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FIBER OPTICAL PARAMETRIC OSCILLATOR WITH SWITCHABLE AND WAVELENGTH-SPACING TUNABLE MULTI-WAVELENGTH

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Abstract—We propose a switchable and wavelength spacing tunable multi-wavelength fiber optical parametric oscillator (MW-FOPO) with two cascaded fiber Bragg gratings (FBGs). The MW-FOPO can operate at two multi-wavelength lasing modes with different wavelength spacings, which can be switched by adjusting some polarization controllers (PCs). Stable multi-wavelength lasing at those two different operation modes at room temperature is achieved due to the four wave mixing (FWM) effect and the broadband gain of the fiber optical parametric amplifier (FOPA) based on a highly nonlinear fiber. The wavelength spacing of the proposed MW-FOPO can be tuned by adjusting the wavelength of the pump light or the central wavelength of the FBG at the two multi-wavelength lasing modes.

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1. INTRODUCTION

Fiber optical parametric amplifiers (FOPAs) [1–7], which have recently been well developed thanks to the high power pump sources and the highly nonlinear fibers (HNLFs) [8, 9], have attracted considerable attention in the past years because of their remarkable features, such as high gain, broadband gain, unidirectional gain, an arbitrary waveband operation, inhomogeneous broadening, sensitivity to polarization. In 2001, Ho et al. successfully implemented a 200-nm-bandwidth fiber optical amplifier [1] based on the parametric and Raman gain. An FOPA with the gain up to 70 dB has also been achieved by Thomas Torounidis et al. [3]. The success in FOPA has also promoted the development of fiber optical parametric oscillators (FOPOs), which benefit a lot from the advantages of the FOPA. So far, several FOPOs including continuous-wave (cw) and pulsed FOPOs have been demonstrated [10–14], which, however, have only a single-wavelength oscillation. Multi-wavelength fiber lasers (MWFLs) have received considerable attention for their potentials in applications such as wavelength-division-multiplexing (WDM) communication, optical instrument testing, optical fiber sensors, microwave photonics and spectroscopy [15–18].

In this paper, a switchable and wavelength-spacing tunable MW-FOPO is proposed for the first time (to the best of our knowledge). The MW-FOPO has a simple line cavity which consists of two FBGs and a Sagnac fiber loop mirror (SFLM) formed by a 50 : 50 optical coupler and a segment of 500-m highly nonlinear dispersion-shifted fiber (HNL-DSF). It can operate at two modes with different wavelength spacings. Stable multi-wavelength lasing can be achieved and the wavelength spacing can be tuned by adjusting the wavelength of the pump light or the central wavelength of the FBG at both modes.

2. EXPERIMENTAL SETUP AND RESULTS

Figure 1 shows the experimental setup of the MW-FOPO. A high power erbium-doped fiber amplifier (HP-EDFA) with a maximal output power of 2 W (limited by the pump power in the HP-EDFA) and an external-cavity tunable laser (TL, Agilent, 81940A) form the pump source. The output wavelength of the external-cavity tunable laser with the output power of 10 dBm can be tuned from 1520 nm to 1630 nm. The maximal output power of the pump source is about 1.5 W after an isolator (ISO). To suppress the stimulated Brillouin scattering (SBS) effect in the HNL-DSF which is due to the high power narrow line laser, we modulate the pump seed light from the tunable laser with a 3.5-GHz-2^{31}–1 pseudorandom bit sequence (PRBS) signal by employing a phase modulator (PM). A tunable filter (Santec, 0TF-30M-08S1) is used to eliminate the excess amplified spontaneous emission (ASE) noise of the pump light after the HP-EDFA.

The line cavity of the MW-FOPO is formed by two FBGs, two PCs, and an SFLM which consists of a 50 : 50 optical coupler, a PC and a segment of 500-m HNL-DSF. The nominal zero-dispersion wavelength (ZDW), loss coefficient, dispersion slope, and nonlinear coefficient of the HNL-DSF are 1553.35 nm, $0.92\,\mathrm{dB \cdot km^{-1}}$, $0.016\,\mathrm{ps \cdot nm^{-2} \cdot km^{-1}}$, $10.7\,\mathrm{W^{-1} \cdot km^{-1}}$, respectively. Two FBGs are used as wavelength selection components. The central wavelength, the full-width at half maximum (FWHM) and the reflectivity are (1549.01 nm, 0.19 nm, 95%) and (1551.06 nm, 0.19 nm, 95%) for FBG1 and FBG2, respectively. All of the three PCs are used to adjust the polarization state of the signal lasing light and the pump light, since the FOPA is sensitive to the polarization of the signal and the pump. The output of the MW-FOPO is measured by an optical spectrum analyzer (OSA, Agilent 86142B).

As shown in Figure 1, it is well known that an FBG and an SFLM will form a line cavity with a single lasing wavelength determined by the central wavelength of the FBG. However, due to the FWM effect

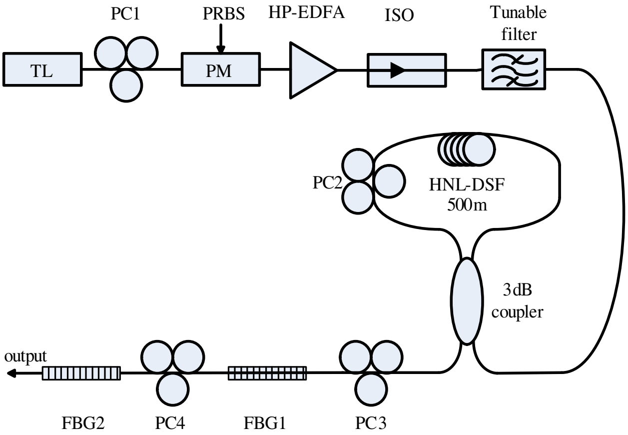


Figure 1. Schematic diagram of the wavelength spacing tunable and switchable MW-FOPO. TL: tunable laser. PC: polarization controller. PM: phase modulator. PRBS: pseudorandom bit sequence. HP-EDFA: high power erbium-doped fiber amplifier. ISO: isolator. HNL-DSF: highly nonlinear dispersion-shifted fiber. FBG: fiber Bragg grating.

in the HNL-DSF inside the SFLM and the high-power pump light, new lasing wavelengths will appear in the line cavity and multi-wavelength lasing is achieved as a consequence of multiple FWM effect between the lasing light and the pump light [19–21]. As a result, using two FBGs produce two multi-wavelength lasing modes with different wavelength spacings, which are the differences of the wavelength of pump light and the central wavelengths of the two FBGs. Since the FOPA is sensitive to the polarization of the signal and the pump, the operation modes of the MW-FOPO can be switchable by adjusting the PCs.

In our first experiment, the wavelength of the pump light is set to be 1553.01 nm and the central wavelength of FBG2 is adjusted to 1551.51 nm by stretching. When the HP-EDFA with the output power of 2 W is turned on, stable multi-wavelength lasing of the MW-FOPO can be achieved after appropriately adjusting the states of PCs in the line cavity. Figure 2 shows the typical output spectra of the MW-FOPO when the wavelength spacings are (a) 4 nm and (b) 1.5 nm, respectively. Note that the wavelength spacings are just the

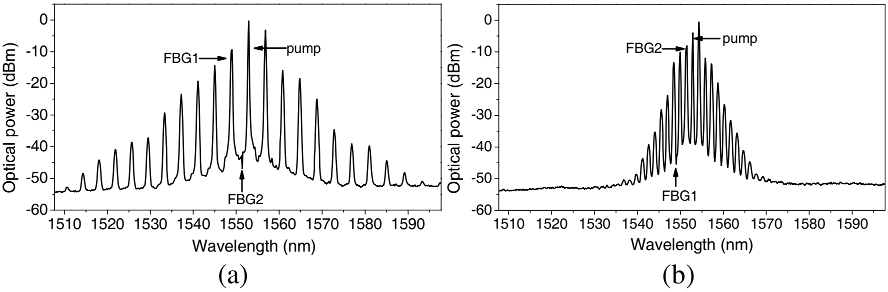


Figure 2. Output spectra of the MW-FOPO at two modes with different spacing of 4 nm (a) and 1.5 nm (b).

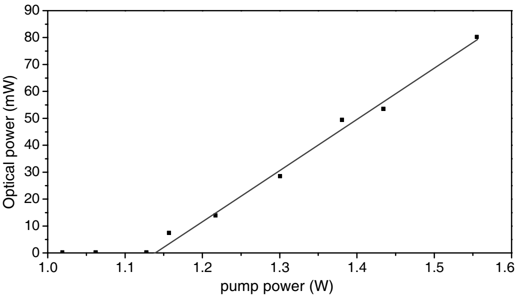


Figure 3. Idler output power as a function of pump power for a pump wavelength of 1553.0 nm after filtering the pump light out.

differences between the pump wavelength and the central wavelengths of the FBGs. Figure 3 shows the idler output power as a function of the pump power for a pump wavelength of 1553.0 nm after filtering the pump light out when the MW-FOPO operate at the mode with wider spacing, which shows the threshold of the MW-FOPO is about 1.14 W, and the slope efficiency is 38.0%. The threshold of the MW-FOPO is high as result of the two direction injection of the pump into the HNLF and the unidirectional gain of the FOPA. The high slope efficiency is owing to more new sidebands generated by increasing the pump power [19]. Note that the gain saturation does not happen at the present pump power level, which indicates that further increasing the pump power will result in much higher output power of the MW-FOPO.

Figure 4 shows the output multi-wavelength lasing as the states of the PCs change. Figure 4(b) is an intermediate state between the state of Figure 4(a) and the state of Figure 4(c). From Figure 4(b), multi-wavelength lasing operating simultaneously at the two modes is achieved. Note that this hybrid mode can not be achieved in wavelength spacing switchable MWFLs based on EDFA.

Here we also demonstrated the wavelength-spacing tunability of the MW-FOPO by simply adjusting the wavelength of the pump light or the central wavelengths of the FBGs. By adjusting the central

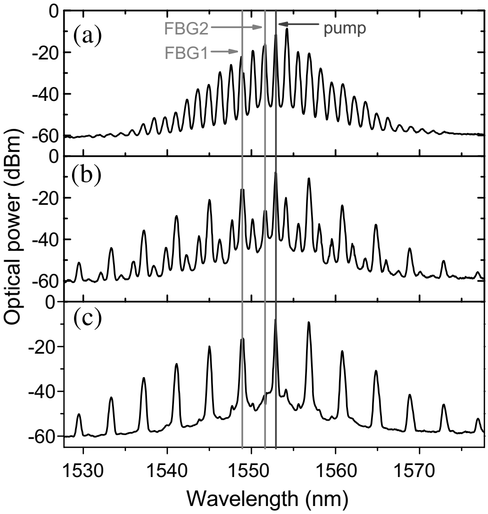
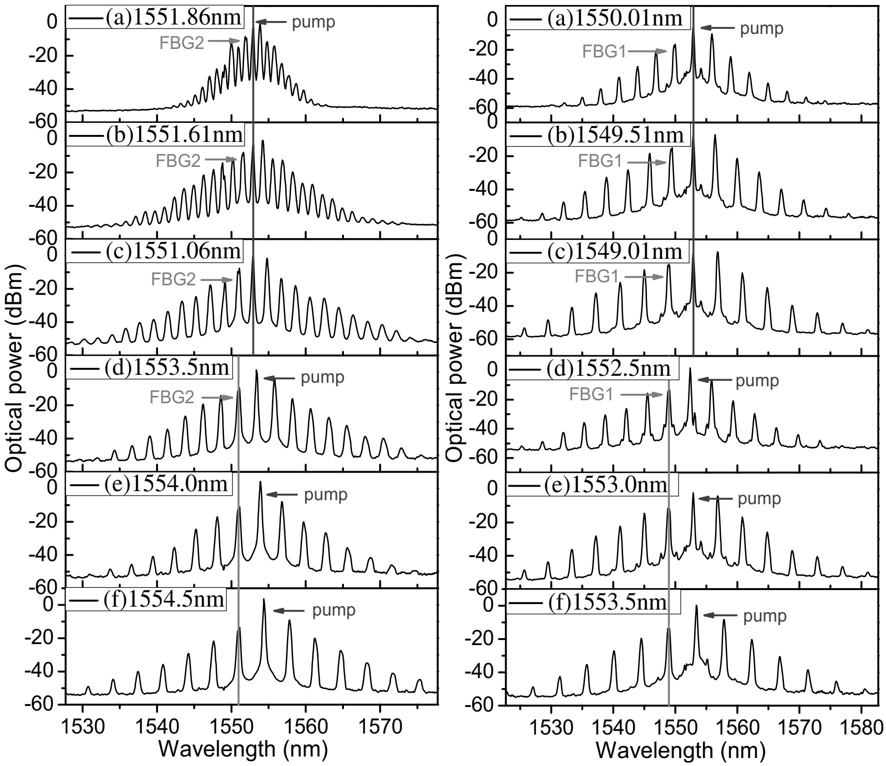


Figure 4. Output spectra of the MW-FOPO varying with the states of the PCs.

wavelengths of the FBGs, we can modify the wavelength-spacings between the pump wavelength and the central wavelengths of the FBGs. Figure 5(I): (a), (b) and (c) show the output spectra of the MW-FOPO when the central wavelengths of FBGs under stretching are with 3 different values, which consequentially result in the different wavelength spacings of 1.14 nm (a), 1.34 nm (b), 1.94 nm (c). Note that the pump wavelength is fixed to 1553.0 nm and the MW-FOPO operates at the mode with narrower spacing (we call it FBG2 mode). Another approach to achieve a tunable wavelength spacing of the MW-



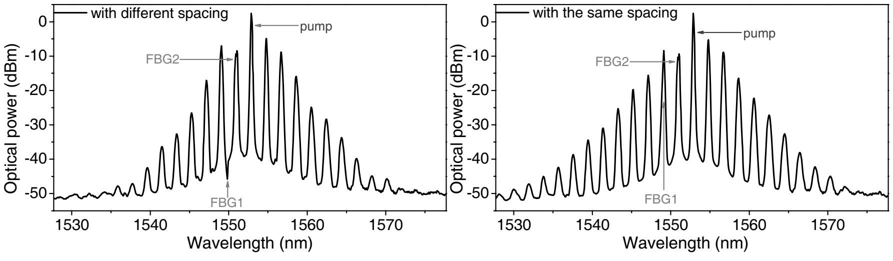
(I) (II)

Figure 5. (I): Output spectra of the MW-FOPO under different central wavelength of the FBG2: (a) 1551.86 nm, (b) 1551.61 nm, (c) 1551.06 nm, and different pump wavelength: (d) 1553.5 nm, (e) 1554.0 nm, (f) 1554.5 nm. (II): Output spectra of the MW-FOPO under different central wavelength of the FBG1: (a) 1550.01 nm, (b) 1549.51 nm, (c) 1549.01 nm, and different pump wavelength: (d) 1552.5 nm, (e) 1553.0 nm, (f) 1553.5 nm.

FOPO is to adjust the pump wavelength. Figure 5(I): (d), (e) and (f) show the output spectra of the MW-FOPO when the pump wavelength of the FBG is adjusted to 1553.5 nm (d), 1554.0 nm (e) and 1554.5 nm (f), which results in the wavelength spacings of 2.44 nm (d), 2.94 nm (e), 3.44 nm (f). It is worthwhile to note that the lasing wavelength regime changes together with the pump wavelength, since the gain spectrum of the FOPA largely depends on the pump wavelength. Similarly, we can achieve wavelength spacing tunability by adjusting the wavelength of the pump light or the central wavelength of the FBG1 when the MW-FOPO operate at the mode with wider spacing, as showed in Figure 5(II).

We also pay attention to the special case of the MW-FOPO that the wavelength spacing between the pump wavelength and the central wavelength of FBG1 is the integral multiple of the wavelength spacing between the pump wavelength and the central wavelength of FBG2. Figure 6(b) shows the output spectrum of the MW-FOPO when the wavelength spacings between the pump wavelength and the central wavelength of the FGB1 and FBG2 are 4.0 nm and 2.0 nm, respectively. Evidently, the number of lasing wavelengths of the MW-FOPO as shown in Figure 6(b) is larger than that shown in Figure 6(a), where the MW-FOPO is in the case when the wavelength spacing between the pump wavelength and the central wavelength of FBG1 is not integral multiple of the wavelength spacing between the pump wavelength and the central wavelength of FBG2.

Besides the wavelength-spacing tunability and switchability, the power stability of the MW-FOPO is also of great importance for the practical applications of the MW-FOPO. We quantitatively investigate the short-term stability of the MW-FOPO by measuring the output spectrum of the MW-FOPO every 10 min for 1 hour while the pump power and pump wavelength are set to 2 W and 1553.91 nm, respectively. The repeated scanning spectra when the MW-FOPO



(a) (b)

Figure 6. Output spectra of the MW-FOPO with a stretching FBG1.

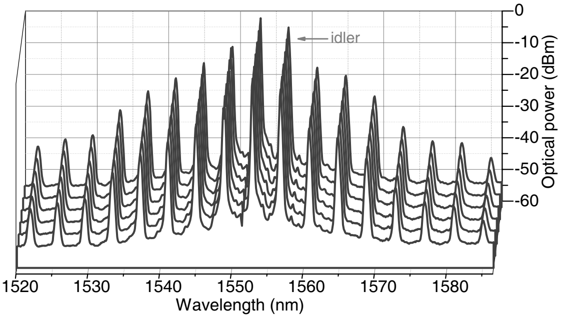


Figure 7. Output spectra of the MW-FOPO under repeated scanning in 1 hours. The time interval of each scan is 10 min.

operates at the mode of wider spacing (the other mode has a similar stability) are shown in Figure 7. No significant peak power fluctuations are observed for the MW-FOPO and the variation of the idler power is less than 0.2 dB. The stability is mainly due to the FWM effect between the lasing wavelengths.

3. DISCUSSION AND CONCLUSION

Owing to the unique features of the FOPAs, such as high gain, broadband gain, unidirectional gain, an arbitrary wave-band operation, inhomogeneous broadening, sensitivity to polarization, FOPOs tend to be very applicable to implement MWFLs. As we have mentioned above, the switchability by adjusting the PCs of the MW-FOPO is owing to the sensitivity to polarization of FOPAs and the stability at room temperature is achieved thanks to the inhomogeneous broadening of FOPAs. The MW-FOPO with the HNL-DSF which provides both the gain (of the FOPA) and multiple FWM effect, is different from the MW-EDFL [21] which is based on the gain of the EDFA and the multiple FWM effect of the PCF. We believe that the MW-FOPO could be more applicable to implement MWFLs after it is further improved.

In conclusion, a switchable and wavelength-spacing tunable MW-FOPO with a simple line cavity has been proposed and demonstrated. It can operate at two multi-wavelength lasing modes with different wavelength spacing which can be switched by adjusting the PCs in the cavity. Stable multi-wavelength lasing at room temperature has been achieved due to both the FWM effect and the broadband gain of the FOPA. The wavelength spacing of the MW-FOPO can be tuned by adjusting the wavelength of the pump light or the central wavelength of the FBGs at both modes.

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