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Amplitude Regeneration of NRZ-DPSK and RZ-DPSK Signals Based on Saturation of Four-wave Mixing In Highly Nonlinear Fiber*

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Abstract: The all-optical amplitude regeneration of both nonreturn-to-zero differential phase-shift keying (NRZ-DPSK) and return-to-zero DPSK (RZ-DPSK) signals at a bit rate of 42.8 Gbit/s is demonstrated experimentally, utilizing saturation of four-wave mixing in a highly nonlinear optical fiber (HNLF). The power transfer curves of the HNLF for both NRZ-DPSK and RZ-DPSK signals are measured. The regenerative performance for both modulation formats are compared at the same average input power of 16 dBm. Experiment results show that the RZ-DPSK signal exhibits better performance of amplitude regeneration.

Key words: Differential phase-shift keying; Four-wave mixing; Optical regeneration

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0 Introduction

Differential phase-shift keying (DPSK) is a promising modulation format in long-haul optical transmission systems. Compared to on-off keying (OOK) modulation format, DPSK signals have advantages like enhancement in receiver sensitivity and improved tolerance to fiber Kerr nonlinearity[1-2]. In DPSK systems intrachannel four-wave mixing (FWM) and amplified spontaneous emission (ASE) noise from erbium-doped fiber amplifier (EDFA) induce amplitude jitter[3], which may further be translated to nonlinear phase noise through the Gordon-Mollenauer effect[4]. Both amplitude jitter and nonlinear phase noise transfer to amplitude noise in the process of demodulation and degrade the demodulated DPSK signal. Therefore, the performance of DPSK systems can be enhanced through amplitude regeneration.

Previously, all-optical DPSK regenerators using phase-sensitive amplifiers (PSAs)[5-6] and cross-phase modulation (XPM)[7] have been investigated. In a PSA the phase-sensitive nature of the optical gain forces the signal (degraded data) phase to a value of 0 or π relative to the strong pump at the same frequency, therefore regeneration is realized. However, this method is difficult to realize because optical pump sources, whose phase is locked to the averaged signal phase, should be provide in the PSA. For regenerator based on XPM, spectral broadening and subsequent filtering can reduce amplitude jitter, which is also difficult to realize because perfectly stable synchronous clock pulse trains are assumed[7]. Signal saturation induced by pump depletion in FWM can also be utilized for amplitude regeneration. The saturation of FWM is easy to realize and has ultra-fast response, so it can be used for high-speed signals. Moreover, optical regenerator based on FWM can regenerate differently modulated signals, which is highly desired in networks using hybrid modulation formats[8]. Amplitude regeneration based on saturation of FWM has been investigated numerically for nonreturn-to-zero DPSK (NRZ-DPSK)[9], and experimentally for return-to-zero DPSK (RZ-DPSK) signals[10-12]. The theoretical analysis of FWM-based all-optical regenerator can be found in the reported papers[9-10]. To our knowledge, the amplitude regeneration experiment for NRZ-DPSK signals based on FWM has not been reported yet, which is probably because the amplitude regeneration for NRZ-DPSK signals needs higher average input power than that for RZ-DPSK signals to establish gain saturation.

In this work, we demonstrate experimentally amplitude regeneration of NRZ/RZ-DPSK signals

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based on saturation of FWM in an HNLF. With pulse pattern waveforms we compare the regenerative performance for NRZ-DPSK and RZ-DPSK formats.

1 Experiment setup

Fig. 1 (PC: polarization controller; Att.: attenuator; PM: phase modulator; HP-EDFA: high power erbium-doped fiber amplifier) illustrates the experimental setup. In an optical transmitter (SHF 5003) light from continuous-wave (CW) laser 1 is modulated by a $LiNbO_3$ Mach-Zehnder modulator with a data stream of $2^{31}-1$ pseudorandom binary sequence (PRBS) at 42.8 Gbit/s to produce NRZ/RZ-DPSK pulses. For the generation of 67% RZ-DPSK format, a 21.4 GHz sinusoidal signal is used for pulse carving. The wavelength of signals is 1 550.0 nm. The operating point of the DC bias applied to the DPSK modulator is adjusted carefully to generate distortion with the same frequency of 42.8G, emulating amplitude fluctuations. The CW pump is derived from laser 2 at a wavelength of 1 548.0 nm and phase modulated with a NRZ PRBS of 1 Gbit/s to broaden its frequency spectrum to suppress stimulated Brillion scattering (SBS)[13]. The SBS threshold of the pump is increased from 14.1 dBm (without phase modulation) to 20.9 dBm (with phase modulation). The DPSK signal and CW pump are amplified in $EDFA_1$ and $EDFA_2$, respectively, and then coupled into a high power EDFA (HP-EDFA) by a 50/50 fiber coupler. The DPSK signal power can be adjusted by a variable attenuator after EDFA1. With 10% power tapped for monitoring the pump and DPSK signals by an optical spectrum analyzer, the output of the HP-EDFA is launched into a 1 200-m-long HNLF, which has zero dispersion at 1 545.0 nm, a dispersion slope of 0.016 ps/(nm^2 • km), and a nonlinear coefficient of 12 W^{-1} • km^{-1}. The signal experience FWM interaction in the HNLF and the FWM saturation suppresses bit-to-bit amplitude fluctuations of signal pulses[14]. At the HNLF output, the regenerated signal is selected by an optical bandpass filter with a full-width half-maximum bandwidth of 1.5 nm. The regenerated signal is then attenuated to 2 dBm with another variable attenuator, before it is finally launched into a digital communications analyzer to show its pattern waveform. The communications analyzer has a photodetector, so the optical signal don′t need optical-electrical conversion before it is launched to the analyzer.

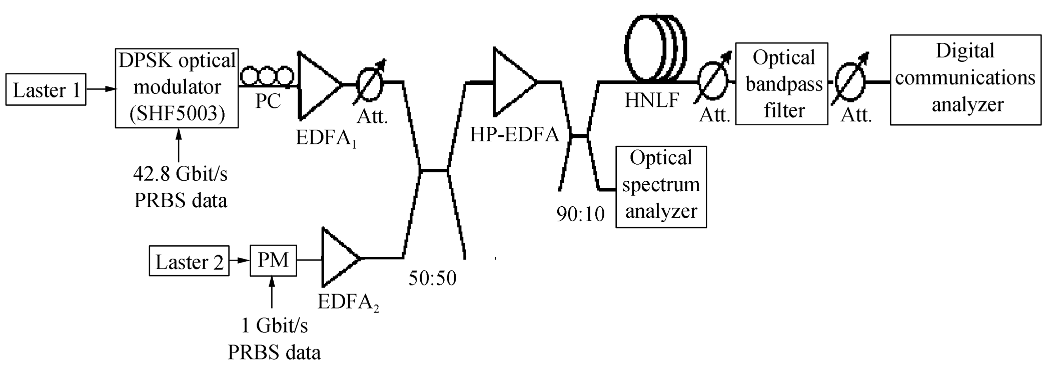

Fig. 1 The experimental setup of DPSK regeneration

2 Results and discussion

We measure the average power of DPSK signals at the HNLF output as a function of that at the input. As shown in Fig. 2, the power transfer characteristic for NRZ-DPSK exhibits close similarity with different pump power settings, and so does RZ-DPSK. The output powers start to saturate at input powers of 18.5 and 15 dBm for NRZ-DPSK and RZ-DPSK signals, respectively. Therefore, a prerequisite for amplitude regeneration is established.

The saturation of FWM in the HNLF is exploited to demonstrate amplitude regeneration of DPSK signals. As illustrated in Fig. 2(a), clear saturation behavior for NRZ-DPSK is obtained at a signal power of 18.5 dBm. However, to balance the trade-off between reducing nonlinear degradation and achieving gain saturation, we set the average power of input NRZ-DPSK signals at a level of 16 dBm. Since the power transfer curves are very similar for different pump settings shown in Fig. 2 (a), the pump power is set to 19 dBm. Because of the limitation of experimental conditions, the DPSK regenerative performance is evaluated with signal pattern waveforms . The

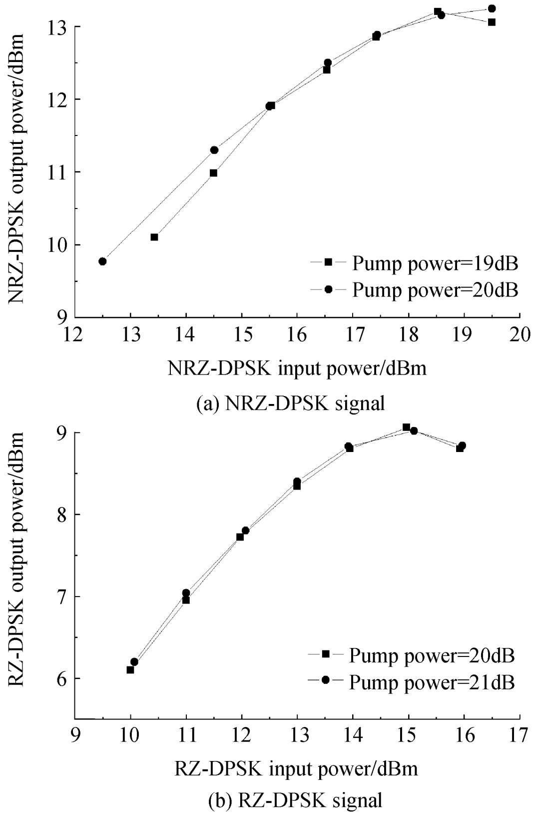

Fig. 2　Measured power transfer functions of the amplitude regenerator

waveform of distorted NRZ-DPSK pulses is shown in Fig. 3 (a). Owing to incomplete gain saturation, the intensity of the signal is partly equalized, which is evident in Fig. 3 (b). When the average input signal power increases beyond 16 dBm, the degradation due to SPM will exceed the regeneration from gain saturation[15], and the regenerated signal will degrade.

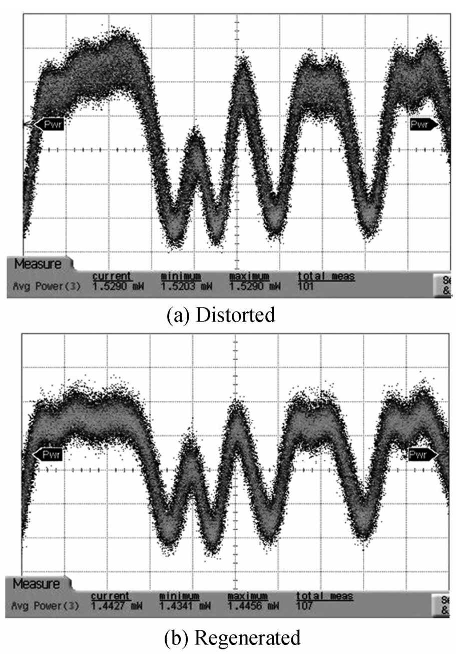

Fig. 3　The pattern waveforms of NRZ-DPSK signal

Fig. 4 shows waveforms of the RZ-DPSK signal before and after amplitude regeneration. The powers of the pump and signal are 20 and 16 dBm, respectively. It is observed that the difference between the amplitudes of the high and low level pulses diminishes, and the amplitude fluctuation of the low level pulses is suppressed. The results are in general agreement with the regenerated results reported by C. Peucheret et al[11]. The FWM saturation suppresses the amplitude jitter and the regeneration is realized. Since the peak power of RZ-DPSK pulses is higher than that of NRZ-DPSK pulses at the same average power, the RZ-DPSK signal obtains stronger gain saturation effect and hence better regenerative performance.

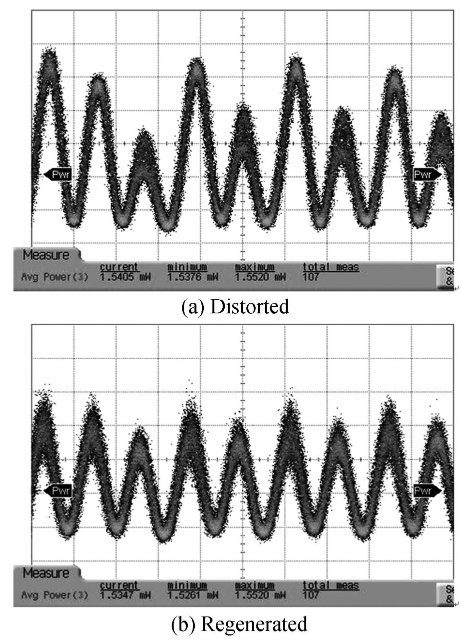

Fig. 4　The pattern waveforms of RZ-DPSK signal

In an optical amplitude regenerator based on FWM, the phase noise of DPSK channel may arise mainly from the pump intensity fluctuation via XPM effect. However, the signal-to-noise ratio (SNR) of demodulated DPSK pulses is more sensitive to amplitude than to phase noise. Thereby, the intensity regeneration improvement overcomes the degradation due to the induced phase noise after demodulation[16]. It can be speculated that the quality of DPSK signals can be improved with our amplitude regenerator because of intensity equalization.

3　Conclusions

We have demonstrated amplitude regeneration of NRZ/RZ-DSPK signals based on saturation of FWM in an HNLF. The optical pattern waveforms before and after regeneration show that the regenerative performance for RZ-DPSK signals is better than that for NRZ-DPSK signals under the condition that their average powers at the HNLF input are the same.

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基于高非线性光纤中四波混频饱和效应的 NRZ-DPSK 和 RZ-DPSK 信号幅度再生实验

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摘 要:利用高非线性光纤中的四波混频饱和效应,实验展示了 42.8 Gbit/s 非归零差分相移键控(NRZ-DPSK)信号和归零差分相移键控(RZ-DPSK)信号的全光幅度再生.测量了 NRZ-DPSK 信号和 RZ-DPSK 信号经过高非线性光纤的功率传递曲线.在平均输入功率均为 16 dBm 的条件下,对两种调制格式的再生性能进行了比较.实验结果显示 RZ-DPSK 信号具有更好的幅度再生性能.

关键词:差分相移键控;四波混频;光再生

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