A novel scheme to generate 40-GHz CSRZ pulse trains using a 10-GHz dual-parallel Mach-Zehnder modulator

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A new technique to generate 40-GHz carrier-suppressed return-to-zero (CSRZ) optical pulse trains using only a 10-GHz dual-parallel Mach-Zehnder modulator (MZM) is presented and experimentally demonstrated. The spectrum of the generated CSRZ pulses is calculated by simulation and compared with conventional MZM-based RZ and CSRZ pulse trains. The experimental results demonstrate that CSRZ pulse trains are obtained, and that the carrier and the unwanted 20-GHz low-frequency component are suppressed by 25 dB. The technique can also be extended to 160-GHz CSRZ pulse generation when 40-GHz devices are employed.

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Return-to-zero (RZ) and carrier-suppressed RZ (CSRZ) optical pulses have been widely discussed and demonstrated in high-speed optical transmission systems due to their robustness to various fiber-based degradations, not only for traditional on-off keying (OOK), but also for newly presented differential phase shift keying (DPSK) and differential quadrature phase shift keying (DQPSK) transmission systems[1−5]. Therefore, an optical pulse train generator or a pulse caver for RZ or CSRZ might be a key component of future RZ-based optical transmission systems. Several techniques to generate RZ pulses have been proposed and demonstrated. One of the most commonly used methods is to employ a $\mathrm{LiNbO_3}$ Mach-Zehnder modulator (MZM) that can generate both chirp-free RZ and CSRZ pulses by adjusting the bias point of the MZM[6].

However, the repetition rate of the pulses acquired by modulating a MZM either equals the electrical driving clock rate (50% RZ), or doubles the clock rate (33% RZ and CSRZ). With the increase of the optical transmission bit rate, the electrical devices reach severe bottlenecks to speed up. Therefore, generating much higher repetition rate optical pulses by an electrical clock with an even lower frequency is necessary. Recently, techniques for generating CSRZ optical pulse trains with repetition rates of four times the clock rate have been reported, including 1) using a phase modulator plus two polarization-maintaining (PM) fibers and two polarizers[7−9], 2) using a MZM followed by a delay-line interferometer (DLI)[10], and 3) using two cascaded dual-drive MZMs[11]. Among the above techniques, more than two devices have been employed, adding to the complexity of the whole system, which might lead to more instability.

In this letter, a new technique to generate 40-GHz CSRZ optical pulse trains using a 10-GHz electrical clock is presented and experimentally demonstrated, employing only a single dual-parallel MZM (DP-MZM). DP-MZM is a commercially available device typically used as a DQPSK modulator. It also acts as a multi-format transmitter, generating signals with three other formats, including duobinary, RZ alternate-mark-inversion (AMI), and Manchester code format[12]. DP-MZM is also used in pulse train generating schemes[13]. However, when DP-MZM is used as a high-extinction-ratio optical intensity modulator, a DLI is still required, similar to the scheme proposed in Ref. [8]. In our schematic configuration, no extra optical devices are needed, aside from a single integrated DP-MZM, which is driven by two relatively delayed electrical clock signals. Thus, a CSRZ optical pulse train with a repetition rate that is four times the clock rate is immediately obtained at the output port of the modulator. Experimentally, we utilize a 10-GHz clock to drive the modulator in order to generate pulses with a repetition rate of 40 GHz. Furthermore, this method might be potentially extended to a 160-GHz CSRZ pulse generation technique, in which the frequency of the driving clock should be changed to 40 GHz.

Figure 1(a) shows the configuration of the 40-GHz CSRZ optical pulse train generator. The DP-MZM is an integrated device consisting of three MZMs, among which, two x-cut MZMs (MZM-a, MZM-b) are embedded in the two arms of the primary Mach-Zehnder (MZ) structure (MZM-c). The structure is originally intended for DQPSK modulation; however, in this letter, we demonstrate that it can also be used to generate CSRZ pulses.

A single MZM can generate 33% and 50% RZ and 67% CSRZ with its direct current (DC) bias set at different points. When the bias is set at the maximum transmission point of the MZM, and a 10-GHz electrical clock is used to drive it between adjacent minima, a 33% RZ pulse train with a repetition rate of 20 GHz can be obtained at the output port of the MZM. If MZM-a and MZM-b of the DP-MZM are biased similarly as the MZM mentioned above, two 33% RZ pulse trains would be formed respectively in the two arms. However, the two 33% RZ pulse trains cannot be observed simultaneously at the output port, where they combine to form a new pulse train. By extinguishing the light in the other arm, the pulse train generated by each MZM can be seen. An electrical delay line is adopted to make sure that a constant phase delay is present between the driving signals of the two arms, which should be odd times of $\pi/2$. Thus, the two driving signals can be described by $\sin(\Omega t)$ and $\cos(\Omega t)$, as shown in Fig. 1(a), in which Ω represents the angular frequency of the driving signals.

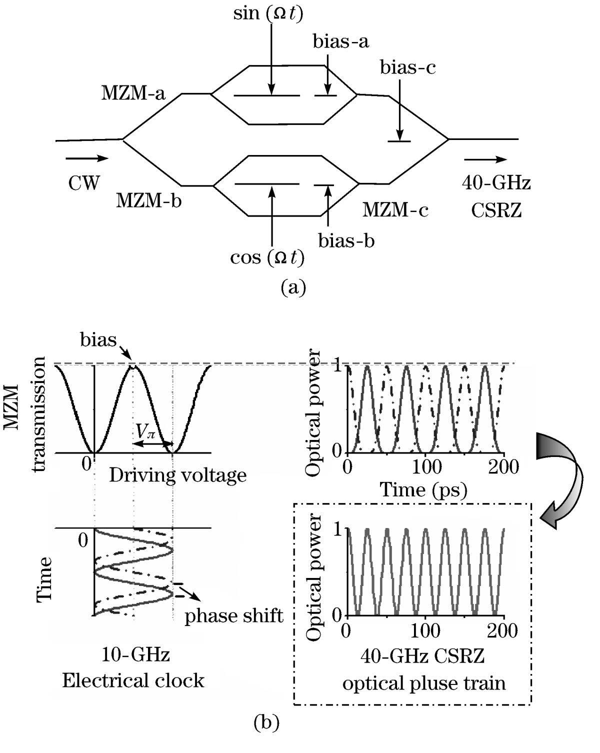
Figure 1(b) shows the conceptual diagram for the 40-GHz CSRZ pulse train generation using a DP-MZM, with a repetition rate that is four times that of the electrical clock signal. With MZM-a and MZM-b biased at the maximum transmission point and driven by a 10-GHz clock between adjacent minima, two 20-GHz 33% RZ pulse trains are generated respectively in the two arms of MZM-c, the optical fields of which can be described by

$$E_1 = \frac{A}{\sqrt{2}} \cos\left[\frac{\pi}{2}\sin(\Omega t)\right]\cos(\omega t), \tag{1}$$

$$E_2 = \frac{A}{\sqrt{2}} \cos\left[\frac{\pi}{2}\cos(\Omega t)\right]\cos(\omega t), \tag{2}$$

where E_1 and E_2 represent the optical fields of the modulated light waves in the two arms of the modulator; A is the amplitude of the input continuous wave (CW) light in the optical field; and the parameters ω and Ω represent the angular frequencies of the optical carrier and the electrical driving clock, respectively. Then, the two pulse trains interfere and combine with each other at the output port. The bias-c is carefully tuned to make sure that the phase shift between the two signals is odd times of π. Thus, the two pulse trains will interleave and interfere destructively with each other, producing the following optical signal:

$$E_3 = \frac{E_1 - E_2}{\sqrt{2}} = A\sin\left[\frac{\pi}{2\sqrt{2}}\sin\left(\Omega t + \frac{\pi}{4}\right)\right] \sin\left[\frac{\pi}{2\sqrt{2}}\cos\left(\Omega t + \frac{\pi}{4}\right)\right]\cos(\omega t). \tag{3}$$



(a)

(b)

Fig. 1. (a) Schematic configuration of the 40-GHz CSRZ optical pulse train generator; (b) conceptual diagram for the 40-GHz CSRZ pulse train generation.

The complex amplitude of E_3 can be expressed as

$$A_3(t') = A\sin\left[\frac{\pi}{2\sqrt{2}}\sin(\Omega t')\right]\sin\left[\frac{\pi}{2\sqrt{2}}\cos(\Omega t')\right]. \tag{4}$$

If T represents the repetition period of the driving clock, then $T = \frac{2\pi}{\Omega}$,

$$A_3\left(t' + \frac{T}{4}\right) = -A_3(t'). \tag{5}$$

Thus, if the driving signal is a 10-GHz electrical clock, the resulting field has the characteristics of a 40-GHz chirp-free CSRZ pulse train. Ideally, the generated CSRZ pulse train has a constant full-width at half-maximum (FWHM), which is 50% of the whole pulse period, without respect to the amplitude of the driving signal. Thus, it behaves differently from conventional RZ or CSRZ generation techniques.

Equations (1) and (2) can be further expanded as

$$E_1 = \frac{A}{\sqrt{2}}\left[J_0\left(\frac{\pi}{2}\right) + 2\sum_{n=1}^{+\infty} J_{2n}\left(\frac{\pi}{2}\right)\cos(2n\Omega t)\right] \cdot \cos(\omega t), \tag{6}$$

$$E_2 = \frac{A}{\sqrt{2}}\left[J_0\left(\frac{\pi}{2}\right) + 2\sum_{n=1}^{+\infty} (-1)^n J_{2n}\left(\frac{\pi}{2}\right)\cos(2n\Omega t)\right] \cdot \cos(\omega t), \tag{7}$$

thus,

$$E_3 = \frac{E_1 - E_2}{\sqrt{2}} = \left\{2\sum_{n=0}^{+\infty} J_{4n+2}\left(\frac{\pi}{2}\right)\cos\left[(4n+2)\Omega t\right]\right\} \cdot A\cos(\omega t). \tag{8}$$

Equation (8) shows that both the carrier tone and the first sideband tone frequencies are eliminated. The simulated optical spectrum is shown in Fig. 2. The left inset shows the waveform of the generated signal, whereas the right inset offers the spectrum of conventional CSRZ pulse trains generated by a single MZM. As shown in Fig. 2, the carrier frequency and higher frequency side tones are both suppressed, partly similarly, but not equally, to 67% CSRZ pulse trains. Further proof is demonstrated by the experiment shown below.

The spectrum of 50% CSRZ-OOK is compared with

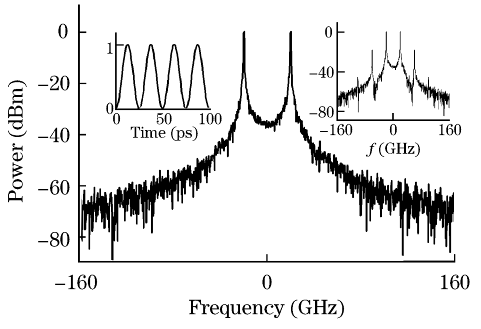


Fig. 2. Spectrum of CSRZ pulse trains.

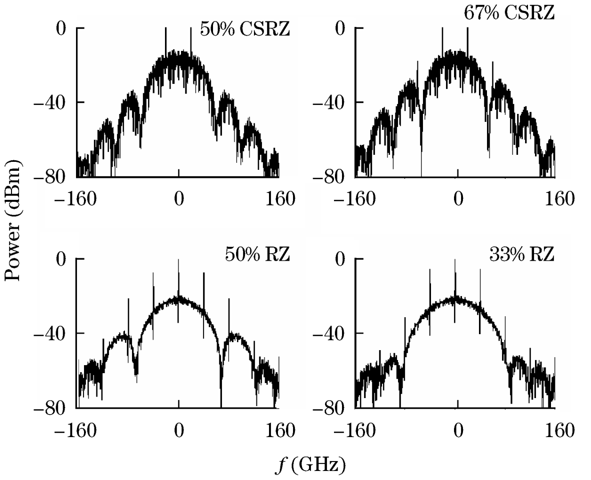


Fig. 3. Simulation results of the spectra of four transmission formats.

Table 1. Parameters for Simulation

Pulse	V_b	V_{pp}	r_c (GHz)	r_p (GHz)
50% CSRZ	0, 0, V_π	$2V_\pi$	10	40
67% CSRZ	V_π	$2V_\pi$	20	40
50% RZ	$V_\pi/2$	V_π	40	40
33% RZ	0	$2V_\pi$	20	40

67% CSRZ-OOK, 50% RZ-OOK, and 33% RZ-OOK by simulation, in which the RZ/CSRZ pulse trains are modulated by 2^7-1 pseudorandom bit sequence (PRBS). The results are shown in Fig. 3.

Compared with 50% RZ-OOK and 33% RZ-OOK, 50% CSRZ-OOK has the characteristic of carrier suppression, which is similar to 67% CSRZ-OOK. However, 50% CSRZ-OOK acts differently from 67% CSRZ-OOK in the frequency domain in that the higher tones are also efficiently suppressed. The parameters for the simulation are listed in Table 1, including the bias point of the modulator V_b, the voltage of the driving clock V_{pp}, the clock rate r_c, and the repetition rate of the optial pulses r_p.

Figure 4 shows the experimental setup for 40-GHz CSRZ pulse train generation. A 1543.5-nm CW light is emitted from a distributed feedback (DFB) laser and then modulated by a DP-MZM. A polarization controller (PC) is utilized to enable the modulator to work effectively. The 10-GHz clock tone is provided by a microwave source and is divided into two parts by a power divider. The phase delay between the two clocks can be controlled by tuning the electrical delay line. Two microwave power amplifiers are employed to ensure that the power of each driving signal is sufficient to drive the modulator. The optical pulses can be observed and measured at the output port by oscilloscope (OSC) and optical spectrum analyzer (OSA).

Figure 5(a) shows the waveform of the generated 40-GHz CSRZ pulse train detected by a 50-GHz photodiode. The observed amplitude fluctuation is caused by the asymmetric characteristics of the two arms, particularly by the power imbalance between the two driving clocks. Its pulse width is approximately 50% of the pulse period,

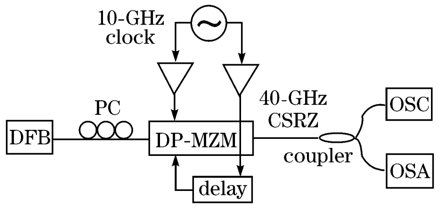


Fig. 4. Experimental setup.

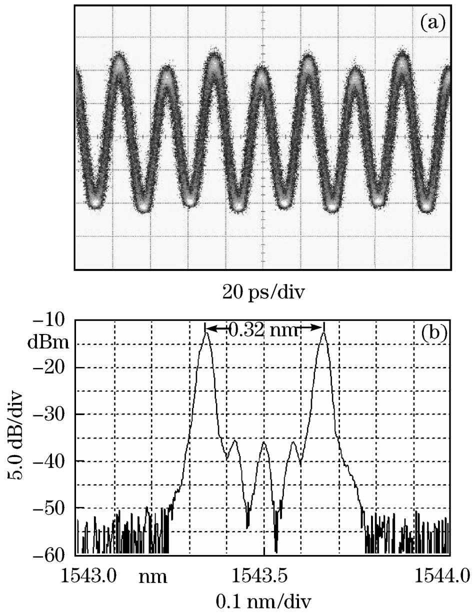


Fig. 5. Experimental results of 40-GHz CSRZ pulse train generation. (a) Waveform; (b) optical spectrum.

which agrees with the theoretical analysis.

Figure 5(b) shows the measured spectrum of the pulse train. The resolution is 0.01 nm. The carrier and the unwanted 20-GHz low-frequency component in the spectrum are both suppressed by approximately 25 dB.

In conclusion, we propose and experimentally demonstrate a new technique to generate CSRZ optical pulse trains using only a single DP-MZM. The new technique can generate 40-GHz CSRZ pulses by employing 10-GHz devices. The experimental results show that the carrier and unwanted lower tones are suppressed by approximately 25 dB. Compared with other models in which more than two devices are employed, the proposed scheme utilizes only one optical device, which may help achieve more stable systems. The operating performance in the new scheme can be controlled by electrically adjusting the bias points of the modulator; however, the electrical circuit may become complex. This technique can be extended to 160-GHz CSRZ pulse generation when 40-GHz devices are employed.

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