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Demonstration of 6×40 Gbit/s all-optical wavelength multicasting exploiting self-phase modulation in photonic crystal fiber

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Abstract: All-optical multicasting by exploiting various optical nonlinearities has received considerable attention for performing data routing function from a single node to several destinations directly in the optical domain. Based on the self-phase modulation and followed spectral filtering, simultaneous one-to-six channels all-optical wavelength multicasting for a 40 Gbit/s RZ signal with 100 GHz channel spacing in a dispersion flattened highly nonlinear photonic crystal fiber was achieved. Dynamic characteristic of proposed wavelength multicasting scheme was further exploited. The results show proposed scheme has wide operating wavelength range and high tolerance to signal power fluctuation.

Key words: photonic crystal fiber; self-phase modulation; all-optical multicasting; optical band-pass filter

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基于光子晶体光纤中自相位调制效应的6×40 Gbit/s 全光波长组播实验研究

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摘　要: 基于非线性效应的全光组播，以其能直接在光域内将信息从单节点路由到多目标节点而受到广泛关注。实验证实了利用色散平坦高非线性光子晶体光纤级联光学滤波器实现全光波长组播的新方案，通过使用窄带光学滤波器依次选择自相位调制加宽光谱分量，对速率为 40 Gbit/s 的归零信号实现了极性保持、通道间距 100 nm 的 1 到 6 信道全光波长组播。进一步研究了所设计全光波长组播器的动态特性,结果表明,它具有 20 nm 的宽带波长调谐范围,同时,对输入信号的光功率波动具有较强的容忍性,系统整体结构简单,在未来透明光子网络中很有应用潜力。

关键词: 光子晶体光纤； 自相位调制； 全光组播； 光学滤波器

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0 Introduction

In the past few years, Internet traffic and multimedia communications are growing incredible. Future optical networks evolution will be toward all-optical networks, which strongly benefit from the introduction of new network functionalities at low cost and low power consumption directly in the optical domain. Wavelength multicasting is an important feature of Internet Protocol in which a single data packet is converted into packets at multiple wavelengths for broadcasting. Many bandwidth-intensity services in metro and access networks such as high definition internet TV, video conferencing and video-on-demand require reliable high-speed multicasting since it provides many benefits, such as increasing the network efficiency, flexiblility, and especially simplification of network layer protocols and optical network design[1-2]. Currently, these functionalities are implemented in IP digital routers and do not support future high speed photonic networks. All-optical wavelength multicasting is promising by avoiding optical-electrical-optical (O/E/O) conversion, exploiting the full potential of the bandwidth of the fiber and has become the subject of intensive studies[3]. So far, various schemes capable of all-optical wavelength multicasting has been demonstrated, such as using cross-gain modulation (XGM)[4], cross-phase modulation (XPM)[5], and four-wave mixing (FWM)[6] in semiconductor optical amplifiers (SOA's), cross-absorption modulation (XAM)[7] in electro-absorption modulator (EAM), cascaded sum- and difference-frequency generation in a periodically poled lithium niobate (PPLN) waveguide[8-9], FWM in conventional dispersion-shifted highly nonlinear optical fiber (HNLF)[10-12]. Nevertheless, most of them suffer from several limitations. For example, relatively long gain recovery time in SOA's[5] ultimately limits their operation speed, and a high manufacturing cost may prevent PPLN waveguides from practical applications; while a walk-off between short pulses due to dispersion in traditional HNLF[11] can ultimately restrict the operation speed of such fiber-based signal processors. Moreover, interferometric structures usually require complex control scheme to guarantee stable operation over long time. Recently, photonic crystal fiber (PCF) based all-optical multicasting schemes[13-14] have received considerable attention due to its widely operation wavelength range, reduces the sensitivity to external environmental disturbances as well as controllable dispersion characteristics. However, the operation speed of most of the PCF based all-optical multicasting schemes is at 10 Gbit/s until now, but future all-optical networks will be needed to support ultrahigh-speed communications. Furthermore, the operating wavelength range and dynamic characteristic of PCF-based wavelength multicasting scheme has not been investigated until now, which are very important for practical engineering design and application.

In this paper, all-optical 1-to-6 channel wavelength multicasting at 40 Gbit/s based on self-phase modulation (SPM) in a 100-m dispersion flattened highly nonlinear photonic crystal fiber (DF-HNL-PCF) has been demonstrated. The return-to-zero (RZ) data signal with higher peak power is injected into the DF-HNL-PCF, which induces a varying refractive index of the medium due to the optical Kerr effect and further causes an intensity-dependent phase shift in the pulse, generating spectral broadening. When different spectral component is selected using a central wavelength tunable optical band-pass filter (OBPF) simultaneously as different output channels, the all-optical wavelength multicasting is achieved. Moreover, the operating wavelength range and dynamic characteristic of PCF-based wavelength multicasting scheme has been investigated. The results demonstrate that the designed wavelength multicasting scheme has advantages of simple structure, wide operating wavelength range, high tolerance to signal power fluctuation and ultrafast response. It is very useful for future ultra-high speed photonic networks.

1 Experiment setup

The experimental setup for designed all-optical wavelength multicasting scheme is illustrated in Fig.1, which basically consists of a high power erbium doped fiber amplifier (HP-EDFA), a 100-m DF-HNL-PCF and an central wavelength tunable OBPF. The wavelength multicasting scheme made up of the DF-HNL-PCF as nonlinear medium and the OBPF as

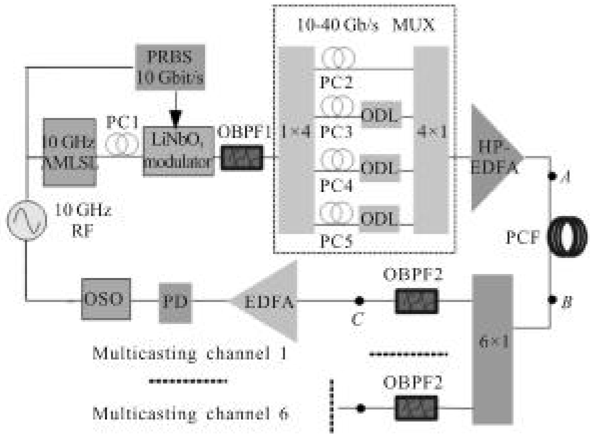

Fig.1 Experimental setup of DF-HNL-PCF based all-optical wavelength multicasting scheme

spectral filtering. In experiment, the pulse with wavelength at λ_{signal}=1 555.2 nm from an actively mode-locked semiconductor laser are modulated by a $LiNbO_3$ modulator at 10 Gbit/s 2^{31}-1 bits pseudorandom binary sequences(PRBS) with a polarization controller (PC1) at its input to align the state of polarization of the pulse train with the transmission axis of the modulator, and then fed into a fiber-based interleaver that performs optical time division multiplexing to produce an 40 Gbit/s optical pulse signal to simulate a high-speed optical data signal for using in the followed all-optical wavelength multicasting process. The PC2 to PC5 are used in MUX to adjust the polarization state of the four channels of the 40 Gbit/s OTDM signal and make them identical. After passing through a HP-EDFA (Keopsys: KPS-CUS-BT-C-35) for power amplification, the 40 Gbit/s RZ signals are then launched into the 100 m DF-HNL-PCF(prepared by Crystal Fiber A/S). The RZ signal achieved sufficient spectral broadening induced by SPM effect when passing through DF-HNL-PCF. The nonlinear coefficient of the DF-HNL-PCF is 11 $W^{-1}\cdot km^{-1}$ and its dispersionwas -0.5 ps/(nm·km) at 1 550 nm with flattened dispersion slope of less than 0.01 ps/nm^2 km. The all-optical wavelength multicasting is demonstrated by exploiting an OBPF with tunable central wavelength to slice the broadened spectrum into six channels with 100 GHz channel separation following the ITU grid.

2 Results and discussions

The experimental results are shown in Fig.2 and Fig.3. Fig.2 shows the optical spectra obtained at the input of the PCF, output of the PCF and after OBPF (corresponding at point **A**, **B** and **C** respectively, see Fig.1). The input data signal is 40 Gbit/s at 1 555.2 nm with a full width half maximum(FWHM) about τ_{FWHM}= 1.9 ps. The input and output power of HP-EDFA is 1.2 and 23 dBm. The output spectrum is broadened obviously due to SPM induced by optical pulse with high peak power. The signal power is reallocated across the broadened optical spectrum. The followed 0.8 nm bandwidth OBPF with tunable central wavelength is used to filter the broadened spectrum component. Fig.2(a) and (b) is for filtering left and right sideband with 100 GHz channel separation following the ITU grid, respectively. Note the central component of broadened spectrum is unsuitable for filtering as multicasting signal due to low **Q** factor while that can be used for format conversion and discussed in other papers[15]. Then, all-optical one-to-six channel wavelength multicasting is obtained. The six channels are denoted as channel 1 to 6 from left to the right accordingly. The eye diagrams of the input original RZ signal and the six output multicasting channels are depicted in Fig.3. In generally, clearly and widely open eye diagrams of the multicasting signals are obtained for all six optical channels with similar output signal quality and extinction ration (ER). But the signal quality is slightly decreased for all six channels from near central to sideband symmetrically. Especially comparatively larger peak-to-peak jitter and amplitude fluctuations are observed in channel one and channel six. This can be attributed to the relatively low output optical signal to noise ratio(OSNR) as a result of insufficient phase modulation for sideband spectrum.

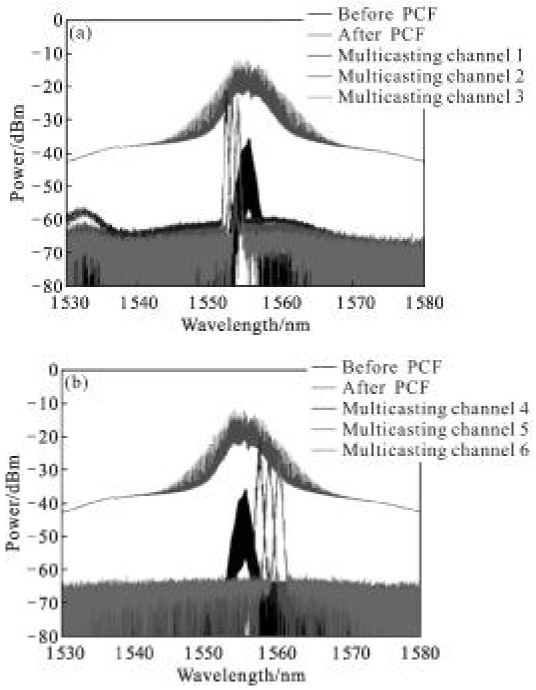

Fig.2 Optical spectrum measured at the input, the output of PCF and the output of OBPF for left sideband and right sideband

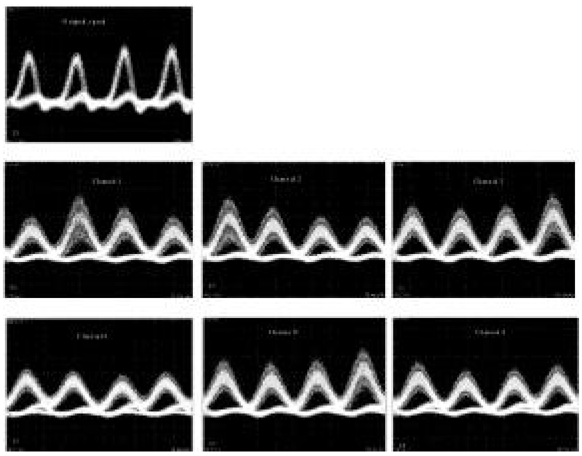

Fig.3 Eye diagrams of the input original RZ signal, and the six filtered multicasting channel signals. Time base: 20 ps/div

2.1 Wavelength tunability

All-optical wavelength multicasting scheme with widely wavelength operation range is highly desirable in future transparent photonic networks. The PCF exhibits weak group velocity dispersion (GVD) and a small dispersion slope, which provides the feasibility of operating with a wide wavelength tunable range. Hence, an experimental investigation was carried out into the wavelength tuning range of designed wavelength multicasting scheme. In experiment, the RZ signal with different wavelengths is obtained by a highly nonlinear fiber (HNLF) based wavelength converter, which consists of a HP-EDFA(Amonics: AEDFA-33-B-FA), a 700-m HNLF and a 1.5 nm bandwidth OBPF (Santec: OTF-950). The experimental setup is shown in Fig.4. The nonlinear coefficient of the HNLF is 9 $W^{-1}\cdot km^{-1}$ and its dispersion is -2.42 ps/(nm·km) at 1 550 nm with dispersion slope of 0.02 ps/$nm^2\cdot km$. Its loss is less than 0.43 dB/km. Due to high nonlinear coefficient and long length of 700-m HNLF, sufficient spectrum broadened of 42 nm induced by SPM is observed. Different components of broadened spectrum are filtered out, and then RZ signal at different wavelengths is obtained. To demonstrate the wide operation wavelength range, the central wavelength of OBPF is set at 1 545 and 1 565 nm, respectively. The spectrum at the input, output of the HNLF, after OBPF2 (corresponding at A, B and C in Fig.4) is shown in Fig.5(a). Furthermore, the wavelength converted RZ signal is launched into 100 m DF-HNL-PCF after power amplification for wavelength multicasting. The typical optical spectrum at the input, output of the DF-HNL-PCF, the output of OBPF3(corresponding at D, E and F in Fig.4) for λ_{signal}=1 545 nm is shown in Fig.5(b). Obviously spectrum broadened induced by SPM is observed. Different sideband components filtered serves as different multicasting channels, and subsequent eye diagrams monitor shows clear eye diagrams are obtained. The results demonstrate that proposed all-optical wavelength multicasting scheme can achieve a wide wavelength multicasting range of nearly 20 nm, which is substantially limited by the operation wavelength range of wavelength converter.

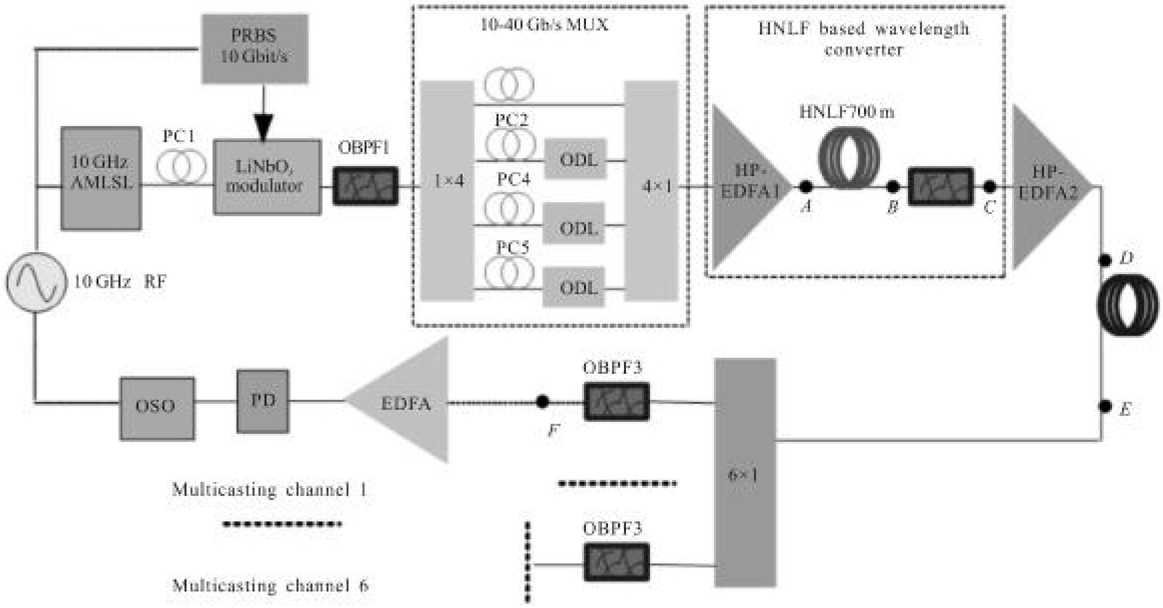

Fig.4 Experimental setup of DF-HNL-PCF based all-optical wavelength multicasting scheme

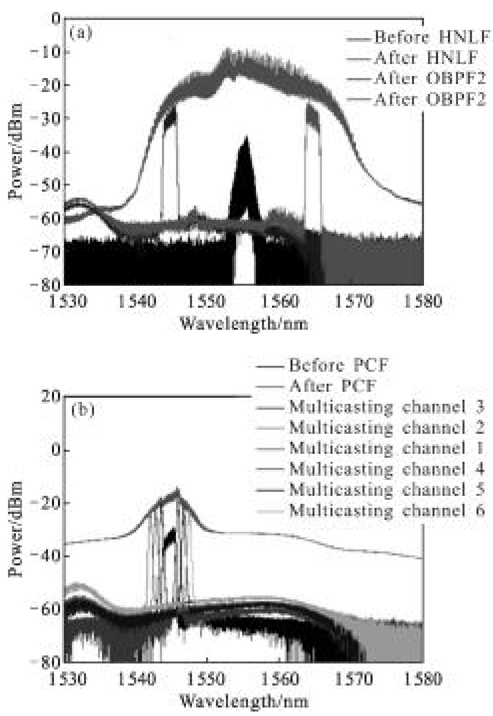

Fig.5 (a) Optical spectrum measured at the input, the output of 700-m HNLF and the output of OBPF2, (b) Optical spectrum measured at the input, the output of DF-HNL-PCF, and the output of OBPF3 for λ_{signal}=1 545 nm

2.2 Impact of signal power

In practical photonic networks, the power fluctuations happen occasionally, which will lower the performance of optical networks. From the viewpoint of engineering applications, the tolerance to changes of the signal power is an important issue on the design of all-optical wavelength multicasting scheme. Then, to facilitate the practical design, an investigation is carried out into the impact of signal power on the **Q** factor of multicasting signals. In experiment, the signal wavelength is fixed at 1 555.2 nm. The OBPF bandwidth is maintained at 0.8 nm as before. The results are shown in Fig.6. Figure 6 (a) shows the broadened spectra induced by SPM under different input signal powers, while the relationship between the **Q** factor of the multicasting signals for six channels versus input RZ signal power for such a wavelength multicasting scheme are shown in Fig.6(b). The results have shown that the proposed all-optical multicasting scheme has some tolerance to the fluctuation of input signal power. This property is very useful for the engineering design and application of DF-HNL-PCF based multicasting scheme, because it can alleviate the strict requirement of controlling the light power in practical photonic networks.

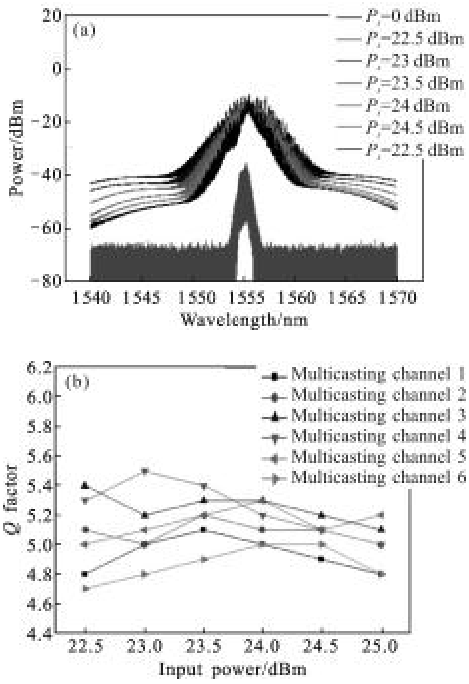

Fig.6 (a) SPM broadened spectrum of RZ signal for different input signal power, (b) **Q** factor versus input signal power for 6 multicasting channels

3 Conclusion

All optical one-to-six wavelength multicasting for 40 Gbit/s RZ signals has been demonstrated based on SPM and followed optical filtering in a 100-m DF-HNL-PCF. Six multicasting channels are obtained with an adjacent channel spacing of 100 GHz. The dynamics characteristics of proposed wavelength multicasting scheme have been investigated. The results show a broadband of 20 nm wavelength tuning range is achieved and the scheme has high tolerance to input signal power fluctuation. The proposed scheme has advantages as follows: (1) simple implementation without any external light source, (2) wide operating wavelength range, (3) high tolerance to power fluctuation and (4) ultrafast response.

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