Theoretical and Experimental Research of Polarization Insensitive Optical Wavelength Convertor in a Photonic Crystal Fiber

Hu Hui[1,2,3] Duan Tao[1] Qian Fengchen[1,2] Huang Xinning[1,2] Su Yulong[1,2,3]
Wang Wei[1,2] Han Biao[1,2] Feng Huan[1,2] Xie Xiaoping[1]
[1] *State Key Laboratory of Transient Optics and Photonics, Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi'an, Shaanxi* 710119, *China*
[2] *University of Chinese Academy of Sciences, Beijing* 100049, *China*
[3] *The School of Science, Xi'an Jiaotong University, Xi'an, Shaanxi* 710049, *China*

Abstract A single pump polarization-insensitive and widely tunable all-optical wavelength conversion for 10 Gbit/s non-return-to-zero (NRZ) signal is experimentally demonstrated by means of four-wave-mixing (FWM) in highly nonlinear photonic crystal fiber (PCF). The residual birefringence in the 50 m dispersion-flattened 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 the polarization dependence of FWM in the PCF can be decreased to be less than 1 dB over 28 nm of wavelength tunable operation. The conversion efficiencies are better than −13 dB and the Q factor of idler signal is larger than 7 over the conversion range with signal polarization change.

Key words fiber optics; wavelength conversion; polarization-insensitive; photonic crystal fiber; four wave mixing
OCIS codes 060.2330; 060.5295; 190.4380

基于光子晶体光纤的偏振不敏感波长变换理论实验研究

胡 辉[1,2,3] 段 弢[1*] 钱凤臣[1,2] 黄新宁[1,2] 苏玉龙[1,2,3]
汪 伟[1,2] 韩 彪[1,2] 冯 欢[1,2] 谢小平[1]
[1]中国科学院西安光学精密机械研究所瞬态光学与光子技术国家重点实验室，陕西 西安 710119
[2]中国科学院大学，北京 10049
[3]西安交通大学理学院，陕西 西安 710049

摘要 实验验证了一种结构简单的10 Gbit/s非归零信号(NRZ)通过高非线性光子晶体光纤(PCF)的四波混频(FWM)效应实现了单抽运偏振不敏感和宽范围可调谐全光波长转换。利用50 m光子晶体光纤较高的双折射效应，固定抽运光的偏振态与高非线性光子晶体光纤的双折射轴成45°夹角入射，信号光与抽运光在光子晶体光纤中进行四波混频时，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28 nm变换范围内，闲频光偏振敏感度低于1 dB，随着10 Gbit/s的信号光偏振态的变化，波长变换效率优于−13 dB的偏振不敏感全光波长变换器，闲频光信号Q因子大于7。

关键词 光纤光学；波长变换；偏振不敏感；光子晶体光纤；四波混频
中图分类号 O438.1 **文献标识码** A
doi: 10.3788/CJL201542.s105002

收稿日期： 2015-01-13；**收到修改稿日期：** 2015-03-06
基金项目： 国家自然科学基金(61231012)

作者简介： 胡 辉(1978—)，男，博士研究生，主要从事超快光网络及光信息传输与处理方面的研究。E-mail：johnhuihui@126.com

* **通信联系人。** E-mail：duantao@opt.ac.cn

1 Introduction

Wavelength conversion enhances network interoperability, reduces network blocking probability, and facilitates full utilization of the bandwidth of fibers deployed in dense wavelength-division-multiplexed networks. Wavelength conversion has been theoretically and experimentally demonstrated in number of researches[1-4], and has been found to have significant advantages. Wavelength conversion can be realized through a variety of theoretical principles of the nonlinear medium[4-7]. Four-wave mixing (FWM) in fiber has emerged as a viable candidate for wavelength conversion due to the relatively instantaneous response of the fiber Kerr nonlinearity, which assures transparency to both bit-rate and modulation format. Highly nonlinear photonic crystal fiber (PCF) has been found to be suitable for wide-band FWM-based wavelength conversion due to its nearly flat dispersion profile and high nonlinearity coefficient[8-11].

However, a serious drawback of FWM-based wavelength conversion is the strong dependence of the FWM efficiency on the states-of-polarization (SOPs) of the signal and the pump. Previous single-pump wavelength conversion techniques require perfect alignment of the signal and the pump SOPs over the PCF. Because of this strongly dependence of conversion efficiency 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. 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 diversion loop [12-15]. However, the conversion bandwidth and polarization insensitivity of these schemes are limited and they are also somewhat complex or need more optical components.

A single pump polarization-insensitive and widely tunable all-optical wavelength conversion for 10 Gbit/s signal is theoretically and experimentally demonstrated by means of FWM in highly nonlinear PCF. In the scheme, the residual birefringence in the 50 m dispersion-flattened guarantees wavelength conversion to be polarization insensitive when the pump polarization is exactly launched at 45° relative to the birefringent axes of the PCF. Experimental results show that the polarization dependence can be decreased to be less than 1 dB over 28 nm of wavelength tunable operation. The conversion Efficiencies are better than −13 dB over the conversion range with 10 Gbit/s signal polarization change.

2 Theoretical and experimental study

2.1 Theoretical principle

Single pump polarization insensitive wavelength converter consists of a beam splitter (PBS) and loop with highly nonlinear PCF as shown in Fig. 1. The continuous-wave amplified pump and signal are coupled into loop and splitted by the PBS. The polarization of pumpand signal remain parallel to each other in a particular direction and undergo separate FWM process inside the loop of highly nonlinear PCF. Wavelength conversion was achieved by PBS combining and output at port 3 of the loop. The polarization of the pump couldbe adjusted by their respective polarization controllers. Using the polarization controller, the pump light is polarized at 45° with respect to the PBS axis to split the pump power equally in both directions. FWM efficiency of idler is the same as both directions, when the polarization of the signal is scrambled as shown in Fig. 2.

In the conventional scheme, idler field are generated for FWM between input signal frequency ω_s and pump frequency ω_p. The converted frequencys of $\omega_{\text{Cov1.}} = 2\omega_s - \omega_p$ and $\omega_{\text{Cov2.}} = 2\omega_p - \omega_s$ are emerged both sides of signal and pump respectively. Considering the signal and pump are splitted by PBS, the power of the input signal varies in the two directions inside the loop. If same pump powers are injected in both directions of the loop, from Fig. 2, following equations are satisfied at the convertedfrequency near the signal of $\omega_{\mathrm{Cov1.}} = 2\omega_{\mathrm{s}} - \omega_{\mathrm{p}}$[15]:

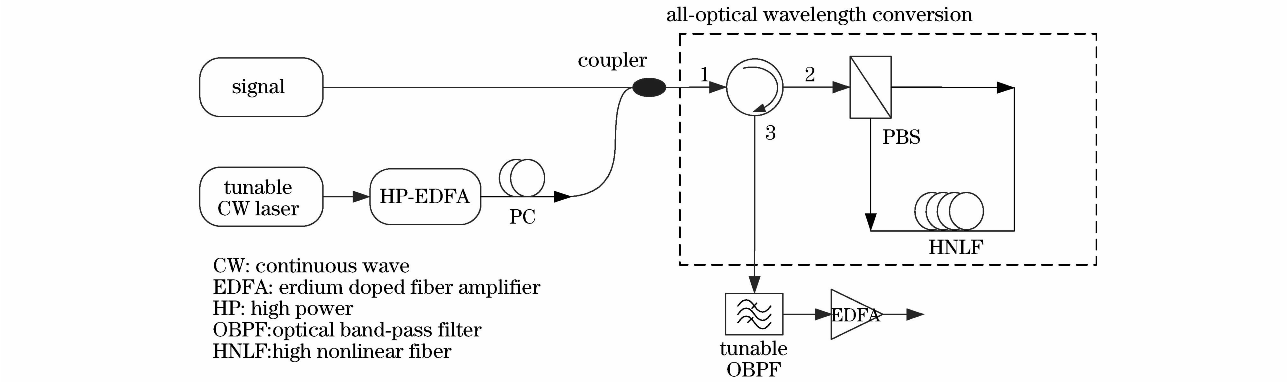


Fig. 1 Schematic diagram of single pump polarization insensitive wavelength converter

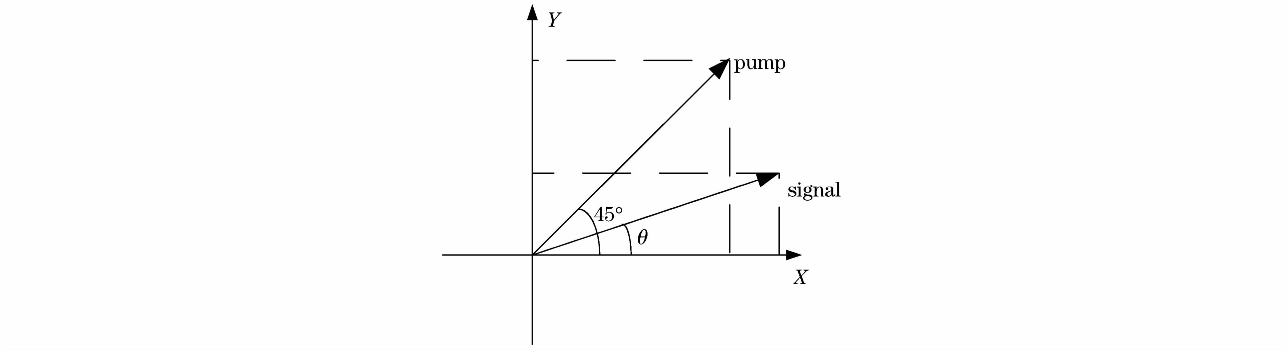


Fig. 2 Polarization angle between pump/signal light and birefringent axis of high nonlinear PCF

$$P_{\mathrm{fwm(cw)}} = (\gamma P_{\mathrm{s}} \sin^2\theta L_{\mathrm{eff}})^2 \cdot \left(\frac{P_{\mathrm{p}}}{2}\right) r(\omega_{\mathrm{s}} - \omega_{\mathrm{p}}) \exp(-\alpha L) \cdot \eta, \tag{1}$$

$$P_{\mathrm{fwm(ccw)}} = (\gamma P_{\mathrm{s}} \cos^2\theta L_{\mathrm{eff}})^2 \cdot \left(\frac{P_{\mathrm{p}}}{2}\right) r(\omega_{\mathrm{s}} - \omega_{\mathrm{p}}) \exp(-\alpha L) \cdot \eta, \tag{2}$$

where $P_{\mathrm{fwm(cw)}}$ and $P_{\mathrm{fwm(ccw)}}$ are the power of the converted signal in the clock wise and counter clock wise direction inside the loop, respectively. Powers of the converted signals in both the directions inside the loop are combined. We can get the total converted power at frequency near the signal as

$$P_{\mathrm{Cov1.}} = (\gamma P_{\mathrm{s}} L_{\mathrm{eff}})^2 \left(\frac{P_{\mathrm{p}}}{2}\right) r(\omega_{\mathrm{s}} - \omega_{\mathrm{p}}) \exp(-\alpha L) \eta (\sin^4\theta + \cos^4\theta). \tag{3}$$

For the converted signal at frequency $\omega_{\mathrm{Cov2.}} = 2\omega_{\mathrm{p}} - \omega_{\mathrm{s}}$ following equation are satisfied in the clock wise and counter clock wise direction inside the loop, respectively:

$$P_{\mathrm{fwm(cw)}} = \left(\gamma \frac{P_{\mathrm{p}}}{2} L_{\mathrm{eff}}\right)^2 \cdot P_{\mathrm{s}} \sin^2\theta r(\omega_{\mathrm{s}} - \omega_{\mathrm{p}}) \exp(-\alpha L) \cdot \eta, \tag{4}$$

$$P_{\mathrm{fwm(cw)}} = \left(\gamma \frac{P_{\mathrm{p}}}{2} L_{\mathrm{eff}}\right)^2 \cdot P_{\mathrm{s}} \cos^2\theta r(\omega_{\mathrm{s}} - \omega_{\mathrm{p}}) \exp(-\alpha L) \cdot \eta. \tag{5}$$

We can get the total converted power at frequency $\omega_{\mathrm{Cov2.}} = 2\omega_{\mathrm{p}} - \omega_{\mathrm{s}}$ as follows:

$$P_{\mathrm{Cov2.}} = \left(\gamma \frac{P_{\mathrm{p}}}{2} L_{\mathrm{eff}}\right)^2 P_{\mathrm{s}} r(\omega_{\mathrm{s}} - \omega_{\mathrm{p}}) \exp(-\alpha L) \eta, \tag{6}$$

where $P_{\mathrm{Cov1.}}$, $P_{\mathrm{Cov2.}}$ are the converted power at the frequency of $\omega_{\mathrm{Cov1.}} = 2\omega_{s} - \omega_{\mathrm{p}}$ and $\omega_{\mathrm{Cov2.}} = 2\omega_{\mathrm{p}} - \omega_{\mathrm{s}}$ respectively, P_{p}, P_{s} are pump and signal power, α is attenuation coefficient, L, L_{eff} are fiber length and effective fiber length respectively, $r(\omega_{\mathrm{s}} - \omega_{\mathrm{p}})$ is relative conversion efficiency coefficient, η is FWM efficiency, γ is nonliear coefficient, and θ is angle between input signal and pump.

It can be seen form Eq. (3) that the converted signal $\omega_{\mathrm{Cov1.}} = 2\omega_s - \omega_p$ is polarization sensitive with the change of the polarization of input signal. On the other hand, the power of the converted signal $\omega_{\mathrm{Cov2.}} = 2\omega_p - \omega_s$ at frequency near the pump, as is shown in Eq. (6), is independent on the change of polarization of the input signal θ. Hence, the converted signal $\omega_{\mathrm{Cov2.}} = 2\omega_p - \omega_s$, at frequency near the pump, considered to be insensitive to polarization and the better choice in the following.

2.2 Experimental setup

The experimental setup for polarization insensitive wavelength converter in a highly nonlinear PCF is shown in Fig. 3. Main optical parameters of high nonlinear PCF is shown in Table 1. Tunable wavelength CW laser (Oclaro TL7000) is fixed at 1547.712 nm. A $LiNbO_3$ phase modulator is used for encoding a CW with 10 Gbit/s (PRBS of 27-1) non-return-to-zero (NRZ) ON-OFF keying (OOK) format, as the optical pulse sequence and the eye diagram of signal are shown in Fig. 4. Another laser source (Oclaro TL7000) provides pump light at the wavelength of 1550.912 nm. The input signal and pump powers are tuned by following an EDFA and variable optical attenuator (VOA) respectively. The combined signal is launched into a HP-EDFA.

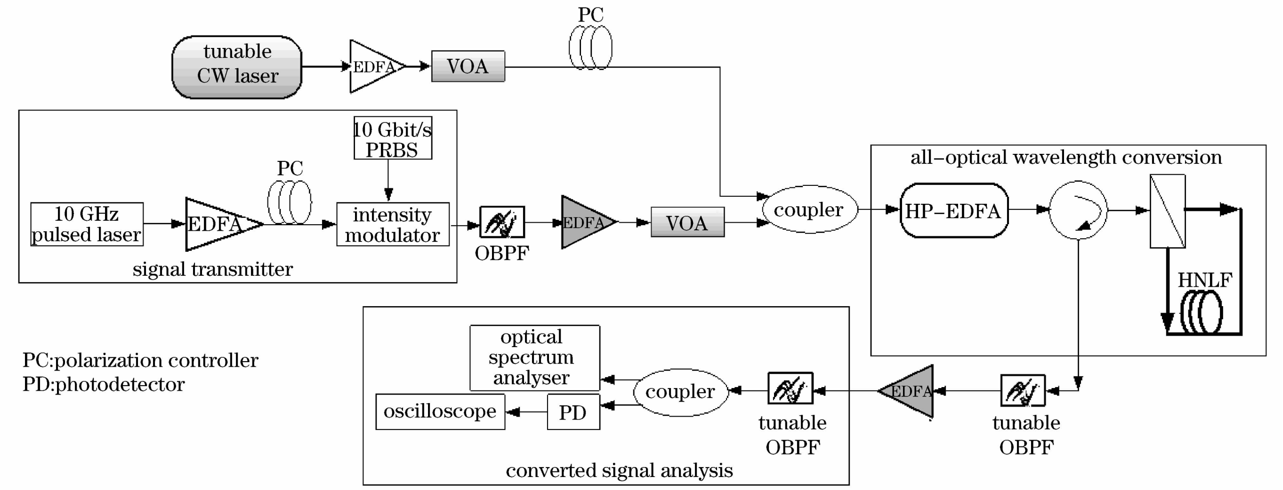


Fig. 3 Experimental setup of polarization insensitive wavelength converter

Table 1 Main optical parameters of high nonlinear PCF

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

A segment of highly nonlinear PCF(POS-1550) of 50 m-long is placed in the loop for FWM process. The characteristics of highly nonlinear PCF are shown in Table 1. The amplified signal enters the PBS through an isolator. Using the polarization controller (PC), the pump light is polarized at 45° with respect to the PBS axis to split the pump power equally in both directions. The combined signal and pump enters the PBS and travels both of the directions inside the loop before entering in the highly nonlinear PCF. The polarization of the output signal is controlled using PC.

At the receiving end, the converted idler signal at 1544.52 nm is selected using wavelength-tunable optical band-pass filter (OBPF) having 3 dB bandwidth of 0.22 nm. The output idler signal is amplified and filtered to estimate the quality of the signal by photodetector (PD: XPDV 3120R) and optical spectrometer analysis (YOKOGAWA OSA AQ6370). 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 branch and recording the corresponding idler power variation.

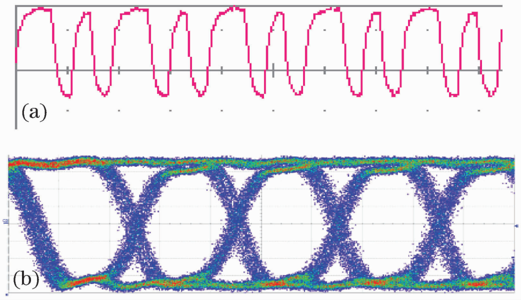
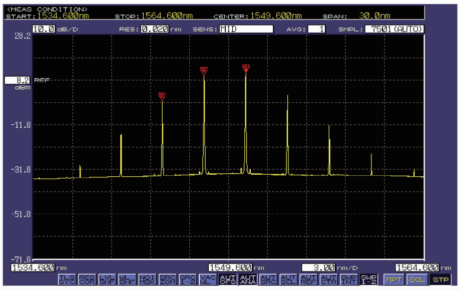


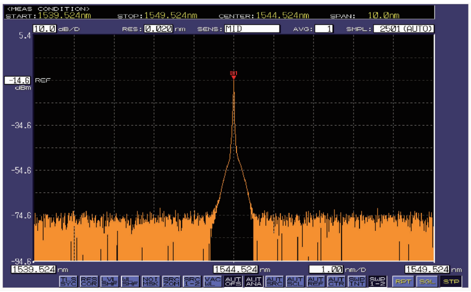
Fig. 4　10 Gbit/s NRZ signal. (a) Optical pulse sequence; (b) eye diagram

2.3　Results and discussion

The powers of signal (1550.912 nm) and pump light (1547.7 nm) are 11.296 dBm and 9.909 dBm respectively adjusting the EDFA and the VOA. The power of idler signal of FWM near the pump at light of 1544.52 nm is −1.481 dBm after 0.22 nm bandwidth filter, as is shown in Fig. 5 and Fig. 6. The conversion efficiency is about −13 dB.



<MEAS CONDITION>
START: 1534.600nm　STOP: 1564.600nm　CENTER: 1549.600nm　SPAN: 30.0nm
10.0 dB/D　RES: 0.020 nm　SENS: MID　AVG: 1　SMPL: 7501 (AUTO)



<MEAS CONDITION>
START: 1539.524nm　STOP: 1549.524nm　CENTER: 1544.524nm　SPAN: 10.0nm
10.0 dB/D　RES: 0.020 nm　SENS: MID　AVG: 1　SMPL: 2501 (AUTO)

Fig. 5　Spectrum of FWM　　　　Fig. 6　Spectrum of idler near the pump light after the filter

First, the pump polarization is carefully adjusted to ensure that 45° launched into the PCF. To study the polarization dependence of this convertor, we scramble the signal polarization by randomly manipulating the PC on the signal branch and record the output idler power variation. From the experimental results, we can conclude that although the signal polarization is changing by step of 5° from −90° to 90°, the idler output power varied insignificantly and conversion efficiency of idler polarization insensitivity is less than 1 dB, as shown in Fig. 7.

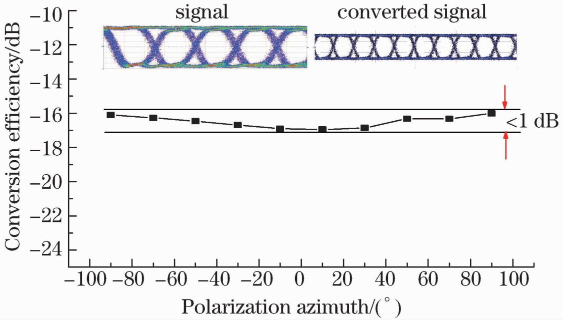
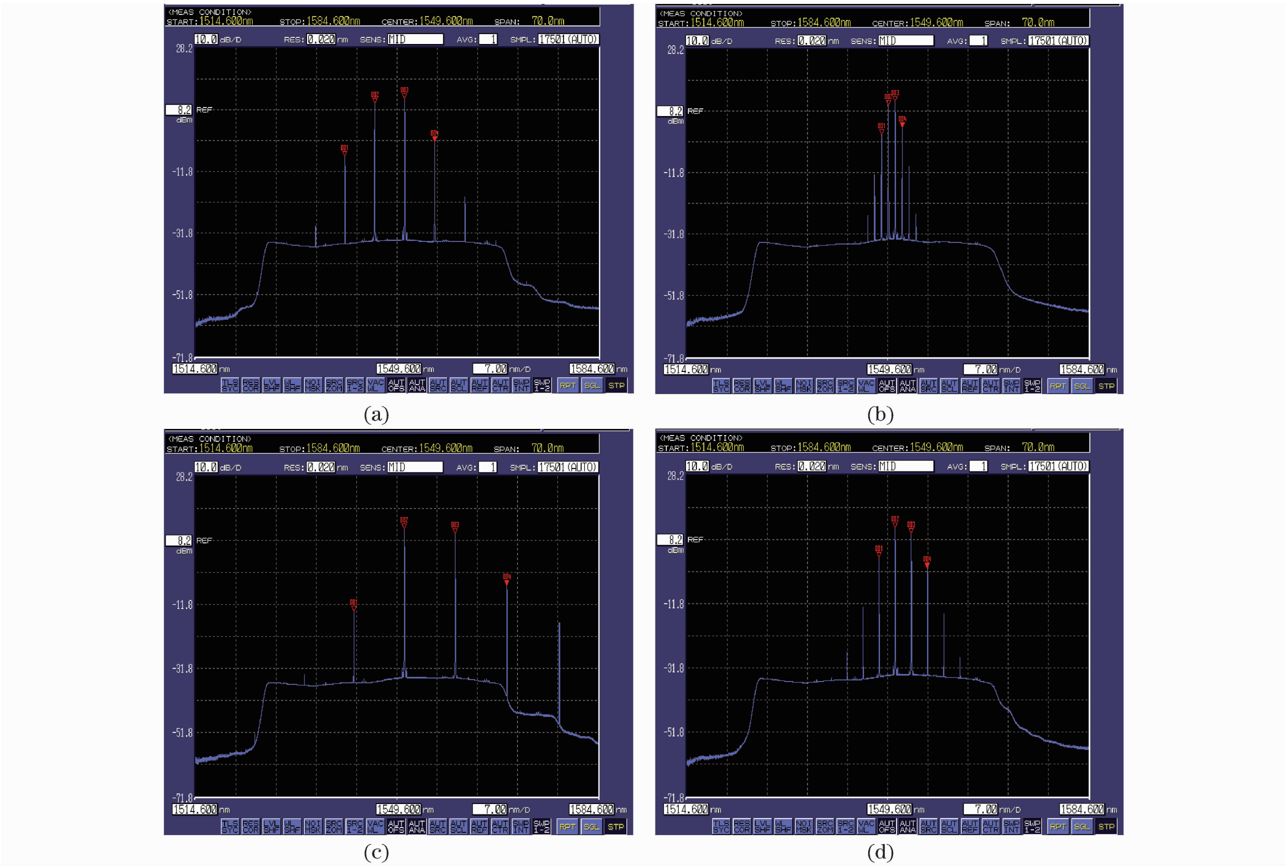


Fig. 7　Conversion efficiency of idler with the signal polarization variation

Then center wavelength of signal is fixed at 1550.9 nm, by tuning the pump wavelength at 2 nm step and the OBPF center wavelength according through the control panel, converted idlers at wavelength ranging from 1534.8 nm to 1562.9 nm (28 nm conversion range), the eye diagram is shown in Fig. 7. The wavelengths of pump light are 1534.8, 1540.6, 1544.5, 1548.5, 1556.3, 1562.9 nm, the power of the converted idler is correspondingly: 1534.8 nm@−2.652 dBm, 1540.6 nm@−1.654 dBm, 1544.5 nm@−1.481 dBm, 1548.5 nm@0.352 dBm, 1556.3 nm@−1.478 dBm, 1562.9 nm@−2.640 dBm, spectrum of FWM is shown in Fig. 8. The conversion efficiency decreases 3 dB, 28 nm conversion bandwidth is measured by OSA, as is shown in Fig. 9.


<MEAS CONDITION>
START:1514.600nm STOP:1584.600nm CENTER:1549.600nm SPAN: 70.0nm
10.0 dB/D RES:0.020 nm SENS:MID AVG:1 SMPL:17501(AUTO)

(a)

(b)

(c)

(d)

Fig. 8 Spectrum of FWM at different pump wavelengths of (a)1545.7 nm, (b)1549.7 nm, (c)1553.7 nm and (d)1559.7 nm

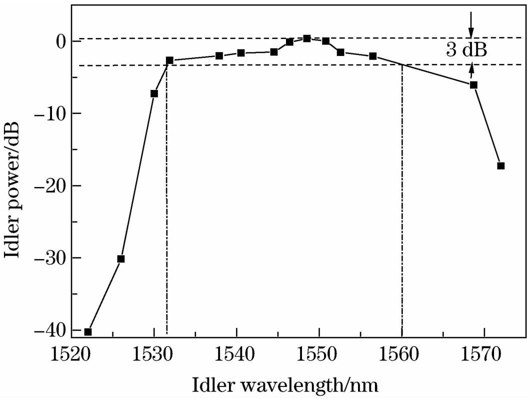


Fig. 9 Conversion efficiency of idler versus wavelength

3 Conclusion

A single pump polarization-insensitive and widely tunable all-optical wavelength conversion for 10 Gbit/s signal is theoretically and experimentally demonstrated by means of FWM in highly nonlinear photonic crystal fiber. The residual birefringence in the 50 m dispersion-flattened guarantees wavelength conversion to be

polarization insensitive when the pump polarization is exactly launched at 45° relative to the birefringent axes of the PCF. Experimental results show that the polarization dependence can be decreased to less than 1 dB over 28 nm of wavelength tunable operation. The conversion efficiencies are better than −13 dB over the conversion range with 10 Gbit/s signal polarization change.

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