Article **Chinese Science Bulletin**

Optoelectronics

September 2011 Vol.56 No.25: 2744–2747
doi: 10.1007/s11434-011-4578-9

Suppression intra-channel four-wave mixing by strong dispersion management in 160 Gb/s OTDM RZ 100 km transmission

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Received November 25, 2010; accepted April 27, 2011

The effect of intra-channel four-wave mixing on the performance of a 160 Gb/s OTDM RZ 100 km transmission system is analyzed. Strong dispersion management to suppress the detrimental effects of intra-channel four-wave mixing is presented theoretically and verified experimentally. Results demonstrate that amplitude fluctuation and ghost pulses are well suppressed by strong dispersion management. Stable (>2 h) error-free (10^{-12}) transmission over 100 km is achieved without forward-error correction, and the power penalty is ~3.6 dB.

optical time-division multiplexing, intra-channel four-wave mixing, strong management, error-free

Citation: Jia N, Li T J, Zhong K P, et al. Suppression intra-channel four-wave mixing by strong dispersion management in 160 Gb/s OTDM RZ 100 km transmission. Chinese Sci Bull, 2011, 56: 2744–2747, doi: 10.1007/s11434-011-4578-9

The demands for huge-capacity transmission have increased with the continuous growth of telecommunication services. Optical time-division multiplexing (OTDM) systems may be viable solutions to these demands. For instance, using OTDM differential quadrature phase-shift keying and polarization multiplexing, signal generation up to 5.1 Tbit/s and error-free demodulation employing direct detection [1] and 1.28 Tbit/s single-polarisation OTDM-OOK (on-off keying) data generation and demultiplexing have been demonstrated [2]. For these high-speed serial data signals, dispersion management is essential for long-haul optical transmission. In a dispersion-managed system, expansion of the transmissible distance is limited by intra-channel nonlinear interactions, which consist of intra-channel cross-phase modulation (IXPM) and intra-channel four-wave mixing (IFWM) [3,4]. IXPM shifts the mean frequency and leads to timing jitter, whereas IFWM brings about amplitude fluctuation via energy transfer and generation of ghost pulses in the zero bit slots, resulting in severe limitations to bandwidth efficiency. The chirped return-to-zero (RZ) pulses are less influenced by IXPM in strongly dispersion-managed lines because the input pulse broadens rapidly and the peak amplitudes become small in spite of the extremely large overlap [4,5]. Therefore, IFWM is the main obstacle for long-distance high-speed transmission. Although IFWM can be reduced using special fibers with low nonlinearity and an ultra-low average dispersion slope [6], it is more cost effective to design the dispersion map than to install new fiber or to modify the transmitter and receiver subsystems when installed systems are upgraded to higher per-channel data rates. Numerical studies have been carried out to understand how to reduce the impact of the amplitude fluctuation and ghost pulse generation induced by IFWM. However, the simulation bit rate has been 40 or 80 Gb/s, which is much [3–10]. Therefore, it is useful to experimentally study and verify strong dispersion management in the case of a 160 Gb/s OTDM RZ transmission system.

In this paper, we theoretically analyze the IFWM process and propose a design of dispersion management to reduce its effect. The proposed dispersion management is then verified experimentally. Excellent BER performances are obtained in back-to-back (B2B) and 100 km transmission.

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1 Theory

Optical pulse propagation in a strongly dispersion-managed system can be described by

$$i\frac{\partial q}{\partial z}+\frac{d(Z)}{2}\frac{\partial^2 q}{\partial T^2}+S(Z)|q|^2 q=0, \tag{1}$$

where *d*(*Z*) is fiber dispersion, *S*(*Z*) is fiber nonlinearity including fiber loss and amplifier gain, and *q*, *Z*, and *T* are the normalized amplitude of the pulse envelope, distance and time, respectively. Here we assume the *j*-th pulse of the data stream with Gaussian shape:

$$q_j=\sqrt{\frac{2E}{\sqrt{\pi}\tau}}\exp\left[-2(1-iC)\left(\frac{T-jT_s}{\tau}\right)^2+i\theta_j\right], \tag{2}$$

where j=0, ±1,···. The center time position of q_{m+n} is $T=jT_S$, and T_S is the pulse period. *E* and $\theta_j(Z)$ are constant energy and the phase of the pulse, respectively. A ghost pulse develops because of resonance of the surrounding pulse q_m, q_n and q_{m+n}. When the amplitude of the ghost pulse is small, the IFWM process can be described as [10]

$$i\frac{\partial q_0}{\partial z}+\frac{d(Z)}{2}\frac{\partial^2 q_0}{\partial T^2}=S(Z)\sum_{m,n}q_m q_n q^*_{m+n}. \tag{3}$$

Note that self-phase modulation and terms containing *m*, *n*, or *m*+*n* are neglected in eq. (3) and we let $R(Z,T)=S(Z)\sum_{m,n}q_m q_n q^*_{m+n}$. Substituting eq. (2) for q_m, q_n and q_{m+n}, the ghost pulse in the spectral domain is given by [10]

$$\tilde{q}_0(Z,\omega)=-i\int_0^z \tilde{R}(\zeta,\omega)\exp\left[i\frac{\omega^2}{2}\{D(\zeta)-D(Z)\}\right]\mathrm{d}\zeta, \tag{4}$$

where

$$\tilde{R}(Z,\omega)=-S(Z)\sqrt{\frac{2E^3}{\pi\sqrt{\pi}(3-iC)\tau}}\sum_{m,n}\exp(\Theta_{m,n}), \tag{5}$$

$$\Theta_{m,n}=i(\theta_m+\theta_n+\theta_{m+n})-4\left(\frac{T_s}{\tau}\right)^2(m^2+mn+n^2+imnC)$$
$$+\frac{2}{3-iC}\left\{(m+n)\frac{2T_s}{\tau}+i\frac{\omega}{4}\tau\right\}^2. \tag{6}$$

The growth rate of the ghost pulse is determined by the perturbation term $\tilde{R}(Z,\omega)$. Because strongest resonance occurs at the averaged carrier frequency $\omega=0$, we only consider the case of $\tilde{R}(Z,\omega=0)$. Employing strong dispersion management, the pulse spreads widely and has a large chirp. Therefore, the expression of $\tilde{R}(Z,0)$ can be simplified as

$$\tilde{R}(Z,0)=-S(Z)\sqrt{\frac{2E^3}{\pi\sqrt{\pi}C\tau}}$$
$$\times\sum_{m,n}\exp\left[i\left(\theta_m+\theta_n+\theta_{m+n}+\frac{\pi}{4}-4mnT_s^2\frac{C}{\tau^2}\right)\right], \tag{7}$$

where $\tilde{R}(Z,0)$ is inversely proportional to $\sqrt{C\tau}$ in eq. (7), and the IFWM is effectively reduced using of narrower input pulse with wider spectral width and designing a dispersion management line with large accumulated dispersion [9,10].

2 Experiment and results analysis

To make a distinct comparison of IFWM suppression, two types of fiber are used: one is dispersion-shifted fiber (DSF) with length of 7.077 km and extremely small dispersion of 0.504 ps nm^{-1} km^{-1} at 1560 nm, and the other is single-mode fiber (SMF) with length of 8.2 km and dispersion of 17.2 ps nm^{-1} km^{-1} at 1560 nm. The repetition frequency of the pulse source is 10 GHz with full-width at half-maximum (FWHM) pulse width of 1.5 ps. The average power of the pulses at the output of an amplifier is 12.05 and 11.95 dBm, respectively. As shown in Figure 1, IFWM degrades the waveform and spectrum obviously. Comparing Figure 2 with Figure 1, the pulse is extremely broadened in the 8.2 km-long SMF fibers. However, its spectrum does not change and IFWM is effectively suppressed.

Figure 3 shows the schematic setup of a 160 Gb/s OTDM RZ 100 km transmission system. The system consists of three parts: transmitter, transmission link and receiver. The 160 Gb/s transmitter has a picosecond pulsed fiber laser (PSL-10-1T, CALMAR OPTCOM Model), which produces an optical pulse train at repetition rates of 10 GHz (FWHM =1.5 ps, λ=1554.3 nm) with timing jitter less than 75 fs. The 10 GHz pulse train is then launched in an external $\mathrm{LiNbO_3}$ Mach–Zehnder modulator (MZM) driven by a pattern generator (Agilent N4901B, 2^7-1). A homemade fiber delay line multiplexer is used to provide a multiplexed 160 Gb/s data signal at the input of the fiber link. The 160 Gb/s RZ data signal is then amplified by EDFA1 to 11 dBm and fed into the 100.11 km transmission link. The total insertion loss of the transmission line is 28 dB including all splices and connectors. As shown in the second dashed box in Figure 3, the 100.11 km transmission link consists of three parts: two spans of SMF with lengths of 46.35 and 43.44 km (total length of 89.79 km), and a span of dispersion-compensation fiber (DCF) with length of 10.32 km. DCF is used to compensate the dispersion caused by the two spans of SMF. Figure 4 shows the optimized dispersion map. Dispersions of DCF and SMF are measured by CD400. At 1554.3 nm, the dispersion and slope values are −149.342 ps nm^{-1} km^{-1} and −4.897 ps nm^{-2} km^{-1} respectively for DCF

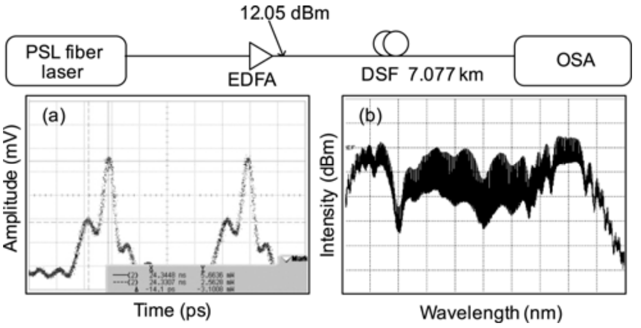

Figure 1 Setup of the DSF test system. (a) Waveform of the pulses after 7.077 km DSF transmission; (b) spectrum of the pulses after 7.077 km DSF transmission.

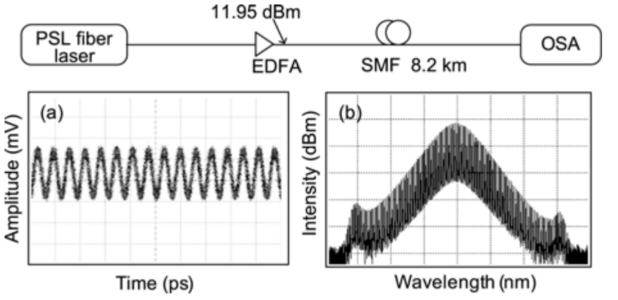

Figure 2 Setup of the SMF test system. (a) Waveform of the pulses after 8.2 km SMF transmission; (b) spectrum of the pulses after 8.2 km SMF transmission.

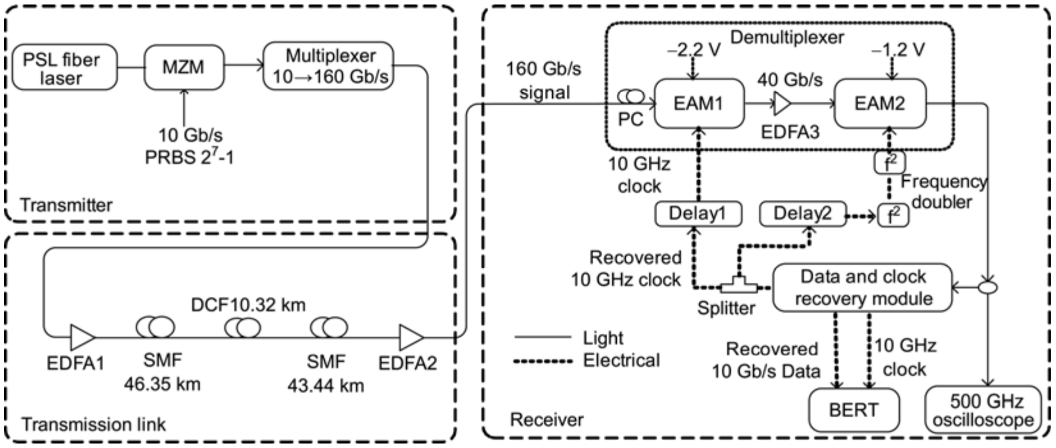

Figure 3 Experimental setup of 160 Gbit/s OTDM RZ transmission over 100 km.

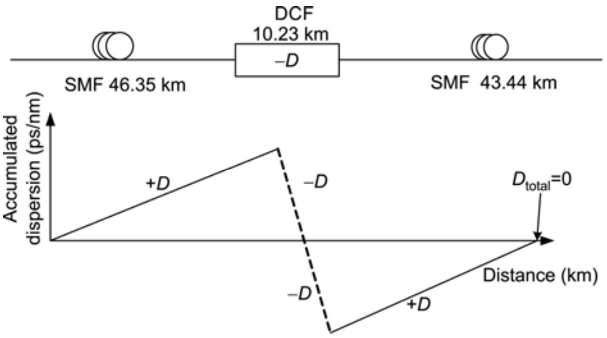

Figure 4 Dispersion map for SMF paired with DCF.

and 16.382 ps nm^{-1} km^{-1} and 0.056 ps nm^{-2} km^{-1} respectively for SMF. After 100 km transmission, the 160 Gb/s signal is amplified to 9 dBm by EDFA2.

The multiplexed signal is then launched into the receiver. The receiver is composed of a pair of concatenated electro-absorption modulators (EAMs) combined with a 10 GHz clock recovery module based on a phase-locked loop (PLL). It is possible to achieve 160 Gb/s signal demultiplexing and clock recovery simultaneously. By delicately adjusting the phase shift of the extracted clock, the 10 Gb/s signal is demultiplexed with high quality. A polarization controller (PC) is placed in front of EAM1 (driven at 10 GHz) to adjust the polarization state of the input signal. EDFA3 is applied to compensate for the larger insertion loss of EAM1. The demultiplexed 10 Gb/s signal is then divided into two parts: one is observed by 500 GHz optical sampling oscilloscopes (PSO-100, provided by EXFO) and the other is injected into the clock recovery module. EAM1 is driven at 10 GHz, whereas EAM2 is driven at 40 GHz.

Compared with the eye diagram of the multiplexed 160 Gb/s signal before 100 km transmission in Figure 5(a), the eye diagram of the multiplexed 160 Gb/s signal after 100 km transmission in Figure 5(b) is clean and open. Figure 6 shows bit-error-rate (BER) curves of the 160 Gb/s signal demultiplexed into 10 Gb/s in both B2B and 100 km transmission with strong dispersion management. After 100 km transmission, the receiver sensitivity (BER of 10^{-12}) is 13.13 dBm; the corresponding sensitivity for B2B at the same BER performance is 16.75 dBm, where the power penalty is ~3.6 dB. The power penalty is due to amplified stimulated emission noise of the erbium-doped fiber amplifier, transmission line and demultiplexer of the two EAMs. The error-free transmission states lasted for more than 2 h and no

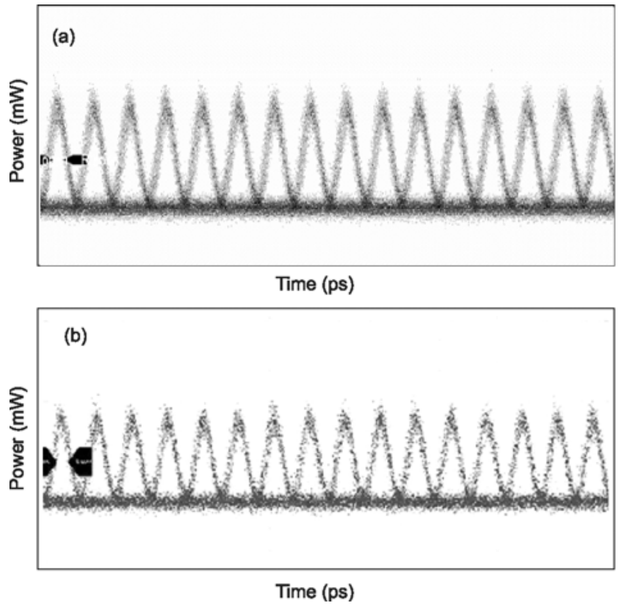

Figure 5 Eye diagram of multiplexed 160 Gbit/s signal. (a) Before lancing into the 100 km fiber; (b) after 100 km strongly dispersion-managed transmission.

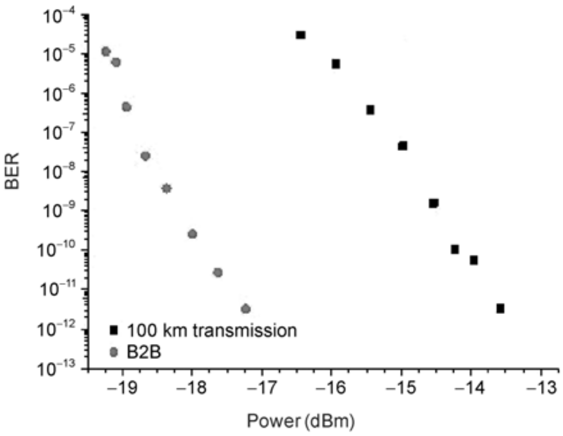

Figure 6 BER curves for 160 to 10 Gb/s.

readjustment was made throughout the measurement. For more than 2 h, the system ran without error corresponding to a BER of less than 10^{-12}. The stable error-free 160 Gb/s transmission over 100 km is attributed to the homemade multiplexer with excellent temperature stability and polarization insensitivity, accurate dispersion compensation and optimized dispersion management, power optimization, and the simple but stable EAMs-PLL loop for demultiplexing and the clock recovery module. All precise adjustments are made with the help of a 500 GHz oscilloscope. These precise adjustments make the system robust against degradation.

3 Conclusion

We analyzed the IFWM process in strong dispersion management and showed that a wide and chirped optical pulse can reduce this effect. The experimental results demonstrate that IFWM can be well suppressed using an ultra-short pulse with wide spectral width and large accumulated dispersion, which can be easily realized in a strong dispersion-management system consisting of SMF and DCF. Stable error-free (BER=10^{-12}) transmission over 100 km is achieved for more than 2 h without forward-error correction, and the power penalty is ~3.6 dB. Additionally, strong dispersion management can be applied in the phase modulation system.

This work was supported by the Fundamental Research Funds for the Central Universities (2009YJS005), National High Technology Research and Development Projects of China (2007AA01Z258, 2008AA01Z15), the National Natural Science Foundation of China (60807003), the Beijing Nova Program (2008A026), the Natural Science Foundation of Beijing (4062027) and the National Natural Science Foundation of China (60877042, 60837003).

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