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Multiwavelength Pulse Generation Using Fiber Optical Parametric Oscillator

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Abstract—We demonstrate a 10-GHz multiwavelength pulsed generator based on a fiber optical parametric oscillator. By introducing two separated intracavity branches, simultaneous mode-locking at two different wavelengths in the L-band is achieved. Due to the parametric process between the pump and the two mode-locked signals, two idlers are generated in the S-band. Hence, simultaneous generation of a 10-GHz pulse train at four different wavelengths located in both the S- and L-band is accomplished. The wavelength of the generated pulse trains can be tuned over 54 nm, with the wavelength span from 1500 to 1617 nm. The stability of the proposed scheme is also experimentally investigated.

Index Terms—Optical fiber laser, optical parametric amplifier, optical parametric oscillator.

I. INTRODUCTION

MULTIWAVELENGTH pulsed fiber lasers are of great interest for their wide applications in WDM communication systems, optical fiber sensing, optical signal processing, and optical instrumentation. Several researchers have demonstrated generation of multiwavelength pulse train in mode-locked fiber lasers based on erbium-doped fiber amplifiers (EDFAs) [1]–[3] and/or semiconductor optical amplifiers (SOAs) [4], [5]. However, the tuning range of the output pulse was usually confined to the C-band due to the properties of the gain medium. Generating multiwavelength pulse in the S- plus L-band is highly desirable to extend the transmission band in WDM communication systems, detect gases with absorption lines in the corresponding band and test S- and L-band devices [6], etc. Fiber optical parametric amplifier (FOPA) [7] based on $\chi^{(3)}$ nonlinear effect of optical fiber offers remarkable properties such as high gain, wide gain bandwidth, and ultra-fast response, which result in spectacular performance of fiber optical parametric oscillator (FOPO) in terms of the wavelength tunability and output power [8]. In the previous efforts pursuing FOPO, the emphasis was on continuous wave (CW) operation oscillating at single wavelength [9], CW operation oscillating at multiwavelength [10], or pulsed operation oscillating at single wavelength [11].

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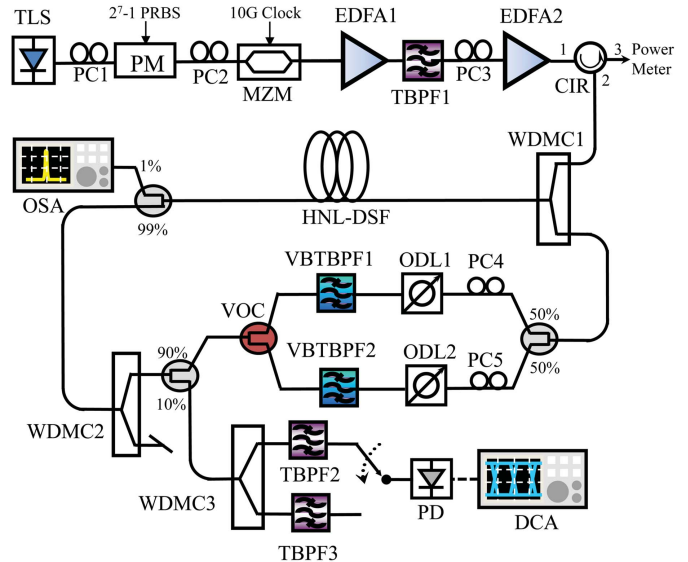


Fig. 1. Experimental setup of the multiwavelength pulsed FOPO. EDFA: erbium-doped fiber amplifier. TBPF: tunable bandpass filter. VBTBPF: variable bandwidth tunable bandpass filter. OSA: optical spectrum analyzer. PM: phase modulator. MZM: Mach-Zehnder modulator. ODL: optical delay line. PC: polarization controller. WDMC: wavelength-division multiplexing coupler. VOC: variable optical coupler. CIR: circulator. HNL-DSF: highly nonlinear dispersion-shifted fiber.

While in this Letter, we demonstrate a stable dual-wavelength mode-locked FOPO by utilizing two intracavity branches which share the same pump and gain medium, for the first time to the best of our knowledge. In addition to the generation of two mode-locked pulse trains in the L-band, we can also obtain two other pulse trains in the S-band due to the parametric process between the pump and the two oscillating signals. Hence, simultaneous generation of 10-GHz pulse train at four different wavelengths with pulsewidth narrower than that of the pump can be obtained. By adopting a gain fiber with a positive $\beta^{(4)}$ which can generate the flat gain spectrum [7], the tuning range of the generated pulse trains is over 54 nm. The proposed scheme has the potential to mode-lock more than two wavelengths and become an efficient and useful multiwavelength pulsed source in nonconventional wavelength bands [12].

II. EXPERIMENTAL SETUP

The experimental setup of the FOPO is shown in Fig. 1. The parametric pump was obtained from a CW tunable laser source (TLS) with a fixed wavelength of 1555.5 nm (λ_p). In order to suppress the stimulated Brillouin scattering (SBS) in the highly-nonlinear dispersion-shifted fiber (HNL-DSF),

the pump was first phase dithered with a 10-Gb/s $2^7 - 1$ pseudo-random binary sequence (PRBS) via a phase modulator (PM). It was then intensity modulated by a 10-GHz clock signal using a Mach-Zehnder modulator (MZM) to produce a sinusoidally modulated pump. The polarization controllers (PC1 and PC2) were used to align the state-of-polarization (SOP) of the pump with the transmission axis of the PM and MZM. Afterwards, the pump was amplified by two stage erbium-doped fiber amplifiers (EDFA1 and EDFA2) to 31 dBm. A tunable bandpass filter (TBPf1) was inserted between two EDFAs to reduce the amplified spontaneous emission (ASE) noise. The amplified pump then passed through a circulator (CIR), and the reflected power due to the SBS was monitored by a power meter at port 3. Then it was coupled into the HNL-DSF through the wavelength-division multiplexing coupler (WDMC1). Note that the two intracavity branches shared a 150-m long HNL-DSF as the gain medium inside the cavity, which had a nonlinear coefficient of $30 \text{ W}^{-1}\text{km}^{-1}$, zero-dispersion wavelength (ZDW) of 1554 nm, dispersion slope of $0.02 \text{ ps/nm}^2/\text{km}$, and $\beta^{(4)}$ of $5.0 \times 10^{-5} \text{ ps}^4/\text{km}$. The two intracavity branches were constructed by: (1) a variable optical coupler (VOC) to balance the net gain/loss of each wavelength; (2) two variable bandwidth tunable bandpass filters (VBTBPf1 and VBTBPf2, each comes with in-band group-velocity dispersion of 0.4 ps/nm) to tune the wavelength; (3) two optical delay lines (ODL1 and ODL2) to synchronize each wavelength with the pump; (4) PC4 and PC5 to align the SOP of each wavelength with that of the pump; (5) a 50/50 coupler. The total cavity loss for each wavelength was measured to be around 18 dB.

The FOPO output spectrum was monitored by an optical spectrum analyzer (OSA) through a 99/1 coupler inside the cavity. The WDMC2 was used to filter out the high power pump. A 90/10 coupler in the cavity provided 90% feedback and 10% output. The output signal from the 10% port of the 90/10 coupler was then filtered by WDMC3 with a cutoff wavelength of 1569 nm, TBPf2 and TBPf3 to obtain the desired wavelength. The waveform of each wavelength was recorded by a digital communication analyzer (DCA).

III. RESULTS AND DISCUSSION

The center wavelength of VBTBPf1 (λ_1) was set to be 1580 nm. Then the center wavelength of VBTBPf2 (λ_2) was chosen to satisfy

$$\frac{1}{\lambda_2} = \frac{2}{\lambda_1} - \frac{1}{\lambda_p} \quad (1)$$

in order to suppress the gain competition between these two oscillating wavelengths and the generation of spurious four-wave mixing (FWM) [2]. The ODL1 and ODL2 were tuned carefully to ensure that the round-trip time of each wavelength matches the same pump repetition rate (f_p)

$$f_p = \frac{m_1 c}{n(\lambda_1) L_1} = \frac{m_2 c}{n(\lambda_2) L_2} \quad (2)$$

where m_1 and m_2 is an integer, c is the light velocity in vacuum, n is the group index for each wavelength, and L is the cavity length for each wavelength. Fig. 2 shows the optical

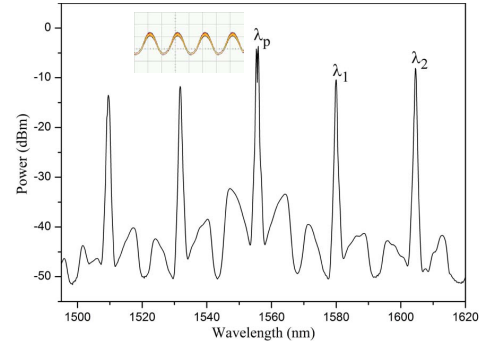


Fig. 2. Optical spectra measured after the 99/1 coupler inside the FOPO cavity. Inset: waveform of the input pump pulse. Time scale: 50 ps/division.

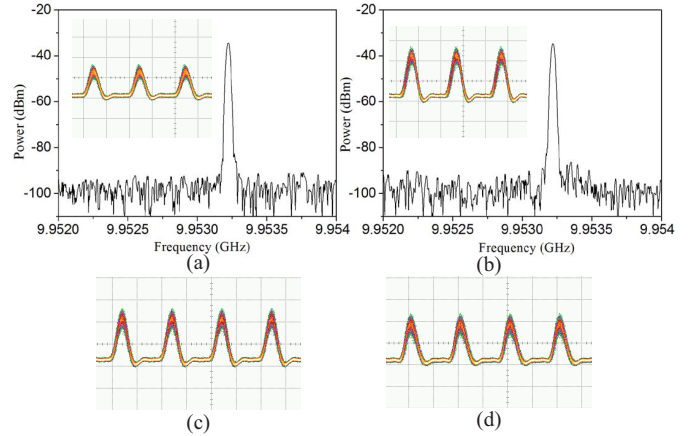


Fig. 3. (a) RF spectrum of λ_1 on a 2-MHz span. Inset: waveform of λ_1 . (b) RF spectrum of λ_2 on a 2-MHz span. Inset: waveform of λ_2 . (c) Waveform of the generated idler at 1531 nm. (d) Waveform of the generated idler at 1509 nm. Time scale: 50 ps/division.

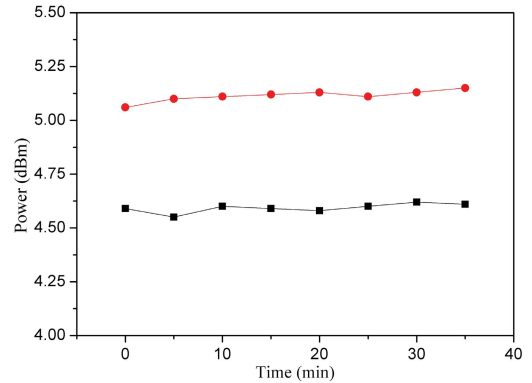


Fig. 4. Power fluctuation of the output over a period of 35 min. Black rectangles: at λ_1 . Red circles: at λ_2 .

spectrum measured after the 99/1 coupler inside the cavity. As can be observed, λ_1 and λ_2 were mode-locked simultaneously. Note that the pedestal at the bottom of the pump is due to the ASE noise of EDFAs and the small peaks of the pump may be caused by the self-phase modulation (SPM). Fig. 3(a) and 3(b) shows the waveforms and the RF spectra of the λ_1 and λ_2 . Due to the compression effect of the FOPO, the pulsewidths of the λ_1 and λ_2 were measured to be 21 ps and 23 ps, which were narrower than that of the pump (45.5 ps). In addition to the two oscillating wavelengths at λ_1 and λ_2 in

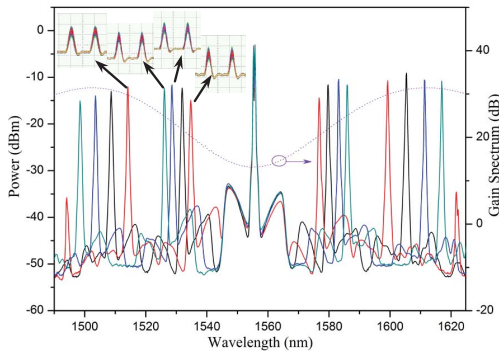


Fig. 5. Optical spectra measured after the 99/1 coupler inside the FOPO cavity when tuning the wavelength. Dotted line: simulated gain spectrum of the single-pass FOPO. Inset: corresponding waveform. Time scale: 50 ps/division.

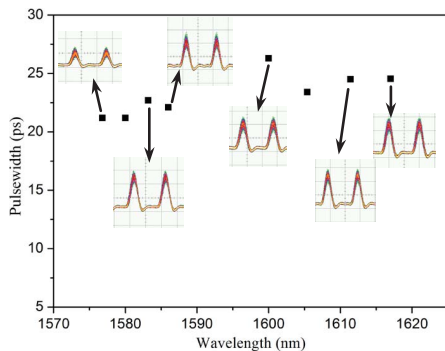


Fig. 6. Pulsewidth of the generated pulse train in the L-band. Inset: corresponding waveforms. Time scale: 50 ps/division.

the L-band, we can also obtain two other idler wavelengths at 1531 nm and 1509 nm in the S-band due to the parametric process between the pump and λ_1 , λ_2 . Fig. 3(c) and 3(d) show the waveforms of the two generated idlers at 1531 nm and 1509 nm. Hence, simultaneous generation of 10-GHz pulse at four different wavelengths was achieved. The noise at the mark level of the generated pulse train was inherited from the ASE noise from the EDFAs. The stability of the scheme was also investigated. The power fluctuation of the output at λ_1 and λ_2 over a period of 35 minutes is shown in Fig. 4. The variation of the output power and the pulse shape was quite small over this period of time. Long term stability of the cavity can be achieved by adopting polarization-maintaining components and feedback loops [13].

Wavelength tuning was achieved by tuning the center wavelength of the VBTBPF1 and VBTBPF2 with the fixed pump wavelength at 1555.5 nm. Fig. 5 shows the optical spectra measured after the 99/1 coupler inside the cavity. The dotted line in Fig. 5 shows the simulated gain spectrum of the single pass FOPO with a 1-W CW pump fixed at 1555.5 nm. The achievable tuning range was about 54 nm, with the wavelength span from 1500 nm to up to 1617 nm. Further tuning was limited by the tuning range of our VBTBPF inside the cavity. Fig. 6 shows the pulsewidth of the oscillating pulse train in the L-band when tuning the wavelength. The insets of Fig. 5 and Fig. 6 show the corresponding waveform of each wavelength. Due to the tuning range of our TBPF,

the waveform of pulse train with wavelength shorter than 1509 nm was not recorded.

IV. CONCLUSION

In conclusion, we demonstrated a 10-GHz multiwavelength pulsed FOPO. By utilizing dual-wavelength mode-locking and parametric process between the pump and the two oscillating pulse trains, simultaneous generation of 10-GHz pulse train at four different wavelengths located in both S- and L-band was obtained. Multiwavelength pulse trains with narrower wavelength spacing and mode-locking more than two wavelengths can be potentially achieved by pursuing different fibers to tailor the gain bandwidth of the FOPO. Therefore, this scheme has the potential to become an efficient multiwavelength pulsed source in nonconventional wavelength bands [14].

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