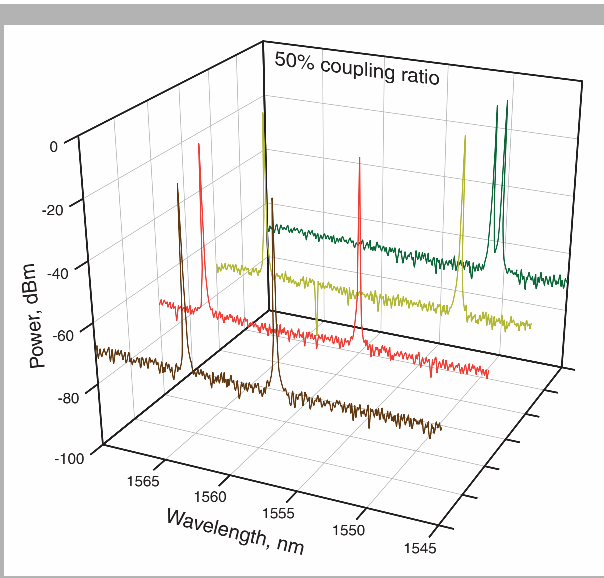
Using optimal cavity loss and saturable-absorber passive filter for stable and tunable dual-wavelength erbium fiber laser in single-longitudinal-mode operation

2011 Laser Phys. Lett. 8 672

(http://iopscience.iop.org/1612-202X/8/9/007)

Laser Phys. Lett. **8**, No. 9, 672–677 (2011) / **DOI** 10.1002/lapl.201110043

Abstract: In this investigation, we propose and demonstrate experimentally tunable and stable dual-wavelength erbium doped fiber (EDF) double-ring laser scheme using different coupling losses inside cavity loop for wavelength and mode spacing tuning. Besides, a shorter unpumped EDF is also used to filter the side-modes for lasing wavelength in single-longitudinal-mode (SLM) operation. However, the output mode spacing of dual-wavelength could be limited owing to the homogeneous broadening nature of EDF. As a result, the output performance of the proposed fiber laser have also been analyzed and discussed, such as wavelength tuning range, output power, side-mode suppression ratio (SMSR), stabilities of lasing wavelength and power, relative intensity noise (RIN), etc.



Output spectra of lasing dual-wavelength with four samples for the proposed fiber laser in the operating wavelengths under the 50% cavity loss status

Using optimal cavity loss and saturable-absorber passive filter for stable and tunable dual-wavelength erbium fiber laser in single-longitudinal-mode operation

C.H. Yeh, [1,*] *C.W. Chow,* [2] *Y.F. Wu,* [1,2] *Y.H. Lin,* [2] *B.C. Cheng,* [3] *and J.H. Chen* [4]

[1] Information and Communications Research Laboratories, Industrial Technology Research Institute (ITRI), Hsinchu 31040, Taiwan
[2] Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan
[3] Department of Physics, Fu Jen Catholic University, New Taipei 24205, Taiwan
[4] Department of Photonics, Feng Chia University, Taichung 40724, Taiwan

Received: 8 April 2011, Revised: 11 April 2011, Accepted: 14 April 2011
Published online: 1 July 2011

Key words: erbium-doped fiber (EDF); dual-wavelength; single-longitudinal-mode (SLM); fiber laser

1. Introduction

Recently, multi-wavelength erbium-doped fiber (EDF) lasers have been widely investigated [1–5]. This is because the multi-wavelength fiber ring lasers are important light source with high potential applying in several applications, which are used in fiber sensing network, optical instrument testing, optical signal processing, and wavelength division multiplexed (WDM) networks [6–9].

However, the homogeneous gain broadening of nature EDF could result in wavelength competition. Many stud-

[*] Corresponding author: e-mail: depew@itri.org.tw, yeh1974@gmail.com

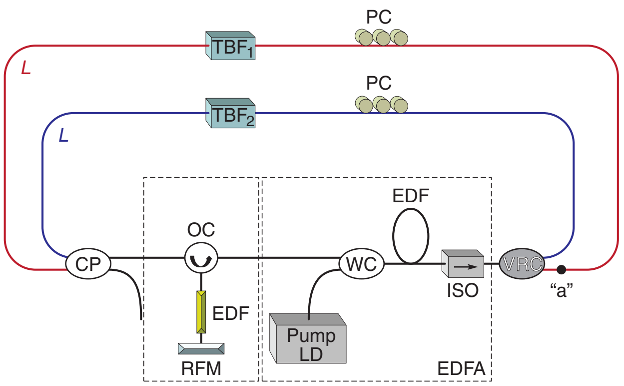


Figure 1 (online color at www.lphys.org) Experimental setup for the proposed EDF laser structure

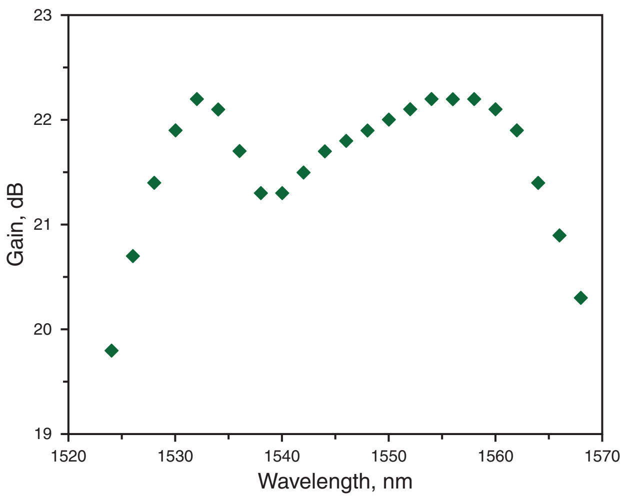


Figure 2 (online color at www.lphys.org) Output gain spectrum of EDFA in the measurement, when the probed power was set at –20 dBm in the wavelength range of 1524 to 1568 nm

ies have been proposed by using optical filters inside the fiber ring cavity for generating single frequency or multi-wavelength output [8–13]. Hence, several technologies of dual-wavelength fiber ring lasers have been reported, such as using a coupled-ring scheme with fiber gratings, utilizing arrayed waveguide grating (AWG), using intracavity loss optimization or Sagnac loop loss designs, employing a twin-peak reflection grating inside fiber cavity, etc. [10–17]. And then, to obtain broadband tuning range for dual-wavelength lasing, high-birefringence fiber loop mirror has also been reported [18]. Besides, employing self-injected Fabry-Pérot laser diode (FP-LD), using distributed feedback laser diode (DFB-LD) with fiber Bragg grating (FBG), and utilizing optical filter to generate wavelength output have also been proposed and analyzed [19–22].

In this study, we propose and demonstrate an EDF laser by using double ring cavities, two tunable bandpass filters (TBFs) and a shorter length of unpumped EDF to achieve stable and tunable dual-wavelength output in single-longitudinal-mode (SLM). Due to the gain competition of EDF nature, it would result in the mode-spacing change when the dual-wavelength lasing in different output band. Hence, we also employ the different coupling loss inside loop cavity to discuss and analyze the output characteristics for the mode-spacing of dual-wavelength. Moreover, a shorter EDF in the laser scheme can be used to serve as the saturable-absorber filter for filtering other side-modes for SLM operation. Here, the wavelength tuning range of the proposed dual-wavelength laser is distributed at 1524.35 to 1566.25 nm. And the minimum and maximum mode-spacing of dual-wavelength are measured at 9.2 and 41.9 nm, 0.9 and 11.1 nm, and 0.7 and 13.35 nm, respectively, when the coupling losses are 10, 30, and 50% in cavity loop. Finally, the output performance of the proposed laser has also been performed and discussed.

2. Experiment and discussions

The experimental setup for the proposed EDF laser structure is shown schematically in Fig. 1. The proposed laser scheme consists of an erbium-doped fiber amplifier (EDFA), two tunable bandpass filters (TBF), one 2×2 and 50:50 optical coupler (CP), two polarization controllers (PCs), a variable ratio coupler (VRC), an optical circulator (OC), a 1 m long EDF and reflected fiber mirror (RFM). The EDFA consisted of a 10 m long EDF, an optical isolators (OIS), a 1550/980 nm WDM coupler (WC), and a 980 nm pumping laser diode with 76.4 mW output power. In the experiment, two TBFs are utilized inside the gain cavity to generate dual-wavelength output. The wavelength tuning ranges and 3 dB bandwidths of two TBFs were both 40 nm (1525 to 1565 nm) and 0.4 nm. One bandpass filter is tuned to lasing then fixed; the other band-pass filter is scanned for the other lasing wavelength. Besides, the two PCs were used to adjust the properly polarization status and obtain maximum output power of lasing dual-wavelength. Here, two ring cavities are set to be the same length of nearly 22 m. To achieve the SLM output for the dual-wavelength, the saturable-absorber filter, which constructed by an OC, a 1 m long EDF and a RFM with 99% reflectivity in C-band window, is employed for signal filtering. This is because that the spatial hole burning (SHB) effect [23–25] can be observed in this reflection-typed saturable absorber unit, and thus a narrow-band Bragg grating filter is created. The output spectrum is monitored and stored by an optical spectrum analyzer (OSA) with a 0.01 nm resolution. The VRC can be changed from 50:50, 30:70, and 10:90, respectively, to produce the different gain cavity losses for dual-wavelength selection, as illustrated in Fig. 1. Once the VRC is setup, two TBFs

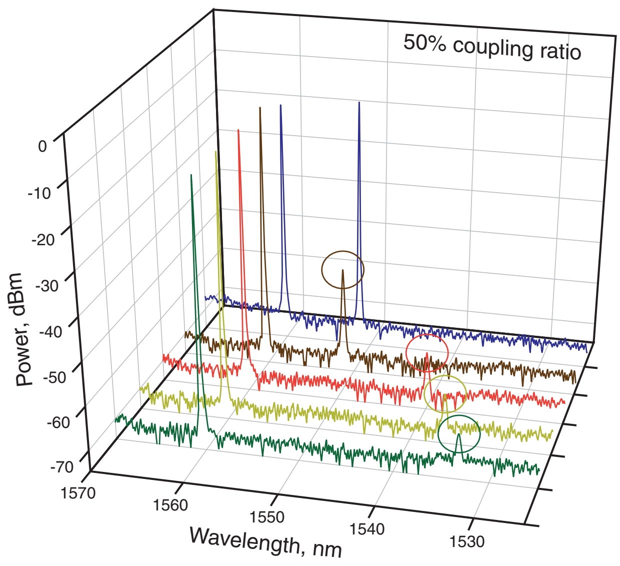


Figure 3 (online color at www.lphys.org) Output spectra of dual-wavelength when the TBF_2 (λ_2) is tuned and shifted to the shorter wavelengths gradually, and the coupling loss is 50%

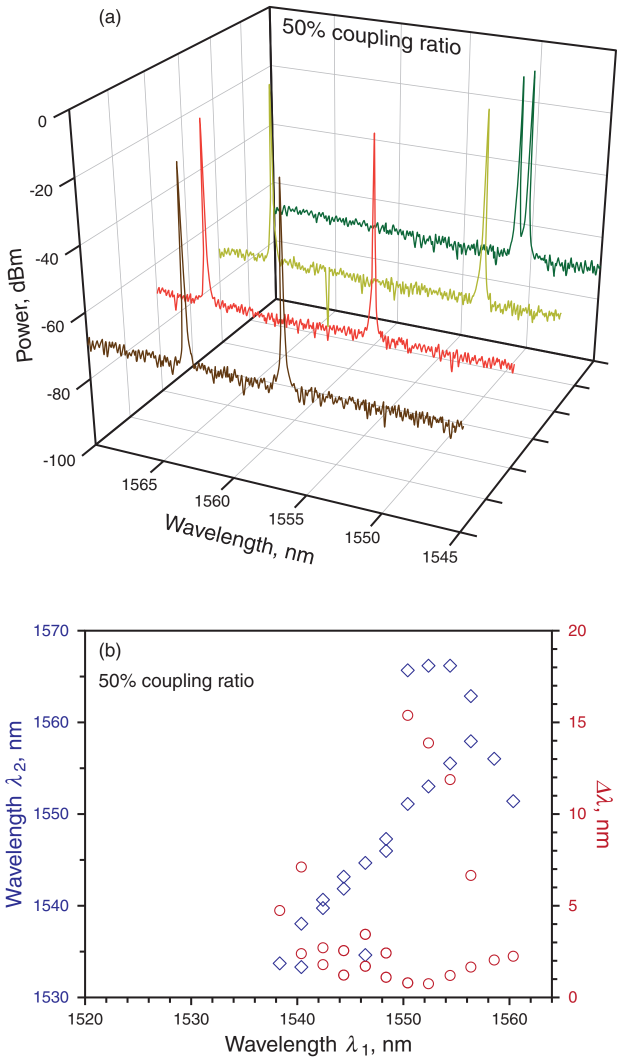


Figure 4 (online color at www.lphys.org) (a) – output spectra of lasing dual-wavelength with four samples for the proposed fiber laser in the operating wavelengths under the 50% cavity loss status and (b) – observed wavelength locations of two lasing wavelengths (λ_1 and λ_2) and its corresponding mode-spacing for the proposed dual-wavelength laser

are adjusted to scan the lasing wavelength from 1525 to 1565 nm; and the lasing wavelength range is limited by the gain nature of EDFA used.

So, Fig. 2 presents the gain spectrum of EDFA in the measurement, when the probed power was set at –20 dBm in the wavelength range of 1524 to 1568 nm. Here, we could also obtain the gain value of >20 dB in the operating region. In this measurement, first we fix the passband of TBF_1 at 1560.35 nm (λ_1) and then tune the TBF_2 to observe the dual-wavelength output when the coupling ratio is set at 50% in "a" point (as seen in Fig. 1). Hence, Fig. 3 presents the output spectra of dual-wavelength when the TBF_2 (λ_2) is tuned and shifted to the shorter wavelengths gradually. We can measure the dual-wavelength at 1560.35 and 1551.45 nm with 2.2 dB power variation (ΔP) first. When the λ_2 is tuned to the shorter wavelengths at 1551.35, 1540.0, 1536.35, and 1533.25, respectively, we also can retrieve the corresponding power variations of 26.7, 47.9, 49.8, and 51.1 dB, as shown in Fig. 3. Even though we can observe the dual-wavelength lasing at the other wavelengths, but the measured ΔP also needs to consider. To observe the smaller ΔP of proposed laser, the power variation of dual-wavelength will be measured within 3 dB in the following experiments.

In the proposed laser, we first use the coupling ratio of 50% at "a" point in Fig. 1. Originally, we fixed the passband of TBF_1 at the wavelength of 1560.35 nm (λ_1). Then, we varied and tuned the passband of TBF_2 from 1560.35 nm (λ_2) to the shorter wavelengths gradually in order to generate different mode-spacing ($\Delta\lambda$) of lasing dual-wavelength. Next, we begin to tune the fixed wavelength l1 to shorter wavelengths gradually with 2 nm tuning step, and then scan the λ_2 to generate the dual-wavelength output. Hence, Fig. 4a shows the output spectra of lasing dual-wavelength with four samples for the proposed fiber laser in the operating wavelengths under the 50% cavity loss status. Fig. 4b presents the wavelength locations of two lasing wavelengths (λ_1 and λ_2) and its corresponding mode-spacing for the proposed dual-wavelength laser. When the fixed wavelength λ_1 is between 1540.35 and 1556.35 nm, we can obtain two sets dual-wavelength lasing at each λ_1 in this measurement. Besides, we observe that the fixed wavelength l1 can be tuned in the wavelength range of 1538.35 to

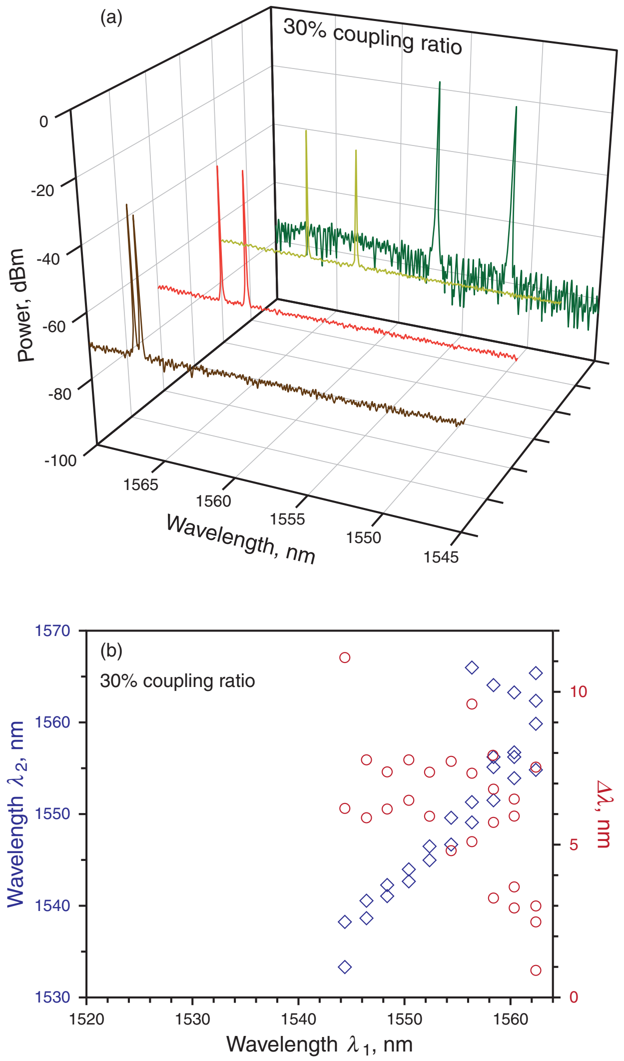


Figure 5 (online color at www.lphys.org) (a) – output spectra of lasing dual-wavelength with four samples for the proposed fiber laser in the operating wavelengths under the 30% cavity loss status and (b) – observed wavelength locations of two lasing wavelengths (λ_1 and λ_2) and its corresponding mode-spacing for the proposed dual-wavelength laser

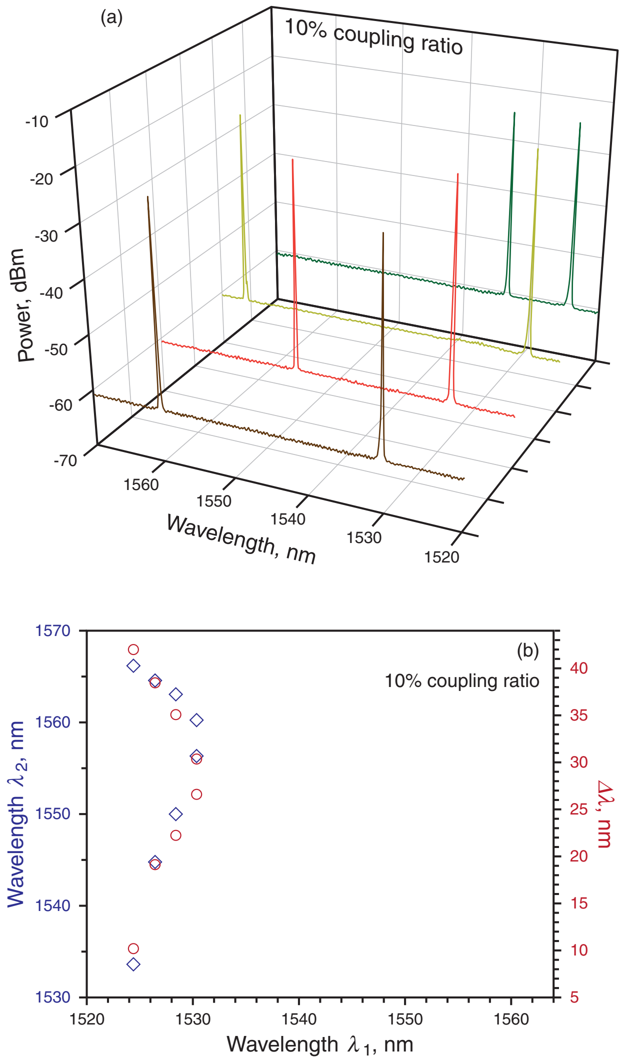


Figure 6 (online color at www.lphys.org) (a) – output spectra of lasing dual-wavelength with four samples for the proposed fiber laser in the operating wavelengths under the 10% cavity loss status and (b) – observed wavelength locations of two lasing wavelengths (λ_1 and λ_2) and its corresponding mode-spacing for the proposed dual-wavelength laser

1560.35 nm and the scanning wavelength λ_2 can be tuned at the wavelengths of 1533.65 to 1566.20 nm to obtain dual-wavelength lasing, as seen in Fig. 4b. And the maximum and minimum mode-spacing are observed at 0.8 and 15.4 nm in the tuning range.

Then, we will change the coupling ratio to 30% at "a" point in the experiment. Hence, Fig. 5a shows the output spectra of lasing dual-wavelength for the proposed fiber laser in the operating wavelengths with four samples under the 30% cavity loss status. Here, Fig. 5b presents the wavelength locations of two lasing wavelengths (λ_1 and λ_2) and its corresponding mode-spacing for the proposed dual-wavelength laser. Moreover, we accomplish that the fixed wavelength λ_1 can be tuned in the wavelengths of 1544.35 to 1562.35 nm with 2 nm tuning step and the scanning wavelength λ_2 can be tuned in the wavelengths of 1533.25 to 1565.95 nm, as shown in Fig. 5b. Furthermore, when the fixed wavelength λ_1 is between 1544.35 and 1562.35 nm with 2 nm tuning step, we can obtain two sets dual-wavelength lasing at the same λ_1 in this measurement. And we even retrieve four sets of dual-wavelength outputs while the wavelength λ_1 is fixed at 1558.35, 1560.25, and 1562.35 nm, respectively. Here, the maximum and minimum mode-spacing are observed at 0.9 and 11.1 nm in the tuning range.

Next, we change the coupling ratio of 10% in the experimental setup. So, Fig. 6a displays the output spectra of lasing dual-wavelength for the proposed fiber laser in the operating wavelengths with four samples under the 10% cavity loss status. And, Fig. 6b presents the wavelength locations of two lasing wavelengths (λ_1 and λ_2) and its corresponding mode-spacing for the proposed dual-wavelength laser. We observe that the fixed wavelength λ_1 only can be tuned at the wavelengths of 1524.35 to 1530.35 nm and the scanning wavelength λ_2 can be tuned at the wavelengths of 1533.55 to 1566.25 nm, as shown in Fig. 6b. In the entire tuning range of fixed wavelength λ_1, we obtain two sets dual-wavelength lasing at each tuned wavelength λ_1. As shown in Fig. 6b, with the increase wavelength of λ_1 in the operating range gradually, the measured mode-spacing would also decrease. And the maximum and minimum mode-spacing are observed at 9.2 and 41.9 nm in the tuning range.

Moreover, we also investigate the stability performances of output wavelength and power in the proposed stable dual-wavelength tuning EDF ring laser. In this experiment, we set the lasing dual-wavelength at 1556.35 (λ_1) and 1547.40 nm (λ_2) with –10.0 and –10.4 dBm output powers initially, when the coupling loss is set at 50% in this laser scheme. So, after 30 minutes observation time, the measured two lasing wavelengths are no change and the two observed maximum power variations are within 2 dB under the observing-time. Furthermore, to realize the performance of SLM output, a self-homodyne measurement is performed. Here, Fig. 7 shows the detected self-homodyne frequency spectrum of the proposed laser at the selected wavelength of 1547.40 nm without and with saturable-absorber filter. If the saturable-absorber filter is removed in the laser cavity, it would produce a noisy and unstable output signal due to the mode-hopping effect, as seen in Fig. 7. The behavior of mode-hopping can be affected by the environment disturbances of temperature and vibration. Clearly, no beating noises are observed in relative intensity to noise (RIN) spectrum of the proposed laser which indicates that single frequency oscillation can be retrieved. Besides, Fig. 7 shows a stable SLM output with side-mode suppression in the measuring bandwidth of 500 MHz. Also after 30 minutes observation time, no spike noise and stable frequency output are observed in the radio frequency spectrum of the proposed laser.

As mentioned above, comparing with the experimental results of Fig. 4 to Fig. 6, they indicate some features. With the reduction of coupling ratio inside the laser cavity gradually, the tuning range of fixed wavelength λ_1 would also reduce. However, the retrieved tuning range of scanning wavelength λ_2 can be also between 1533 and 1566 nm under different three coupling ratios. Besides, when the coupling ratio was decreasing, we could get more sets of dual-wavelength lasing at the same λ_1 and also observe the larger mode-spacing, as seen in Fig. 4 to Fig. 6.

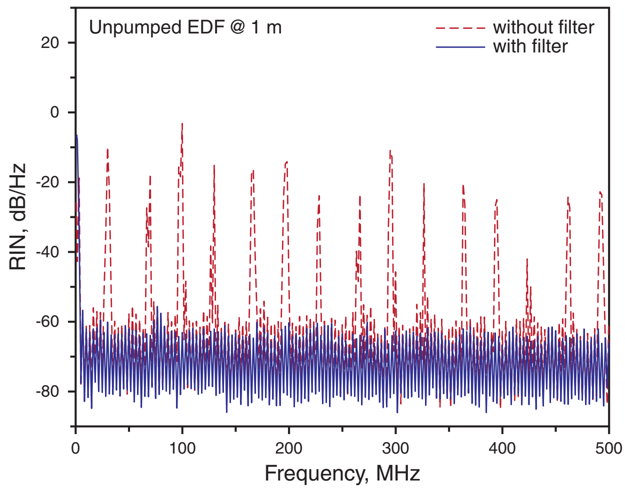


Figure 7 (online color at www.lphys.org) Detected self-homodyne frequency spectrum of the proposed laser at the selected wavelength of 1547.40 nm without and with saturable-absorber filter

3. Conclusion

In summary, we have proposed and demonstrated experimentally tunable and stable dual-wavelength EDF double-ring laser scheme using different coupling ratios insides cavity loop for wavelength and mode spacing tuning. In addition, a shorter unpumped EDF is also used to filter the side-mode in SLM operation. Here, the proposed laser construction is simple but efficiency and the spectrum distributions and wavelength differences of this construction with three different coupling ratios are analyzed. However, the output mode spacing of dual-wavelength is limited due to the homogeneous broadening of EDF under various cavity loss used. And, the output performance of the proposed fiber laser are analyzed and discussed, such as wavelength tuning range, output power, SMSR and stabilities of lasing wavelength and power, etc. As a result, the proposed laser has the following advantages: (i) two wavelengths can be tuned separately using the two TBFs; (ii) the mode-spacing can also be tuned by adjusting the coupling ratio inside cavity; (iii) the laser has a broadly tuning range; and (iv) the laser structure is relatively simple.

References

[1] C.-H. Yeh, C.-W. Chow, Y.-F. Liu, and C.-L. Pan, Laser Phys. **21**, 496–499 (2011).
[2] C.-H. Yeh and C.-W. Chow, Opt. Fiber Technol. **16**, 271–273 (2010).
[3] N. Park and P.F. Wysocki, IEEE Photon. Technol. Lett. **8**, 1459–1461 (1996).
[4] S.-Y. Chou, C.-H. Yeh, and S. Chi, Laser Phys. Lett. **4**, 382–384 (2007).

[5] C.-H. Yeh, F.-Y. Shih, C.-T. Chen, C.-N. Lee, and S. Chi, Opt. Express **15**, 13844–13848 (2007).
[6] S.P. Li, H. Ding, and K.T. Chan, Electron. Lett. **33**, 52–53 (1997).
[7] S.-P. Chen, L. Ding, S.-M. Wang, Y.-G. Li, K.-C. Lu, and S.-H. Zhou, Laser Phys. Lett. **3**, 584–587 (2006).
[8] G. Das and J.W.Y. Lit, IEEE Photon. Technol. Lett. **14**, 606–608 (2002).
[9] L. Talaverano, S. Abad, S. Jarabo, and M. López-Amo, J. Lightwave Technol. **19**, 553–558 (2001).
[10] H. Okamura and K. Iwatsuki, Electron. Lett. **28**, 461–463 (1992).
[11] S.V. Chernikov, J.R. Taylor, and R. Kashyap, Opt. Lett. **18**, 2023–2025 (1993).
[12] S.V. Chernikov, R. Kashyap, P.F. McKee, and J.R. Taylor, Electron. Lett. **29**, 1089–1091 (1993).
[13] C.-H. Yeh, F.Y. Shih, C.T. Chen, and S. Chi, Opt. Express **15**, 17980–17984 (2007).
[14] A.A. Latif, M.Z. Zulkifli, N.A. Hassan, S.W. Harun, Z.A. Ghani, and H. Ahmad, Laser Phys. Lett. **7**, 597–602 (2010).
[15] A.A. Latif, M.Z. Zulkifli, N.A. Awang, S.W. Harun, and H. Ahmad, Laser Phys. **20**, 2006–2010 (2010).
[16] A.W. Al-Alimi, M.H. Al-Mansoori, A.F. Abas, M.A. Mahdi, M. Ajiya, and F.R. Mahamd Adikan, Laser Phys. **20**, 2001–2005 (2010).
[17] M. Durán-Sánchez, A. Flores-Rosas, R.I. Álvarez-Tamayo, E.A. Kuzin, O. Pottiez, M. Bello-Jimenez, and B. Ibarra-Escamilla, Laser Phys. **20**, 1270–1273 (2010).
[18] H.B. Sun, X.M. Liu, Y.K. Gong, X.H. Li, and L.R. Wang, Laser Phys. **20**, 522–527 (2010).
[19] S.Q. Yang, Z.H. Li, S.Z. Yuan, X.Y. Dong, G.Y. Kai, and Q.D. Zhao, IEEE Photon. Technol. Lett. **14**, 1494–1496 (2002).
[20] P.-C. Peng, H.-Y. Tseng, and S. Chi, IEEE Photon. Technol. Lett. **15**, 661–663 (2003).
[21] C.-H. Yeh, C.-W. Chow, F.-Y. Shih, C.-H. Wang, Y.-F. Wu, and S. Chi, IEEE Photon. Technol. Lett. **21**, 125–127 (2009).
[22] C.H. Yeh, F.Y. Shih, C.H. Wang, C.W. Chow, and S. Chi, Laser Phys. Lett. **5**, 821–824 (2008).
[23] C.-H. Yeh and S. Chi, Opt. Express **15**, 3680–3684 (2007).
[24] C.-H. Yeh, M.-C. Lin, and S. Chi, Opt. Express **13**, 6828–6832 (2005).
[25] C.H. Yeh and C.W. Chow, Laser Phys. Lett. **7**, 158–163 (2010).