IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 3, Number 1, February 2011

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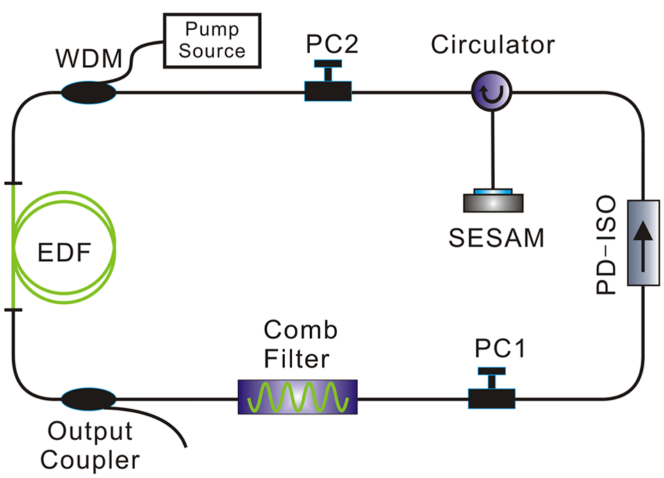

DOI: 10.1109/JPHOT.2010.2102012
1943-0655/$26.00

Tunable and Switchable Multiwavelength Passively Mode-Locked Fiber Laser Based on SESAM and Inline Birefringence Comb Filter

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DOI: 10.1109/JPHOT.2010.2102012
1943-0655/$26.00 ©2010 IEEE

Manuscript received November 16, 2010; revised December 17, 2010; accepted December 18, 2010. Date of publication December 23, 2010; date of current version January 24, 2011. This work was supported by the National Natural Science Foundation of China under Grant 11074078, the Specialized Research Fund for the Doctoral Program of Higher Education, China under Grant 20094407110002, and the Foundation for Distinguished Young Talents in Higher Education of Guangdong, China under Grant C10183. Corresponding authors: A.-P. Luo and W.-C. Xu (e-mail: luoaiping@scnu.edu.cn; xuwch@scnu.edu.cn).

Abstract: A tunable and switchable multiwavelength passively mode-locked fiber laser by using a semiconductor saturable absorber mirror (SESAM) and an inline birefringence fiber filter is proposed and demonstrated. By properly rotating the polarization controllers (PCs), up to 7-wavelength mode-locked pulses in 3-dB bandwidth with 3.65-nm channel spacing are obtained. The wavelength switchable operation is determined by the characteristics of the comb filter used in the experiment. Taking advantage of an intensity-dependent loss mechanism caused by the nonlinear polarization rotation (NPR) effect, the mode competition is efficiently suppressed. In addition, the lasing locations of multiwavelength mode-locked pulses can be flexibly tuned via the wavelength-dependent loss mechanism.

Index Terms: Multiwavelength fiber lasers, passively mode-locked, saturable absorber, comb filter.

1. Introduction

Multiwavelength pulsed fiber lasers have attracted great interest due to their wide applications in optical fiber sensing, optical signal processing, optical instrumentation, and wavelength-division-multiplexed (WDM) fiber communication systems. The mode-locking technique is considered to be one of the most efficient and powerful approaches to generate optical pulses. It has been demonstrated that the active mode-locking technique was an effective way to generate the multiwavelength pulses [1]–[6]. The multiwavelength actively mode-locked fiber lasers have the advantage of high repetition. Nevertheless, a modulator has to be incorporated into the laser cavity, which increases the cost and the insertion loss. In addition, to generate stable multiwavelength pulses, all the pulses should pass through the modulator synchronously in the active mode-locking scheme. It means that the round-trip frequencies should be the same or have a common multiple for all the lasing wavelengths. Therefore, other techniques have to be employed to ensure the stable multiwavelength mode-locked operation due to the dispersion in the cavity. These make the implementation of multiwavelength actively mode-locked fiber laser complex and especially limit the tunable operation.

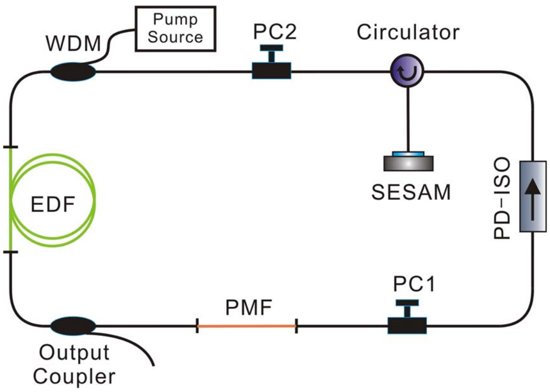

Fig. 1. Schematic of the proposed multiwavelength passively mode-locked fiber laser.

Different from the multiwavelength pulses generation using active mode-locking techniques, the multiwavelength passively mode-locked operation can be achieved as long as the individual lasing wavelength satisfies the mode-locked condition and the cavity round-trip frequencies do not need to be equal for the lasing pulses at different wavelengths. Therefore, the tunability of multiwavelength passively mode-locked fiber laser can be easily achieved, despite the cavity dispersion. Moreover, since no modulator is required in a passively mode-locked fiber laser, the laser system is much simpler. The nonlinear polarization rotation (NPR) and nonlinear amplifying loop mirror (NALM) techniques were used to realize the multiwavelength mode-locked operation [7]–[9]. However, the mode-locked condition is strict by using NPR and NALM techniques. Thus, it is difficult to obtain multiwavelength passive mode-locking from the fiber laser because the cavity parameters, such as cavity loss and polarization states, should be carefully adjusted. Alternatively, by the virtue of semiconductor saturable absorber mirror (SESAM), the fiber laser can more easily and efficiently achieve the mode-locked operation [10], [11]. Recently, Zhang *et al.* reported a triple-wavelength dissipative soliton fiber laser with a SESAM in an all-normal dispersion cavity [12]. Nevertheless, no comb filter was inserted into the cavity to define the lasing wavelengths, causing the lasing wavelengths to be random and limiting some practical applications. From the viewpoint of practical applications, multiwavelength passive mode-locking with definite channel spacing, as well as the tunable operation, needs to be investigated. In this paper, we report a tunable and switchable multiwavelength passively mode-locked fiber laser by exploiting a SESAM and a polarization-maintaining fiber (PMF) filter. In the experiment, up to 7-line wavelength switchable mode-locked pulses with a channel spacing of 3.65 nm in a 3-dB bandwidth were obtained. Furthermore, the lasing locations can be flexibly tuned by using wavelength-dependent loss mechanism. The stable multiwavelength mode-locked output is achieved through the intensity-dependent loss mechanism induced by the NPR effect, which contributes to the suppression of the mode competition.

2. Experimental Setup and Operation Principle

The schematic of the proposed fiber laser is shown in Fig. 1. A 4.5-m long erbium-doped fiber (EDF) with a dispersion parameter of $D \approx 15$ ps/(nm $\cdot$ km) pumped by a 980-nm laser diode (LD) is used as the gain medium. The absorption coefficient of the EDF is 12.5 dB/m at 980 nm. The length of fiber pigtails of optical components is about 21 m single-mode fiber (SMF) with a dispersion parameter of $D \approx 17$ ps/(nm $\cdot$ km). The fundamental repetition, which is determined by the cavity length, is 7.44 MHz. Two polarization controllers (PCs) are employed to adjust the polarization state of the lasing light. The polarization-dependent isolator (PD-ISO), apart from the assurance of unidirectional operation, also provides two functions: 1) When combining the 1.6-m-long PMF with fiber birefringence of 4.11×10^{-4} used in this experiment, it serves as a Lyot comb filter, which also produces the wavelength switchable operation [13], [14]; 2) when combining the PCs, it can optimize the multiwavelength operation by the wavelength-dependent loss mechanism [15]. The

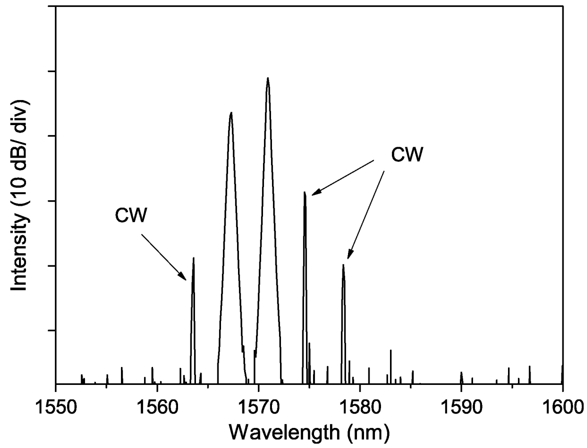

Fig. 2. Typical multiwavelength mode-locked spectrum when the PCs were not in proper adjustment.

efficiently self-starting mode-locked operation was achieved by using a commercial SESAM (Batop GmbH), which was incorporated into the laser cavity with a circulator. The SESAM is fiber pigtailed and has a low-intensity absorption of 30%, a modulation depth of 18%, a recovery time of 10 ps, and a saturation fluence of 70 $\mu J/cm^2$. The output is taken by a 5% fiber coupler. An optical spectrum analyzer (OSA) and an oscillograph are used to study the laser spectra and the output pulse-train, respectively. The pulse duration is measured by a commercial autocorrelator.

When we remove the SESAM, the fiber laser is a typical setup based on the NPR technique. Both the NPR effect and SESAM can act as the saturable absorber, which are widely used to attain the passively mode-locked operation. However, in our experiment, only the unstable continuous wave (CW) multiwavelength operation was observed if it was without the SESAM. It is because the NPR-based mode-locking requests that the PCs settings and the cavity loss should be finely controlled to act as an effective artificial SA, which is difficult for all the lasing wavelengths with narrow spectral bandwidth defined by the comb filter to achieve mode-locking states. While the SESAM was incorporated into the laser cavity, the multiwavelength mode-locked operation could be easily and efficiently obtained by increasing the pump power since the SESAM can relax the mode-locking condition, and the mode-locking of the fiber laser need not carefully adjust the PCs, as long as the lasing wavelengths are in the high reflection band of SESAM. It demonstrated that the SESAM contributes to the onset of the multiwavelength passively mode-locked operation. Once the multiwavelength mode-locked operation was initiated, the peak powers of the circulating pulses were much higher than those of CW operation, and the pulses were shaped by both the SESAM and NPR effect, resulting in an intensity-dependent loss mechanism in the laser cavity. Therefore, the intensity-dependent loss induced by the NPR technique is employed to suppress the mode competition [16], [17] and guarantee the stable multiwavelength passively mode-locked operation.

3. Experimental Results

In the experiment, the cavity loss for a specific wavelength can be tuned by rotating the PCs. When the cavity loss was adjusted to a low level, the self-starting stable multiwavelength passively mode-locked operation was always achieved by increasing the pump power to about 30 mW in our fiber laser. Then, we set the pump power at a proper value of about 80 mW and fixed it in the following experiment. However, when the PCs were not rotated in proper positions, it was found that only a few wavelengths of pulsed operation was observed. Furthermore, the lasing lines were uneven. A typical dual-wavelength passively mode-locked operation is shown in Fig. 2 when the PCs were not properly adjusted. Moreover, unstable CW lasing lines were observed in the output spectrum besides the dual-wavelength mode-locked pulses centered at 1567.27 nm and 1570.92 nm.

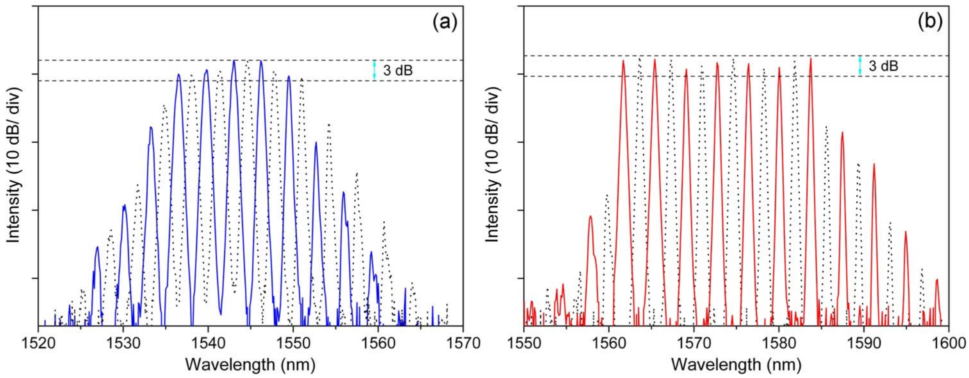

Fig. 3. Wavelength switchable multiwavelength passively mode-locked operation. (a) Lasing location centered at 1543 nm. (b) Lasing location centered at 1573 nm.

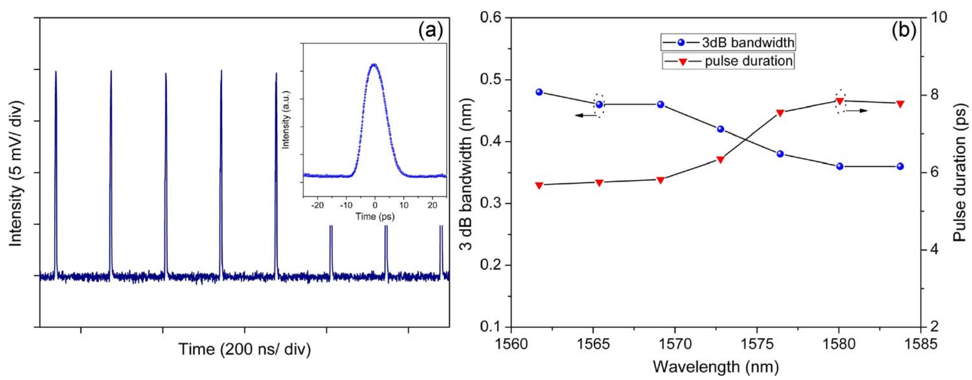

Fig. 4. (a) Output pulse-train of the lasing wavelength centered at 1561.71 nm; Inset: Corresponding autocorrelation trace. (b) Output spectral bandwidths and pulse durations of the main seven lasing wavelengths corresponding to Fig. 3(b) with a red curve.

Nevertheless, despite the unstable CW lasing, it is worth noting that the dual-wavelength mode-locked pulses were rather stable during the experimental observation.

When the PCs were finely adjusted, one could control the loss of the lasing lines located at different wavelengths due to the wavelength-dependent loss mechanism produced by the laser ring cavity. Therefore, the lasing location, the number of the lasing lines, and the lasing flatness could be flexibly tuned. Fig. 3(a) presents the multiwavelength passively mode-locked operation with the lasing location centered at 1543 nm. We obtained 5-wavelength mode-locked pulses within 3-dB bandwidth. Here, the average output power is about 1.6 mW. Note that the comb filter used in our fiber laser provides the wavelength switchable operation by adjusting the polarization state of the lasing light launched into the PD-ISO. Therefore, the wavelength switchable multiwavelength mode-locked operation was obtained when we slightly rotated the PCs in the experiment, as shown in Fig. 3(a) with a black dotted curve. When the PCs were further rotated, as mentioned above, the multiwavelength operation including the lasing location and the lasing flatness can be optimized by the wavelength-dependent loss mechanism. Up to 7-wavelength switchable mode-locked pulses centered at 1573 nm with a channel spacing of 3.65 nm in 3-dB bandwidth were obtained when the PCs were adjusted at optimum positions, as shown in Fig. 3(b), and the average output power is about 1.8 mW.

Then, we observed the multiwavelength mode-locked pulses in the time domain by using an oscillograph. Apart from the intensity differences, the pulse characteristics at different wavelengths, such as pulse durations and shapes shown on the oscillograph, were similar with each other due to the limited bandwidth of the photodetector. Typically, we illustrated the pulse-train of the lasing

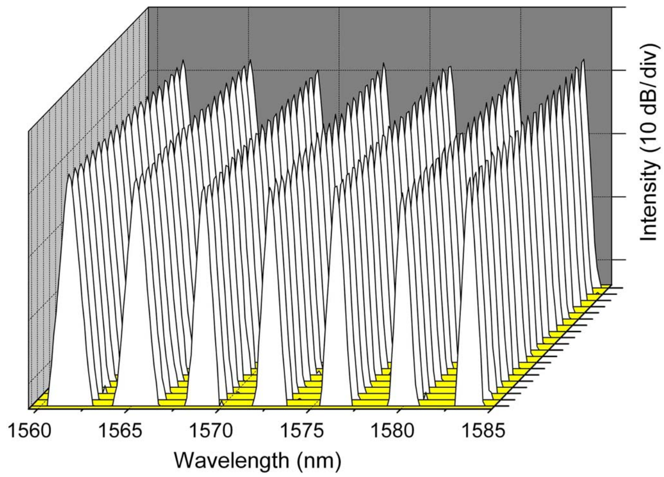

Fig. 5. Repeatedly scanned output 20 times with a 3-min interval.

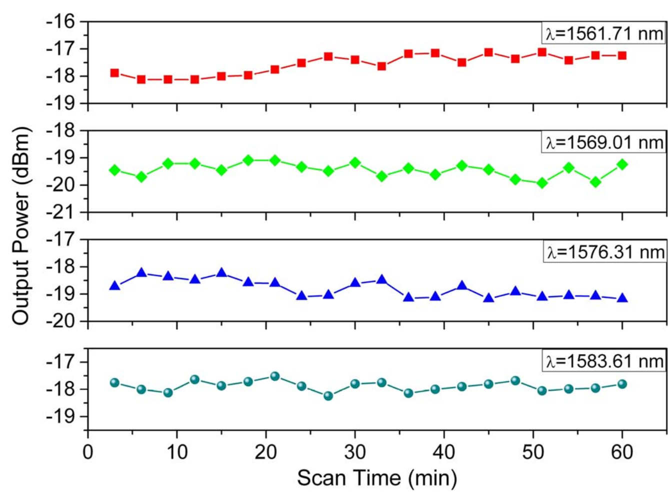

Fig. 6. Power fluctuations of four channels during scanning. The power variations were less than 1 dB.

wavelength centered at 1561.71 nm in Fig. 4(a). The pulse repetition is 7.44 MHz. Note that the 3-dB bandwidth of the lasing wavelength centered at 1561.71 nm is 0.48 nm. The pulse duration measured by an autocorrelator, which is assumed to be the fit of hyperbolic secant pulse shape, is 5.68 ps, as shown in the inset of Fig. 4(a). Thus, the time-bandwidth product is 0.335. It is also to be noted that no free-running pulses were observed when the multiwavelength passive mode-locking was achieved, indicating that the pulses at different wavelengths bunched together. It may find some potential applications in fields such as microwave generation [18]. Fig. 4(b) further illustrates the 3-dB spectral bandwidths and pulse durations of the main 7 lasing wavelengths corresponding to Fig. 3(b) with a red curve. The pulse durations and 3-dB bandwidths are not identical among the main 7 lasing wavelengths because the multiwavelength passively mode-locked operation should simultaneously satisfy both the mode-locked condition and the transmission function of the birefringence comb filter.

To verify the stability of the proposed multiwavelength passively mode-locked fiber laser, we repeatedly scanned the laser output 20 times with a 3-min interval. The scanned results of the main 7 lasing wavelengths are shown in Fig. 5. In the experiment, no significant wavelength drifts and power variations for each lasing line were directly observed. For better clarity, Fig. 6 presents the power variations of four channels in the experimental observation. As can be seen in Fig. 6, the maximum power fluctuation is less than 1 dB. These results indicate that the proposed fiber laser operated stably at room temperature.

4. Discussions

In the experiment, the fundamental repetitions of multiwavelength pulses are 7.44 MHz, which are not as high as that of using the active mode-locking technique. However, we can increase the repetition rate by reducing the cavity length [19], i.e., using a highly doped gain fiber [20]. As demonstrated above, the characteristics of multiwavelength passively mode-locked operation are determined by the comb filter used in the laser cavity. By using the proposed scheme, one can obtain multiwavelength passively mode-locked operation in conjunction with various comb filters. Therefore, if a channel spacing tunable comb filter is used [21], we can potentially realize the channel spacing tunable multiwavelength passively mode-locked operation. We also believe that the multiwavelength pulses with shorter duration can be obtained with a larger comb spacing filter. Since all the lasing wavelengths achieve the mode-locking state, the proposed fiber laser also might have the potential application in the fiber communication system exploiting the combined WDM and time-division-multiplexed (TDM) access techniques. Note that the soliton spectral sidebands were absent and that the 3-dB bandwidths were narrower than 1 nm because the narrow spectral filtering effect defined by the comb filter was employed in our experiment. Moreover, although one can also achieve multiwavelength pulses by placing a comb filter external to the output of a mode-locked laser [22], the spectral envelope of the multiwavelength pulses is decided by the shape of the broadband pulse spectrum, which makes it difficult for the laser to tune the flatness of the multiwavelength pulses. It is also to be noted that the saturable absorber is a commercial SESAM in our experiment. The SESAM has a finite bandwidth for high reflectivity, which seems to limit the tunable performance of lasing locations. Thus, for the purpose of achieving wider tunable range, we can replace the SESAM with other saturable absorbers, such as graphene mode locker [23], [24], which offers the advantage of wavelength-insensitive ultrafast saturable absorption.

5. Conclusion

In conclusion, we have proposed and demonstrated a tunable and switchable multiwavelength passively mode-locked fiber laser based on a SESAM and an inline PMF filter. Up to 7-wavelength passively mode-locked pulses within 3-dB bandwidth were obtained in the experiment. The channel spacing is 3.65 nm, which is determined by the comb filter. By properly rotating the PCs, both the wavelength switchable and the lasing location tunable operations were achieved. The mode competition of the proposed fiber laser can be efficiently suppressed by employing the intensity-dependent loss mechanism induced by the NPR technique.

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