Broadband wavelength-tunable single-longitudinal-mode erbium-doped fiber ring laser using saturable-absorber filter

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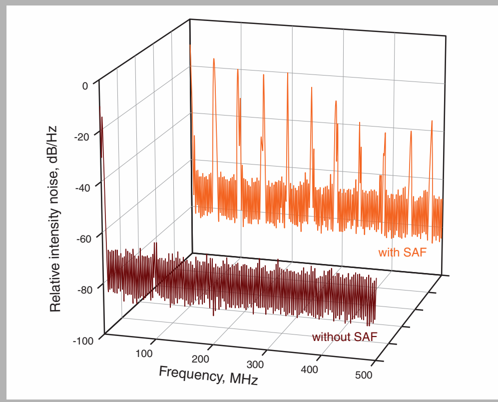
Abstract: In this paper, a broadband wavelength-tunable erbium-doped fiber (EDF) ring laser with single longitudinal mode (SLM) output achieving 82.6 nm lasing bandwidth from 1481.0 to 1563.6 nm is proposed and experimentally demonstrated. For the proposed laser scheme, the S- and C-band erbium-doped fiber amplifiers (EDFAs) in parallel structure are used to serve as the gain medium for broadband wavelength tuning. Furthermore, we use a saturable-absorber filter (SAF) inside the fiber cavity to serve as a narrow band filter to guarantee a SLM operation. Besides, the performance of output power, wavelength, side-mode suppression ratio (SMSR) and stability are also analyzed and discussed.



Self-homodyne spectra of the proposed fiber ring lasers with and without SAF operates at the wavelength of 1541.8 nm

Broadband wavelength-tunable single-longitudinal-mode erbium-doped fiber ring laser using saturable-absorber filter

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1. Introduction

Recently, the fiber ring lasers are attractive with high potential applicability in several applications, such as in fiber sensing network, performance testing of optical component, optical signal processing, and wavelength division multiplexed (WDM) networks [1–5]. Besides, fiber laser sources are important for optical instrument testing, spectroscopy, network protection, and fiber-optic gyro [6,7]. Hence, in order to achieve the broadband wavelength tuning for fiber ring lasers, the S- (1470 to 1520 nm), C- (1530 to 1560 nm), and L-bands (1560 to 1620 nm) erbium-doped fiber amplifiers (EDFAs) were used to act as gain medium inside fiber ring cavity [8–10]. Moreover, the Raman laser can also obtain widely tuning range [11], but need more expensive pumping lasers to perform. Nowadays, several technologies to generate the wavelength-tunable ring lasers have been reported and discussed, such as the FBG and mirror ends laser [10], dual-ring fiber laser [12], coherence combining fiber laser [13], bending-based laser [14], and so on.

However, due to the long fiber in the ring cavity, it has possibility of mode-hopping and results in super mode noise in frequency domain. Therefore, single longitudinal mode (SLM) output for erbium-doped fiber (EDF) ring

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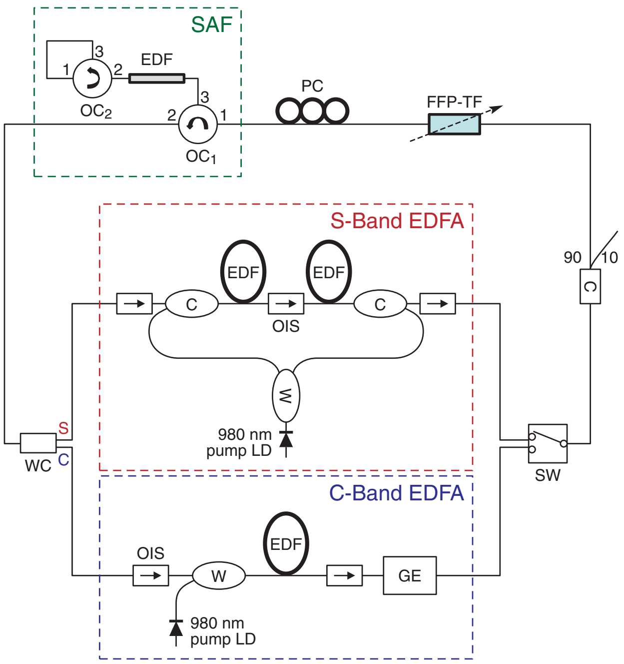

Figure 1 (online color at www.lphys.org) Experimental setup of proposed widely wavelength-tunable EDF ring laser with SLM output lasing in S- to C-band

laser is becoming all the more necessary. Several methods to achieve SLM operation have been studied, such as using multi-ring cavity scheme [15], integrating two cascaded fiber Fabry-Perot tunable filters (FFP-TFs) insides cavity [16], and using unpumped EDF as a narrow bandwidth autotracking filter [17,18]. Moreover, there were several fiber laser technologies [19–23] having been also proposed and discussed to guarantee the wavelength-tunable single-, dual-, or multi-wavelength in different operating wavelength bands for the future optical communications.

In this paper, we propose and experimentally investigate a broadband wavelength-tuning EDF ring laser using an S-band EDFA and a C-band EDFA in parallel scheme inside the ring cavity as gain medium for achieving widely wavelength tuning. To guarantee a SLM wavelength output and suppress mode hopping, a short unpumped EDF length (acting as a saturable-absorber filter (SAF)) and a tunable filter are used. The tunable filter can also be used for precise wavelength tuning. Besides, the laser performance of output power, wavelength, side-mode suppression ratio (SMSR) and stability has also been analyzed and discussed.

2. Experiments and results

Fig. 1 shows the experimental setup of the proposed fiber laser scheme. The proposed laser is consisted of an S-band EDFA, a C-band EDFA, a 1×2 C-/S-bands WDM coupler (WC), a 1×2 optical switch (SW), a 1×2 and 10:90 optical coupler (C), a fiber Fabry-Perot tunable filter (FFP-TF), a polarization controller (PC), and a saturable-absorber filter (SAF). As illustrated in Fig. 1, the S- and C-band EDF, as used inside cavity is in parallel architecture.

For the S-band EDFA module, it is composed of two-stage amplifier and a power-sharing 980 nm pump laser. And the S-band EDF inside the EDFA module with depressed cladding design can provide the sharp, high-attenuation, long-wavelength cutoff filtering. Here, the S-band EDFs in the first and second stages have different characteristics. The EDF of the first-stage is 20 m long and it can provide low noise figure and medium gain by forward pumping. The EDF of the second-stage is 30 m long and it can produce large output power by backward pumping. In addition, the optical isolator between these two stages can reduce backward amplified spontaneous emission (ASE) and improve noise figure performance. The total pump power of this amplifier module was $\sim$280 mW while the operating current was operated at 356 mA. Thus, the saturated output power at 1500 nm can be up to 14 dBm for input power of 0 dBm.

The C-band EDFA is constructed by an 20 m EDF long, a 980/1550 nm WDM coupler, a 980 nm pumping laser with 100 mW, a gain equalizer (GE), and two optical isolator (ISO). The GE of EDFA can equalize the gain profile effectively. Besides, the C-band EDFA has the gain 25 dB, noise figure 5 dB, and output saturated power 15 dBm.

As seen in Fig. 1, the input ports of S- and L-band EDFAs connect with the S-/C- band WDM coupler (WC) and the output ports of the two EDFAs connect to the 1×2 SW, which can connect with the S- or C-band EDFAs individually. Hence, the WC will separate the S- and C-band paths and the SW can select the wavelength-tuning range in S- or C-bands, respectively. The proposed SAF is constructed by two optical circulators (OCs) and an unpumped C-band EDF (model DF 1500F of Fibercore Ltd.) of 1 m long. Using a shorter unpumped EDF inside fiber cavity as a narrow bandwidth filter has been proposed and reported in [17,18]. Therefore, the proposed SAF also could be utilized as a filter to achieve SLM output.

SLM oscillation can be retrieved by employing a FFP-TF and a SAF inside fiber cavity. The FFP-TF is an all-fiber device having a widely tunable range, low insertion loss ($<$0.5 dB), and low polarization-dependent loss ($\sim$0.1 dB). This FFP-TF having the free spectral range (FSR) of 40 nm and the finesse of 100 can provide wavelength selection in the ring laser cavity by applying external voltage ($<$12 V) on the piezoelectric transducer (PZT) of FFP-TF. And the FFP-TF can be used and operated at S- and C-bands simultaneously by switching the 1×2 SW. Furthermore, the PC inside the ring cavity is adjusted to achieve the maximum output power and maintain the polarization state. Here, the FFP-TF not only determines a lasing wavelength but also serves as a mode-restricting component to provide the first restriction on the possible laser modes. Then, the proposed SAF can provide sec-

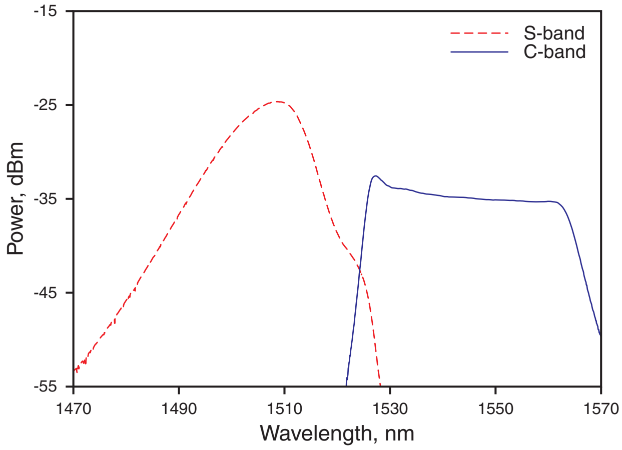

Figure 2 (online color at www.lphys.org) Output ASE spectra of original S-band and C-band EDFAs used in the proposed fiber laser scheme

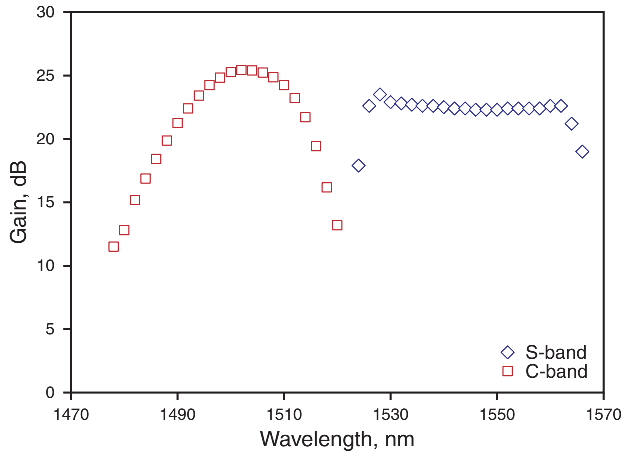

Figure 3 (online color at www.lphys.org) Original gain spectra of S- and C-band EDFAs for the input signal power of –20 dBm between 1478 and 1520 nm and 1524 and 1566 nm, respectively

ond restriction to filter the side-mode and avoid mode-hopping. The unpumped EDF, with maximum absorption coefficient of 6.3 dB/m at 1531 nm, serves as a saturable absorber. Using an OC2 to form a back reflection mirror in the proposed SAF can reflect nearly 100% of counter propagating signal to interfere spatially with propagating light in the saturable absorber, as illustrated in Fig. 1. As a result, the spatial hole burning (SHB) effect [17] can be observed in this reflection-typed saturable absorber unit, and thus a narrow-band Bragg grating filter is created. By using this SAF and FFP filter inside the gain cavity, this proposed fiber laser can provide broadband wavelength-tuning range and retrieve a single-frequency lasing. And the lasing light can be observed in the 10% output port of coupler, as seen in Fig. 1.

In addition, the output wavelength and power are monitored and captured by and optical spectrum analyzer (OSA) with a 0.05 nm resolution and optical power meter (PM), respectively. Furthermore, SLM operating performance can be verified by using the delayed self-homodyne detection method. The optical circuit for this measurement is composed of a photodetector (PD) with 3 dB bandwidth of 12 GHz and a Mach-Zehnder interferometer with 25 km standard single-mode fiber (SSMF). The linewidth spectrum of the fiber laser can be measured at photodetector by a radio frequency (RF) spectrum analyzer with 1.8 GHz bandwidth.

Fig. 2 shows the output ASE spectra of the original S- and C-band EDFAs used in the proposed fiber ring laser architecture. The bandwidths of ASE spectra for S- and C-band EDFAs are between 1480 and 1525 nm and 1523 and 1567 nm, respectively, when the ASE powers are larger than –45 dBm. The output peak powers of ASE of two S- and C-band EDFAs are also measured in Fig. 2 at –24.6 and –32.56 dBm at the wavelengths of 1508.13 and 1527.32 nm, respectively.

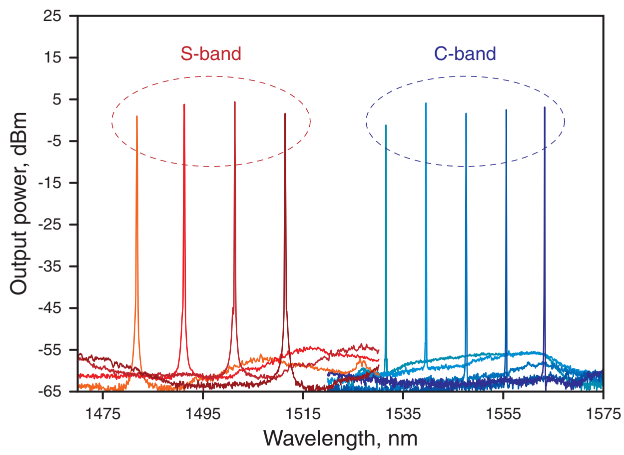

Figure 4 (online color at www.lphys.org) Output wavelength spectra of the proposed fiber ring laser in the two operating ranges of 1481.0 to 1521.1 nm and 1523.6 to 1563.6 nm

In order to realize the effective operating bandwidth of the two EDFAs used, we also measure their gain. As shown in Fig. 3, the gain values of the S-band EDFA used can be larger than 11.5 dB in the wavelengths of 1478 to 1520 nm for the input signal power of –20 dBm. Fig. 3 also shows the gain value of $>$ 18 dB in the bandwidth of 1524 to 1566 nm for –20 dBm input wavelength power. And the gain variation (ΔG) of C-band EDFA is 1.2 dB (23.5 to 22.3 dB gain distribution) between 1528 and 1562 nm due to the GE device in the module. Furthermore, the maximum gain values of S- and C-band EDFAs are obtained having 25.5 and 23.5 dB at the wavelengths of 1502 and 1528 nm, respectively. According to the measured results of Fig. 2 and Fig. 3, the effective operating bandwidths

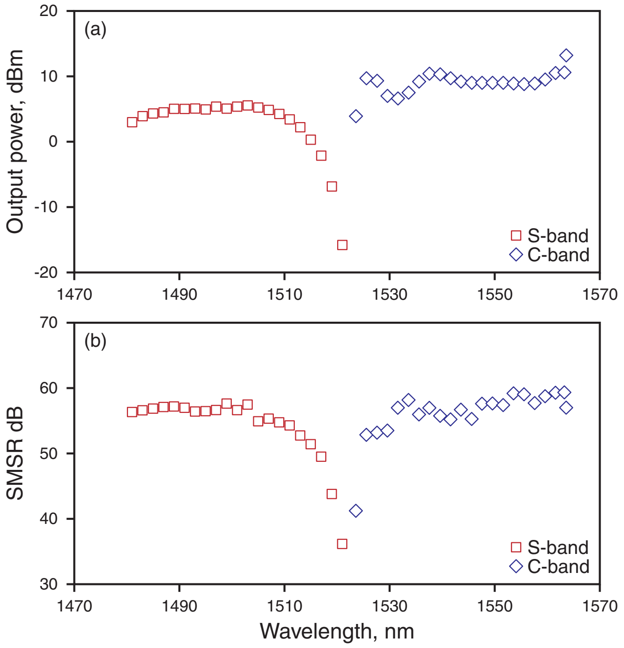

Figure 5 (online color at www.lphys.org) (a) – output powers and (b) – SMSRs versus different lasing wavelengths of the proposed fiber laser

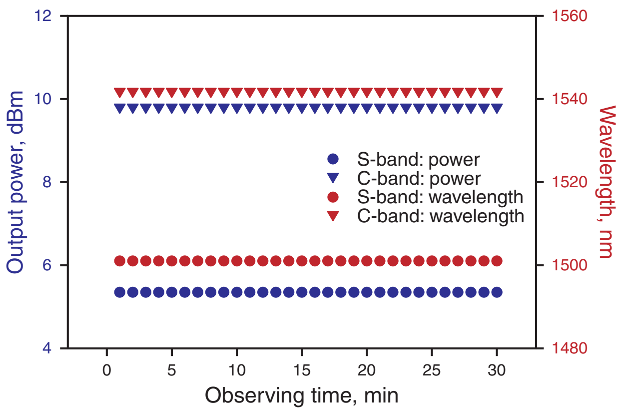

Figure 6 (online color at www.lphys.org) Output power fluctuations and the wavelength variations of proposed SLM fiber ring laser while two wavelengths are set at 1501.0 and 1541.8 nm initially for S- and C-band operations

of two EDFAs are around 1480 to 1520 nm and 1524 to 1566 nm for widely wavelength tuning in the proposed fiber laser scheme.

Fig. 4 presents the output wavelength spectra of the proposed fiber ring laser in the two operating ranges between 1481.0 and 1521.1 nm and 1523.6 and 1563.6 nm, respectively. As seen in Fig. 4, the red and blue lines are operated in S- and C-bands, when the 1×2 SW is controlled to connect with S- or C-band EDFAs, respectively. The results reveal that the wider wavelength tuning range can be achieved in SLM operation by using the shorter length of unpumped EDF (∼ 1 m long). Fig. 5a and Fig. 5b show the output power and SMSR versus different lasing wavelength operating in S- (1481.0 to 1521.1 nm) and C-band (1523.6 to 1563.6 nm) ranges for the proposed laser scheme. Due to the band gap insertion loss of 1×2 the S-/C-band WDM coupler, two loss curves of output ports (S- and C-bands) will cross around 1522 nm with ∼4 nm band gap (1520 to 1524 nm). Here, the lasing wavelength around the band gap would be dropped gradually due to the gap loss of WC. Fig. 5a presents the maximum output powers of 5.6 and 5.0 dBm at 1503.0 and 1561.6 nm, respectively. In S-band operating range, the output power would drop from 5.6 to 4.3, 0.3 and –6.9 dBm at 1503.0, 1509.0, 1515.1, and 1519.1 nm, respectively. And the output power variation of 1.2 dB and the SMSRs of 54.3 to 57.2 dB are also measured between 1483.0 and 1511.1 nm. Moreover, Fig. 5b shows the SMSRs of 36.16 to 57.6 dB in the wavelengths of 1481.0 to 1521.1 nm and the maximum SMSR is at 1489.0 nm.

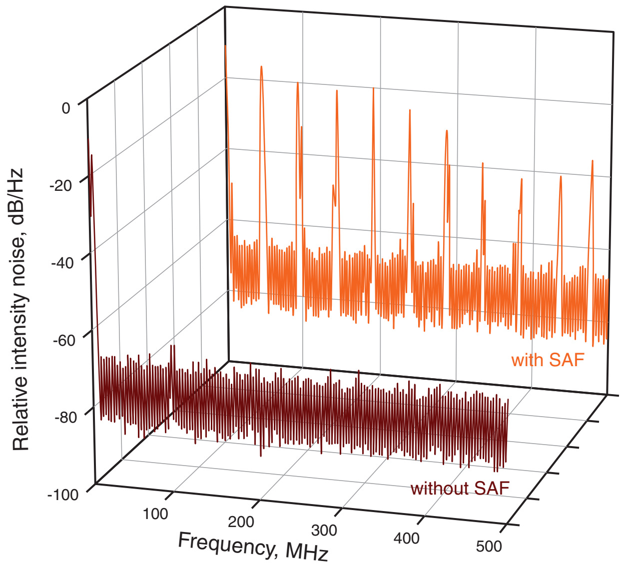

Figure 7 (online color at www.lphys.org) Self-homodyne spectra of the proposed fiber ring lasers with and without SAF operates at the wavelength of 1541.8 nm

Fig. 5a and Fig. 5b present the output powers and SMSRs between –1.6 and 5.1 dBm and 41.2 and 59.3 dB in the wavelength range of 1523.6 and 1563.6 nm, respectively. Due to the gain equalization of C-band EDFA, Fig. 5a also presents a flattener output power curve between 3.3 and 5.0 dBm (∼ 1.7 dB power variation) in the wavelengths of 1535.6 to 1563.6 nm; together with the SMSRs of 55.2 to 59.3 dB. Besides, the minimum power and SMSR on the two operating bandwidths are –15.8 and –1.6 dBm and 36.2 and 41.2 dB at 1521.1 and 1523.6 nm around the

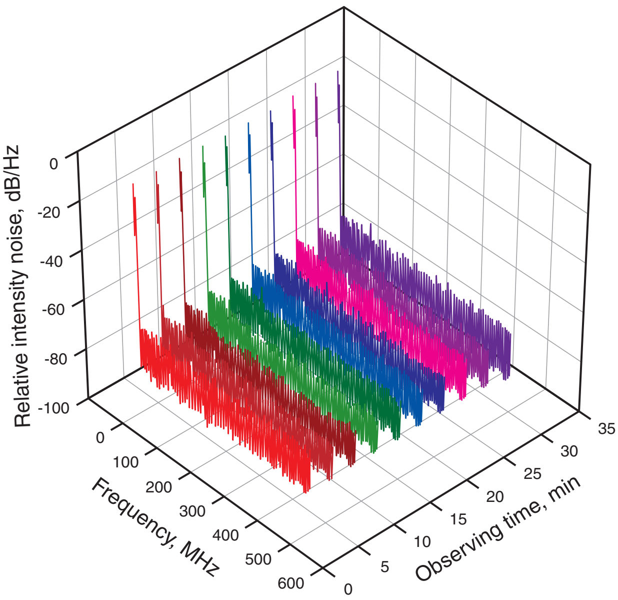

Figure 8 (online color at www.lphys.org) Self-homodyne spectra of the proposed fiber ring lasers with SAF operates at the wavelength of 1501.1 nm under 30 minutes observation time

band gap of WC, respectively, as illustrated in Fig. 5a and Fig. 5b.

Next, we will realize and analyze the stability performances of output power and wavelength for the proposed fiber laser using SAF in the effective lasing range. As indicated in Fig. 6, two lasing wavelengths are set at 1501.0 and1541.8 nm initially with 5.4 and 4.2 dBm output power in S- and C-band operation and the total observing time is over 30 minutes. Experimental results show that the proposed fiber laser has excellent stabilities. Thus, the output power fluctuations are less than 0.02 and 0.03 dB and the central wavelength variation are less than 0.01 and 0.01 nm, respectively for the two lasing lights. Besides, during the observation time of one hour, the output stability of the proposed fiber laser is still kept and maintained.

Finally, in order to confirm the lasing light is SLM, a self-homodyne measurement is used. As shown in Fig. 1, when the proposed fiber laser scheme has no SAF inside cavity, the fiber laser would result in the mode-hopping and super mode noise lasing. Therefore, Fig. 7 shows the detected self-homodyne frequency spectrum of the proposed laser at the wavelength of 1541.8 nm without and with SAF at 4.2 dBm output power. If the SAF 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. Here, when the SAF is used in the proposed fiber laser scheme, the SLM oscillation is much easier to achieve. 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, as also illustrated in Fig. 7. Furthermore, Fig. 7 presents a stable SLM output spectrum with side-mode suppression in the measuring bandwidth of 500 MHz. In addition, we also measure self-homodyne frequency spectrum at the wavelength of 1501.0 nm with SAF in S-band operation (in Fig. 1) versus various observing time. Here, Fig. 8 also shows that no beating noises are measured and in the RIN spectrum while a SAF is employed under 30 minutes observation time. As a result, after an hour observation time, no spike noise and stable frequency output are observed in the RF spectrum of the proposed fiber laser in the two operating bandwidths.

In [17], it only generated a single-wavelength output by using a FBG and a shorter unpumped EDF inside ring cavity in SLM. And [18] proposed and employed two erbium-based fiber amplifiers in cascade scheme to obtain the larger gain in C-band operation for wavelength tuning. However, our proposed broadband wavelength-tuning fiber laser utilizes two erbium amplifiers (S- and C-bands) in parallel scheme by using a narrow bandwidth filter to achieve SLM operation and it can also obtain larger output wavelength powers. Besides, we add an optical SW inside cavity to select the wavelength-tuning range in S-band or L-band. In general, the switching time of SW used can be less than 10 ms. In our experiment, the switching time of SW is nearly 7 ms. Thus, the SW can also switch lasing light in S- or C-band fast based on the switching time of SW. Compared with [17] and [18], our proposed fiber laser can not only obtain the widely wavelength-tuning range (1481.0 to 1563.6 nm) in SLM operation, but also can fast switch in two different operating bands (S- and C-bands) simultaneously.

3. Conclusion

In summary, we have proposed and experimentally demonstrated a widely wavelength-tunable fiber ring laser with SLM output using a SAF inside cavity. To achieve a widely wavelength tuning, we use the S- and C-band EDFAs in parallel scheme inside the cavity. Here, a SAF was used inside the fiber cavity to serve as a narrow band filter to guarantee a SLM operation. Furthermore, the wavelength tuning ranges can be up to 82.6 nm from 1480.1 to 1563.6 nm; however, with 4 nm band gap from 1522 to 1524 nm cannot be used for the proposed fiber laser due to the insertion loss of WC. In the experiment, we can obtain two operating bandwidths of 1481.0 to 1521.1 nm and 1523.6 to 1563.6 nm, respectively. For the two operating bandwidths, we can obtain two maximum output powers and SMSRs of 5.5 and 5.0 dBm and 56.4 and 59.3 dB/0.05 nm at 1503.0 and 1561.6 nm, respectively. Besides, the power fluctuations and the central wavelengths are less 0.02 and 0.03 dB and 0.01 and 0.01 nm, respectively, for the two wavelengths of 1541.8 and 1501.1 nm. In our past studies for SLM fiber laser [24,25], we used hybrid dual-ring and saturable-absorber-based filter scheme or Fabry-

Perot laser diode (FP-LD) in fiber laser architecture to obtain SLM output in C-band window. However, in this paper, we only employ a passive saturable-absorber filter inside ring cavity to filter the super-mode in SLM operation in the operating range of 1481.0 to 1563.6 nm. As a result, the proposed broadband SLM wavelength-tunable fiber ring laser is promising for future optical communication applications.

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