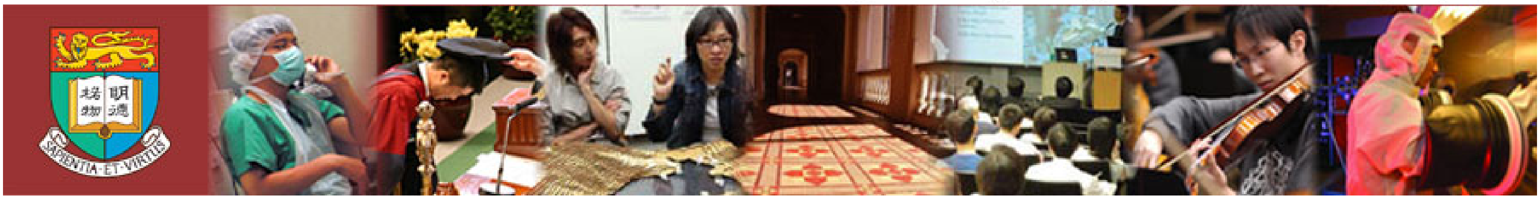
View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by HKU Scholars Hub

The HKU Scholars Hub The University of Hong Kong 香港大學學術庫



Title	Quad-Wavelength Pulse Generation Based on Fiber Optical Parametric Oscillator with Equally Distributed Dispersion
Author(s)	WANG, X; ZHANG, C; XU, J; WEI, X; Wong, KKY
Citation	IEEE Photonics Technology Letters, 2013, v. 25 n. 10, p. 940-943
Issued Date	2013
URL	http://hdl.handle.net/10722/189010
Rights	Creative Commons: Attribution 3.0 Hong Kong License

Quad-Wavelength Fiber Optical Parametric Oscillator With Equally Distributed Dispersion

Xie Wang, Chi Zhang, Jianbing Xu, Xiaoming Wei, and Kenneth Kin-Yip Wong, *Senior Member, IEEE*

***Abstract*— We demonstrate a 10-GHz quad-wavelength pulse source based on fiber optical parametric oscillator with equally distributed dispersion. By adopting two spools of single-mode fiber inside the cavity with nearly the same dispersion, simultaneous mode-locking at two different wavelengths with the wavelength spacing of around ∼1.9 nm in the *L*-band is achieved. Owing to the parametric process between the pump and the two mode-locked signals, two idlers are generated in the *S*-band with the same wavelength spacing. Hence, simultaneous generation of 10-GHz pulse train at four different wavelengths located in both *S*- and *L*-band is obtained. The wavelength of the generated pulse trains can be tuned over 67 nm, from 1504 to 1536 nm and from 1575 to 1610 nm, with the wavelength span of around ∼106 nm.**

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

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. In the previous efforts pursuing multiwavelength pulsed fiber laser [1]–[4], the tuning range of the output pulse was usually confined to the $C-$ band due to the properties of the gain medium. Fiber optical parametric amplifier (FOPA) [5] 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 [6]. In our previous work [7], we have first demonstrated multiwavelength pulsed FOPO with two separated cavities which is relatively inefficient. The wavelength location of the two oscillating signals should be fine-tuned separately to suppress the gain competition which results in large wavelength spacing (∼25 nm) and narrow wavelength tuning range specified by the Eq. (1) in [7].

In this Letter, we demonstrate a 10-GHz quad-wavelength FOPO with narrower wavelength spacing and wider tuning range in a single cavity. By utilizing the equally distributed dispersion inside the cavity, simultaneously mode-locking at two different wavelengths with the wavelength spacing of around 1.9 nm in the $L-$ band is achieved. 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. Hence, simultaneous generation of 10-GHz pulse train at four different wavelengths can be obtained more efficiently than our previous work. By adopting a gain fiber with a positive $\beta^{(4)}$ which can generate the flat and broadband gain spectrum [8], the tuning range of the generated pulse trains is over 67 nm, from 1504nm to 1536 nm and from 1575 nm to 1610 nm, with the wavelength span of around 106 nm.

Manuscript received February 4, 2013; revised March 6, 2013; accepted April 6, 2013. Date of publication April 12, 2013; date of current version April 25, 2013. This work was supported in part by a grant from the Research Grants Council of the Hong Kong Special Administrative Region of China under Project HKU 7172/12E.

The authors are with the Department of Electrical and Electronic Engineering, The University of Hong Kong, Hong Kong 999077, Hong Kong (e-mail: wangxie@eee.hku.hk; zhangchi@eee.hku.hk; jbxu@eee.hku.hk; xmwei@eee.hku.hk; kywong@eee.hku.hk).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2013.2257722

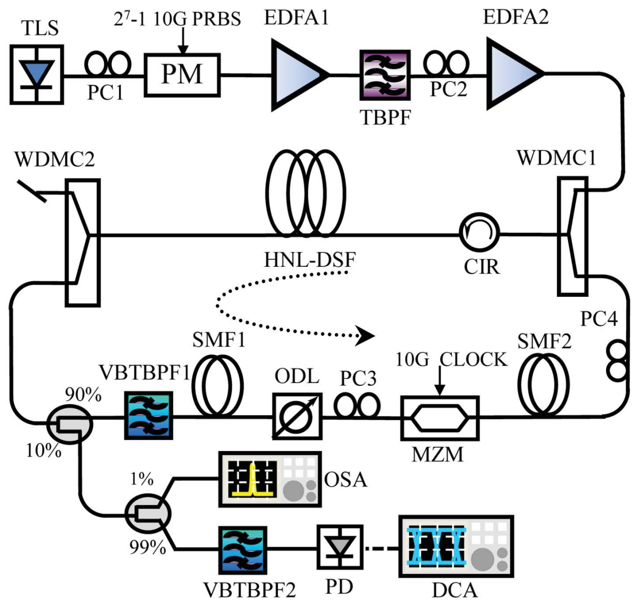


Fig. 1. Experimental setup of the quad-wavelength pulsed FOPO.

II. Principle and Experimental Setup

The operating principle is as follows. Suppose that pulses at wavelength λ_1 and λ_2 in the $L-$ band are simultaneously mode-locked in the cavity, the wavelength spacing between these two pulses is decided by [9]

$$\Delta\lambda = \frac{1}{fD_s(L_1+L_2)} \quad (1)$$

where f is the modulation frequency, D_s is the dispersion parameter of the single-mode fiber (SMF), L_1 and L_2 are the fiber length of SMF1 and SMF2 in Fig. 1, respectively. Eq. (1) also indicates that the round trip time difference between

1041-1135/$31.00 © 2013 IEEE

λ_1 and λ_2 is exactly $1/f$ =100 ps. Note that in order to achieve dual-wavelength active mode-locking, pulses at wavelength λ_1 and λ_2 should pass through the time-gating element (a $LiNbO_3$ Mach-Zehnder modulator (MZM) in our case) simultaneously. Then after passing through the MZM and SMF2 in Fig. 1 (before launching into the highly-nonlinear dispersion-shifted fiber (HNL-DSF)), the time separation between pulses at λ_1 and λ_2 should be

$$\Delta T = \Delta\lambda D_s L_2 = \frac{L_2}{f(L_1 + L_2)} \quad (2)$$

If we assume that L_1equals to L_2, the pulses at λ_1 and λ_2 should be separated by the time of $1/2f = 50$ ps after passing through the MZM and SMF2. Thus the gain competition between each other can be nearly perfectly suppressed when passing through the HNL-DSF [2], [4]. Owing to the parametric process between the pump and λ_1, λ_2 in the HNL-DSF, we can also obtain two other idler wavelengths at λ_3 and λ_4 in the S-band. Hence, simultaneous generation of 10-GHz pulse at four different wavelengths was obtained at the output of the HNL-DSF. Note that we can potentially mode lock more than two wavelength if we select proper ratio of L_1 to L_2.

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. In order to suppress the stimulated Brillouin scattering (SBS) in the HNL-DSF, the pump was phase dithered with a 10-Gb/s 2^7-1 pseudo-random binary sequence (PRBS) via a phase modulator (PM). The polarization controller (PC1) was used to align the state-of-polarization (SOP) of the pump with the transmission axis of the PM. Afterwards, the pump was amplified by two stage erbium-doped fiber amplifiers (EDFA1 and EDFA2) to about 32 dBm. A tunable bandpass filter (TBPF) was inserted between two EDFAs to reduce the amplified spontaneous emission (ASE) noise. Then the amplified pump was coupled into the cavity through the wavelength-division multiplexing coupler (WDMC1). Before launching into the HNL-DSF, the pump passed through a circulator (CIR) to ensure unidirectional operation in the cavity and the reflected power due to the SBS was monitored by a power meter. The gain medium was a 150-m long HNL-DSF, which had a nonlinear coefficient of 30 $W^{-1}km^{-1}$, zero-dispersion wavelength (ZDW) of 1554 nm, dispersion slope of 0.02 ps/nm^2/km, and $\beta^{(4)}$of 5.0$\times$ 10^{-5} ps^4/km. 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 variable bandwidth tunable bandpass filter (VBTBPF1) with in-band group-velocity dispersion (GVD) of 0.4 ps/nm was operated in the $L-$ band to restrict the lasing wavelength. A $LiNbO_3$ MZM driven by a 10-GHz clock signal was inserted in the cavity to achieve active mode-locking. PC3 was employed due to the polarization dependence of the MZM. Note that the intracavity GVD was provided by two spools of single-mode fiber (SMF1 and SMF2) with the fiber length of 1.31 km and 1.45 km, which had a dispersion of 17 ps/nm/km and a dispersion slope of 0.06 ps/nm^2/km at 1550 nm. The optical delay line (ODL) was used to adjust the cavity length. The PC2 and PC4 were used to align the SOP of the oscillating signal with that of the pump. The VBTBPF2 operating in $S-$ or $L-$ band was used to filter out the desired pulse trains. The total cavity loss excluding the MZM was measured to be around 13 dB. The FOPO output spectrum was monitored by an optical spectrum analyzer (OSA) through a 99/1 coupler after the cavity output. The waveform of the output was recorded by a digital communication analyzer (DCA).

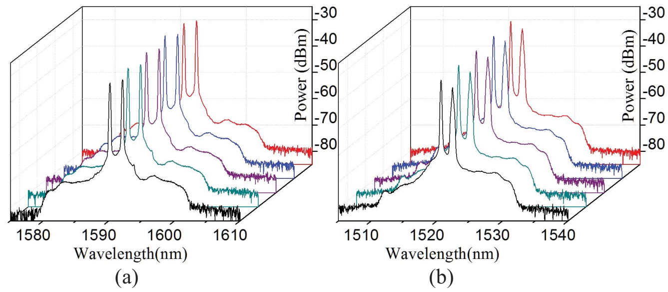


Fig. 2. The optical spectra of the (a) $L-$band and (b) $S-$band pulse trains measured at a 5-minute interval.

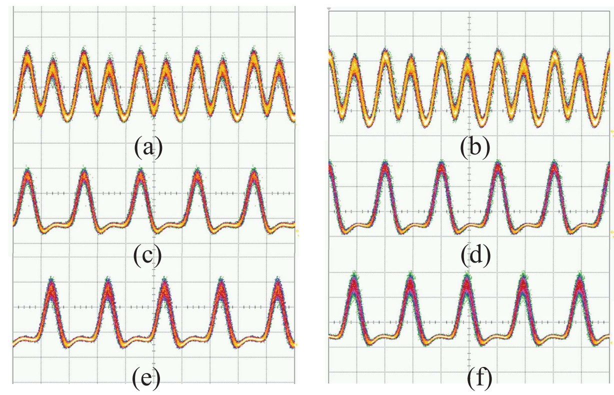


Fig. 3. The waveform of the time- and wavelength-interleaved pulses in the (a) $L-$band and (b) $S-$band; the waveform of the generated pulses at (c) 1592.2 nm, (d) 1520.5 nm, (e) 1590.3 nm, and (f) 1522.3 nm. Time scale: 50 ps/div.

III. Results and Discussions

Fig. 2 shows repeated scan of the optical spectra measured after the 99/1 coupler by the OSA. As can be observed, two oscillating signals at 1590.3 nm and 1592.2 nm in the $L-$ band were simultaneously mode-locked and reasonably stable. The wavelength and power variation were within 0.4 nm and 1 dB over this time period. Long term stability of the cavity can be achieved by adopting polarization-maintaining components and feedback loops. The wavelength spacing was around 1.9 nm, which agreed well with the theoretical predication (1.87 nm) from Eq. (1). In addition to these two oscillating wavelengths in the L-band, we can also obtain two other idler wavelengths at 1522.3 nm and 1520.5 nm in the $S-$ band. Fig. 3(a) and 3(b) show the time- and wavelength-interleaved waveforms in the $L-$ and $S-$ band when we tuned the bandwidth and wavelength of the VBTBPF2 to filter out the both wavelengths simultaneously. These two

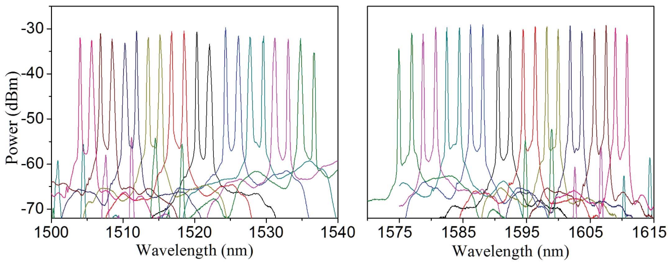


Fig. 4. Optical spectra measured after the 99/1 coupler when tuning the center wavelength of the VBTBPF1.

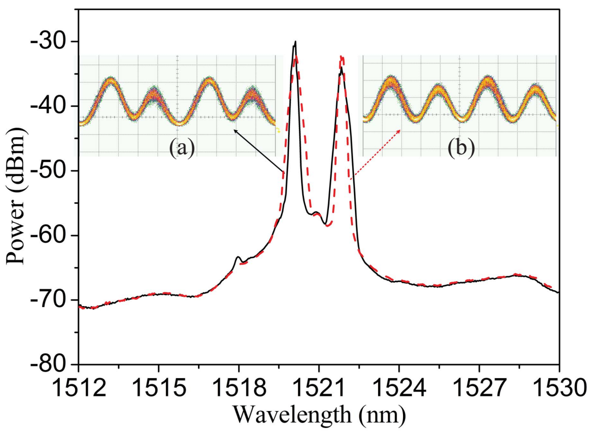


Fig. 5. Optical spectra of the generated pulse train in the $S-$band when tuning the electrical delay of the PRBS. The insets show the corresponding waveform of (a) black solid line and (b) red dashed line. In both (a) and (b), the leading pulse was at 1520.1 nm and the trailing pulse was at 1521.9 nm. Time scale: 25 ps/div.

time- and wavelength-interleaved pulse trains are intrinsically synchronized because of the nature of the parametric process. As can be observed in Fig. 3(a) and Fig. 2(a), pulse trains at 1590.3 nm and 1592.2 nm are separated by nearly 50 ps which are in good agreement with our theoretical predication and there is no spurious four-wave mixing between each other. It also indicates the gain competition in the HNL-DSF has been suppressed. Note that these time- and wavelength-interleaved pulses may also find application in optical signal processing [10]. Fig. 3(c)–3(f) show the waveforms of 10-GHz pulse trains at 1592.2 nm, 1520.5 nm, 1590.3 nm and 1522.3 mm respectively when we changed the bandwidth and wavelength of the VBTBPF2. The corresponding pulsewidths were measured to be 25 ps, 25.5 ps, 23.2 ps and 24.6 ps. The corresponding time-bandwidth products were calculated to be around 0.591, 0.529, 0.495 and 0.732, which indicates the pulses are chirped. This is mainly due to the relatively long cavity length and pump phase modulation. The chirp on the pulses may be compensated by adopting a segment of dispersion-compensating fiber after the cavity output [11].

Coarse wavelength tuning was achieved by setting the center wavelength of the VBTBPF1 (with the bandwidth of ∼4 nm) and within the bandwidth of the VBTBPF1, fine wavelength tuning can be achieved by adjusting the ODL. Fig. 4 shows the optical spectra measured after the 99/1 coupler. The achievable tuning range is over 67 nm, from 1504nm to 1536 nm and from 1575 nm to 1610 nm, with the wavelength span of around 106 nm. Further tuning was only limited by the tuning range of our VBTBPF inside the cavity. The generated pulse trains exhibit more noise when locating at the edge of the FOPA gain spectrum since the parametric gain is more sensitive to perturbation of the pump power at the edge [12]. Further improvement can be achieved by pursuing different fibers to tailor the gain shape and bandwidth of the FOPA.

Finally, we investigate the impact of pump phase modulation on the spectra and pulse quality of the generated idlers by solely tuning the electrical delay of the 10-Gb/s PRBS signal. Note that the two oscillating pulse trains were separated by nearly 50 ps before launching into the HNL-DSF. A phase jump in the pump will introduce idler spectrum broadening and parametric gain variation, and then degrade the generated pulse train [13]–[15]. We first tuned the electrical delay to ensure that the pulse train at 1520.1 nm was generated without the phase jump in the pump. As can be observed from Fig. 5 (a) and the black solid line, the pulse train at 1520.1 nm has better quality and narrower spectrum. Then we tuned the electrical delay by around 50 ps so that the phase jump in the pump occurred during the generation of pulse train at 1520.1 nm, in this case the pulse train at 1521.9 nm will in turn exhibit better quality and narrower spectrum as shown from Fig. 5(b) and red dashed line. Better performance can be achieved by adopting more advanced SBS suppression technique such as the strain-based method [16].

IV. Conclusion

In conclusion, we demonstrated a 10-GHz quad-wavelength FOPO. Simultaneous generation of pulse trains at four different wavelengths in $S-$ band $L-$ band can be obtained by utilizing equally distributed dispersion inside the cavity. The tuning range was over 67 nm, from 1504 nm to 1536 nm and from 1575 nm to 1610 nm, with the wavelength span of around 106 nm. The proposed scheme has the potential to mode-lock more than two wavelengths if we change the length ratio of $L_1$to L_2 and become an efficient and useful multiwavelength pulsed source out of $C-$ band.

V. Acknowledgment

The authors would like to acknowledge Sumitomo Electric Industries for providing the HNL-DSF and Alnair Laboratories for providing the VBTBPF.

References

[1] B. Bakhshi and P. A. Andrekson, “Dual-wavelength 10-GHz actively mode-locked erbium fiber laser,” *IEEE Photon. Technol. Lett.*, vol. 11, no. 11, pp. 1387–1389, Nov. 1999.

[2] L. R. Chen, G. E. Town, P. Y. Cortes, S. LaRochelle, and P. W. E. Smith, “Dual-wavelength, actively mode-locked fibre laser with 0.7 nm wavelength spacing,” *Electron. Lett.*, vol. 36, no. 23, pp. 1621–1923, Nov. 2000.

[3] Y. D. Gong, M. Tang, P. Shum, C. Lu, J. Wu, and K. Xu, “Dual-wavelength 10-GHz actively mode-locked erbium fiber laser incorporating highly nonlinear fibers,” *IEEE Photon. Technol. Lett.*, vol. 17, no. 12, pp. 2547–2549, Dec. 2005.

[4] S. Pan and C. Lou, “Multiwavelength pulse generation using an actively mode-locked erbium-doped fiber ring laser based on distributed dispersion cavity,” *IEEE Photon. Technol. Lett.*, vol. 18, no. 4, pp. 604–606, Feb. 15, 2006.

[5] M. E. Marhic, *Fiber Optical Parametric Amplifiers, Oscillators and Related Devices*. Cambridge, U.K.: Cambridge Univ. Press, 2007.

[6] J. E. Sharping, "Microstructure fiber based optical parametric oscillators," *J. Lightw. Technol.*, vol. 26, no. 14, pp. 2184–2191, Jul. 15, 2008.

[7] X. Wang, C. Zhang, J. Xu, and K. K. Y. Wong, "Multiwavelength pulse generation using fiber optical parametric oscillator," *IEEE Photon. Technol. Lett.*, vol. 25, no. 1, pp. 33–35, Jan. 1, 2013.

[8] C. Floridia, M. L. Sudheimer, L. S. Menezes, and A. S. L. Gomes, "Optimization of spectrally flat and broadband single-pump fiber optical parametric amplifiers," *Opt. Commun.*, vol. 223, nos. 4–6, pp. 381–388, Aug. 2003.

[9] S. Li and K. T. Chan, "Electrical wavelength tunable and multiwavelength actively mode-locked fiber ring laser," *Appl. Phys. Lett.*, vol. 72, no. 16, pp. 1954–1956, Feb. 1998.

[10] C. Shu and G. K. P. Lei, "Time- and wavelength- interleaved laser pulses: Prospects and challenges in optical signal processing," in *Proc. Asia Commun. Photon. Conf. Exhibit.*, Nov. 2011, pp. 830701–830703.

[11] K. Tamura and M. Nakazawa, "Dispersion-tuned harmonically mode-locked fiber ring laser for self-synchronization to an external clock," *Opt. Lett.*, vol. 21, no. 24, pp. 1984–1986, Dec. 1996.

[12] A. Vedadi, M. A. Shoaie, and C. S. Bres, "Experimental investigation of pulse generation with one-pump fiber optical parametric amplification," *Opt. Express*, vol. 20, no. 24, pp. 27344–27354, Nov. 2012.

[13] A. Mussot, *et al.*, "Impact of pump phase modulation on the gain of fiber optical parametric amplifier," *IEEE Photon. Technol. Lett.*, vol. 16, no. 5, pp. 1289–1591, May 2004.

[14] S. Radic, C. J. McKinstrie, R. M. Jopson, A. H. Gnauck, J. C. Centanni, and A. R. Chraplyvy, "Performance of fiber parametric-processing devices using binary-phase-shift-keyed pump modulation," *IEEE Photon. Technol. Lett.*, vol. 16, no. 2, pp. 548–550, Feb. 2004.

[15] A. Vedadi, A. M. Ariaei, M. M. Jadidi, and J. A. Salehi, "Theoretical study of high repetition rate short pulse generation with fiber optical parametric amplifier," *J. Lightw. Technol.*, vol. 30, no. 9, pp. 1263–1268, May 1, 2012.

[16] B. P. P. Kuo, J. M. Fini, L. Gruner-Nielsen, and S. Radic, "Dispersion-stabilized highly-nonlinear fiber for wideband parametric mixer synthesis," *Opt. Express*, vol. 20, no. 17, pp. 18611–18619, Aug. 2012.