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High-Speed Optical Signal Processing for Telecom Applications

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Abstract—**We discuss high-speed optical signal processing for telecom applications. We focus on the optical wavelength conversion and self-clocking, respectively. In the optical wavelength conversion, we report 40 Gb/s wavelength conversion that is capable of converting the same wavelength using a single semiconductor optical amplifier. Experimental proofs are presented. In addition, we report a novel self-clocking method based on in-band clock pilot insertion at the transmission data signal. The method provides clock recovery without an ultrafast phase comparator and a phase-locked loop in the receiver. Fast synchronization, low timing jitter and a highly stable recovered clock is demonstrated from 160 Gb/s OTDM data signal after 51-km fiber transmission.**

Keywords-optical signal processing, optical wavelength conversion, semiconductor optical amplifier, optical clock recovery, optical time-division multiplexing

I. INTRODUCTION

Optical signal processing is receiving considerable attention since it can play an important role in reducing footprint and power consumption of high-speed optical networks [1].Optical wavelength conversion and clock recovery are two important topics in the field of optical signal processing.

In the semiconductor-based wavelength conversion approaches, error-free 320 Gb/s wavelength conversion has been achieved by using semiconductor optical amplifiers (SOAs) with co-propagation scheme [2], In the system application, it is desirable for the wavelength converter to have the capability to convert any input wavelength to any output wavelength. This requires the wavelength converter has the capability of converting the information to the same wavelength. Currently, most wavelength converters utilize co-propagation scheme that can achieve high operating speed [2-6], but can not convert the same wavelength directly. In the co-propagation scheme, an optical filter is used to block the pump data signal and allow the converted probe light to pass through. To convert the information to the same wavelength, one needs firstly convert the pump data signal to a different wavelength, and then convert it back to the original input wavelength. Therefore, two wavelength converters are required [7].

Clock recovery is essential for a receiver to synchronize to a transmitted data signal in an optical communication system. In an optical time-division multiplexing (OTDM) network, the clock should be recovered at the base-rate for the requirement of optical demultiplexing and time-division add-drop multiplexing. The typical way for clock recovery is injection-locked optical phase comparison between the received OTDM signal and the locally generated clock signal. Non-linearities such as four-wave mixing [8] or cross-phase modulation in SOAs [9] or nonlinear fibers [10], three wave-mixing in periodically-poled lithium niobate (PPLN) waveguides [11] or electro-absorption modulation (EAM) [12], have been exploited to provide the phase comparator functionality. Nevertheless, when ultra-high speed operation ($\geqslant$160 Gb/s) is involved, the major difficulty for the phase comparator lies in the very high time-resolution required because of the short duration of the bit time-slot. Also, often in the phase-locked loop (PLL) scheme, the locking time works inversely with the timing jitter: shorter locking time means larger timing jitter [11]. So, clock recovery methods which are capable of reducing the locking-time and at the same time keeping the timing jitter low are of great interest.

In this paper, we firstly demonstrate 40 Gb/s wavelength conversion that is capable of converting the same wavelength using a single SOA in a counter-propagation scheme. Error-free operation is achieved. Secondly, we report a self-clocking method that allows for fast synchronization, low timing jitter and highly stable clock performance for time-demultiplexing functions. The method consists of inserting a 10 GHz clock pilot signal at the transmitter, and extracting this pilot signal at the receiver. The wavelength of the pilot signal is within the 20dB bandwidth of the data signal. The base-rate clock signal is recovered by spectrally separating the pilot from the data, photodetecting, and quadrupling ($\times$4) the pilot signal to 40 GHz. This method eliminates the use of an ultrafast phase comparator and a PLL in the receiver. Error-free operation from 160-to-40 Gb/s demultiplexing after 51 km of fiber transmission with a power penalty of 1.1 dB is demonstrated.

II. 40 GB/S WAVELENGTH CONVERSION CONVERTING THE SAME WAVELENGTH

The experimental setup of all-optical wavelength conversion (AOWC) is shown in Figure 1. The setup was constructed by using commercial available fiber-pigtailed components. A tunable laser emits a continuous wave (CW) probe beam at wavelength λ_{probe} that is fed into an SOA via an
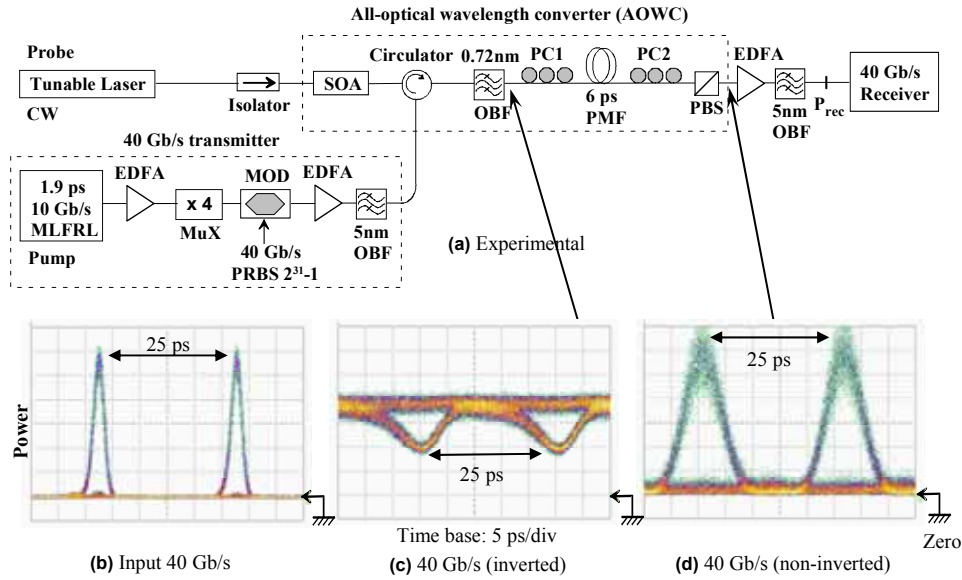
Figure 1. (a) 40 Gb/s all-optical wavelength conversion setup. (b) eye-diagram of the 40 Gb/s input pump signal. (c) and (d) are eye-diagrams at various positions in the all-optical wavelength converter. The eye diagrams are measured by a 700-GHz optical sampling scope. X: pulse interleaver,

optical isolator. A 10 Gb/s optical clock signal with 1.9 ps-wide optical pulses, generated by an actively mode-locked fiber ring laser, is amplified and is subsequently sent into an optical multiplexer, where passive fiber-based pulse interleavers are used to multiplex the 10 Gb/s optical clock to 40 Gb/s. The 40 Gb/s optical clock is subsequently modulated by an external modulator at 40 Gb/s to form a 2^{31}-1 return-to-zero (RZ) pseudo random binary sequence (PRBS). This 40 Gb/s RZ-PRBS data signal is launched into the SOA via an optical circulator. The system has a counter-propagated configuration since the CW probe light and the 40 Gb/s RZ-PRBS pump signal travel through the SOA with an opposite direction.

As shown in the dashed box in the Figure 1, the AOWC is made out of an SOA, a 0.72 nm optical bandpass filter (OBF) and a delayed-interferometer. The delayed-interferometer consists of two polarization controllers (PCs), a polarization maintaining fiber (PMF) with 6 ps differential delay, and a polarization beam splitter (PBS). In principle, the delayed-interferometer in Figure 4 can be replaced by an integrated version shown in [4]. The SOA in the AOWC is a commercial product from JDS Uniphase, having an active length of 800 μm and employing a strained bulk active region. The SOA is pumped with 350 mA. The center wavelengths of the 40 Gb/s data signal is 1552.52 nm. The wavelength of the CW probe beam is firstly set at 1552.52 nm (the same wavelength as the data signal) to test the performance of converting the same wavelength. Then the wavelength of the CW probe beam is changed to be 1560.63 nm to perform the function of converting the different wavelength. The optical power is measured at the input pigtail of the SOA. The average optical power of the 40 Gb/s data stream is −3.5 dBm and 3 dBm for CW probe light.

The injected 40 Gb/s data signal modulates the SOA gain. As a result, the CW probe light is modulated via cross-gain modulation, causing inverted wavelength conversion. Moreover, the injected data signal also modulates the refractive index of the SOA, resulting in a chirped converted signal. The leading edges of the (inverted) converted probe light are red-shifted, whereas the trailing edges are blue-shifted. As a consequence, the spectrum of probe light at the SOA output is broadened. The 0.72 nm optical bandpass filter that is placed at the SOA output is 0.5 nm blue-detuned to select the blue-shifted sideband of the probe light, and shorten the recovery time of the SOA [3].

At the output of the 0.72 nm optical bandpass filter, the converted probe light is monitored by using an optical sampling scope with an optical measurement bandwidth up to 700 GHz. The result is presented in Fig. 4c. An inverted 40 Gb/s signal with a clear open eye-pattern is obtained, which ensures the pattern-independence of 40 Gb/s wavelength conversion. The inverted 40 Gb/s converted signal is subsequently injected into the delayed-interferometer, where the polarity of converted signal is changed, i.e., inverted signal is changed into non-inverted signal. In addition, the slow gain saturation time is suppressed. The result is presented in Figure 1d.

After wavelength conversion, the converted signal is fed into a 40 Gb/s receiver and a bit-error-rate (BER) tester. Fig. 2 shows BER measurements of the 40 Gb/s input signal @1552.52nm and the converted signal (@1552.52nm and @1560.63nm, respectively). It can be observed that the sensitivity penalty of the wavelength conversion at a BER=10^{-9} is about 3.5 dB for converting the same wavelength, and 2 dB for converting the different wavelength (1552.52nm to 1560.63nm). Moreover, it is visible that no error-floor is observed, which indicates excellent performance of the proposed wavelength

conversion. The system has a larger penalty when the pump and probe light has the same wavelength. This is due to the reflected pump light at the SOA facet, which has the same wavelength as the probe light. The penalty can be improved by reducing the reflection from the SOA facet.
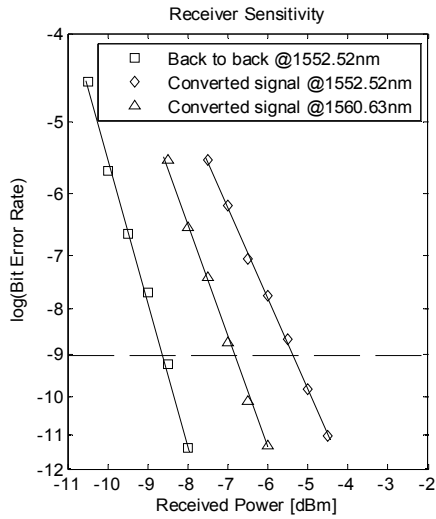

Figure 2. BER performance of 40 Gb/s wavelength conversion

The inverted 40 Gb/s eye-diagram presented in Figure 2c shows a slow gain saturation time and a fast recovery time, which is different from the co-propagation scheme shown in [2-3]. The fast recovery time is obtained because of the used blue-detuned optical filtering technology [3], which shortens the effective SOA-recovery time from 100 ps to less than 6 ps. This indicates that blue-detuned optical filtering technology still functions well in speeding up the recovery time of the counter-propagation system. In contrast to the ultra-fast gain saturation time in the co-propagation scheme [2-7], the counter-propagation scheme has a much more slow gain saturation time, which becomes a determinant factor for the operating speed of our scheme. The slow gain saturation time is caused by the active length of the SOA and the slow gain recovery time of the SOA. This long lived-tailed saturation time can be cancelled by using the delayed-interferometer, as shown in Figure 1d. This indicates higher operating speed (>80 Gb/s) would be possible.

III. SELF-CLOCKING FROM 160GB/S OTDM DATA SIGNAL

The proposed self-clocking method is schematically shown in Figure 3. It consists of a 160 Gb/s OTDM transmitter and receiver, connected by a dispersion-managed fiber span of 51 km. In the transmitter, optical return-to-zero pulses generated by a fiber mode-locked laser (FMLL) with duration of 1.4 ps at 1557 nm and 40 GHz repetition rate (driven by a master clock), are optically gated to form an optical pseudo-random binary sequence (PRBS) signal. We characterize the clock and demultiplexing performance using three 40 Gb/s PRBS patterns: 2^7-1, $2^{15}-1$ and $2^{31}-1$. The 40 Gb/s pulses are sent

through fiber-based interleaver and time-multiplexed to constitute a 160 Gb/s signal (shown in Figure 4(a)). Due to the fiber-based multiplexer, it is observed that the 160 Gb/s signal is not phase-stable in the spectrum domain, so we determine the 160 GHz peak lines from the stable spectrum of the 40 GHz pulsed signal.
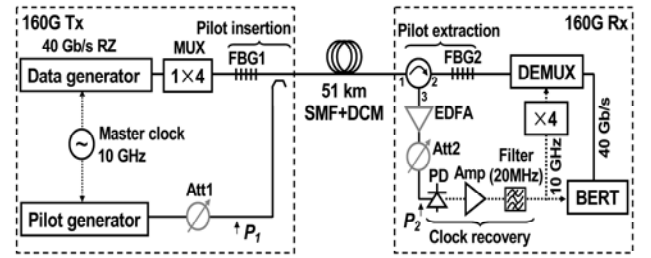

Figure 3. Experimental setup for self-clocking based on the in-band pilot method. MUX: Optical Time-domain Multiplexer, FBG: Fiber-Bragg Grating, Att: Attenuator, PD: Photodetector, Amp: Electrical Amplifier, DEMUX: Demultiplexer, EDFA: Erbium-Doped Fiber Amplifier, SMF: Single-mode Fiber, DCM: Dispersion Compensation Module.

The 160 Gb/s data signal is then coupled into an optical fiber Bragg-grating (FBG1) with 0.4 nm bandwidth that carves a portion of the data spectrum where the pilot is going to be inserted. The central wavelength of the FBG1 is located at 1558.93 nm (Δλ=1.93 nm with respect to the data carrier), which is chosen to avoid crosstalk with the 160 GHz spectral lines of the data signal in order to eliminate distortions and noise as much as possible. The pilot is generated by modulating a CW laser (λ=1558.93 nm) with the 10 GHz master clock. The bias and driving power are optimized to suppress high-order harmonics and to keep a linear intensity modulation. Finally, the pilot is combined with the 160 Gb/s data through an optical coupler.

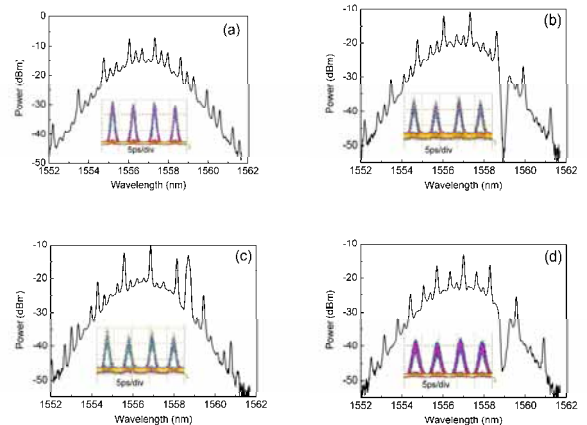Figure 4. Spectra and waveforms of the 160 Gb/s data signal. (a) Original signal, (b) Carved spectrum before pilot insertion, (c) In-band pilot insertion, (d) In-band pilot extraction.

The carved data-spectrum and the inserted pilot in the signal spectrum are shown in Figure 4 (b) and (c), respectively. The 160 Gb/s data and the 10 GHz pilot are transmitted together through a dispersion-managed fiber link consisting of

51 km of standard single-mode fiber (SMF) and a dispersion compensation module (DCM). In the receiver part, the co-propagated data and pilot are separated via an optical circulator (OC) and the FBG2. The FBG2 holds an identical central frequency and bandwidth to the FBG1. The data after pilot extraction, in port 2, is shown in Figure 4(d).

The extracted in-band pilot is converted to the electrical domain by a photodiode followed by a transimpedance amplifier whose output is fed to a bandpass filter and then quadrupled (×4) to form a 40 GHz clock that drives the EAM-based demultiplexer. Because the pilot and the data are synchronized in the transmitter and are spectrally located close to each other, they are affected by the same fiber impairments leading to the same phase drifts. Therefore, the relative phase difference between clock and data is preserved along the fiber links.
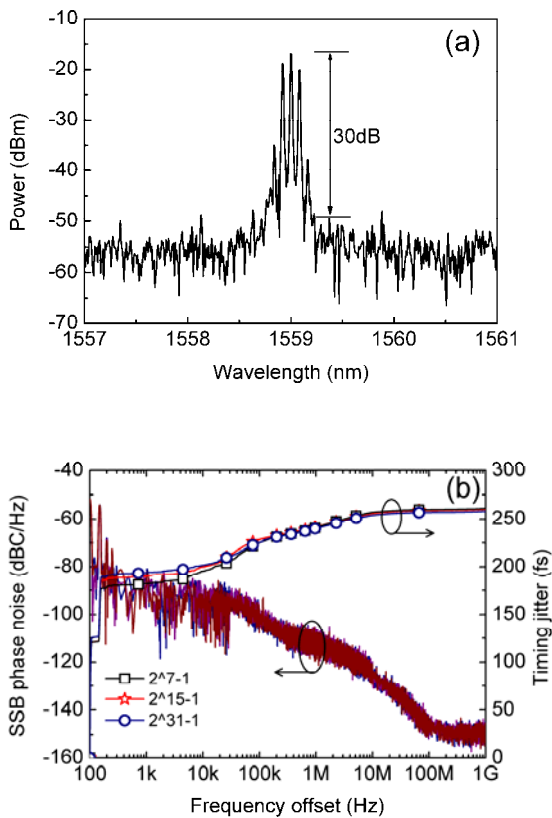

Figure 5. (a) Optical spectrum of the recovered clock, (b) SSB phase noise and timing jitter of the recovered clock after 51 km fiber-transmission for three different PRBS sequences.

In Figure 5(a) we can observe the quality of the recovered clock that holds modulation peaks at 10 GHz with a signal to noise ratio of more than 30 dB. Figure 5(b) illustrates the single sideband (SSB) phase noise and timing jitter estimation of the recovered clock after transmission using three different data patterns: 2^7-1, 2^{15}-1 and 2^{31}-1. For these three pattern lengths we obtained timing jitters of approximately 260 fs using a

20MHz electrical filter, proving that the concept is not pattern-length dependent.

In order to evaluate the proposed method we use the recovered clock to drive an EAM-based demultiplexer, and carry out BER measurements on the extracted tributaries. The BER performance of the system is described in Figure 6(a). The circles illustrate the 160-to-40 Gb/s in the back-to-back configuration used as a reference. The squares represent the 160-to-40 Gb/s before transmission employing the recovered clock, whereas the stars represent the case after transmission. Error-free operation is achieved on all the channels with an average received power of -11 dBm. This value corresponds to an average power penalty of 1.1 dB between the reference and the case after transmission. This penalty is mainly due to the carving effect of the FBGs on the data signal. In the experiment, we use two 0.4nm (50GHz) bandwidth FBGs. The penalty can be reduced if more narrow FBGs are employed, ideally with 0.16nm (20 GHz) bandwidth. We also observe a penalty of 0.1 dB between the case before transmission and after transmission that indicates excellent dispersion compensation of the fiber-span. The eye diagrams of the extracted channels before and after transmission are also shown in Figure 6(a), demonstrating excellent working of the demultiplexer.
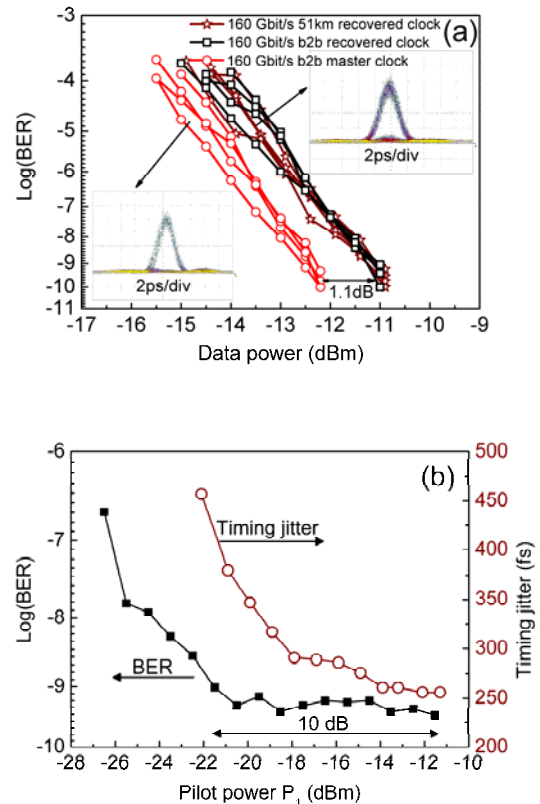

Figure 6. (a) BER curves of the 40 Gb/s channels: using the master clock (circles) and the recovered clock before (squares) and after transmission (stars); (b) BER and timing jitter vs pilot power P_1.

The dependence of timing jitter on the optical power of the clock pilot P_1 and its effect on the BER is investigated. This so called dynamic range measurement was done by varying the pilot power P_1 and by keeping the input power P_2 to the clock-recovery unit constant. As shown in Fig. 1, an attenuator (Att1) varies P_1 by 14 dB and a combination of an EDFA and Att2 keeps P_2 constant at a certain level for driving the DEMUX and the BERT. As shown on Figure 6(b), if the pilot power decreases by 10 dB, then the timing jitter increases by approximately 200 fs. This timing jitter increase will not lead to a dramatic increase of BER values. BER values will sharply increase when the pilot power fluctuates by more than 10 dB. This result is in general similar to the analyses presented in [13]. It is worth to note that when the pilot power is increased above -14 dBm, the timing jitter remains at about 260 fs which is determined by the noise level of the photodiode and electrical amplifiers. However, with the increasing of the pilot power, the residual signal of the pilot after pilot extraction will affect the data signal due to the only 30 dB suppression of rejection band of the FBGs, so we keep the pilot power close to that of the neighboring 160 GHz peak, which causes a negligible influence on the OTDM data signal and introduces an acceptable timing jitter. The results were obtained using a PRBS pattern of 2^7-1 and can be extended to longer data pattern lengths since this concept is pattern-length independent. During the experiments no loss of clock was observed and the receiver showed stable and repeatable results.

IV. CONCLUSIONS

We have demonstrated a high-speed optical wavelength converter that is capable of converting the data to the same wavelength using a single SOA. Error-free 40 Gb/s operation is demonstrated. The wavelength converter utilizes counter-propagation scheme assisted by blue-detuned optical filtering technology. The blue-detuned optical filtering technology still functions well to dramatically speed up the recovery time of our counter-propagation system. The counter-propagation system shows a slow gain saturation time, which becomes a determinant factor for the operating speed. This wavelength converter has a simple configuration and allows photonic integration. We have also presented a novel self-clocking concept based on inserting at the transmitter and extracting at the receiver a clock pilot which is located in the data spectrum. The clock recovery function is realized by the proposed method, which eliminates the need for an ultrafast phase comparator and a phase locked loop scheme. The concept leads to fast synchronization, low timing jitter and highly stable demultiplexing performance. The proposed method simplifies the design of an OTDM receiver and requires minor modifications of the standard OTDM transmitter.

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