Fiber optical parametric oscillator based on photonic crystal fiber pumped with all-normal-dispersion mode-locked Yb:fiber laser*

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We demonstrate a cost effective, linearly tunable fiber optical parametric oscillator based on a home-made photonic crystal fiber pumped with a mode-locked ytterbium-doped fiber laser, providing linely tuning ranges from 1018 nm to 1038 nm for the idler wavelength and from 1097 nm to 1117 nm for the signal wavelength by tuning the pump wavelength and the cavity length. In order to obtain the desired fiber with a zero dispersion wavelength around 1060 nm, eight samples of photonic crystal fibers with gradually changed structural parameters are fabricated for the reason that it is difficult to accurately customize the structural dimensions during fabrication. We verify the usability of the fabricated fiber experimentally via optical parametric generation and conclude a successful procedure of design, fabirication, and verification. A seed source of home-made all-normal-dispersion mode-locked ytterbium-doped fiber laser with 38.57 ps pulsewidth around the 1064 nm wavelength is used to pump the fiber optical parametric oscillator. The wide picosecond pulse pump laser enables a larger walk-off tolerance between the pump light and the oscillating light as well as a longer photonic crystal fiber of 20 m superior to the femtosecond pulse lasers, resulting in a larger parametric amplification and a lower threshold pump power of 15.8 dBm of the fiber optical parametric oscillator.

Keywords: fiber optical parametric oscillator, photonic crystal fiber, mode-locked fiber laser

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1. Introduction

Fiber optical parametric oscillators (FOPOs) have been receiving increasing attention in recent years for the merits of generating widely tunable, coherent radiation in non-conventional spectral regions and fast gain recovery time superior to the traditional lasers.[1,2] Hence FOPOs are extensively recognized as viably potential sources to provide a turnkey system for biomedical spectroscopy and imaging.[3] Based on cascaded four-wave mixing (FWM) in the fiber optical parametric amplification (FOPA) process operating at the phase-matched region, optical parametric oscillating can be constructed by matching the FOPO cavity length carefully to the pump laser repetition rate.[4] Basically, the zero-dispersion wavelength (ZDW) of the optical fiber plays a critical role. FOPOs benefit from the promotion of photonic crystal fibers (PCFs) and can generate super wide range wavelengths inaccessible to the conventional fibers due to the amazing property of ultrahigh nonlinearity and highly tunable dispersion of PCFs.[5,6] The reported results show succeess in obtaining large wavelength shifted parametric sidebands away from the pump wavelength when pumping PCFs in the normal dispersion regime.[7–10] In our research, a vast amount of effort has been exerted to obtain a special PCF with a ZDW around 1064 nm.[11] On consideration of the difficulty in accurate controlling the dimensions of PCFs during the fiber drawing process, eight types of PCFs with gradually changed structural parameters were fabricated as samples. Finally, we succeeded in demonstrating a systematic procedure for design, fabrication, and confirmation of PCFs operating for parametric generation near 1.06 μm.

On account of lacking a gain storage, the generation of parametric oscillation in optical fibers has relied seriously on the technique of synchronous pumping with those of the ultrafast picosecond or femtosecond source based on mode-locked solid state lasers such as Ti:sapphire lasers. Compared with the fiber lasers, the Ti:sapphire lasers suffer from the general features of increasing cost, high complexity, large size, and difficult maintenance. The resultant disadvantage is that the ultrashort pulse of the pump requires a very short gain fiber in the FOPO due to the low walk-off tolerance. In contrast, the mode-locked fiber laser can work as an effective pump source for the FOPO due to its low cost, easy maintenance,

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fine compatibility, and stability.[12] What is more, the generated pulse train with wide pulsewidth from the mode-locked fiber laser means that a longer gain fiber can be used due to the large walk-off tolerance. Consequently, the longer PCF always leads to larger amplification and lower pump power to the benefit of the FOPO. In this paper, we propose a PCF-based FOPO pumped by a home-made, all-normal-dispersion cavity, tunable, passively mode-locked ytterbium-doped fiber (Yb:fiber) laser based on a semiconductor saturable absorber mirror (SESAM).[13] The approach enables adequate interaction time between the pump and the generated signal pulses within the PCF to generate parametric amplification, permitting a longer PCF as well as a lower threshold pump power compared with the femtosecond pump configuration.

To the authors' knowledge, very few of the reported FOPOs are pumped directly by a mode-locked Yb:fiber laser. In this paper, based on a home0made 20-m-long PCF with the ZDW near 1064 nm, a compact and low cost FOPO pumped by a home-made tunable all-normal-dispersion mode-locked Yb:fiber laser around 1064 nm with a 38.57 ps pulsewidth is demonstrated. The FOPO operates effectively in a stable state with a tuning range from 1097 nm to 1117 nm for the signal wavelength and from 1018 nm to 1038 nm for the idler wavelength via tuning both the pump wavelength and the cavity length. The output wavelengths reveal highly linear relationships with respect to either pump wavelengths or the shifts of the cavity length.

2. Design and fabrication of PCF

Based on our developed full vector frequency domain finite difference (FDFD) algorithm with the uniaxial perfect matched layer (UPML) absorbing boundary condition,[14] the PCF for the OPA generation is designed theoretically. The cross section of the theoretical design is shown in Fig. 1(a). By using this method, the group velocity dispersion (GVD) of the desired PCF is calculated numerically with respect to the wavelength as shown in Fig. 1(b). A ZDW of 1.061 μm is obtained here with structural parameters of 3.6 μm for the hole pitch and 1.8 μm for the hole diameter.

Taking account of the unavoidable deviation of the structural parameters from the theoretical design in the fiber drawing process, we fabricate eight samples with gradually changed structural parameters. The respective pitch sizes of samples 1–8 are 2.48 μm, 2.71 μm, 2.93 μm, 3.16 μm, 3.38 μm, 3.54 μm, 3.61 μm, and 3.95 μm, corresponding to the scanning electron microscopy (SEM) images shown in Figs. 2(a)–2(h), respectively.

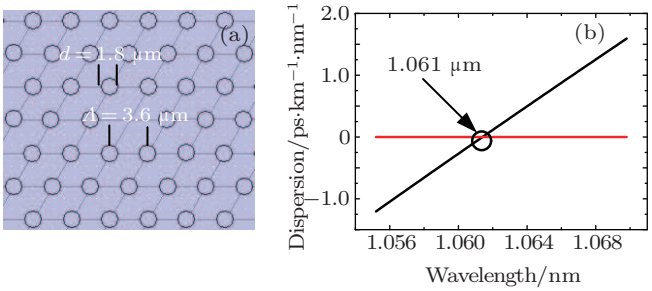


Fig. 1. (color online) Theoretical design of the PCF with a ZDW at 1.061 μm: (a) cross section; (b) chromatic dispersion curve.

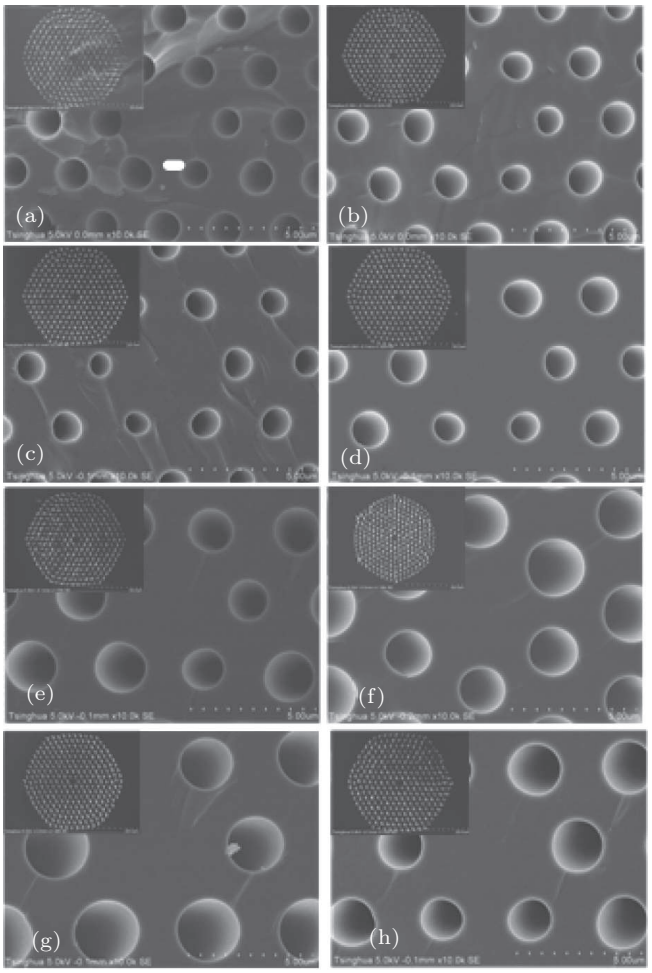


Fig. 2. (a)–(h) SEM images (S-5500) of eight PCF samples. The distance between adjacent dots on the right of the bottom stands for 0.5 μm.

3. Verification of FOPA generation by PCF pumped with a home-made fiber laser

Basically, it is difficult to control the ZDW of a PCF rigorously during the fabrication process according to the theoretical design, since a very small deviation in the structural parameters would lead to a large shift of the ZDW. We measure the FOPA to verify whether the ZDW of the fabricated sample fiber is located in the operating wavelength band by using a mode-locked fiber laser as illustrated in Fig. 3.

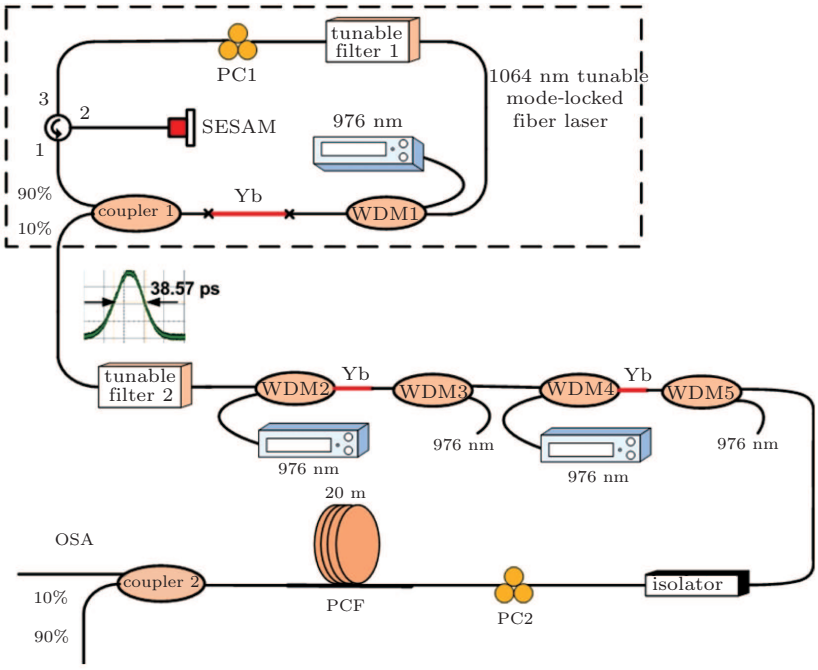


Fig. 3. (color online) Experimental setup of the FOPA. The inset shows the pulsewidth of the mode-locked fiber laser.

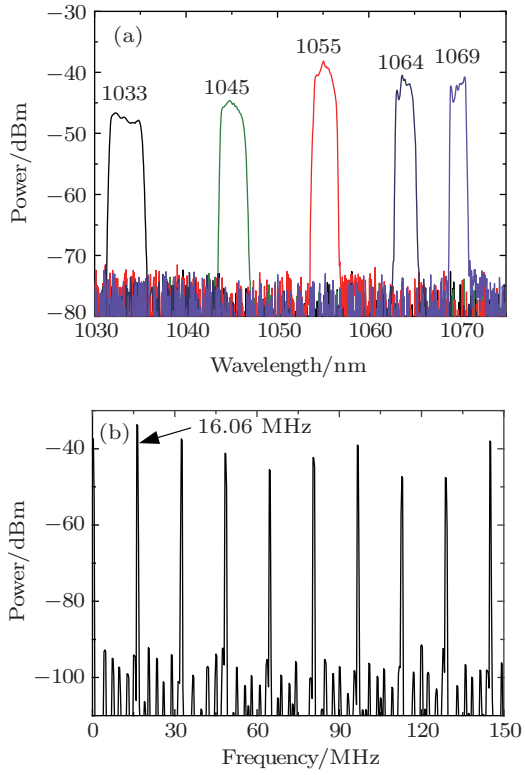


Fig. 4. (color online) Single-pulse generation: (b) optical spectrum (OSA: 0.02 nm resolution); (a) frequency spectrum (RBW: 100 kHz).

Here we use a home-made all-normal-dispersion passively mode-locked Yb:fiber laser as the pump seed. Pumped by a 976-nm fiber-pigtailed laser diode, a 93-cm-long ytterbium-doped single-cladding single-mode fiber affords sufficient cavity gain, with 250 dB/m absorption at 976 nm and 7.5-μm core diameter at 1060 nm. With 70% reflectivity and a very small dispersion in the wavelength range from 1020 nm to 1070 nm; an SESAM is connected to the cavity via a circulator to achieve mode locking. The circulator also works as an isolator in the cavity to ensure unidirectional propagation by suppressing parasitic reflections with an isolation of 35 dB from port 2 to port 1 as well as from port 3 to port 2. By adjusting the polarization controller (PC1) and the tunable filter to an appropriate state, light pulses can be generated at different wavelengths. A 10:90 fiber splitter serves as an output coupler via its 10% port. In order to minimize the intracavity loss, all the fiber pigtails of all kinds of devices are fusion spliced together. After passing through a tunable band-pass filter with a 3-dB bandwidth of 1 nm, the seed light from the mode-locked fiber laser is amplified via a two-stage ytterbium-doped fiber amplifier (YDFA) to a high power so as to serve as the pump. Residual 976 nm pump power is dumped by WDM2 and WDM4. An isolator is employed to restrain any undesired back reflections. In addition, the PC2 is necessary to adjust the polarization of the amplified pump light before coupling into the 20-m-long PCF.

The fiber laser has a tuning range from 1033 nm to 1070 nm measured by an optical spectrum analyzer (OSA) at an output power about 5.9 dBm, as shown in Fig. 4(a). The repetition rate is 16.06 MHz measured by a 40 GHz electrical spectrum analyzer (ESA), corresponding to a cavity length of 12.8 m long, as shown in Fig. 4(b). The dispersion coefficient of the Hi-1060 single mode fiber used in the cavity is −38 ps/nm·km and the SESAM shows a zero dispersion

around 1060 nm, so the total cavity demonstrates a net normal dispersion of 0.29 ps^2 according to our calculation, which results in a wide pulsewidth for the strong chirp. The generated pulse has a full width at half maximum (FWHM) of 38.57 ps measured via an autocorrelator as shown in the inset of Fig. 3 and the single pulse power is calculated to be 0.22 nJ.

We use the amplified spontaneous emission (ASE) from the YDFA as the seed source and infer the FOPA gain spectrum from the measurement of the output ASE spectrum after the FOPA, as shown in Fig. 5. Robust FWM phenomena operating in both normal and anomalous dispersion regimes are observed through samples 2–8 except sample 1. Here we choose four typical PCFs as examples, which are shown in Fig. 5(a). We have reasons for the suggestion that the ZDW of sample 1 is absent from the 1.06 μm scope. When we enlarge the pump power enough at 1033 nm in the anomalous regime, the powerful Raman gain caused by the high-order nonlinear effect is investigated. An obvious supercontinuum spectrum as wide as 510 nm is measured as shown in Fig. 5(c). Meanwhile, when sample 3 is pumped at 1045 nm in the normal regime as shown in Fig. 5(b), a supercontinuum spectrum appears with a bandwidth of 360 nm via the FWM effect. In addition, a convincing FWM effect of small amplification with 192 nm span is observed in sample 8 as shown in Fig. 5(d). Hence a conclusion can be drawn that we obtain the target PCF and sample 8 is the ideal one providing over 30 dB gain when pumped around the 1064 nm wavelength.

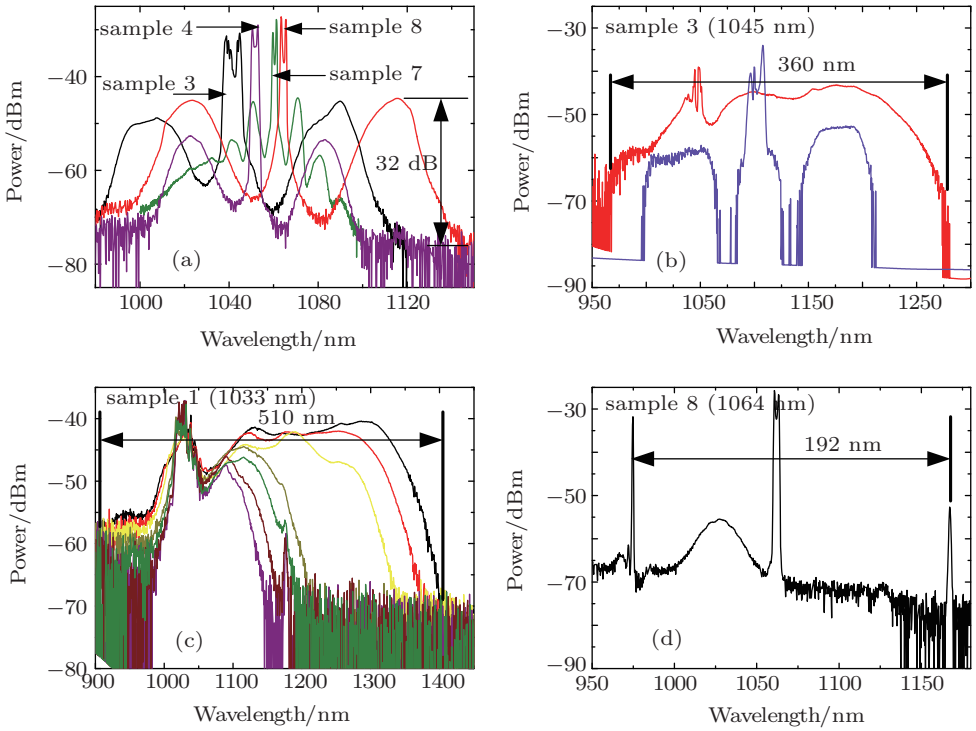


Fig. 5. (color online) (a) Remarkable FOPA gain spectra of sample 3, sample 4, sample 7, and sample 8; (b) supercontinuum spectra of sample 3; (c) supercontinuum spectra of sample 1 at different pump powers; (d) small signal amplification by sample 8.

4. Experimental results and discussion for FOPO

Based on the successful results of the FOPA described above, the FOPO is constructed as shown in Fig. 6. The pump light is seeded by our home-made fiber laser around 1064 nm and amplified by a two-stage YDFA to a high power. Then the pump is transferred to propagation in free space via the collimator AL1. The polarization state of the amplified pulse train can be adjusted via a half wave plate (HWP) without affecting the pump pulse duration or spectral linewidth, as well as another intracavity polarization controller PC2. The resonant cavity is composed of optical mirror L1 and reflector mirror L4. The particular mirror L1 acts as one end of the resonant cavity with a high reflectance ratio above 99% over the wavelength ranges from 950 nm to 1060 nm and from 1068 nm to 1550 nm, as well as a transmission window from 1062 nm to 1066 nm. Meanwhile, undesired diffused reflections caused by L1 also grow up here, which brings an overlarge insertion loss into the cavity. As a solution, a plano-convex lens is adopted to improve the reflection, which is better optimized compared with the convex lens due to the spherical aberration of different wavelengths. Relying on the plano-convex lens M2 exactly positioned at the focus 75 cm away from L1, the roundtrip

insertion loss between the collimator AL2 and L1 is significantly reduced from 10.8 dB to 2.3 dB at the wavelength of 1053.3 nm. The other plano-convex lens M3 is utilized for the same reason with a roundtrip insertion loss of 5 dB between the collimator AL3 and L4. Consequently, the same plano-convex lens M1 is mounted symmetrically between AL1 and AL2 with an insertion loss of 1.8 dB at the 1064.1 nm wavelength. So high output light power from the amplifiers can be optimally coupled into the cavity to generate gain by inspiring the 20-m-long PCF. Then 30% of the power is transmitted through a beam splitter BS as the output port of the cavity. The lens M3 is mounted together with L4 on a moveable stage to ensure that L4 is always at the focus of M3. Finally, the total intracavity loss is calculated to be 8.5 dB.

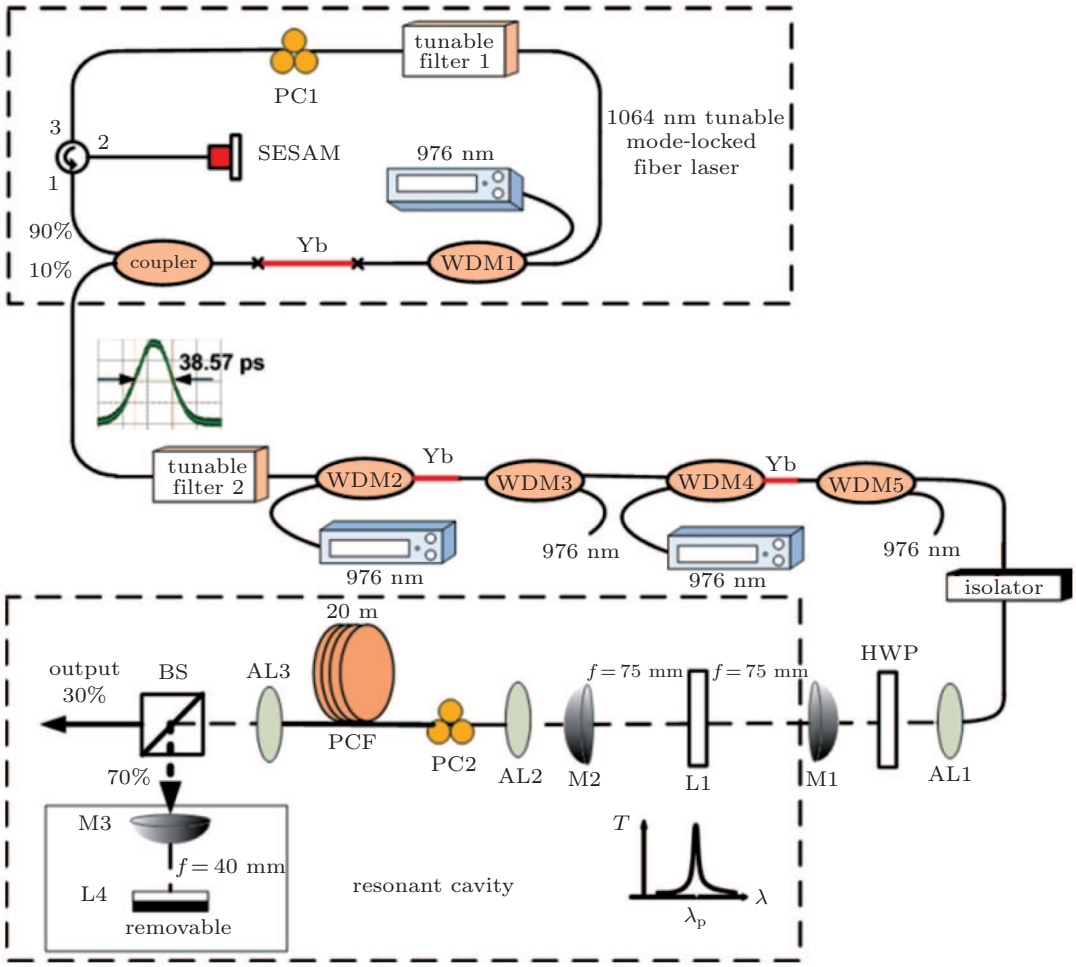


Fig. 6. (color online) Experimental setup of the FOPO.

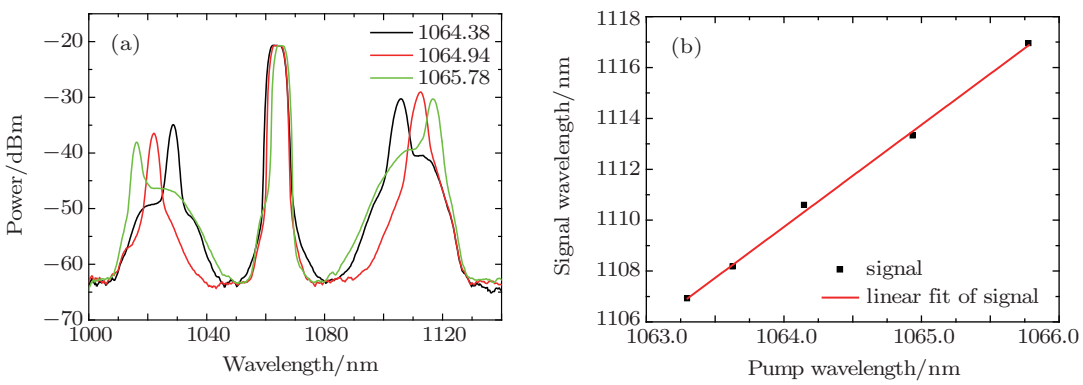


Fig. 7. (color online) (a) Output spectra of FOPO via tuning the pump wavelength; (b) linear fit for signal wavelengths with respect to pump wavelengths.

A typical laser oscillation can be built up once the pump power exceeds the threshold value, which is at a low level less than 15.8 dBm benefited from the low cavity insertion loss and the 38.57 ps pulse train compared with the femtosecond pulse train. The cavity length is about 38.4-m long in the 1 mm margin range of error for the rigorous requirement of synchronization with the pump pulse train.

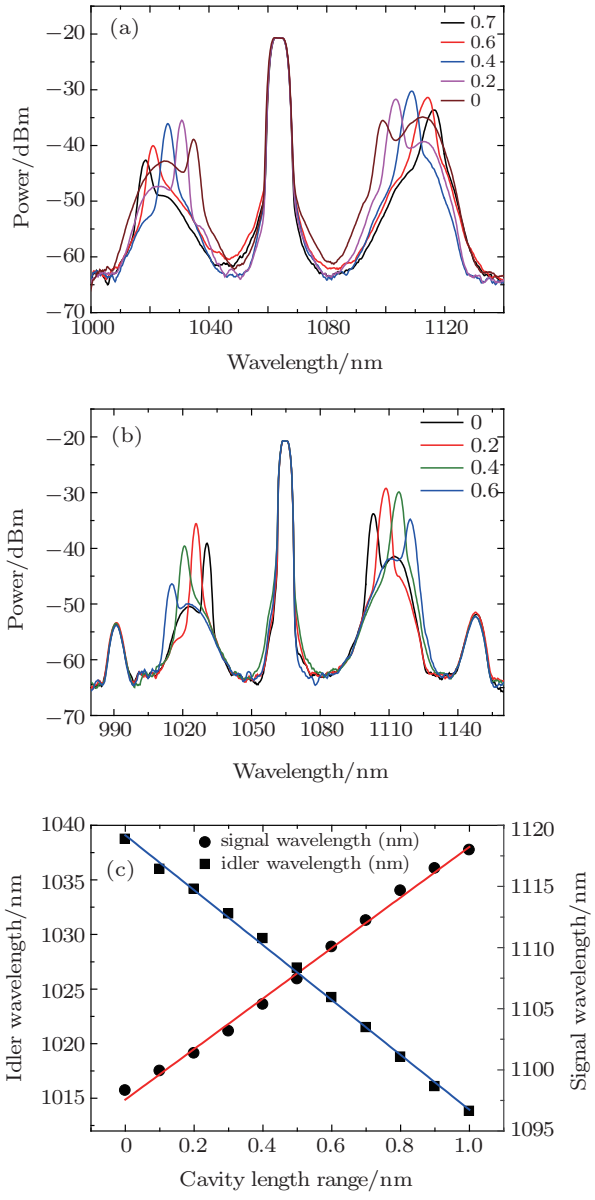


Fig. 8. (color online) (a) Output spectra of FOPO via tuning the cavity length; (b) output spectra of FOPO via tuning the cavity length based on cascaded FWM; (c) linear fit for signal and idler wavelengths with respect to cavity length shift at the pump wavelength of 1064.38 nm.

The oscillating wavelength can be tuned by tuning the pump wavelength with a fixed cavity length or adjusting the cavity length with a fixed pump wavelength. When the pump wavelength is tuned from 1063.3 nm to 1065.8 nm while the cavity length is constant, the vast majority of pump power propagates through L1 and eventually is transferred to signal and idler light. This approach enhances a forceful parametric gain of more than 35 dB, as shown in Fig. 7(a). The oscillating signal light reveals a linear evolution with respect to the pump light from 1106.9 nm to 1116.9 nm, as shown in Fig. 7(b). The output power of the FOPO is measured to be 0.7 dBm at the pump wavelength of 1064 nm. A grating is used to split the output light into three beams of pump, signal, and idler light, corresponding to the powers of −6.7 dBm, −11.5 dBm, and −12.93 dBm, respectively. Thus the internal conversion efficiency is calculated to be 36.3%.[15]

An alternative method is to translate the stage in which L4 together with M3 is mounted. Due to the intracavity dispersion, the oscillating wavelength will shift to a new wavelength adaptively so as to synchronize with the pump. As the translation of L4 varies from 0 to 1 mm, the signal wavelength increases from 1097.7 nm to 1117.7 nm accompanied with the decrease of the idler wavelength from 1038.9 nm to 1017.6 nm, as illustrated in Figs. 8(a) and 8(c). Similar to the linearly tunable characteristic shown in Fig. 7(b), the oscillating signal light plotted with a red line in Fig. 8(c) shows a linear evolution with respect to the cavity length shift, as well as the oscillating idler light plotted in a blue line. In addition, the cascaded FWM sidebands are investigated, as shown in Fig. 8(b).

5. Conclusion

In conclusion, based on our self-developed PCF with a ZDW around 1064 nm, we demonstrate a low-cost and linearly tunable FOPO pumped by a home-made tunable all-normal-dispersion mode-locked Yb:fiber laser. The FOPO operates at a low threshold pump power of 15.8 dBm benefitted from the 20-m-long PCF for parametric generation gain attributed to the use of a 38.57-ps pulsewidth pump laser. A complete procedure of design, fabrication, and verification for PCF is firstly presented. The oscillating signal demonstrates a linear relationship in the wavelength with respect to the pump or the shift of the cavity length. More than 40 nm overall tuning range is obtained via tuning the pump wavelength or the cavity length.

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