Half baudrate electrical clock based demultiplexing scheme for OTDM-DQPSK signal using SOA and optical filter

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Received July 4, 2011; accepted October 13, 2011; posted online December 28, 2011

A demultiplexing scheme based on semiconductor optical amplifier (SOA) and optical filter for optical time division multiplexing differential quadrature phase shift keying (OTDM-DQPSK) system is proposed and investigated experimentally. With only a common half baudrate electrical clock modulated 33% duty cycle return-to-zero (RZ-33) optical clock signal as pump, this scheme is cost-effective, energy-efficient, and integration-potential. A proof-of-concept experiment is carried out for the demultiplexing of a 2×40-GBd OTDM-DQPSK signal. Error-free performance is demonstrated, and the average power penalty for both channels is about 3 dB.

OCIS codes: 060.2330, 190.7110.
doi: 10.3788/COL201210.040601.

Optical time division multiplexing (OTDM) is very attractive for optical long haul transmission, especially due to its characteristics of high speed and large capacity but simple wavelength control, flexible network management, and less power consumption[1−5]. On one hand, as a key technique of OTDM systems, demultiplexing has been demonstrated through various approaches, including schemes based on Mach-Zehnder modulator (MZM)[6,7], phase modulator (PM)[8], electro-absorption modulator (EAM)[9−11], semiconductor optical amplifier (SOA)[12,13], fiber-based optical gates[14−17], and planar lightwave circuits (PLCs)[2], either utilizing electro-optical on/off gates or nonlinear effects, such as cross phase modulation (XPM) and four wave mixing (FWM). However, schemes aside from those based on SOA are either power consuming, input power limited, unstable, or suffer a large insertion loss. Thus, SOA-based demultiplexer is preferred owing to its low switching power, small size, integration potentiality, and high stability. This scheme also has diverse variants, such as SOA-array integrated on PLC[18] and Mach-Zehnder interferometer (MZI)-SOA[19]. On the other hand, in order to further increase bit rate or improve spectral efficiency, advanced modulation formats, such as quadrature phase shift keying (QPSK)[20,21], 16 quadrature amplitude modulation (16QAM)[22,23] and even 32QAM[24], have been utilized. In contrast, QPSK is most attractive since it could provide the best tradeoff between system complexity and spectral efficiency. Thus, SOA-based demultiplexer for QPSK modulated OTDM system is a promising approach.

Due to the offset filtering technique, the total recovery time of SOA can be released, thus SOA with a relatively long recovery time can be applied to high speed OTDM systems. This kind of demultiplexing scheme was first proposed by Tangdiongga *et al.*[25]. A similar one demonstrated in Ref. [26] has been realized to demultiplex the OTDM differential phase shift keying (DPSK) signal. However, both schemes use optical short pulse trains as pump; with the former using a mode-locked fiber laser (MLFL) as pump source, which is expensive and unstable. Furthermore, MLFL is inappropriate with phase modulated signals for its large phase noise. On the other hand, the scheme reported in Ref. [26] utilizes short pulses as well as sophisticated filters and fiber Bragg gratings that are costly and complicated.

In this letter, we use a non-short pulse optical clock (33% duty cycle retum-to-zero (RZ-33) optical clock) as pump signal and a single Gaussian-shaped filter to ease demultiplexing process while reducing system cost. Only the half base baudrate electrical clock is utilized to greatly decrease the demand for modulator bandwidth and relevant electrical devices. We experimentally demonstrate OTDM differential QPSK (DQPSK) demultiplexing from 80 to 40 GBd while only employing a 20-GHz electrical clock, which to the authors' best knowledge, is the first time the SOA-based demultiplexing scheme is applied to an OTDM-DQPSK system. The average power penalty of this half baudrate clock demultiplexing scheme is about 3 dB for 4 tributaries of the 2 channels.

The basic operation principle is shown in Fig. 1, which has been fully explained in Refs. [26,27]. However, in Ref. [26], a short pulse train is used as a pump signal, and very complicated filtering techniques are applied, whereas in this letter, we use RZ-33 pulse as pump signal to simplify the structure and reduce the cost of the system. As shown, when a weak probe signal and a strong pump signal transmit simultaneously in a nonlinear medium, such as SOA, the XPM effect occurs, thus resulting in a shift in the frequency components of the probe signal. Theoretically, each part of the probe signal can be decomposed; however, due to the wide spectrum of the OTDM-DQPSK signal, only one channel could be demultiplexed by aligning with the pump properly.

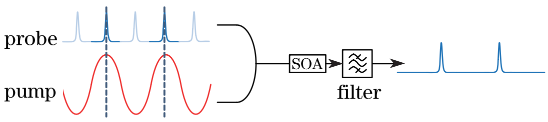

Fig. 1. (Color online) Principle of demultiplexing based on the SOA and optical filter.

The base rate optical clock driven with half base rate radio frequency (RF) clock is injected into a SOA as pump while the data signal is launched as the probe. In Fig. 1, one channel (dark blue) can be demultiplexed, when the filter is suitably set to filter out frequency components that are shifted from the original center wavelength of the probe signal owing to the XPM effect in SOA.

In order to investigate the feasibility of the proposed scheme, a proof-of-concept experiment is demonstrated for the demultiplexing of a 2×40-GBd OTDM-DQPSK signal. The experimental setup is shown in Fig. 2. A 40-GHz short pulse source consisted of a tunable laser source, an EAM, 2 PMs, and a 20-m dispersion compensation fiber (DCF). The full-width at half-maximum (FWHM) of the short pulse was about 2 ps at the wavelength of 1 540 nm. After QPSK modulation, the 40-GBd DQPSK signal was sent to an optical multiplexer (OMUX) to generate a single polarization 80-GBd RZ-DQPSK signal. Since the bandwidth of the OTDM-DQPSK signal was large, a Gaussian-shaped optical bandpass filter (BPF) with a 3-dB bandwidth of 3 nm was utilized to increase optical signal to noise ratio (OSNR) by pre-filtering the signal to decrease spectrum components that may have potential crosstalk with the demultiplexed components. However, the pre-filter may be unnecessary if the pulse width is less narrow. A continuous wave light at 1 550 nm was modulated by a 20-GHz electrical clock though an amplitude modulator (AM) biased at the null point to generate a RZ-33 optical clock to be used as pump. The pump waveform is shown in Fig. 3(a). The pump was carefully aligned with the probe through an optical delay line (ODL) to maximize the XPM effect.

The demultiplexer consisted of a SOA and an optical filter. The injected power levels of the probe and pump signals were 0 and 12 dBm respectively, which were optimized to generate a suitable frequency shift. Two polorization controllers (PCs) were applied to obtain the maximum gain. The saturated gain recovery time of the SOA (CIP® PS-NLL-1550.12-OEM-80) was 10 ps when the current was 500 mA, and input power was above 0 dBm at 1 555 nm. The polarization dependent gain (PDG) was 1 dB. An optical filter (Finisar® Waveshaper 4 000 s) with a relatively sharp roll-off was applied to filter the target signal, which can be replaced with an arrayed waveguide grating (AWG), or a wavelength-division multiplexer (WDM) for compact and cost-effective purpose. After amplification and filtering, the demultiplexed signal was sent to the DQPSK receiver for bit error rate (BER) testing.

Figure 3(b) shows the 80-GBd OTDM-DQPSK signal with FWHM of around 2 ps. Figures 3(c) and (d) show the waveforms of the input signals of SOA. The alignment between pump and probe signals demonstrates that the probe signal needs to be placed at the peak of the pump signal to acquire the maximum frequency shift due to the XPM effect. Figures 3(e) and (f) show the correspondingly demultiplexed eye diagrams.

The measured spectrums are depicted in Fig. 4. Figure 4(a) shows the 80-GBd OTDM-DQPSK spectra before (red line) and after (blue line) pre-filter. Spectra before (red line) and after (blue line) SOA, as well as the output of the waveshaper (black line) are shown in Fig. 4(b). The pump signal at this wavelength acquires the maximum gain in SOA, while probe signal broadens as a result of XPM effect. The spectrum of the pump signal is also broadened mainly due to the SPM effect. The center wavelength of the post-filter is optimized to align with the blue-shift component at 1 538.62 nm with a bandwidth of 150 GHz. The frequency curve of the filter is shown in Fig. 4(c).

The BER results for both I and Q tributaries of each demultiplexed 40-GBd DQPSK channel are shown in Fig. 5, while insets are the electrical eye diagrams at BER=1×10^{-9} and BER=1×10^{-3}. Both channels could achieve error-free performance. It should be noted that the received power is measured before DI, which is a little different with Ref. [26]. As shown, back-to-back (B2B) sensitivities (@BER=1×10^{-9}) for the I and Q tributaries are –6.72 and –6.34 dBm, respectively. For the demultiplexed channels, the sensitivities (@BER=1×10^{-9}) are –3.9 dBm (channel 1, I tributary), –3.69 dBm (channel 1, Q tributary), –3.5 dBm (channel 2, I tributary), and –3.46 dBm (channel 2, Q tributary). Then, slope variation is mainly due to the effects induced by SOA, such as SPM, XPM, and nonlinear amplification. The average

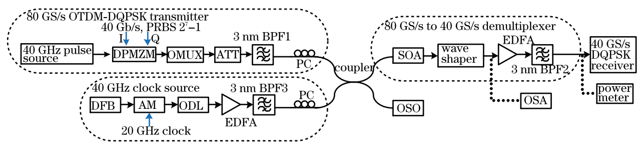

Fig. 2. Experimental setup. (DPMZM: dual-parallel MZM; ATT: attenuator; DFB: distributed feedback laser; OSO: optical sampling oscilloscope; OSA: optical spectrum analyzer).

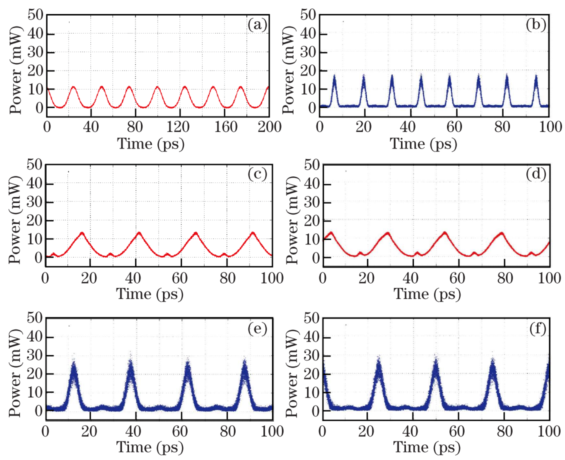

Fig. 3. Waveforms of (a) 40-GHz pump signal, (b) 80-GBd OTDM-DQPSK signal, (c) mixed signal of pump and probe before SOA while demultiplexing channel 1, and (d) signal of pump and probe before SOA while demultiplexing channel 2. Eye diagrams of the demultiplexed channels (e) 1 and (f) 2.

power penalty is approximately 3 dB. As a result, the proposed scheme performs well in the proof-of-concept experiment for the demultiplexing of a 2×40-GBd OTDM-DQPSK signal. However, we should also note that since the power along each pump pulse is not constant (Gaussian shaped), the XPM-induced frequency shift to the probe signal is not constant in a single symbol duration. Thus, the filter parameters should be carefully optimized to minimize the distortion of the demultiplexed signal.

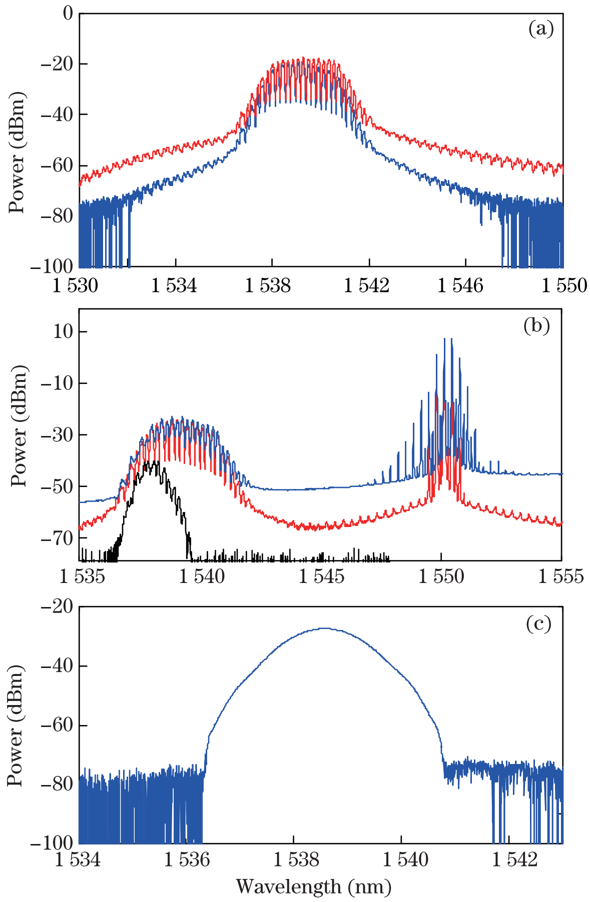

Fig. 4. (Color online) Optical spectra: probe before (red line) and after (blue line) 3 nm optical BPF; (b) probe and pump before (red line) and after (blue line) SOA and after the waveshaper (black line). (c) The frequency curve of the offset filter.

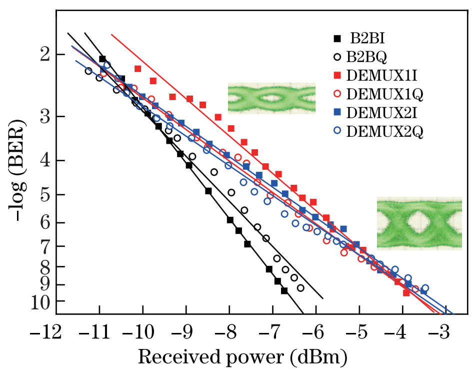

Fig. 5. (Color online) BER performance for B2B (black) operation and channels 1 (red) and 2 (blue). DEMUX: demultiplexed channel.

In conclusion, we propose a demultiplexing scheme based on SOA and optical filter for OTDM-DQPSK system employing RZ-33 pulse as pump signal. This scheme is cost-effective and energy-efficient and has large integration potential. Demands for bandwidths of electrical devices and modulator have been greatly reduced thanks to the usage of the half baudrate electrical clock. An experiment for the demultiplexing of a 2×40-GBd OTDM-DQPSK signal is carried out to verify the feasibility. Results have shown that error-free performance can be achieved for all 4 tributaries of 2 channels with average power penalty of around 3 dB.

This work was partly supported by the National "973" Program of China (No. 2011CB301702), the National Natural Science Foundation of China (Nos. 61001121, 61006041, 60736036, and 60932004), the Specialized Research Fund for the Doctoral Program of Higher Education (No. 200800131007), and the Fundamental Research Funds for the Central Universities (No. 2009CZ05).

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