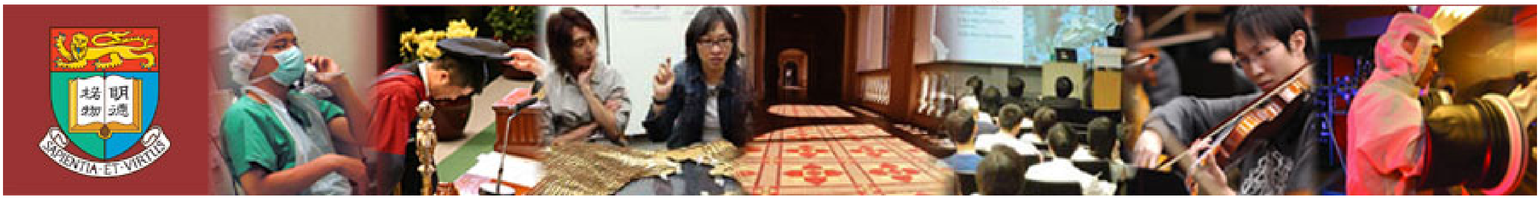


Title	FM mode-locked fiber optical parametric oscillator
Author(s)	Yang, S; Li, Q; Lui, KS; Wong, KKY
Citation	The 37th European Conference and Exhibition on Optical Communication (ECOC 2011), Geneva, Switzerland, 18-22 September 2011. In 37th ECOC Proceedings, 2011, p. 1-3
Issued Date	2011
URL	http://hdl.handle.net/10722/158743
Rights	European Conference on Optical Communication Proceedings. Copyright © IEEE.

FM Mode-Locked Fiber Optical Parametric Oscillator

*Sigang Yang(1), Qin Li(2), K.S. Lui(2), and Kenneth K. Y. Wong(2)
(1)Dept. of Electronic Engineering, Tsinghua University
(2)Dept. of Electrical and Electronic Engineering, The University of Hong Kong
*ysg@tsinghua.edu.cn

Abstract: An FM mode-locked fiber optical parametric oscillator is demonstrated. By introducing periodic phase perturbation in the cavity, 10-GHz pulse train can be obtained. The output signal has a side-mode suppression ratio of 55 dB.
OCIS codes: (190.4410) Nonlinear optics, parametric processes; (190.4970) Parametric oscillators and amplifiers; (140.4050) Mode-locked lasers

1. Introduction

Fiber-optic parametric amplifiers (FOPAs), based on four-wave mixing (FWM) occurring inside optical fibers, have attracted considerable attentions recently because of their remarkable characteristics, such as broadband amplification, ultrafast response time due to an instantaneous electronic response of the silica nonlinearity responsible for FWM in optical fibers [1]. Fiber optical parametric oscillators (FOPOs), which utilize the merits of FOPAs, manifest broader tuning range and faster tuning rate in comparison to the traditional fiber lasers based on Erbium-doped fiber amplifier (EDFA) [2]. However, compared with fiber lasers relying on the doped fiber as the gain medium, a major drawback of FOPOs is the requirement for relatively long gain fiber, especially those silica-based fibers [3]. For example, for a pulsed-pump FOPO, 50-m highly-nonlinear dispersion-shifted fiber (HNL-DSF) is used for the FOPA gain [4]. As a comparison, typically < 1~3-m doped fiber is used in a fiber lasers. Consequently, the cavity length of FOPOs is much longer than that of fiber lasers. The immediate outcome of long cavity length is that the longitudinal mode spacing of FOPOs is much smaller than that of fiber lasers. Hence FOPOs are inherently multimode [3], and these longitudinal modes have random phase relationship. As a result, these superimposed longitudinal modes behave as noise [5]. Therefore, it is necessary to improve the output signal quality of FOPOs. The first solution is to allow only single longitudinal mode to oscillate. We have experimentally demonstrated a single-longitudinal-mode FOPO [6]. The alternative method is to allow multiple longitudinal modes to oscillate, while, the phases of the longitudinal modes are locked to each other. The superimposed longitudinal modes with fixed phase relationship demonstrate as pulse train [5]. We have experimentally demonstrated an actively mode-locked FOPO by introducing an amplitude modulator in the cavity [7]. In that scheme, the cavity loss is varied periodically in a manner that the external modulation frequency is synchronized with the longitudinal mode spacing of the cavity. Another mode-locked method is to introduce periodic phase perturbation in the cavity. An intracavity phase modulator which is tuned exactly to the round-trip transit time of a laser cavity can lead to a pulsed kind of mode locking in the laser [8]. It is the laser cavity phase or frequency, not its amplitude, that is being modulated. So, it is called frequency modulation (FM) mode locking.

In this paper, we report an FM mode-locked FOPO. By introducing periodic phase modulation in the cavity of the FOPO, it can produce 10-GHz pulse train. To the best of our knowledge, it is the first demonstration of the FM mode-locked FOPO.

2. Experimental setup

The proposed configuration and experimental setup is shown in Fig. 1. The pump was seeded by an external cavity tunable laser source (TLS). To suppress the stimulated Brillouin scattering (SBS), light from the TLS was first phase-modulated with a 10-Gb/s pseudo-random bit sequence (PRBS) signal via a phase modulator (PM). A polarization controller (PC1) was used to align the pump's state of polarization (SOP) with the transmission axis of the PM. The SBS could be suppressed by up to 28 dB. Then the pump was amplified by a two-stage configuration of EDFAs, in which the first stage (EDFA1) provided small signal gain to prevent self-saturation by amplified spontaneous emission (ASE). A 0.8-nm tunable bandpass filter (TBPF1) was used to reduce ASE noise. It was further amplified by the second stage (EDFA2), with a maximum average output power of 33 dBm. A circulator that could stand high power was subsequently connected for monitoring the reflected SBS. Then the pump was coupled into a 400-m HNL-DSF via the P-port (transmission band: 1554.89 ~ 1563.89 nm) of a WDM coupler (WDMC1). The high power pump propagated through the HNL-DSF and was then rejected through the P-port of another similar WDM coupler (WDMC2). The amplified signal was coupled into the ring cavity through the R port of WDM coupler (WDMC2). In order to obtain clean signal, an intracavity tunable filter (TBPF2) was placed immediately

978-1-55752-932-9/11/$26.00 ©Optical Society of America

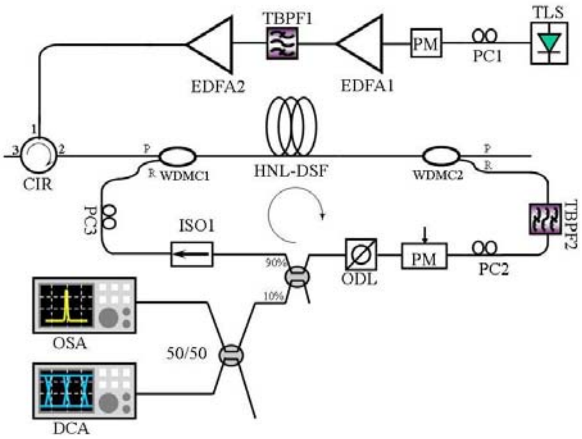


Fig. 1. Schematic diagram of the FM mode-locked FOPO

after WDMC2. A LiNbO3 phase modulator (PM) driven by a signal generator was inserted after the filter. Due to the polarization dependence of the phase modulator, a polarization controller (PC2) was employed to adjust the SOP of the incident pulses. A tunable optical delay line (ODL), ranging from 0 to 350 ps, was used to adjust the cavity length. A 10/90 coupler was used to extract part of the oscillating signal as output. The light from the 10% port of the coupler was then divided equally by a 50/50 coupler for the measurement by the digital communication analyzer (DCA) with 34-GHz bandwidth and the optical spectrum analyzer (OSA). An optical isolator was inserted after the 10/90 coupler to restrict any reflections in the cavity. Another polarization controller (PC3) was adopted to adjust the SOP of the intracavity signal so as to maximize the OPA gain. Finally the intracavity signal was coupled back into the HNLDSF via the R port of WDMC1.

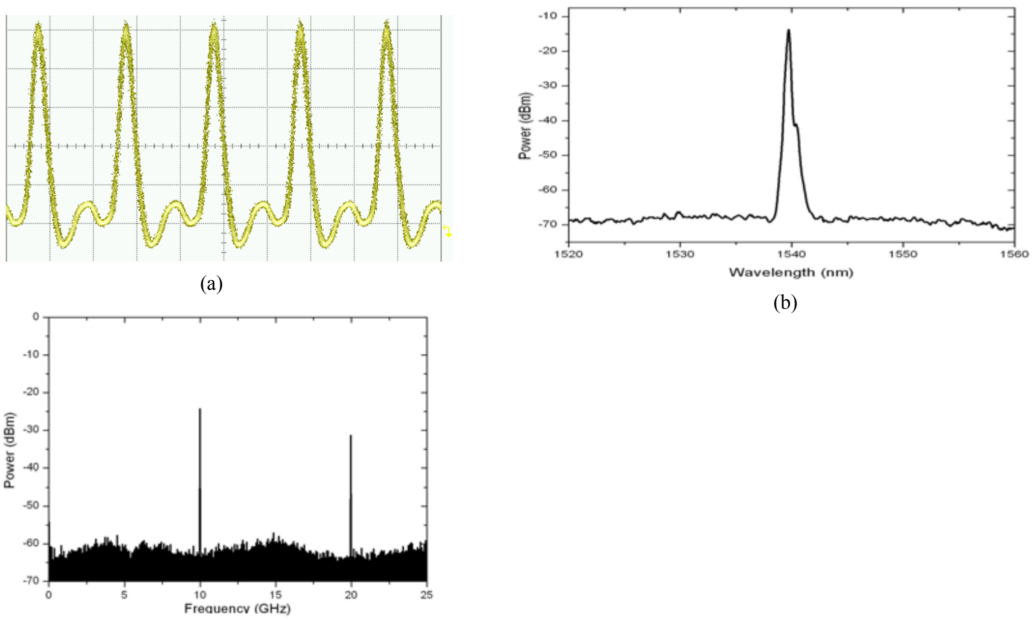
3. Experimental results and discusssions

The HNL-DSF used in the experiment has a nonlinear coefficient of 14 $W^{-1}km^{-1}$ and its zero-dispersion wavelength is located at 1554 nm. The OPA worked in its anomalous dispersion regime since the pump wavelength was chosen to be 1556 nm. We used ASE from pump EDFA as the seed source and inferred the OPA gain spectrum from the measurement of the output ASE spectrum after the FOPA. It demonstrated that for a CW pump at 1556 nm, the maximum gain occurred at the signal wavelength of 1542 nm and the idler wavelength of 1570 nm, respectively. The 3 dB gain bandwidth for both gain bands is 10 nm, limited by the FOPA gain spectrum.

The function of the intracavity phase modulation can be understood in the frequency domain. The phase modulator driven by a sinusoidal electrical signal can induce a small, sinusoidal varying frequency shift in the light passing through it. If the modulation frequency matches to the round-trip time of the cavity, then some light in the cavity sees repeated up-shifts in frequency, and some repeated down-shifts. After many repetitions, the up-shifted and down-shifted lights are swept out of the gain bandwidth of the FOPO. The only light which is unaffected is that which passes through the modulator when the induced frequency shift is zero, which forms a narrow pulse of light. The zero frequency shift occurs at the extremum of the phase shift. That is to say, a light pulse passes through the modulator either at times where either a minimum or a maximum of the phase delay is reached. So in principle, there are two stable mode-locking states that can occur.

The central transmission wavelength of TBPF2 was set to be within the gain bandwidth of the FOPA. The total loss of the ring cavity was measured to be 16.5 dB. Only if the OPA gain exceeded the cavity loss, the cavity could oscillate, which manifested a sharp enhancement of the output power. The external driven frequency for the PM was 10 GHz. When the pump power exceeded 1.23 W, by tuning PC3, the FOPO provided an output power of 2 dBm. By finely tuning the optical delay line and the polarization controller PC2, clear pulse train could be observed. Fig. 2(a) shows the typical FM mode locked waveform in which a sub pulse train is located in the interval of the main pulse train. By finely tuning the optical delay line, the sub pulse train could also be enhanced to be the main pulse train while the previous main pulse train was suppressed down. The pulse width of the generated pulse train is 21.5 ps. The timing jitter is about 1.2 ps.

Fig. 2(b) shows the optical spectrum of the generated pulse train measured with an optical spectrum analyzer (OSA). The peak is located at wavelength of 1569.03 nm. The lasing wavelength has more than 55 dB suppression over other nonlasing modes. The RF spectrum of the generated pulse train is also measured with an electrical spectrum analyzer (ESA) as is shown in Fig. 2(c). The RF spectrum was measured using a photodetector with 3 dB bandwidth of 26 GHz and an electrical spectrum analyzer (ESA) with 10 dB attenuation. Both the 10 GHz and 20 GHz frequency components can be observed, however the 10 GHz frequency component dominates. Due to the large deviation from sinusoidal waveform, the generated pulse train includes its fundamental frequency component and the harmonics. So we can see both the 10 GHz and 20 GHz frequency components within the bandwidth of the PD.



(a) (b) (c)

Fig. 2 (a) Pulse train generated from the FM mode-locked fiber OPO; (b) Optical spectrum of the output pulse train; (c) Electrical spectrum of the output pulse train

4. Conclusion

In conclusion, we have proposed and demonstrated experimentally an FM mode-locked FOPO. By introducing periodic phase perturbation in the cavity, pulse train can be generated providing that the external perturbation frequency coincides with the harmonics of the fundamental frequency of the cavity of the FOPO. 10 GHz pulse train with pulse width of 21.5 ps can be generated.

Acknowledgement

The work was partially supported by grants from the research Grants Council of the Hong Kong Special Administrative Region, China (Project No. HKU7179/08E and HKU7183/09E).

References

[1] M. E. Marhic, N. Kagi, T.-K. Chiang, and L. G. Kazovsky, “Broadband fiber optical parametric amplifiers”, Opt. Lett., v21, 573-575(1996).
[2] J. E. Sharping, “Microstructure Fiber Based Optical Parametric Oscillators,” J. Lightwave Technol. 26, 2184-2191(2008).
[3] M. E. Marhic, “Fiber optical parametric amplifibers, oscillators and related devices”, (Cambridge University Press, 2008).
[4] Y. Zhou, K. K. Y. Cheung, S. Yang, P. C. Chui and K. K. Y. Wong, “Widely-tunable picosecond optical parametric oscillator using highly-nonlinear fiber”, Opt. Lett., 34, 989-991(2009).
[5] O. Svelto, “Principles of lasers”, (New York: Plenum Press, 1998).
[6] S. Yang, K. K. Y. Cheung, Y. Zhou, and K. K. Y. Wong,” Tunable single-longitudinal-mode fiber optical parametric oscillator,” Opt. Lett., 35, 481-483(2010).
[7] S. Yang, Y. Zhou, J. Li, and K. K. Y. Wong, “Actively Mode-Locked Fiber Optical Parametric Oscillator,” IEEE J. Select. Topics Quant. Electron. 15, 393-398(2009).
[8] D. J. Kuizenga and A. E. Siegman, “FM and AM mode locking of the homogeneous laser—Part I: Theory,” IEEE J. Quantum Electron., vol.QE-6, 694–708(1970).