A cost-effective 100-Gb/s transmitter with low-speed optoelectronic devices and high spectral efficiency

Junming Gao (高俊明), Qingjiang Chang (昌庆江), Tao Wang (王 涛), and Yikai Su (苏翼凯)

State Key Lab of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering,
Shanghai Jiao Tong University, Shanghai 200240

Received December 3, 2007

A 100-Gb/s high-speed optical transmitter is proposed and experimentally demonstrated. Based on frequency-quadrupling technique, two sub-channels with a fixed 50-GHz spacing are obtained from one laser source. Using return-to-zero differential quadrature phase-shift keying (RZ-DQPSK) modulation format and polarization multiplexing (PolMux), only low-speed electronic devices of 12.5 GHz are needed for the 100-Gb/s transmitter. This eliminates the need of ultrahigh-speed optoelectronic devices and thus greatly reduces the cost. The experimental results show that this transmitter can achieve good performance in dispersion tolerance of a 25-km single mode fiber (SMF).

OCIS codes: 060.0060, 060.2360, 060.5060.
doi: 10.3788/COL20080608.0550.

With the wide deployment of Ethernet, data based traffic has grown dramatically. Currently 10-Gb/s Ethernet (10 GbE) has been employed in the local area networks (LANs). As broad bandwidth services, such as IPTV, IP video are emerging, higher capacity networks will be desirable in the near future. Recently, the High-Speed Study Group (HSSG) of Institute of Electrical and Electronics Engineers (IEEE) voted and came to a conclusion that the next generation of Ethernet would be 100 GbE. It is also expected that 100 GbE will play an important role in metropolitan area networks (MANs) and wide area networks (WANs)[1].

The predicted application of 100 GbE in the near future has led to significant research[2−6]. There have been several methods demonstrated for 100-GbE implementations at the physical layer. Electrical time-division multiplexing (ETDM) was used to generate 100-Gb/s optical non-return-to-zero (NRZ) signal[7,8]. This method needs immature ultrahigh-speed electronic devices and optical modulator. Another approach used two 50-Gb/s electrical data streams and one 40-G differential quadrature phase-shift keying (DQPSK) modulator to achieve a 100-Gb/s DQPSK signal[9]. In addition, based on multi-carrier generation scheme using a 40-G phase modulator and 40-GHz electrical clock, four 25-Gb/s electrical signals were used to generate a 100-Gb/s signal[10]. These schemes[7−10] need high-speed optoelectronic devices with relatively high cost.

In this letter, we propose and experimentally demonstrate a 100-Gb/s transmitter realized with electrical data rate as low as 12.5 Gb/s. Only low-speed optoelectronic devices are used for this transmitter thus greatly reducing the system cost. The transmitter is experimentally investigated through a 25-km transmission setup showing its good tolerance to residual dispersion.

The schematic diagram of the proposed 100-Gb/s transmitter is shown in Fig. 1. The continuous-wave (CW) light from a tunable laser (TL) is firstly modulated by a 12.5-GHz electrical clock signal through frequency-quadrupling technique[11], generating two sub-wavelengths with a fixed spacing of 50 GHz. After separation by a 50/100-GHz inter-leaver, the two sub-wavelengths are modulated respectively. A Mach-Zehnder modulator (MZM) is biased at the quadrature point and driven by a 12.5-GHz clock, modulating each sub-wavelength to generate a 12.5-GHz optical return-to-zero (RZ) pulse train with a 50% duty cycle. The pulses are divided into two parts by a 3-dB coupler and each part is modulated by a DQPSK modulator driven by two 12.5-Gb/s electrical data streams to generate 25-Gb/s RZ-DQPSK signal. Then the two RZ-DQPSK signals are polarization-multiplexed by a polarization beam splitter (PBS). After the polarization multiplexing (PolMux), the two sub-channels are combined by a 50/100-GHz inter-leaver, resulting in the 100-Gb/s optical signal.

The experimental setup is depicted in Fig. 2. A CW light at a wavelength of 1553.95 nm is used as the light source. It is first modulated by two cascaded MZMs biased at the null points to realize optical-carrier suppressed (OCS) modulation. The 12.5-GHz driving signal from a radio frequency (RF) synthesizer (Agilent E8257D) is divided by a 3-dB power splitter to drive

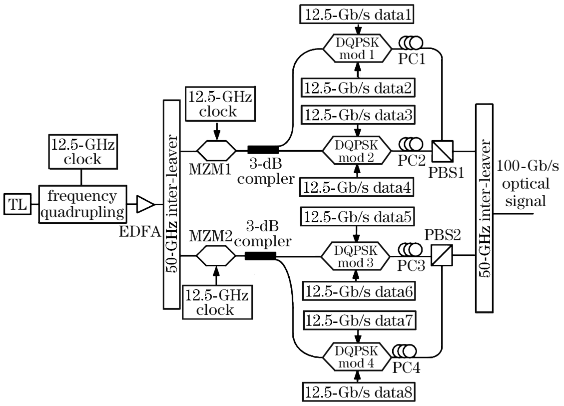

Fig. 1. Schematic diagram of the proposed 100-Gb/s transmitter. PC: polarization controller; mod: modulator.

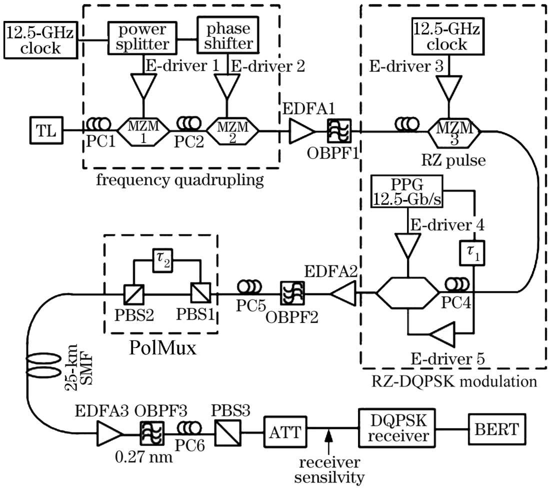

Fig. 2. Experimental setup. E-driver: electrical driver; ATT: attenuator; BERT: bit error ratio test.

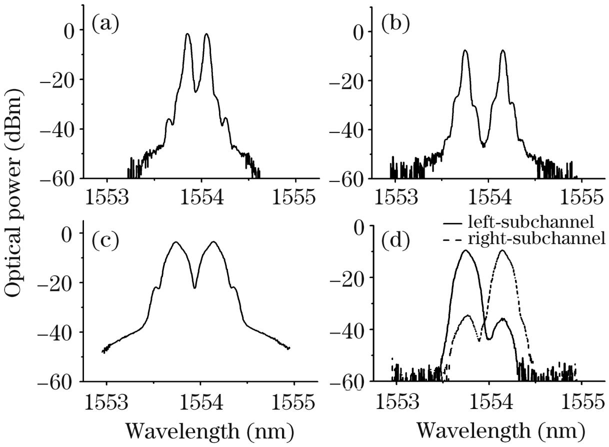

Fig. 3. Optical spectra of (a) OCS, (b) frequency quadrupled, (c) 100-Gb/s signal, and (d) signal after wavelength filtering and PolDemux, with a resolution of 0.07 nm.

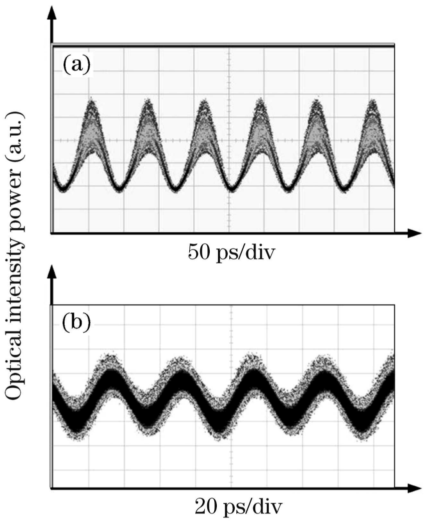

Fig. 4. Eye diagrams (a) before and (b) after PolMux.

the two modulators, respectively. A phase shifter is used to induce a 90° phase difference between the two driving signals so as to achieve frequency quadrupling. The spectra at the output of MZM1 and MZM2 are shown in Figs. 3(a) and (b). It can be seen that the two sub-wavelengths with the 50-GHz spacing are obtained after MZM2, and the zero-order, first-order and third-order side components are well suppressed. The signals are then amplified through an erbium-doped fiber amplifier (EDFA) followed by an optical band-pass filter (OBPF) to suppress the amplified spontaneous emission (ASE) noise. MZM3 is biased at the quadrature point and driven by a 12.5-GHz sinusoidal wave as a pulse carver with 50% duty cycle. Due to the lack of two DQPSK modulators, the two sub-wavelengths are not separated and we modulate them with the same patterns. The pulses are modulated by the same DQPSK modulator which is driven by two 12.5-Gb/s electrical data streams with inversed patterns and a word length of $2^7 - 1$ from a pulse pattern generator (PPG). There is a 33-bit delay between the two data streams for decorrelation. After amplification and filtering, the modulated signals are divided into two orthogonal parts in polarization states by a PBS, and then they are recombined by another PBS with a $\sim$ 15-ns relative delay between the two paths. The eye diagrams before and after the PolMux are depicted in Figs. 4(a) and (b), respectively. After the PolMux, each sub-wavelength carries 50-Gb/s RZ-DQPSK signal. The spectrum of the 100-Gb/s signal is shown in Fig. 3(c).

We study the dispersion tolerance of the generated signal through a 25-km single mode fiber (SMF) transmission. The input optical power into the SMF is 0.6 dBm, so nonlinear impairments are not significant. At the receiver side, the signal is amplified by an EDFA and filtered by an optical tunable filter with a 3-dB bandwidth of 0.27 nm to select the desired sub-channel. The signal is further polarization demultiplexed by the third PBS. The spectra after the filtering and polarization demultiplexing (PolDemux) are shown in Fig. 3(d), showing that the two sub-channels are well separated. The back-to-back (BTB) eye diagram is depicted in Fig. 5(a), and Fig. 5(b) provides the eye diagram after the transmission. The eye diagram is blurred due to the dispersion effect. The residual dispersion in this system is $D = 25$ km × 17 ps/nm/km = 425 ps/nm.

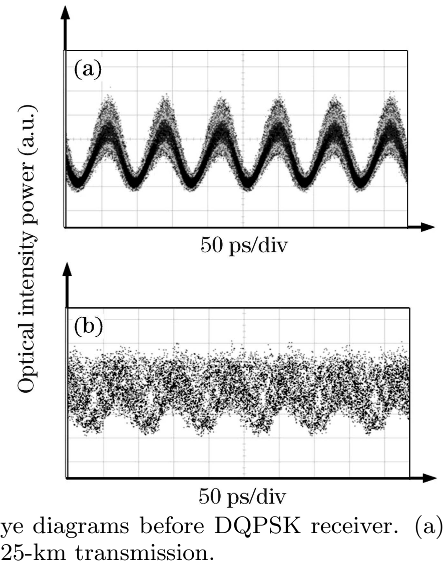

Fig. 5. Eye diagrams before DQPSK receiver. (a) BTB and (b) after 25-km transmission.

A Mach-Zehnder delay interferometer (MZDI) is used to demodulate the DQPSK signal. By tuning the differential optical phase between the two arms, we gets either the in-phase (I) or quadrature-phase (Q) component of the RZ-DQPSK signal. A balanced receiver composed of two photo-detectors (PDs) with a 3-dB bandwidth of 9 GHz is used to detect the demodulated signal. The detected eye diagrams in BTB and after transmission are shown in Figs. 6(a) and (b), respectively. The bit error ratios (BERs) of all the eight tributaries are measured. Due to the nature of DQPSK modulation, the received data sequence is not a pseudorandom pattern, thus we calculate the pattern to measure the BER performance. The receiver input power is defined as the optical power before the DQPSK receiver, as shown in Fig. 2. The BTB BERs are measured and depicted in Fig. 7(a). After transmission, the measured BERs as a function of input power are shown in Fig. 7(b), which indicate that all the eight tributaries have similar performances with sensitivities of ~ -8.7 dBm at BER $= 10^{-9}$. The power penalties after the 25-km transmission are ~ 1.6 dB, which can be mainly attributed to the uncompensated chromatic dispersion.

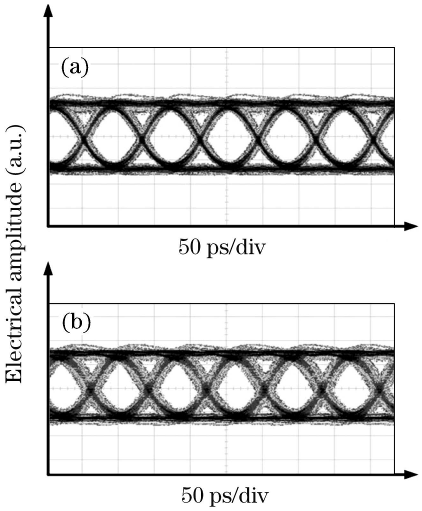

Fig. 6. Eye diagrams after demodulation. (a) BTB and (b) after 25-km transmission.

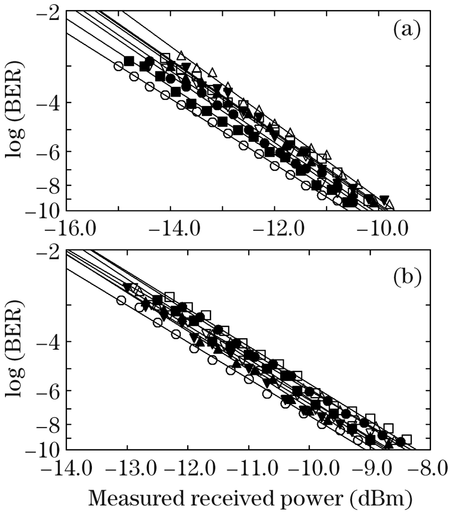

Fig. 7. BER curves. (a) BTB and (b) after 25-km transmission.

In conclusion, we propose and experimentally demonstrate a 100-Gb/s transmitter with low-speed optoelectronic devices, which can be expected to greatly reduce the system cost. With the frequency quadrupling technique to obtain two sub-channels, the RZ-DQPSK modulation and the PolMux, the baud rate can be reduced to 12.5 GB/s. The 20-dB bandwidth of the generated 100-Gb/s signal is $\sim$ 100 GHz thus a high spectral efficiency can be expected. Experimental results indicate that the transmitter has good performances after the 25-km SMF transmission and the power penalties are only $\sim$ 1.6 dB with a residual dispersion of 425 ps/nm.

This work was supported by the "863" Program of China under Grant No. 2006AA01Z255. Y. Su is the author to whom the correspondence should be addressed, his e-mail address is yikaisu@sjtu.edu.cn.

References

1. M. Duelk, in *Proceedings of ECOC* Tu3.1.2 (2005).
2. C. R. S. Fludger, T. Duthel, and C. Schulien, in *Proceedings of LEOS* ME1.2 (2007).
3. H. Barrass, M. Gustlin, O. Trainin, and M. Nowell, in *Proceedings of LEOS* TuX 2 (2007).
4. A. F. Benner, P. K. Pepeljugoski, and R. J. Recio, IEEE Communications Magazine **11,** 10 (2007).
5. S. Melle, J. Jaeger, D. Perkins, and V. Vusirikala, IEEE Communications Magazine **11,** 18 (2007).
6. S. J. Trowbridge, IEEE Communications Magazine **12,** 120 (2007).
7. P. J. Winzer, G. Raybon, and M. Duelk, in *Proceedings of ECOC* Th 4.4.1 (2007).
8. G. Raybon, P. J. Winzer, and C. R. Doerr, in *Proceedings of OFC* PDP32 (2006).
9. M. Daikoku, I. I. Morita, H. Taga, H. Tanaka, T. Kawanishi, T. Sakamoto, T. Miyazaki, and T. Fujita, in *Proceedings of OFC* PDP36 (2006).
10. J. Yu, X. Zhou, L. Xu, P. N. Ji, and T. Wang, in *Proceedings of OFC* JThA42 (2007).
11. J. Zhang, H. Chen, M. Chen, T. Wang, and S. Xie, IEEE Photon. Technol. Lett. **19,** 1057 (2007).