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MULTI-WAVELENGTH FIBER OPTICAL PARAMETRIC OSCILLATOR BASED ON A HIGHLY NONLINEAR FIBER AND A SAGNAC LOOP FILTER

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Abstract—A novel multi-wavelength fiber optical parametric oscillator (MW-FOPO) with a ring cavity structure is proposed. In the ring cavity of the MW-FOPO, a Sagnac loop filter which is formed by a 3-dB optical coupler, a polarization controller and a segment of polarization maintained fiber is used as the comb filter, and a segment of highly nonlinear fiber is used as the gain medium. Multi-wavelength lasing of the MW-FOPO with a wavelength spacing of about 0.8 nm is achieved and its power stability at room temperature is demonstrated by measuring peak power fluctuation within 42 minutes for 5 lasing wavelengths. The output spectrum of the MW-FOPO covers a large wavelength region from 1500 nm to 1610 nm. A comparison of the output spectra between the MW-FOPO and the multi-wavelength Erbium-doped fiber laser is also presented.

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1. INTRODUCTION

This year we welcome the 50th anniversary of the laser technology, which has powered remarkable progress [1–18] in the past 50 years since the invention of the first laser in 1960 [19]. Fiber lasers are one kind of the most important lasers, which also include multi-wavelength fiber lasers (MWFLs) with a huge potential in applications such as WDM optical communication systems, optical fiber sensors, optical component testing, microwave photonics and spectroscopy [20–23]. A great variety of MWFLs have been well developed based on various optical amplifiers including Erbium-doped fiber amplifiers (EDFAs) [24–29], fiber Raman amplifiers (FRAs) [30–33], fiber Brillouin amplifiers (FBAs) [34–36] and semiconductor optical amplifiers (SOAs) [37–40] in the past several years. Thereinto, multi-wavelength Erbium-doped fiber lasers (MW-EDFLs) have been widely investigated due to their advantages such as low cost, low threshold, high power conversion efficiency and compatibility with the optical fiber communication system. However, special approaches such as using the four wave mixing (WFM) effect of special fibers [25–27], the hybrid gain [28], or the frequency-shifted feedback technique [29] should be employed to achieve stable multi-wavelength lasing since MW-EDFLs are not stable at room temperature due to the strong homogenous line broadening and cross-saturation gain of the Erbium-doped fiber (EDF) [41]. The multi-wavelength Raman fiber laser has not been considered as a promising MWFL due to the limited gain bandwidth of the FRA. MWFLs based on the SOA usually suffer from the low output power and MWFLs based on FBAs suffer from the fixed wavelength spacing (determined by the Brillouin shift). Besides the above-mentioned optical amplifiers, fiber optical parametric amplifiers (FOPAs) [42–48] with excellent performances such as high gain, large gain bandwidth, arbitrary center wavelength, low noise figure and compatibility with high power have been well developed particularly after the emergence of the high power EDFA and the highly nonlinear fiber (HNLF) [49, 50], which result in the fast rise of the research on fiber optical parametric oscillators (FOPOs) recently [51–61]. So far, various FOPOs, which include picosecond FOPO [53], femtosecond FOPO [54, 55], Q-switched FOPO [56], wavelength-tunable FOPO [57–59], single-longitudinal-mode FOPO [60] and so on, have been proposed and demonstrated. A multi-wavelength fiber optical parametric oscillator (MW-FOPO) has also been demonstrated by employing a dual-pump FOPA and a superimposed chirped fiber Bragg grating [61], which, however, suffers from the complex structure and limited lasing wavelengths. The performances of the MW-FOPO should be further

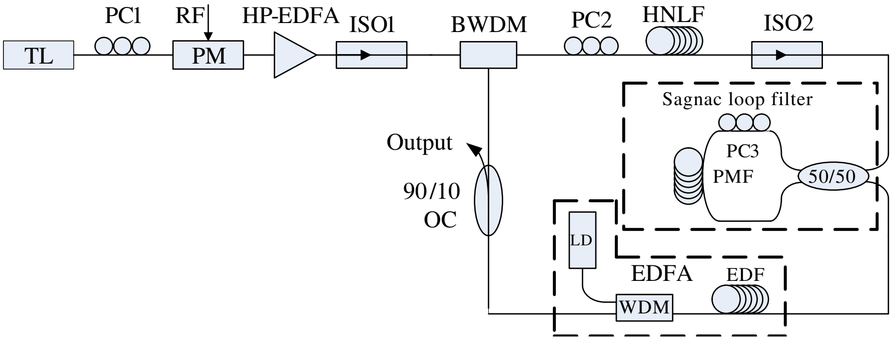

Figure 1. Experimental setup of the proposed MW-FOPO. TL: tunable laser; PC: polarization controller; PM: phase modulator; HP-EDFA: high power Erbium-doped fiber amplifier; ISO: isolator; BWDM: broadband wavelength division multiplexer; HNLF: highly nonlinear fiber; OC: optical coupler; PMF: polarization maintained fiber; EDF: Erbium-doped fiber; LD: Laser diode.

improved due to the large gain bandwidth of the FOPA.

In this paper, an MW-FOPO with one pump and a simple ring cavity structure is proposed and demonstrated. A segment of HNLF is used as the gain medium in the MW-FOPO. A Sagnac loop filter which is formed by a 3-dB optical coupler, a polarization controller and a segment of polarization maintained fiber is used as the comb filter in the ring cavity of the MW-FOPO. Stable multi-wavelength lasing with a wavelength spacing of about 0.8 nm in a wide wavelength region from 1500 nm to 1615 nm is achieved at room temperature which benefit from the large gain bandwidth.

2. EXPERIMENTAL SETUP AND RESULTS

Figure 1 shows the experimental setup of the proposed MW-FOPO. On the left side of Fig. 1, a tunable laser (TL, Agilent 81940A, with a tunable wavelength region from 1520 nm to 1630 nm) provides the pump seed light. A polarization controller (PC1) is used to align the state of polarization (SOP) of the light from the tunable laser (TL) with the transmission axis of the phase modulator (PM) so as to maximize the modulation depth. The stimulated Brillouin scattering (SBS) effect will results in a very low efficiency of pump light's injecting into the HNLF when we use the amplified pump light from the tunable laser with a very narrow linewidth. Thus, we use a phase modulation method to broaden the linewidth of the pump seed light by employing a phase modulator (PM) driven by a RF signal of a 3.5-Gb/s-(2^{31}-1) pseudorandom bie sequence (PRBS), which can successfully suppress the SBS when the high power pump light is injected into the HNLF. A high power Erbium-doped fiber amplifier (HP-EDFA) with a maximal output power of 2 W is used to achieve a high power pump light. An optical isolator (ISO1) is used after the HP-EDFA. By way of a broadband wavelength division multiplexer (BWDM), the pump light is injected into the HNLF, which is used as the gain medium of the proposed MW-FOPO. The length, the loss, the zero-dispersion wavelength, the dispersion slope at the zero-dispersion wavelength and the nonlinear coefficient (at 1550 nm) of the HNLF are about 520 m, 0.92 dB/m, 1553.35 nm, 0.016 ps/(nm^{2}km) and 15 W^{-1}km^{-1}, respectively. An optical isolator (ISO2) ensures a clockwise ring cavity and a polarization controller (PC2) is used to adjust the SOP of the lasing light since the FOPA is sensitive to the polarization of both the pump light and the signal light. One arm (with a 10% power ratio) of a 90/10 optical coupler (OC) is used as the output port of the MW-FOPO. A Sagnac loop filter which is formed by a 3-dB optical coupler, a polarization controller and a segment of polarization maintained fiber (PMF) is used as the comb filter in the ring cavity of the MW-FOPO. The wavelength spacing of two adjacent transmission peaks of the Sagnac loop filter is given by [62]

$$\Delta\lambda = \frac{\lambda^2}{\Delta n L} \tag{1}$$

where λ is the wavelength and L is the length of the PMF. In our experiments, we choose the PMF with a suitable length (about 15 m) to achieve a wavelength spacing of about 0.8 nm around 1550 nm. Fig. 2(a) shows the experimentally measured transmission spectrum of the Sagnac loop filter with the insertion loss of about 3.4 dB, the peak-to-notch contrast ratio of about 18 dB, and the peak fluctuation within 0.2 dB.

In order to show a comparison of the output spectra between the proposed MW-FOPO and the conventional MW-EDFL, Fig. 1 also shows the case when an EDFA formed by a Laser diode (as a pump) with a central wavelength of 1480 nm, a wavelength division multiplexer (WDM) and a segment of EDF is inserted into the ring cavity of the proposed MW-FOPO (building an MW-EDFL when the HP-EDFA is shut down). The length, the numerical aperture, the cutoff wavelength and the peak absorption (at 1531 nm) of the EDF are 6.3 m, 0.25, 950 nm and 19.2 dBm, respectively.

The wavelength of the tunable laser is chose to be 1555.8 nm due to the dispersion property of the HNLF. The output power of the tunable laser is 6 dBm in our experiments. The HP-EDFA is adjusted

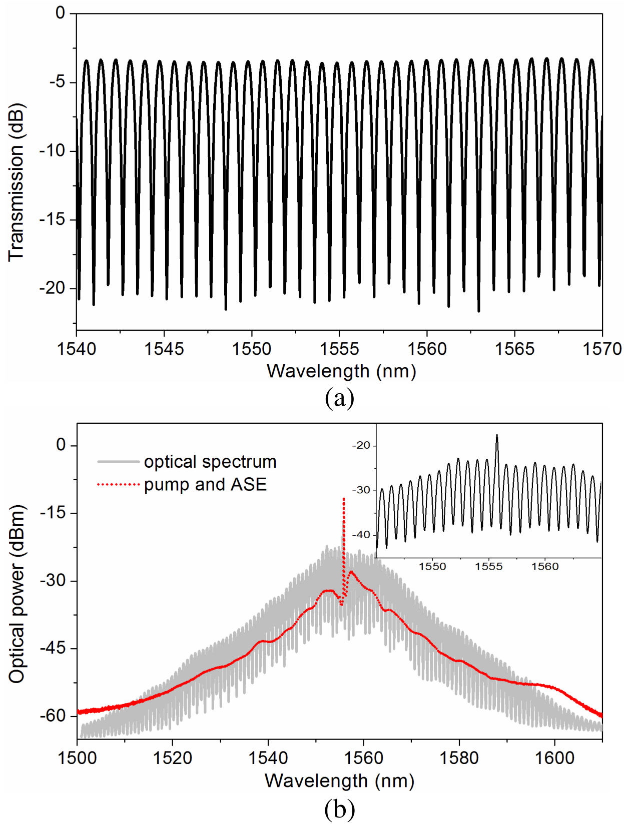

Figure 2. (a) Transmission spectrum of the Sagnac loop filter. (b) Spectra of the proposed MW-FOPO (gray solid curve) and the ASE of the FOPA (red dotted curve). Inset shows a local enlargement of the spectrum from 1545 nm to 1565 nm.

to achieve the maximal output power and the pump power after the optical isolater (ISO1) is measured to be about 1.53 W. Note that in our first experiment, the EDFA formed by LD, WDM and a segment of EDF is absent in the ring cavity. By carefully adjusting the three polarization controllers (PC1, PC2, and PC3), stable multi-wavelength lasing of the proposed MW-FOPO is achieved. Fig. 2(b) shows the output spectrum (black solid curve) of the proposed MW-FOPO which covers a wide wavelength region from 1500 nm to 1610 nm. Inset shows a local enlargement of the spectrum from 1545 nm to 1565 nm and one can see that the wavelength spacing of the MW-FOPO is about 0.8 nm (100 GHz at the optical fiber communication window, compatible with the ITU grid). Note that we use an optical spectrum analyzer (OSA) (Ando, AQ6317) with a resolution of 0.01 nm in our experiments. The large lasing wavelength region of the proposed MW-FOPO is mainly due to the large gain bandwidth of the FOPA based on the HNLF in the proposed MW-FOPO. The red dotted curve in Fig. 2(b) shows the amplified spontaneous emission (ASE) spectrum when the pump light is directly injected into the HNLF, where one can see that the envelope profile of the output spectrum of the MW-FOPO is similar as the ASE spectrum profile of an FOPA based on the HNLF.

Besides the large lasing wavelength region, power stability is also one of the most improtant properties of the MWFLs for practical applications. It is well known that the EDFA suffers from the strong homogenous line broadening at room temperature and the cross-saturation gain for signals with different wavelengths, which results in poor stability of the MW-EDFL. However, the FOPA exhibits the inhomogenous line broadening at room temperature and the cross-saturation gain appears markedly only when the signal power is comparable with the pump power. In addition, the FWM effect in the ring cavity of the MW-FOPO provides self-stability of multi-wavelength lasing, which has been well demonstrated in some MW-EDFLs [25–27]. The power stability of the porposed MW-FOPO is also demonstrated in our experiment. We use the OSA to repeatly scan the output spectrum of the MW-FOPO per 3 minutes within 42 minutes for the 5 lasing wavelengths. Fig. 3 shows the peak power fluctuation of the 5 lasing wavelengths of the MW-FOPO within 42 minutes and the maximal peak power fluctuation is less than 0.4 dB, which shows

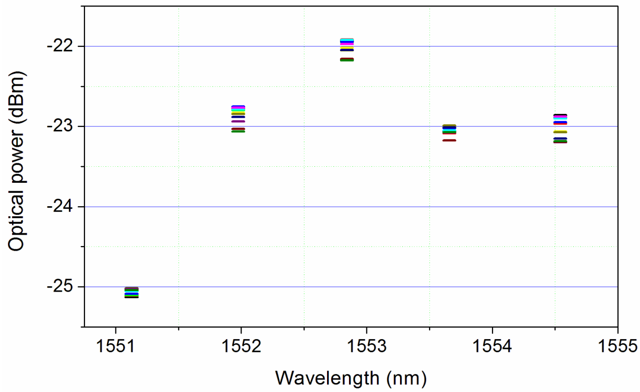

Figure 3. Peak power fluctuation within 42 minutes for the 5 lasing wavelengths of the proposed MW-FOPO.

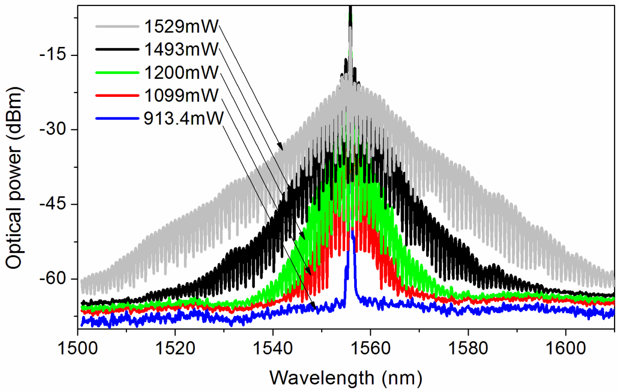

Figure 4. Output spectra of the proposed MW-FOPO when the pump power are 0.913 W, 1.099 W, 1.200 W, 1.493 W and 1.529 W, respectively.

the proposed MW-FOPO is quite stable at room temperature.

Besides the power stability, the FWM effect in the ring cavity of the MW-FOPO will also contribute to the power uniformity of each lasing wavelength. Fig. 4 shows the output spectra of the proposed MWFOPO when the pump power are 0.913 W, 1.099 W, 1.200 W, 1.493 W and 1.529 W, respectively. The envelope profile of the output spectrum of the MW-FOPO becomes flattened when the pump power increases. It is expected that uniform and stable multi-wavelength lasing can be achieved in a larger wavelength region when a pump (HP-EDFA) with a higher output power is used in the proposed MW-FOPO.

A comparison of the output spectra between the MW-FOPO and the MW-EDFL is also introduced in this paper. We show three different cases for the experimental setup in Fig. 1: Case I, the proposed MW-FOPO with the gain of only FOPA when the HP-EDFA is switched on and the EDFA is not inserted into the ring cavity; Case II, the MW-FOPO with the gain of both FOPA and EDFA when the HP-EDFA is switched on and the EDFA is also inserted into the ring cavity; Case III, the MW-EDFL with the gain of only EDFA when the HP-EDFA is switched off and the EDFA is inserted into the ring cavity. Fig. 5 shows the output spectra for the three cases. Evidently, the lasing wavelength region of the MW-EDFL is the smallest one although the multi-wavelength lasing is stable at room temperature due to the FWM effect of the HNLF in the ring cavity.

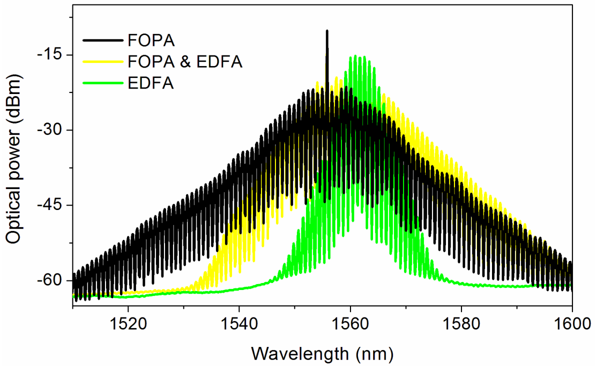

Figure 5. Spectra of the proposed MW-FOPO with the gain of only FOPA (black curve) or the gain of FOPA and EDFA (yellow curve), and the MW-EDFL (green curve).

3. DISCUSSION AND CONCLUSION

Regarding the MWFL, the lasing wavelength region, the power stability, and the flexible wavelength spacing are the most important properties. The lasing wavelength region and the power stability of the MWFL mainly depend on the property of the optical amplifier used in the MWFL. Thanks to the recent development of the HP-EDFAs and the HNLFs (which also include the highly nonlinear photonic crystal fibers), FOPAs have exhibited excellent performances such as high gain, large gain bandwidth, arbitrary center wavelength, low noise figure and compatibility with high power, which are very appreciated to achieve MWFLs, namely, MW-FOPOs. In this paper, we have shown the lasing wavelengths of the MW-FOPO covers a large wavelength region which is much larger then the conventional MW-EDFL. The wavelength spacing of the MWFL depends on the comb filter used in the MWFL. A Sagnac loop filter is suitable for applications in FWFLs due to its advantages such as fiber compatibility, high power compatibility and flexiable control of the wavelength spacing. Thus, the proposed MW-FOPO with a Sagnac loop filter could be one of the most promising MWFLs.

In conclusion, we have proposed and demonstrated an MW-FOPO based on an HNLF and a Sagnac loop filter. Stable multi-wavelength lasing at room temperature has been achieved. The wavelength spacing of the proposed MW-FOPO is about 0.8 nm. The output spectrum of the MW-FOPO covers a large wavelength region from 1500 nm to 1610 nm, which is much larger than that of the conventional MW-EDFL.

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