Effects of active fiber length on the tunability of erbium-doped fiber ring lasers

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Abstract: We numerically investigate the effects of the active fiber length on the tunability of erbium-doped fiber ring lasers for the cases of with and without pair-induced quenching (PIQ). The numerical results are confirmed by experiments. We have found that the tuning range shifts from C-band to L-band with an increase in the active fiber length. A maximum tuning range of over 100 nm, covering both the C- and L-band, can be achieved with an optimized active fiber length. It is also found that the PIQ is favorable for L-band lasing though it reduces the output power and degrades the power flatness. Using these findings, a novel method employing active fiber length switching is proposed to extend the tuning range of the laser, which is only limited by the free spectral range (FSR) of the tunable filter. A large tuning range of 102 nm is obtained using a tunable fiber Fabry-Perot filter with an FSR of 75 nm.

OCIS codes: (060.2320) fiber optics amplifiers and oscillators; (140.3500) lasers, erbium; (140.3560) lasers, ring; (140.3600) lasers, tunable

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1. Introduction

Widely tunable, narrow line-width and single-frequency erbium-doped fiber lasers (EDFLs) have been studied extensively for their potential applications in wavelength-division-multiplexed (WDM) transmission systems and for performance testing of optical fiber components [1-4]. One of their most important advantages is the large wavelength tunable range that matches well to the gain range of the erbium-doped fiber amplifiers (EDFAs). Widely tunable erbium-doped fiber ring lasers (EDFRLs) covering both the conventional wavelength band (C-band) and long wavelength band (L-band) have recently been investigated to have large wavelength tunability, high optical signal-to-noise ratio, recently small effective linewidth (0.1~1 GHz), and excellent wavelength and power repeatability [5,6]. These advantages, especially the large wavelength tunability of over 100 nm, of EDFRLs have made them suitable for use as a laser source to take advantage of the L-band of EDFA for increasing the transmission capacity [7,8]. However, previous studies have shown that the tunability of EDFL depends very much on the active fiber length [5,6]. In addition, a concentration-related process called pair-induced quenching (PIQ) may significantly degrade the performance of erbium-doped fibers (EDFs) [9-12]. The effect of PIQ has also been found to cause a detrimental increase in the threshold, a reduction in conversion efficiency in EDFLs [13], as well as degradation in the power flatness of tunable EDFLs [14,15].

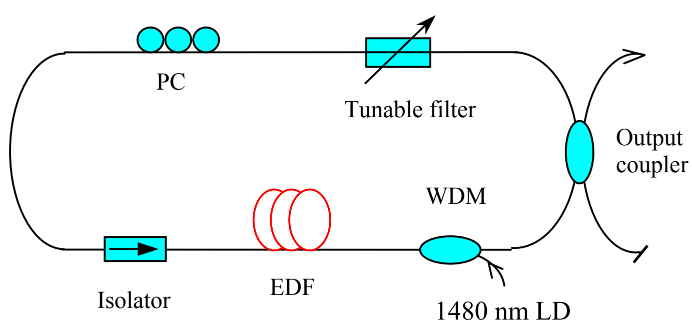

Fig. 1. Schematic diagram of the proposed tunable erbium-doped fiber ring laser.

In this paper, the effects of the active fiber length, with and without PIQ taken into consideration, on the performance of the tunable EDFRL are numerically investigated. It is shown that, with an increase in the active fiber length, the tuning range of EDFRL shifts from C-band to L-band, and a maximum tuning range covering both the C- and L-band can be achieved at an optimal active fiber length. In addition, PIQ is found favorable for L-band lasing though it reduces the output power and degrades the power flatness. Based on these findings, we propose a novel method employing the active fiber length switching to extend the laser's tuning range, which is only limited by the FSR of the tunable filter. We have found experimentally that a large tuning range of 102 nm can be obtained using a tunable fiber Fabry-Perot (FFP) filter with an FSR of 75 nm.

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2. Laser configuration

The schematic diagram of the proposed laser configuration is shown in Fig. 1. The EDF is backward pumped by a 90 mW laser diode (LD) emitting at 1480 nm through a micro-optic WDM coupler. A widely tunable narrow bandpass filter is used to select the emission wavelength. An optical isolator and a polarization controller (PC) are inserted into the ring to ensure unidirectional operation and to control the polarization state of the laser light, respectively. The light is coupled out through one port of a 3-dB fiber coupler. The EDF used in the numerical modeling and experiment has an erbium concentration of ~ 9.2×10^{24} ions/m^3, absorption coefficients of α (1480 nm) = 7 dB/m, α (1532 nm) = 15 dB/m, cutoff wavelength of 1000 nm, core diameter of 3.2 μm and a numerical aperture of 0.29. As a tunable filter with a sufficiently large tuning range is not commercially available, we used a multiplex tunable filter, which is the same as the one described in Ref. 15, in our experiment. A tuning range of 120 nm (1500-1620 nm) can be achieved using this filter, and the total insertion loss of the filter is found to be ~3.5 dB.

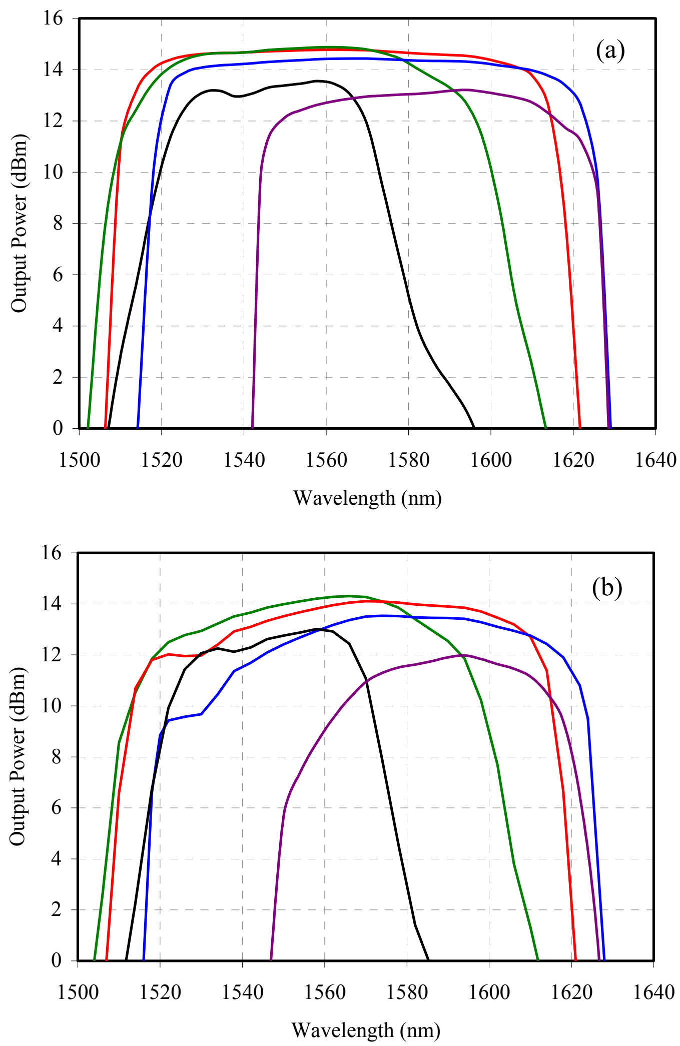

Fig. 2. Simulation results (a) without PIQ, and (b) with PIQ at different EDF lengths of 2.5 (——), 5.0 (——), 8.0 (——), 12.5 (——), and 30 m (——).

3. Results and discussion

In the simulation of the tunable EDFRL, we use the model recently reported in Ref. [14]. The EDF is assumed to be a homogeneously broadened two-level laser system. An iterative solution of the rate equations, the propagation equations for the pump and for both the forward and backward propagating amplified spontaneous emission (ASE) powers is implemented using a fourth-order Runge-Kutta routine. We consider all the wavelength components from 1450 to 1640 nm by dividing them into 950 slots of 0.2 nm wavelength interval to ensure high accuracy in the numerical modeling. All the erbium ions in the EDF are assumed to have two distinct species: single ions and paired ions. The concentration of the paired ions is denoted as $n^p = kn_t$, where n_t is the total concentration of the erbium ions, k is the ratio of the paired ions to the total ions, which normally increases with the total erbium-doping concentration. It has been suggested that, when both ions of a pair are excited, a rapid cross-relaxation process, called pair-induced quenching (PIQ), takes place, which causes a reduction in the population inversion of the pumped EDF [11]. In this model, the effects of PIQ in the paired ions are considered by introducing rate equations different from those of single ions (as shown in Eq. (1) of Ref. [14]), and can be analyzed at different value of k for various degrees of erbium ion clustering [14]. In the following modeling, we set k = 0 and 5.2% for the cases with and without PIQ, respectively. The value of k = 5.2% was deduced from the experimental data for the same EDF in Ref. [14].

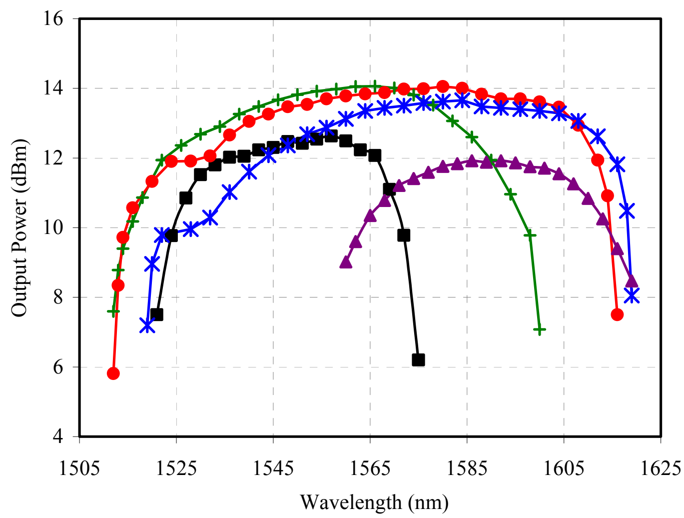

Fig. 3. Measured output powers at different EDF lengths of 2.5 (■), 5.0 (+), 8.0 (●), 12.5 (ж), and 30 m (▲).

Figure 2 shows the simulation results of the laser output powers, with and without PIQ taken into account, against the emission wavelength for various EDF lengths of 2.5, 5.0, 8.0, 12.5 and 30 m. The total intra-cavity loss including the loss introduced by the output coupler is supposed to be 6.6 dB, in agreement with that measured from the experimental setup. From Fig. 2(a), it can be seen that, for the EDF length of 2.5 m, the tuning range is narrow (which is ~50 nm for 3-dB flatness) in the C-band with a center wavelength of 1546 nm. With an increase in the length of the EDF between 2.5 and 8.0 m, the tuning range becomes broader, and the center wavelength shifts to the longer wavelength region because the tuning range increases faster in the longer wavelength region than in the shorter wavelength region. For EDF length from 8.0 to 12.5 m, the laser tuning range reaches to a maximum value of 105 nm and becomes relatively stable, however, the center wavelength still shifts towards longer wavelength along with a slight reduction in power. For EDF longer than 12.5 m, the tuning

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range decreases rapidly and shifts to the L-band along with a significant reduction in power. At EDF length of 30 m, the tuning range is only 78 nm, has a center wavelength of 1584 nm, and most of the tuning range moves into the L-band and the maximum power is reduced by 1.6 dB compared with that for EDF length of 8.0 m.

From Fig. 2(b), it can be seen that, with PIQ taken into account, the laser power levels for all the cases are reduced as compared with those without PIQ consideration. And the PIQ-induced reduction in power is more serious at the shorter wavelength band, especially at around 1530 nm, than at the longer wavelength band, resulting in a degradation in the power flatness. For example, in the case of 8.0 m of EDF, the power is reduced by 2.63 dB, from 14.61 to 11.98 dBm, at 1530 nm but only 0.65 dB, from 14.76 to 14.11 dBm, at 1570 nm. Consequently the 3-dB tuning range is reduced from 105 to 80 nm. In the cases of 12.5 and 30 m of EDF, the 3-dB tuning ranges are reduced from 105 to 84 and 78 to 58 nm, respectively. In experiment, we measured the laser output power versus emission wavelength for all the five EDF lengths. The measured data, as shown in Fig. 3, are in good agreement with the simulated ones. The small discrepancy between the simulated and experimental results may be caused by the different intra-cavity loss arising from splicing for different EDF lengths, as well as the limited tuning range of the tunable filter at the longer wavelength end (especially for EDF length of 12.5 and 30 m). However, we have verified the accuracy of the theoretical model and have shown the effects of active fiber length on the output power and tunability in an EDFRL. Compared with the previous reports [5,6], we have studied the effects of the active fiber length within a much larger range that gives much more, nearly entire details of its influences on the laser performance, and have included the effects of PIQ for the first time.

Although the PIQ is undesirable in most cases of fiber lasers because it causes a detrimental increase in the threshold, a reduction in conversion efficiency in EDFLs [13], it is found from our studies that PIQ is favorable for achieving laser emission in the L-band. It is well known that laser oscillation may occur first at a wavelength of the highest output power due to the mode competition. As the PIQ-induced power reduction is larger at the shorter wavelength region than at the longer wavelength region, the wavelength of the highest output power for a PIQ affected laser system will be located at a longer wavelength than that for a non-PIQ affected one, as shown in Fig. 2. This is just favorable for achieving laser emission in the L-band. Even for multi-wavelength and tunable EDFLs, PIQ may have the same influence.

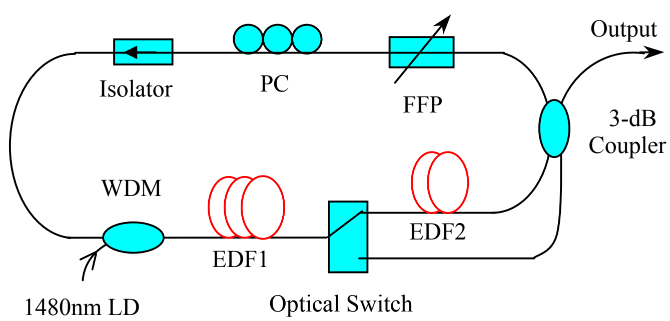

Fig. 4. Proposed laser configuration to extend the tuning range by EDF length switching.

4. Extending laser tuning range by active fiber length switching

As described in Section 2, a multiplex tunable filter for tuning the wavelength of the EDFRL was used in the experiment because a conventional tunable filter with a large tuning range is not available commercially. However, this multiplex tunable filter is inconvenient to use due to the difficulty of obtaining a continuous tuning range, and may cause some variation of the intra-cavity loss. Although we have a FFP filter with an FSR of 75 nm it cannot cover the whole tuning range of the EDFRL. Therefore, based on the aforementioned observations of the dependence of laser tunability on the active fiber length, a novel ring laser structure is developed to extend the tuning range using the method of active fiber length switching.

The laser design is shown in Fig. 4. A 1×2 optical switch is inserted into the ring cavity between the 3-dB output coupler and the EDF1. One of the output ports of the switch is directly spliced to one port of the 3-dB coupler while the other port is connected to another input port of the 3-dB coupler through a second length of active fiber, EDF2. Thus, there are two routes in the ring cavity and can be selected by the optical switch. The total active fiber length for the two routes are L_1 and $L_1 + L_2$ (L_1 and L_2 are the lengths of EDF1 and EDF2, respectively). For each route a maximum tuning range of 75 nm may be achieved but the center wavelengths are different due to the difference in total active fiber lengths. Although more than half of the two tuning ranges may be overlapped, the total tuning range is enhanced, which may be much broader than the FSR of the tunable filter by optimizing the length of the two EDFs. In the experiment, the lengths of EDF1 and EDF2 are 5.0 and 12.5 m, respectively. The total tuning range is extended to 102 nm (1516-1618 nm). The measured output power is shown in Fig. 5, which, for each EDF length, is about 0.5 dB lower than the corresponding result shown in Fig. 3. This is mainly caused by the insertion loss of the optical switch, which is about 0.8 dB for both the output ports measured at 1550 nm.

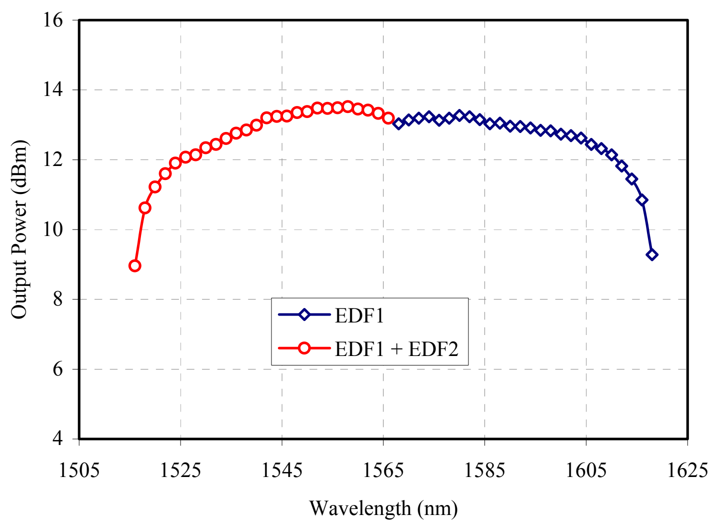

Fig. 5. Measured output power of the proposed laser design using active fiber length switching.

5. Summary

We have investigated the effects of the active fiber length, with and without taking PIQ into consideration, on the tunability of EDFRLs. The simulation results have been verified by experiments. We have found that the tuning range shifts from C-band to L-band with an increase in the active fiber length. A maximum tuning range over 100 nm, covering both the C- and L-band, can be achieved with an optimized active fiber length. In addition, the PIQ has been found to be favorable for achieving L-band lasing though it reduces the output power and degrades the power flatness. Based on these findings, a novel method employing active fiber length switching has been proposed to extend the laser's tuning range, and a large tuning range of 102 nm has been obtained using a tunable FFP filter with an FSR of 75 nm.