Suppression of stimulated Brillouin scattering with phase modulator in soliton pulse compression

Bo Lü (吕 博)*, Taorong Gong (龚桃荣), Ming Chen (陈 明), Muguang Wang (王目光), Tangjun Li (李唐军), Genxiang Chen (陈根祥), and Shuisheng Jian (简水生)

Key Lab of All Optical Network and Advanced Telecommunication Network of Ministry of Education of China, Institute of Lightwave Technology, Beijing Jiaotong University, Beijing 100044, China

**E-mail: fengdieer_13@126.com*

Received October 30, 2008

A phase modulator is employed in the scheme of soliton pulse compression with dispersion shifted fiber (DSF). Stimulated Brillouin scattering (SBS) effect, as a negative influence here, can be dramatically suppressed after optical phase modulation. The experimental result shows that the launched power required for high-order soliton pulse compression has been significantly increased by 11 dB under the condition of 100-MHz phase modulation. Accordingly, the experiment of picosecond pulse compression generated from electro-absorption sampling window (EASW) has also been implemented.

OCIS codes: 320.5520, 320.5390, 190.0190, 190.5890.

doi: 10.3788/COL20090707.656.

Optical pulse compression technique is important for the future optical communication systems. The soliton pulse compression with dispersion shifted fiber (DSF) or dispersion decreasing fiber (DDF) is an attractive way[1−4]. However, the usable optical power level is limited by nonlinear optical effects, particularly stimulated Brillouin scattering (SBS) because most of the input optical power can be converted into the Stokes wave traveling along the backward direction[5]. According to the fundamental condition[6] with the soliton order N of optical soliton transmission in

$$N^2 = \frac{\gamma P_0 T_0^2}{|\beta_2|},$$

where γ is the nonlinear coefficient, T_0 is optical pulse width, and β_2 is the second-order dispersion coefficient, the input optical power P_0 is indeed necessary for soliton compression. Several techniques have been proposed aiming to increase SBS threshold, e.g., changing the core dimension[7], dopant concentration[8], strain[9], and temperature distribution[10] along the fiber, etc. But these ways require expensive equipments as well as complex controlling devices. In this letter, we introduce a simple and effective way to suppress negative SBS effect utilizing optical phase modulator (PM)[11]. Furthermore, the experimental result with electro-absorption sampling window (EASW) and DSF verifies that this scheme can improve the performance of soliton pulse compression.

It has been indicated that SBS properties would be different when the input light is modulated at frequencies higher than spontaneous Brillouin bandwidth[12,13]. The SBS effect could be suppressed to some extent and the backward SBS gain could be small if the PM scheme is optimally proposed. Moreover, it is found that SBS threshold is almost independent of the bit rate in amplitude- and phase-shift keying systems, which ensures that SBS suppression based on phase modulation is realistic and stable. The SBS gain G is minimized when introducing a proper phase-modulated function $m(t)$ using a phase shift $k_{\mathrm{p}} = (2k+1)\pi$, where $k = 0,1,2,\cdots$, as[11]

$$G = [1 - 2\widetilde{m}(1-\widetilde{m})(1-\cos k_{\mathrm{p}})]G_0, \tag{1}$$

where $\widetilde{m}$ is the time average of modulation function $m(t)$ and G_0 denotes the non-modulation backward SBS gain factor which can be expressed as

$$G_0 = \frac{4K_1K_2}{n\varepsilon_0 c\Gamma}\left(\frac{P_{\mathrm{L}}}{A}\right), \tag{2}$$

where K_1 and K_2 represent for coupling coefficients, n is the effective refractive index, ε_0 is the free space permittivity (SI units), c is the velocity of light in vacuum, Γ^{-1} is the acoustic phonon lifetime, P_{L} refers to the launched optical power into the fiber, and A is its effective area. Thereby the modulated optical signal S can be obtained as

$$S = S_0\exp(\mathrm{i}\phi(t)), \tag{3}$$

where S_0 is the un-modulated signal, $\phi(t)$ is the fluctuation function expressed as

$$\phi(t) = k_{\mathrm{p}}[m(t) - \widetilde{m}]. \tag{4}$$

An important conclusion according to Eq. (1) here is that the SBS gain factor after phase modulation can be dramatically decreased by selecting proper parameters, in other words, ensuring $G < G_0$, thus theoretically allowing higher input power for soliton pulse compression.

Figure 1 shows the experimental setup of picosecond optical pulse compression with 2-km G.655 fiber. Here EASW provided by CIP company was used to generate the original optical pulse sequence. In fact, EASW could be regarded as the specific optical sampling switch when a continuous-wave (CW) laser was injected, under the condition that the inverse voltage was set to about −3 V and the radio-frequency (RF) clock was simultaneously combined with 40-GHz repetition rate (the principle was demonstrated in Fig. 1(a)). It is noted that here we introduce only 10-GHz RF clock signal and convert it into 40-GHz driving signal via two series-wound frequency multiplexers in electrical domain. The duration time of generated pulse was about 5 ps (assuming a sech^2 pulse shape), as would be expected for the sampling width of EASW working at 40-GHz repetition rate alone. In particular, a PM was equipped after EASW in our system, which was insensitive to polarization and had low insertion loss (<4 dB). We selected a proper modulation function $m(t)$ as approximate 100-MHz periodic square-wave signal and adjusted the modulated signal according to the observed backward SBS suppression in detail. Then a dual-pump erbium-doped fiber amplifier (EDFA) with high gain was applied to supply extremely high launched optical power for high-order soliton compression. In order to obtain effective input pulses, the central wavelength was optimally configured at 1549.77 nm in which EDFA could provide the best optical signal-to-noise ratio (OSNR) as seen in Fig. 1(b). Figure 2 shows the optical spectrum of pulse sequence after PM and EDFA which would be launched into DSF. An optical circulator (OC) was used to capture the optical signal including lower-frequency Stokes light due to SBS effect in the backward direction above SBS threshold. Meanwhile, the optical pulses from dual-pump EDFA were compressed along the forward direction of 2-km DSF fiber, which could be illustrated in oscilloscope. The backward optical signal was significantly weakened, of which the details are presented in Fig. 3. It is clearly observed by an optical spectrum analyzer (OSA) that the SBS suppression scheme using PM can effectively decrease the reflected optical power at the specific points of Stokes frequency shift (about 0.08-nm wavelength shift of DSF in this experiment). In particular, the peak power at 1549.736 nm has been reduced by almost 27.11 dB compared with the traditional way without PM. It is noted that there are still some residual optical spectra of input pulse due to the inevitable Rayleigh scattering. Amplified spontaneous emission (ASE) from high gain EDFA is kept as well without adopting broadband optical filter.

The practical forward or backward power with different ports of optical circulator (see Fig. 1) can be measured respectively when PM is adopted or not. The experimental results show that the optical power launched into 2-km DSF has been improved by 11 dB, from 14 to 25 dBm when the PM is introduced to suppress SBS effect. Moreover, the measured waveform of the compressed optical pulse sequence over DSF is shown in Fig. 4(b) with the initial pulse generated from EASW in Fig. 4(a). The full-width at half-maximum (FWHM) is about 3.75 ps compared with 5 ps of the original pulse. Sufficient input optical power is essential for high-order soliton compression. According to the actual measured results such as $T_0 = 5$ ps, dispersion $D = 0.05$ ps/(nm · km) $\beta_2 = -0.06376$ ps^2/km at $\lambda = 1549.77$ nm, and the nonlinear coefficient $\gamma = 3$ (W · km)$^{-1}$, we have theoretically calculated the fundamental optical power P_0 for three-order soliton compression (N=3) equal to 18 dBm at least (neglecting extra insertion loss brought by OC and optical connectors). Therefore, it is obvious that the forward optical power without PM ($P_0 = 14$ dBm) could not support high-order soliton compression at length due to the limitation of launched power by negative SBS effect. On the other hand, the power bottleneck has been broken simply using PM ($P_0 = 25$ dBm). However, there is still a trade-off with PM because it may be hard to eliminate uncorrelated ASE noise once we have suppressed SBS effect, in this sense extra ASE background noise is introduced, as can be seen in Fig. 4(b). This problem can be solved by adding a broadband optical filter.

In conclusion, a simple and effective scheme with PM has been investigated aiming to suppress SBS in

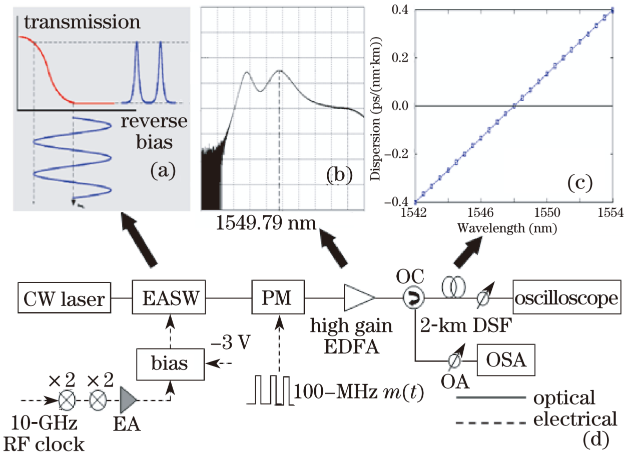

Fig. 1. Experimental scheme of soliton pulse compression. (a) Principle of short optical pulse generated from EASW at reverse bias voltage; (b) ASE spectrum of dual-pump high gain EDFA; (c) measured curve of dispersion versus wavelength (the wavelength of zero-dispersion is 1548.02 nm); (d) experimental stup. EA: electro-amplifier; OA: optical attenuator.

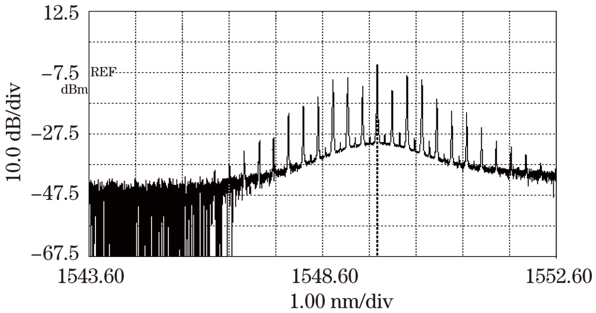

Fig. 2. Spectrum of optical pulse with 40-GHz repetition rate after PM and EDFA.

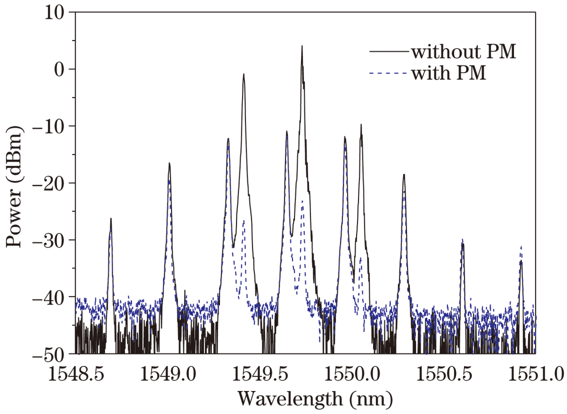

Fig. 3. Spectrum of backward optical signals.

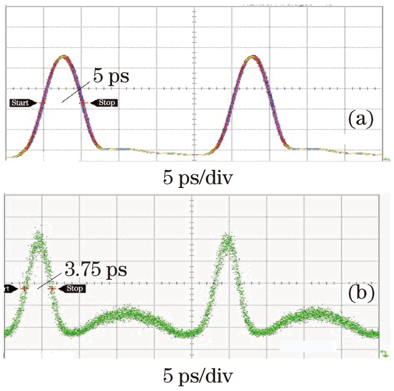

Fig. 4. Waveforms of optical pulse. (a) Initial optical pulse from EASW; (b) compressed optical pulse with PM over 2-km DSF.

the experiment of picosecond soliton pulse compression. The experimental result shows that the measured optical power launched into 2-km DSF has been dramatically raised by 11 dB when a 100-MHz PM is introduced. Accordingly, the FWHM of optical pulse has been compressed to 3.75 ps in comparison with 5 ps of the initial pulse generated from EASW. In the future, we will optimize the parameters of PM modulation function used in high-order soliton pulse compression.

This work was supported by the Natural Science Foundation of Beijing (No. 4062027) and the National “863” Project of China (No. 2007AA01Z258).

References

1. F. Xu, J. Liu, R. Li, and Z. Xu, Chin. Opt. Lett. **5,** 490 (2007).
2. S. W. Chan, K. K. Chow, and C. Shu, Acta Opt. Sin. (in Chinese) **23,** (suppl.) 395 (2003).
3. S. V. Chernikov, E. M. Dianov, D. J. Richardson, and D. N. Payne, Opt. Lett. **18,** 476 (1993).
4. H. Zhang, K. Xie, and H. Jiang, Chinese J. Lasers (in Chinese) **35,** 1951 (2008).
5. C. Wang, Chinese J. Lasers (in Chinese) **33,** 1630 (2006).
6. G. P. Agrawal, *Nonlinear Fiber Optics* (2nd edn.) (Academic, New York, 1995).
7. K. Shiraki, M. Ohashi, and M. Tateda, Electron. Lett. **31,** 668 (1995).
8. K. Shiraki, M. Ohashi, and M. Tateda, J. Lightwave Technol. **14,** 50 (1996).
9. N. Yoshizawa and T. Imai, J. Lightwave Technol. **11**, 1518 (1993).
10. Y. Imai and N. Shimada, IEEE Photon. Technol. Lett. **5,** 1335 (1993).
11. D. Cotter, Electron. Lett. **18**, 504 (1982).
12. N. A. Olsson and J. P. Van Der Ziel, J. Lightwave Technol. **5,** 147 (1987).
13. Y. Aoki, K. Tajima, and I. Mito, J. Lightwave Technol. **6,** 710 (1988).