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Influence of degenerate four-wave mixing on the performance of supercontinuum-based multiwavelength optical source*

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The influence of degenerate four-wave mixing (FWM) on the performance of supercontinuum-based multiwavelength optical source has been investigated in detail experimentally and theoretically. Numerical simulation results show that the degenerate FWM effect has a deteriorative influence on the spectral uniformity and the optical signal-to-noise ratio (OSNR) of supercontinuum-based optical source, and by suppressing degenerate FWM effect the performance enhancement of the supercontinuum can be achieved successfully. These results are also confirmed by our experiments. Experimentally, by suppressing degenerate FWM the crosstalk of adjacent channels to the filtered channel can be reduced by as much as 15 dB, and consequently the measured receiver sensitivity at 10 Gbit/s for the filtered optical source is improved from −1.7 to −17.8 dBm.

Keywords: supercontinuum, self-phase modulation, degenerate four-wave mixing
PACC: 4230Q, 4265

1. Introduction

Dense wavelength division multiplexing (DWDM) technique has made it possible to increase the capacity of the backbone networks. Supercontinuum (SC) generation has been developed as a promising technique to obtain multiwavelength continuous-wave (CW) light sources for present DWDM optical communication systems. It also has attracted considerable interest for its potential in many other applications including the generation of multiwavelength ultrashort optical pulse,[1] generation of terahertz radiation,[2] and optical coherence tomography.[3] Supercontinuum has many modes whose frequency spacing is equal to the repetition frequency of the pulse. The generated supercontinuum is fed into a demultiplexer and one mode is extracted. The extracted light is not a pulse train but CW light, because the light is practically monochromatic if the transmission of the demultiplexer is narrow enough and thus a multiwavelength optical source is obtained. However, for the communication use the supercontinuum-based optical source has not been practically adopted since it suffers from the problems such as noise amplification and optical signal-to-noise ratio (OSNR) degradation during the supercontinuum generation.[4] So a good OSNR is of great importance for practically employed supercontinuum multiwavelength optical source so that the low-noise characteristic can be inherited by all the spectral-slicing channels. Distinguished results have been obtained on the contributions of self-phase modulation (SPM) and group velocity dispersion (GVD) to supercontinuum generation.[5−7] However, the role of degenerate four-wave-mixing (FWM) in this process has not been clearly presented. In this paper, we investigate theoretically the influence of degenerate FWM on the performance of supercontinuum and obtain the suitable conditions for generating supercontinuum optical source with excellent spectral uniformity, low noise and high OSNR. Experimentally, by applying the obtained condition of simulation a 135 channel CW multiwavelength optical source with 25 GHz spacing for 10 Gbit/s DWDM systems is demonstrated successfully. The high OSNR characteristic of the extracted CW optical source is confirmed by the

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crosstalk of other channel less than -28 dB and the presentation of 10 Gbit/s eye diagram and bit error rate (BER) performance.

2. Theoretical analysis and numerical simulation

Supercontinuum generation in nonlinear fibres has been explained to be the result of dispersive and various nonlinear effects.[8] In the initial process, SPM dominates the spectral broadening and combines the effect of GVD to maintain the pulse shape and further broaden the supercontinuum spectrum envelope as the propagation distance increases. In this phase, the seed optical pulse can remain stable even if the propagation distance along the fibre is long enough. But if the supercontinuum spectrum is generated in the abnormal dispersion region or extends across the zero-dispersion wavelength, degenerate FWM occurs due to its phase-matching and plays a crucial role in the enhanced spectral broadening. FWM can broaden the spectrum greatly, and therefore has been utilized as an effective method for ultra-wide supercontinuum generation.[9] However, degenerate FWM interaction between optical signal and the noise caused by the amplified spontaneous emission (ASE) in erbium-doped fibre amplifier (EDFA) initially will occur simultaneously. Energy is subtracted from the signal and then enhances the noise. With the increase of propagation distance, the noise level grows rapidly along the fibre due to the energy increase caused by degenerate FWM, which acts accumulatively to make a strong impact on the OSNR and power uniformity of the supercontinuum. In this way, the degenerate FWM gives rise to the power nonuniformity in the supercontinuum longitudinal modes and the OSNR degradation due to the signal reduction and noise amplification. The BER at the receiver will significantly rise and consequently lead to the power penalty increase of the system.

For the generation of degenerate FWM, it has been found that the pump wavelength operating in the abnormal dispersion regime, especially in the vicinity of the zero-dispersion wavelength, is capable of maximizing the degenerate FWM efficiency because it is relatively easy to satisfy the phase-matching requirement $\Delta\beta = \beta_{\rm s}+\beta_{\rm as}-2\beta_p+2\gamma I_{\rm p} = 0$, where $\beta_{\rm s}$, $\beta_{\rm as}$ and $\beta_{\rm p}$ denote the propagation constant of Stokes, anti-Stokes and pump wavelength respectively, γ denotes the nonlinearity constant and $I_{\rm p}$ the peak power.[10] However, the degenerate FWM does not occur in the normal dispersion regime.[8] In this region, supercontinuum generation is mainly the result of SPM combined with GVD. The noise amplification during the supercontinuum generation is alleviated because the degenerate FWM is suppressed sharply due to the phase-mismatching. The GVD (β_2) is always positive and thus the total wave vector mismatch is further increased. As a result, the transfer of the energy between optical signal and ASE noise is reduced dramatically. The low noise characteristic can be inherited from the optical seed pulse by the generated supercontinuum so that a high OSNR is maintained at an acceptable level for the spectral-slicing optical source. Besides, the spectral uniformity of the supercontinuum is also improved because the spectral broadening is dominated by SPM which always induces symmetrical spectral broadening, while no degenerate FWM is concerned with the spectral broadening. Combined with GVD, SPM can lead to the generation of smoothly broadened supercontinuum. It means that the supercontinuum generation in the normal dispersion region has obvious advantages over the abnormal dispersion of excellent stableness, high OSNR and great power uniformity.

Here we consider a typical model of supercontinuum generation in the presence of ASE noise for numerical simulation. The optical seed pulse train is amplified, filtered and launched into the SC fibre. The input seed pulse train is an ideal Gaussian pulse with a full width at half-maximum of 3 ps, repetition rate of 12.5 GHz. The peak power is set at 12 W. The SC fibre is high-nonlinearity dispersion-shifted fibre with a length of 1 km, nonlinear coefficient $\gamma = 5.3\ {\rm W}^{-1}\cdot{\rm km}^{-1}$, zero-dispersion wavelength $\lambda_0 =$ 1567 nm, and dispersion slope $S_0 = 0.05\ {\rm ps/nm}^2{\rm .km}$. Then supercontinuum spectrum can be obtained by numerically solving the nonlinear Schrödinger equation using split-step Fourier methods. Figure 1(a) shows the supercontinuum generation in the abnormal dispersion region with a pump wavelength of 1574 nm. The spectrum is extremely broadened to 93 nm at -20 dB level while the spectrum has a multi-peak structure. The spectral fluctuation of the generated supercontinuum is intense enough to influence the power uniformity of the spectrum-slicing channels. We also calculate the OSNR of supercontinuum modes around the pump wavelength to determine the influence of degenerate FWM. The OSNR of supercontinuum is defined as the ratio of the peak level to the

bottom level of the comb and corresponds to the visibility of the longitudinal mode. Figure 1(b) shows the dependence of OSNR on the propagation distance of the seed pulse train along the SC fibre and the input peak power. It shows that as the propagation distance increases, the OSNR declines sharply and is aggravated as the input peak power increases from 2 to 12 W. This means that the performance of supercontinuum optical source is severely degraded when the pump wavelength operates in the abnormal dispersion region due to the degenerate FWM effect between the optical signal and ASE noise. In contrast, the generated supercontinuum with a pump wavelength of 1560 nm in the normal dispersion region is shown in Fig.2(a). The spectrum is symmetrically broadened to 55 nm by SPM at −20 dB level with a good spectral flatness. Figure 2(b) presents the dependence of OSNR of the supercontinuum on the propagation distance and input peak power. The decline of the OSNR is very slow as compared with the case of abnormal dispersion. The OSNR can be maintained at 20 dB level even if the peak power is as high as 12 W after 1 km propagation along the SC fibre. These results indicate that the pump wavelength operating in the normal dispersion region of SC fibre can be used to obtain a high OSNR of the supercontinuum optical source as compared with that in the abnormal dispersion regime.

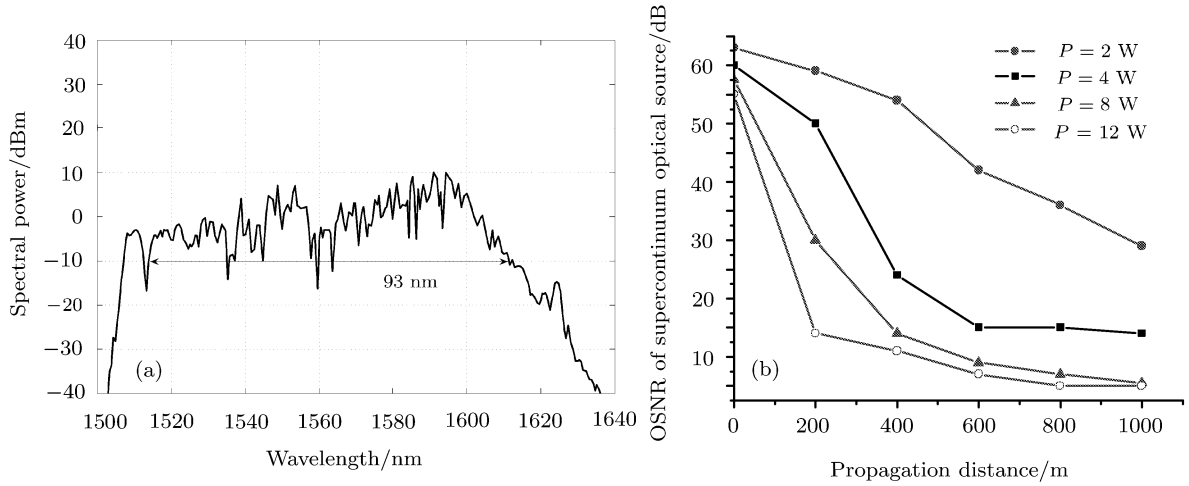


Fig.1. (a) SC generation with a pump wavelength of 1574 nm in the abnormal dispersion region, (b) dependence of OSNR on the propagation distance and input peak power.

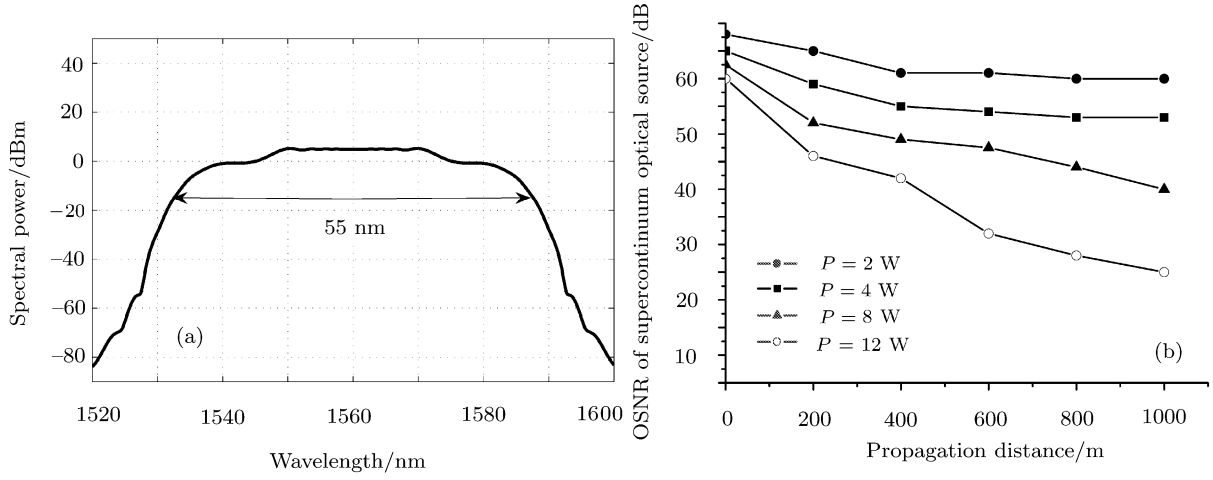


Fig.2. (a) SC generation with a pump wavelength of 1560 nm in the normal dispersion region, (b) dependence of OSNR on the propagation distance and input peak power.

3. Experiment

To confirm our theoretical results above, a series of experiments on supercontinuum generation has been carried out. The experimental setup is schematically shown in Fig.3. A pulse train is generated by a tunable laser combined with an electro-absorption modulator (EAM) to which a 12.5 GHz microwave signal is applied. The generated optical pulse is compressed to 4 ps by the following two-stage nonlinear compressor[11] and amplified to a peak power of several watts by EDFA1. The 1 km SC fibre are two sections of high-nonlinearity fibre with zero dispersion wavelength of 1555.5 nm, 1567 nm, respectively, a slope of dispersion of 0.018 ps/km/nm^2, and a nonlinear coefficient of $\gamma = 8.5$ /W/km. At the output of the SC fibre, supercontinuum is generated and then filtered by the following Fabry-Perot etalon (F-P etalon) with a free spectral range of 25 GHz to enlarge the frequency spacing between the supercontinuum longitudinal modes from 12.5 to 25 GHz and also filter the ASE noise inherited from the amplifiers. To estimate the quality of the generated supercontinuum, one supercontinuum longitudinal mode is extracted by the narrow bandwidth fibre Bragg grating (FBG) to obtain the CW light. Then the CW light is modulated by the $LiNbO_3$ modulator at 10 Gbit/s with a $2^{31}-1$ pseudo random binary sequence and the BER measurement is carried out.

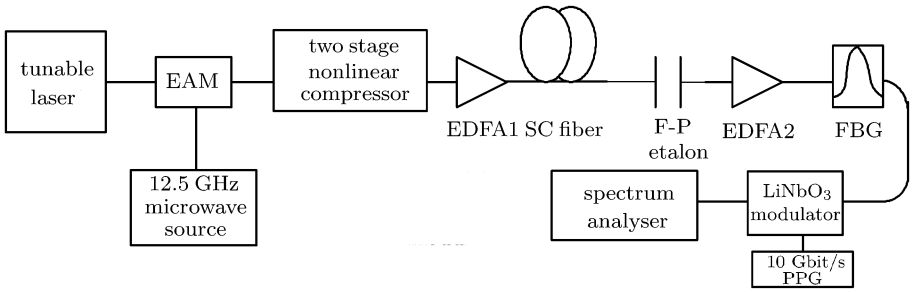


Fig.3. Experimental setup.

Figure 4 shows the supercontinuum generation with a pump wavelength of 1555.5 nm almost in the abnormal dispersion region of the SC fibre. The zero dispersion wavelength of the fibre is 1555.5 nm. The mean power of the pulse is 25 dBm, and the −20 dB bandwidth of the generated supercontinuum is 83 nm due to the nonlinear effects in this region. Although the supercontinuum spectrum is extremely broad, the supercontinuum envelope in Fig.4(a) is fluctuant and the part of spectrum in Fig.4(b) is not smooth. The asymmetric and multi-peak structure arises from degenerate FWM in addition to SPM because the pure SPM always broadens the spectrum asymmetrically.

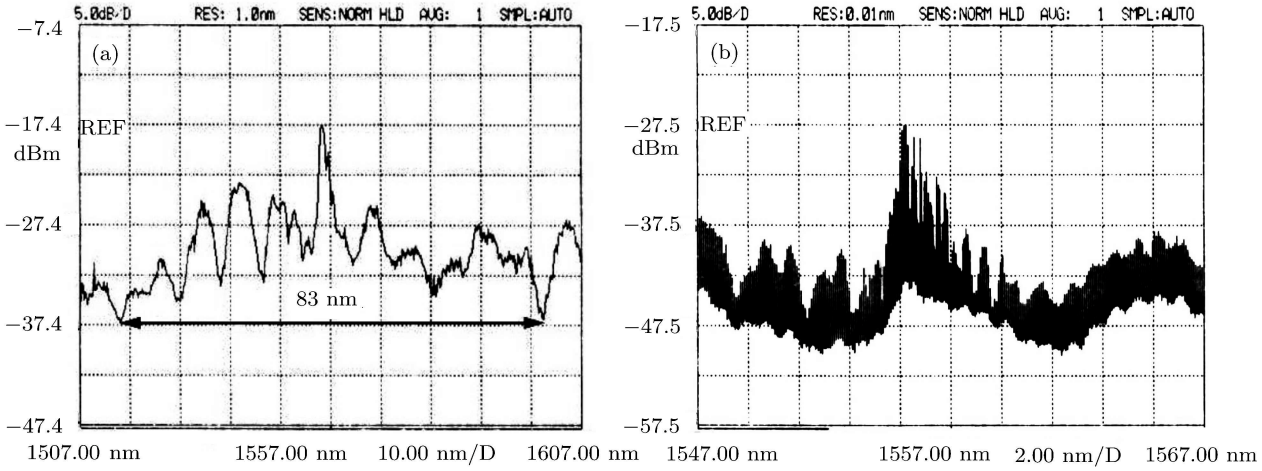


Fig.4. (a) SC envelope and (b) part of the SC spectrum with a pump wavelength of 1555.5 nm in the abnormal dispersion regime.

The spectrum of a single CW channel extracted from the generated supercontinuum by the FBG is shown in Fig.5(a). The crosstalk of adjacent channels is as much as −13 dB due to the degenerate FWM-induced noise amplification. Figure 5(b) presents the eye diagram and BER performance of the extracted CW channel modulated at 10 Gbits/s. From the inset of Fig. 5(b), the mark level of the eye diagram is very thick and the eye opening is small. The corresponding receiver sensitivity at a BER of 10^{-10} at 10 Gbit/s is −1.7 dBm.

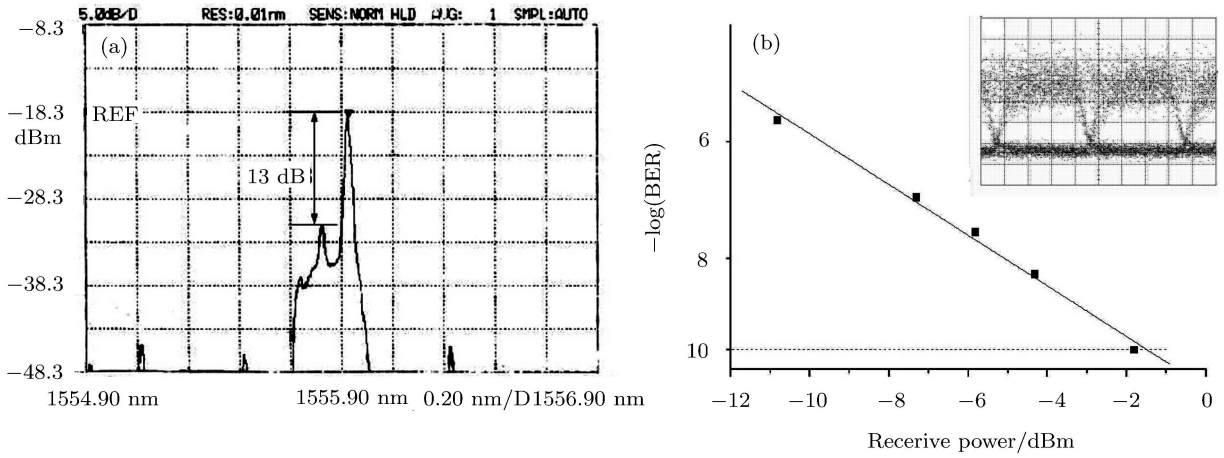


Fig.5. (a) Spectrum of the extracted CW channel, (b) 10 Gbit/s back-to-back eye-diagram and BER performance.

In the above experiment, the degenerate FWM-induced noise amplification is responsible for the performance degradation of the supercontinuum multi-wavelength optical source, which agrees well with our theoretical results. In contrast to the case of abnormal dispersion, supercontinuum generation in the normal dispersion regime with a pump wavelength of 1553 nm is shown in Fig.6. The zero dispersion wavelength of the fibre is 1567 nm. To obtain a high OSNR, the mean power injected into the SC fibre is reduced to 20 dBm and the −20 dB bandwidth of the supercontinuum spectrum is 27 nm, which corresponds to 135 CW channels with a frequency spacing of 25 GHz. In Fig.6(a), the spectrum is very smooth and much flatter than that in Fig.4(a). Such a supercontinuum obtained is smoothly broadened over the whole spectral range and shows itself an almost symmetric structure, indicating that only SPM leads to the spectral broadening.

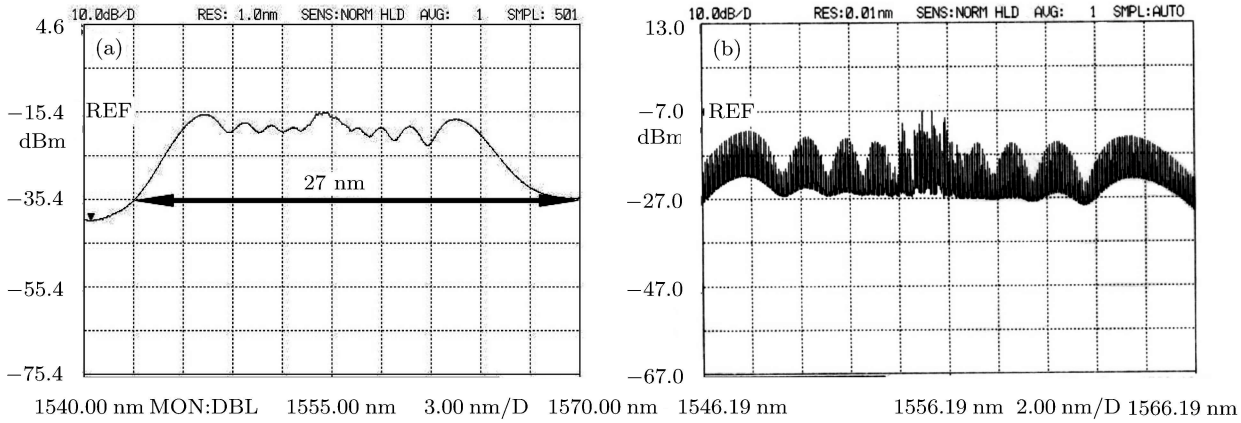


Fig.6. (a) SC envelope and (b) part of the SC spectrum with a pump wavelength of 1553 nm in the normal dispersion region.

The spectrum of the single CW channel filtered by the FBG is shown in Fig.7(a). It is remarkable that the crosstalk of other channels is only −28 dB, which shows an improvement of 15 dB compared with the case of abnormal dispersion. The inset of Fig.7(b) presents a clean eye diagram. The mark level is much thinner than that in the inset of Fig.5(b) and the eye diagram is more opened. The resulting receiver sensitivity at a BER of 10^{-10} at 10 Gbit/s is as low as −17.8 dBm.

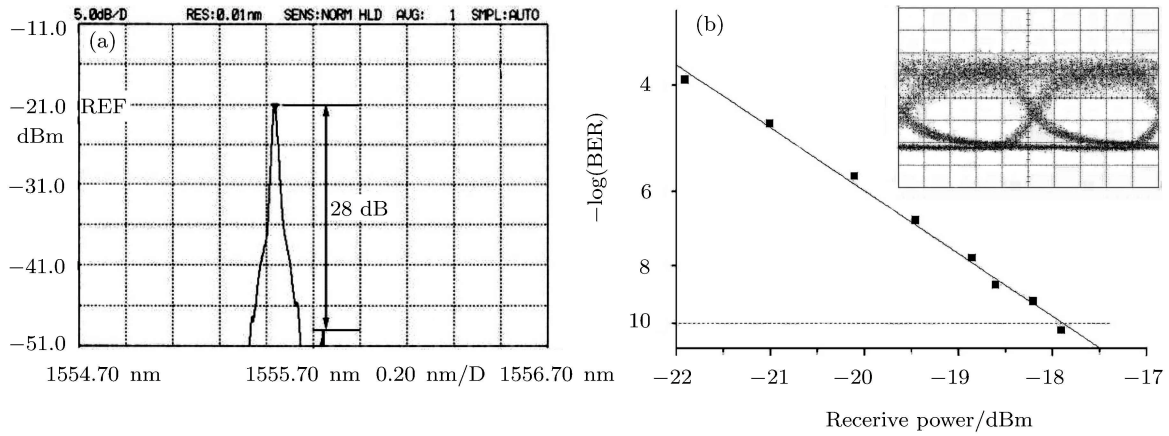


Fig.7. (a) Spectrum of the extracted CW channel, (b) 10 Gbit/s back-to-back eye-diagram and BER performance.

4. Conclusion

In summary, we have successfully demonstrated the influence of degenerate FWM on the performance of supercontinuum-based multiwavelength optical source theoretically and experimentally. The existence of the degenerate FWM effect during the supercontinuum generation process can severely degrade the spectral uniformity and the OSNR of the broadened spectrum. It is also found that the system operating in the normal dispersion region can efficiently suppress the degenerate FWM between optical signal and ASE noise, and thus a performance enhancement of supercontinuum optical source can be achieved greatly. Furthermore, experiments are carried out for confirming our theoretical analysis and simulation results. Experimentally, the system operating in the normal dispersion region reduces the crosstalk of adjacent channels to the filtered channel by as much as 15 dB in contrast to the case of abnormal dispersion, and the resulting receiver sensitivity for the filtered channel is improved from −1.7 to −17.8 dBm at 10 Gbit/s.

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