Performance improvement of a supercontinuum continuous-wave optical source

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We have studied the influence of degenerate four wave mixing (FWM) on the performance of the multiwavelength continuous-wave (CW) optical source based on supercontinuum (SC). By suppressing degenerate FWM, a 100-channel SC CW optical source with 25-GHz spacing for 10-Gb/s dense wavelength division multiplexing (DWDM) systems is experimentally demonstrated. Confirmation is provided with the generation of CW channel with crosstalk of other channels less than –28 dB and the presentation of 10-Gb/s eye diagram and bit error rate (BER) performance.

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Dense wavelength division multiplexing (DWDM) technology has made it possible to increase the capacity of the backbone networks. To exploit the vast range of wavelength resources using DWDM technology, multiwavelength optical sources are necessary that emit optical wavelengths aligned on the standardized optical frequency grid in a required spectral range. Using one distributed feedback (DFB) laser diode (LD) for each channel requires complicated procedures for monitoring and controlling the wavelength of each LD by controlling either temperature or injection current. It is also costly to prepare backup laser sources for all the required wavelengths. A multiwavelength continuous-wave (CW) source for DWDM applications based on longitudinal modes of the supercontinuum (SC) generated in optical fibers will be a strong candidate for future optical networks[1,2]. The SC generation is a phenomenon in which an intense pump optical pulse spectrum is broadened over a continuous range due to nonlinear effects in a SC fiber. The broadened spectrum has many modes whose frequency spacing is equal to the repetition rate of the pump pulses. The SC optical pulses are fed into a wavelength division dumultiplexer such as an arrayed waveguide grating (AWG) and one mode is extracted. The extracted light is not the pulse train but CW light, because the light is practically monochromatic if the demultiplexer has a sharp transmission characteristic. Each light is modulated individually by an external modulator and transmitted. One of the great advantages of using SC for optical frequency chain generation is its fixed channel spacing with accuracy equivalent to the repetition rate of the pump optical pulses[3]. This means that the entire wavelength channels can be fixed to ITU-T grid frequencies by locking just one wavelength[4].

The broad SC has been explained to be a result of self-phase modulation (SPM) and degenerate four wave mixing (FWM)[5,6]. In the initial process of SC generation, SPM plays primary role. With the combined interplay of SPM and group velocity dispersion (GVD), the spectrum is broadened slowly, and the shape of the spectrum envelope is smooth. As the spectrum is broadened over the zero dispersion wavelength of the SC fiber, and if the spectral component near zero dispersion wavelength is strong enough, not only SPM still broadens the spectrum of all spectral components, but also degenerate FWM is initiated among these newly generated spectral components because it is relatively easy to satisfy the phase-matching requirement $\Delta\beta = \beta_{\mathrm{s}} + \beta_{\mathrm{as}} - 2\beta_{\mathrm{p}} + 2\gamma I_{\mathrm{p}} = 0$ in the vicinity of zero-dispersion wavelength, where β_{s}, β_{as}, β_{p} are the propagation constants of Stokes, anti-Stokes, and pump wavelength respectively, γ is the nonlinearity constant, and I_{p} is the peak power[7]. So, the spectrum is further broadened and the SC bandwidth increases rapidly. At the same time, lots of substructures[8,9] emerge on the spectrum envelope. Furthermore, it has been found that only when the pump wavelength is in the anomalous dispersion region of the SC fiber, can the phase-matching requirement be satisfied and is the efficiency of degenerate FWM high[10].

Recently, some research groups have studied ultrawide SC generation by enhancing degenerate FWM[7,11]. Although degenerate FWM can broaden the spectrum greatly, it also results in degradation of the spectral flatness as well as fluctuations in spectrum intensity of the SC. Moreover, degenerate FWM will amplify the amplified spontaneous emission (ASE) during the SC generation, which is the main reason for degradation of the coherence and decrease of the modulation depths of longitudinal modes of SC. This means that the multiwavelength CW optical source based on SC will suffer from power non-uniformity of CW channels as well as degradation of the coherence and decrease of the signal-to-noise ratio (SNR), which limits the applications of the optical source in DWDM systems.

In this letter, a 100-channel SC CW optical source with 25-GHz spacing for 10-Gb/s DWDM systems is experimentally demonstrated by suppressing degenerate FWM. Confirmation is provided with the generation of CW channel with crosstalk of other channels less than −28 dB and the presentation of 10-Gb/s eye diagram and bit error rate (BER) performance.

Figure 1 shows the experimental setup. The pump pulse source was an optical pulse generator based on electroabsorption modulator and two-stage nonlinear compression[12] with 12.5-GHz repetition rate and 1555-nm central wavelength. The output pulses had a pulsewidth of 4 ps. Then the pulses were amplified to a peak power of several watts by an erbium-doped fiber amplifier (EDFA1) and launched into the SC fiber, which was highly nonlinear fiber (HNLF) of 1000 m, with the zero dispersion wavelength of 1555.5 nm and the slope of dispersion of 0.018 ps/(km·nm^2). To get optical pulse train with 25-GHz repetition rate, the SC fiber was followed by a Fabry-Perot (F-P) etalon, which had a free

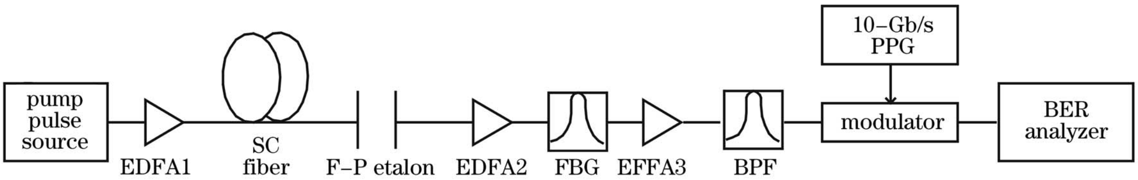

Fig. 1. Experimental setup of SC CW optical source. PPG: pulse pattern generator.

spectrum range (FSR) of 25 GHz. Since the total power of the light source was divided among several hundred modes and the power of each longitudinal mode was quite low, EDFA2 was inserted after the F-P etalon to boost the power of each mode. Then one single longitudinal mode of the SC spectrum could be filtered with a fiber bragg grating (FBG), and modulated in a LiNbO_3 modulator at 10 Gb/s (non-return-to-zero (NRZ), $2^{23}-1$ pseudorandom bit sequence (PRBS)). EDFA3 was used to amplify the power of the filtered single mode and an optical bandpass filter (BPF) was used to reduce the ASE.

The spectrum of pump pulses with average power of 27 dBm and 1557-nm central wavelength in the anomalous dispersion region was broadened due to nonlinear effects in the SC fiber and the 20 dB bandwidth of the SC was 83 nm, as shown in Fig. 2. The multipeak structure in the SC envelope originated from degenerate FWM in addition to SPM. Although degenerate FWM led to wide spectral broadening, due to FWM the intensity of spectral components which satisfied the phase-matching requirement was higher than that of spectral components which did not satisfy the requirement, which resulted in degradation of the spectral flatness (Fig. 3(a)) and then power non-uniformity of CW channels of the multiwavelength CW optical source based on SC.

Degenerate FWM also induced the substructures on the spectrum envelope, corresponding to fluctuations in spectrum intensity of SC which could turn into intensity noise of the CW source. Furthermore, degenerate FWM amplified the ASE during SC generation, resulting in degradation of the coherence and decrease of SNR of the multiwavelength CW optical source based on SC. One single longitudinal mode of the SC spectrum was filtered with a FBG, as shown in Fig. 3(b), and the crosstalk of the other channels was as much as −13 dB. Figure 4(a) shows the 10 Gb/s back-to-back eye diagram of the single longitudinal mode (Fig. 3(b)) after modulated by a PRBS in a LiNbO_3 modulator. The mark level was too thick and error-free result could not be achieved, as shown in Fig. 4(b), suggesting that the CW optical source was not suitable for DWDM applications.

When the average power of pump pulses was reduced to 20 dBm and the pump wavelength was chosen to be 1555 nm, degenerate FWM was suppressed because the pump power was low and the phase-matching requirement could not be satisfied in the normal dispersion region of the SC fiber. The width of SC spectrum was only 20 nm in the –20-dB bandwidth, as shown in Fig. 5(a). However, the SC spectrum was flatter and the modulation depths of longitudinal modes were larger in Fig. 5(b) compared with Fig. 2(b). Moreover, the shape of

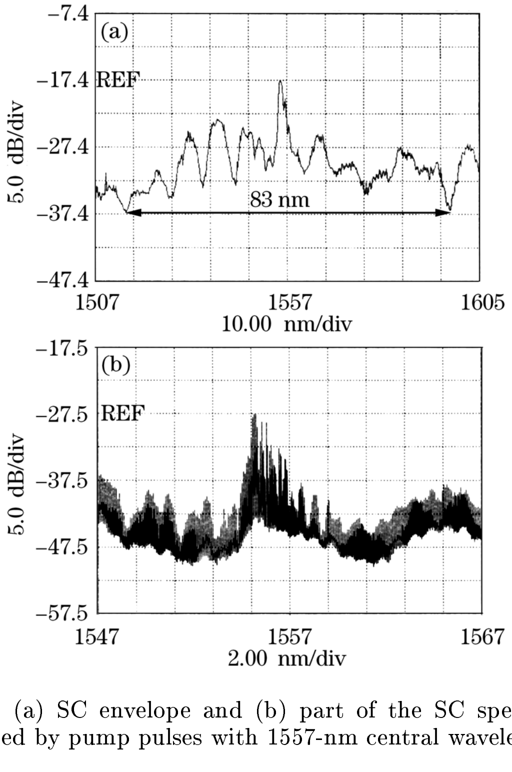

Fig. 2. (a) SC envelope and (b) part of the SC spectrum generated by pump pulses with 1557-nm central wavelength.

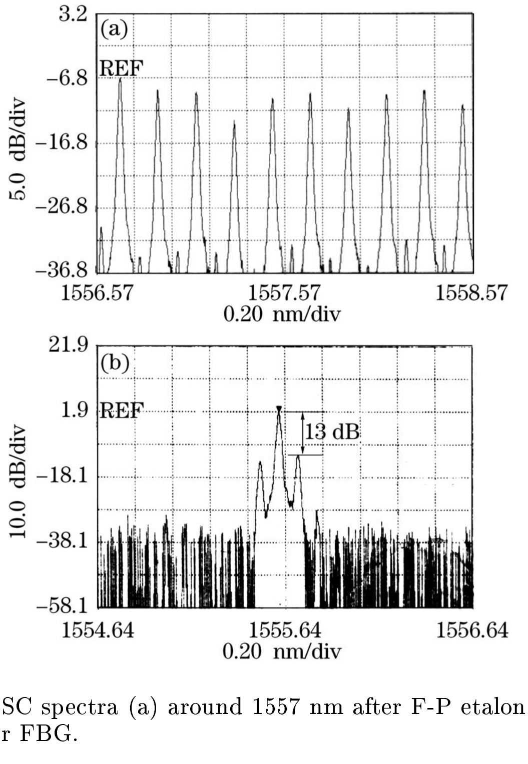

Fig. 3. SC spectra (a) around 1557 nm after F-P etalon and (b) after FBG.

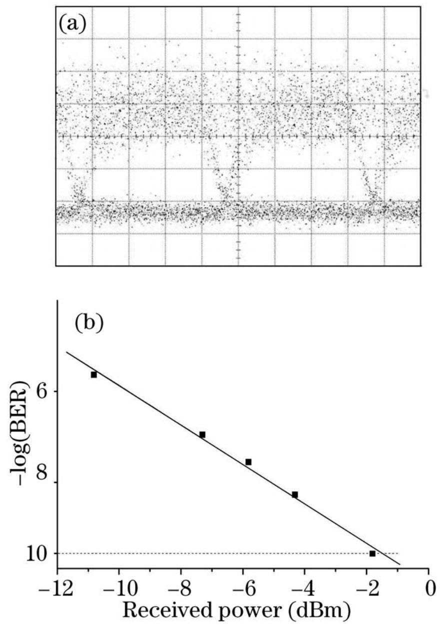

Fig. 4. (a) 10-Gb/s back-to-back eye diagram and (b) BER performance.

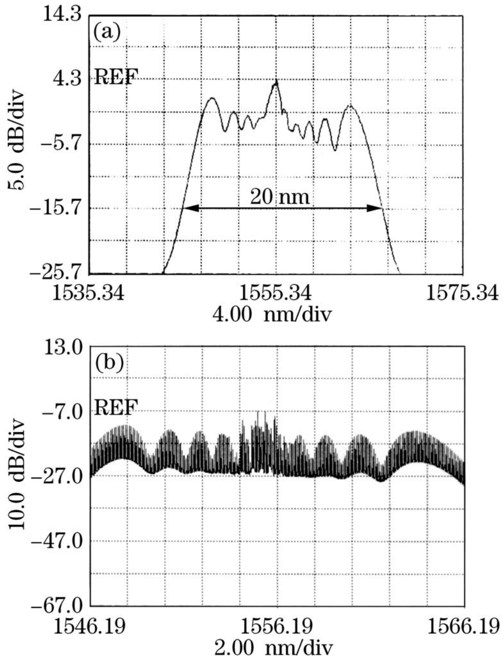

Fig. 5. (a) SC envelope and (b) part of the SC spectrum generated by pump pulses with average power of 20 dBm.

the spectrum envelope was smooth, accompanied by an oscillatory structure covering the entire frequency range, which indicated that the spectral broadening was mainly induced by SPM effect in the SC fiber[10]. SPM induced the same chirp and instantaneous frequency at two different time values of the optical pulse, which represented two waves of the same frequency but different phases. The oscillatory structure could be understood as a result of the interference between these two points of the optical pulse[10].

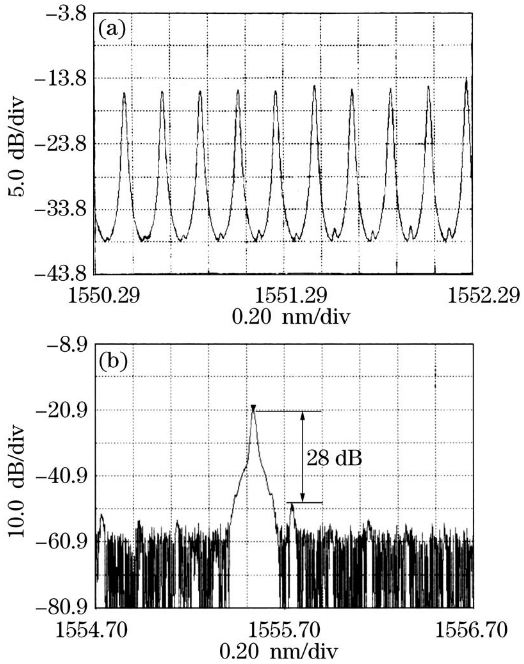

Fig. 6. SC spectrum around 1551 nm before (a) and after F-P etalon (b).

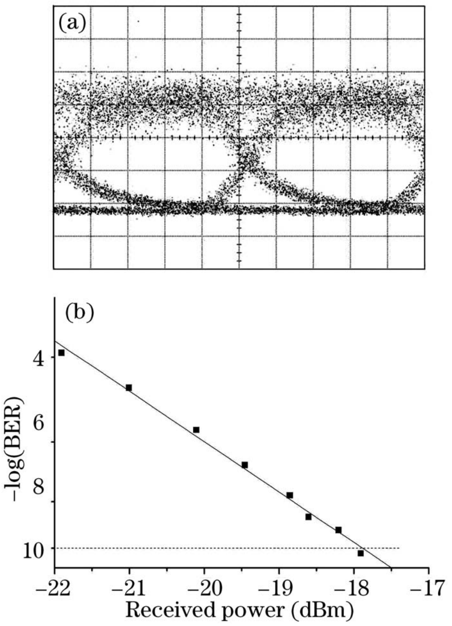

Fig. 7. (a) 10-Gb/s back-to-back eye diagram and (b) BER performance.

To get SC spectrum with 25 GHz spacing, the SC fiber was followed by a F-P etalon with the FSR of 25 GHz. Figure 6(a) shows the SC spectrum around 1551 nm after the F-P etalon. The results suggest that the frequency spacing is enlarged to 25 GHz, and the 20-nm SC spectrum corresponds to a 100-channel multiwavelength CW optical source with 25-GHz spacing. It is notable that the modulation depths of the longitudinal modes are also increased by the F-P etalon. Figure 6(b) shows one single longitudinal mode of the SC spectrum filtered with a FBG. The crosstalk of the other channels was less than −28 dB. Then the CW optical source was modulated by a PRBS in a $LiNbO_3$ modulator at 10 Gb/s. Figure 7 shows the 10 Gb/s back-to-back eye diagram and BER performance. The eye openings were good, and the BER was below 10^{-10} when the received power was −17.9 dBm and error-free result was achieved by increasing the received power, which indicated that the CW optical source featured high quality.

In summary, we have studied the influence of degenerate FWM on the performance of multiwavelength CW optical source based on SC. It is found that degenerate FWM results in power non-uniformity of CW channels as well as degradation of the coherence and decrease of SNR, which limits the applications of the multiwavelength CW optical source based on SC in DWDM systems. By suppressing degenerate FWM, a 100-channel supercontinuum CW optical source with 25-GHz spacing for 10-Gb/s DWDM systems was experimentally demonstrated. Confirmation was provided with the generation of CW channel with crosstalk of other channels less than −28 dB and the presentation of 10-Gb/s eye diagram and BER performance.

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