Repetition-rate-tunable return-to-zero and carrier-suppressed return-to-zero optical pulse train generation using a polarization modulator

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An approach is proposed to generating return-to-zero (RZ) and carrier-suppressed return-to-zero (CS-RZ) pulse trains with a high and tunable repetition rate by using a polarization modulator (PolM). The PolM is a special phase modulator that can support both TE and TM modes with opposite phase modulation indices. A linearly polarized cw light with its polarization state oriented with an angle of 45° to one principal axis of the PolM is modulated by a sinusoidal signal at the PolM. The output light from the PolM is then sent to a polarization beam splitter (PBS), with one axis of the PBS aligned at an angle of 45° to one principle axis of the PolM. At the two outputs of the PBS, two optical signals with one consisting of the even-order optical sidebands and the other consisting of the odd-order optical sidebands are obtained, leading to the generation of an RZ and a CS-RZ pulse train having a repetition rate that is twice the frequency of the drive sinusoidal signal. The proposed approach is demonstrated by a proof-of-concept experiment in which an RZ and a CS-RZ pulse train with tunable repetition rates of 7.2 and 8 GHz are generated. © 2009 Optical Society of America

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Return-to-zero (RZ) and carrier-suppressed return-to-zero (CS-RZ) pulse trains can find important applications in high-speed optical communications, photonic signal processing, high-speed optical sampling, and ultrafast optical characterization [1,2]. A high-speed RZ or CS-RZ pulse train can be generated from a low-repetition-rate pulse train through pulse multiplication using a superimposed chirped [3] or sampled fiber grating [4]. The repetition rate of a periodic pulse train can also be increased based on the temporal self-imaging effect in a chirped fiber grating [5]. A pulse train with a tunable pulse waveform can be generated by line-by-line spectral shaping using a tunable optical slit [6] or an arrayed waveguide grating (AWG) [7]. A high-repetition-rate optical pulse train can also be generated using a Mach–Zehnder modulator (MZM) [8] or two cascaded MZMs [9]. Recently, an approach to generating a high-speed optical pulse train using a phase or intensity modulator in conjunction with an optical comb filter was proposed [10–13]. For example, a large sinusoidal signal can be applied to a phase modulator to generate multiple spectral lines. The optical comb filter is then used to select the even- or odd-order optical sidebands such that an RZ or CS-RZ optical pulse train with a repetition rate that is twice the frequency of the sinusoidal signal would be generated.

Major limitations associated with the technique using an optical comb filter for pulse train generation with tunable repetition rate are that the free spectral range (FSR) of the optical comb filter is hard to tune or a complex tuning mechanism has to be incorporated to tune the FSR of the comb filter, which makes the system complicated and costly. To solve this problem, in this Letter we propose a simple approach to generating RZ and CS-RZ pulse trains with high and adjustable repetition rates using a polarization modulator (PolM). A PolM is a special phase modulator that can support both TE and TM modes with opposite phase modulation indices. In the proposed approach, a linearly polarized light is sent to the PolM to be modulated by a microwave signal, with the incident light polarized at an angle of 45° to one principal axis of the PolM. The output from the PolM is then sent to a polarization beam splitter (PBS) with one of its principal axes oriented at an angle of 45° to that of the PolM. At the two outputs of the PBS, we obtain two optical signals along the two principal axes, with one signal consisting of all even-order optical sidebands and the other consisting of all odd-order optical sidebands, leading to the generation of an RZ and a CS-RZ pulse train. The entire system is equivalent to a pulse generator that consists of a phase modulator and a complementary comb filter pair, to select the even- and odd-order sidebands. The key advantage of the proposed approach is that no physical complementary comb filter pair is used, which makes the tuning of the repetition rate greatly simplified. In addition, the proposed system required a modulation voltage that is only half of that in the schemes using a single MZM [8], making the realization simplified.

The proposed approach is schematically shown in Fig. 1(a). The system consists of a cw laser source, a PolM, and a PBS. A linearly polarized lightwave from the cw laser source is sent to the PolM. The polarization state of the incident light is rotated at an angle of 45° to one principal axis of the PolM using a polarization controller (PC). A microwave signal is applied to the PolM via the rf port, with two complementary

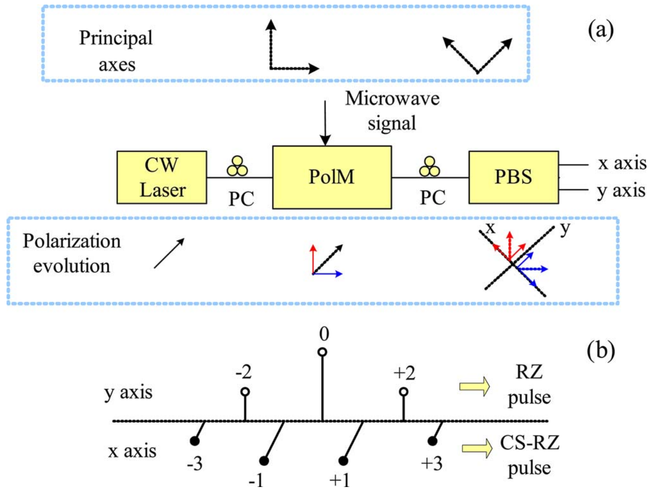

Fig. 1. (Color online) Schematic of the proposed approach for RZ and CS-RZ pulse train generation. PC, polarization controller; PolM, polarization modulator; PBS, polarization beam splitter. (b) The distribution of odd- and even-order sidebands along the two principal axes of PBS.

phase modulations along the two orthogonal principal axes [14–16]. The PBS is connected at the output of the PolM with one principal axis oriented at an angle of 45° to one principal axis of the PolM. At the two outputs of the PBS, two signals along the x and y axes, E_x and E_y, are generated. If the modulation index is $\pi/2$, we have the expressions for the two signals,

$$E_x = \cos[\omega t + \beta \cos(\Omega t)] - \cos[\omega t - \beta \cos(\Omega t)] = \sum_{k=-\infty}^{+\infty} J_{2k+1}\left(\frac{\pi}{2}\right)\cos[(\omega + (2k+1)\Omega)t + (2k+1)\pi/2], \tag{1a}$$

$$E_y = \cos[\omega t + \beta \cos(\Omega t)] + \cos[\omega t - \beta \cos(\Omega t)] = \sum_{k=-\infty}^{+\infty} J_{2k}\left(\frac{\pi}{2}\right)\cos[(\omega + 2k\Omega)t + k\pi], \tag{1b}$$

where $J_k(\,)$ is the kth Bessel function of the first kind, $\beta=\pi/2$ is the modulation index, and ω and Ω are the angular frequencies of the incident lightwave and the microwave signal, respectively.

It is clearly seen that the two signals along the two principal axes are obtained at the outputs of the PBS, with one consisting of the even-order sidebands and the other consisting of the odd-order sidebands, corresponding to an RZ pulse train and a CS-RZ pulse train, respectively. The duty cycles of the RZ pulse train and the CS-RZ pulse train are 33% and 67%, respectively, both having a repetition rate that is twice the frequency of the microwave drive signal. Note that the generation of the optical pulse trains with a doubled repetition rate here is achieved with a modulation index of $\beta=\pi/2$, which is half of the modulation index $\beta=\pi$ adopted in the conventional schemes where a single MZM is used [8].

The proposed approach is simulated. In the simulation, a microwave signal with a frequency of 40 GHz is applied to the PolM. As can be seen from Fig. 2, an RZ pulse train and a CS-RZ pulse train with an identical repetition rate of 80 GHz are generated at the two outputs of the PBS.

To verify the proposed approach, an experiment is performed. The key device in the proposed system is the PolM, which is a commercially available 40 Gbits/s GaAs-based PolM from Versawave Technologies [15] with a polarization extinction ratio of 20 dB, an insertion loss of 3.5 dB, and a pseudorandom binary sequence drive voltage of 5.3 V at 40 Gbits/s. In the experiment, a linearly polarized cw lightwave from a tunable laser source is sent to the PolM with a PC connected before the PolM, to align the polarization direction of the lightwave to have an angle of 45° to one principal axis of the PolM. A 4 GHz microwave signal is applied to the PolM via the RF port. A PBS is connected to the PolM via a second PC. This PC is used to align one principle axis of the PBS to have an angle of 45° with respect to one principle axis of the PolM. The total insertion loss of the link with the PolM and the PBS is about 4 dB, which is close to the insertion loss (4–5 dB) of a typical MZM. At the two outputs of the PBS, two optical signals (one consisting of the even-order sidebands and the other consisting of the odd-order sidebands are obtained), as shown in Figs. 3(a) and 3(b), which correspond to an RZ pulse train and a CS-RZ pulse train in the time domain, as illustrated in Figs. 3(c) and 3(d). The RZ pulse train has a duty cycle of 33% and the CS-RZ pulse train has a duty cycle of 67%. The extinction ratio of the two generated pulse trains is measured to be 11.5 dB, which can be improved if high-accuracy polarization controllers and a high-extinction-ratio PBS are employed. As discussed earlier, the two pulse trains have an identical repetition rate of 8 GHz, which is twice the frequency of the microwave drive signal.

The tunability of the repetition rate is also studied. To do so, we tune the frequency of the microwave drive signal from 4 to 3.6 GHz. Since the half-wave voltage of the PolM varies with the microwave frequency, to ensure the modulation index is maintained at $\pi/2$, we slightly adjust the microwave power to keep a constant modulation index. The optical spectra of the two optical signals at the outputs of the PBS are shown in Figs. 4(a) and 4(b). Again, one signal consisting of the even-order sidebands and the other consisting of the odd-order sidebands are generated, which correspond to an RZ pulse train and a CS-RZ pulse train, as shown in Figs. 4(c) and 4(d).

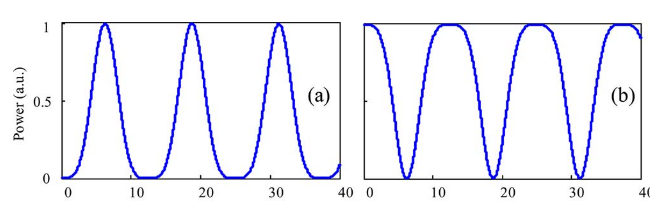

Fig. 2. (Color online) Simulated pulse trains with a repetition rate of 80 GHz when the input microwave frequency is 40 GHz. (a) The RZ pulse train, (b) the CS-RZ pulse train.

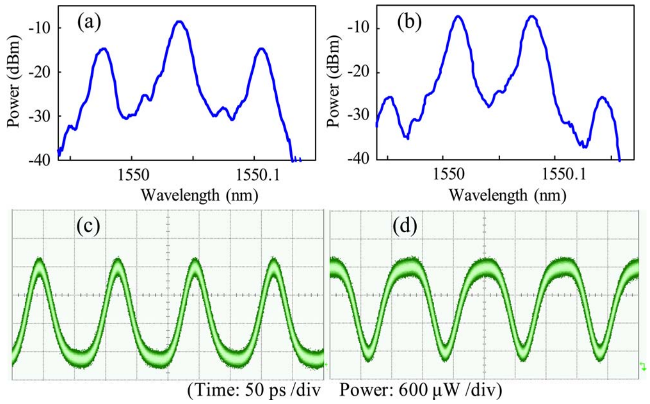

Fig. 3. (Color online) Experimentally generated pulse trains with a repetition rate of 8 GHz: the spectra of (a) the RZ pulse train and (b) the CS-RZ pulse train, temporal waveforms of (c) the RZ pulse train and (d) the CS-RZ pulse train.

The RZ pulse train has a duty cycle of 33%, and the CS-RZ pulse train has a duty cycle of 67%. Since the frequency of the microwave drive signal is tuned to 3.6 GHz, the two pulse trains have an identical repetition rate of 7.2 GHz, which again is twice the frequency of the microwave drive signal. In this experimental study, owing to the lack of a high-frequency microwave amplifier, the experiment is performed for microwave frequencies of 4 and 3.6 GHz. Considering that the PolM can operate up to 40 GHz, if a high-frequency microwave amplifier is used, the tunable repetition rate of the generated pulse trains can be as high as 80 GHz.

In summary, we have proposed and experimentally demonstrated a novel but simple approach to generating repetition-rate-tunable RZ and CS-RZ pulse trains using a PolM. Because a PolM supports both TE and TM modes but with opposite phase modulation indices, when a microwave drive signal is applied to the PolM, complementary phase-modulated signals are generated at the output of the PolM. A PBS was connected at the output of the PolM with one of its principal axis aligned with an angle of 45° to one principal axis of the PolM, two optical signals with one consisting of the odd-order optical sidebands and the other consisting of the even-order optical sidebands were generated, leading to the generation of an RZ and a CS-RZ pulse train. The key significance of the approach is that the repetition rate of the generated pulse trains can be simply tuned by tuning the frequency of the microwave drive signal. The proposed approach was verified by an experiment, in which a microwave signal with its frequency tuned from 4 to 3.6 GHz was applied to the PolM, an RZ and a CS-RZ pulse trains with the repetition rate from 8 to 7.2 GHz were generated.

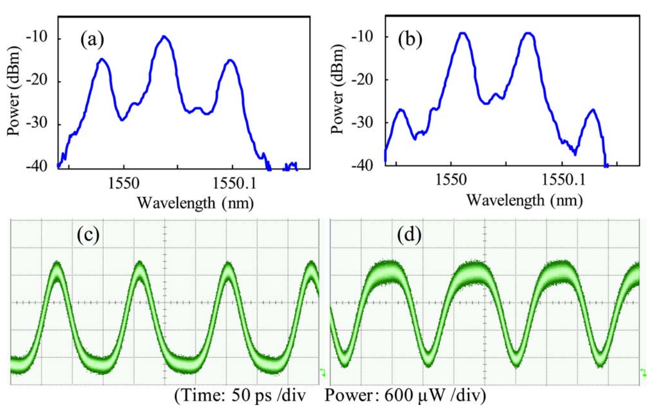

Fig. 4. (Color online) Experimentally generated pulse trains with a repetition rate of 7.2 GHz: the spectra of (a) the RZ pulse train and (b) the CS-RZ pulse train, temporal waveforms of (c) the RZ pulse train and (d) the CS-RZ pulse train

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