A high-power multi-wavelength comb laser source

Z.G. Lu, F.G. Sun, A. Lavigne, P. Lin, and C. P. Grover
Institute for National Measurement Standards, National Research Council Canada,
1200 Montreal Road, Ottawa, ON K1A 0R6, Canada; E-mail: Zhenguo.Lu@NRC.CA

ABSTRACT

We present a simple method to generate a stable high-power (> 30 dBm) multi-wavelength ytterbium / erbium co-doped double-cladding fiber ring laser source at room temperature. This method is based a wavelength-dependent filter through spatial mode beating between the LP_{01} and LP_{11} modes within the multimode fiber section. We also investigate the relationship between the lasing wavelengths and the length of the ytterbium /erbium fibers (YEFs), the number of lasing wavelength lines dependent on the total pumping power level and the polarization states, and the characteristics of both the wavelength switching operation and the total output power. Eight simultaneous lasing wavelengths with 0.78 nm spacing were generated at room temperature.

Key words: Simultaneous multi-wavelength generation; fiber ring laser; ytterbium/ erbium co-doped double-cladding fiber; multi-mode fiber; spatial mode beating filter

1. INTRODUCTION

Simultaneous multi-wavelength rare-earth-doped fiber lasers have attracted considerable interest due to its importance in fiber sensor systems, optical instrument testing and signal processing, and in optical communications [1-3]. Due to the relatively large homogenous gain broadening of rare-earth-doped fibers at room temperature, simultaneous multi-wavelength lasing in rare-earth-doped fiber lasers is very sensitive to variations in the cavity losses [4]. Various techniques for the reduction of wavelength competition, which originates from the homogeneous gain broadening of rare-earth-doped fibers, have been used to achieve stable simultaneous multi-wavelength oscillations [5-9]. However, the total output power of all these reported multi-wavelength laser sources [4-9] are less than 23 dBm. As we know, high brightness, high power, specially multi-wavelength lasers at the eye-safe 1550-nm range wavelengths find more and more applications in many areas such as free-space communication, spectroscopy, laser and amplifier pumping, frequency conversion and medicine [10, 11]. Because fiber-type components such as intra-cavity filters are easily damaged in the high-power (>30 dBm) output situations, there is no reported papers, as our best knowledge, to achieve a high-power multi-wavelength laser with the output power of larger than 30 dBm in the fiber ring cavity structure.

In this paper, we have experimentally demonstrated a simple method to generate a stable high-power (> 30 dBm) multi-wavelength ytterbium / erbium co-doped double-cladding fiber ring laser (YECDFRL) source at room temperature. This method is based on a wavelength-dependent filter through spatial mode beating between the LP_{01} and LP_{11} modes within the multimode fiber section by incorporation of a section of multimode optical fiber into an otherwise single-mode fiber ring cavity. We also investigate their relationships between the lasing wavelengths and the length of the ytterbium /erbium fibers (YEFs), the number of lasing wavelength lines dependent on the total pumping power level and the state of the polarization (SOP) of the lasing lights, and the characteristics of both the wavelength switching operation and the total output power. The main advantages of this high-power YECDFRL have the simple structure and the controllable output. Experimental results indicate that the spatial mode beating effect for the wavelength-dependent filter can be enhanced and adjusted by the changes of the SOP of the lasing lights in the YECDFRL. Eight simultaneous lasing wavelengths with 0.78 nm spacing were generated at room temperature and the total output power of the multi-wavelength YECDFRL was larger than 1550 mw when the length of the YEF was 1220 cm.

Information Optics and Photonics Technology, edited by Guoguang Mu,
Francis T. S. Yu, Suganda Jutamulia, Proceedings of SPIE Vol. 5642
(SPIE, Bellingham, WA, 2005) · 0277-786X/05/$15 · doi: 10.1117/12.573038

2. EXPERIMENTAL SET-UP AND RESULTS

Fig. 1 shows the configuration of an ytterbium / erbium co-doped double-cladding fiber ring laser (YECDFRL) that shows the effect of incorporating the multimode optical fiber to generate a multi-wavelength comb. The ring cavity consists of an ytterbium / erbium co-doped double-cladding fiber, a polarization controller (PC), a high-power (>5W) polarization-independent isolator, a multi-mode tapered fiber bundle (MMTFB) as a 970-nm / 1550-nm wavelength-division- multiplexing (WDM) fiber coupler, a single-mode tapered fiber bundle (SMTFB) as another 970-nm /1550-nm WDM fiber coupler and a 3-dB single-mode fiber coupler. The Yb^{3+} / Er^{3+} co-doped fibers were optically pumped by two multimode laser diodes of 970-nm, which total maximum pumping power can reach up to 6200 mW, through a MMTFB and a SMTFB. The 3-dB single-mode fiber coupler acted as a 50% output coupler for the YECDFRL. A fiber polarization controller (P.C.) was used in the cavity to control the state of polarization (SOP) of the YECDFRL. Here, we are using the MMTFB as two roles: one is as a WDM to combine the 970-nm multi-mode pump laser and the 1550-nm signal together and the second is as a multimode fiber to form a spatial mode beating filter. In order to eliminate the spatial hole burning and to prevent any back reflections, a high-power (>5W) polarization-independent optical isolator was employed in the ring cavity to ensure unidirectional operation.

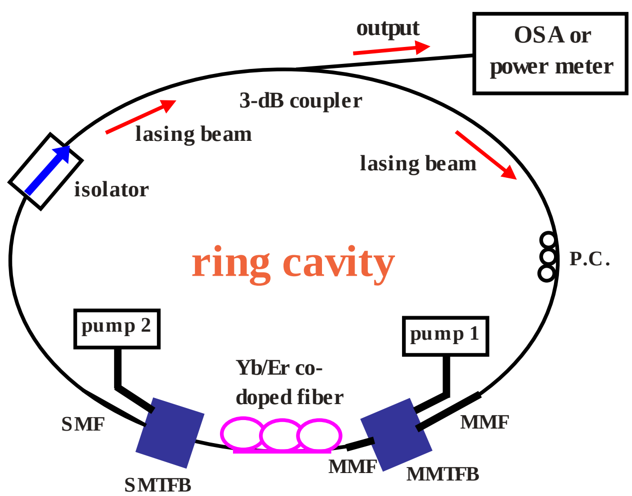

Fig. 1. Configuration of a multi-wavelength ytterbium / erbium co-doped double-cladding fiber ring laser (YECDFRL)

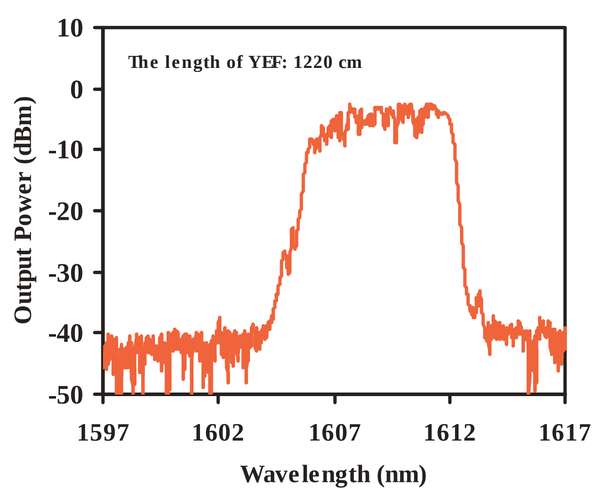

Fig. 2. The optical output spectrum of the YECDFRL when the ring cavity contained only single-mode optical fibers

We have investigated the performance characteristics of the YECDFRL. In the experiment, we have used a 10/90 coupler to ensure 10% output signals to an Ando AQ6317B Optical Spectra Analyzer (OSA) and 90% output signals to an ILX Lightwave's 10-W Fiber Optic Multimeter (OMM-6810B) for our data taking. Fig. 2 shows the lasing spectra obtained with an OSA when the ring cavity contained only single-mode optical fibers, in which we have used the single-mode tapered fiber bundle (SMTFB) to replace the multi-mode tapered fiber bundle (MMTFB). The lasers oscillated with a relatively broad structureless output spectrum, which was expected for a fiber laser cavity with no frequency-selective elements. Even we used an arrayed waveguide grating (AWG) filter with 100-GHz spacing in the YECDFRL as a multi-wavelength selective component, the stable simultaneously multi-wavelength laser could not be obtained due to the serious mode competition in homogeneous broadening gain medium [12]. However, when we have used the MMTFB with the length of 6 m as the 970-nm / 1550-nm WDM in the YECDFRL as shown in Fig.1, i.e. when the multimode fiber section was included in the laser cavities, the laser output spectra has been significantly changed, as shown in Fig.3. With a multi-mode fiber in the YECDFRL, the coupling between different modes can overcome the mode competition at room temperature. In such a single-mode and multi-mode fiber structures, lot of modes with different polarization states experienced a series of energy interchanging processes, which result in a transmission comb filter [13]. The lasers then emitted several wavelengths simultaneously, forming a comb-type structure because of the transmission function of the spatial mode beating filter [14]. The multi-wavelength output occurred even though there was no special control over the precise splicing details between the single-mode and multimode optical fibers. The wavelength-dependent loss produced by this effective filter is also evident as a modulation on the amplified spontaneous emission (ASE) background on the laser spectra as shown in Fig.3.

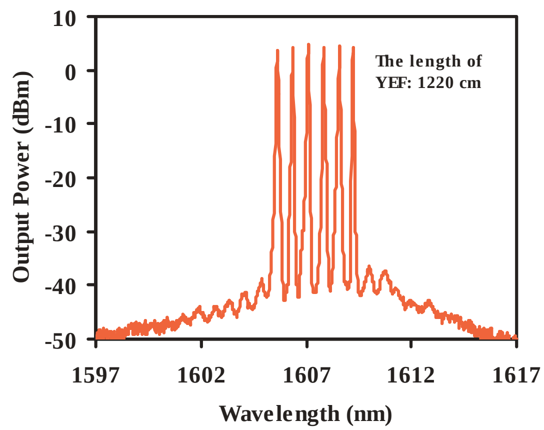

Fig.3. The optical output spectrum of the YECDFRL when the cavity contained a piece of multimode optical fiber

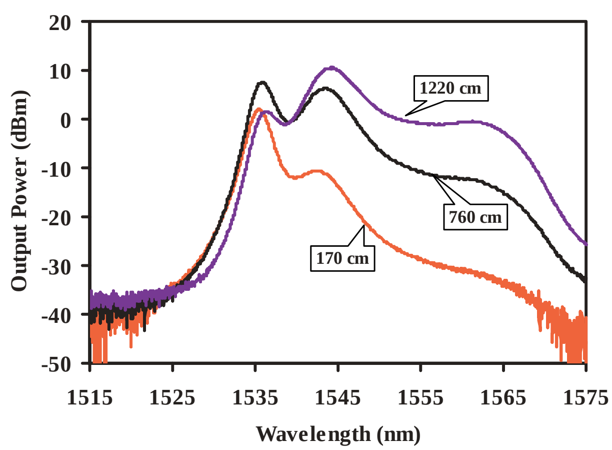

Fig.4. Optical spectra of the ASE from YECDFAs with different lengths of YEF. The total pump power is 5 W

The spectra of the ASE from Yb^{3+} / Er^{3+} co-doped fiber (YEF) amplifiers with different YEF length were different when we disconnected the ring cavity at the after-isolator point as shown in Fig.1. Fig.4 shows the spectra of the ASE. From Fig.4, we know the ASE spectra and the ASE power were shifting to longer wavelength when we increased the length of YEF. When we use these three different YEFs to build the YECDFRL as shown in Fig.1, we can achieve the different multi-wavelength laser output spectra as shown in Fig.5 (a)-(c). From Fig.5, it is clearly indicated that the lasing wavelength is shifting to the longer wavelength when the YEF length is increasing. The gain of any wavelength obtained from the section of Yb^{3+} / Er^{3+} co-doped fiber (YEF) will be affected by each other. Thus, the lasing wavelengths may suppress each other through cross-gain saturations in the YEFs. However, the strengths of the competition effects depend on the lengths of YEFs and the different pump levels. Therefore, if the lengths of the YEFs were optimized, the oscillation condition for each potential lasing wavelength might be satisfied simultaneously, resulting in simultaneous multi-wavelength oscillations. If the oscillation conditions for different wavelengths were satisfied at different pump levels, wavelength switching operation may be achieved by changing the pump input power for the certain YEF length. Figs. 6 (a) – (c) shows the spectra of the multi-wavelength lasers pumped with different power level: (a) 800 mw; (b) 2000 mw; and (c) 4000 mw when the YEF's length was 1220 cm. The results have clearly indicated the YECDFRL has the characteristics of the wavelength switching operation and the number of the lasing multi-wavelength is decreasing when the total pump power is increasing.

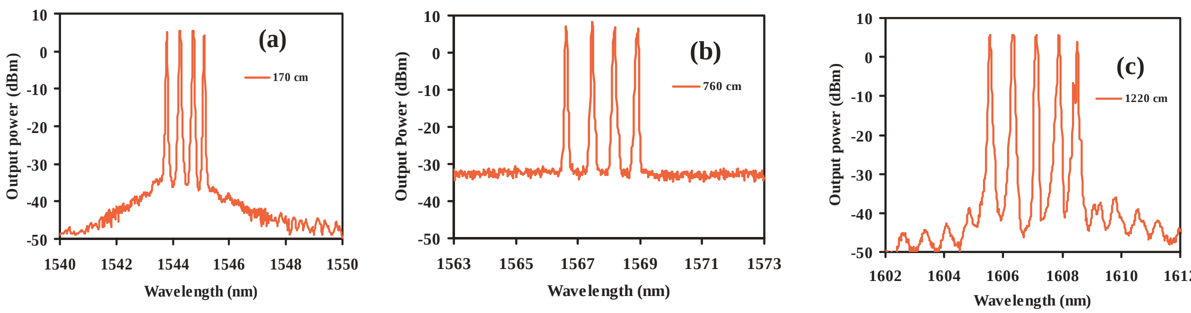

Fig.5. The multi-wavelength laser output spectra of the YECDFRL for different lengths of YEF. (a) The length of YEF: 170 cm; (b) The length of YEF: 760 cm; (c) The length of YEF: 1220 cm

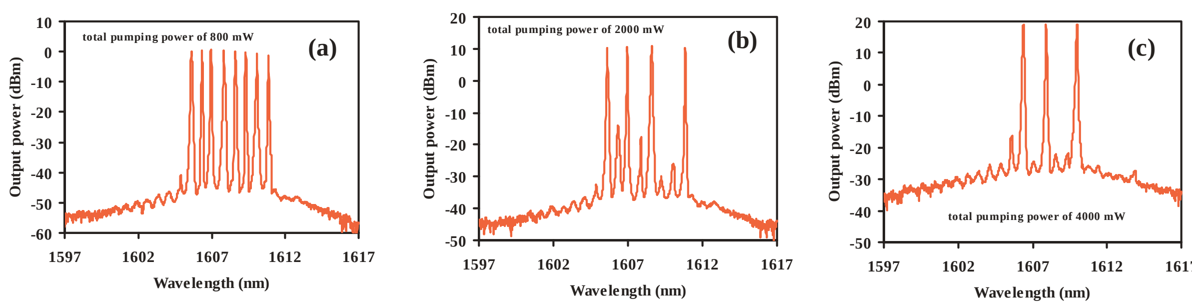

Fig. 6. The multi-wavelength laser output spectra of the YECDFRL pumped with different power level: (a) 800 mw; (b) 2000 mw; and (c) 4000 mw when the length of the YEF was 1220 cm.

Fig.7 has shown the total output power characteristics of YECDFRL versus the total pump power in three different lengths of YEF. When the length of the YEF was 1220 cm and the total pumping power was larger than 4000 mw, the output power of the multi-wavelength YECDFRL was larger than 30 dBm. By precisely controlling the P.C. to achieve the proper SOP of the lasing multi-wavelength lines, the YECDFRL tends to oscillate at different number of wavelengths with different peak spaces at room temperature, as shown in Figs. 8 (a) and (b). The lasing wavelengths are located in the range of 1597 nm – 1611 nm when the length of YEF is 1220 cm. The smallest peak space obtained in the experimental is 0.78 nm between two adjacent wavelength, with as many as eight simultaneous discrete peaks. Position and number of laser wavelengths depend on the SOP of the lasing lights. Tw0 adjacent peak space with a range of 0.78 nm to 10.94 nm can be obtained as shown in Fig.8 (a) and (b). In our experiments, the shortest and longest wavelengths are 1597.68 nm and 1610.78 nm, respectively, when the length of the YEF was

1220 cm and we had carefully adjusted the P.C. within the YECDFRL. For our multi-wavelength YECDFRL, the two adjacent peak spaces were between 0.78 nm and 10.94 nm. The line-width of each lasing wavelength was less than 0.1 nm, and the side-mode-suppression-ratio (SMSR) was over 40 dB. The multi-wavelength oscillation was quite stable when the number of the lasing wavelength lines was less than 9 and the total pumping power was less than 6000 mW for the YEF length of 1220 cm. When the number of the lasing wavelength lines was more than 8, the oscillation of the YECDFRL was not stable because too much wavelengths of lasers enhanced the competition in the same gain medium.

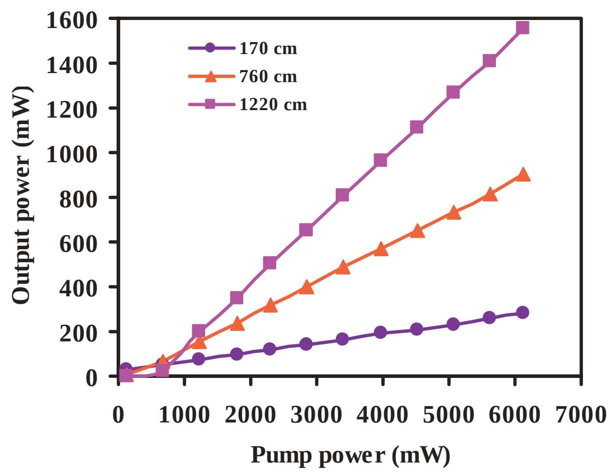

Fig.7. The total output power of the multi-wavelength YECDFRL versus the total pump power in three different lengths of YEF

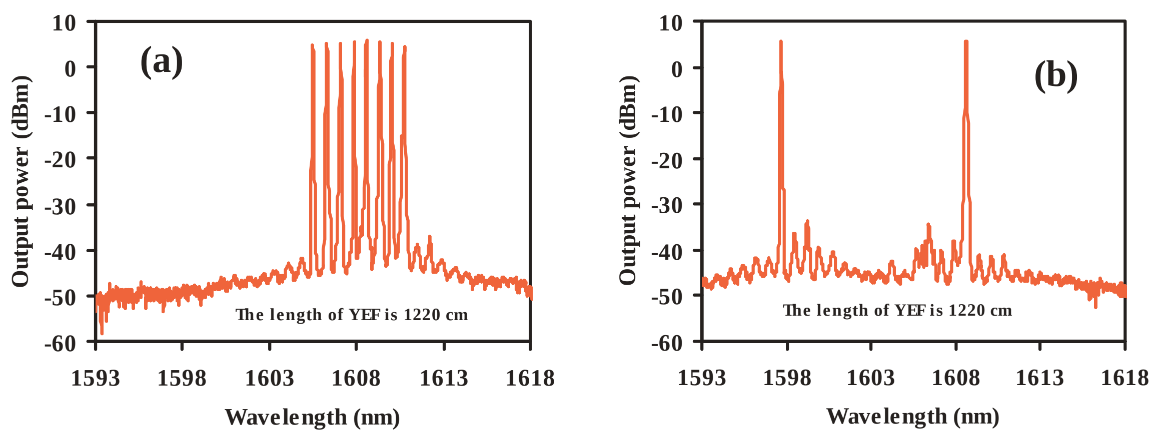

Fig.8. The output spectra of the multi-wavelength YECDFRL when precisely controlling the state of the polarization controller: (a) eight wavelengths with the space of 0.78 nm; (b) two wavelengths with the space of 10.94 nm

3. ANALYSIS AND DISCUSSIONS

In this paper, we investigate how the simple inclusion of a section of multimode optical fiber in an otherwise single-mode fiber ring laser can change the optical spectrum of the laser so that it emits several well-defined wavelength lasing lights simultaneously. We used multimode fiber that supports only a few waveguide modes, specifically, the LP_{01} and LP_{11} mode families. The oscillation wavelengths are determined from the loss modulation produced in the laser cavity by an effective optical filter made up of a single-mode / multimode / single-mode fiber combination. The wavelength filtering action arises from the spatial mode beating that occurs between the LP_{01} and LP_{11} guided modes in the multimode optical fiber section. The symmetric LP_{01} and antisymmetric LP_{11} modes are both excited in this section if the first single-mode waveguide is slightly laterally offset with respect to the multimode guide. This will in general occur at a typical fusion splice between the optical fibers. These modes propagate down the multimode fiber with a differential propagation constant $\Delta\beta = (LP_{01}) - \beta(LP_{11})$ and a beat length given by the $L_B = 2\pi/(\Delta\beta)$. In a typical optical fiber, this beat length is of the order of a few hundred micrometers. At the second single-mode / multimode interface, the fraction of the optical power launched back into the single-mode waveguide from the multimode section is determined by the overlap of the composite electric field with the single-mode waveguide field. When the length of the multimode fiber is a large number of spatial beat lengths, the wavelength-dependent transfer function of this multiple-beat-length filter becomes a comb, and lasing preferentially occurs at the peaks of the transmission.

The fiber polarization controller (P.C.) was used to control the state of polarization (SOP) of the YECDFRL and the number of lasing multi-wavelength lines in the laser output spectrum. The reasons are altering the fiber cavity birefringence by the P.C. allowed the different polarized mode components within the LP spatial mode families to be excited in the multimode fiber. The spatial mode beating with these different mode polarizations generated a different filter transmission function for each polarization component due to the birefringence in the multimode fiber. This effect permitted the P.C. to be adjusted so that the laser generated a polarization-degenerate output or two orthogonally polarized wavelength combs.

4. CONCLUSIONS

We have demonstrated that introducing a multimode optical fiber section into an ytterbium / erbium co-doped double-cladding fiber ring laser to construct high-power simultaneous multi-wavelength sources. The output power with simultaneous multi-wavelength lasing lines is larger than 1550 mW. Stable eight wavelengths with the 0.78-nm spacing between two adjacent peaks are generated at room temperature. The fiber filters based on spatial mode beating between the LP_{01} and LP_{11} modes within the multi-mode fiber section have the advantages of effective optical pathlength control through the use of fiber polarization controllers. This high power multi-wavelength YECDFRL is compact and easy to construct and tune. It can be used to characterize the spectral properties of optical systems at several wavelengths simultaneous.

REFERENCES

1. L. Talaverano, S. Abad, S. Jarabo, and M. Lopez-Amo, “Multiwavelength fiber laser sources with bragg-grating sensor multiplexing capability,” J. Lightwave Technol., vol.19, No.4, pp. 553-558, April 2001.
2. B.R. Washburn, S.A. Diddams, and N.R. newbury, J.W. Nicholson, M.F. Yan, and C.G. Jorgensen, “Phase-locked, erbium-fiber-laser-based frequency comb in the near infrared,” Opt. Lett., Vol. 29, No. 3, pp.250-252, February 2004.
3. Z.G. Lu, F.G. Sun, G.Z. Xiao, and C.P. Grover, “A tunable multi-wavelength fiber ring laser for measuring polarization mode dispersion in optical fibers,” IEEE Photonics Technology Letters, Vol.16, 1280-1282, May 2004.
4. J. Chow, G. Town, B. Eggleton, M. Ibsen, K. Sugden, and I. Bennion, “Multiwavelength generation in an erbium doped fiber laser using in fiber comb filters,” IEEE Photon. Technol. Lett., vol.8, pp. 60-62, Jan. 1996.
5. Q. Mao, and J.W.Y. Lit, “Multiwavelength erbium-doped fiber lasers with active overlapping linear cavities,” J. Lightwave Technol., vol.21, pp.160-169, January 2003.
6. X.P. Dong, S. Li, K.S. Chiang, M.N. Ng, and B.C.B. Chu, “Multiwavelength erbium-doped fiber laser based on a high birefringence fiber loop mirror,” Electron. Lett., vol. 36, no.19, pp. 1609-1610, 2000.
7. J. Yang, S.C. Tjin, and N.Q. Ngo, “Multiwavelength tunable fiber ring laser based on sampled chirp fiber Bragg grating,” IEEE Photon. Technol. Lett., Vol.16, pp.1026-1028, April 2004.
8. Y.G. Han, C.S. Kim, J.U. Kang, U.C. Paek, and Y. Chung, “Multiwavelength Ramam fiber-ring laser based on tunable cascaded long-period fiber gratings,” IEEE Photon. Technol. Lett., vol.15, pp.383-385, March 2003.
9. P.C. Peng, H.Y. Tseng, and S. Chi, “A tunable dual-wavelength erbium-doped fiber ring laser using a self-seeded Fabry-Perot laser diode,” IEEE Photon. Technol. Lett., vol.15, pp.661-663, May 2003.

10. S.G. Grubb, “High-power fiber amplifiers and lasers,” Proceeding of Conference in Optical Amplifiers and their Applications, vol.5, Washington, DC, pp. 42-44, 1996.
11. S.D. Jackson, and A. Lauto, “Diode-pumped fiber lasers: A new clinical tool?” Lasers Surgery Med., vol.30, pp. 184-190, 2002.
12. Z.G. Lu, P. Lin, and C.P. Grover, “A dynamically gain erbium-doped fiber amplifier,” Microwave and Optical Technology Letters, Vol.39, pp.8-11, October 2003.
13. M. Earnshaw, N. Finlayson, A. Poustie, G. Maxwell, “An optical multiwaveguide interference filter,” Optics Communications, Vol. 116, pp. 339-342, May 1995.
14. A.J. Poustie, N. Finlayson, and P. Harper, “Multiwavelength fiber laser using a spatial mode beating filter,” Optics Letters, Vol.19, No.10, pp.716-718, May 1994.