IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 6, Number 5, October 2014

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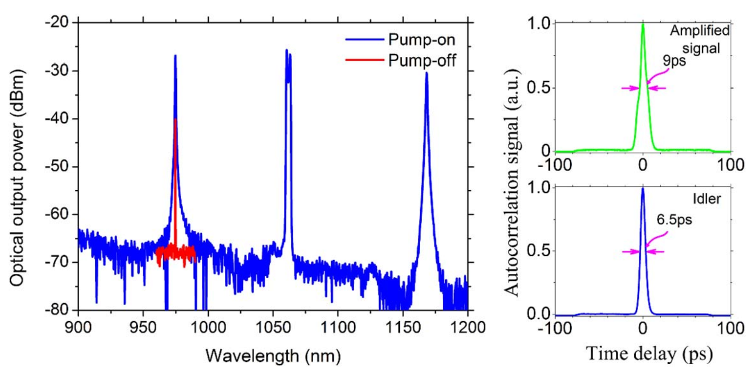


DOI: 10.1109/JPHOT.2014.2353616
1943-0655 

# Photonic Crystal Fiber Based Wavelength-Tunable Optical Parametric Amplifier and Picosecond Pulse Generation

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*DOI: 10.1109/JPHOT.2014.2353616*


Manuscript received July 5, 2014; revised August 20, 2014; accepted August 25, 2014. Date of current version September 18, 2014. This work was supported in part by the National Basic Research Program of China (973 Program) under Contract 2010CB327606, by the National Natural Science Foundation of China under Contract 61108007 and Contract 61335002, and by the Opened Fund of the State Key Laboratory on Integrated Optoelectronics. Corresponding author: S. Yang (e-mail: ysg@tsinghua.edu.cn).

**Abstract:** We report a fiber optical parametric amplifier (FOPA) based on a photonic crystal fiber (PCF) with optimized dispersion and nonlinear properties pumped by a mode-locked ytterbium-doped fiber laser. Wavelength-tunable parametric gain bands can be obtained by adjusting the pump wavelength from the anomalous to the normal dispersion regime. By utilizing the PCF-based FOPA, weak signals located in the parametric gain bands can be amplified. Wavelength-tunable picosecond pulses can be generated at the signal and idler wavelengths. A 58-dB maximum gain and a wide gain bandwidth from 999 to 1139 nm have been achieved by pumping near the zero-dispersion wavelength. When the FOPA is pumped at 1062.5 nm in the normal dispersion regime of the PCF, the 974-nm weak continuous-wave signal is significantly amplified, and the idler pulse is generated at 1168 nm.

**Index Terms:** Four-wave mixing, fiber nonlinear optics, laser amplifiers, fiber lasers.

## 1. Introduction

Ultrafast fiber lasers with broad wavelength-tunable ranges are in growing demand for a variety of applications, such as biomedical imaging, spectroscopy, and so on [1], [2]. The present fiber lasers and amplifiers are mainly operated at several spectral regimes (1.06 $\mu$m, 1.5 $\mu$m, and 2.0 $\mu$m), and the wavelength tunability are confined in limited ranges. It is highly desirable to extend the operating wavelength ranges of optical sources and amplifiers. Based on the four-wave mixing effect in optical fibers, widely tunable parametric gain bands can often be generated by pumping the fibers near the zero dispersion wavelengths [3]. Usually, the parametric gain bands can be inferred from the measurement of the output parametric fluorescence spectra. The 3-dB bandwidth is often broad [4]. The energy converted from the pump is distributed in a wide wavelength band, so the intensity focused at a specific wavelength region is relatively weak.

In fiber optical parametric amplifiers (FOPAs), the pump and the weak signal are coupled into the gain fiber simultaneously. Weak signals with narrow linewidth can be selected to be amplified, and the energy converted from the pump is focused on a narrow spectral linewidth. Amplified signals with high intensities can be obtained. Large gain with low noise can be achieved [5]–[7]. Wideband parametric gain can often be obtained by pumping in the anomalous dispersion regime [8], [9]. When the FOPA is pumped in normal dispersion regime, narrow bandwidth gain with large separation from the pump can be achieved based on the gain medium of highly nonlinear dispersion shifted fiber (HNL-DSF) at the communication band [10], [11]. Furthermore, based on the high gain and the ultrafast response properties of the FOPAs, the continuous-wave (CW) signals with low intensities can be amplified by a pulsed pump. And new pulses can be generated at the signal and the corresponding idler wavelengths [11], [12].

Thanks to the flexible dispersion tailoring property of photonic crystal fibers (PCFs), the zero dispersion can be moved to nearly "any" transparent wavelength in PCFs [13]. In the 1.06 $\mu$m regime, parametric generators [14], [15] and fiber optical parametric oscillators [16]–[20] have been reported by using the PCFs as the gain media. Wavelength tunable pulses can be generated. However, the pulse energy is too small to be used practically. These new wavelength pulses can be amplified by the PCF-based optical parametric amplifiers. A PCF-based FOPA operated from 1040 nm to 1090 nm has been reported [21]. A wavelength tunable FOPA has been demonstrated by heating a PCF [22]. In an all-fiber FOPA operated at 1 $\mu$m regime, a high gain over 30 dB has been achieved [23]. In another experiment, a high gain of more than 30 dB has been obtained in femtosecond regime by using the chirped-pulse amplification scheme [24]. In a continuous wave (CW) FOPA, large gain can be obtained in a bandwidth of 20 THz [25]. And a flat gain band over 16 nm has been reported by using dual-pump CW FOPA setup [26].

In this paper, we design and manufacture a PCF. The dispersion and nonlinear properties of the PCF are optimized carefully in order to satisfy the phase matching condition for four wave mixing in a wide wavelength range. Based on this PCF, a FOPA is built up. A homemade mode-locked ytterbium doped fiber laser (YDFL) is used as the pump. A 58 dB maximum gain and a wide gain bandwidth from 999 nm to 1139 nm have been obtained by pumping near the zero dispersion wavelength. When the pump wavelength of the FOPA is 1062.5 nm in the normal dispersion regime of the PCF, a 974 nm weak signal can be amplified, and the idler is generated at 1168 nm. The frequency gap between the signal and idler is 51 THz. The signal and idler generated in PCF-based optical parametric amplifier with large frequency gap are attractive in the generation of correlated photon pair with low noise [27]. Based on the high gain of the FOPA, picosecond pulses can be generated in a broad wavelength regime. To the best of our knowledge, this is the first time that a PCF-based optical parametric amplifier pumped at both of the anomalous and the normal dispersion wavelength regimes is achieved at the 1.06 $\mu$m region.

## 2. Theory

In FOPA, the amplification of the signal and the generation of the idler require the phase-matching condition of

$$\kappa = \Delta\beta + 2\gamma P = 0 \tag{1}$$

where $\kappa$ is the phase mismatch parameter, $P$ is the pump power, $\gamma$ is the nonlinear coefficient, and $\Delta\beta$ is the linear phase mismatch term, which can be expressed approximately by

$$\Delta\beta = \Omega^2\beta_2 + \Omega^4\beta_4/12 \tag{2}$$

where $\Omega$ is the frequency detuning between the pump and the signal. $\beta_2$ and $\beta_4$ are the second order and fourth order dispersion coefficients at the pump wavelength, respectively. When the FOPA is pumped in normal dispersion regime, $\beta_2$ is positive. Only after (1) is satisfied with a negative $\beta_4$, signal and idler with large frequency detuning can be efficiently generated. The parametric gain can be theoretically written as

$$G = 1 + \left(\frac{\gamma P}{g}\sinh(gL_{eff})\right)^2 \tag{3}$$

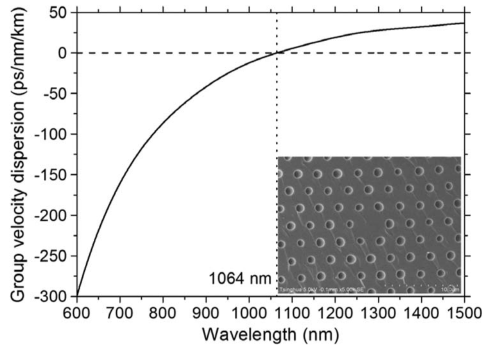


Fig. 1. The calculated group velocity dispersion for the fundamental mode of the PCF; the vertical dotted line corresponds to the zero dispersion wavelength of 1064 nm. The inset shows the SEM image of the cross section of the PCF.

where, $L_{\mathrm{eff}}$ is the effective length of the fiber, and the parametric gain factor satisfy the expression of

$$g^2 = (\gamma P)^2 - \left(\frac{\kappa}{2}\right)^2. \tag{4}$$

In experiment, ultrafast pulses are usually used as the pump source. Suppose the full width at half maximum (FWHM) of the pump pulse is PW, and the repetition rate is RR. The duty cycle of the pump pulse $\eta_{\mathrm{p}}$ can be expressed as

$$\eta_P = RR \times PW. \tag{5}$$

When a weak CW signal and a pulsed pump are coupled into the FOPA simultaneously, the signal is amplified to pulses. The repetition rate of the amplified signal is the same with the pump pulse, and the pulse width is narrower than that of the pump pulse due to the pulse compression effect of FOPAs [12]. The pulse compression ratio is supposed to be C, and the duty cycle of the signal pulse $\eta_s$ can be expressed as

$$\eta_s = C \times RR \times PW. \tag{6}$$

When the power of the CW signal is $P_s$, only a portion of the power $P_s \times \eta_s$ participate in the amplification process. And the other portion of the signal power $P_s \times (1 - \eta_{\mathrm{s}})$ is just transmitted through the fiber. At the output of the FOPA, the signal power is measured to be $P_{as}$. The portion of the unamplified signal power is removed, hence the power of the amplified signal $P_{ras}$ can be expressed as

$$P_{ras} = P_{as} - P_s \times (1 - \eta_s). \tag{7}$$

The parametric gain can be calculated by

$$G = 10\log\left(\frac{P_{ras}}{P_s \times \eta_s}\right). \tag{8}$$

According to this equation, the parametric gain can be experienced by signals located in different wavelengths regions, depending on the pumping wavelength.

## 3. Fiber Properties and Experimental Setup

In order to build up a FOPA operated at 1 $\mu$m regime, a PCF is carefully designed and fabricated. The scanning electron microscope (SEM) image of the cross section of the PCF is shown in the inset of Fig. 1. The pitch of air holes is 2.55 $\mu$m, the core diameter is 4.2 $\mu$m, and the diameter of air holes is 0.9 $\mu$m. The dispersion and nonlinear properties of the PCF are optimized.

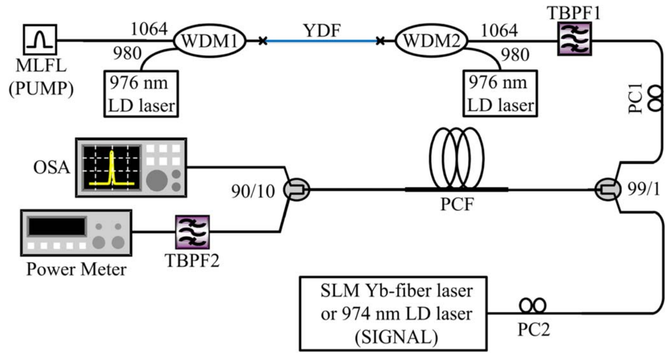


Fig. 2. The experimental schematic of the PCF-based optical parametric amplifier.

Its zero dispersion wavelength is located at 1064 nm, as shown in Fig. 1. In the 1.06 $\mu$m regime, the fourth order dispersion coefficient is negative. Its nonlinearity coefficient $\gamma$ is calculated to be 15 $W^{-1} \cdot km^{-1}$, and the fiber loss is measured to be 25 dB/km by the cut back method at the wavelength of 1064 nm.

The experimental setup for parametric amplification is shown in Fig. 2. The pump source used is a homemade tunable mode-locked ytterbium-doped-fiber laser (MLFL). Its wavelength can be tuned from 1050 nm to 1070 nm, the repetition rate is 16 MHz, and the FWHM is 38.5 ps. The original pump pulse is amplified by a bidirectional core-pumped fiber amplifier using 1-meter ytterbium-doped fiber (YDF). A tunable band-pass filter (TBPF1) is used to suppress the ASE noise from the amplifier. After the TBPF1, the FWHM of the amplified pulse is measured to be 30 ps. The signal source used is a homemade tunable single-longitudinal-mode (SLM) ytterbium doped fiber laser or a 974 nm laser diode (LD). The wavelength of the SLM ytterbium doped fiber laser can be tuned from 1010 nm to 1090 nm. Both of the pump pulse and the signal are coupled into the 10-meters PCF through a 99/1 fiber optical coupler via the 99% port and 1% port, respectively. The polarization controller PC1 and PC2 are employed to align the polarization states of the pump and signal with respect to the principle axis of the PCF. At the output port, 10% of the power is coupled to the optical spectrum analyzer (OSA). A TBPF2 after the 90% port of the fiber coupler is used to suppress the parametric noise. After the TBPF2, the amplified signal power can be measured by a power meter.

## 4. Experimental Results and Discussions

First of all, the parametric fluorescence characteristics in this PCF are measured. Fig. 3 shows the output optical spectra for pumping at several different wavelengths with an average pump power of 17 dBm. It can be seen that with the pump wavelength moved from the anomalous dispersion regime to near the zero dispersion wavelength (from 1069.5 nm to 1064.5 nm), the detuning between the pump and signal becomes larger, and the 3 dB bandwidth of the sideband becomes broader. When the pump moves from the region near the zero dispersion wavelength to the normal dispersion wavelength regime (from 1064.5 nm to 1062.5 nm), the detuning between the signal and the pump increases rapidly, and the 3 dB bandwidth becomes narrow again.

In order to obtain parametric gain in a wideband wavelength regime, the pump is fixed at 1064.5 nm which is close to the zero dispersion wavelength of the PCF and in the anomalous dispersion regime. Firstly, the parametric gain is verified with a small optical signal injected into the PCF. Fig. 4(a) shows the output spectrum of the FOPA. The signal is provided by a SLM YDF laser and its wavelength is set at 1032 nm. The signal is amplified significantly once the pump is launched into the PCF and the idler is generated at 1099 nm. And the cascaded four-wave mixing sidebands can also be observed at 1002 nm and 1136 nm, respectively. The average pump power is adjusted to be 13.3 dBm (corresponding to a peak pump power of 45 W).

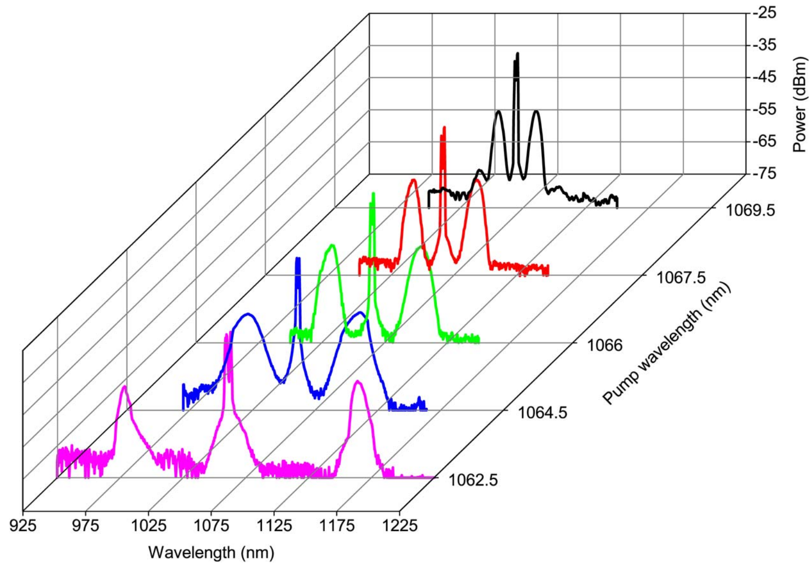


Fig. 3. The measured optical spectra for the PCF pumped from the anomalous to the normal dispersion wavelength regime.

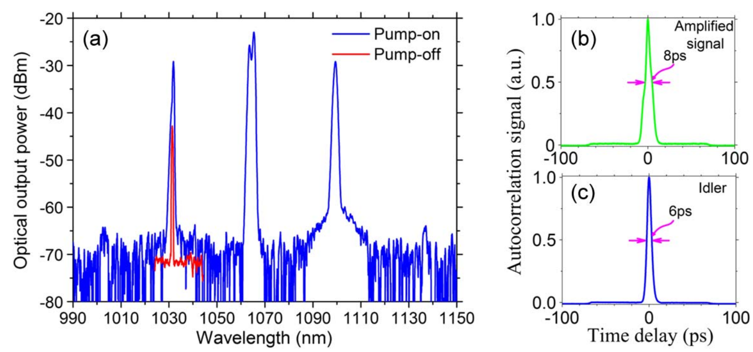


Fig. 4. (a) The output optical spectrum of the FOPA pumped close to the zero dispersion wavelength of the PCF. The pump and the signal are operated at 1064.5 nm and 1032 nm, respectively, as well as the autocorrelation waveforms of the amplified signal (b) and the generated idler (c).

When the pump is switched off, the signal power is measured to be $-15$ dBm at the output of the FOPA. When the pump is switched on, the signal power is measured to be $-5.9$ dBm. The FWHMs of the amplified signal and the idler pulses are measured to be 8 ps and 6 ps, respectively, as shown in Fig. 4(b) and (c). Due to the exponential amplification effect of the FOPAs, the pulse widths of the signal and idler pulses are narrower than that of the pump pulse [12]. In a four wave mixing process, the spectral width of the idler is usually wider than that of the signal because the pump has a certain spectral width. Hence the idler has a narrower pulse width than the signal. The pulse compression ratios of the amplified signal and idler pulses are 15/4 and 5/1, respectively.

The parametric gain at 1032 nm is calculated to be 47.4 dB by using (8), as shown by the blue arrow in Fig. 5(a). Then the parametric gain bandwidth for the pump at 1064.5 nm is measured by tuning the signal wavelength. The experimentally measured parametric gain at different signal wavelengths are shown by the red filled circles in Fig. 5(a). The peak gain of 52.9 dB is obtained with the signal at 1017 nm. To certificate the parametric gain, we also compute the gain that satisfy the (3). At 1064.5 nm, $\beta_2 = -2.09 \cdot 10^{-4}$ ps$^2$/$^{\mathrm{m}}$ and $\beta_4 = -2.11 \cdot 10^{-9}$ ps$^4$/m. In the simulation, the effective length of the PCF is set to be 10 m by neglecting the fiber loss. The black solid

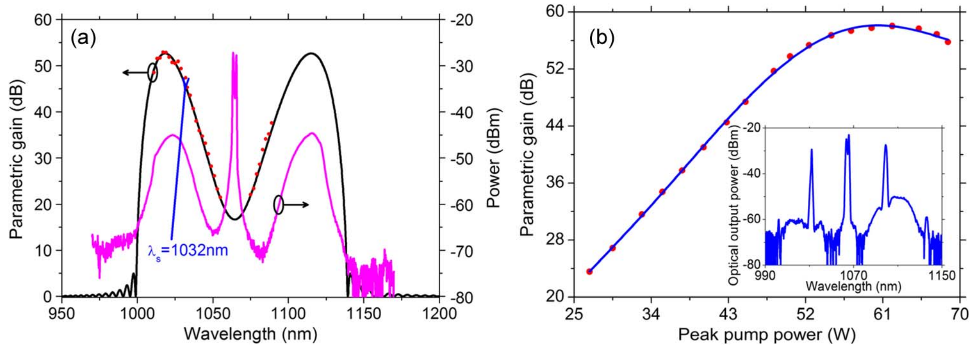


Fig. 5. (a) Parametric gain spectrum of the FOPA pumped at 1064.5 nm with the peak power of 45 W. The filled circles are the experimental data, and the solid black line is the simulation result. The purple line is the parametric fluorescence spectrum with the average pump power of 17 dBm. (b) The parametric gain with respect to the peak pump power for the signal wavelength at 1032 nm. The inset shows the output optical spectrum of the saturated FOPA for the peak pump power of 65 W.

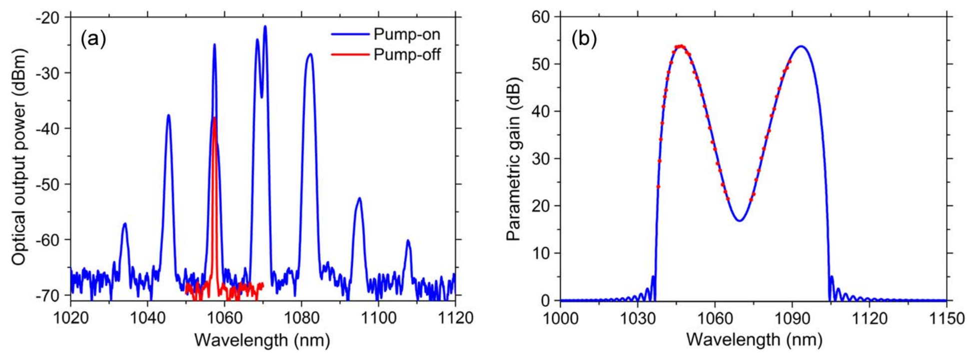


Fig. 6. (a) The output spectrum of the FOPA pumped at the anomalous dispersion regime of the PCF. The pump and the signal are operated at 1069.5 nm and 1057.5 nm, respectively. (b) Parametric gain spectrum of the FOPA pumped at 1069.5 nm with the peak power of 45 W. The filled circles are the experimental data, and the solid black line is the simulation result.

line in Fig. 5(a) shows the simulation results. By comparing the simulation results with the experimentally measured parametric gain, it can be seen that they agree well with each other. Parametric gain can be obtained in the wavelength range from 999 nm to 1139 nm. The gain bandwidth is roughly identical to the parametric fluorescence spectrum as shown in Fig. 5(a). Fig. 5(b) shows the evolution of the parametric gain versus the peak pump power. It can be seen that the parametric gain grows monotonously with the peak pump power firstly. However, when the gain reach a maximum value of 58 dB, it begins to decrease with the pump power. This is because the FOPA is saturated by the dramatic increase of the parametric fluorescence as shown in the inset of Fig. 5(b).

Fig. 6(a) shows the output spectrum of the FOPA pumped in the anomalous dispersion regime of the PCF. The pump and the signal are operated at 1069.5 nm and 1057.5 nm, respectively. It can be seen that the signal is amplified and the corresponding idler is generated at 1082 nm. Four additional sidebands at 1045.5 nm, 1095 nm, 1034 nm, and 1107.5 nm are also generated simultaneously. They are attributed to the cascaded four-wave mixing effect [28]. The intensities of the cascaded second-order four-wave mixing sidebands are larger than that in the FOPA pumped at 1064.5 nm as shown in Fig. 4(a). This is because the detuning between the signal and pump is smaller than that in the case of pumping at 1064.5 nm. The signal and idler are closer to the zero dispersion wavelength of the PCF than in the case of pumping at 1064.5 nm. The phase mismatch parameter $\kappa$ of the cascaded four-wave mixing is less. The profile of the parametric gain band for the pump at

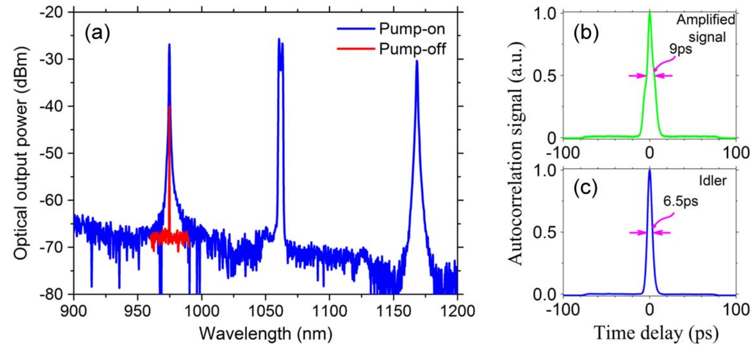


Fig. 7. (a) The output optical spectrum of the FOPA pumped at the normal dispersion regime of the PCF. The pump and the signal are operated at 1062.5 nm and 974 nm, respectively, as well as the autocorrelation waveforms of the amplified signal (b) and the generated idler at 1168 nm (c).

1069.5 nm can be obtained by tuning the signal wavelength as shown in Fig. 6(b). The peak gain of 53.8 dB is achieved at 1047 nm.

After tuning the pump wavelength to the normal dispersion regime, benefited from the negative value of the fourth order dispersion at the 1.06 $\mu$m regime, the FOPA can also be operated. The detuning between the parametric gain band and the pump is increased significantly. As shown in Fig. 7(a), the weak signal at 974 nm is amplified in the FOPA pumped at 1062.5 nm, and the corresponding idler is generated at 1168 nm. It demonstrates a narrow gain bandwidth with large separation from the pump, which is first observed in PCF-based optical parametric amplifier pumped near 1064 nm. The FWHM of the amplified signal and the idler pulses are measured to be 9 ps and 6.5 ps, respectively, which are shown in Fig. 7(b) and (c). When the pump wavelength is adjusted in the region near the zero dispersion wavelength, the parametric gain bands can be tuned, and the wavelength tunable signal and idler pulses can be generated.

## 5. Conclusion

In conclusion, we have demonstrated a PCF-based optical parametric amplifier pumped by a homemade mode-locked ytterbium doped fiber laser. The dispersion and nonlinear properties of the PCF are optimized carefully in order to satisfy the phase matching condition for four wave mixing in a wide wavelength range. The zero dispersion wavelength located at 1064 nm. And the fourth order dispersion is negative at 1.06 $\mu$m regime. The weak signal is offered by a SLM ytterbium doped fiber laser or a 974 nm LD. The FOPA can be operated by pumping both in the anomalous and normal dispersion regime. Wavelength tunable parametric gain bands can be obtained by tuning the pump wavelength. Tunable picosecond signal and idler pulses can be generated. The consistent gain are obtained by experimental measurements and theoretical simulation, respectively. A maximum parametric gain of 58 dB is achieved. The Parametric gain can be obtained in the wavelength range from 999 nm to 1139 nm when pumped near the zero dispersion wavelength. When the FOPA is pumped in the normal dispersion wavelength regime of the PCF, the detuning between the signal and the pump is increased significantly. A 974 nm CW signal can be amplified by the pump at 1062.5 nm, and the idler pulse can be generated at 1168 nm. The PCF-based optical parametric amplifier and the pulse generator can be operated in a broader wavelength range potentially by filtering a supercontinuum as the weak signal.

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