etalon, and other diffraction gratings have successfully emerged to meet these demands. More recently, novel external-feedback or self-seeding techniques have also been demonstrated. Various cavity configurations have been demonstrated to implement tunable single-mode Er-doped fiber lasers [3-6]. Single wavelength output with high SMSR (>40 dB) has been developed by using a compound-ring EDFL with two piezoceramic stretchers [12]. Among these demonstrations, the most popular implementation to build up a mode-suppressed EDFL is by adding a commercially available, intracavity optical band-pass filter (OBPF) due to its important merit of wavelength-tuning simplicity. More recently, a diode-pumped, broadly tunable, single frequency EDFL is reported. Wavelength-tuning and single-longitudinal-mode selection can be accomplished by use of two fiber-pigtailed Fabry-Perot etalons. The wavelength of EDFL can be tuned from 1.530 μm to 1.575 μm with its linewidth of less than 5.5 kHz [13]. The compound-ring resonator ensures single-longitudinal-mode oscillation with output power of up to 20 mW by adding the mode-restricting intracavity tunable bandpass filter [13]. On the other hand, a 750Hz linewidth single-mode EDFL with wide tunability using a widely tunable fiber Bragg grating (FBG) has emerged 40-nm continuous tuning range of ranging from 1522 nm to 1562 nm [14]. Similar performance has also been implemented by using a unidirectional loop mirror configuration [15]. To date, an integrated standing-wave and single frequency EDFL with linewidth of less than 47 kHz is reported via the use of two highly reflective intracore Bragg reflectors which provide both cavity feedback and adequate longitudinal mode discrimination [16].

Up to now, numerous researchers are interested in building up Er-doped fiber lasers for such as characterizations of fiber-optics devices and submodules in tunable single-mode sources, owing to their striking features such as broadband spontaneous emission property of Erbium-doped narrow linewidth, low intensity noise, high output power, and direct fiber compatibility etc. In this work, we demonstrate a new approach for generating a single-mode and ultrahigh SMSR EDFL source by only adding a Fabry-Perot laser diode (FPLD) into the fiber loop. The single-mode operation is achieved via the optical injection and feedback control of the FPLD without using any high unit price components such as optical circulator, fiber Bragg grating, and optical bandpass filter. Such system further benefits from advantages including simple design, compact, and low cost as compared to the conventional apparatus. The performances of the FPLD-controlled single-mode EDFL system operated at optimal driving condition are reported. The relationship between the FP-LD driving current and side mode suppressing ratio (SMSR) of the system is discussed. Furthermore, we have summarized the performances of the proposed system in comparison with several kinds of commercially available or reported single-mode sources such as DFB LD, Self-injection seeded FPLD with fiber-Bragg-grating, and the other linear and ring cavity EDFLs, etc. The key parameters of the single-mode sources are listed in table 1.

2. Experimental Setup

In Fig. 1, the close-loop of the EDFL system consists of a dual-pumped EDF amplifier, a fiber-pigtailed 1.55 μm FPLD with central wavelength of 1560 nm at specified temperature of 35 °C, a polarization controller, and four optical couplers (OCs) with various power-splitting ratios. Such a design excludes the use of other expansive components such as optical circulators, fiber Bragg gratings, DBR or DFB LDs, and narrow band-pass filters. In experiments, the OC1 (90/10) couples the output of FPLD into EDFL with OC2 (50/50) and feedback the EDFL light into the FPLD with OC3 (90/10). The optical output of EDFL is coupled by OC4 (65/35) which is also preserving the gain saturation in the fiber ring. The polarization controller between the FPLD and OC1 is carefully adjusted to control the polarization of the light feedback into the FPLD since it is important to align the states of polarization (SOP) with one of the eigenstates of polarization of the FPLD and EDF ring. This arrangement guarantees single-mode oscillation, optimize the SMSR, and suppress the laser noise concurrently. The threshold of the LD at 35 °C is about 13mA and the mode spacing is about 0.79 nm. The 35 % EDFL output is monitored by optical spectrum analyzer with 0.01 nm resolution (Advantest, Q8384) and optical power meter (ILX Lightwave, OMM-6810B).

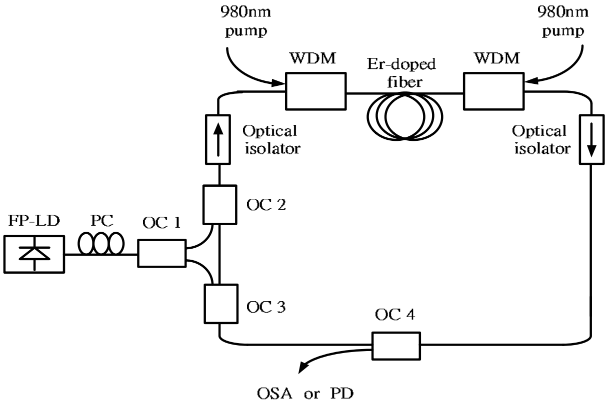

Fig. 1. The experimental setup of narrow-linewidth EDFL. PC: polarization controller; four optical couplers; OSA: optical spectrum analyzer.

3. Results and Discussions

The best single-mode operation is obtained under FPLD biasing at just below threshold, as shown in Fig. 4. As the partial output of EDFL feedback-injects into the FPLD, the EDFL lasing spectrum with peak wavelength at 1559.886 nm is observed, and the measured spectral linewidths are of 0.016 nm and 0.05 nm at 3-dB decay and 10-dB decay with SMSR is of > 48 dB, respectively. Such performance is determined under the resolution limit of the optical spectrum analyzer, and is almost as same as the measured value of a commercial DFB LD (Nortel LCM 155W-20A) wavelength of EDFL. Note that the typical linewidth of the FPLD when used as an active filter is still 0.25 nm (assuming the cavity length of FPLD is 250 μm).

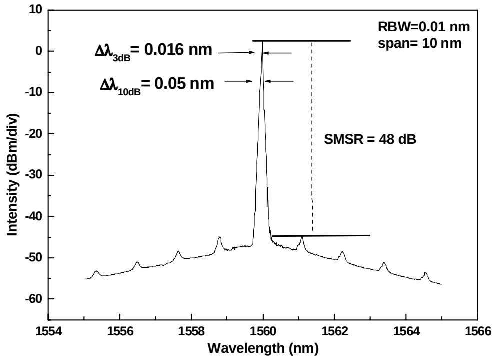

Fig. 2. The closed loop EDFL with the feedback-injection FPLD (dash line) biased at 13 mA and operated at 35 °C.

These results clearly illustrate that the proposed EDFL system could probably exhibit a narrow-linewidth or even a single-FPLD-mode spectrum which has already beyond the systematic resolution. A state-of-the-art determination on the actual linewidth of this system is unavailable at current stage due to the lack of a narrow-bandwidth (EDFL linewidth is less than 1MHz) and ultrahigh finesse (>500) Fabry-Perot Etalon filter. On the other hand, although a maximum SMSR of up to 50 dB in transient (~10 minutes) is obtained, a slightly decayed but relatively stable SMSR of 48 dB at measuring duration of 1 hour or larger is preferred. Experimental results also reveal that either the increasing in dc bias (or decreasing in operating temperature) may not only lead to the growth of other FPLD modes and the broadening of spectral width, but also causes a red shift in the lasing spectrum.

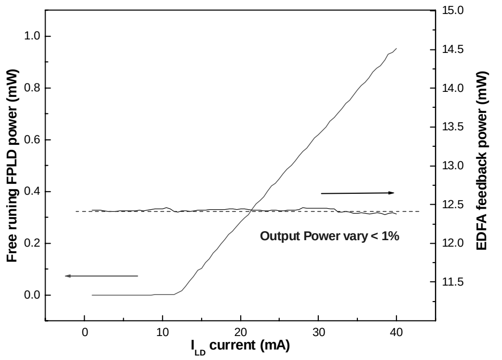

Fig. 3(a) The P-I curve of free-running FPLD operated at 35 °C and the closed loop EDFL.

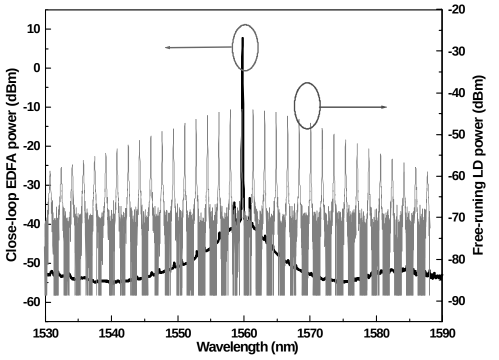

Fig. 3(b) The output spectra of the free-running FPLD biased at 13 mA and operated at 35 °C and the free-running EDFL closed loop.

The power-current characteristics of the free-running FPLD operated at 35 °C (solid line) and the close-loop EDFL with intracavity feedback-injection controlled FPLD (dash line) that functions as an intra-cavity optical band-pass filter is shown in Fig. 3(a). It is seen that the EDFL has already been lasing even though FPLD is unbiased, however, the output spectrum of the free-running EDFL is relatively broadened no matter the FPLD is turning off, biasing at well-below threshold condition, or lasing at well-above threshold condition. The former two cases clearly interpret that the filtering ability of FPLD to EDFL is less decisive when operated at such conditions; the EDFL is thus lasing at self-seeding mode in these cases. In contrary, the EDFL acts rather like a close-loop amplifier (or slave laser) for the FPLD in the latter case. As the FPLD biased at nearly threshold current, it becomes close to transparent region, which leads to the amplification of a broad-band spontaneous-emission-limited spectrum in the EDFL ring cavity.

After several round-trips, one of the amplified longitudinal modes within the correlated gain profile of EDFL and FPLD eventually overcome the loss of the intra-cavity FPLD operated at just below-threshold condition, which then predominates the lasing wavelength of the FPLD as well as the EDFL. The threshold current of FPLD is about 12.1 mA and the output power of EDFL is up to 12.4 mW. It is found that the power stability of EDFL is superior, which exhibits very low fluctuation (of about 1%) as the driven current of FPLD increased. The tiny variation is attributed to the red-shifted gain peak of the FPLD and the less flattened EDFL gain profile. As a result, the lasing spectra of the free-running FPLD biased at 13 mA and the close-loop EDFL (near threshold current) and the operating temperature is about 35 °C and shown in Fig. 3(b). It is clearly observed that the FPLD has a multimode output, with peak wavelength and the mode spacing at 1560 nm and 0.79 nm, respectively. The lasing peak of the close-loop EDFL matches well with the peak mode of the multimode from the FPLD output.

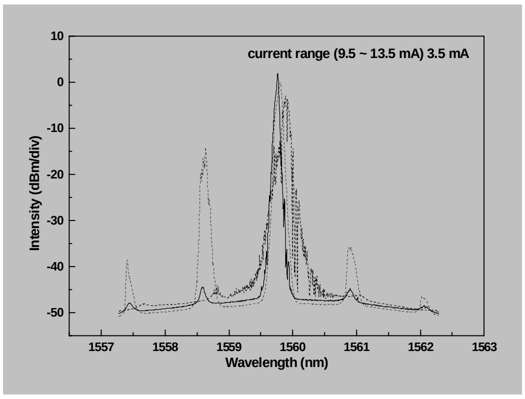

Fig. 4(a) The evolution of EDFL spectra at different FPLD currents.

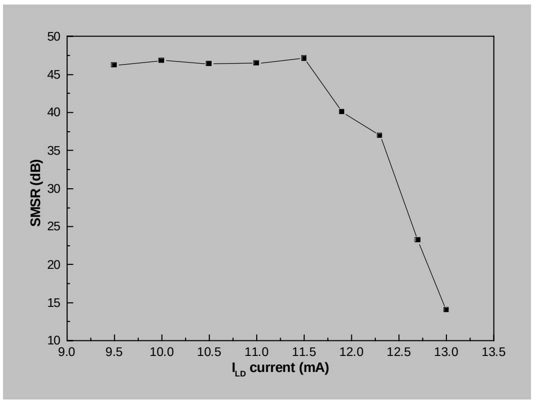

Fig. 4(b) The evolution of SMSR of EDFL at different FPLD currents.

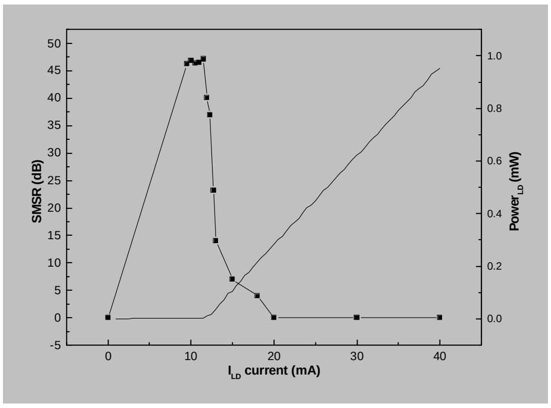

Fig. 4(c) The FPLD current-dependent SMSR and output power.

The EDFL spectra observed at different FPLD driven currents are shown in Fig. 4(a). The single mode generation can only be achieved by driving the FPLD at below threshold, whereas the other side-mode arises when the current of the FPLD exceeds the threshold current. The shift in peak wavelength of the principle lasing mode under increasing FPLD current is negligible. The SMSR of the EDFL spectrum can still be maintained at 35 dB or larger when detuning the FPLD driven current from 9.5 mA to 13 mA, as shown in Fig. 4(b). It is found that such a high SMSR decreases dramatically as the FPLD driven current becomes equivalent to or slightly higher than threshold value. The power-current relationship of the FPLD and the SMSR of EDFL are shown in Fig. 4(c). As the driven current of FPLD increases up to 20 mA, the SMSR is below 5 dB since all of the side-modes of FPLD has already oscillated in the EDFL cavity simultaneously with almost equivalent power as compared to that of the principle mode.

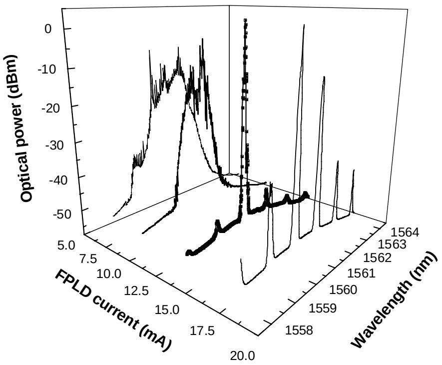

Fig. 5 The measured spectra of EDFL with the feedback-injection FPLD biased at different current conditions.

The evolution in output spectrum of the EDFL controlled with the intra-cavity feedback-injected FPLD driven at different current conditions (below, near and above threshold current) and constant operating temperature of 35 ^{o}C is illustrated in Fig. 5. On the other hand, it is found that the output spectrum is slightly broadened and the SMSR is greatly reduced due to the amplification of the side-modes when FPLD is driven at higher currents. That is, the mode numbers of the EDFL abruptly increases as the bias current of the FPLD increases. This clearly interprets that the peak wavelength among these modes is still predominated by the cross-correlated gain profile of the EDFA and FPLD [17], however, the effect of FPLD is more pronounced. One striking feature of our proposed scheme is to operate the EDFL at single-FPLD-mode with high SMSR regime 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 between cavity modes results from spontaneous emissions. At this stage, even a small intra-cavity feedback power can efficiently lead to single-mode sustain in cavity, which eventually suppresses the other lasing modes of the EDFL [10]. The mode-selection is therefore achieved by fine-tuning the power and polarization of the feedback light from the EDFL cavity.

The temporal stability of the peak wavelength of EDFL is shown in Fig. 6(a). It is found that the variation in peak wavelength is ± 0.1 nm. The peak wavelength of the system is high stable without the mechanical or environmental disturbance. The fluctuation in output power of the EDFL measured from OC4 (35%) shown in Fig. 6(b) is below 30 nW within 2.5 hrs. At last, the temperature-dependent wavelength output of the FPLD is shown in Fig. 6 (c). The linear wavelength tuning can be obtained by simply changing the FPLD temperature from 10℃ to 50℃ but maintain its bias current at just below threshold (I_{th} from 16 to 20 mA). Under this condition, the output wavelength of the EDFL linearly increases from 1551.5 nm to 1557.7 nm. This corresponds to a wavelength-tuning sensitivity of about 0.16 nm/℃. Although the SMSR of the EDFL at different FPLD temperatures is unavailable to keep as a constant, the best SMSR of the EDFL with FPLD operated at 45 ℃ can still be as high as 24 dB. Figure 6(d) confirms the output stability of the EDFL at different temperatures.

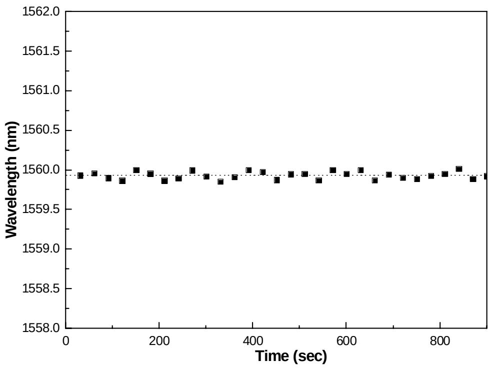

Fig. 6(a) The stability in peak wavelength of the EDFL.

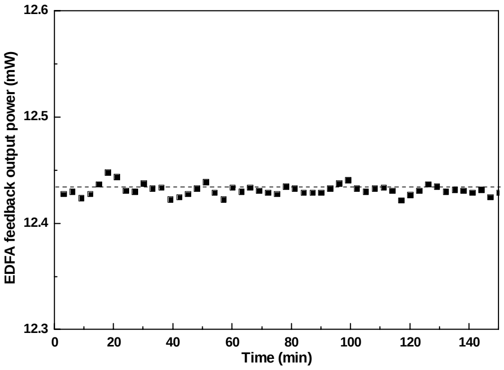

Fig. 6(b) The long-term EDFL output power stability.

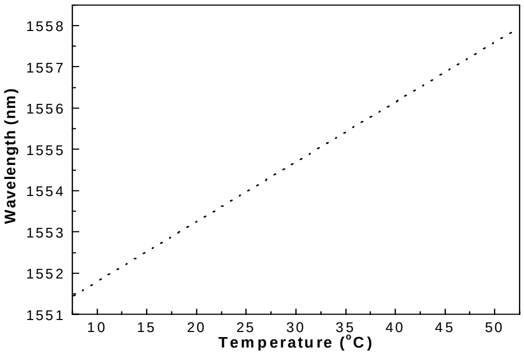

Fig. 6(c) The temperature-dependent wavelength output of the FPLD controlled EDFL from 10℃ to 50℃

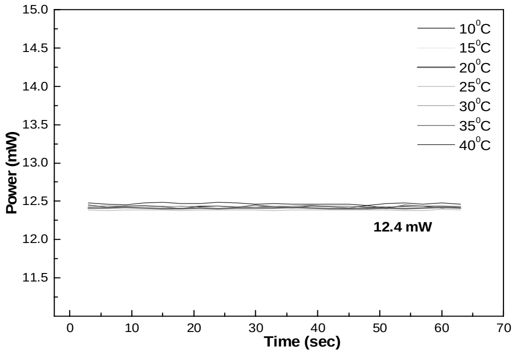

Fig. 6(d) The EDFL output power under FPLD at different temperature.

4. Conclusion

In conclusion, we demonstrate a novel approach for obtaining narrow-linewidth or single-FPLD-mode EDFL with high SMSR by adding a FPLD into the EDFL ring cavity (connecting by commercial optical couplers) and feedback-injection the FPLD with part of the EDFL output via polarization controller. To help selecting the strongest mode from the gain-spectrum of FPLD for lasing in the EDFL ring cavity, the FPLD biased at just below threshold condition with operating temperature of 35°C also functions as an active optical band-pass filter. The lasing wavelength of EDFL is controlled by both the gain profiles of EDFA and FPLD, however, the effect of FPLD injection modes is found to be more pronounced. Such a scheme successfully links the high-gain amplification characteristic of a typical EDFA ring cavity, the mode-selecting and the wavelength-tuning capability of FPLD. The relationship between the biased current of FPLD and SMSR of EDFL is discussed. With this technique, the narrowest 3 dB and 10 dB spectral widths and the highest SMSR are 0.016 nm, 0.05 nm and >48 dB, respectively. Such an EDFL provides average output power up to 12.4 mW. The high SMSR can be maintained within current detuning of less than 3.5 mA. The fluctuation in the peak wavelength and the output power are less than 0.2 nm and 30 nW, respectively. The value of the SMSR abruptly decreases as the driven current of the FPLD increases beyond threshold. Linear wavelength tuning of >6 nm (from 1551.6 nm to 1557.7 nm) by adjusting temperature of FPLD from 10 ℃ to 50 ℃ at just below threshold is reported. The wavelength-tuning performance of the FPLD-injected single-mode EDFL system implemented by controlling the temperature of FPLD with accuracy to 0.1℃ is also reported. Such system essentially benefits from advantages such as simple design, compact, and cost-effective as compared to the conventional single-mode and wavelength-tunable lasers.

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