Demonstration of 100Gbit/s Optical Time-Division Demultiplexing with 1-to-4 Wavelength Multicasting by Using the Cascaded Four-Wave Mixing in Photonic Crystal Fiber with a Single Control Light Source

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Abstract

Dispersion-flattened highly nonlinear (DF-HNL) photonic crystal fibers are useful for ultrafast optical signal processing. In this paper, 100Gbit/s-to-10Gbit/s optical time demultiplexing with simultaneous 1-to-4 wavelength multicasting is successfully demonstrated by use of the cascaded four-wave mixing (FWM) in a 50m DF-HNL photonic crystal fiber, for the first time. This scheme uses a single control-pulse light source only and a simple architecture. The wavelength multicasting of the time-demultiplexed optical signal is achieved on four wavelength channels of which two can have the minimum power penalty of 3.2 dB at 10^{-9} bit error rate compared to the 10Gbit/s back-to-back measurement. With the cascaded FWM, our proposed scheme can be used to improve the functionality of ultrahigh-speed optical time-division multiplexed systems/networks so as to support wavelength multicasting applications in a cost-effective manner.

***Keywords*:** Optical time-division multiplexing, four-wave mixing, wavelength multicasting, photonic crystal fiber, optical fiber communications

1. Introduction

Optical time-division multiplexing (OTDM) is an attractive technique for ultrahigh-speed optical data transmission on a single wavelength channel [1]. Compared with wavelength-division multiplexing (WDM) scheme, the use of OTDM can avoid adopting a large number of wavelength channels in an optical fiber communication system to maintain a given system capacity. In doing so, this can

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result in the reduction of management effort, complexity, power consumption and cost per bit for high-capacity optical fiber communication systems, while improving the spectral efficiency [2]. A distinguishing feature of OTDM systems is that ultrashort optical pulses generated by a variety of pulsed lasers are employed to achieve ultrahigh-speed optical data communications by means of optical time-division multiplexing [3]. As a result, all-optical time demultiplexers are regarded as a key component in OTDM systems. In effect, OTDM demultiplexing requires the ultrafast "logical AND" operation. The output of an optical time demultiplexer is logical "1" (i.e., an optical data pulse from the selected OTDM channel of rate f_d) if and only if a pulse of OTDM signal at f_s and a pulse of control pulse sequence with repetition rate of f_{cp} are simultaneously present in a selected time slot per OTDM frame. To correctly demultiplex OTDM channels, both f_s and f_{cp} should satisfy a relationship of $f_s = N \cdot f_{cp}$, where N is the number of OTDM channels and $f_{cp} = f_d$. Furthermore, the widths of both OTDM and optical control pulses should not exceed the time-slot width $1/f_s$ of an OTDM signal.

Generally speaking, all-optical time demultiplexers have been implemented by exploiting optical nonlinearities in various optical fibers [1][4]-[9], semiconductor optical amplifiers (SOAs) [10], nonlinear As_2S_3 and silicon waveguides [11][12], respectively. Nevertheless, these schemes have their respective drawbacks. For example, SOAs are mature and commercially available, but the relatively long gain recovery time in SOAs can ultimately limit their operation speed. Although nonlinear As_2S_3 and Si waveguides are very attractive for OTDM demultiplexing, they require a sophisticated fabrication process which can prevent them from practical applications nowadays, and they also have a large coupling loss when they are connected with fiber-based devices in photonic communication networks. At present, the use of optical fibers for OTDM demultiplexing appears to be a cost-effective solution, as optical fibers have the femtosecond response time of Kerr nonlinearity and low coupling loss with other fiber-based devices, besides massive production of optical fibers with mature technology. If a dispersion-shifted fiber (DSF) is employed, a long interactive length or high input power is normally required to obtain sufficient nonlinear effects in the conventional DSF. This problem can be feasibly resolved by replacing the DSF with a highly nonlinear fiber (HNLF) to shorten the fiber length [5], which in turn can improve the operation stability of the fiber-based OTDM demultiplexer. However, a walk-off between optical pulses or a phase mismatch due to dispersion in traditional HNLFs can restrict the operational wavelength range (or flexibility) of HNLF-based optical processors [4][13]. To overcome this difficulty, an optical processor can use the photonic crystal fiber (PCF) that exhibits both a high nonlinear coefficient and a flat dispersion. High-speed PCF-based OTDM demultiplexers were demonstrated by using cross-phase modulation (XPM) in the PCF [6]-[8], but they did not deal with wavelength multicasting and are capable of demultiplexing only a single OTDM channel each time. Recently, an efficient OTDM demultiplexing scheme was reported in [14], which is capable of simultaneously demultiplexing a 40Gbit/s OTDM signal with N = 4 to all the four distinct time channels at four different wavelengths, respectively. This was achieved by using the pump-modulated four-wave mixing (FWM) in a single dispersion-flattened highly nonlinear PCF (DF-HNL-PCF) and a periodic sequence of both time- and wavelength-interleaved optical pulses at 40 GHz [14]. However, the resulting OTDM demultiplexer can have a high complexity and is also difficult to be implemented when N becomes large and/or f_s is high, because it requires the use of a complicated optical pulse source to produce the multi-wavelength probe pulse lights (each has a pulse repetition rate of f_{cp}) which must be precisely time interleaved to form a pulse sequence with high repetition rate $F_{cp} = N \cdot f_{cp} = f_s$ and wavelength interleaving [14]. Moreover, such an OTDM demultiplexer does not have a function of wavelength multicasting.

With the increasing demand on video applications, a multicasting function is highly desirable for optical communication networks [13][15][16]. The wavelength multicasting of an OTDM signal followed by the OTDM demultiplexing was reported in [9], but it employed two HNLFs in multicasting and demultiplexing blocks, respectively. Moreover, the wavelengths of OTDM signal and control lights should be normally selected in the vicinity of a zero-dispersion wavelength of the used HNLF in order to minimize a walk-off between control and signal pulses or a phase mismatch due to dispersion in the HNLF. As a result, the walk-off or phase mismatch will ultimately restrict the operational speed or wavelength range of HNLF-based OTDM demultiplexers. For cost-effective video distributions, it is advantageous to use an OTDM demultiplexer that also performs wavelength multicasting simultaneously. We have recently demonstrated the use of XPM and FWM in two PCFs for 80Gbit/s wavelength conversion and 80Gbit/s-to-10Gbit/s OTDM demultiplexing with wavelength multicasting of two channels [16], respectively. In the resulting OTDM demultiplexer, a FWM interaction process between the control-pulse and OTDM-signal lights results in the generation of the first-order FWM components at two distinct wavelengths of λ_{FWM1} and λ_{FWM2}, and therefore, could not be used to support wavelength multicasting applications if the required number of multicasting channels is larger than 2. In this paper, we propose a simple scheme which uses the cascaded FWM in a single DF-HNL-PCF to realize the ultrahigh-speed OTDM demultiplexing together with 1-to-4 wavelength multicasting. We also demonstrate the 100Gbit/s-to-10Gbit/s OTDM demultiplexing with simultaneous four wavelength-multicasting channels by employing the cascaded FWM in a PCF-based OTDM demultiplexer, for the first time. This scheme has a transparency to signal modulation format and bit rate, because of using FWM.

2. Principle of Operation and Experimental Demonstration

In this section, we describe the principle of operation for the proposed scheme using the cascaded FWM in a single DF-HNL-PCF to achieve the simultaneous

OTDM demultiplexing and 1-to-4 wavelength multicasting. Then we report the experimental demonstration of our designed OTDM demultiplexer with a function of 1-to-4 wavelength multicasting.

The schematic diagram of a PCF-based OTDM demultiplexer with 1-to-4 wavelength multicasting is shown in Figure 1. The proposed OTDM demultiplexer consists of a 3dB optical coupler (OC), a high-power erbium doped fiber amplifier (EDFA), a 50m DF-HNL-PCF, a 1×4 optical splitter (OS), and 4 optical bandpass filters (OBPFs), respectively. To demultiplex an OTDM data signal on the *i*th channel for $i \in [1, N]$, the 10GHz optical control pulse train is adjusted to synchronize with the time slot of the selected OTDM channel by using a tunable optical delay line (ODL). For convenience, let v_s and v_{cp} be the optical frequencies of OTDM data signal and control pulse, respectively. The polarization states of these two lights are assumed to be identical in order to maximize the FWM efficiency in the PCF. This can be practically achieved by employing two polarization controllers (PCs) to adjust the polarization states of the lights at two input ports of a 3dB optical coupler in the experiment as shown in Figure 1. Then both OTDM-signal and control-pulse lights of proper powers are combined via the 3dB optical coupler and are input into a 50m DF-HNL-PCF. When the light intensity is high enough in an optical fiber, this can result in the power-dependent refractive index of the fiber, which has an origin in the third-order nonlinear susceptibility $\chi^{(3)}$ [17]. Consequently, a FWM interaction process between OTDM-signal and control lights occurs due to $\chi^{(3)}$, and new waves (i.e., idlers) are generated, as will be discussed later. To make FWM efficient, a phase-matching condition must be satisfied. This is achieved in our experiment by using a short-length DF-HNL-PCF with low and very flat dispersion and selecting the wavelengths of two lights in the 1550nm region.

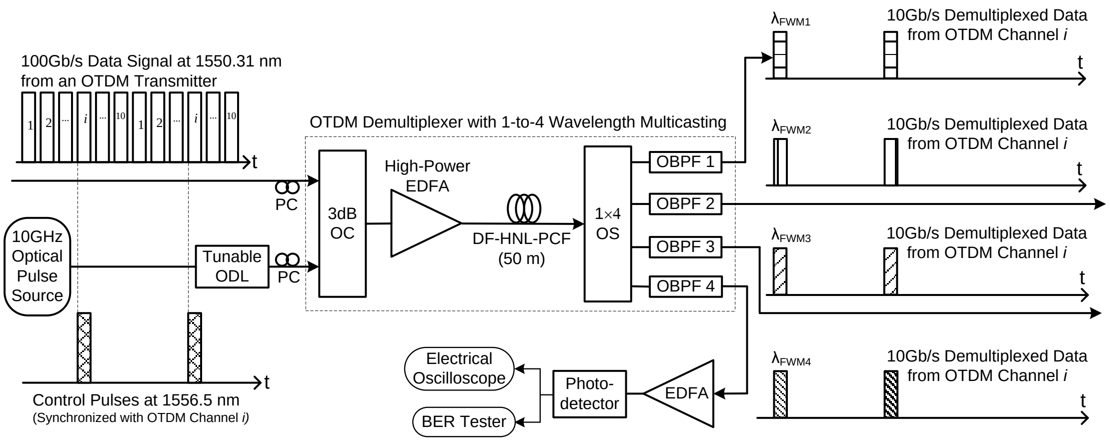

Figure 1: Schematic diagram and experimental setup of the proposed OTDM demultiplexer with 1-to-4 wavelength multicasting.

Under the phase-matching condition, FWM between the control pulse at ν_{cp} and the data signal (on the selected OTDM channel) at ν_s leads to the generation of idler waves at the new optical frequencies (different from ν_{cp} and ν_s) in the DF-HNL-PCF. This implies that a FWM-resultant pulse would be produced only if both optical control pulse and OTDM signal pulse are simultaneously present in a given time slot, otherwise no FWM products would be generated in the nonlinear fiber. Hence, an all-optical "logical AND" operation is achieved. At the DF-HNL-PCF output, a tunable OBPF can be employed to filter out the desired FWM spectral component at the specific wavelength in order to implement a function of optical time demultiplexing. Moreover, the wavelength multicasting of the time-demultiplexed optical data signal would be realized, if a bank of tunable OBPFs is connected with the individual output ports of a $1\times K$ optical splitter (see Figure 1) and these OBPFs are adjusted to select different FWM spectral components, respectively. Note that the number of wavelength multicasting channels, K, is set to 4 in our experiment, as will be described subsequently.

In a degenerate FWM process, two photons at ν_s (or at ν_{cp}) are annihilated, while two new photons at ν_{cp} and ν_{FWM1} (or at ν_s and ν_{FWM2}) are created [17]-[19], respectively. As a result, two idler waves are generated at the new optical frequencies of ν_{FWM1} and ν_{FWM2}, i.e.

$$\nu_{FWM1} = 2\nu_s - \nu_{cp} \tag{1}$$

$$\nu_{FWM2} = 2\nu_{cp} - \nu_s \tag{2}$$

It is clear that a conventional FWM interaction process between the control-pulse and OTDM-signal lights results in the generation of the first-order FWM components at ν_{FWM1} and ν_{FWM2}, respectively. This in turn limits the number of wavelength multicasting channels to be equal to 2 after OTDM demultiplexing as reported in [16]. To improve the wavelength-multicasting capability without increasing the demultiplexer complexity, we present a new design for the PCF-based OTDM demultiplexer by using the cascaded FWM process. When OTDM-signal and control-pulse lights are launched into a DF-HNL-PCF and their powers also become higher, now both lights can serve as two intense pump waves which in turn initiate the cascaded FWM process in the nonlinear fiber to produce additional wavelengths under the phase-matching condition [18]-[20]. The process can be understood in such a way that two strong incident fields at v_{cp} and v_s make a refractive index moving grating that is temporally modulated at the beat frequency [19]

$$\Delta v = |v_s - v_{cp}| \quad (3)$$

In this case, if any wave at an optical frequency of v propagates in the corresponding optical fiber, it would be inelastically diffracted by the grating at the frequencies of $v \pm \Delta v$. When these waves propagate in the fiber, they can be further diffracted to produce new waves at other frequencies [19][20]. As a result, not only FWM between the control pulse and the data signal on the selected OTDM channel generates the first-order FWM components at the optical frequencies v_{FWM1} and v_{FWM2} in a DF-HNL-PCF, but also FWM among the OTDM signal, control pulse, and their first-order FWM products would lead to the generation of other two significant cascade waves at the different optical frequencies of v_{FWM3} and v_{FWM4}, respectively, if the input powers of control-pulse and OTDM-signal lights are sufficiently high in the DF-HNL-PCF to create the cascaded FWM efficiently. In this case, the phase-matching condition is still satisfied, as we use a short-length DF-HNL-PCF with low and very flat dispersion over a wide wavelength range in the 1550nm region. Note that the study of possible FWM combinations leading to higher-order sidebands via cascaded FWM is a complicated issue and is beyond the scope of this paper. The readers may refer to Ref. 21 for discussions on estimating the amplitude of light waves involved in FWM cascades around the zero-dispersion wavelength of an optical fiber and the wave evolution of a pump-pump or pump-signal FWM cascade. For convenience, let $v_s > v_{cp}$. Using the method reported in [19], we can calculate the optical frequencies of two additional waves at v_{FWM3} and v_{FWM4} as follows

$$v_{FWM3} = 3v_s - 2v_{cp} \quad (4)$$

$$v_{FWM4} = 3v_{cp} - 2v_s \quad (5)$$

Now the 1-to-4 wavelength multicasting of the time-demultiplexed optical data signal would be realized, if 4 sets of tunable OBPFs are employed in parallel at the output of a 1×4 optical splitter to select the FWM spectral components at v_{FWM1}, v_{FWM2}, v_{FWM3}, and v_{FWM4}, respectively.

From Figure 1 and the above discussions, we can see that our proposed OTDM demultiplexer with a function of 1-to-4 wavelength multicasting has a simple architecture, because only a common control-light source and a single DF-HNL-PCF are used for both OTDM demultiplexing and 1-to-4 wavelength multicasting simultaneously.

In the experiment, OTDM data signal and control pulse signal are based on a 10GHz optical clock pulse train (with pulsewidth of 1.9 ps) obtained from an actively mode-locked semiconductor laser at the wavelength λ_s = 1550.31 nm. Employing a conventional fiber delay-line multiplexer (similar to those in [1][6]-[8]), we obtain the 100Gbit/s OTDM signal by time multiplexing the optical clock pulses modulated at 10 Gbit/s with a 2^{31}-1 return-to-zero (RZ) pseudorandom binary sequence. The resulting eye diagram is measured by using a 70GHz electrical sampling oscilloscope cascaded with a 70 GHz photodetector, as shown in Figure 2(a). Note that a small peak-power variation of OTDM signal pulses can be seen in Figure 2(a), which is caused by using an imperfect OTDM multiplexer in our experiment. The 10GHz control pulse signal at another wavelength λ_{cp} = 1556.5 nm is provided simply by wavelength conversion (of the split 10GHz original optical clock pulse train) based on supercontinuum (SC) generation in a 300m dispersion-shifted HNLF [22]. Since the SC generation leads to broadening the spectrum of the clock-pulse light, a tunable optical bandpass filter with 3dB bandwidth of 1.0 nm is required at the HNLF output to filter out the resulting SC spectrum at 1556.5 nm in order to obtain a 10GHz control signal [see Figure 2(b)].

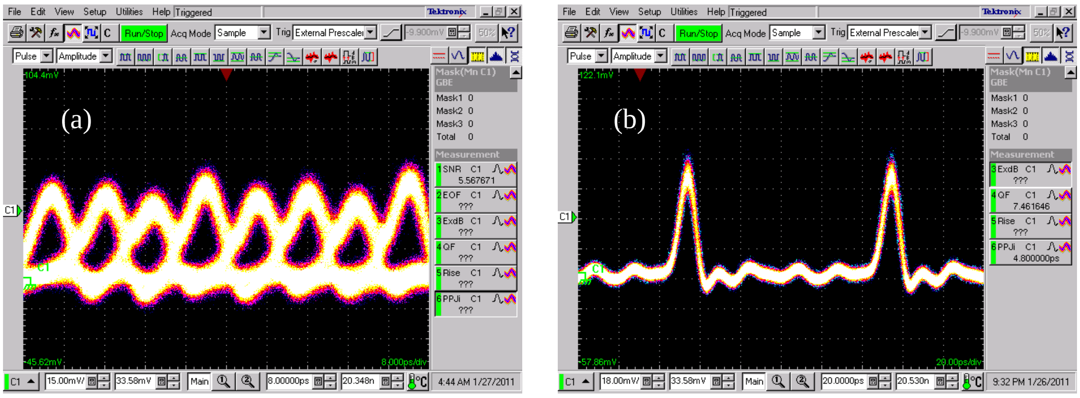

Figure 2: (a) Eye diagram of an input 100Gbit/s OTDM data signal and (b) the measured waveform of a 10GHz optical control pulse signal.

At the input of our designed OTDM demultiplexer with 1-to-4 wavelength multicasting, two polarization controllers are used to adjust the polarization states of both OTDM signal and control pulse lights so as to optimize the FWM effect in a DF-HNL-PCF. A tunable optical delay line is employed to align the 10GHz control pulse train with the desired OTDM basic-channel signal. Then 100Gbit/s OTDM signal at λ_s and 10GHz control signal at λ_{cp} are combined by a 3dB optical coupler and is amplified by a high-power EDFA which provides the 24.7dBm average output signal power. The amplified OTDM and control lights are launched into a 50m DF-HNL-PCF which has a nonlinear coefficient of 11 W^{-1} km^{-1} and an attenuation coefficient of 9 dB/km. Both ends of the PCF are spliced to single-mode fibers, resulting in a total loss of about 1 dB. This DF-HNL-PCF has a low and very flat dispersion of ~1.25 ps nm^{-1} km^{-1} with a variation < 0.25 ps nm^{-1} km^{-1} from 1500 nm to 1610 nm, which in turn can ensure a wider operation wavelength range for the designed OTDM demultiplexer than that based on a HNLF. Under the phase-matching condition, FWM between the control pulse at v_{cp} and the data signal (on the selected OTDM channel) at v_s is induced in a 50m DF-HNL-PCF. Due to a strong FWM effect, four significant idler waves are generated at the optical frequencies of v_{FWM1}, v_{FWM2}, v_{FWM3}, and v_{FWM4} which are determined by Eqs. (1) to (5), respectively. In this way, the same OTDM demultiplexed signal at 10Gbit/s is thus multicast over four wavelength channels. At the output of a 1×4 optical splitter, one of four multicasting signals is extracted by using a tunable OBPF with bandwidth of 0.38 nm tuned to one of the central wavelengths of four idler waves (i.e., λ_{FWM1}, λ_{FWM2}, λ_{FWM3} and λ_{FWM4}), respectively. The used OBPF (Santec OTF-300-004-S3) has a Gaussian filtering profile with a 3dB bandwidth of 0.38 nm which should be sufficiently wide for a 10Gbit/s optical signal to pass through. However, a 20dB bandwidth of this optical filter is less than 1.2 nm, thus resulting in a high roll-off rate outside the passband. In this case, the OBPF can provide a sufficient rejection to the crosstalk from adjacent wavelength channel(s) and the optical noise from a high-power EDFA. Clearly, our proposed scheme has the advantage of using a single control-light source and a single DF-HNL-PCF of 50 m in the simple architecture to simultaneously achieve the OTDM demultiplexing together with 1-to-4 wavelength multicasting. Then an optical spectrum analyzer (Yokogawa AQ6370) with 0.02nm resolution is used at the PCF input & output and the outputs of four OBPFs to monitor the corresponding optical spectra as shown in Figure 3. The results indicate that the generated first-order and second-order FWM products are clearly seen, while the optical power of the second-order product is lower than that of the first-order product.

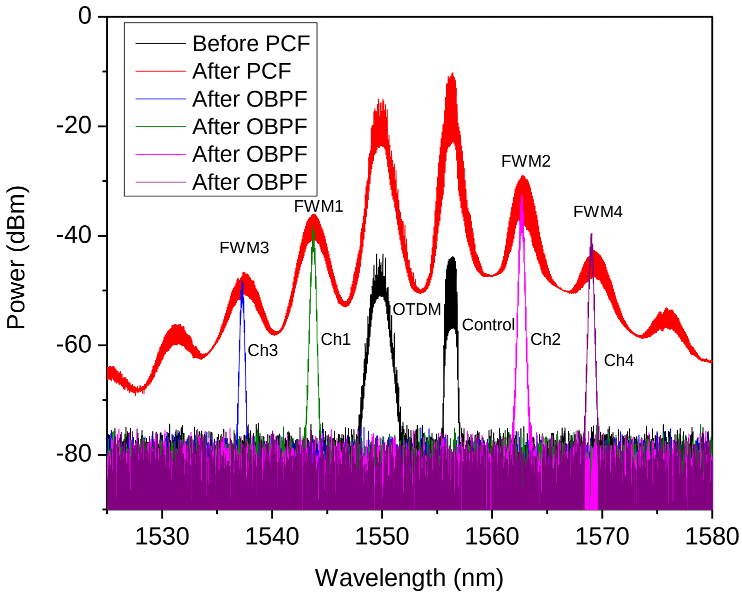

Figure 3: Optical spectra measured at the PCF input & output and the outputs of four OBPFs, respectively. Ch: Channel.

The conversion efficiency is a crucial parameter for evaluating the performance of FWM-based optical time-division demultiplexers with multicasting functionality, which can be defined as the ratio of the converted signal power to the input signal power. Generally speaking, the FWM efficiency would be optimized if a phase-matching condition is satisfied [23]. In this situation, conventional dispersion-shifted fibers can have a very low conversion efficiency of FWM, when both wavelengths of OTDM-signal and control-pulse lights are not selected in the vicinity of a zero-dispersion wavelength of the DSF and/or the separation between those two wavelengths is large, causing the phase mismatch. However, the satisfactory conversion efficiency could be easily achieved if we use DF-HNL-PCFs with a low & very flat dispersion, a high nonlinear coefficient and a short length to implement FWM-based OTDM demultiplexers. In practice, we can calculate the conversion efficiency for four multicasting channels of our designed OTDM demultiplexer by using the measured input signal power and powers of the generated first-order and second-order FWM products, respectively. The obtained results are summarized in Table 1. We can see that relatively good conversion efficiency is achieved for the first-order FWM products (i.e., on multicasting channels 1 and 2). Meanwhile, the conversion efficiency for the second-order FWM products can be still satisfactory (see channels 3 and 4 in Table 1).

Table 1: FWM conversion efficiency of four multicasting channels

Channel	1	2	3	4
Efficiency (dB)	-20.2	-14.26	-31.56	-26.52

To further investigate the performance of newly designed time demultiplexer with multicasting functionalities, we measure the eye diagram and bit error rate (BER) of the 10Gbit/s multicasting signals. The output signal from OBPF is amplified and fed into a 70GHz photodetector connected to an electrical sampling oscilloscope or a BER tester (Anritsu model number MP1800a). Figure 4 shows the output BER against the received optical power of each multicasting channel. Clear and open eyes are observed for all four multicasting signals with no intersymbol interference, as shown in the insets of Figure 4. The error-free multicasting of an OTDM demultiplexed signal is achieved on the first two wavelength channels at λ_{FWM1} and λ_{FWM2}, showing the minimum power penalty of 3.2 dB at a 10^{-9} BER compared to the 10Gbit/s back-to-back measurement. This penalty can be attributed to arising from the combination of the imperfect multiplexing, EDFA noise, and pulse broadening through OBPF. The other two multicasting channels at λ_{FWM3} and λ_{FWM4} suffer from a high BER, due to the utilization of the second-order FWM products and the degraded optical signal-to-noise ratio. From Figure 3, we can easily observe that there is a significant spectral overlapping between two multicasting signals at λ_{FWM2} and λ_{FWM4}. Moreover, multicasting channel 2 has a much higher optical power than multicasting channel 4 does. A severe crosstalk from the adjacent channel is thus induced on multicasting channel 4, and it could not be eliminated by optical filtering. To alleviate the effect of such a crosstalk on the desired multicasting signal 4, the tunable OBPF with a 3dB bandwidth of 0.38 nm and a high roll-off rate outside the passband is used in our experiment to extract the 10 Gbit/s multicasting signal at the output of a 1×4 optical splitter. In this case, the severe crosstalk makes the BER of multicasting signal 4 to be worst among those four wavelength channels, although the optical power of the FWM product at λ_{FWM3} is lower than that at λ_{FWM4}. Nevertheless, both multicasting channels at λ_{FWM3} and λ_{FWM4} can still achieve a 10^{-5} BER (see Figure 4) which is sufficient to obtain a post-decoding BER $\leq 10^{-12}$ if a proper forward error correction (FEC) code is used [1][24]. To attain this goal, we can use, for example, a continuously-interleaving Bose-Chaudhuri-Hocquenghem (CI-BCH) error-correcting code of standard 6.7 percent overhead to significantly improve the BER performance of the proposed OTDM system with simultaneous 1-to-4 wavelength multicasting. As reported in Ref. 24, the post-decoding BER can be reduced to 2.0×10^{-11} or lower even if the input BER of this CI-BCH code decoder is less than or equal to 4.65×10^{-3}, resulting in a net coding gain ≥ 7.81 dB. This implies that, after the FEC-code decoding, the error-free multicasting of the OTDM demultiplexed signal could be achieved on all four wavelength channels at λ_{FWM1}, λ_{FWM2}, λ_{FWM3} and λ_{FWM4}, respectively, if a proper error-correcting code (e.g., CI-BCH code) is employed in such an OTDM system with simultaneous 1-to-4 wavelength multicasting. Nevertheless, we need to further study this topic in our future work.

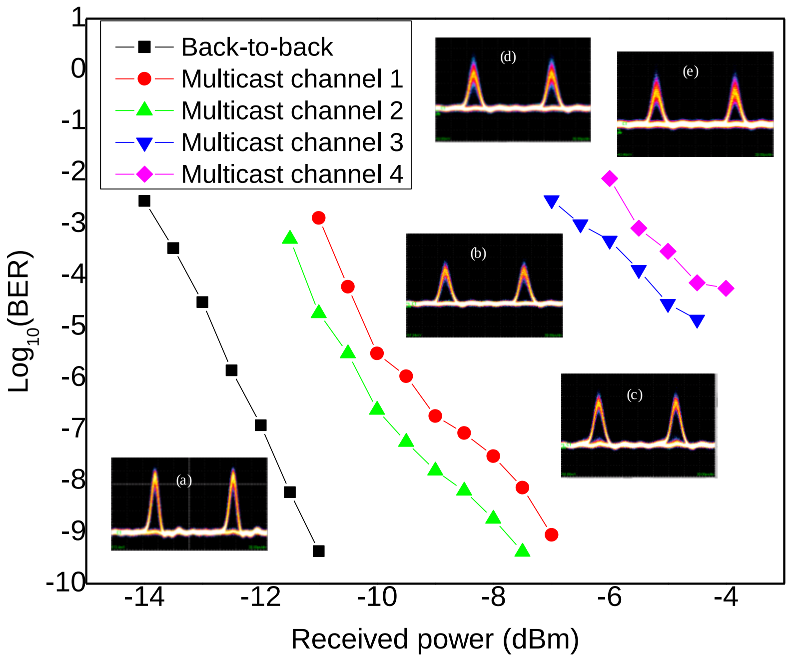

Figure 4: BER versus the received power for 10Gbit/s back-to-back signal and OTDM demultiplexed signal on four wavelength channels. The inset shows the eye diagrams of (a) original 10Gbit/s signal and (b)-(e) multicasting signals on channels 1, 2, 3 and 4, respectively.

3. Conclusions

In this paper, we have demonstrated the 100Gbit/s-to-10Gbit/s OTDM demultiplexing with simultaneous 1-to-4 wavelength multicasting by using the cascaded FWM in a 50m DF-HNL-PCF, for the first time. Error-free operation is achieved on two multicasting channels for the OTDM demultiplexed signal. The proposed scheme uses a single DF-HNL-PCF of short length and a single control-pulse light source, which is easy to be implemented with a simple architecture. Since wavelength multicasting is a useful function required by WDM networks, the use of our newly designed optical time-division demultiplexers can improve the functionality and applicability of conventional OTDM networks by cost-effectively providing wavelength multicasting. In doing so, OTDM networks can be employed to flexibly support the future video distribution and teleconferencing applications.

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LIST OF FIGURE CAPTIONS

Fig.1. Schematic diagram and experimental setup of the proposed OTDM demultiplexer with 1-to-4 wavelength multicasting.

Fig.2. (a) Eye diagram of an input 100Gbit/s OTDM data signal and (b) the measured waveform of a 10GHz optical control pulse signal.

Fig.3. Optical spectra measured at the PCF input & output and the outputs of four OBPFs, respectively. Ch: Channel.

Fig.4. BER versus the received power for 10Gbit/s back-to-back signal and OTDM demultiplexed signal on four wavelength channels. The inset shows the eye diagrams of (a) original 10Gbit/s signal and (b)-(e) multicasting signals on channels 1, 2, 3 and 4, respectively.