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REVIEW ARTICLE

Signal generation and processing at 100 Gb/s based on optical time division multiplexing

Li HUO (✉), Qiang WANG, Yanfei XING, Caiyun LOU

Tsinghua National Laboratory for Information Science and Technology, State Key Laboratory of Integrated Optoelectronics,
Department of Electronics, Tsinghua University, Beijing 100084, China

Abstract In this paper, we review our recent works in 100 Gb/s signal generation and processing. A high-speed 100 Gb/s system with on-off keying (OOK) modulation format is implemented by using optical time division multiplexing (OTDM) method. As modifications of this system, simultaneous multicolor optical signal generation and 100 Gb/s return-to-zero (RZ)-to-non-return-to-zero (NRZ) format conversion are presented. We also demonstrate basic all-optical signal processing functions of 100 GHz clock recovery and 100 Gb/s all-optical 2R generation based on semiconductor optical amplifiers (SOAs).

Keywords optical time division multiplexing (OTDM), 2R regeneration, clock recovery, semiconductor optical amplifier (SOA)

1 Introduction

In recent years, the demand of internet bandwidth has been growing rapidly as a result of the growth of video traffics, social networks, cloud computing, and the accelerated acceptance of mobile smart-phone and tablets. An effective way to reduce the capital and operational costs for the service provider is to increase the transmission rate of single channel on optical layer. Previous experience shows that when the single channel rate is increased by 4 times, the cost for transmitting each bit decreases about 30%–40%. Currently, 40 Gb/s systems have already been highly accepted by the market and 100 Gb/s system becomes the next focus.

Single wavelength transmission of 100 Gb/s can be achieved by pure 100 Gb/s electrical time domain multiplexing (ETDM) [1], 28-Gbaud/s dual polarization differential quadrature phase shift keying (DP-DQPSK) [2], 56-Gbaud/s DQPSK [3], and optical time division multiplexing (OTDM). The first three methods depend on electronics, for which it becomes more and more difficult to keep up with the speed requirements of optical transmission while maintaining a relatively low cost. On the other hand, OTDM relies on ultra-short optical pulses. The narrower the pulse can be generated, the faster single wavelength transmission rate can be obtained. With simple on-off keying (OOK) modulation format, OTDM technology can easily achieve a speed of 160 Gb/s [4], and 640 Gb/s [5]. A 1.28 Tb/s [6] OOK-OTDM has also been demonstrated. Recently, with the introduction of advanced modulation format and polarization multiplexing into OTDM, single wavelength systems with aggregated bit rates of 2.56 [7] and 5.12 Tb/s [8] have been reported.

At the same time, the increased single channel rate also brings huge pressure to the switching nodes of the core network. Conventional switching technology depends on parallel processing with electronics at a typical speed of ~GHz of multiple de-serialized high speed data streams. Each time the optical signal enters a switching node, it has to go through a series of steps of O-E-O conversions, header strip-off/add-on and data split/recombination. With the increasing of speed, this architecture will become awkward by ending up with a massive footprint and huge amount of power consumption.

Optical signal processing provides a possible solution for this dilemma and promises transparent or translucent network architectures in which no O-E-O or only minimum O-E-O conversions are needed. Basic optical signal processing functions include wavelength conversion, format conversion, optical switches, 2R/3R regeneration, clock recovery, optical logics, optical buffers, and so on. The main advantage of optical signal processing is the ultra-high speed of optical responses which could handle data rate ranging from ~10 GHz to even ~THz.

There are several devices available for the optical signal processing such as high nonlinearity fiber (HNLF) [9],

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E-mail: lhuo@tsinghua.edu.cn

periodically-poled $LiNbO_3$ (PPLN) [10], silicon nanowire [11], chalcogenide glass [12] and semiconductor devices such as semiconductor optical amplifier (SOA) [13] and electroabsorption modulator (EAM) [14]. Among them, SOA is attractive for its potential of integration and low power consumption. However, a problem for the SOA is its relatively slow gain recovery time (~100 ps), which limits its high bit rate performance with the associated adverse patterning effect [15]. One method to circumvent the slow gain recovery time is to utilize the faster response of phase change by using interferometric configurations [16,17] or filtering out the blue-shifted ultrafast component with a narrow bandpass filter [18,19]. An alternative way to combat the slow gain recovery is to use quantum-dot (QD) SOA [20] which has a much faster gain recovery time, or to use SOA with long waveguide length [21], in which amplified spontaneous emission (ASE) saturates the gain and results in an equivalently faster recovery time. So far, wavelength conversion using SOA has been demonstrated at 160 [18] and 320 Gb/s [19], however, it is still difficult to perform 2R and 3R regeneration with SOA at a speed beyond 100 Gb/s.

In this paper, we review our recent progresses in 100 Gb/s signal generation and processing. In Section 2, we first demonstrate a high-speed 100 Gb/s OTDM system with OOK modulation format. As a modification as well as an improvement, simultaneous 4-channel optical signal generation is also presented. In Section 3, we show format conversion from return-to-zero (RZ) to non-return-to-zero (NRZ) at 100 Gb/s with a narrow bandpass filter. In Section 4, all-optical signal processing functions of 100 GHz clock recovery is given and Section 5 presents 100 Gb/s all-optical 2R generation based on SOAs.

2 100 Gb/s OOK signal generation with OTDM method

OOK system of 100 Gb/s based on OTDM is the foundation, on which different 100 Gb/s optical signal processing functions are carried out. In this system, the ultrashort pulse generator is the most essential. Previously, we demonstrated ultrashort pulse generators at 10 GHz with external modulators such as EAM or $LiNbO_3$ intensity modulator followed by cascaded pulse compression stages of comb-like dispersion profiled fiber (CDPF) and HNLF [22–24] for 80 and 160 Gb/s applications. In this study, the base rate is improved to 25 GHz. We used a single phase modulator (PM) in conjunction with a piece of single mode fiber (SMF), in which the chirp introduced by the PM was converted into intensity modulation. After this initial stage, the pulses were sent into HNLF in which self-phase-modulation (SPM) broadened the optical spectrum substantially and an optical bandpass filter was used to select a segment of the broadened spectrum to form the ultrashort pulses required by OTDM. The schematic of the 100 Gb/s OTDM system is shown in Fig. 1 and the ultrashort optical pulse source is shown in the solid box.

Inside of the pulse source, continuous wave (CW) light from a distributed feedback (DFB) laser with a wavelength of 1547 nm was modulated at 25 GHz by the PM. The half wave voltage V_π of the PM was 3.5 V, the applied peak-to-peak voltage was 7.2 V. The phase-modulated signal was then sent into a section of SMF with a length of 1 km. Due to the dispersion of the SMF, the chirp introduced in the PM was converted into amplitude modulation and an initial pulse with a full width at half maximum (FWHM) of ~ 5 ps was obtained. This pulse was further amplified with a booster Erbium-doped optical fiber amplifier (EDFA) with an output power of 23 dBm and then injected into the 1 km HNLF with a nonlinear coefficient of 8 /W/km, a group velocity dispersion of 1.8 ps/nm/km, a dispersion slope of 0.08 ps/nm^2, and a zero dispersion wavelength of 1557 nm. The spectrum of the pulse was broadened by SPM in the HNLF. An optical bandpass filter with a 3 dB bandwidth of 3 nm and a central wavelength of 1550.5 nm was used to filter out the red-shifted region of the broadened spectrum. After the filter, a 25 GHz pulse train with narrow FWHM

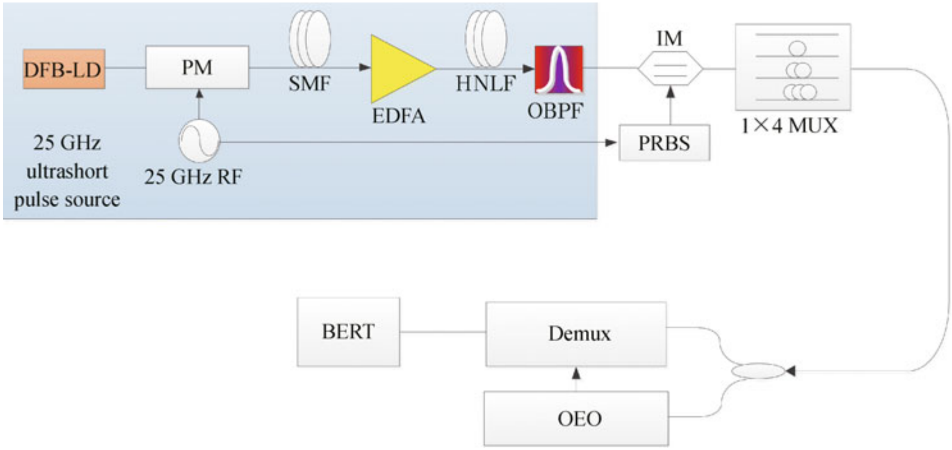


Fig. 1 Schematic of 100 Gb/s OOK OTDM system

pulsewith of 2 ps was obtained. The ultrashort pulse train was then modulated synchronously by an intensity modulator driven by 2^{31}–1 pseudo random bit sequence (PRBS). A home-spliced 1 × 4 passive multiplexer made of optical couplers and fiber delay-lines was used to multiplex the 25-Gb/s tributary data to a final line-rate of 100 Gb/s. In the receiver end, the 100 Gb/s OTDM signal was split into two parts. One part was injected into an optoelectronic oscillator (OEO) [25] with a free-running oscillation frequency of 25 GHz to obtain a synchronized clock at 25 GHz. The extracted clock was in electrical form and had a timing jitter of 230 fs measured by single-side-band (SSB) phase noise integration over a RF spectral range between 100 kHz and 10 MHz. The extracted clock was sent into a demultiplexer (a $LiNbO_3$ intensity modulator in this experiment) for gating the other part of the OTDM signal to demultiplex 100 Gb/s aggregated signal into 25 Gb/s tributary for bit error ratio (BER) test. The eye-diagram of the 100 Gb/s OOK signal was observed by a 500 GHz optical sampling oscilloscope and is shown in Fig. 2. Figure 3 shows the BER curve of the demultiplexed signal of all four tributaries. Compared with 25 Gb/s base line, the power penalty introduced by multiplexing and demultiplexing is between 0.5 and ~ 2.4 dB.

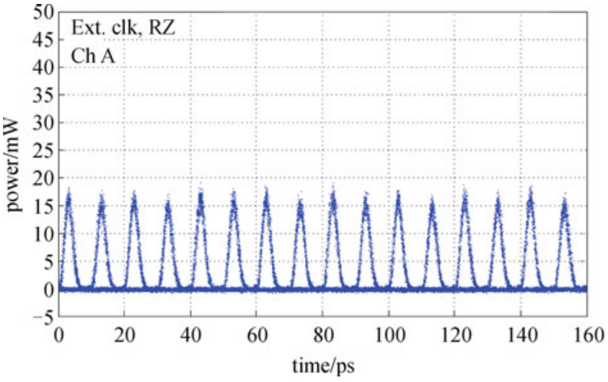


Fig. 2 Eye-diagram of 100 Gb/s OOK OTDM signal

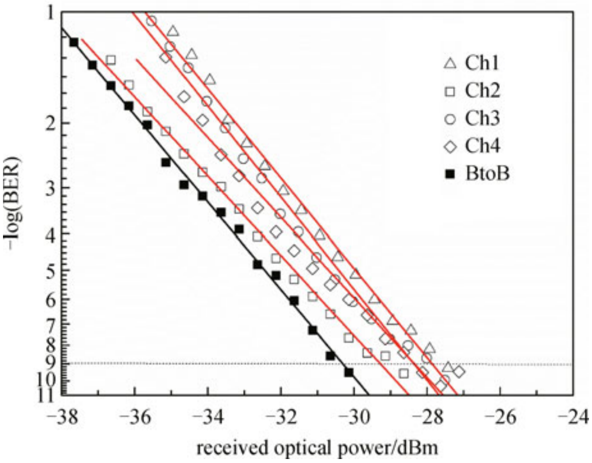


Fig. 3 BER curve of 4 demultiplexed tributaries of 100 Gb/s signal

There are both a red-shifted and a blue-shifted part in the SPM-broadened spectrum. In principle, two ultrashort pulse trains at different wavelengths can be generated simultaneously simply by placing different optical filters at both sides. As an extension of this fact, we managed to simultaneously generate 4 ultrashort pulse trains by using 2 different CW lasers. The schematic of the experimental setup is shown in Fig. 4. The wavelengths of the two DFB-lasers were set as 1554.8 and 1534.8 nm. They were injected together into a single PM driven by a 25 GHz sinusoidal radio frequency (RF) signal. To avoid four-wave-mixing (FWM) in the HNLF, the two initial pulse trains were separated by a 3 dB coupler and two optical filters centered at 1554.8 and 1534.8 nm. The two pulse trains at different wavelengths were carefully delayed in time with an optical delay line (ODL) in order to minimize the pulse overlapping in the following HNLF. A tunable optical attenuator (ATTN) was also used in one branch to equalize the gain of the two wavelengths in the following high power EDFA. The recombined signals was boosted to a total power of 25 dBm and launched into the HNLF. Finally, four optical filters with a bandwidth of 2.8 nm were engaged to filter out the 4 wavelengths.

Figure 5(a) shows the measured SPM-broadened optical spectrum after the HNLF. Owing to the careful power equalizing before the high power EDFA, the aggregated optical powers around the 2 original wavelengths were quite similar. The 1554.8 nm signal had a 20 dB spectral width of 17 nm which was 6 nm larger than the 1534.8 nm signal. The optical spectra of the four wavelengths filtered were also shown in the same figure. The 3 dB bandwidth of the filtered signal was all ~2.8 nm and the center wavelengths were 1529.4 (WL-1), 1538.2 (WL-2), 1549.3 (WL-3) and 1560.2 nm (WL-4), respectively. Figures 5(b)–5(e) show the waveforms of the filtered out signals at different wavelengths captured with an optical sampling oscilloscope. The repetition rate of all the four wavelengths was 25 GHz and the FWHM pulsewidth were measured to be 1.9, 2.1, 2.1 and 2.0 ps, respectively for WL-1–WL-4. The pulsewidth of all four wavelengths was short enough to be further multiplexed to 100 GHz using the OTDM multiplexer.

3 100 Gb/s RZ-OOK to NRZ-OOK data format conversion

OOK is the most fundamental modulation format in optical communication systems and it is also the natural interface with terminal devices like computers and smart phones. Generally, RZ-OOK format is often used in the core networks due to its superior long haul transmission performance, while NRZ-OOK is widely deployed in metro networks for its low cost and high spectral

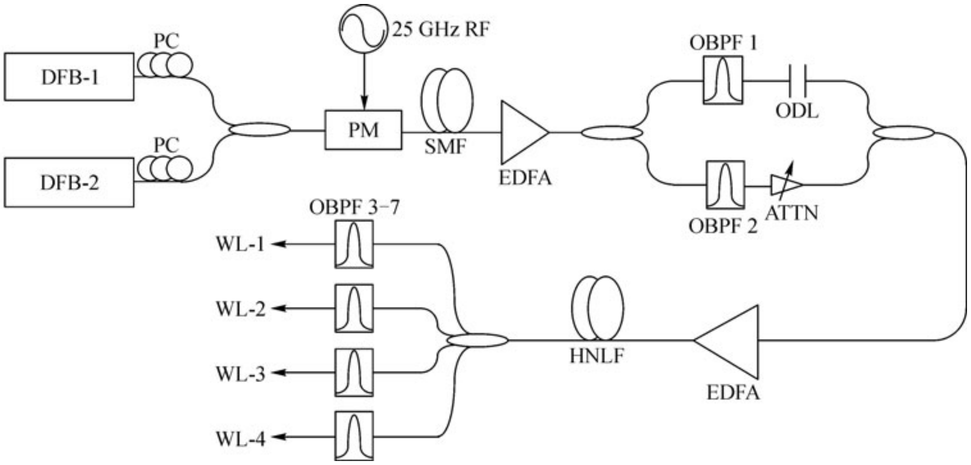


Fig. 4 Schematic of multicolor ultrashort pulse source

efficiency. To connect the core and the metro networks transparently, it requires functions of realizing RZ-to-NRZ and NRZ-to-RZ format conversion. Currently, it is still very difficult to generate NRZ signal directly at a high speed of 100 Gb/s. However, by making some minor modification of the 100 Gb/s RZ-OOK system, we can easily generate 100 Gb/s NRZ signal.

The 100 Gb/s RZ-to-NRZ format conversion is carried out simply by spectral confinement. RZ signal has a large bandwidth, which is often several times of the bit rate in order to maintain a decent pulse shape. For NRZ signal, the bandwidth is usually 70%–100% of the bit rate. In our experiment, we employed an optical bandpass filter with a 3 dB bandwidth of 0.88 nm and a sharp edge with a fast roll-off of 20 dB/nm after the 100 Gb/s RZ-OOK OTDM signal. The eye-diagrams of the RZ-OOK and NRZ-OOK signal are shown in Fig. 6. The converted NRZ-OOK is featured with a widely opened eye, which indicates the good quality of the signal.

4 100 GHz clock recovery

All-optical clock recovery is one of the enabling technologies of 3R regeneration. It is also important for other applications, like OTDM demultiplexing and serial-to-parallel conversion [26], etc. An effective method for all-optical clock recovery is using a Fabry-Perot cavity (FPC) as optical tank followed by a SOA as amplitude equalizer. This method was demonstrated to recover optical clocks from incoming RZ data signals at 10 [27] and 40 Gb/s [28]. Compared with other clock recovery methods, such as multi-sectional self-pulsating laser [29] and QD- Fabry-Perot (FP) lasers [30], this scheme features with extremely structural simplicity, low cost of components and the potential of being integrated. However, due to the slow gain recovery time of the SOA, it is still difficult to apply this method to a speed of 100 Gb/s. In this study, we used a highly nonlinear SOA with a very fast gain recovery time of ~10 ps, which is comparable with the 100 Gb/s time slot. Another SOA with a slower gain recovery time of ~ 40 ps was also used as a controlled reference.

Figure 7 shows the experimental setup, the solid box is the 100 Gb/s OTDM system mentioned in Section 2. In the clock recovery part, the 100 Gb/s RZ-OOK optical signal was first launched into a FPC, which acted as an optical tank, capable of storing energy inside its cavity. The free spectral range (FSR) of the FPC was tuned to 100 GHz to match the data rate of the injected signal. The temperature of the distributed feedback laser diode (DFB-LD) in the 100 Gb/s light source was controlled precisely to move the carrier frequency to the exact position of one of the FPC transmission peaks. The finesse of the FPC was measured to be ~310 and the loss at the transmission peak was 5 dB. When a ‘1’ bit followed by a long ‘0’ bit stream is injected into the FPC, the first optical pulse bounces back and forth between the two highly reflective surfaces of the FPC. Each time the pulse hits the surface connecting to the output, it releases part of its energy. The energy release is still in a pulse shape but its power decays with constant determined by the *Q* value of FPC. Since the FSR is 100 GHz, the time interval between the released pulses is 10 ps and the previous empty ‘0’ bit positions are now filled with optical pulses. In this way, optical clock is recovered from the injected data. The clock recovered with FPC only had a very large amplitude fluctuation. This large fluctuation is on one hand due to energy decaying of long ‘0’ sequences, and on the other hand is introduced by the interference between the reflected previously injected pulses and the following ‘1’ pulses. The amplitude fluctuation must be alleviated by equalizer. In this study, we used a simple method of SOA as the equalizer. The SOA works in saturation region, optical pulses with high energy experiences low gain and pulses with low energy experiences high SOA gain. In this way, the amplitude fluctuation can

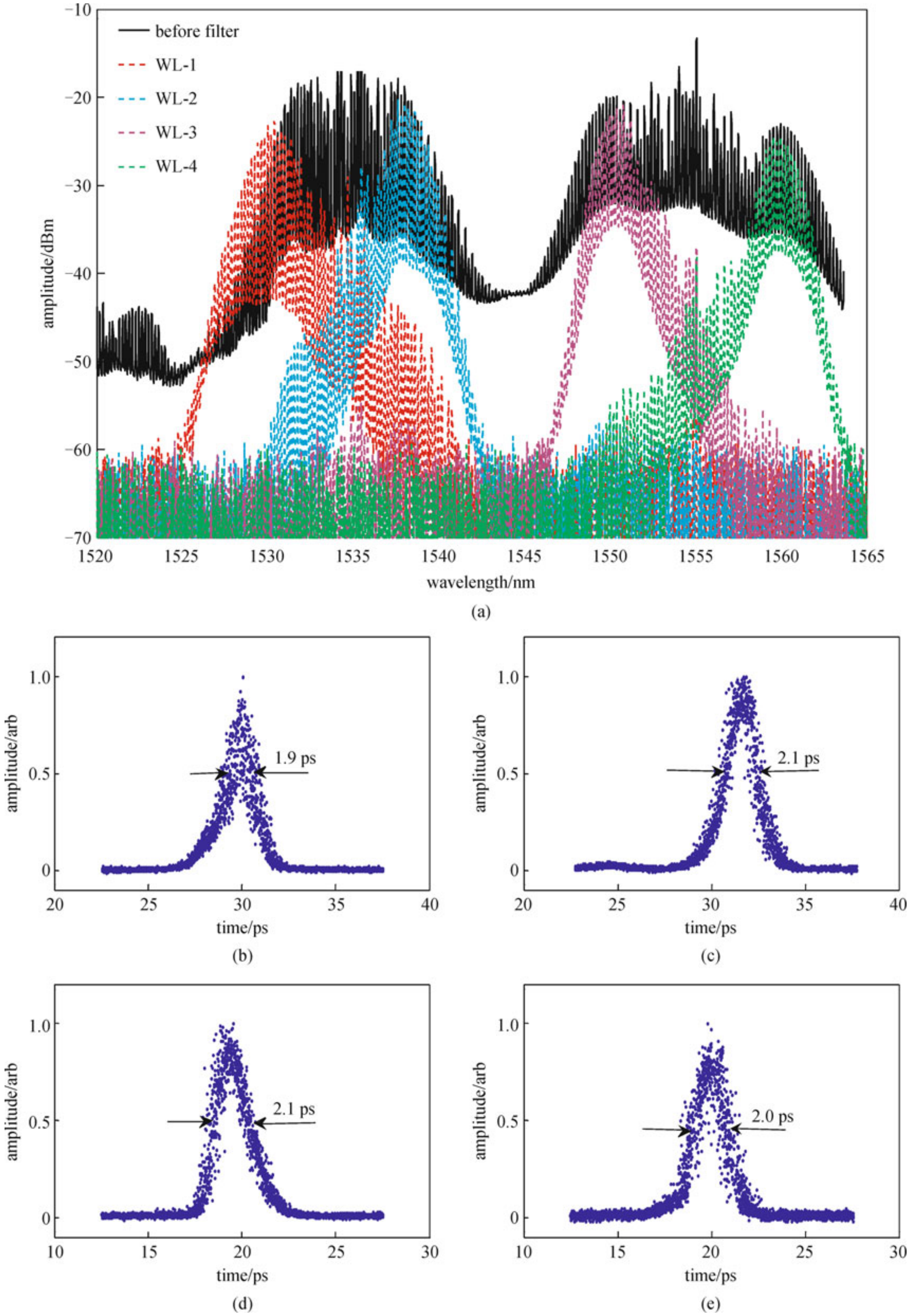


Fig. 5 (a) Optical spectrum of signal after HNLF (black) and spectra of filtered 4 wavelengths (colored); (b)–(e) waveforms of filtered optical pulse on four wavelengths, corresponding to WL-1–WL-4, respectively

be equalized. Apparently, the performance of the equalizer depends on the gain recovery time. If the gain could be fully recovered within 10 ps, the SOA will have sufficient gain to amplify a pulse with very small amplitude; and if

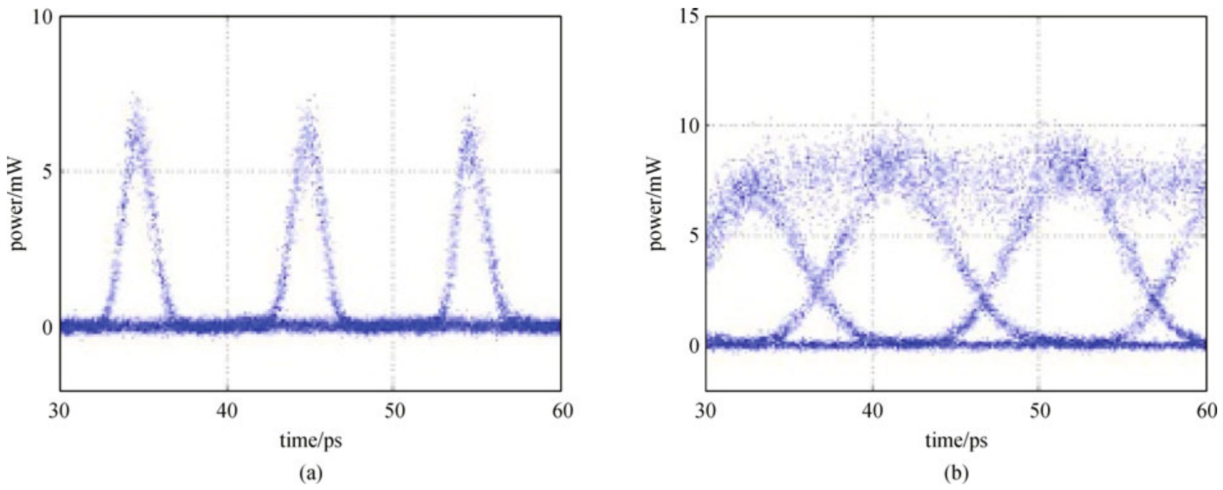


Fig. 6 Eye-diagrams of 100-Gb/s RZ-OOK signal (a) and converted NRZ-OOK signal (b)

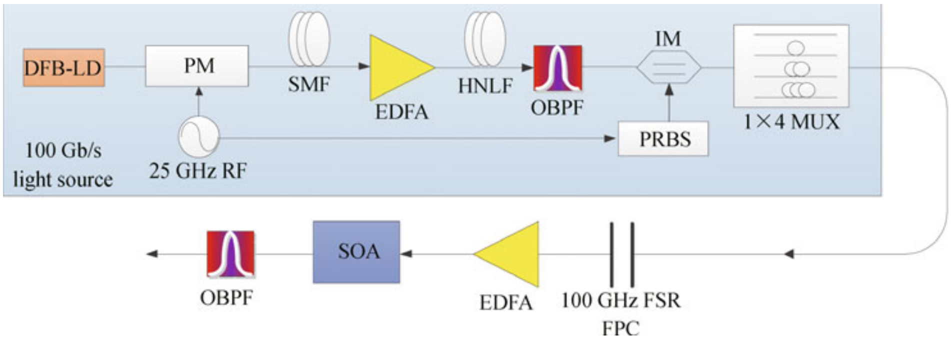


Fig. 7 Experimental setup of 100 GHz clock recovery

the gain is only partly recovered, the output of the SOA will still suffer from patterning effect.

We used two SOAs, with a 1/e gain recovery time of 40 and 10 ps respectively. Before the SOA, an EDFA was used to amplify the output power of the FPC to 6 dBm to guarantee the SOA worked in saturation region. An optical bandpass filter with a center wavelength of 1551.2 nm and bandwidth of 3.8 nm was used to reject the out-of-band optical noise from the SOA.

Figure 8 shows the waveforms of the optical clocks recovery by the FPC only, by the combination FPC and SOA with 40 ps gain recovery time, and by the combination FPC and SOA with 10 ps gain recovery time. Substantial improvement of clock signal quality can be observed from the waveforms. We define the amplitude fluctuation as the ratio of the standard deviation to the mean of the clock peak power. The amplitude fluctuation of the clock with FPC has a large value of 46%. After the SOA with ~40 ps recovery time and optical filter, the amplitude fluctuation was reduced to 12%. With the faster ~10 ps gain recovery SOA, the amplitude fluctuation was further reduced to 5%. The timing jitter of the clock after the equalizer was also measured by the optical sampling oscilloscope with a best value of 154 fs, including 50 fs jitter intrinsic to the oscilloscope itself.

5 100 Gb/s 2R regeneration with SOA

All-optical signal regeneration is an effective method to combat the signal degradation introduced by various impairments along the optical fiber transmission line, such as chromatic dispersion, polarization mode dispersion, fiber nonlinearity and OSNR reduction due to ASE from in-line EDFAs. Regeneration is also needed in the switching nodes of the transparent optical networks to eliminate the potential signal degradation from other optical signal processing units like optical switch fabrics, buffers, format conversion, and wavelength conversion. 2R means re-amplification and re-shaping. The key technology in 2R regeneration is a fast optical switch with reshaping capability. It is related with wavelength conversion but is more difficult to achieve than the latter, in which a negative power penalty is not required.

Cross gain compression (XGC) in SOAs provides a promising method for 2R regeneration for both NRZ and

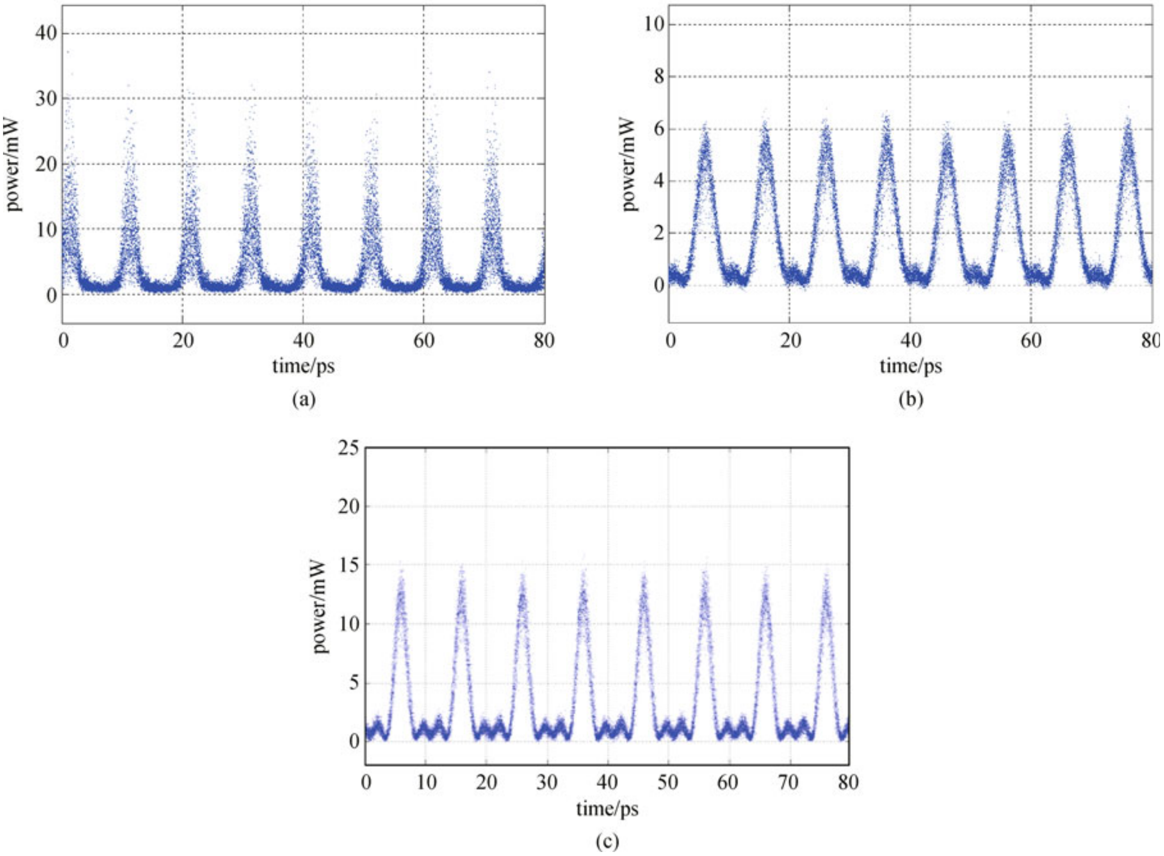


Fig. 8 (a) Waveforms of recovered clock with FPC only; (b) FPC and 40 ps SOA; (c) FPC and 10 ps SOA

RZ formats [31]. It features with wavelength-preserving 2R function, patterning effect free operation, and improved stability by eliminating interferometric structures required by other contemporary SOA-based schemes. Previously, wavelength-preserving 2R regenerations with XGC at 10 Gb/s [31] and 40 Gb/s [32] were already reported, preliminary result at 80 Gb/s was also shown [32] which indicated the potential possibility of an ultra-high operation speed of 100 Gb/s and beyond.

The working principle of XGC is shown in Fig. 9. When an optical data stream is injected into SOA simultaneously with its polarity-inversed copy on another wavelength, the combined optical power is almost constant with small ripples fluctuating. The SOA under this circumstance can be regarded as a high-pass filter [31], which is able to smooth out the ripples. Moreover, the gain for ‘0’ on one wavelength is depleted by its corresponding ‘1’ signal on the other wavelength. Thus, the extinction ratio of the two signals can be both increased.

The polarity-inversed copy is usually generated by cross gain modulation (XGM) in another SOA. However, when the data rate increase to 100 Gb/s, it is impossible to perform XGM while keeping the associated patterning effect under an acceptable level. In this study, we utilized transient cross phase modulation (T-XPM) [33] to enhance the XGM effect.

The experimental setup is shown in Fig. 10. 100 Gb/s OTDM signal was generated at λ_1 = 1547.22 nm. An EDFA was used as a noise loader to degrade original signal. A tunable CW probe laser at λ_2 = 1559.81 nm of 2.5 dBm power was combined with degrade signal of 6 dBm power and was injected in a SOA (SOA 1). Output

Fig. 9 Illustration for principle of XGC

signals of the SOA 1 were separated with optical band-pass filters of 1.5 nm 3 dB bandwidth centered at λ_1 (for amplified degraded signal) and close to λ_2 (for the logic-inverted copy). The center of the optical filter close to λ_2 was slightly detuned to the blue side of λ_2 so that faster T-XPM could assist the XGM effect to get a much better logic-inverted signal. The separated logic-complementary copies from XGM stage were realigned with ODL, power-balanced with tunable attenuators (Att), recombined with a coupler and finally injected into a second SOA (SOA 2) to perform XGC. The gain recovery time of SOA 2 is only ~10 ps in order to enhance the performance of XGC. A total constant combined optical power of 6.3 dBm was fixed to keep the SOA 2 in deep-saturated region in which the amplitude fluctuation of the degraded signal was reduced due to a compressed optical gain. After SOA 2, optical filters were used to separate the wavelength-preserving 2R regenerated signal at λ_1 and wavelength converted signal close to λ_2. Figure 11 shows the 100 Gb/s eye-diagrams of the ASE-degraded optical signal, logic preserved, logic inverted signal after the XGM stage, and the 2R regenerated signal at λ_1, respectively.

Notice that the eye-diagram of logic preserved signal at the output of SOA 1 at λ_1, compared with original degraded signal, had a reduced mark amplitude jitter and a 3.1 dB Q factor enhancement. It mainly resulted from the self-gain modulation in the saturated SOA 1. The signal quality of the regenerated signal was substantial improved

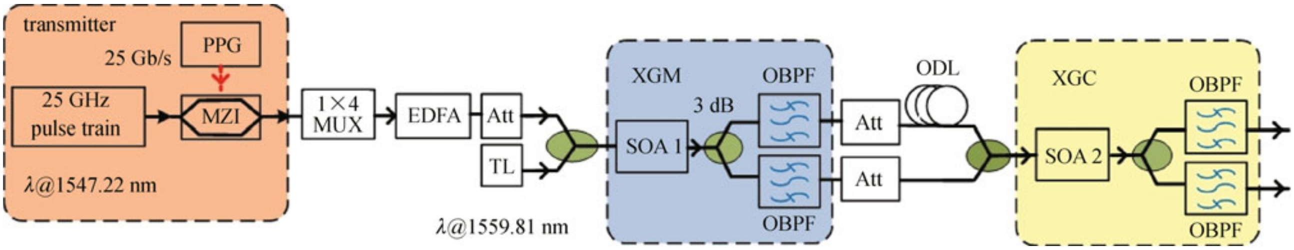
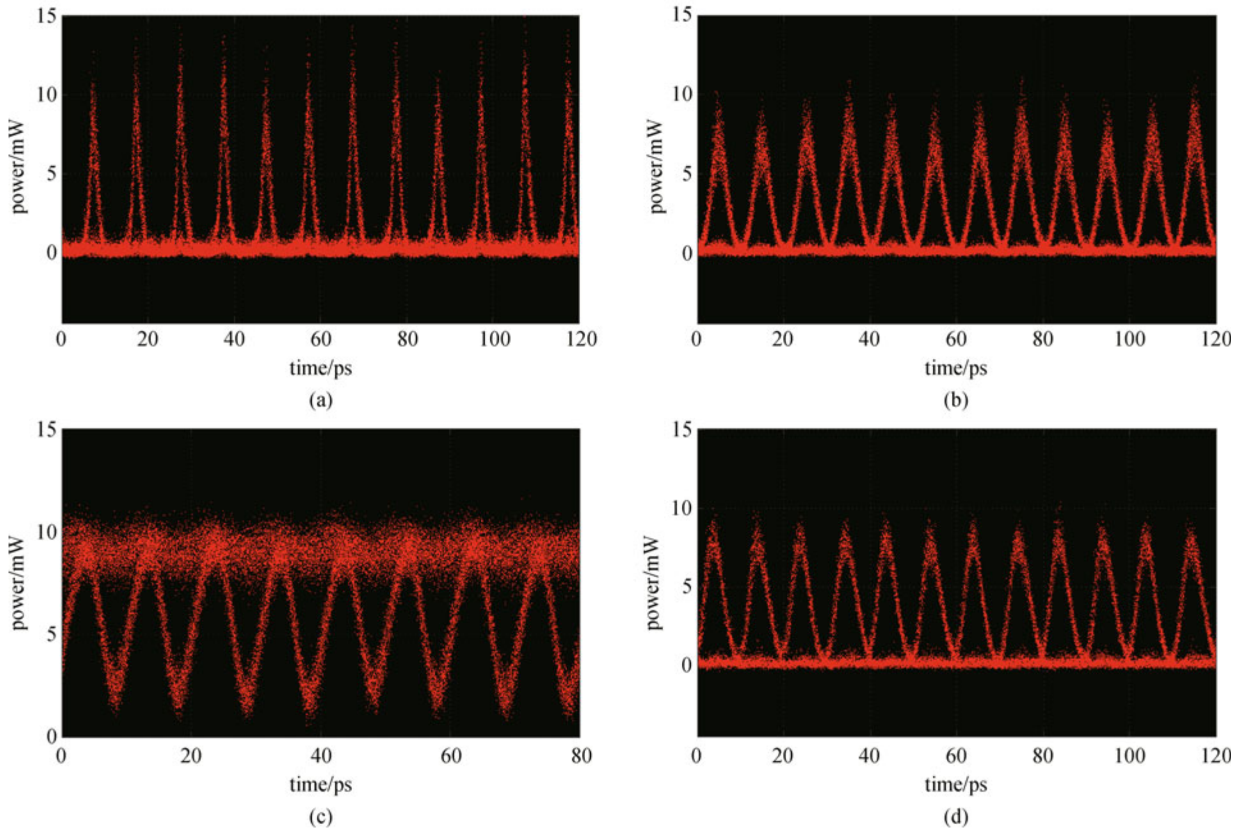


Fig. 10 Experimental setup for 100-Gb/s 2R regeneration



(a) (b) (c) (d)

Fig. 11 (a) Eye-diagrams of degraded 100-Gb/s signal with Q factor of 9.2 dB; (b) logic-preserved signal with Q factor of 12.3 dB at SOA 1 output; (c) logic-inverted signal at SOA 1 output; (d) 2R regenerated with Q factor of 19.6 dB at SOA 2 output compared with the degraded signal and a *Q* factor of 19.6 dB (10.4 dB improvement over the original degraded signal) was obtained.

6 Conclusions

In this paper, we review our recent progresses in signal generation and processing at the bit rate of 100 Gb/s with OOK modulation format. The high-speed 100 Gb/s OOK system was implemented by using OTDM method. An ultrashort pulse generator consists of PM modulator and HNLF was able to generate 25 GHz 2 ps FWHM pulse train. With two CW lasers and careful control of FWM, ~2 ps pulse trains at four wavelengths were generated simultaneously. We demonstrated successful 100 Gb/s RZ-to-NRZ format conversion with a 0.88 nm optical filter by spectral confinement. 100 GHz all-optical clock recovery was implemented with a FPC in conjunction with a SOA with fast recovery time. The recovered clock has only a 5% amplitude fluctuation. 100 Gb/s all-optical 2R generation was demonstrated based on the combination of T-XPM assisted XGM and XGC in an ultrafast SOA. A *Q* factor improvement of 10.4 dB was obtained. Notice all the demonstrated schemes for optical signal processing in this paper (i.e., format conversion, clock recovery and 2R regeneration) can be integrated into small optical chips. We anticipate these chips as well as the technologies could one day benefit the future ultrafast transparent networks.

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