Mutual optical format conversion between on-off keying and binary phase-shift keying based on stimulated brillouin scattering

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Received May 10, 2013; accepted June 28, 2013; posted online September 29, 2013

We propose and experimentally demonstrate mutual optical format conversion between signals characterized as 10-Gb/s nonreturn-to-zero on-off-keying (NRZ-OOK) and NRZ binary phase-shift keying (BPSK) types. The conversion is based on stimulated Brillouin scattering (SBS) in a single-mode optical fiber. An OOK signal is converted into a BPSK signal through optical carrier absorption, for which a SBS loss of 30 MHz is used in long-haul transmission. The converted BPSK signal is reverted to an OOK signal with a corresponding SBS gain of 30 MHz for direct detection. The proposed OOK-to-BPSK and BPSK-to-OOK format conversions can be implemented in transmitter and receiver nodes by using a laser source as the Brillouin pump.

OCIS codes: 060.2330, 060.4370.

doi: 10.3788/COL201311.100601.

On-off keying (OOK) and binary phase-shift keying (BPSK)[1] are highly attractive modulation formats in current optical communication systems. The former is widely used in metro and access networks because of its simplicity and low cost. The latter is highly popular in long-haul transmission because of its 3-dB improvement of receiver sensitivity, high tolerance to nonlinear fiber impairments, and amplified spontaneous emission noise. Conversion between OOK and BPSK is necessary at network edge nodes because these formats have different applications. All-optical modulation format conversion features higher speeds and lower costs than does optical-electrical-optical conversion. OOK to BPSK conversion can be realized using versatile techniques, such as using the gain saturation and self-phase modulation in a single semiconductor optical amplifier (SOA)[2], utilizing the cross-phase modulation effect in a SOA Mach–Zehnder interferometer[3], and using a micro-ring resonator to filter carriers[4]. Among these techniques, the carrier filtering method is the simplest, but the bandwidth of the notch filter must be very narrow to minimize the distortion of low-frequency components. Such components are difficult to design. Phase-to-intensity conversion or phase demodulation can be realized by a 1-bit delay Mach–Zehnder interferometer (MZDI)[5], Gaussian-shaped optical filter[6,7], and four-wave mixing-based phase conversion[8]. Researchers have recently proposed stimulated Brillouin scattering (SBS) to amplify residual carriers in BPSK signals and realize self-coherent detection[9], in which special data coding is required to minimize low-frequency components. Such minimization is necessary because SBS also amplifies the aforementioned components and therefore diminishes demodulation performance. Intensity-to-phase and phase-to-intensity conversions are based on different mechanisms. Scholars seldom demonstrate such conversions, in which the same mechanism is used to achieve flexible and simple transformations.

In this letter, we propose the use of the SBS effect in optical fibers as an active optical filter to realize format conversion between OOK and BPSK. Narrowband SBS absorption is used to suppress carriers and achieve OOK-to-BPSK conversion. A corresponding SBS gain is used to recover carrier power, thereby realizing BPSK-to-OOK conversion. No data coding is required because SBS amplification can completely recover both the absorbed carrier and low-frequency components. The proposed format conversion method features flexible tunability of both wavelength and bit rate, an attribute lacking in other methods. In an experiment, we demonstrate error-free modulation format conversion between 10-Gb/s OOK and BPSK signals. We also compare the demodulation performance of the proposed conversion with that of the traditional 1-bit delay MZDI.

The main difference between OOK and BPSK signals in the frequency domain is the existence of optical carriers. By varying the bias voltage of an intensity modulator, output signals can be converted from OOK to BPSK types. For in-line format conversion, a passive notch filter is used to suppress a carrier, thereby achieving OOK-to-BPSK conversion[4]. Aside from the carrier, however, some low-frequency components are also suppressed because an unlimitedly narrow filter bandwidth cannot be used. This suppression degrades the converted BPSK signals. Therefore, using a conventional 1-bit delay interferometer to demodulate converted BPSK signals also degrades the quality of intensity signals. If carriers and low-frequency components can be recovered from degraded BPSK signals, an ideal intensity signal can also be retrieved. On the basis of this analysis, we propose using SBS loss as an active filter that suppresses carriers, realizing OOK-to-BPSK conversion. For BPSK signal demodulation, we propose using SBS gain to recover both the carriers and low-frequency components suppressed by SBS loss, thereby achieving ideal BPSK-to-OOK conversion. We first run a simulation to evaluate the feasibility of this idea, and the simulation results are shown in Fig. 1. The word length of pseudo-random bit sequence (PRBS) data is $2^{12}-1$. The longer the PRBS word length, the narrower the frequency tone spacing and the worse the quality of the BPSK signals converted by a 1-bit delay interferometer. These negative effects occur given that more low-frequency components are suppressed by SBS loss. Nevertheless, the word length of PRBS data imposes no effect on SBS-based demodulation because under this approach, all frequency components are recovered.

We conduct an experiment to evaluate the performance of the SBS-based OOK-BPSK-OOK conversion. The experimental setup is shown in Fig. 2. A distributed feedback (DFB) laser diode (LD) operated at 1 550 nm serves as both the Brillouin pump and signal source for easy pump and signal frequency matching. The laser is divided into two parts by a 3-dB coupler. In the upper path, the light is modulated by a Mach–Zehnder modulator (MZM1) using 10.86-Gb/s PRBS data with a word length of $2^{31}-1$; the data are derived from a pulse pattern generator. The broadband signal is boosted to 15 dBm by an Er-doped fiber amplifier (EDFA1) and then launched into a 20-km single-mode fiber (SMF). The SMF, available in our laboratory, has a Brillouin frequency of 10.86 GHz and a length that can be shortened to a few kilometers by using high–nonlinearity fiber. In the lower path, the light is modulated by MZM2 at the Brillouin

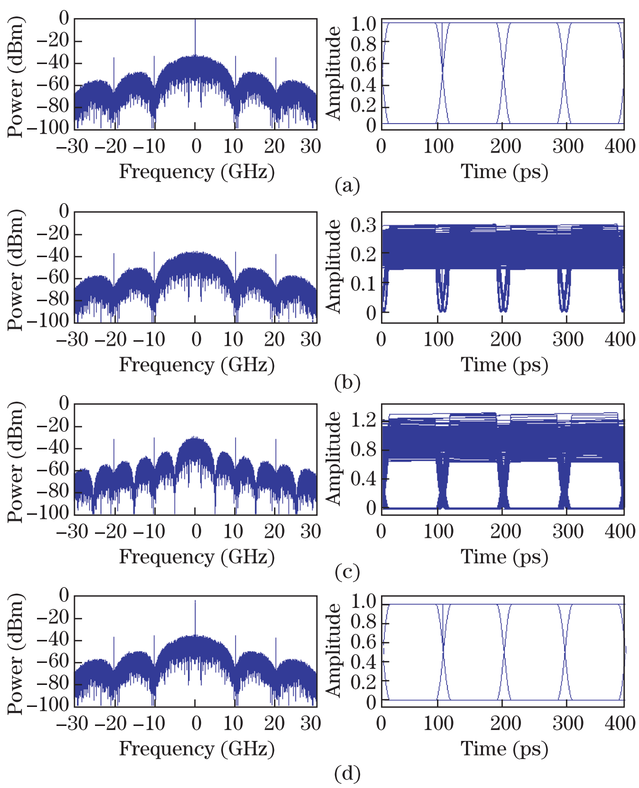

Fig. 1. Simulated frequency spectra and eye diagrams of the 10-Gb/s signal. (a) NRZ-OOK signal, (b) NRZ-BPSK signal obtained by filtering out the carrier of NRZ signal using SBS loss, (c) signal demodulated by a 1-bit delay interferometer, and (d) NRZ-OOK signal recovered by SBS gain.

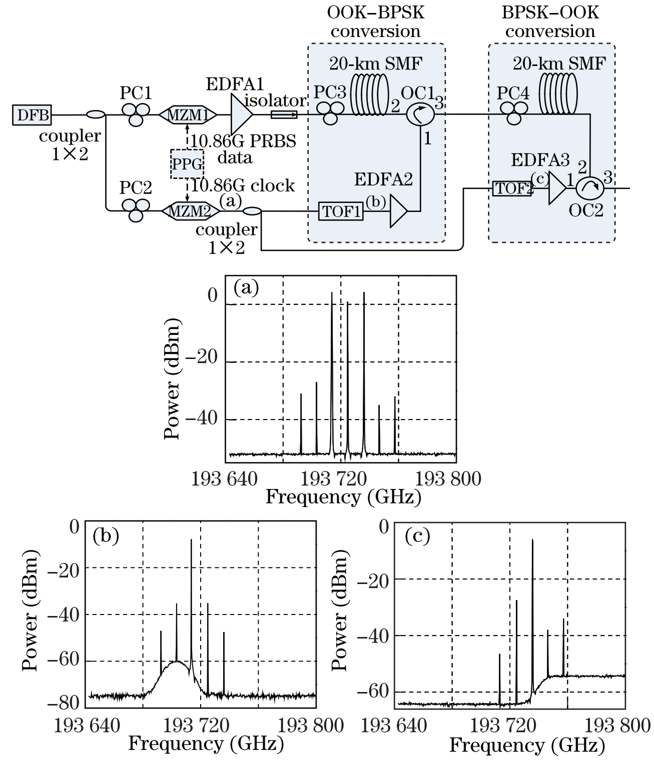

Fig. 2. Experimental setup and corresponding optical spectra.

frequency of the SMF; modulation is implemented by the optical carrier-suppressed double sideband technique. The modulated light is divided by a 3-dB coupler, and two tunable filters are employed to separate the left and right sidebands that serve as Brillouin pumps. Insets (a), (b), and (c) in Fig. 2 show the optical spectra of the carrier-suppressed double sideband, the filtered left sideband, and the right sideband. The plateau in the high-frequency region of Fig. 2(c) is due to the large bandwidth of TOF2. EDFA2 and EDFA3 are used to control the power of the Brillouin pump. The output power of EDFA2 and EDFA3 is approximately 17 dBm. The low-frequency Brillouin pump is launched into the SMF through an optical circulator (OC1), thereby generating a SBS loss peak and suppress the carrier. The high-frequency Brillouin pump is launched into another spool of SMF with the same Brillouin frequency shift as SMF1 through OC2; this execution enables the generation of a SBS gain peak and recovering of the carrier. PC3 and PC4 are used to control the polarization states of signals to maximize the Brillouin gain. The converted BPSK signal and the recovered OOK signal are exported from port 3 of OC1 and OC2, respectively.

Figures 3(a), (b), and (c) show the eye diagrams of NRZ-OOK, the BPSK generated by SBS loss, and the signal recovered by SBS gain, respectively. The eye diagram of the delay-interferometer (DI)-demodulated BPSK signal is shown in Fig. 3(d) for comparison. Given that the converted signal can be demodulated by DI, we confirm that the converted signal is a BPSK signal. Similar to the simulation results, the experimental findings show that SBS gain can completely demodulate the BPSK signal because both the carrier and low-frequency components are recovered. However, the demodulated

BPSK signal for which a DI is used is distorted because the low-frequency components suppressed by SBS loss cannot be recovered by the DI.

Figure 4 shows the optical spectra of the original OOK signal, the BPSK signal converted by SBS loss, and the OOK signal recovered by SBS gain. The spectrum change from Figs. 4(a) to (b) shows that the eye diagram can be converted from OOK to BPSK type (Fig. 3(b)) as long as the carrier is completely absorbed (~20 dB) by SBS loss. A SBS gain peak is generated at low frequency as a noise component. The Rayleigh backscattering of the Brillouin pump is also a noise component. The difference in eye diagram between Figs. 3(a) and (c) is attributed mostly to the aforementioned noise components and the noise from SBS amplification.

Figure 5 shows the measured BER results of the original NRZ-OOK signal and BPSK demodulation using SBS gain and DI. Despite the noises in the SBS gain-recovered signal, the power penalty is almost 0 compared with that in the original OOK signal. This finding confirms the feasibility of using SBS loss and gain to realize OOK-BPSK-OOK format conversion. We use a DI demodulator to verify that the converted signal is of BPSK type, but DI is unsnitable for demodulating BPSK signals converted by SBS loss. The power penalty of the DI demodulation is as high as ~25 dB because a SBS bandwidth loss of a ~30 MHz strongly absorbs the frequency components near the optical carrier. This loss can be compensated by the corresponding SBS gain demodulator rather than by the DI demodulator. Unlike the self-coherent detection proposed in Ref. [9], in which SBS gain is used, the method proposed in the this letter requires no special coding in minimizing low-frequency components. This feature is attributed to the fact that BPSK signals are also generated by SBS.

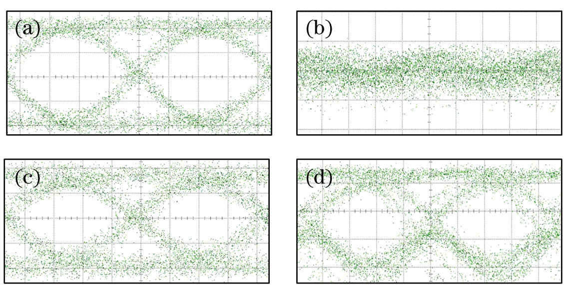

Fig. 3. Eye diagrams of the 10.86-Gb/s signal. (a) Original OOK signal, (b) converted BPSK signal, (c) BPSK signal demodulated by SBS amplification, and (d) BPSK signal demodulated by a 1-bit DI.

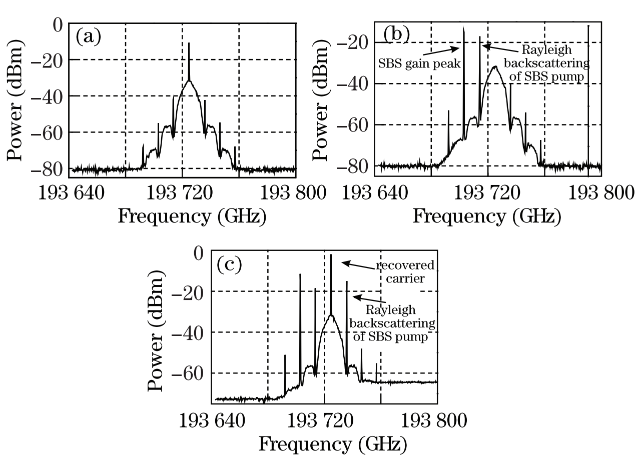

Fig. 4. Optical spectra of (a) original OOK signal, (b) BPSK signal converted by SBS loss, and (c) OOK signal recovered by SBS gain.

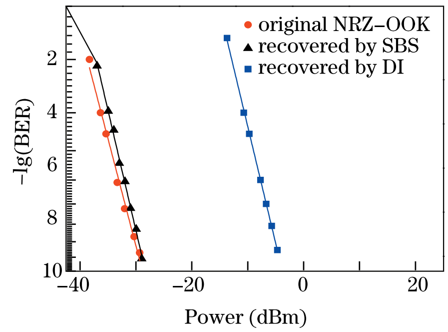

Fig. 5. Measured BER curves of the original OOK signal and BPSK signal demodulated by SBS gain and DI.

In conclusion, we experimentally demonstrate and realize optical format conversion between 10.86-Gb/s NRZ-OOK and NRZ-BPSK signals on the basis of narrowband absorption and optical carrier amplification using SBS. The proposed format conversion method enables flexible conversion between BPSK and OOK signals.

This work was supported by the National Natural Science Foundation of China (Nos. 61007041, 61090393, and 61132004), the Shanghai Chen Guang Scholars Program (No. 11CG11), and the Excellent PhD Holders in China Program (No. 201155).

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