Appl. Phys. B 79, 61–64 (2004)
DOI: 10.1007/s00340-004-1491-9

Applied Physics B
Lasers and Optics

Y. NAN✉
C. LOU
J. WANG
T. WANG
L. HUO

Signal-to-noise ratio improvement of a supercontinuum continuous-wave optical source using a dispersion-imbalanced nonlinear optical loop mirror

Department of Electronic Engineering, Tsinghua University, Beijing 100084, P.R. China

Received: 10 December 2003/
Revised version: 13 February 2004
Published online: 7 April 2004 •

ABSTRACT A multiwavelength continuous-wave (cw) optical source is based on supercontinuum (sc) produced in a highly nonlinear fiber. Noise properties of this optical source are studied through numerical simulations based on the nonlinear Schrödinger equation. The numerical simulations show that the amplified spontaneous emission (ASE) generation in an erbium-doped fiber amplifier and the ASE amplification during the sc generation result in a serious degradation of the signal-to-noise ratio (SNR). A novel scheme for improvement of the SNR of the multiwavelength cw optical source based on sc by using a dispersion-imbalanced nonlinear optical loop mirror is presented and the numerical simulation results are given. As a result, the average level of the SNR improvement is 11 dB and the eye-opening penalty is reduced by 0.91 dB due to the SNR improvement. In addition, the scheme can also be applied for improvement of the SNR of a pulse-type multiwavelength light source.

PACS 42.50.Lc; 42.65.Re; 42.79.Sz; 02.60.Cb

1 Introduction

Dense wavelength division multiplexing (DWDM) technology is a competitive way of constituting an optical communication network with large capacity. Using one distributed feedback laser diode (DFB 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) optical source based on supercontinuum (sc) [1, 2] is a promising alternative. Supercontinuum generation is a phenomenon in which an intense optical pump pulse spectrum is broadened over a continuous range due to nonlinear effects in a sc fiber. The sc generation directly encompasses many basic nonlinear optical phenomena, such as self-phase modulation (SPM), cross-phase modulation (XPM), four-wave mixing and the formation of shock waves in the propagation of short pulses through nonlinear media. 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 demultiplexer 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 beam is modulated individually by an external modulator and transmitted. One of the great advantages of using sc for optical chain generation is its fixed channel spacing with an accuracy equivalent to the repetition rate of the pump optical pulses [3]. This feature enables us to lock the entire wavelength channels to ITU-T grid frequencies by locking just one wavelength [4].

Supercontinuum generation needs an optical pump pulse source with high optical power, which can be obtained using an erbium-doped fiber amplifier (EDFA). However, the amplified spontaneous emission (ASE) of the EDFA is also added to the pump pulses and then to the sc spectrum. Meanwhile, the power of each longitudinal mode is quite low, because the total power of the light source is divided among several hundred modes. Indeed, an optical amplifier can boost the power of each mode, but the ASE component is boosted simultaneously. So the signal-to-noise ratio (SNR) cannot be improved with the EDFA; even the added new ASE results in the further degradation of the SNR. So, the ASE component having the same optical frequency as the mode extracted from the sc results in the degradation of the coherence [5] and the generation of the signal–spontaneous beat noise, which is the main reason for the degradation of the SNR [6] of the multiwavelength cw optical source based on sc. Thus, the system scale in which the multiwavelength cw optical source can be applied is limited.

In this letter, a novel scheme for improvement of the SNR of a multiwavelength cw optical source based on sc by using a dispersion-imbalanced nonlinear optical loop mirror (DI-NOLM) is presented and numerical simulation results are given.

2 Principle of SNR improvement with DI-NOLM

Because the ASE is white noise, it will be reduced uniformly in the frequency domain when the ASE component between the pulses is suppressed in the time domain. The

✉ Fax: +86-10/6277-0317, E-mail: nanyinbo98@mails.tsinghua.edu.cn

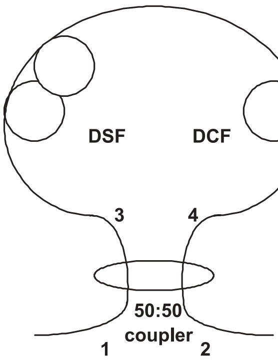

FIGURE 1 Setup of the NOLM

power of the pulses themselves is not affected, so the signal power of each mode remains unchanged and the SNR is consequently improved. Sanjoh et al. have reduced the ASE and then improved the SNR for a multiwavelength light source by means of synchronous modulation with an electroabsorption (EA) modulator [7]. However, the ASE-reduction setup is complex because a phase shifter is needed to synchronize the driving signal with the optical pulses. The insertion loss is also too large. Moreover, the shape of this optical gate cannot accord with that of the pulses absolutely.

An asymmetric NOLM has been used to reduce the amplifier noise imposed on the signal from a pulse-type optical source [8]. In this letter, a DI-NOLM, as shown in Fig. 1, is used to enhance the SNR of the supercontinuum cw optical source. Optical pulses spread clockwise and counter-clockwise respectively after they are sent into port 1 and divided into two pulse trains through a 50:50 coupler. The transmission of the pulses in the NOLM can be described with (1) under the presupposition of ignoring the cross-phase modulation between the clockwise and counter-clockwise pulses:

$$\frac{\partial U}{\partial z}+\frac{\mathrm{i}}{2}\beta_2\frac{\partial^2 U}{\partial t^2}-\frac{1}{6}\beta_3\frac{\partial^3 U}{\partial t^3}=\mathrm{i}\gamma\,|U|^2U, \tag{1}$$

where U defines the normalized envelope function of the electric field at the main axis. The left-hand side of the equation gives the linear pulse propagation under the influence of group-velocity dispersion (GVD) and third-order dispersion (TOD), where β_2 is the second-order dispersion constant and β_3 is the TOD constant. The perturbation caused by the nonlinear effects in the fiber is given by the term of self-phase modulation on the right-hand side of the equation. The nonlinearity constant is defined by γ [9].

The normalized envelope function of the electric field, U, at four ports of the coupler accord with (2) and (3). In the equations, α is the coupling ratio of the coupler and its value is 0.5 here.

$$U_3=\alpha^{1/2}U_1+\mathrm{i}(1-\alpha)^{1/2}U_2, \tag{2}$$

$$U_4=\mathrm{i}(1-\alpha)^{1/2}U_1+\alpha^{1/2}U_2. \tag{3}$$

In the first instance clockwise pulses spread through a dispersion-shifted fiber (DSF), which has low dispersion and small pulse broadening in it, and nonlinear effect overwhelms. So nonlinear phase shift φ_{cw} brought about by high pulse peak power is considerable. However counter clockwise pulses firstly spread through a dispersion-compensating fiber (DCF), which has high dispersion and large pulse broadening, and the pulse peak power reduces sharply. Thus nonlinear phase shift φ_{ccw} is much less. A quantitative study shows that the nonlinear phase shift is proportional to the intensity of the optical pulses and their transmission distance through the fiber. When the difference between φ_{cw} and φ_{ccw} is π, they will interfere to disappear at port 1 of the coupler and to be enhanced at port 2, and then optical pulses will be emitted from port 2 of the NOLM. If the fiber distance is designed properly so that the difference between φ_{cw} and φ_{ccw} at the pulse peak is π, the pulses will pass through the NOLM. But the nonlinear phase-shift difference brought about by the ASE component between pulses is much less than π due to its low intensity, and the ASE will be suppressed strongly at port 2.

Thus, the DI-NOLM possesses optical self-switching properties due to the nonlinear effects in the fiber. That is to say, the optical switch changes its state automatically with the input optical power. At the moment of high optical power (optical pulses plus some ASE component) the optical switch opens, while at the time of low optical power (the ASE component between pulses) the switch closes. Compared with the EA modulator, this switch setup is simpler and cheaper, without an additional rf driving signal, and no phase shifter is required to adjust the switch synchronized with the optical pulses.

3 Simulation results and discussion

Figure 2 shows the numerical simulation setup. The pulse source is an actively mode-locked Er^{3+}-doped fiber laser (AML-EDFL) with 10-GHz repetition rate and 1550.18-nm central wavelength followed by a nonlinear pulse compressor. The output pulses have a pulse width of 2 ps. The 2-ps pulses are amplified to a peak power of 3 W by EDFA1 and then launched into the sc fiber, which is a highly nonlinear fiber (HNLF) of 700 m, with a zero-dispersion wavelength of 1555.5 nm and a slope of dispersion of 0.018 ps/km/nm^2. To get an optical pulse train with a 50-GHz repetition rate, the sc fiber is followed by a Fabry–Perot (F-P) etalon, which has a free spectral range (FSR) of 50 GHz and a finesse of 60. Then each single longitudinal mode of the sc spectrum can be demultiplexed with an AWG filter that has a 25-GHz bandwidth, and modulated in a $LiNbO_3$ modulator at 10 Gbit/s (NRZ 2^{23}-1 PRBS). Before the AWG filter, a DI-NOLM is inserted to reduce the ASE between the sc pulses and thus improve the SNR of the supercontinuum cw optical source. The DI-NOLM is constructed by a 3 dB coupler and two segments of fibers: a 250-m dispersion-shifted fiber (DSF) with a dispersion of $D=0.5$ ps/km/nm and a 20-m dispersion-compensating fiber (DCF) with a dispersion of $D=-100$ ps/km/nm at 1550.18 nm. The generation of sc in the sc fiber is modeled by the nonlinear Schrödinger equation, which describes the pulse propagation under the influence of nonlinear and linear effects in the fiber [9].

According to the simulation, the width of the sc spectrum is 120 nm in the -20 dB bandwidth, as shown in the inset of Fig. 2. Figure 3 shows the sc spectrum from 1545 nm to 1565 nm with the inset of the wavelength range 1554–1556 nm, which shows that the sc spectrum is a fre-

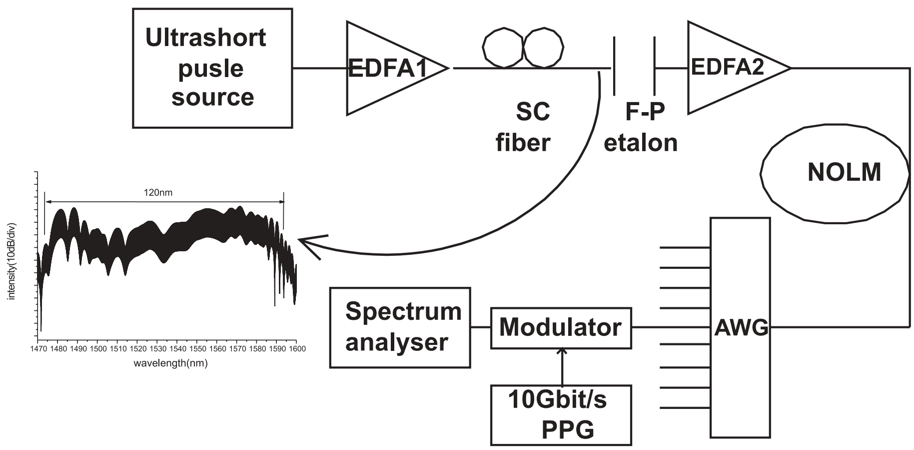

FIGURE 2 Setup of the numerical simulation. *Inset*: optical spectra of sc

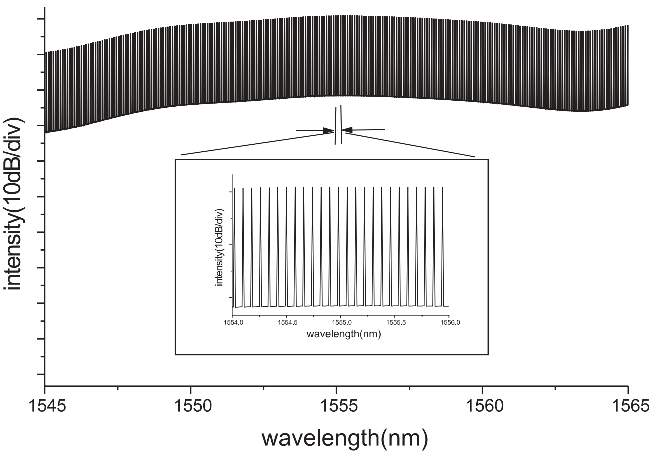

FIGURE 3 Supercontinuum spectrum from 1545 to 1565 nm. *Inset*: wavelength range 1554–1556 nm

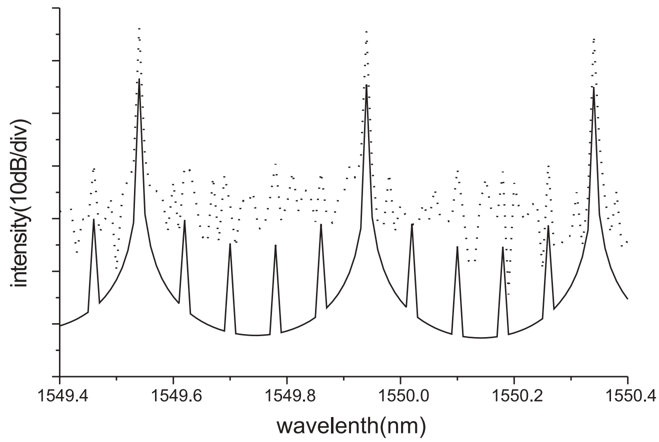

FIGURE 4 Influence of the ASE on the sc. *Solid line*: not considering the ASE, *dotted line*: considering the ASE

quency comb with the fixed spacing of 10 GHz, equal to the repetition rate of the pump pulses.

The output from the F-P etalon is a frequency comb with the fixed spacing of 50 GHz in the frequency domain, which is also an optical pulse train with 50-GHz repetition rate in the time domain. In order to simulate the ASE, we generate a background noise with random amplitude and phase using a Gaussian random-number generator in the simulation [10]. The ASE of the EDFA has considerable influence on the sc spectrum and submerges the optical frequency comb, as shown in Fig. 4. The results shown in Fig. 4 suggest that the ASE generation in the EDFA and the ASE amplification by

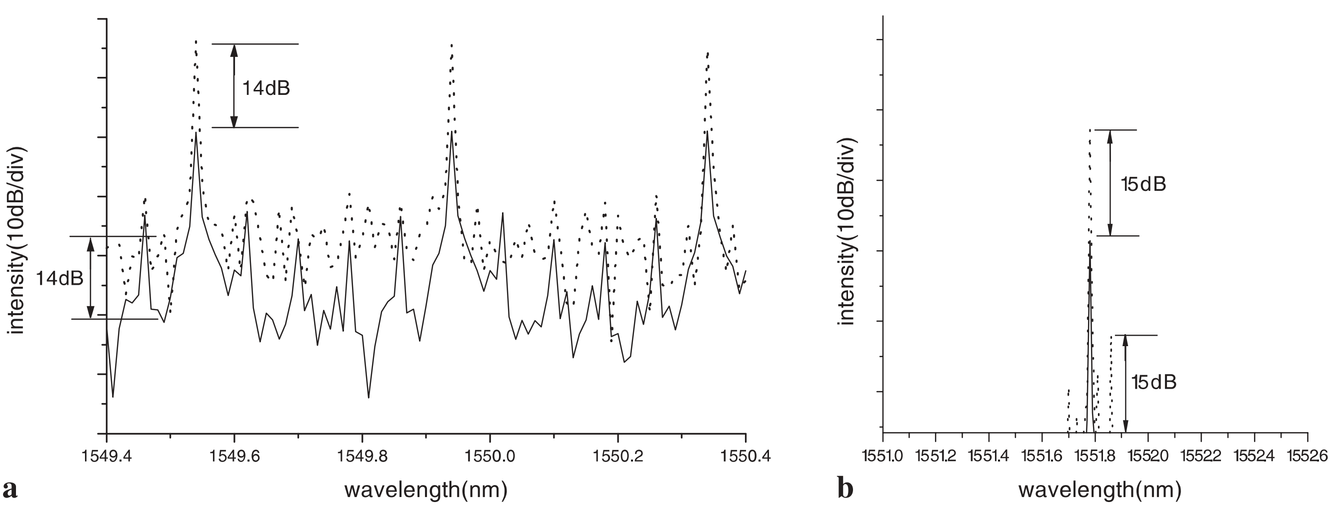

FIGURE 5 ASE reduction after the DI-NOLM: **a** around 1550 nm, **b** 1551.78 nm (after AWG). *Solid line*: with the DI-NOLM, *dotted line*: without the DI-NOLM

modulational instability and due to a four-wave-mixing process during the sc generation result in a serious degradation of the SNR of the multiwavelength cw optical source based on sc [6].

To improve the SNR, EDFA2 is followed by a DI-NOLM. The ASE is suppressed sharply with the DI-NOLM and then the frequency comb reappears, as shown in Fig. 5a. In particular, the power of each optical frequency is reduced by a uniform amplitude, which proves that it is the ASE component that is reduced, and the signal power remains unchanged. The ASE between pulses in the time domain is significantly reduced by the optical switching, and the ASE level is lowered uniformly over the whole spectrum in the frequency domain. Especially noteworthy is that even the ASE component with the optical frequency of the modes is lowered. These results demonstrate the principle described in Sect. 2. Figure 5b shows the optical spectrum at the 1551.78-nm output port of the AWG. Without the DI-NOLM, the ASE component is added to the longitudinal mode and the performance of the cw source is limited by the signal–spontaneous beat noise due to the incoherent nature of the ASE. The ASE component is reduced by 15 dB with the DI-NOLM and the signal–spontaneous beat noise is lowered. Thus, the SNR is enhanced. In addition, the coherence of the cw source is improved.

The noise characteristics of a cw optical source created by slicing the longitudinal mode of a sc spectrum were first studied with the relative intensity noise (RIN) calculation [2]. In this paper, in order to investigate the SNR improvement quantitatively, the SNR of each cw mode was calculated by integrating the RIN from 100 kHz to 10 GHz after one mode was extracted with a 50-GHz-spaced AWG for the cases of without and with the DI-NOLM. Figure 6 shows the wavelength dependences of the SNR improvement from 1545 to 1565 nm. Although the SNR improvement varies with the wavelength, it is positive at each channel, which shows that the SNR of each cw mode is enhanced. Indeed, the simulation shows that the size of the fluctuation in SNR improvement with wavelength is 4 dB and the average level of the SNR improvement is 11 dB.

Then the 1551.78-nm-wavelength channel at the AWG output was modulated in a $LiNbO_3$ modulator at 10 Gbit/s.

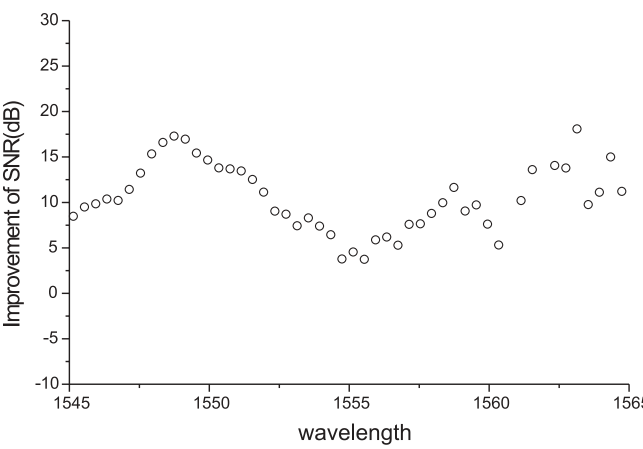

FIGURE 6 Calculated SNR improvement of cw mode over 20 nm

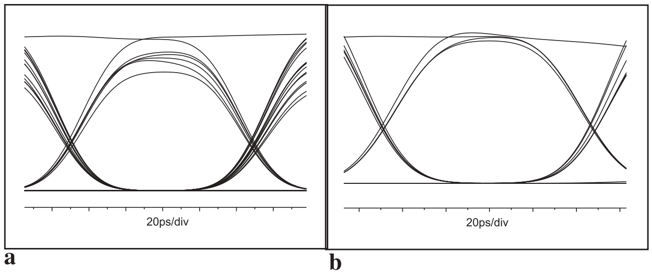

FIGURE 7 10 Gbit/s back-to-back eye diagram: **a** without the DI-NOLM, **b** with the DI-NOLM

Figure 7 shows the 10 Gbit/s back-to-back eye diagrams, which confirm better eye opening with the DI-NOLM. The eye-opening penalty (EOP) is 1.12 dB and 0.21 dB in the cases of without and with the DI-NOLM, respectively. The EOP is reduced by 0.91 dB due to the SNR improvement.

4 Conclusion

In summary, we have characterized the noise properties of a multiwavelength cw optical source based on sc. Numerical simulations using the nonlinear Schrödinger equation show that the ASE of the EDFA, especially the ASE component having the same optical frequency as the signal, results in the generation of the signal–spontaneous beat noise, which is the main reason for the degradation of the SNR. Employing the DI-NOLM to reduce the signal–spontaneous beat noise and consequently improve the SNR is a very effective way. We calculated the SNR improvement of a cw mode over 20 nm and found that the DI-NOLM uniformly suppresses the ASE component and improves the SNR by 11 dB on average. Meanwhile, the EOP is reduced by 0.91 dB due to the SNR improvement. Furthermore, the scheme can also be applied for improvement of the SNR of a pulse-type multiwavelength light source. For the advantages of low cost, simple structure and high SNR, the supercontinuum cw optical source should be a competitive one for DWDM systems.

ACKNOWLEDGEMENTS This work was supported by the National Hi-Tech Project (863 Project) of China (No. 2002AA122033).

REFERENCES

1 E. Yamada, H. Takara, T. Ohara, K. Sato, T. Morioka, K. Jinguji, M. Itoh, M. Ishii: Electron. Lett. **37**, 304 (2001)
2 J. Kim, Ö. Boyraz, M.N. Islam: in *Proc. Optical Fiber Communication Conf.* (OFC 2000) Paper ThA2, pp. 5–7
3 K. Imai, M. Kourogi, M. Ohtsu: IEEE J. Quantum Electron. **QE-34**, 54 (1998)
4 M. Teshima, K. Sato, M. Koga: IEEE J. Quantum Electron. **QE-34**, 1588 (1998)
5 M. Nakazawa, K. Tamura, H. Kubota, E. Yoshida: Opt. Fiber Technol. **4**, 215 (1998)
6 Ö. Boyraz, M.N. Islam: J. Lightwave Technol. **20**, 1493 (2002)
7 H. Sanjoh, K. Tsuzuki, Y. Yushikuni: IEEE Photon. Technol. Lett. **15**, 757 (2003)
8 M. Meissner, M. Rösch, B. Schmauss, G. Leuchs: IEEE Photon. Technol. Lett. **15**, 1297 (2003)
9 G.P. Agrawal: *Nonlinear Fiber Optics*, 2nd edn. (Academic, New York 1995)
10 Ö. Boyraz, J. Kim, M.N. Islam, F. Coppinger, B. Jalali: J. Lightwave Technol. **18**, 2167 (2000)