

Wavelength Tunability of a Coupler and Air-Gap Etalon Controlled High-Efficiency *L*-Band Mode-Locked Erbium-Doped Fiber Laser

Gong-Ru Lin, *Senior Member, IEEE*, Hai-Han Lu, and Jun-Yuan Chang

Abstract—Mode-locked erbium-doped fiber laser with a full *L*-band wavelength tunability from 1567 to 1612 nm by controlling the ratio of its output coupler is demonstrated, which exhibits intracavity gain of 34 dB and maximum output power of 91 mW. The dual-wavelength (980 and 1480 nm) bidirectional pumping scheme enhances quantum efficiency and power conversion ratio to 42% and 37%, respectively. Continuous-wave lasing linewidth of 0.02 nm is obtained with the introduction of an intracavity air-gap Fabry–Pérot filter made by polishing the fiber connector end. A 45-nm wavelength tunability with pulsewidth of 2.4 ps and linewidth of 6.8 nm are observed under mode-locking regime. Tuning resolution of 0.3 nm and wavelength-dependent power variation of <1.2 dB are also reported.

Index Terms—Air-gap etalon, erbium-doped fiber laser (EDFL), *L*-band, mode-locking, tunable-ratio coupler, wavelength tunable.

I. INTRODUCTION

TYPICALLY, the wavelength tuning of the long-wavelength band (*L*-band) erbium-doped fiber (EDF) (1565–1600 nm) [1], erbium–ytterbium codoped double clad fiber (1589–1623 nm) [2], or Brillouin-erbium fiber (1592–1602 nm) [3] based laser systems can be configured by versatile *L*-band fiber-optic filters. The dielectric filter is the most common one with a tunable range limited to 40 nm. Alternatively, the tunable optical bandpass filters with multiple wavelength-selective gratings ranging from 1520 to 1600 nm [4] were also introduced. The grating filter was comprehensively used in tunable external-cavity laser diode systems with a maximum tunable range over 100 nm, however, which exhibits a large polarization dependency and a large splicing loss of >5 dB during fiber coupling. The Fabry–Pérot etalon filter was reported to be a best candidate owing to its wide tuning range of >100 nm, relatively low loss of <2 dB, and extremely low polarization dependence of 0.1 dB [5]. Later on, it was reported that the wavelength tunability of *L*-band erbium-doped fiber laser (EDFL) via cavity loss control [6] was simply demonstrated by optomechanically bending the single-mode fiber in the EDFL cavity [7]. With these techniques, the vintage *L*-band EDFLs

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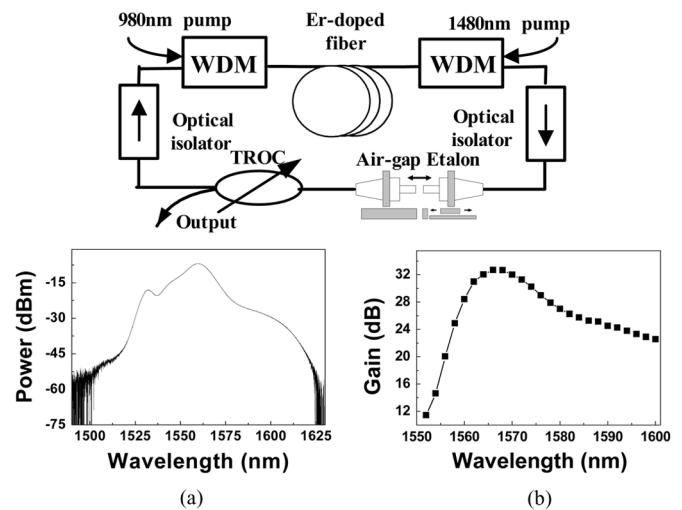


Fig. 1. Coupling-ratio controlled wavelength tunable *L*-band EDFL with a TROC. (a) ASE spectrum of the EDFL. (b) Small-signal gain of the EDFL at input power of -20 dBm.

with wavelength-tuning range covering from 1571 to 1604 nm have been demonstrated. To meet the cost-effective demand, we present an output-coupling-ratio controlled EDFL with a wavelength-tunable range covering full *L*-band. The pumping parameters and EDF length of the EDFL are adjusted to reach extremely high quantum efficiency and power conversion ratio (PCR). Mode-locking performances of the EDFL with a picosecond pulsewidth and full *L*-band tunability are also demonstrated.

II. EXPERIMENT AND PRINCIPLE

The experimental setup of the coupling-ratio controlled wavelength-tunable EDFL is shown in Fig. 1. It consists of an optimized *L*-band erbium-doped fiber amplifier (EDFA) with a bidirectionally 980/1480 pumping scheme. In optimized operation, a 17.5-mW forward pumping at 980 nm and a 200-mW 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 ultrawide amplified spontaneous emission spectrum ranged between 1538 and 1628 nm [6] [see Fig. 1(a)] with comparable gain [see Fig. 1(b)] at a reduced fiber length and suppressed noise power. The forward and backward pumping powers are launched into the EDF by a 980-nm/1550-nm and a 1480-nm/1550-nm wavelength-division-multiplexing couplers, respectively. Two optical isolators are used to ensure the unidirectional propagation of the light, thus preventing a spatial hole burning in the EDFA caused by bidirectional operation and simultaneously

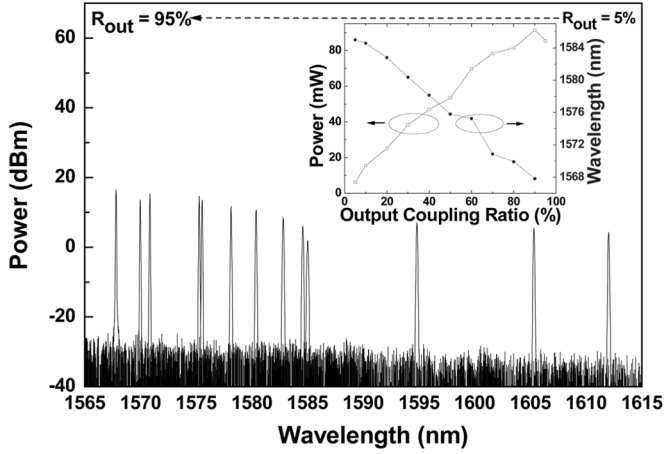


Fig. 2. Lasing spectra of EDFL with detuning output coupling ratio. Inset: the trend of lasing wavelength, output power, and quantum efficiency with detuning output coupling ratio.

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.

III. RESULTS AND DISCUSSION

A 980-nm (forward)/1480-nm (backward) cascaded pumping geometry is selected. By adjusting the highly doped EDF length to 30 m, the bidirectionally pumped *L*-band EDFL provides an optimized quantum efficiency of 42%. In principle, the PCR is defined as $PCR = (P_{sig-out} - P_{sig-in})/P_{pump}$, where $P_{sig-out}$, P_{sig-in} , and P_{pump} denote the signal output power, signal input power, and pump power, respectively. With such a simplified EDFA of optimized EDF length, a maximum PCR up to 36.6% under a total pumping power of 215 mW has been obtained. Such an optimized configuration provides a small-signal gain of 33.5 dB accompanied with a wavelength-dependent gain deviation of only 6 dB. The high PCR shows more than 10% improvement compared with that reported using conventional *L*-band EDFA [8] configuration. The gain profile of our EDFL shown in Fig. 1 clearly declined below 1560 nm, which is due to the transfer of *C*-band power toward the *L*-band within the extremely long EDF [10]. Such an EDFL could not operate in the *C*-band due to the lack of *C*-band amplified spontaneous emission (ASE) spectrum under a significant gain-shifting effect in the extremely long EDF.

Fig. 2 illustrates the lasing spectra of the EDFL at wavelengths corresponding to maximum output power. Previously, a similar simulating result concerning the cavity-loss-dependent tuning range of the *L*-band EDFL system was proposed, which described a increasing sensitivity of the EDFL output power and bandwidth at lower intracavity losses. As the cavity-loss increases, the maximum output power and the wavelength tuning range are concurrently reduced [11]. The EDFL operated at a certain wavelength must satisfy the following relation [12]:

$$\ln \left[\frac{P(L)}{P(0)} \right] = -\alpha_p \frac{g(\lambda)L - \ln[\Gamma(\lambda)]}{g(\lambda) + a(\lambda)} \equiv -\alpha_p \Psi(\lambda) \quad (1)$$

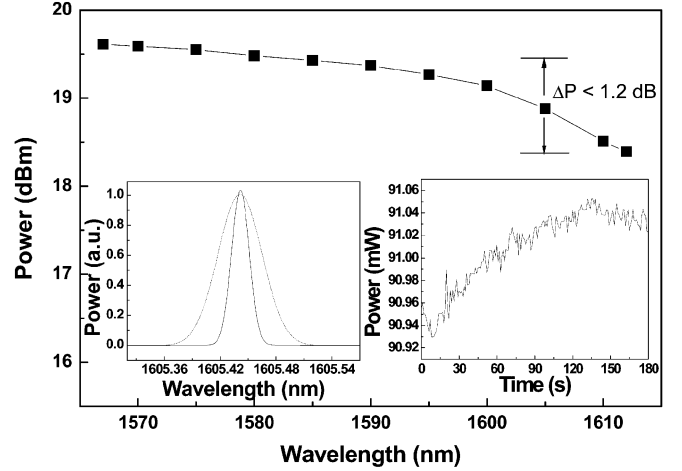


Fig. 3. Variation of wavelength-dependent output power. Inset (left): linewidth narrowing via an air-gap inserted between fiber connectors. Inset (right): Power stability of the *L*-band EDFL measured within 10 min.

where $P(0)$ and the $P(L)$ denote the input and the output power of the EDFL with an EDF length of L , Γ is the product of the output coupler loss and the intrinsic cavity loss, $g(\lambda) = \sigma_E A_s \rho$, $a(\lambda) = \sigma_A(\lambda) A_s \rho$, and $\alpha_p = \sigma_p A_p \rho$ denote the gain, the attenuation, and the pumping absorption coefficients, respectively. This wavelength of gain peak can be varied as the cavity loss of EDFL changes the degree of population inversion, since the net gain profile of the EDFL is proportional to the linear superposition of its emission and absorption curves with different shape and spectral position. These results sophisticate the operation of a widely tunable *L*-band EDFL since the minimizing in intracavity loss may achieve an extremely large tuning range at a scarification on output power of the EDFL, as shown in Fig. 2.

The maximum tuning range of the lasing wavelength can be up to 45 nm under a change of output coupling ratio (R) from 5% to 95%. Therefore, we evaluate the linear wavelength tuning slope of such an EDFL as $\Delta\lambda/\Delta R = 3.43$ nm/dB, which means the wavelength of the EDFL can be detuning by 0.25 nm under an adjustment on the output coupling ratio of 1 dB. Nonetheless, the theoretical simulation also interpreted that the maximum tuning range of the *L*-band EDFL is greatly reduced when increasing the output coupling ratio from 0.1 to 0.99 [12]. The inset of Fig. 2 shows the output laser wavelength, power, and corresponding quantum efficiency as a function of the output coupling ratio detuned by the TROC. The wavelength of the EDFL can be linearly tunable from 1567 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 intracavity losses result in the EDFL lasing at shorter wavelengths. Otherwise, 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 the inset of Fig. 2. Even at a low-output and wideband-tunable condition with a coupling ratio of only 10%, the corresponding quantum efficiency of 8% can be still comparable with previous results [9], [11]. In comparison, the problem left in the previous approach [7] is a tightly bending fiber required to provide an extremely large cavity loss

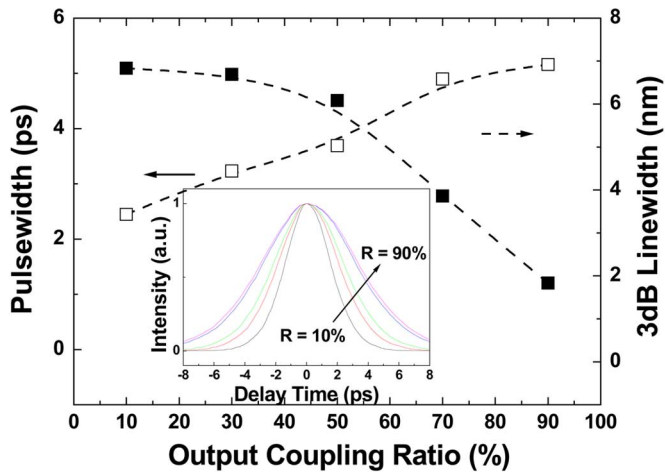


Fig. 4. Pulsewidths and linewidths of the wavelength-tunable *L*-band mode-locked EDFL at different output coupling ratios. The inset figure illustrates the autocorrelated pulse shapes of the EDFL obtained at different output ratio (*R*). (Color version available online at <http://ieeexplore.ieee.org>.)

for tuning toward short wavelengths, which will break up the fiber if the radius of curvature becomes too small. In our configuration, the cavity loss ranging from 1% to 99% can easily be detuned with the TROC, which facilitates a much larger wavelength tuning range.

Each output channel exhibits power of >18.4 dBm and a maximum of 19.6 dBm is observed, as shown in Fig. 3. Such a deviation of 1.2 dB is already smaller than best value of 1.5 dB reported previously [6]. Moreover, a highly stable output with power variation of 0.036 mW (0.04%) is obtained during a monitoring interval over 10 min, as shown in the right inset of Fig. 3. 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. Note that the lasing linewidth of the EDFL output can be further narrowing from 0.05 to 0.02 nm by simply inserting a tiny air-gap between the connectors of the fiber patch cord, which functions as an intracavity Fabry-Pérot filter in the cost-effective *L*-band EDFL system. In comparison with previous approaches, our proposed scheme covers the full *L*-band wavelength tunability (from 1567 to 1612 nm) by simply manipulating the coupling ratio to change cavity loss. With the introduction of an intracavity air-gap Fabry-Pérot filter made by polishing the connector end, both the lasing wavelength and spectral linewidth of the *L*-band EDFL can be further improved.

By adding a Mach-Zehnder intensity modulator into the EDFL cavity and driving it with an amplified RF signal of 18 dBm at 1 GHz, the *L*-band EDFL can be actively mode-locked to generate wavelength-tunable picosecond pulses. The autocorrelated pulse shape of the mode-locked EDFL at different output coupling ratios are shown in the inset of Fig. 4. It is observed that the EDFL pulsewidth is broadened as the output coupling ratio increases, which is mainly attributed to the reduction on the spectral linewidth of the EDFL at shorter wavelength. Since the gain profile of the EDFL at shorter wavelengths inevitably becomes narrower as that at

longer wavelengths due to the *C*-to-*L* band, ASE pumping effect occurred in such a long EDF segment. As a result, the pulsewidth and linewidth of the mode-locked EDFL are plotted as a function of the output coupling ratio and shown in Fig. 4. A mode-locked pulsewidth of 2.4 ps accompanied with a 3-dB linewidth of 6.8 nm are observed when operating at 1609 nm under an output coupling ratio of 10%. In brief, these results have shown the capability of such a simple EDFL architecture in the *L*-band wavelength-tunable picosecond pulse generation, while the applications of such a system in fiber-optic communication or diagnostics are straightforward.

IV. CONCLUSION

We have experimentally demonstrated an output-coupling-ratio controlled *L*-band EDFL that is wavelength-tunable from 1567 to 1612 nm at a maximum quantum efficiency of 42%, respectively, with ultrahigh PCR of 37%, comparable gain of 34 dB, and maximum output power of up to 91 mW. 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 <1.2 dB and a stable output with 0.04% power fluctuation is observed. Short pulsewidth of 2.4 ps and spectral linewidth of 6.8 nm are observed.

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