Coupling-ratio controlled wavelength tunability of a power conversion efficiency improved L-band Erbium-doped fiber laser

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ABSTRACT

A coupling-ratio controlled wavelength tunable L-band erbium-doped fiber laser with tuning range of 45nm (1567 - 1612 nm), quantum efficiency of 42%, power conversion efficiency of 37%, tuning resolution of 0.3 nm is reported. The wavelength-tuning is achieved by a tunable band-pass filter (TBPF) or by adjusting the tunable-ratio optical coupler (TROC) without TBPF because of the difference of intracavity loss. The output wavelength can be tunable in the full L-band with TBPF, from 1567 to 1612 nm, and the pulse-width is <14.2 ps. Specially, during the wavelength-tunable process without TBPF, the modulation frequency of about 1 GHz remains unchanged and near-transform-limited pulses are generated by linear compression with 32.5 m single mode fiber (SMF) under 10% output coupling ratio.

Keywords: EDFA, L-band, C-band, mode-lock, fiber laser, soliton, pulse compensation

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1. INTRODUCTION

Long-wavelength-band erbium-doped fiber amplifiers (L-band EDFAs) [1] have been developed rapidly following the conventional 1550-nm-band (C-band) EDFA as a key component for wavelength division multiplexing (WDM) transmission systems, which made it possible to transmit several terabit per second. Though the gain region of EDFAs is wider than 100 nm, EDFAs using only about 30-nm bandwidth in the C-band were developed in the first few years. With the enhancement of the erbium-doped fiber (EDF) and pump laser diode (LD) manufacturing technology, and also the need for more optical bandwidth in optical communications, the EDFA for the L-band with another optical bandwidth between 1570 and 1600 nm has been developed. The application of the L-band EDFA to WDM transmission systems is very attractive because the system capacity can be doubled when used in conjunction with the

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conventional C-band EDFA as in-line repeaters. Using dispersion-shifted fibers, it is also possible to construct effective WDM systems with narrow channel spacing of less than 100 GHz without the degradation caused by nonlinear effects, such as four-wave mixing and cross-phase modulation. Moreover, the EDFA without gain-flattening filters can achieve flat gain easier than the C-band EDFA.

Owing to the insufficient channel capacity of the current dense wavelength division multiplexed (DWDM) systems, long-wavelength band erbium-doped fiber amplifier (EDFA) with wavelength ranging from 1570 nm to 1610 nm have been investigated in order to widen the transmission capacity. In addition, L-band tunable fiber lasers are essential for testing the L-band devices used in WDM transmission systems. Therefore, the realization of economical and efficient L-band fiber laser architecture becomes necessary for its commercialization. Previously, the gain medium for L-band fiber laser includes dense erbium-doped fiber, erbium-ytterbium co-doped double clad fiber [2], and brillouin-erbium fiber [3], etc. Typically, the L-band erbium-doped fiber laser (EDFL) can be configured with such as dual resonant cavity [4], linear overlapping cavity [5], and single ring cavity [6]. The wavelength-tuning are mainly based on the intra-cavity Fabry–Perot filters [7], fiber Bragg gratings (FBGs) [8], and cavity loss [9] adjustment. In particular, the wavelength tunability of L-band EDFL via cavity loss control was simply demonstrated by optomechanically bending the single-mode fiber in the EDFL cavity [9, 10]. To meet the cost-effective demand, we present a coupling-ratio controlled wavelength tunable, full L-band erbium-doped fiber ring laser (EDFRL) with a tunable range over 45nm and low variation (<1.2dB) of the output laser power over all the tuning range. In addition, the quantum efficiency of the EDFRL which simultaneously reaches an extremely high value is 42%. In the aspect of EDFA, by using highly doped EDF and adjusting fiber length, an optimized bi-directional pumped L-band EDFA of the EDFL which possesses extremely high power conversion efficiency (PCE) about 37% provides gain to the loop. The high PCE shows more than 10% improvement compared with that reported using conventional L-band EDFA [11] configuration.

2. EXPERIMENTAL SETUP

The experimental setup of the coupling-ratio controlled wavelength-tunable EDFL is shown in Fig. 1. It consists of an optimized L-band EDFA with a bi-directionally 980/1480 pumping scheme. In optimized operation, a 17.5mW forward pumping at 980 nm and a 200mW backward pumping at 1480 nm is employed. This EDFA further takes the advantage of high erbium (Er^{3+}) concentration in a specially designed L-band fiber, which offers an ultra-wide amplified spontaneous emission spectrum ranged between 1538 nm and 1628 nm [12] (see Fig. 2(a)) with comparable gain (see Fig. 2(b)) at a reduced fiber length and suppressed noise power. The forward and backward pumping powers are launched into the EDF by a 980nm/1550nm and a 1480nm/1550nm WDM couplers, respectively.

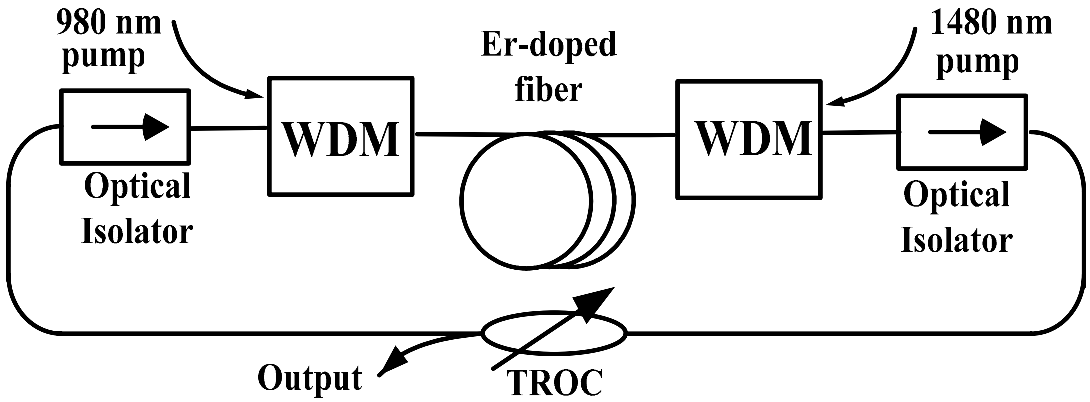

Fig. 1. A coupling-ratio controlled wavelength tunable L-band EDFL with a tunable-ratio optical coupler (TROC)

Two optical isolators are used to ensure the unidirectional propagation of the light, thus preventing spatial hole burning in the EDFA caused by bi-directional operation and simultaneously allowing a stable single-frequency operation. In particular, a 1×2 tunable-ratio optical coupler (TROC) with variable output coupling ratio is inserted into the close-loop EDFA ring-cavity. The coupling ratio can be manually detuned from 0.5% to 99.5%. Initially, the output coupling ratio is set at 90% to obtain maximum output power.

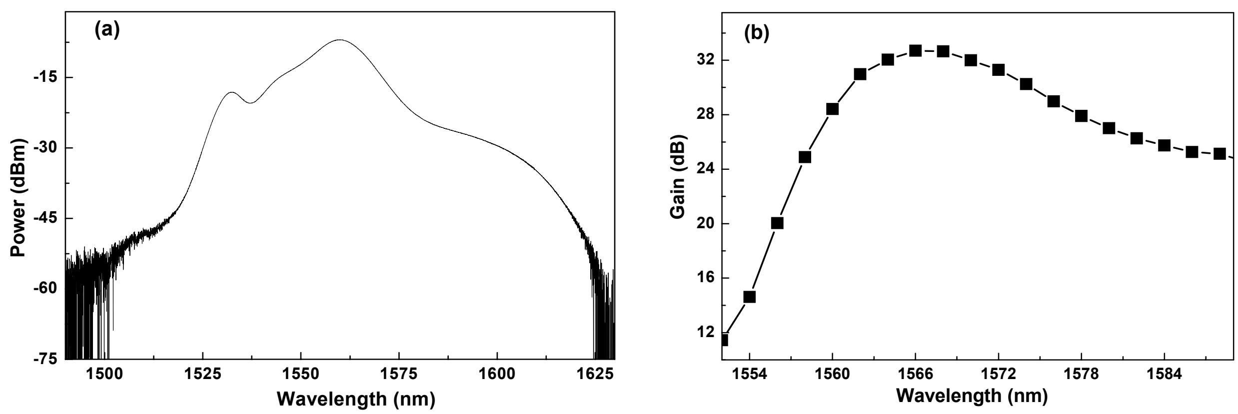

Fig. 2 Basic properties of the EDFA. (a) ASE spectrum of the EDFA. (b) Small-signal gain of the EDFA at input power of -20 dBm.

2. THEORICAL MODELING

The active medium is an Er^{3+}-doped fiber amplifier (EDFA) of length L described by the three-level system rate equations [13]:

$$\frac{dP_p(z)}{dz} = -\sigma_p A_p \rho n_1 P_p(z), \tag{1}$$

$$\frac{dP_s(z)}{dz} = A_s \rho[\sigma_E(\lambda) n_2 - \sigma_A(\lambda) n_1] P_s(z), \tag{2}$$

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

$$n_1 = 1 - n_2, \tag{3}$$

where

$$P_{p\,sat} = \frac{h\nu_p}{\sigma_p \tau}\frac{A}{A_p}, \qquad P_{s\,sat} = \frac{h\nu_s}{\sigma_E \tau}\frac{A}{A_s}. \tag{4}$$

The quantities appearing in the above formulas are defined as follows: $P_p(z)$ is the pump power at the longitudinal coordinate z inside the active fiber, $P_s(z)$ the forward signal power, σ_p the pump absorption cross section, $\sigma_{E,A}(\lambda)$ are the emission and the absorption cross sections, ρ is the dopant concentration, $A_{p,s}$ is the pump and the signal overlap integrals, $n_{1,2}$ is the lower and the upper laser level population fractions, τ is the upper laser level lifetime, and A is the fiber core area. Because the laser operates unidirectionally, the backward signal power has been neglected.

The laser cavity has a loss

$$\Gamma_{TOT} \equiv P_1 / P_3, \tag{5}$$

which can be conveniently attributed to two different contributions. The first contribution is the output coupler loss γ. If the coupler extracts a fraction T of the power, we have

$$P_{out} = TP_1, \qquad 0 < T < 1,$$

(6)

and hence

$$\gamma \equiv \frac{P_1}{P_2} = \frac{1}{1-T}, \qquad \gamma > 1. \tag{7}$$

The second loss contribution comes from the intrinsic cavity loss defined as

$$\Gamma \equiv P_2 / P_3, \qquad \Gamma > 1, \tag{8}$$

so that the total cavity loss FTOT can be expressed as

$$\Gamma_{TOT} \equiv P_1 / P_3 = \gamma\Gamma. \tag{9}$$

As is well known, for laser emission to occur it is necessary that the amplifier gain G satisfy the threshold condition

$$G(\lambda_0) = \Gamma_{TOT}(\lambda_0), \qquad G(\lambda \neq \lambda 0) < \Gamma_{TOT}(\lambda), \tag{10}$$

where λ_0 is the emission wavelength. Note that including a wavelength dependence inΓ_{TOT} also accounts for any cavity element that may spectrally modulate the transmission (etalons, Lyot filters, etc.).

In the case of an EDFA the gain is [14]

$$G(\lambda, L) = \exp\{A_s \rho \int_0^L [\sigma_E(\lambda) n_2 - \sigma_A(\lambda) n_1]dz\}, \tag{11}$$

and hence, from Eq. (1) and the second of Eq. (3),

$$G(\lambda, L) = \exp\{g(\lambda)L + \frac{g(\lambda) + a(\lambda)}{\alpha_p}\ln[\frac{P_p(L)}{P_p(0)}]\}, \tag{12}$$

where $g(\lambda) = \sigma_E A_s \rho$, $a(\lambda) = \sigma_A(\lambda) A_s \rho$, and $\alpha_p = \sigma_p A_p \rho$ are the gain, the attenuation, and the pump absorption coefficients, respectively. Introducing conditions (10), we find that the laser operates at the wavelength that satisfies the following relation:

$$\max_{\lambda}\{g(\lambda)L+\frac{g(\lambda)+a(\lambda)}{\alpha_p}\ln[\frac{P_p(L)}{P_p(0)}]-\ln[\Gamma_{TOT}(\lambda)]\}=0. \quad (13)$$

Equivalently, the minimization with respect to λ of

$$\ln[\frac{P_p(L)}{P_p(0)}]=-\alpha_p\frac{g(\lambda)L-\ln[\Gamma_{TOT}(\lambda)]}{g(\lambda)+a(\lambda)}\equiv-\alpha_p\Psi(\lambda), \quad (14)$$

determines the emission wavelength of the laser.

Note that when the cold-cavity loss Γ_{TOT} is changed the emission wavelength λ changes, too. Because the derivative of Eq. (14) is an implicit expression containing the dependence of the emission wavelength on cavity loss, gain, and the attenuation coefficient, the minimum of Eq. (14) can be found numerically.

4. RESULTS AND DISCUSSIONS

Several pumping schemes have been investigated in order to construct low-noise and high-gain L-band EDFA as the gain medium, and a 980nm (forward)/1480nm (backward) cascaded pumping geometry is selected. The forward pumping at 980nm is effective for improving the noise characteristics, while the backward pumping at 1480nm benefits from a better quantum conversion efficiency and gain coefficient [14]. With such a simplified EDFA, a extremely high PCE of 37% with a wavelength dependent gain deviation of 7 dB is achieved. The power conversion ratio (PCE) is defined as PCE = (Psigout – Psigin)/Ppump, where Psigout, Psigin and Ppump denote the signal output power, signal input power, and pump power, respectively. The measured results of EDFA that is shown in table 1.

Pumping Wavelength	Length (m)	PCE (%)	Gain(max) (dB)
980/1480	15	24.7	30.9
1480/1480	15	21.2	35.7
980/1480	30	36.55	33.5
1480/1480	30	33.08	37.2
980/1480	45	30.6	31.1
1480/1480	45	37	34.8
980/1480	60	20	35.2
1480/1480	60	23.6	38.5

Table 1 The PCE and maximum of the EDFA constructed with different pumping schemes (Forward/Backward).

Figure 3 illustrates the output laser wavelength, power, and corresponding quantum efficiency as a function of the output coupling ratio detuned by the TROC. As a result, the wavelength of the EDFL with maximum output power can be linearly tunable from 1567 nm to 1612 nm as the output coupling ratio of the TROC detunes from 95% to 5 %, while the output power of the EDFL is monotonically decreasing from 90 mW to 7 mW, as shown in Fig. 3. It is seen that higher output coupling ratios as well as intra-cavity losses result in the EDFL lasing at shorter wavelengths. The lasing spectra of the EDFL at wavelengths corresponding to maximum output power also corroborates the maximum tuning range up to 45 nm (see Fig. 4). Previously, a similar simulating result concerning with the cavity-loss dependent tuning range of L-band EDFL system was proposed, which described a increasing sensitivity of the EDFL output power and bandwidth at lower intra-cavity losses. As the cavity-loss increases, the maximum output power and the wavelength tuning range are concurrently reduced [15]. By using the TROC based coupling ratio detuning technique, our experimental results not only correlate well with the theoretical observation, but also demonstrate the coupling-ratio dependent peak EDFL wavelength shifting phenomenon.

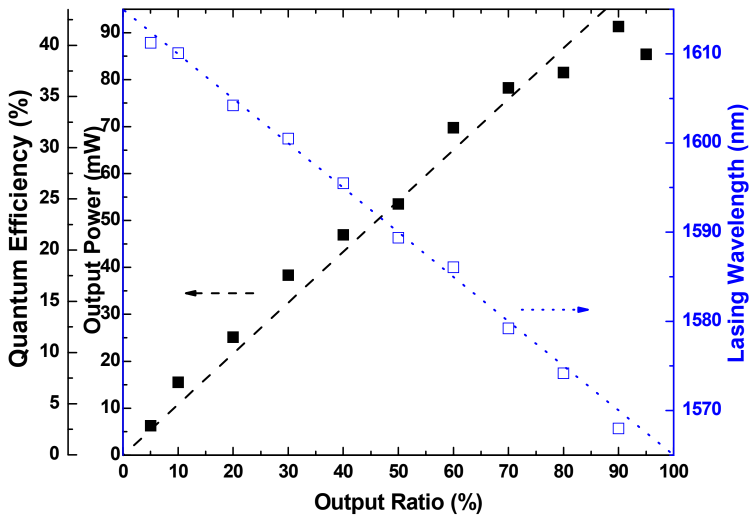

Fig. 3 The trend of lasing wavelength, output power, and quantum efficiency with detuning output coupling ratio.

These results sophisticate the operation of a widely tunable L-band EDFL since the minimizing in 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, an accurate and repeatable wavelength selection is easily achieved with 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/%. On the other hand, the theoretical simulation also interpreted that the maximum tuning range of the L-band EDFL is greatly reduced when increasing output coupling ratio from 0.1 to 0.99. A maximum and stable output power associated with a maximum quantum efficiency of up to 42% is obtained at an output coupling ratio of 0.9, as shown in Fig. 3.

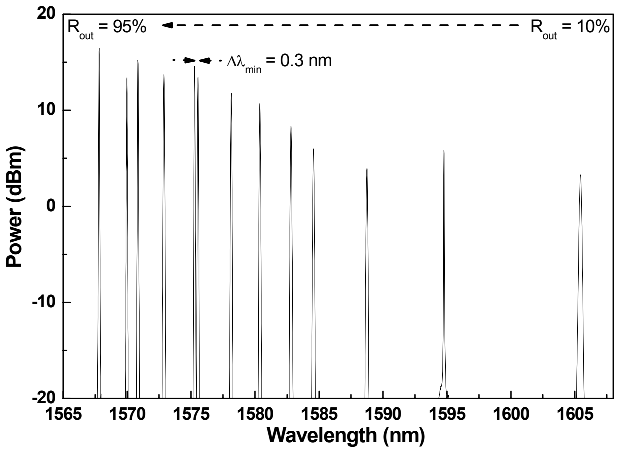

Fig. 4 The lasing spectra of EDFL with detuning output coupling ratio.

Even at a low-output and wide-band tunable condition with coupling ratio of only 10 %, the corresponding quantum efficiency of 8% can be still comparable with previous results [15, 16]. Under a pumping power of 217.5 mW, each output channel exhibits power of greater than 18.4 dBm and a maximum of 19.6 dBm in observed, as shown in Fig. 5. Such a deviation of 1.2 dB is already smaller than best value of 1.5 dB reported previously [10]. Note that the lasing linewidth of the EDFL output can be further narrowing from 0.05 nm to 0.02 nm by simply inserting an tiny air-gap between the FC/PC connectors of fiber patch cord, which functions as a intra-cavity Fabry-Perot filter in the cost-effective L-band EDFL system.

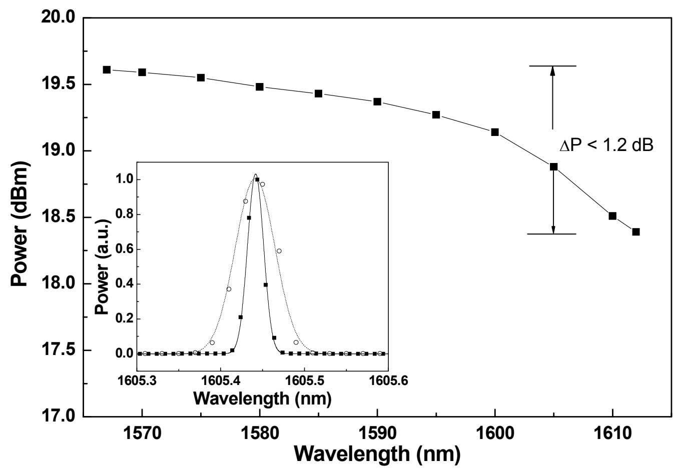

Fig. 5 Variation of wavelength dependent output power. Inset: linewidth narrowing via an air-gap inserted between FC/APC fiber connectors.

Moreover, a highly stable output with power variation of 0.036mW (0.04%) is obtained during a monitoring interval over 10 min, as shown in Fig. 6. The tuning range and resolution of lasing wavelength was mainly determined by the gain profile of the EDF since 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.

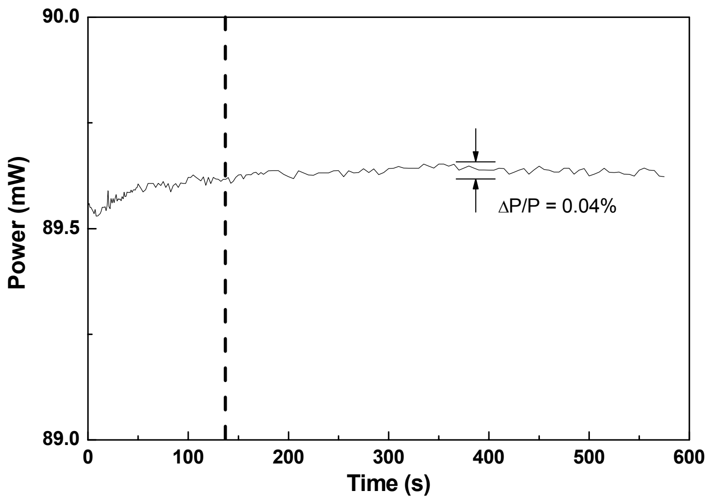

Fig. 6 Power stability of the L-band EDFL measured within 10 minutes.

4. CONCLUSION

We have experimentally investigated and 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 a tunable ratio optical coupler. 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 observed.

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