Continuous-Wave Single-Longitudinal-Mode Fiber-Optical Parametric Oscillator With Reduced Pump Threshold

Sigang Yang, Xing Xu, Yue Zhou, Kim K. Y. Cheung, and Kenneth K. Y. Wong

Abstract—**A single-longitudinal-mode (SLM) fiber-optical parametric oscillator (FOPO) is proposed and demonstrated experimentally. The FOPO operates fundamentally by resonating the nondegenerate signal and idler in two separate optical cavities independently, combined with a subring cavity inserted inside the signal cavity as a mode restricting device. The proposed structure is first reported, to the best of our knowledge, which reduces the threshold pump power at a ratio of 38% compared with the usual singly resonant FOPO, and achieves an SLM oscillation with side-mode suppression ratio of greater than 51 dB.**

Index Terms—**Nonlinear optics, optical fiber lasers, parametric amplifiers, parametric oscillators.**

I. INTRODUCTION

FIBER-OPTICAL parametric oscillator (FOPO), based on four-wave mixing (FWM) inside optical fibers, has attracted considerable attention for its ability to eliminate the complicated alignment as in bulk OPO, and be ready to satisfy phase matching and compatible with the fiber-based devices as in optical communications [1]. However, one primary difficulty for FOPO is that the cavity length required is typically tens or even hundreds of meters so as to obtain sufficient gain. For example, 100-m-long highly nonlinear fiber (HNLF) was used in a continuous-wave (CW) pump FOPO with a Fabry–Pérot cavity [2]. Another CW FOPO was achieved in a passive cavity with 115-m standard single-mode fiber [3]. Compared with bulk OPOs, FOPOs tend to have longer cavity length. The frequency spacing between the longitudinal modes is very small, typically in the order of megahertz. As a result, it is difficult to make an intracavity optical filter to select and track a single frequency. Consequently, multiple longitudinal modes oscillate simultaneously. Under ordinary circumstances, phases of these multiple longitudinal modes have random relationships, and for CW oscillation beam, intensity shows random time variation as well as noise. In order to solve this problem, one solution is to lock the phase of the multiple longitudinal modes. We have previously proposed an active mode-locking method to produce pulse trains in a CW pumped FOPO [4]. An alternative solution is to allow single-longitudinal-mode (SLM) oscillation only. However, the CW SLM FOPO has not yet been proposed to the best of our knowledge.

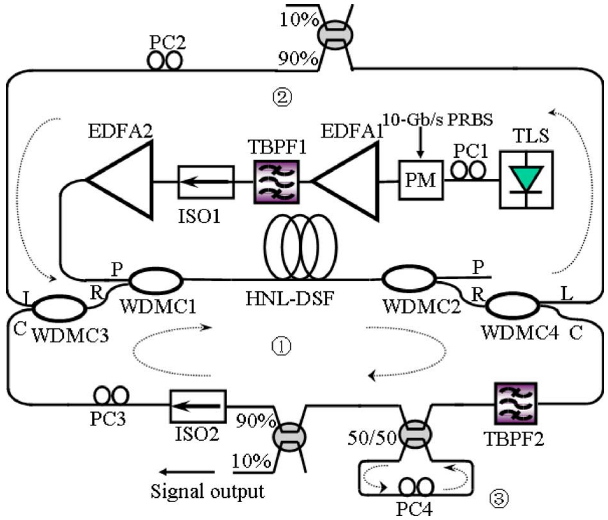

Fig. 1. Schematic diagram of the SLM FOPO: ① signal cavity; ② idler cavity; ③ subring cavity.

In this letter, we propose and demonstrate experimentally an FOPO with SLM oscillation. The FOPO utilizes two separate main cavities to resonate the signal and idler independently. A subring cavity is inserted inside the main signal cavity to further suppress the longitudinal modes. The proposed structure can lower the threshold pump power remarkably compared with singly resonant FOPO and ensure SLM oscillation simultaneously.

II. EXPERIMENTAL SETUP

In fiber OPA, a strong pump wave creates two sidebands located symmetrically at the signal and idler. So FOPO can emit photons at two different wavelengths that are closely correlated [5]. Here we oscillate both signal and idler simultaneously in the separate optical cavities. The proposed configuration and experimental setup is shown in Fig. 1. The pump is seeded by an external cavity tunable laser source (TLS) at wavelength of 1556 nm. To suppress the stimulated Brillouin scattering (SBS), light from the TLS is first phase-modulated with a 10-Gb/s

Manuscript received June 29, 2009; revised August 24, 2009. First published November 06, 2009; current version published December 01, 2009. This work was supported in part by grants from the research Grants Council of the Hong Kong Special Administrative Region, China (Project HKU7172/07E and HKU7179/08E).

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Digital Object Identifier 10.1109/LPT.2009.2035056

pseudorandom bit sequence (PRBS) signal via a phase modulator (PM). A polarization controller (PC1) is used to align the pump's state of polarization (SOP) with the transmission axis of the PM. The SBS can be suppressed by up to 28 dB. Then the pump is amplified by a two-stage configuration of erbium-doped fiber amplifiers (EDFAs), in which the first stage (EDFA1) provides small signal gain to prevent self-saturation by amplified spontaneous emission (ASE). A 0.35-nm tunable bandpass filter (TBPF1) is used to reduce ASE noise. After an isolator (ISO1), it is further amplified by the second stage (EDFA2), with a maximum average output power of 33 dBm. Then the pump is coupled into a 400-m highly nonlinear dispersion-shifted fiber (HNL-DSF) with the zero dispersion wavelength at 1554 nm via P-port (transmission band: 1554.89 ~ 1563.89 nm) of a wavelength-division-multiplexing (WDM) coupler (WDMC1). The high power pump propagates through the HNL-DSF and is then rejected through P-port of another similar WDM coupler (WDMC2). By passing through the R-port (reflection bands: 1500 ~ 1551 nm, 1567 ~ 1620 nm) of WDMC2 and a subsequent C/L-band WDM coupler (WDMC4), the amplified signal and idler are coupled into the separate ring cavities. In regard to the signal cavity ①, signal from C-port of WDMC4 is filtered by a 0.35-nm bandpass filter (TBPF2) which determines the lasing wavelength and provides the first restriction on the possible oscillating modes. The subring cavity ③ with a cavity length about 5.2 m is then inserted after TBPF2. It is composed of a PC and a 50/50 coupler. A 10/90 optical coupler is used to couple 10% of the signal light out which is the output of the FOPO. The isolator (ISO2) eliminates any back reflection including SBS due to the oscillating wavelength. PC3 is used to align the signal's SOP with the pump so as to maximize the signal gain. In regard to the idler cavity ②, light from L-port of WDMC4 propagates through a 10/90 coupler for monitoring the idler and is then passing through a polarization controller (PC2) before entering into the HNL-DSF via L-port of WDMC3.

III. EXPERIMENTAL RESULTS AND DISCUSSION

First of all, the threshold pump power of the FOPO with singly and doubly resonant cases are investigated separately. Fig. 2 shows the relationships between the output power and the pump power in these two cases. In both cases, when the pump power exceeds the respective threshold, the output power ascends sharply, which indicates the start of oscillation. The optical spectrum observed by the optical spectral analyzer (OSA) indicates that the oscillating wavelength is 1544.51 nm with a sidemode suppression ratio (SMSR) of >51 dB. In the singly resonant case (① + ③ connected, and ② disconnected), the threshold pump power is 0.82 W. Nevertheless, when the idler cavity is also connected (①, ②, and ③ all connected), the threshold pump power is reduced to be 0.51 W only, i.e., dropped by 38%. It indicates that, with signal and idler oscillated simultaneously, the threshold pump power can be reduced significantly compared with the singly resonant case. In the singly resonant case, output power rises monotonically with the pump power before the gain is saturated. Whereas, in the doubly resonant case, the output power first rises monotonically and then drops with the pump, as the pump power of 0.79 W is the inflexion. And the output power of the doubly resonant FOPO is smaller than that in the singly resonant case under the same pump power, which can be explained as follows: Since there is no mode restriction device in the idler cavity for the doubly resonant case, wavelengths in a broadband spectral range oscillate simultaneously as the pump power is high enough. The spectrum of the oscillating wavelength in the idler cavity is as wide as the OPA gain spectrum. Hence the oscillation in a broadband spectral range in the idler cavity depletes the pump significantly in the doubly resonant case.

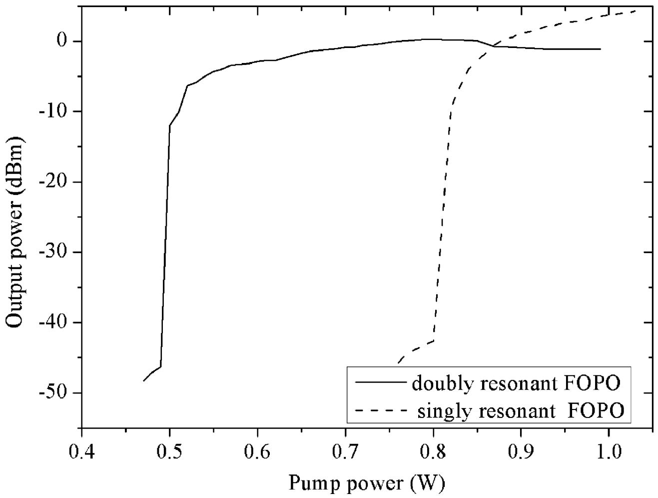
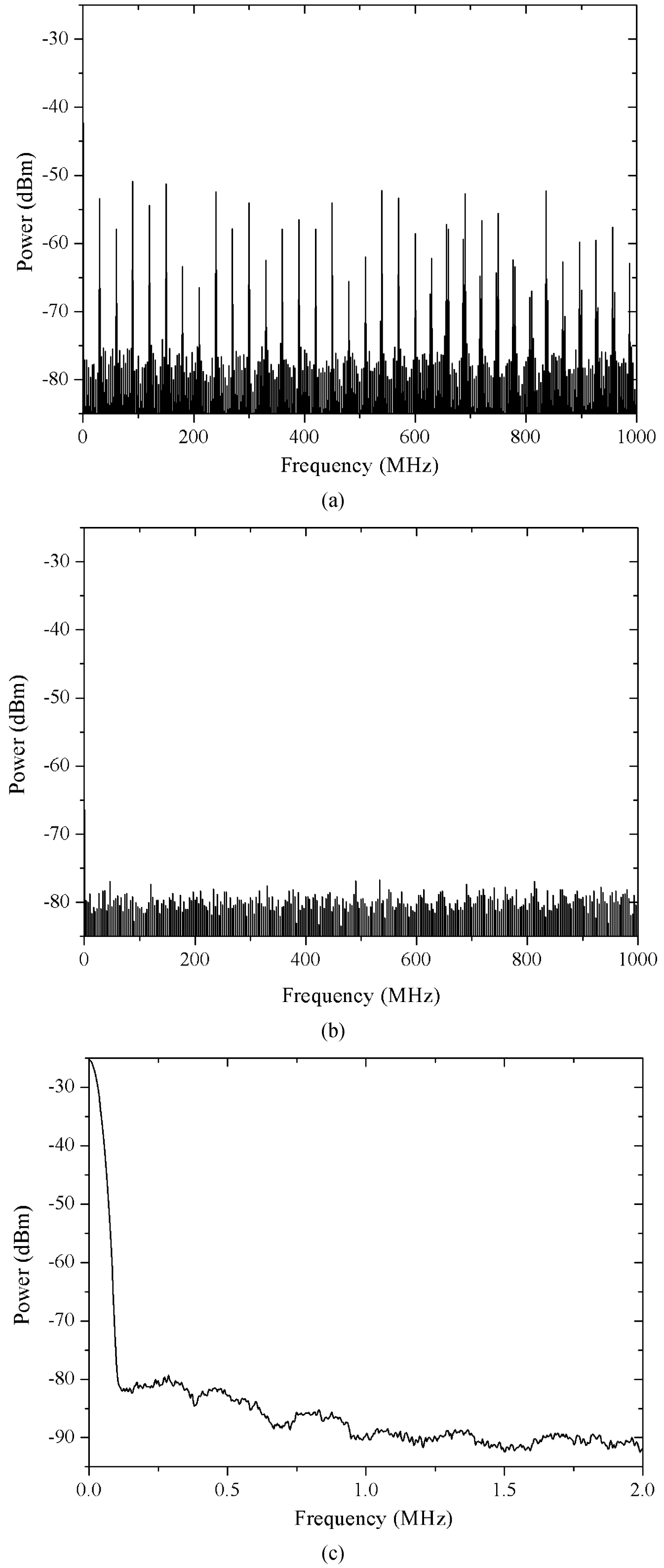


Fig. 2. Output power versus pump power with singly and doubly resonant configurations.

The resonant frequencies of the ring cavities can be obtained by imposing the condition that the total phase shift along the ring path must equal an integral multiple of 2π [6], which results in that the free spectral range (FSR) of a resonant cavity is in inverse ratio of its cavity length. To further suppress the longitudinal modes and increase the longitudinal mode spacing in the signal cavity, a coupled subring cavity with short cavity length is inserted as a mode filter. The main signal cavity and the subring cavity are on resonance. Hence radiation can couple effectively from a mode of the main cavity to a mode of the subring cavity [7]. Because of the shorter cavity length compared with the main signal cavity, the subring cavity has larger FSR. Thus the introduction of the subring cavity can suppress the oscillation of longitudinal modes of the main signal cavity greatly. Finally the FOPO oscillates only at a frequency that satisfies the resonant conditions of all the three cavities simultaneously [8].

The mode spacing is measured by a self-homodyne method. At first, only the main signal cavity ① is connected, while the subring ③ and idler ② cavities are disconnected. The FSR measured by the self-homodyne method is 445 kHz. And then the FSR of the idler cavity ② is measured to be 469 kHz. In a doubly resonant OPO, according to Giordmaine and Miller diagram, only if the signal and idler modes overlap perfectly, the energy conservation condition is fulfilled and those pairs of modes which are in exact coincidence are emitted [9], [10].The composite cavity of the rings 1 and 2 leads to an effective FSR of 208.7 MHz which is the least common multiple of 445 and 469 kHz. To further suppress the longitudinal modes, a small cavity ③ is introduced. In succession, The FSR of the signal



(a)

(b)

(c)

Fig. 3. Measured self-homodyne spectrum: (a) in the singly resonant case with cavities ① and ③ connected; (b) in the doubly resonant case with cavities ①, ② and ③ connected. (c) Fine structure of the spectrum near zero frequency in the doubly resonant case.

cavity with the subring cavity connected (① + ③ connected) is measured. Fig. 3(a) shows the measured beating signal from the electrical spectrum analyzer (ESA). It can be observed that, with a subring cavity inserted, the FSR of the signal cavity is increased from 445 kHz to 38.17 MHz which is determined by the FSR of the subring cavity. The fundamental and higher-order beating signal can be observed clearly. The spectrum is very noisy and unstable owing to the mode hopping. Once the idler cavity is also connected (i.e., the cavities ① + ② + ③ connected), the beating signal disappears and no spike signals are observed, as shown by the detected self-homodyne frequency spectrum in Fig. 3(b). Fig. 3(c) shows the fine structure of the spectrum near zero frequency. Only the direct current (dc) peak can be observed while the other longitudinal modes of the signal cavity are suppressed. It indicates that an SLM operation with sidemode suppression to 1 GHz can be achieved by the proposed structure.

IV. CONCLUSION

We have presented an SLM FOPO. The FOPO is fundamentally structured by resonating the nondegenerate signal and idler in two separate optical cavities independently, combined with a subring cavity inserted inside the signal cavity as a mode-restricting device. The FOPO can lower the threshold pump power significantly compared with the traditional singly resonant CW FOPO. The measurement from self-homodyne method shows that the FOPO allows only SLM to oscillate with SMSR of greater than 51 dB.

ACKNOWLEDGMENT

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

REFERENCES

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

[2] M. E. Marhic, K. K.-Y. Wong, L. G. Kazovsky, and T.-E. Tsai, “Continuous-wave fiber optical parametric oscillator,” *Opt. Lett.*, vol. 27, pp. 1439–1441, 2002.

[3] S. Coen and M. Haelterman, “Continuous-wave ultrahigh-repetition-rate pulse-train generation through modulational instability in a passive fiber cavity,” *Opt. Lett.*, vol. 26, pp. 39–41, 2001.

[4] S. Yang, Y. Zhou, J. Li, and K. K. Y. Wong, “Actively mode-locked fiber optical parametric oscillator,” *IEEE J. Sel. Topics Quantum Electron.*, vol. 15, no. 2, pp. 393–398, Mar./Apr. 2009.

[5] G. P. Agrawal, *Nonlinear Fiber Optics*. New York: Academic, 2007, ch. 10.

[6] O. Svelto, *Principles of Lasers*. New York: Springer, 1998, ch. 5.

[7] A. Gloag, R. J. Forster, and N. Langford, “Theoretical model and experimental demonstration of frequency control in rare-earth-doped fiber lasers with a 3 $*$ 3 nonplanar fused-fiber coupler,” *J. Opt. Soc. Amer. B*, vol. 14, pp. 985–901, 1997.

[8] C. C. Lee, Y. K. Chen, and S. K. Liaw, “Single-longitudinal-mode fiber laser with a passive multiple-ring cavity and its application for video transmission,” *Opt. Lett.*, vol. 23, pp. 358–360, 1998.

[9] J. A. Giordmaine and R. C. Miller, “Optical parametric oscillation in LiNbO3,” *Phys. Quantum Electron.*, pp. 31–42, 1966.

[10] B. Scherrer, I. Ribet, A. Godard, E. Rosencher, and M. Lefebvre, “Dual-cavity doubly resonant optical parametric oscillators: demonstration of pulsed single-mode operation,” *J. Opt. Soc. Amer. B*, vol. 17, pp. 1716–1729, 2000.