A High-Efficiency Tunable Polarization-Insensitive Wavelength Convertor Based on Degenerate Four-Wave Mixing in a Highly Nonlinear Photonic Crystal Fiber

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Abstract A high-efficiency tunable polarization-insensitive all-optical wavelength convertor for 10 Gb/s return-to-zero on-off keying (RZ-OOK) signals using degenerate four-wave mixing (FWM) in a highly nonlinear photonic crystal fiber (PCF) is demonstrated. The residual birefringence in the 50 m dispersion-flattened PCF with 11 $W^{-1}\cdot km^{-1}$ nonlinear coefficient guarantees the FWM-based wavelength conversion to be polarization-insensitive when the pump polarization is exactly at 45° to the birefringent axes of the PCF. Experimental results show that with 45° pump launch, the polarization dependence of FWM in the PCF can be decreased to less than 0.6 dB over the entire 25 nm conversion bandwidth. The optical signal-to-noise ratios (OSNR) of the converted signals are better than 40 dB and the conversion efficiencies are better than −15 dB over the conversion range with 10 Gb/s signal polarization-scrambled.

Key words nonlinear optics; wavelength conversion devices; four-wave mixing; photonic crystal fiber

OCIS codes 190.4380; 060.2330; 060.5295

基于光子晶体光纤中简并四波混频效应的高效可调谐偏振不敏感波长变换器

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摘要 实验验证了一种结构简单、变换效率高的可调谐偏振不敏感全光波长变换器。光子晶体光纤由于其特殊的纤芯结构,能够保有较高的双折射效应。通过调节抽运光的偏振态,使之与光子晶体光纤的双折射轴成 45°夹角入射,则此时信号光与抽运光在光子晶体光纤中进行简并四波混频过程时,其变换效率对信号光偏振态的随机变化不敏感,闲频光输出功率几乎保持不变。实验结果表明,所搭建的全光波长变换器在 25 nm 变换范围内,闲频光偏振敏感度低于 0.6 dB,变换效率优于−15 dB(峰值可达−7.6 dB),输出闲频光的光信噪比优于 40 dB,长时间工作性能稳定,可实现开机自启动,是一种实用性强的偏振不敏感全光波长变换器。

关键词 非线性光学;波长变换器;四波混频;光子晶体光纤

中图分类号 O437 **文献标识码** A **doi:** 10.3788/CJL201441.0505005

1 Introduction

All-optical wavelength conversion (AOWC) has attracted extensive interests for its capability of increasing flexibility and reducing blocking probability in wavelength-division-multiplexing (WDM) systems as well as in WDM- OTDM (optical time-division multiplexing) mixed networks and, thus developing a practical wavelength convertor which appeals to a considerable number of researchers[1-4]. Among many theoritical principles which can be used to realize the AOWC functionality, four-wave mixing (FWM) in fiber is a promising way because the nonlinear process can preserve phase and intensity modulation information

收稿日期: 2013-10-20; **收到修改稿日期:** 2013-12-14

基金项目: 国家自然科学基金重点项目(61231012)

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simultaneously[5-7]. Meanwhile, since the Kerr nonlinearity response in silica-based highly nonlinear fiber is essentially instantaneous, FWM-based wavelength conversion in highly nonlinear fiber can satisfy major requirements of modern high-speed all-optical systems adopting more complex and advanced modulation formats.

The major obstacle for a practical FWM-based wavelength convertor is the polarization-dependent conversion efficiency (CE), defined as the power ratio between the idler at the convertor output to the signal. Because of this strongly dependence of CE on the polarization matching between the signal and the pump, the random variation polarization of a long-distance transmitted signal at the convertor input will lead to a deteriorated or even invalid output[7-8]. Several schemes have been demonstrated to reduce the FWM polarization sensitivity such as utilizing orthogonal/ co-polarized dual-pump with limited pump-detuning or using single pump with polarization-diversity loop[9-11]. However the conversion bandwidth and polarization insensitivity of these schemes are limited and they are also somewhat complex or need more optical components.

A compact tunable polarization-insensitive wavelength convertor based on degenerate FWM in a highly nonlinear photonic crystal fiber (PCF) was experimentally demonstrated in this article. By using the straight-line structure with the single pump launching at 45° to the PCF birefringent axes, the convertor polarization dependence of 0.6 dB or less, the output idler optical signal-to-noise ratio (OSNR) better than 40 dB and the conversion efficiency better than −15 dB, are obtained. This polarization-insensitive FWM-based wavelength convertor utilizes less optical components compared to the polarization-diversity loop structure[12] and is free of optical interference which deteriorates the output idler and has to be carefully avoided in the polarization-diversity loop.

2 Principle and experimental results

2.1 Experimental setup

Figure 1 depicts our experimental setup of the convertor. A 50 m highly nonlinear PCF (NL•1550•POS•1) spliced to a standard fiber via an intermediate fiber with total spicing loss less than 0.5 dB, is used as the nonlinear medium. The fiber cross-section and measured dispersion curve is shown in Fig. 2 and the main optical parameters are listed in Table 1.

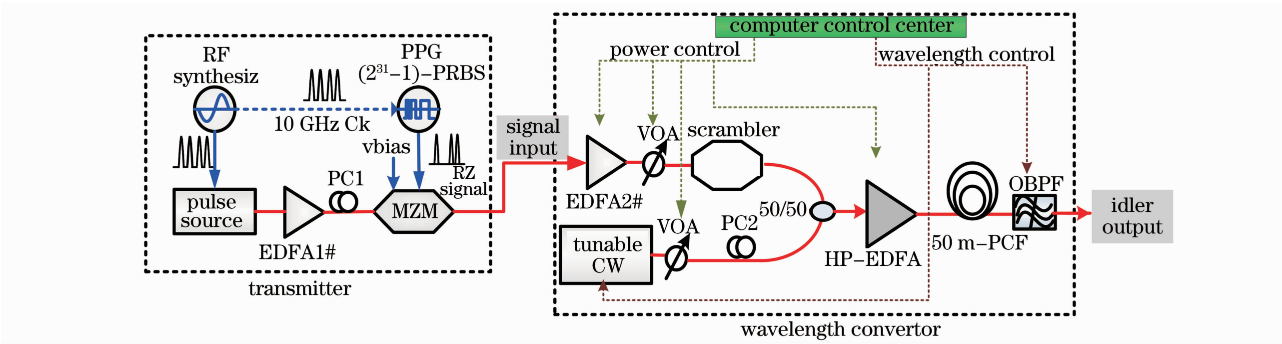

Fig. 1 Experimental setup of the polarization-insensitive wavelength convertor

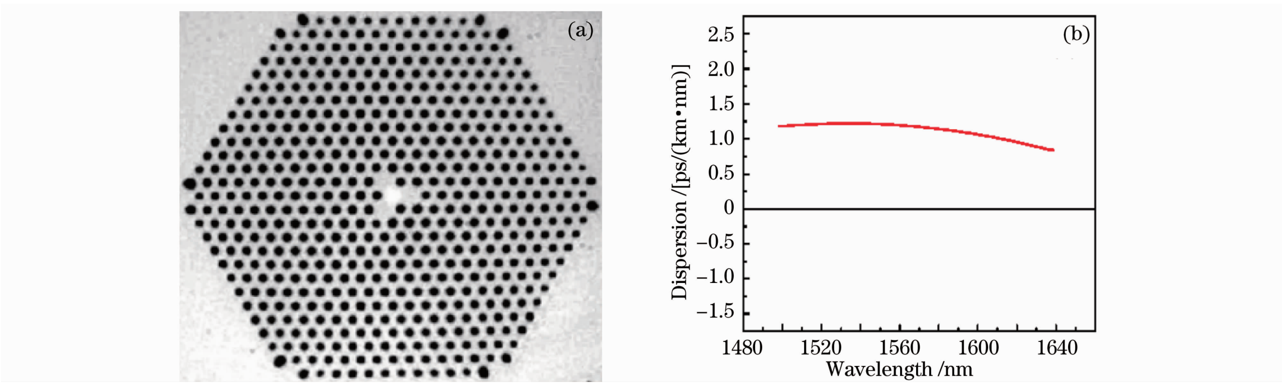

Fig. 2 (a) Cross-section and (b) measured dispersion curve of the PCF

As shown in Fig. 1, light from a wavelength-tunable continuous-wave (CW) laser (Amonics, ATL-C-12-B-FA) is used as the FWM pump and its power can be tuned by a following variable optical attenuator (VOA). Pump polarization is carefully adjusted so that it can be 45° launched to the birefringent axes of the 50 m-PCF. A 10 Gb/s return-to-zero on-off keying (RZ-OOK) signal, as shown in transmitter block of Fig. 1, is generated by intensity modulating a 10 GHz pulsed source (U^2T Photonics, TMLL1550) with a 2^{31}-1 pseudorandom binary sequence (PRBS) generated from a RF pulse-signal generator (CENTELLAX, TG1B1A10G BERT) and its power can be adjusted using the following EDFA and VOA. The waveforms of the pulsed source and generated RZ-OOK signal are shown in Fig.3.

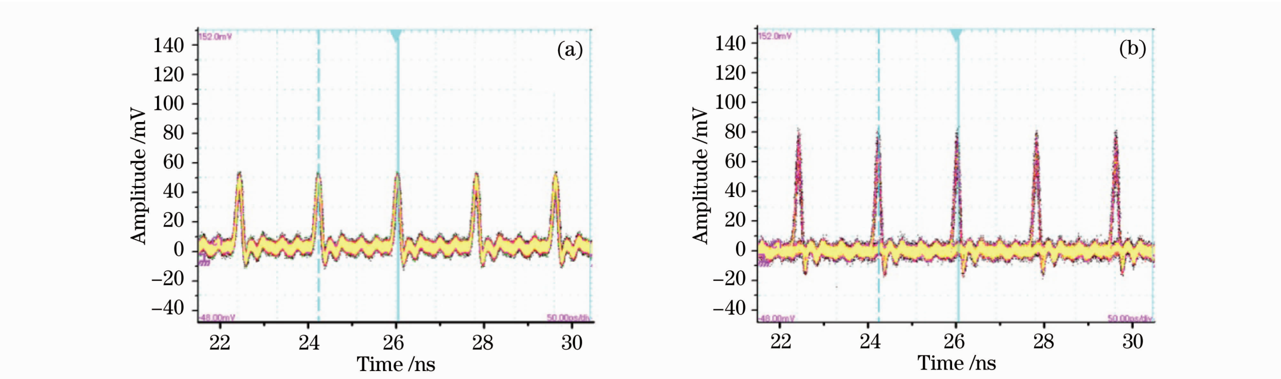

Fig.3 (a) Waveform of 10 GHz pulse source and (b) eye diagram of 10 Gb/s RZ-OOK signal

Table 1 Main optical parameters of the PCF

Parameter	Unit	Value
Dispersion@1510～1620 nm	ps/(nm·km)	>0.5
Dispersion@1480～1620 nm	ps/(nm·km)	>1.5
Arrenuaton@1510～1620 nm	dB/km	<9
Numerical aperture@1550 nm	NA	0.4±0.5
Nonlinear coefficient@1550 nm	$(W\cdot km)^{-1}$	～11
Splicing loss@1550 nm	dB	<0.5

Then the signal and the pump are combined using a 3 dB coupler with power of about −2 dBm. The combined light is amplified to a total power of about 26 dBm by a high-power erbium doped fiber amplifier (HP-EDFA, Amonics, AEDFA-33-B-FA) and launch to the highly nonlinear 50 m PCF. A wavelength-tunable optical band-pass filter (OBPF, Santac, OTF-930) with 0.25 nm bandwidth is used following the PCF to filter out the FWM idler signal. The polarization dependence of this convertor, which is defined as the difference between the maximal and minimal power of the output idler, can be studied by scrambling the signal polarization with polarization scrambler on the signal branch and recording the corresponding idler power variation. All the power and wavelength adjustment of this convertor are controlled by a computer with controlling software developed by ourselves.

2.2 Principle of operation

The theoretical principle of this straight-structure realizing polarization-insensitive FWM process can be briefly explained as the Ref. [13−14]. By solving the vector nonlinear Schrödinger equation[14] under the assumptions of negligible loss and dispersion, as well as negligible pump depletion, the output FWM idler field amplitude finally is related to the function $\mathrm{sinc}^2(L\Delta k/2)$ (where Δk is the phase-mismatch between signal and pump and $\Delta k = 2\pi(\Delta n_s/\lambda_s - \Delta n_p/\lambda_p)$, Δn_s, Δn_p are the PCF birefringence and the wavelength of signal and pump, respectively) and the pump components of E_{px} and E_{py} along the PCF x and y birefringence axes. Since the pump is 45° launched to the PCF birefringence axes, we get $E_{px} = E_{py}$, meanwhile with the pump-signal wavelength-detuning be properly selected to ensure $\Delta k \geqslant 2\pi/L$, the value of the sinc function is close to zero, therefore the FWM idler output power will be free of the signal random polarization fluctuation.

2.3 Experimental results and discussion

In our experiment, the generated 10 Gb/s RZ-OOK signal is fixed at 1550.24 nm and injected into the input port of the wavelength convertor with power of about 0 dBm. First, the pump polarization is carefully adjusted to ensure that it is 45° launched into the PCF, then by tuning the pump wavelength at 50 GHz step (corresponding to 0.4 nm wavelength spacing) and the OBPF center wavelength accordingly through the control panel, converted idlers at wavelengths ranging from 1535.74 nm to 1560.88 nm (25 nm conversion range) with clear eye diagrams are obtained (measured by Tektronix TDS8200 Digital Sampling Oscilloscope). For the sake of brevity, we just show in Fig. 4 the experimental measured eye diagrams at the middle as well as two-side wavelength of the 25 nm conversion range. By comparing the eye diagrams to that of the input signal shown in Fig. 3 (b), we can find that the output idler is slightly broadened, which is caused by the high nonlinear coefficient of the PCF.

The OSNR of each output idler is better than 40 dB (shown in Fig.5(a), measured by Agilent, PSA Series Spectrum Analyzer, E4447A) and the conversion efficiency (CE) is better than −15 dB over the 25 nm conversion bandwidth (shown in Fig. 5(b), measured by YOKOGAWA OSA AQ6370), with the best CE reaching to −5.3 dB.

To study the polarization dependence of this convertor, we scramble the signal polarization by randomly manipulating the polarization controller (PC) on the signal branch and record the output idler power variation. From the experimental results we can conclude that although the signal's state of polarization (SOP) is changing randomly, the idler output power varied insignificantly and the convertor polarization dependence is

0.6 dB or less over the 25 nm bandwidth. The polarization variation of the signal is shown in Fig. 6(a) and the idler polarization-insensitivity in Fig. 6(b).

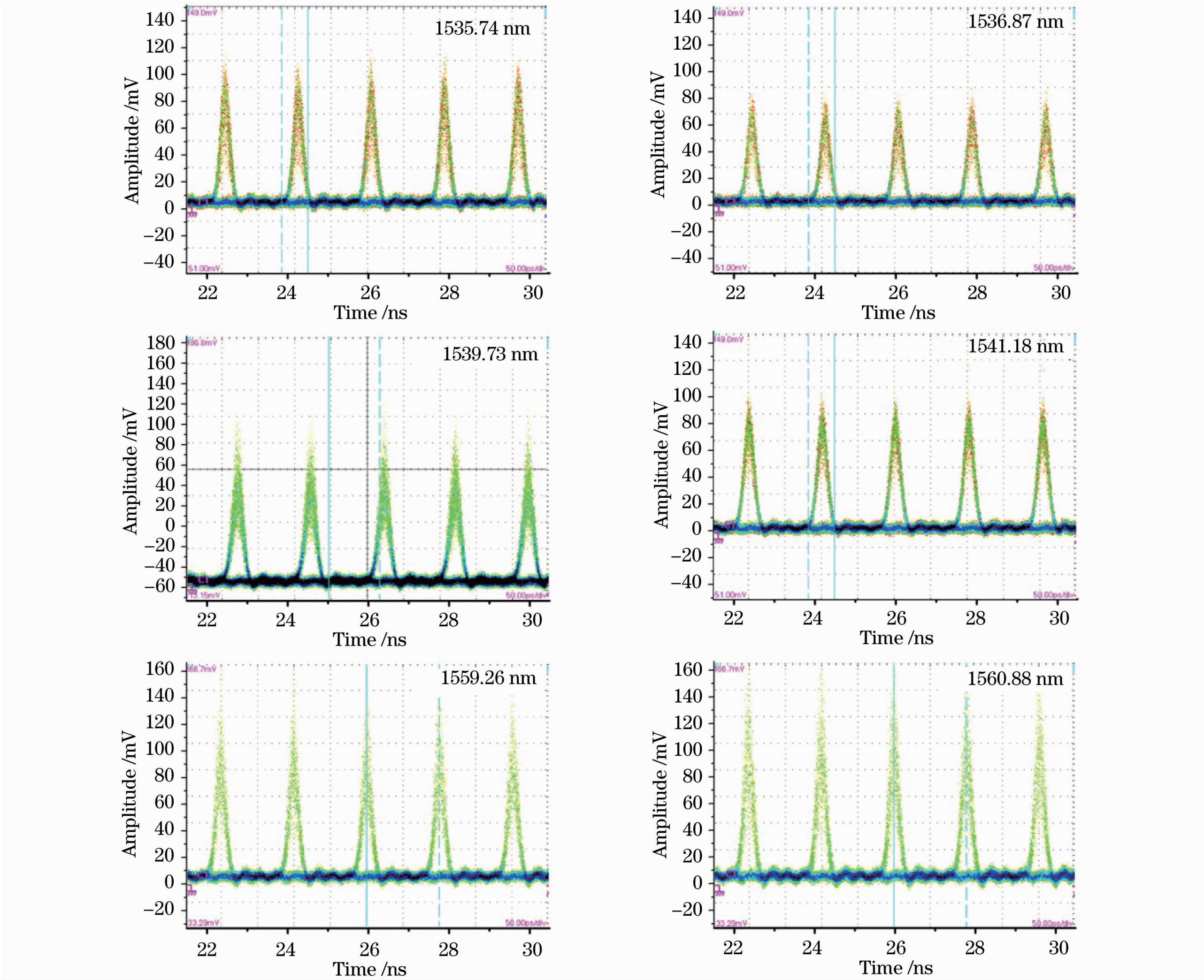

Fig. 4　Eye diagrams of different idler wavelengths over the conversion range

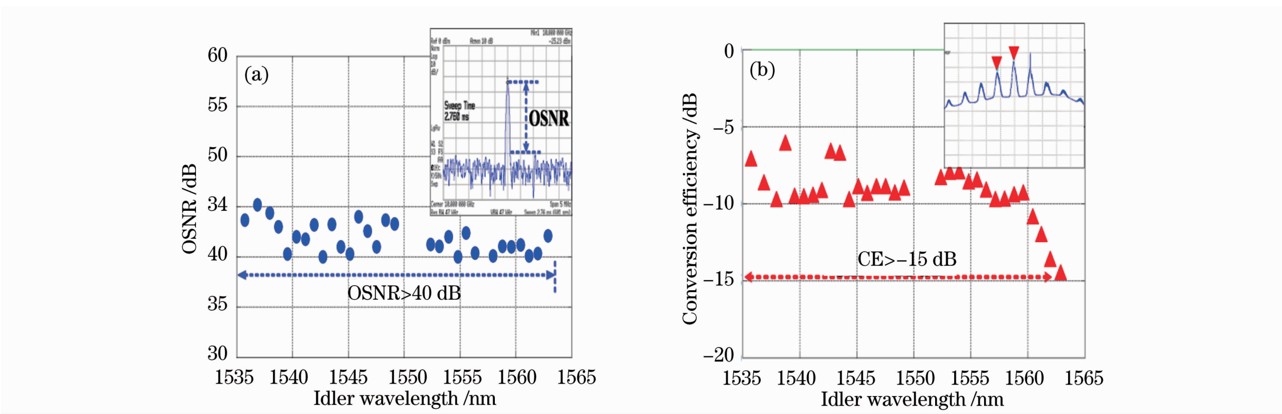

Fig. 5　OSNR and conversion efficiency of the idlers over the 25 nm conversion range

All the above experimental results are obtained based on the pump 45° launching condition as mentioned in section 2.1. When the pump polarization deviated from the 45° launching to the PCF birefringent axes, the output idler eye diagram deteriorates as shown in Figs. 7(a) and (b). This is because the FWM process is sensitive to the polarization match between signal and pump, when the two polarizations are not exactly identical to each other, the conversion efficiency will decrease and if they are perpendicular to each other, the FWM process will not occur, which is undesirable in the wavelength convertor designing.

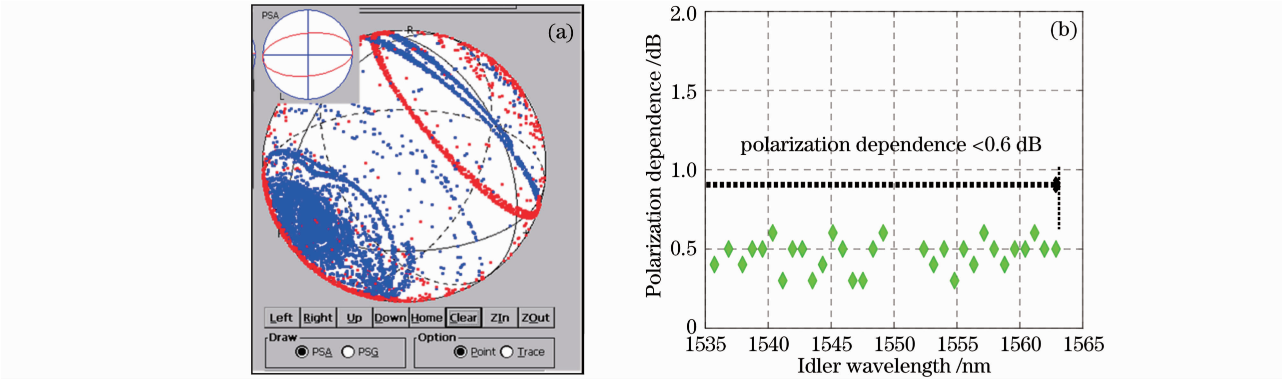

Fig.6 (a) Polarization variation of the signal and (b) the idler polarization dependence over the 25 nm conversion range

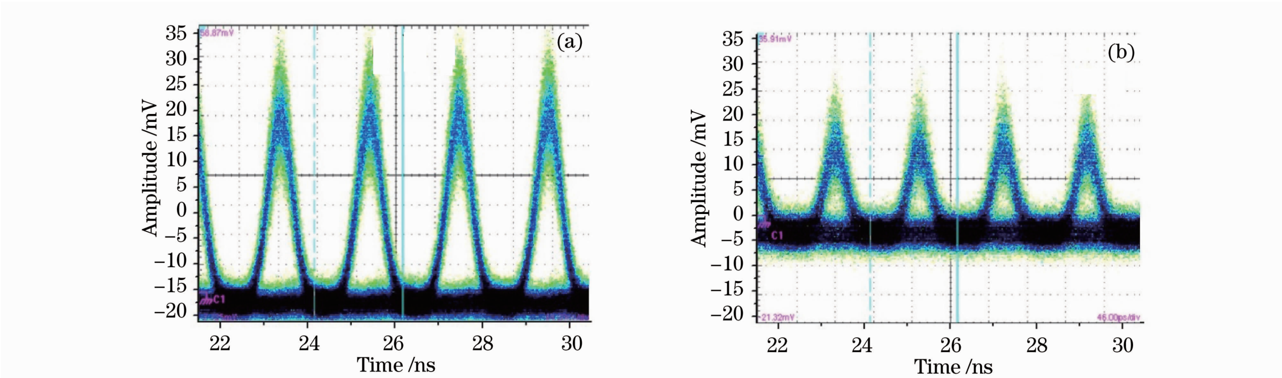

Fig.7 Comparing of idler eye diagrams (a) with and (b) without pump 45° launching

3 Conclusion

A compact and high-efficiency tunable polarization-insensitive wavelength convertor of 10 Gb/s RZ-OOK signal using degenerate FWM in a 50 m highly nonlinear PCF is demonstrated in this letter. The output idler power variation is 0.6 dB or less with the SOP of the input signal changed randomly and the conversion efficiency is better than −15 dB with peak value of −7.6 dB over the 25 nm conversion bandwidth. The results we obtained are outstanding compared to related reports using the same structure.

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栏目编辑: 殷建芳