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RESEARCH ARTICLE

Generation of 40 GHz phase stable optical short pulses using intensity modulator and two cascaded phase modulators

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Abstract Pulse sources based on lithium niobate modulators are very attractive for optical time division multiplexing (OTDM) transmission systems because the modulators are now commercially available, qualified for system use, and can operate up to very high speeds and over a wide wavelength range. In this paper, we describe the principles of operation and performance of the pulse source based on lithium niobate modulators. The pulse source is based on a Mach-Zehnder intensity modulator (IM) and two phase modulators (PMs). The continuous-wave (CW) light is modulated in an IM and then strongly phase modulated in two cascaded PMs. The chirped pulses are subsequently compressed to desired width using dispersion compensation technology. This method has the advantage of acquiring larger chirp using normal PM rather than that special designed PM of very low V_π. It can also generate shorter pulses than conventional methods incorporating only one PM driving by a radio frequency (RF) signal with the power larger than 1 W which may damage the device. Generation of 40 GHz optical pulses shorter than 2 ps is theoretically illustrated, simulated and experimentally verified. Experimental results show that 40 GHz phase stable optical pulses with pulse-width of 1.88 ps, extinction ratio (ER) larger than 20 dB, the timing jitter of 57 fs and signal-to-noise ratio (SNR) of 32.8 dB can be achieved. This is also a cavity-less pulse source whose timing jitter is determined only by the RF source rather than by the actively controlled cavity. In the experiment, the phase noise of the RF source we used is as low as −98.13 dBc/Hz at a 10 kHz offset frequency which resulting very low timing jitter of generated pulses. The pulses are then modulated at 40 Gbaud/s with an inphase/quadrature (I/Q) modulator and multiplexed to 160 Gbaud/s with less interference between each other. After back-to-back demultiplexing by an electro-absorption modulator (EAM) to 40 Gbaud/s and demodulation by a delay interferometer (DI), clear and opened eye diagrams of 40 Gbaud/s I and Q tributary signals are obtained which verify the good performance of generated pulses in the 160 Gbaud/s differential quadrature phase shift keying (DQPSK) OTDM system and further prove the phase stability and high quality of generated pulses.

Keywords short pulse, intensity modulator, phase modulator, pulse compression, phase stable, differential quadrature phase shift keying (DQPSK)

1 Introduction

Generation of high-quality ultra-short optical pulses with high repetition rate and phase stability is an important technique for phase modulated optical time division multiplexing (OTDM) transmission systems such as differential phase shift keying (DPSK) and differential quadrature phase shift keying (DQPSK) systems [1–4]. Many schemes have been proposed to generate short optical pulses. Generating pulses from active mode-locked pulsed fiber lasers which, although capable of producing high-power, low timing-jitter, sub-picosecond pulses at high repetition-rate, requires a phase-locking control system to maintain the stability, which increases the cost and complexity [1]. The generation of pulses from cascaded electro-absorption modulators (EAMs) [2] is very simple, but the large insertion loss of the EAM will degrade the optical signal-to-noise ratio (SNR) of generated pulses. In Refs. [3,4], pulse compression based on fiber nonlinearity usually requires long fiber length and high input optical power. However, pulse generation from electro-optic components such as the $LiNbO_3$ Mach-Zehnder modulator (MZM) [5,6] can offer a simpler, highly stable and potentially lower cost solution with

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desirable features of low insertion loss and wide operating wavelength range. Just a sinusoidal driving voltage and a direct current (DC) bias are required for pulse generation, and it can carve pulses with ultra-low timing jitter. Therefore the generation of phase stable optical pulses using cascaded intensity modulators (IMs) and phase modulator (PM) is a compact and cost effective method for high speed OTDM systems. To the best of our knowledge, the shortest pulse generated by this method reported is 2.2 ps using a PM of low V_π driving by a radio frequency (RF) signal with voltage swing over $2V_\pi$ at 40 GHz and the RF power is over 1 W which may damage the device [5]. In addition, the requirement of the pulse source in 160 Gbaud/s OTDM systems is less than 2 ps, and thus the generated pulses using one PM are not suitable for 160 Gbaud/s OTDM systems.

In this work, we experimentally demonstrate a scheme to generate phase stable short optical pulses using a $\mathrm{LiNbO_3}$ intensity modulator followed by two cascaded optical phase modulators instead of a single optical phase modulator of the conventional method and a roll of dispersion compensation fiber [4]. This method does not require the special designed phase modulator of low V_π at 40 GHz and also avoids taking the risk of damaging devices. The generated optical pulses are measured to have a full width at half maximum (FWHM) of 1.88 ps with extinction ratio (ER) larger than 20 dB, timing jitter as low as 57 fs and SNR of 32.8 dB which have been successfully employed in a 160 Gbaud/s DQPSK OTDM system.

2 Principle and simulations

Principle of the pulse source relies on utilizing linear compression of the pulses. The original pulses are generated by an IM driven by a DC bias and an RF signal. The nonlinear transfer nature of the MZM is used by biasing the modulator below the quadrature point, resulting in return-to-zero (RZ) pulse output at the repetition rate the same as the frequency of driving RF signal as shown in Fig. 1. Then pulses passes through two phase modulators to obtain strong phase modulation. Suppose the linear negative chirped light is used to compression, the phase relationship between phase modulation and intensity modulation is shown in Fig. 2, in which the solid curve is the light intensity after IM and the dashed line is the relative frequency chirp induce by two phase modulators.

The complex optical electric field of input optical signal can be expressed as follows:

$$E_{\mathrm{in}}(t) = E_0 e^{\mathrm{j}\omega t}. \tag{1}$$

After the IM, the complex optical electric field of the pulses is given by

$$E_1(t) = E_{\mathrm{in}}(t)\cdot\cos\left[\frac{\pi}{2V_\pi}(V_{\mathrm{in}}(t) - V_{\mathrm{bias}})\right] e^{\mathrm{j}\frac{\pi V_{\mathrm{bias}}}{2V_\pi}}, \tag{2}$$

where V_{bias} is the DC bias voltage, $V_{\mathrm{in}}(t)$ is the RF signal and V_π is the half wave voltage of IM.

Changing the DC bias and RF signal, the output signal will vary correspondingly. Then pulses phase modulated

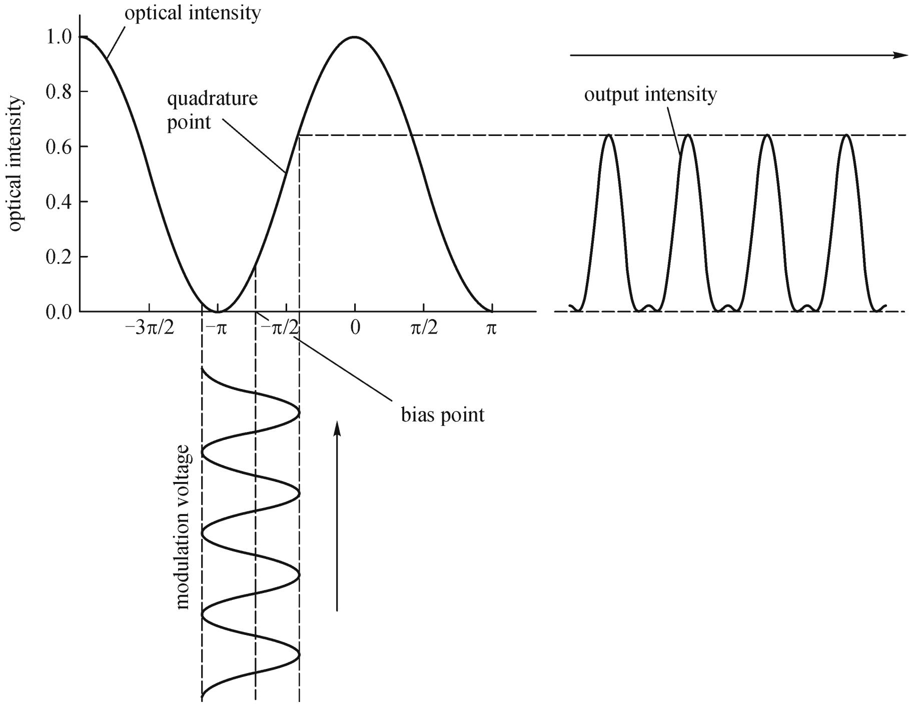


Fig. 1 Principle of pulses generated by IM

by two cascaded PMs are written as

$$E_{\text{out}}(t) = E_1(t)e^{\mathrm{j}\pi V_1 \cos(\Omega t)/V_{\pi 1}} \times e^{\mathrm{j}\pi V_2 \cos(\Omega t)/V_{\pi 2}}, \quad (3)$$

where V_1 and V_2 are the amplitudes of the RF signals that applied on each PM. Ω is the angle frequency of the RF signal. $V_{\pi 1}$ and $V_{\pi 2}$ are the half wave voltages of each PM.

In the simulation, the V_π of IM and each PM is 3.5 and 10 V, respectively. The DC bias is set at 2.2 V and the $V_{\text{p-p}}$ of RF signal is 2.8 V. Pulses generated by IM are as shown in Fig. 3 with the pulse width of 10.7 ps. Then pulses getting into two cascaded PMs with driving RF signals of $V_{\text{p-p}}$= 20 V respectively to obtain large chirp as shown in Fig. 4, the dashed line is the frequency chirp while the solid line is the intensity of the pulses. In order to totally compensate the chirp, the DCF length versus the output pulse width is plotted in Fig. 5. As the calculated result shown 35 m dispersion compensation fiber (DCF) with dispersion coefficient of −95 ps/nm/km will generate shortest pulses in the conditions mentioned above. The shortest pulses are shown in Fig. 6 in which the solid line is the normalized amplitude and the dashed line is the frequency chirp. From Fig. 6, it can be seen that the chirp in the pulse center is zero which means the pulse chirp is totally compensated by the DCF. The generated pulses are 1.81 ps with pedestal for the reason that non-ideal electric signal is applied to PM or relatively broad initial pulses generated by IM.

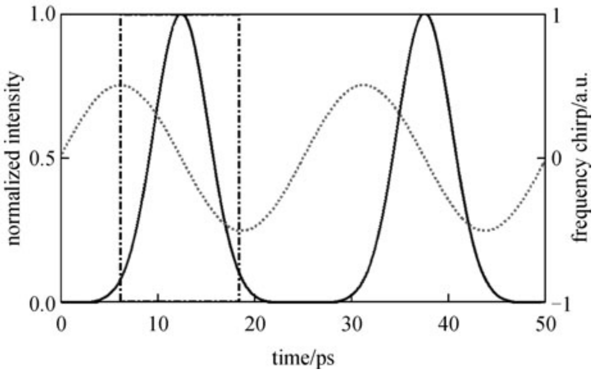


Fig. 2 Relationship of intensity and phase modulation

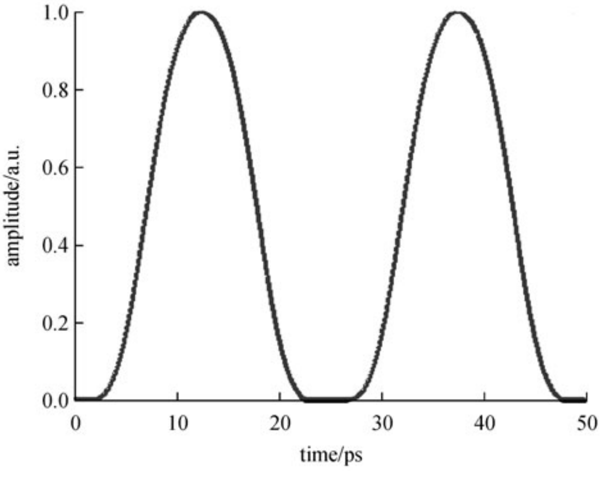


Fig. 3 Pulses generated from IM

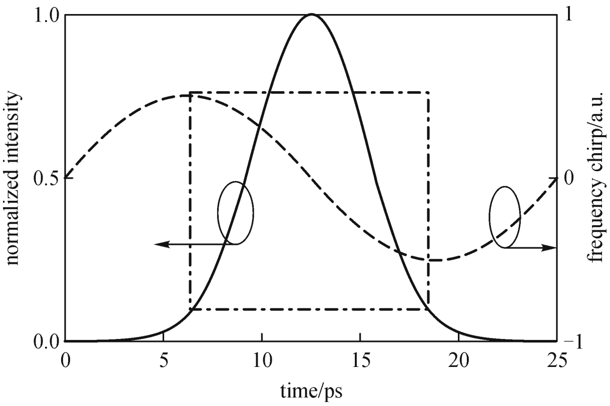


Fig. 4 Intensity and phase properties of pulses after PMs

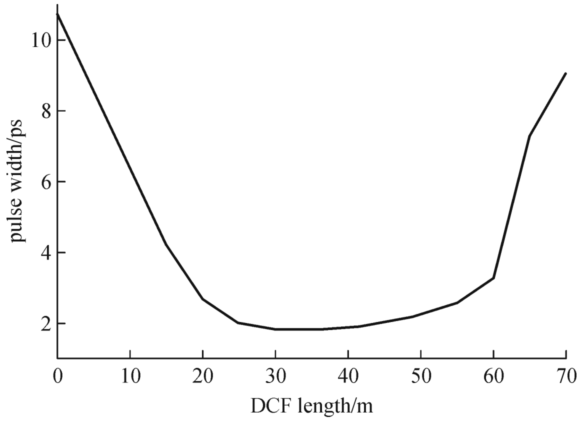


Fig. 5 Pulse width versus DCF length

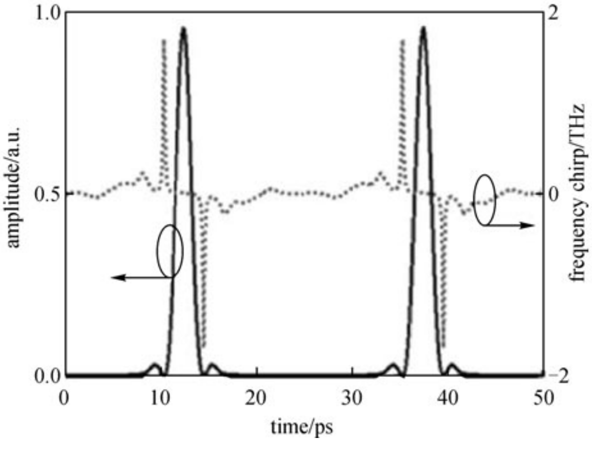


Fig. 6 Generated pulses after DCF

3 Experimental setup

Figure 7 shows the experimental setup of the proposed pulse generation scheme. An IM and two cascaded PMs are all driven by a 40 GHz sinusoidal RF signal from a low phase noise signal synthesizer. A wavelength tunable continuous wave (CW) light with output power of 12.8 dBm is firstly modulated in the IM with DC bias and the RF driving signal. The IM we used is a single drive device with a 3 dB bandwidth of 28 GHz and an insertion loss of 3.5 dB. After the IM, an erbium-doped fiber amplifier (EDFA) is used to compensate the loss and a 3 nm band pass filter is used to suppress the amplified spontaneous emission (ASE) noise. The pulses are then phase

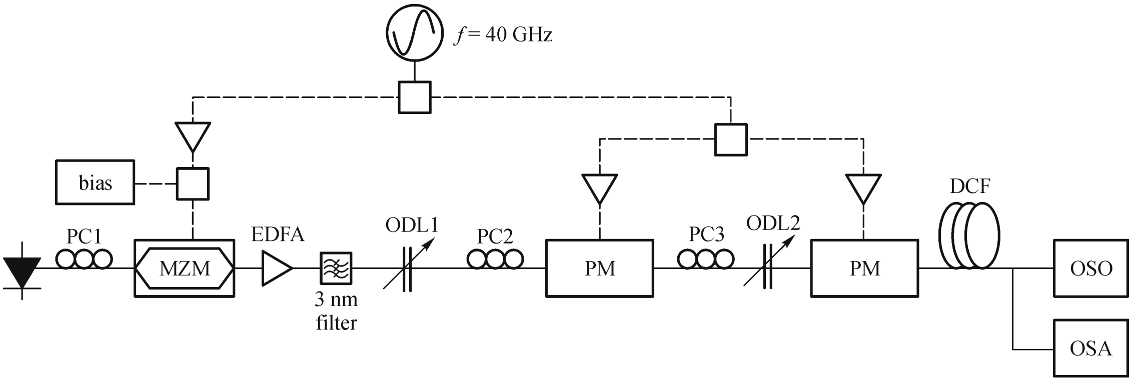


Fig. 7 Experimental setup of proposed short pulse source

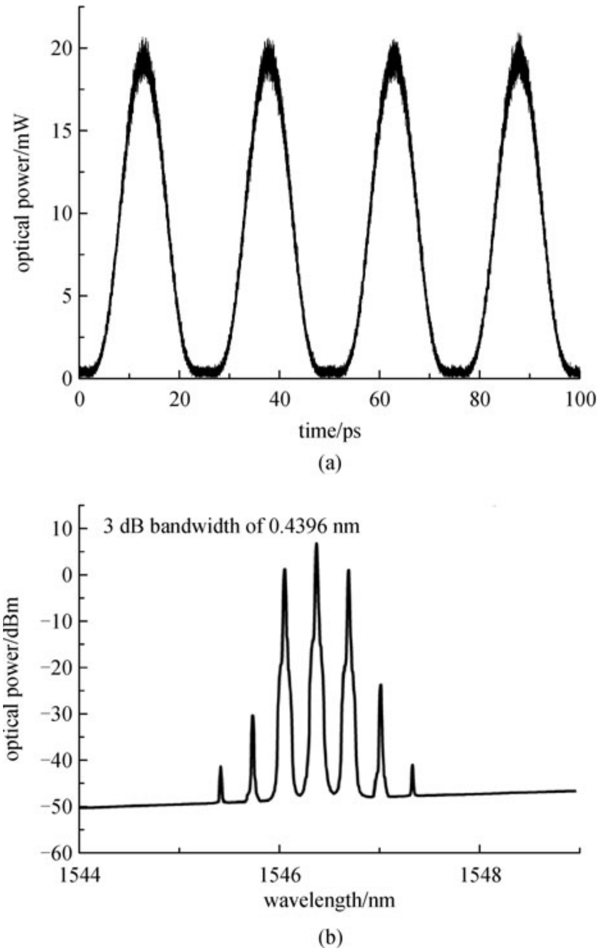


Fig. 8 Generated pulse train and its spectrum after IM. (a) Waveform of pulse train; (b) corresponding spectrum

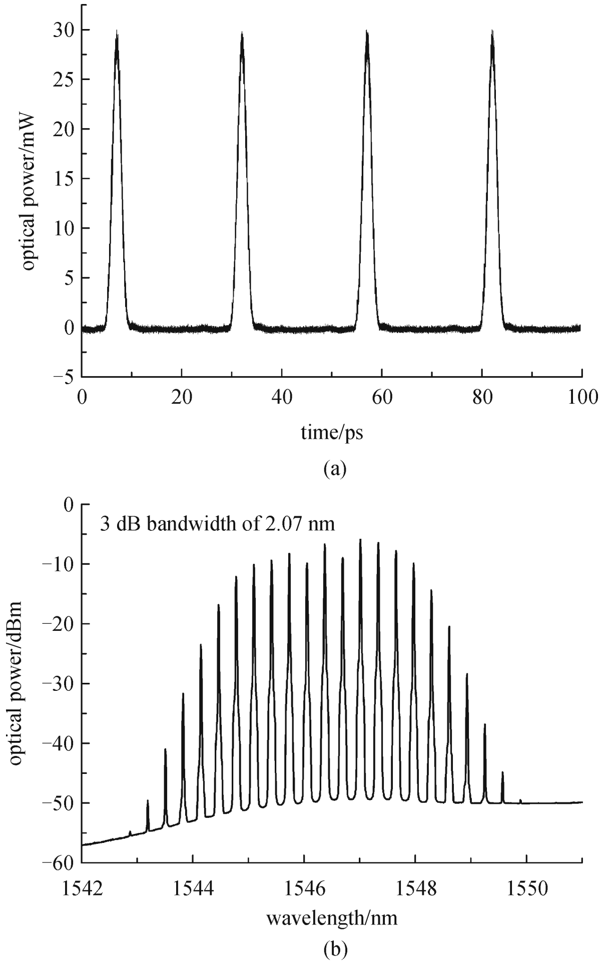


Fig. 9 Generated pulse train and its spectrum after DCF. (a) Waveform of pulse train; (b) corresponding spectrum

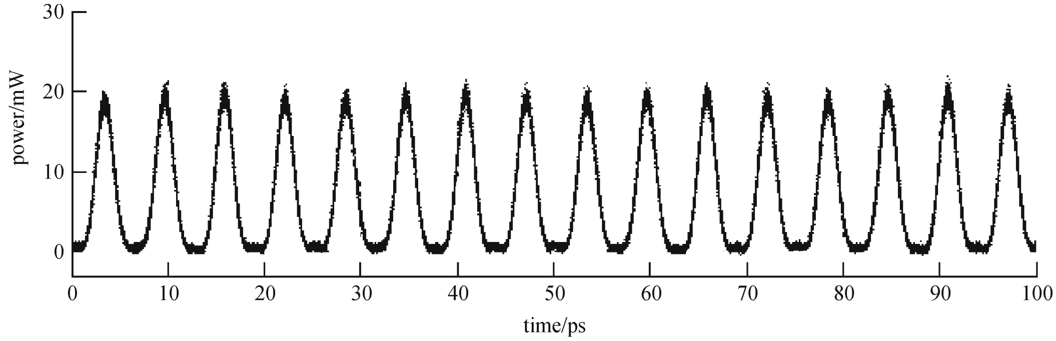
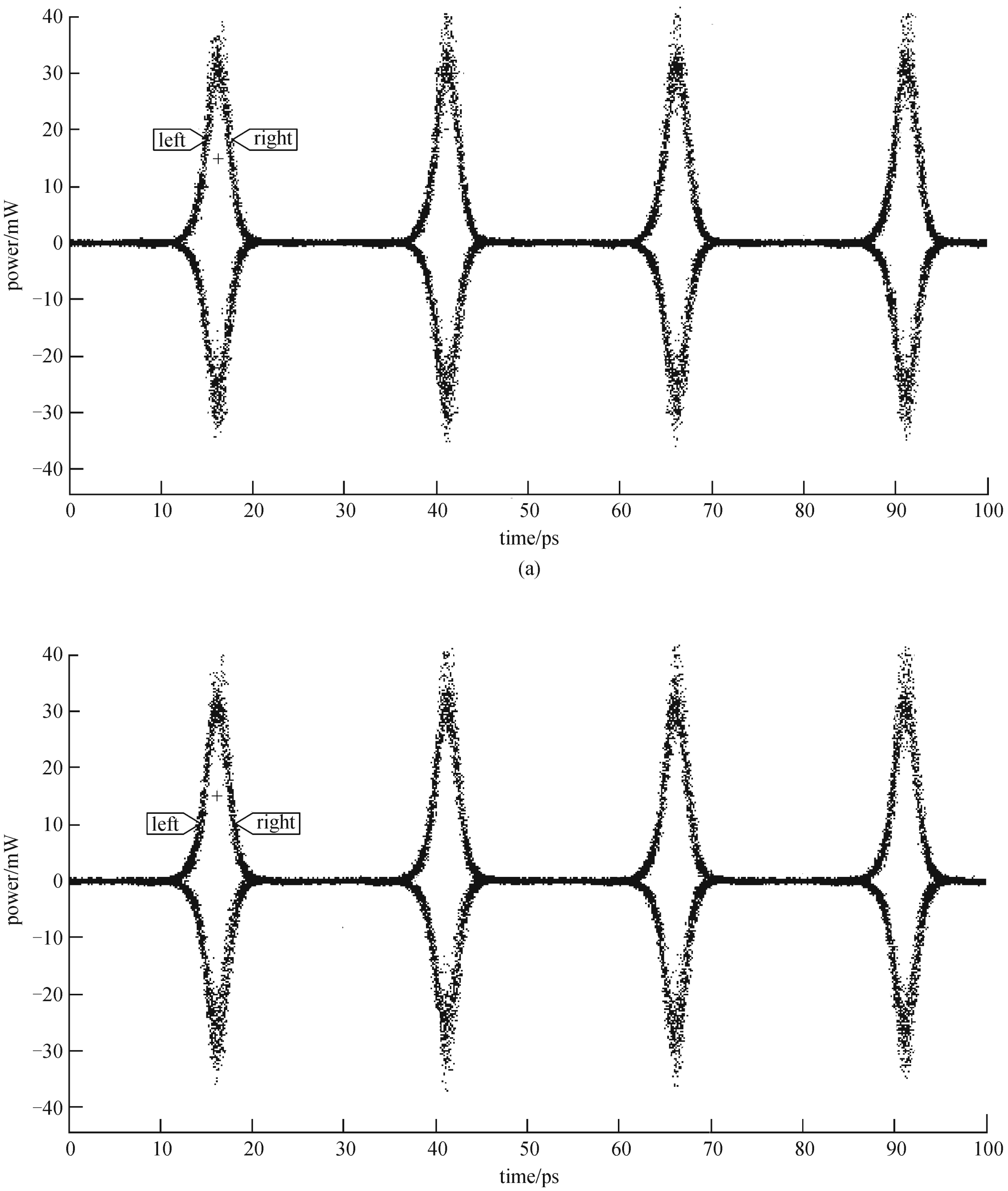


Fig. 10 Eye diagram of 160 Gbaud/s OTDM signal



(a)

(b)

Fig. 11 Demodulated eye diagrams. (a) 40 Gbaud/s I tributary signals; (b) 40 Gbaud/s Q tributary signals modulated by two cascaded PMs with typical V_π of 10 V each and the insert loss of each PM is 4 dB. In order to impose large frequency chirp on the pulses, two electric amplifiers with maximum output power of 27 and 30 dBm respectively are employed. The synchronization of these driven RF signals applied on IM and PMs are realized by the two tunable optical delay lines (ODLs), and then a 36 m DCF with accumulated dispersion of – 3.4 ps/nm is used to compensate the chirp induced by the IM and PMs. The total insert loss of IM and two PMs is much smaller than cascaded two EAMs because the minimum insert loss of one EAM is 10 dBm (CIP 40G-PS-EAM-1550). The waveform and spectrum of the generated optical pulses are measured with a 500 GHz bandwidth optical sampling oscilloscope (OSO, EXFO PSO-102) and an optical spectrum analyzer (OSA) with resolution of 0.02 nm, respectively.

4 Results and discussion

In the experiment, after optimization, the DC bias is set below the quadrature point of the IM nonlinear transfer curve, and the peak to peak driving voltage applied on IM is 3 V, 40 GHz optical pulses with FWHM of 9.5 ps are generated and its 3 dB spectral bandwidth is 0.4396 nm, as shown in Figs. 8(a) and 8(b). After two cascaded PMs and the DCF, the pulse width, ER, timing jitter and SNR of the generated 40 GHz optical pulse are 1.88 ps, 21 dB, 57 fs and 32.8 dB at the wavelength of 1546.3 nm which consist with the simulation results very well. The waveform and spectrum are shown in Figs. 9(a) and 9(b). The spectrum is much broader than that directly generated from the IM. The time-band product is 0.48 that is very close to the Gaussian pulse transform limit.

To verify the phase stability of the optical pulses, the 40 GHz pulses are modulated at 40 Gbaud/s with an I/Q modulator and multiplexed to 160 Gbaud/s. The corresponding eye diagram is shown in Fig. 10. After back-to-back demultiplexing by an EAM to 40 Gbaud/s and demodulation by a delay interferometer (DI), the eye diagrams for 40 Gbaud/s I and Q tributary signals are shown in Figs. 11(a) and 11(b). Clear and opened eye diagram means high phase stability of the pulse, which can be used in 160 Gbaud/s DQPSK OTDM systems.

5 Conclusion

We have demonstrated a scheme for phase stable short optical pulses generation using an IM, cascaded two normal PMs rather than a special designed PM of very low V_π and a short length of DCF. The proposed method produces pulses with high ER of 21 dB, ultra-low timing jitter of 57 fs and shorter pulse width than the usual method incorporating a single PM. The generated 1.88 ps optical pulses are experimentally verified to be phase stable with high SNR and the multiplexing and demodulation results show that the pulse has high phase stability and this scheme finds good application in 160 Gbaud/s DQPSK OTDM systems.

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