L-band Erbium-doped fiber laser with coupling-ratio controlled wavelength tunability

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Abstract: By controlling the output coupling ratio, we demonstrate a novel wavelength-tunable L-band Erbium-doped fiber laser (EDFL) with a maximum tuning range up to 58 nm (from 1567 to 1625 nm) by controlling its output coupling ratio between 1% and 99%. The L-band EDFL is configured by using a bi-directionally dual-wavelength pumped EDFA in close-loop with an output coupler of tunable coupling ratio and an air-gap inserted FC/PC connector pair. Such an EDFL exhibits a quantum efficiency of 42% and an ultra-high power conversion efficiency of 37% under optimized pumping scheme, providing the small-signal gain and output power of ~34 dB and 91 mW, respectively. Low variation of <1.2 dB on channel power, power fluctuation of 0.04% and a narrow linewidth of 0.03 nm are obtained.

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1. Introduction

Owing to the insufficient channel capacity of the dense-wavelength-division-multiplexed (DWDM) systems at C-band, the long-wavelength band (L-band) Erbium-doped fiber amplifier (EDFA) covering a wavelength range from 1570 nm to 1610 nm[1] have been comprehensively investigated to enlarge the transmission capacity. Versatile economic and efficient schemes of the wavelength-tunable Erbium-doped fiber lasers (EDFLs) operated at L-band have also emerged to meet the demand on testing L-band fiber-optic devices. Typically, the gain media such as the dense erbium-doped fiber, the erbium-ytterbium co-doped double clad fiber[2], and the brillouin-erbium fiber[3], etc., were employed to configure the L-band EDFLs in dual resonant cavity[4], linear overlapping cavity[5], and single ring cavity[6]. Different approaches for wavelength-tuning the EDFL with the intra-cavity Fabry–Perot filters[7] and the fiber Bragg gratings (FBGs)[8] were proposed. In particular, the wavelength-tunability of L-band EDFL via a cavity-loss control was demonstrated by opto-machinically bending the single-mode fiber in the EDFL cavity[9]. In this work, we present a coupling-ratio controlled scheme to demonstrate a full L-band EDFL with a wavelength-tuning range over 45 nm and a low variation on the output powers of different channels. By using a highly doped EDF with an optimized length, the ultra-high quantum efficiency and power-conversion rate of the EDFL can be approached under optimized bi-directional pumping scheme, which shows an improvement on conversion efficiency of more than 10% than those reported using conventional L-band EDFA configurations[10].

2. Experimental setup

The experimental setup of the coupling-ratio controlled wavelength-tunable EDFL is shown in Fig. 1. It consists of an L-band EDFA with a bi-directionally 980nm/1480nm pumping scheme. The specific EDF (Fibercore L-band fiber, DF1500L) exhibits a large absorption of 17.5 dB/m at 1531nm. Under an optimized operation, both a forward pumping of 17.5 mW at 980 nm and a backward pumping of 200 mW at 1480 nm are employed.
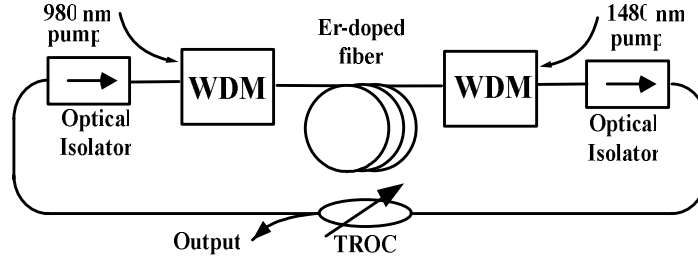

Fig. 1. A coupling-ratio controlled wavelength tunable L-band EDFL with a tunable-ratio optical coupler (TROC).

This EDFA further takes the advantage on using a reduced length of the specially designed L-band fiber with high Erbium (Er^{3+}) concentration, which offers an ultra-wide amplified spontaneous emission spectrum ranged between 1538 nm and 1628 nm (see Fig. 2) with a comparable gain and a suppressed noise power. Versatile pumping schemes have been investigated to construct a low-noise and high-gain L-band EDFA as the gain medium. The forward 980nm and backward 1480nm cascaded pumping geometry is selected for pumping the 45m-long EDF via the 980nm/1550nm and 1480nm/1550nm WDM couplers, respectively, in which the forward pumping at 980nm is effective for improving the noise characteristics, and the backward pumping at 1480nm benefits from a better quantum conversion efficiency and gain coefficient[11, 12]. With such a simplified EDFA, an extremely high power conversion efficiency (PCE) of 37% associated with a small-signal gain of 34.8 dB and a wavelength dependent gain deviation of 6 dB is achieved.

Table.1 PCE and Gain of the EDFA constructed with different Forward/Backward pumping schemes.

Pumping Wavelength	Power (mW)	Length (m)	PCR (%)	Gain (dB)
980/1480	215	15	24.7	30.9
1480/1480	215	15	21.2	35.7
980/1480	215	30	36.6	33.5
1480/1480	239	30	33.1	37.2
980/1480	270	45	30.6	31.1
1480/1480	225	45	37	34.8
980/1480	230	60	20	35.2
1480/1480	400	60	23.6	38.5

To configure the EDFL, two optical isolators are used to ensure the unidirectional propagation of the light, preventing the spatial hole burning effect in the EDFA from bi-directional operation and allowing a stable single-frequency operation simultaneously. In particular, a 1×2 tunable-ratio optical coupler (TROC) is inserted into the EDFL ring-cavity, in which the coupling ratio can be detuned from 0.5% to 99.5%. The maximum output power is obtained at an output ratio of 90%, whereas the longest output wavelength has to be achieved at a coupling ratio of 10 %.

3. Operating Principle

To discuss the wavelength tuning mechanism in more detail, we have referred to a modeling work published by Franco et al.[13], in which the wavelength tuning mechanism is deducted by considering the rate equations of a three-level system employed for the EDFL with an EDF length of L.

$$\frac{dP_p(z)}{dz} = -\sigma_p A_p \rho n_1 P_p(z),$$

$$\frac{dP_s(z)}{dz} = A_s \rho [\sigma_E(\lambda)n_2 - \sigma_A(\lambda)n_1]P_s(z),$$

$$n_2 = \{n_1 \frac{P_p(z)}{P_{p\,sat}} - [n_2 - \frac{\sigma_A(\lambda)}{\sigma_E(\lambda)}n_1]\frac{P_s(z)}{P_{s\,sat}}\} = 1 - n_1,$$

Where $P_{p\,sat}=[h\nu_p A]/[\sigma_p \tau A_p]$, $P_{s\,sat}=[h\nu_s A]/[\sigma_s \tau A_s]$, $P_p(z)$ is the pumping power, $P_s(z)$ is the forward signal power, σ_p is the pumping absorption cross-section, $\sigma_E(\lambda)$ and $\sigma_A(\lambda)$ are the emission and the absorption cross sections, ρ is the doping concentration, A_p and A_s are the integrals of the pump and the signal, n_1 and n_2 are the lower and the upper laser level population fractions, τ is the upper laser level lifetime, and A is the core area of the EDF. The EDFL cavity loss of $\Gamma_{TOT}\equiv P_1/P_3=\gamma\Gamma$ is mainly attributed to the output coupler loss (γ) and the intrinsic cavity loss (Γ). By extracting the EDFL power from the output coupler of a fraction T, the output power of the EDFL can be described as $P_{out}=TP_1$ with $0<T<1$, and the output coupling and intrinsic cavity losses is defined as $\gamma\equiv P_1/P_2=1/(1-T)$ with $\gamma>1$ and $\Gamma\equiv P_2/P_3$ with $\Gamma>1$, respectively. The gain of EDFL satisfies the conditions of $G(\lambda_0)=\Gamma_{TOT}(\lambda_0)$ and $G(\lambda\neq\lambda_0)<\Gamma_{TOT}(\lambda)$, where λ_0 is the emission wavelength. In the case, the gain of the EDFL is given by

$$G(\lambda,L) = \exp\{A_s\rho\int_0^L [\sigma_E(\lambda)n_2 - \sigma_A(\lambda)n_1]dz\} = \exp\{g(\lambda)L + \frac{g(\lambda)+\alpha(\lambda)}{\alpha_p}\ln[\frac{P_p(L)}{P_p(0)}]\},$$

where $g(\lambda)=\sigma_E A_s \rho$, $\alpha(\lambda)=\sigma_A(\lambda)A_s\rho$, and $\alpha_p=\sigma_p A_p \rho$ denote the gain, the attenuation, and the pumping absorption coefficients, respectively. Therefore, the EDFL operated at a certain wavelength of λ must satisfy the following relation:

$$\max_\lambda\{g(\lambda)L + \frac{g(\lambda)+\alpha(\lambda)}{\alpha_p}\ln[\frac{P_p(L)}{P_p(0)}] - \ln[\Gamma_{TOT}(\lambda)]\} = 0.$$

A correlation between the cavity loss and the lasing wavelength can equivalently be expressed as a function of λ by

$$\ln[\frac{P_p(L)}{P_p(0)}] = -\alpha_p \frac{g(\lambda)L - \ln[\Gamma_{TOT}(\lambda)]}{g(\lambda)+\alpha(\lambda)} \equiv -\alpha_p \Psi(\lambda)$$

The above equation obtained from previous work[13] thus determines the emission wavelength of the EDFL under a specific loss parameter. The net gain profile of the EDFL results from the linear superposition of the emission and the absorption curves, in which the corresponding coefficients are added and determined by different population inversion conditions occurred in the laser cavity. Since the emission and the absorption curves of the EDFL differ from each other in both the shape and the spectral position, the gain-maximum wavelength could also be detuned as the cavity loss or coupling ratio of the EDFL changes. That is, a corresponding variation of the gain-maximum position as well as the lasing wavelength of the EDFL can be determined as the cold-cavity loss of EDFL changes.

4. Results and discussion

The amplified spontaneous emission of the EDFA has revealed a wide spectral response covering the C- and L-bands, as shown in Fig. 2. In principle, the wavelength tunablility of an EDFL can be greatly affected by several cavity parameters such as the intra-cavity loss, the

output coupling ratio (or reflectivity), and the active fiber length[14-19]. A deeply saturated EDFA under high-power feedback injection has shown the capability to offer wide-band and flat gain[20], and the L-band EDFL can be readily available by minimizing the intra-cavity loss to keep largest gain in the EDFL cavity. The total intra-cavity loss has previously been understood as the most important factor that affects both the output power and the wavelength tuning range[21]. The tuning bandwidth increases significantly as the intra-cavity loss is reduced, whereas the output power of the EDFL shows an opposite trend. That is, the wavelength tuning range can be broadened by reducing the output coupling ratio. Previously, a numerical modeling for the C+L-band EDFL at different intra-cavity losses also supports this statement[11], the numerical results on the wavelength dependent output power for an EDFL at different intra-cavity losses has confirmed that the reducing cavity loss can effectively extend the wavelength tuning rage of the EDFL. In our case, the output-coupling-ratio or cavity-loss dependent wavelength tuning rage of the EDFL has also been determined with a bandpass filter, the EDFL is found to exhibit an ultra-wide wavelength tuning range of nearly 60 nm under a 10% cavity-loss condition (see Fig. 3). Large bandwidth covering C- and L-bands can be obtained under a very low intra-cavity loss, while for high intra-cavity loss only a narrow bandwidth in C-band is obtained. Both the laser output power and the tunable range are very sensitive to the intra-cavity loss. The wavelength tuning range significantly increases, whereas the output power of the EDFL enlarges as the intra-cavity loss is reduced.
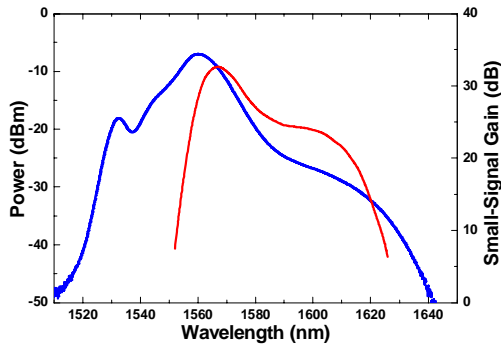

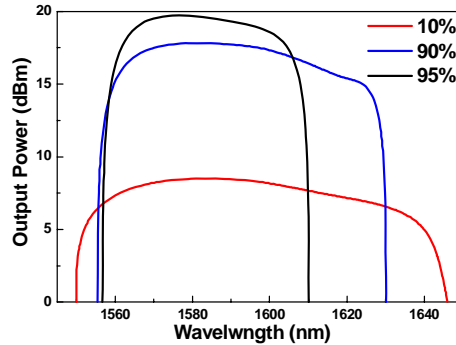Fig. 2. ASE (blue) spectrum of the EDFA and L-band gain (red) profile of the EDFL at coupling ratio of 90%.

Fig. 3. The wavelength tuning range of the EDFL obtained under different output coupling rations.

Figure 4 illustrates the lasing spectra of the EDFL covering a tuning range of 45 nm at output coupling ratios ranging between 5% and 90%. The maximum tuning range can extend to 58 nm by minimize output coupling ratio to <1%, which corroborates well with theoretical prediction in previous works. As the cavity-loss increases, the maximum output power and the wavelength tuning range are concurrently reduced[22]. By using the TROC based coupling ratio detuning technique, our experimental results not only correlate well with the theoretical observation[21], but also demonstrate the coupling-ratio dependent peak EDFL wavelength shifting phenomenon. These results sophisticate the operation of a widely tunable L-band EDFL. The detuning of intra-cavity loss may achieve an extremely large tuning range at a scarification on output power of the EDFL, as shown in Fig. 4. Nonetheless, the accurate and repeatable wavelength selection can easily be achieved with a precise control on the output coupling ratio. In experiment, a minimum wavelength tuning resolution of 0.3 nm can be obtained under a change in coupling ratio of 0.6%, corresponding to tuning slope of 0.5 nm/%. Figure 5 shows the output laser wavelength, power, and corresponding quantum efficiency as a function of the output coupling ratio detuned using TROC. As a result, the maximum output power of the EDFL is monotonically decreasing from 91 to 7 mW as its wavelength is linearly tuned from 1567 to 1612 nm under a variation of output coupling ratio from 95% to 5 %. A maximum quantum efficiency of up to 42% is obtained at an output coupling ratio of 90%.
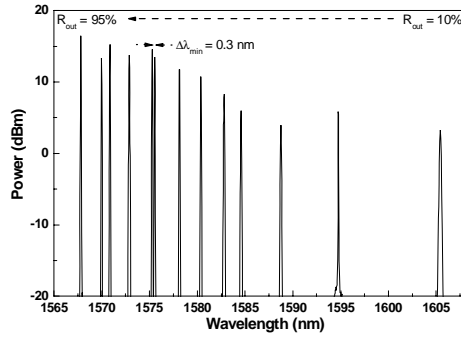
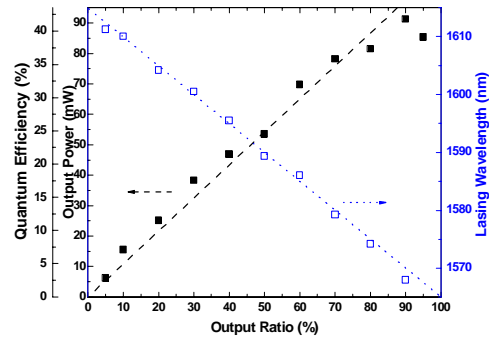Fig. 4. Lasing spectra of EDFL with detuning output coupling ratio.

Fig. 5. Trend of lasing wavelength, output power, and quantum efficiency with output coupling ratio.

Under a low-output and wide-band tunable condition with coupling ratio of only 10 %, the corresponding quantum efficiency of 8% is still comparable with previous results[11, 12]. At a constant output coupling ratio of 90%, it is found that each filtered output channel exhibits the power of greater than 18.4 dBm and the maximum of 19.6 dBm in observed under the pumping power of 217.5 mW, as shown in Fig. 6. Such a deviation of 1.2 dB is already smaller than the best value of 1.5 dB reported in previous work[9]. Nonetheless, it is unavailable to obtain a tunable-filtered EDFL with such a broadband wavelength range as compared to the coupling loss controlled EDFL with its maximum lasing wavelength up to 1625 nm. Moreover, a highly stable output with power variation of 0.036mW (0.04%) over 10 min is obtained. The tuning range and resolution of lasing wavelength was mainly determined by the gain profile of the EDF since the dynamic range on the coupling ratio of the TROC is nearly 100% in our case. The EDFL is unable to operate in the C-band with insufficient gain as the design of the specific EDF which benefits from a better transition of the power from C-band to L-band. In comparison, similar phenomenon has previously been observed using a fiber bending architecture proposed by Melo et al.[9], in which the taper-bending curvature of the intra-cavity single-mode fiber (SMF) is adjusted to provide wavelength tunability. The smaller output coupling ratio not only makes the wavelength tuning range broader, but also favors the EDFL lasing at a longer wavelength. The increased bending radius of the SMF introduces additional cavity loss in the EDFL ring cavity, thus enabling a blue-shifted EDFL wavelength. However, the induced loss can only be determined as a function of a the position of the micrometer drive, and the corresponding EDFL wavelength can not be accurately controlled due to the difficulty of experimentally determining the exact curvature radius applied to the SMF taper.
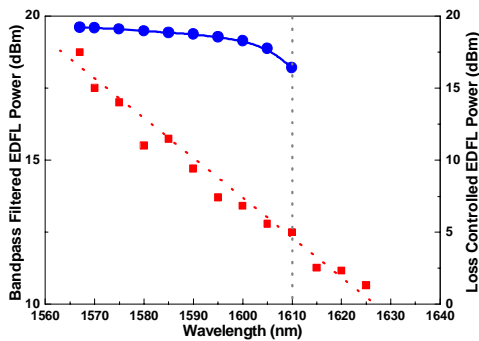

Fig. 6. Wavelength dependent output power of a coupling loss controlled EDFL (solid square) a tunable filter controlled EDFL (hollow circle) at output coupling ratio of 90%.
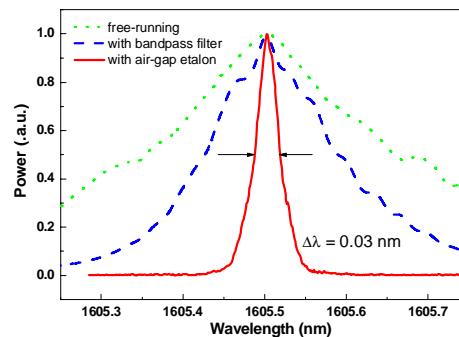

Fig. 7. The lasing linewidth without (dotted line) or with (solid square) an air-gap inserting between FC/PC fiber connectors. The bandpass filtered EDFL spectrum (dashed line) is also show for comparison.

In addition, the dielectric, grating, and fiber Fabry-Perot (FFP) filters were extensively employed to implement widely tunable EDFLs covering C+L band (1520-1600 nm)[23]. The dielectric filter is frequently used with a tunable range limited to 40 nm, which is recently replaced by the grating filter tunable over 100 nm. Nonetheless, the grating usually exhibits a large polarization dependency and a large splicing loss of >5 dB during fiber coupling. The FFP filter is an all-fiber based device having a most wide tuning range of >100 nm, a relatively low loss of <2 dB and an extremely low polarization dependence of 0.1 dB[24]. It is preferable to have an all-fiber based architecture since which exhibits the advantages such as robust, easily connectable, and potentially cost-effective. The innovation of the proposed L-band EDFL system is to introduce a tiny air-gap between the FC/PC connectors of the fiber patch cord prior to the output coupler of the EDFL. This is done by first mounting the FC/PC connector at a precisely aligned holder and then separating the FC/PC connector each other by using one-dimensional translation stage. The home-made air-gap adjuster functions as not only an intra-cavity Fabry-Perot filter but also a cavity loss controller in the L-band EDFL system. Note that the lasing linewidth of the EDFL output can be further narrowing from 0.3 nm to 0.03 nm (see Fig. 7) by simply inserting such a tiny air-gap between the FC/PC connectors of fiber patch cord. In principle, the wavelength tuning of the L-band EDFL through loss modulation is well known and it generally results in step tuning rather than the continuous tuning reported by our work. Presumably, our approach is based on the convolution of the spectral responses in the tunable coupler and a weak fiber-based air-gap etalon, which releases any kinks in the gain tilt function of the EDFL. The air-gap based etalon thus becomes an interesting innovation when combining with the loss modulation technique, as it concurrently results in single-frequency and wavelength tuning operation of the L-band EDFL.

5. Conclusions

We have demonstrated an output-coupling-ratio controlled, full long-wavelength-band erbium-doped fiber ring laser by using a bi-directionally dual-wavelength pumped EDFA in close-loop with an output coupler of tunable coupling ratio. The L-band EDFL is wavelength-tunable from 1567 nm to 1612 nm at a maximum quantum efficiency of 42%, respectively with ultra-high power conversion efficiency of 37%, comparable gain of 34 dB, and maximum output power of up to 91mW. The minimum wavelength tuning resolution of 0.3 nm is achieved under the maximum wavelength tuning range of up to 45 nm covering whole L-band, while a low channel power variation of <1.2dB and a stable output with 0.04% power fluctuation is reported.

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