Novel scheme of clock recovery for high-speed OTDM signals based on stimulated Brillouin scattering

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Received February 26, 2009

A new but simply implemented optical clock recovery scheme for optical time-division multiplexing (OTDM) systems based on stimulated Brillouin scattering (SBS) effect is presented and demonstrated experimentally. According to the unequal-amplitude even-multiplexed OTDM signals, the frame clock is extracted. In addition, the clock with multiple tributary rates is recovered from 160-Gb/s OTDM signal in simulation by utilizing the clock recovery module.

OCIS codes: 060.0060, 060.2330, 290.0290, 290.5830.

doi: 10.3788/COL20090708.0683.

Optical time-division multiplexing (OTDM) technology has steadily developed as a mean of increasing the capacity of future optical communication networks. As a key technology in high-speed OTDM networks, clock recovery at tributary rates from the multiplexed data stream is an essential process as it synchronizes operations such as demultiplexing and reshape, reamplify, retime (3R) data generation at each network node. Though fast photo detectors and electronic devices beyond rates of 40 Gb/s exist, clock recovery systems become expensive and complex to be implemented. A solution to alleviate this problem is to conceive all-optical or optoelectronic systems. Numerous all-optical or optoelectronic clock recovery methods are being studied using optoelectronic microwave oscillators[1], optoelectronic phase-locked loops (PLLs)[2,3], optical tank circuits[4], and injection locking lasers[5,6]. Besides, clock recovery for return-to-zero (RZ) data based on stimulated Brillouin scattering (SBS) has already been demonstrated[7,8].

In this letter, we introduce the optimized scheme suitable for OTDM systems, with the advantage of insensitivity to the polarization of the injection signal compared with the two-section distributed-feedback (DFB) laser. The scheme could be extended to ultrahigh speed OTDM networks and easy to extract clock with any or multiple tributary rates. The 40-GHz and 10-GHz clock are recovered experimentally in the 40-Gb/s OTDM system. Furthermore, clock recovery for 160 Gb/s and upper rates OTDM networks based on the scheme are discussed in simulation.

The process of SBS can be described classically as a nonlinear interaction between the pump and backward-propagating Stokes fields through an acoustic wave, which is generated by the pump field through the process of electrostriction. When the pump power is higher than the SBS threshold, the stimulated scattering process transforms most of the energy of the pump light to the counter-propagating wave, and the comb gain spectrum is generated to amplify the corresponding components of the seed signal, and thus facilitating the extraction of the clock in the optical domain. In Ref. [8], Kawakami *et al*. used several extra continuous-wave (CW) lights with different center frequencies as pumps to amplify multiple clock-related line spectral components of the optical data signal, however, the center frequencies of the CW laser must be tuned carefully in the bandwidth range of Brillouin gain (20−40 M) and automatic frequency control (AFC) should be applied. Whereas, additional modulator is introduced here to down-shift the original signal, and we directly use the comb spectral components of the signal light as the pump lights, and then the clock can be recovered in optical domain without the knowledge of the incoming data bit rate. With extra modulation, the modulation frequency used to down-shift the signal is fixed, so control over the frequency of the seed signal is unnecessary. Moreover, the scheme based on SBS is transparent to the modulation format and without pattern effect because the pump and the seed are generated from the same signal.

SBS can be calculated by coupled-mode theory similar to the following equations[9]:

$$\frac{\partial P_\mathrm{s}}{\partial z} = -\frac{g_\mathrm{B}}{A_\mathrm{eff}} P_\mathrm{p} P_\mathrm{s} + \alpha P_\mathrm{s} \quad , \tag{1}$$

$$\frac{\partial P_\mathrm{p}}{\partial z} = -\frac{g_\mathrm{B}}{A_\mathrm{eff}} P_\mathrm{p} P_\mathrm{s} - \alpha P_\mathrm{p} \quad , \tag{2}$$

where P_p and P_s is the power of the pump and seed, respectively, A_eff is its effective area, and assuming that the acoustic wave attenuated by $\exp(-\Gamma_\mathrm{B} t)$, g_B is the peak value of the Brillouin gain expressed as

$$g_\mathrm{B}(\omega) = g_0 \frac{(\Gamma_\mathrm{B}/2)^2}{(\omega-\omega_\mathrm{B})^2 + (\Gamma_\mathrm{B}/2)^2} \quad , \tag{3}$$

where $\Gamma_B = \tau_p^{-1}$ denotes the acoustic-phonon decay rate, and g_0 is the Brillouin-gain coefficient at the line center. Owing to the extra modulation, $\Delta f_s = 2nv_A |1/\lambda_i - 1/\lambda_0|$, to represent signal-frequency-variation-induced pump detuning, has already been discussed[8]. Owing to the additional modulation, the variation of the pump detuning due to the signal frequency has also been discussed[10]. Furthermore, the upper bound of data rate for the clock extraction scheme is about 400 Gb/s[10] since the pump is obtained directly from the incoming signal.

Generally speaking, the coupled intensity equations under steady-state conditions can be applied to describe the power transfer of SBS process for specific frequency component in optical spectrum, as long as the spectrum of high-speed signal is steady. Here, the calculation is predigested, and the variation of the power for the specific corresponding frequency component is analyzed according to the coupled equations using the Fourier transformation. For 40-Gb/s and 160-Gb/s OTDM signals, the pulse width are 25 and 6 ps in simulation, respectively. Through the classical parameter-coupling model of stimulated scattering, an SBS active filter acts as a linear filter when pump depletion caused by SBS is negligible. We use the comb-pumped gain spectrum generated by several pump light frequencies to selectively amplify multiple-frequency components. If considering the simulation for extracting 10-GHz clock from 40-Gb/s OTDM signal, we use the Fourier transformation of the coupled equations, and just choose specific frequency components (10-GHz separation) of the seed signal to experience the SBS process. We assume that the signal light is launched into the fiber at $z = 0$ and travels to the receiver at $z = L$, and the pump light is fed back down the fiber from the receiver. We take the pump linewidth into account, but still neglect the signal-light linewidth. The numerical method to solve the resulting coupled equations is discussed in Ref. [11]. τ_p and g_0 are set to be 4×10^{-9} s and 4×10^{-11} m/W, respectively. We calculate the optimum value of the length of dispersion shift fiber (DSF) (7.6 km) and the ratio of the pump to the Stokes wave (95:5). The value obtained is subsequently employed in experiment.

Figure 1 shows the experimental setup of 4×10 Gb/s OTDM clock recovery and demultiplexing. The 10-Gb/s data stream is generated by modulating the output of a picosecond pulsed fiber laser (PSL) with an external $LiNbO_3$ Mach-Zehnder modulator (MZM) driven by pattern generator (Agilent N4901B) with a pseudo random bit-sequence (PRBS $2^{23}-1$). The PSL produces an optical pulse train at repetition rates of 10 Gb/s and the pulse width is 1.23 ps at a wavelength of 1550 nm, which

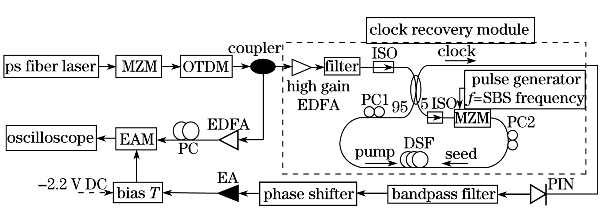

Fig. 1. Experimental setup of clock recovery and demultiplexing in 4×10 Gb/s OTDM system. PC: polarization controller; EDFA: erbium-doped fiber amplifier; EAM: electro-absorption modulator; EA: electro-amplifier.

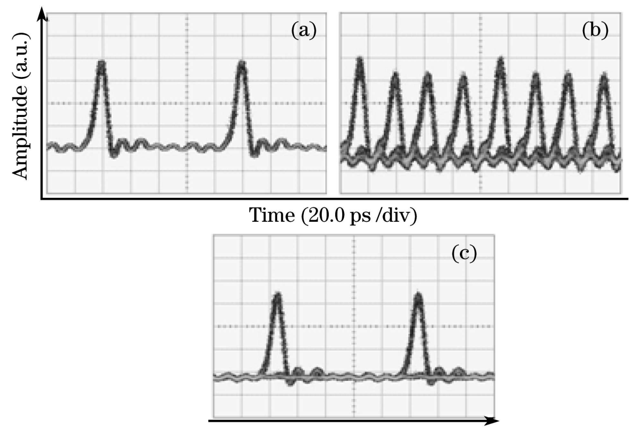

Fig. 2. Waveforms of (a) source, (b) after OTDM, and (c) after DeMux with scale of 2.50 mV/div and time of 20.0 ps/div.

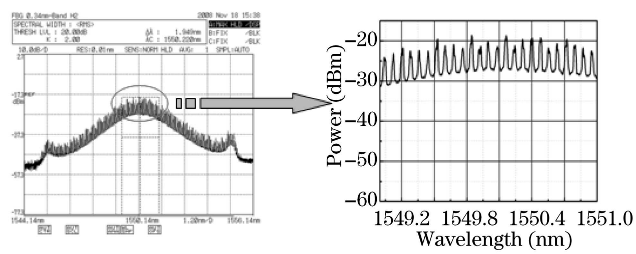

Fig. 3. Experimental spectra of 40-Gb/s multiplexed signal.

is shown in Fig. 2(a). The performance of the system is investigated by a digital sampling oscilloscope (Agilent DCA 86100 B).

The multiplexer is fabricated using a 1×4 fiber coupler following with optical variable delay lines to induce different time delays, and a corresponding 4×1 coupler is employed subsequently. Hence, the 10-Gb/s data signal is multiplexed to a 40-Gb/s signal at the output. Figure 2(b) shows the waveform of the 40-Gb/s signal, and the amplitude of one branch is higher than the others. The unequal-amplitude phenomenon is induced by insert loss, interference, and delay line owing to the special structure of the multiplexer. In the frequency domain, the spectrum of multiplexed signal is measured, as shown in Fig. 3.

The amplitude of the four channels should be equivalent ideally, and only 40-GHz frequency component exits in the corresponding spectrum, which can be seen from the simulation shown in Fig. 4(a). Then we consider the unequal-amplitude phenomenon into simulation. As a result, the plenteous 10-GHz and 20-GHz frequency components can be observed, as shown in

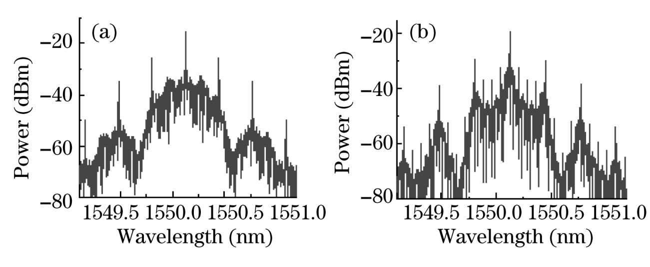

Fig. 4. Spectrums of 40-Gb/s multiplexed signal in simulation for (a) ideal case and (b) nonideal case.

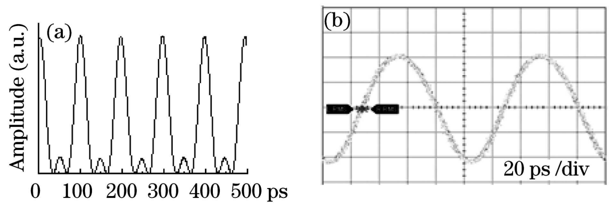

Fig. 5. (a) Simulated waveform and (b) measured eye-diagram of 10-GHz recovered clock.

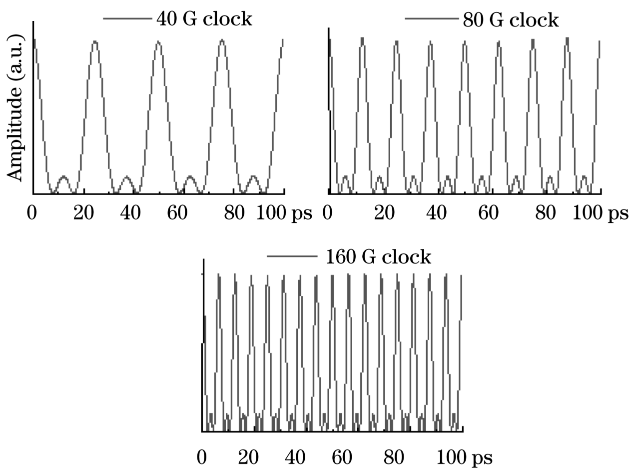

Fig. 6. Simulated clock recovered from 160-Gb/s OTDM system.

Fig. 4(b). It should be pointed that the unequal-amplitude phenomenon is the precondition and advantage for clock recovery in OTDM systems.

Considering the clock recovery module, a high gain EDFA is used to increase the power of the signal above 100 mW to exceed the SBS threshold. Then an optical filter is applied for restraining amplified spontaneous emission (ASE) from the high gain EDFA. The amplified signal is split into two beams propagating in opposite directions: the clockwise propagating signal is modulated by the Brillouin shift (10.484 GHz) of DSF using the MZM to be the Stokes wave, and the anti-clockwise signal with 95% of the total power functions as the pump. The pump and Stokes waves try to experience the strongest SBS effects in DSF fiber by adjusting the polarization controllers. Optical isolators are used to prevent the Stokes signal from reentering into the input or appear in the forward direction. The 10-GHz recovered clock is shown in Fig. 5, including the simulation result. The time jitter is 870 fs.

The 10-GHz recovered optical clock is then converted into the electrical domain utilizing the conversion module provided by NEL company, which works as a radiofrequency (RF) signal to drive the electroabsorption modulator (EAM) for demultiplexing. The EAM is a high-speed, semiconductor device capable of generating <25 ps (FWHM) temporal optical sampling windows with a repetition rate up to 10 GHz and an external circuit, including a bias T and an electro-amplifier. By adjusting the inverse voltage injected on the bias T, the appropriate switching window can be achieved. Furthermore, utilizing an extra electrical phase shifter, the 10-Gbps signal can be demultiplexed, as shown in Fig. 2(c). The lob of the trace caused by reflection of fiber connections can be repaired by using angled physical contact (APC) or ultra physical contact (UPC) connections.

Besides, the clock extracted from 160-Gb/s OTDM signal is simulated based on the upper clock recovery scheme. A comb filter should be applied before the presented module. Figure 6 shows the simulated waveforms of recovered 40-, 80-, and 160 GHz clock. It demonstrates that the clock recovery scheme can be extended to ultrahigh speed OTDM networks and easy to extract clock with multiple tributary rates. The simulation results will be subsequently employed in the future experiments.

In conclusion, a new and effective scheme based on stimulated brillouin scattering (SBS) is investigated for clock recovery in OTDM systems. Experiment of 10-GHz clock recovery from 40-Gb/s OTDM signal is demonstrated. The experimental results are in good agreement with the theoretical analysis and simulation. Meanwhile, the deep simulation research and extracted clock with multiple tributary rates in 160-Gb/s and upper rates OTDM signal show us a bright direction for demultiplexing or 3R in ultrahigh speed OTDM networks.

This work was supported by the Excellent Doctoral Scientific Innovation Projects of Beijing Jiaotong University (No. 141051522), the Beijing Science Foundations (No. 4062027), and the National “863” Project of China (No. 2007AA01Z258).

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