Generation of a chirp-free optical pulse train with tunable pulse width based on a polarization modulator and an intensity modulator

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A simple method for the generation of a chirp-free optical pulse train with tunable pulse width using a polarization modulator (PolM) and a zero-chirp intensity modulator (IM) is proposed and demonstrated. In the proposed system, a light wave with its polarization direction oriented at an angle of 45° with respect to the principal axis of the PolM is polarization modulated by a sinusoidal drive signal. An optical polarizer is connected after the PolM to convert the polarization-modulated signals to a pulse train with the main peaks having a narrow pulse width. Then, the main peaks are selected by the IM, leading to the generation of a short optical pulse train with a repetition rate that is identical to or twice the frequency of the sinusoidal drive signal, depending on the dc bias of the IM. The pulse width of the generated pulse is easily tuned by adjusting the phase modulation index of the PolM. An experiment is carried out, and a pulse train with a duty cycle as small as 8.16% is generated. © 2009 Optical Society of America

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High-repetition-rate ultrashort optical pulses are widely used for applications such as optical time-division-multiplex communications, optical imaging, and modern instrumentation. Numerous techniques have been proposed to generate ultrashort optical pulses with high repetition rate [1,2]. One of the most widely used techniques for ultrashort pulse generation is the use of a mode-locked laser, either actively or passively mode locked. To ensure a stable operation, the mode-locked laser should be controlled with sophisticated circuitry, which would increase the system complexity and cost. Optical short pulses can also be generated using a simpler system based on a gain-switched laser diode [1]. The key limitation associated with this technique is that the generated pulses are strongly chirped and have considerably large timing jitter. As an alternative, pulse generation using a cw light source and an electroabsorption modulator (EAM) was suggested [2], but the large insertion loss of the EAM tends to degrade the optical signal-to-noise ratio of the pulses. Recently, a simple and reliable optical-pulse-generation technique using an electro-optical modulator was reported in which a cw light was phase modulated by a sinusoidal signal at a phase modulator (PM) and compressed into a short-pulse train by a dispersive element [3–8]. The generated pulse train with a duty cycle of around 15% could be further compressed into subpicosecond or femtosecond pulses by a pulse compressor, such as a nonlinear soliton compressor [9]. A significant advantage of this method is that the pulse width of the generated pulse is controllable by simply adjusting the phase-modulation index. However, a dispersion element can compensate for only part of the chirp induced by the PM, and the chirp in the other part of the pulse remains, usually located at the pedestals. In addition, when the phase modulation index of the PM is changed, the dispersion provided by the dispersive element should be varied accordingly to compensate for the frequency chirp at the center of the pulse. Because a wideband dispersion-tunable device is commercially unavailable, pulses with different pulse widths obtained by adjusting the phase modulation index would lead to different frequency chirps.

In this Letter, we propose an effective method to generate a short-pulse train using a polarization modulator (PolM) and a zero-chirp intensity modulator (IM). In the proposed system, a cw lightwave from a laser diode is sent to a PolM driven by a sinusoidal electrical signal with a frequency of ω_m. The PolM is a special PM that can support both TE and TM modes with, however, opposite phase-modulation indices [10]. When a linearly polarized incident light is oriented at an angle of 45° to one principal axis of the PolM, complementary phase-modulated signals are generated along the two principal axes. Applying the two signals to a polarizer with its principal axis oriented at 45° to one principal axis of the PolM, the phase-modulated signals will be combined to generate an intensity-modulated signal. If the phase-modulation index is large enough, the output signal at the polarizer is a pulse train with the main peaks having a narrow pulse width. With an IM connected at the output of the polarizer, the main peaks would be selected leading to the generation of a short-pulse train with a repetition rate of ω_m or $2\omega_m$, depending on the dc bias of the IM. Since the phase information is completely converted into the intensity variations, the generated short-pulse train is chirp free. In addition, the pulse width can be easily tuned if the phase-modulation index is adjusted. Furthermore, the proposed approach is wavelength independent and capable of generating a short optical pulse train at various repetition rates.

A diagram illustrating the proposed pulse generation is shown in Fig. 1. A cw light wave from a laser

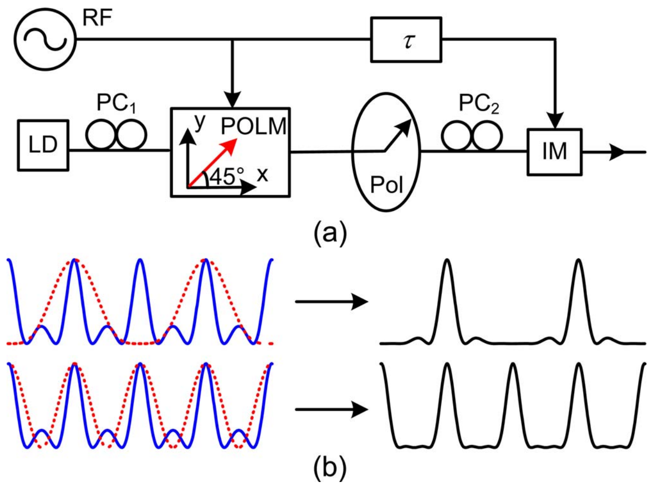

Fig. 1. (Color online) Diagram showing the generation of a chirp-free optical pulse train: (a) block diagram of the proposed pulse generator, (b) operation principle. The solid line shows the pulse train at the output of the polarizer, and the dashed line shows the microwave signal applied to the IM with a proper time delay introduced to select the main peaks in the pulse train. LD, laser diode; RF, radio frequency; IM, intensity modulator; PC, polarization controller; PolM, polarization modulator.

diode that is oriented at an angle of 45° to one principal axis of the PolM is phase modulated along the x and y directions in a PolM driven by a sinusoidal electrical signal with an angular frequency of ω_m. The normalized optical field at the output of the PolM along the x and y directions can be expressed as

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} \exp\left[j\omega_c t + j\frac{\beta}{2}\sin\omega_m t\right] \\ \exp\left[j\omega_c t - j\frac{\beta}{2}\sin\omega_m t\right] \end{bmatrix}, \tag{1}$$

where ω_c is the angular frequency of the optical carrier and β is the phase modulation index of the PolM. Applying the two signals to a polarizer with its principal axis oriented at 45° to one principal axis of the PolM, as shown in Fig. 1, we get

$$E_o = \frac{\sqrt{2}}{2}[E_x(t) + E_y(t)] = \sqrt{2}\cos\left(\frac{\beta}{2}\sin\omega_m t\right)\exp(j\omega_c t). \tag{2}$$

As can be seen from Eq. (2), the phase information is completely converted into intensity variations, with the temporal profile plotted in Fig. 1(b) (solid curve). It is a chirp-free pulse train with the main peaks having a narrow pulse width together with other sidelobes. The repetition rate of the main peaks is $2\omega_m$. To eliminate the sidelobes, at the output of the polarizer we utilize an IM, to which the same sinusoidal signal is applied with a proper time delay introduced to select the main peaks. If the IM is biased at the quadrature transmission point or the minimum transmission point, as shown in Fig. 1(b), a pulse or two pulses in one period is chosen. As a result, a chirp-free short-pulse train with a repetition rate that is identical to or twice the frequency of the microwave drive signal is generated.

Figure 2(a) shows the simulated pulse waveform. As a comparison, a pulse generated using a PM and a dispersive element [5] is also shown. In the simulation, the phase modulation indices of the PolM and the IM are π, and the frequency of the rf signal is set to be 10 GHz. As can be seen, the FWHM of the pulses generated by the two methods is almost identical; however, the distributions of the frequency chirp in the pulses are different. Using the proposed method, the frequency chirp at anywhere of the pulse equals to 0; therefore, the pulse is chirp free. But for the pulse generated by a PM and a dispersive element, a large chirp is observed at the edges of the pulse, since the dispersive element can compensate for only the positive or negative chirp induced by the phase modulation. The dotted line in Fig. 2(b) shows the dependence of the pulse FWHM on the phase-modulation index of the PolM. Clearly, the width of the generated pulse can be tuned by adjusting the phase-modulation index. The sensitivity of the extinction ratio to the timing and the IM bias is also investigated. When the time delay between the rf signals to the PolM and IM departs from the optimal value by 5%, the extinction ratio of the pulses decreases by 1.5 dB (from 19.1 dB to 17.6 dB). When the IM bias departs from the optimal value by 5%, the extinction ratio decreases by 1.3 dB (from 19.1 dB to 17.8 dB). Therefore, the generated pulses should be very stable.

An experiment is performed based on the setup shown in Fig. 1. A light wave from a tunable laser source (TLS) with a wavelength of 1553.44 nm is sent to the PolM (Versawave Technologies) for complementary phase modulation. The PolM is driven by a sinusoidal signal with a frequency of 10 GHz and a power of 25 dBm. The phase-modulation index is approximately 0.84π. The phase-modulated signals are converted to a pulse train at a polarization beam splitter (PBS, polarization extinction ratio >30 dB), which is used as a polarizer. A $LiNbO_3$ zero-chirp IM (JDS Uniphase, polarization extinction ratio >20 dB) driven by the same sinusoidal signal that is properly time delayed to select the main peaks in the pulse train. The IM is biased at the nonlinear region near the minimum transmission point of its transfer func-

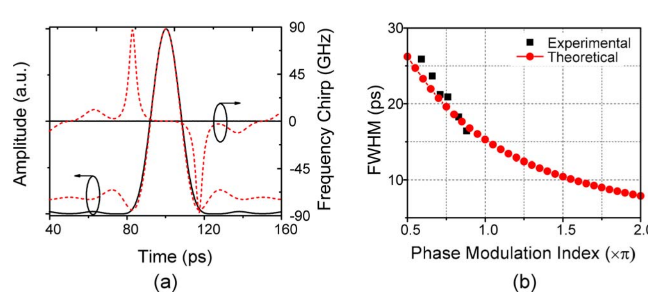

Fig. 2. (Color online) Theoretical study of the proposed pulse generator. (a) Comparison between the proposed method (solid curve) and pulse generation using a phase modulator and a dispersive element (dashed curve). (b) Dependence of the pulse FWHM on the phase-modulation index of the PolM.

tion. By properly selecting the power of the sinusoidal signal to the IM, a narrow temporal window is formed that would further compress the pulse and improve the extinction ratio. The output pulse train is detected by a high-speed photodetector (PD) with the waveforms observed by a high-speed sampling oscilloscope (Agilent 86100C) and the spectra measured by an optical spectrum analyzer (Ando AQ 6317B) with a resolution of 0.01 nm.

Figure 3 shows the normalized waveform and the optical spectrum of the generated pulses. A simulated waveform under the same condition is also shown (dashed curve). As can be seen, the experimentally generated pulse is almost identical to the simulation result. The FWHM of the pulse is 16.4 ps. The pulse has a pedestal, but the peak of the pedestal is less than 0.05. Correspondingly, the extinction ratio of the generated pulse is about 13 dB, which can be further improved by using a nonlinear optical loop mirror [8]. The polarization extinction ratio of the generated pulses is more than 25 dB. Figure 3(b) shows the corresponding spectrum, which gives a 3 dB bandwidth of 0.30 nm. The time-bandwidth product is calculated to be 0.615, which is very close to the theoretical value of 0.606 of a chirp-free pulse under this condition, indicating that the generated pulse train is indeed chirp free. The average optical pulse power without amplification is about −6.2 dBm, corresponding to a pulse energy of 24 fJ. Considering that the output power of the TLS is 11.6 dBm, the conversion loss of the whole system is 17.8 dB. On the other hand, if the IM is biased at the minimum transmission point, a 20 GHz short-pulse train would be generated with the waveform shown in the inset in Fig. 3(a). The pulse width tunability is also investigated. By adjusting the microwave power to the PolM to change the phase-modulation index, the pulse width is changed, as shown by the square points in Fig. 2(b). In addition, when the wavelength of the TLS is tuned from 1535 to 1565 nm, no visible changes in the waveforms and the spectra are observed, which demonstrates that the proposed pulse generator is wavelength independent. The stability of the proposed pulse generator is also investigated. In a room environment during a 1 h observation, no visible changes in the pulse shape and spectrum are found.

Because the duty cycle of the pulse is governed by the phase-modulation index in the PolM, a micro-

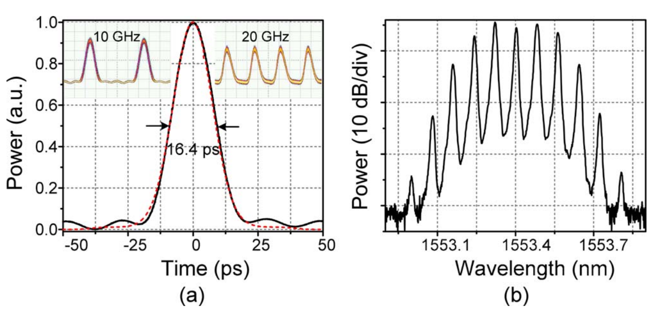

Fig. 3. (Color online) (a) Waveform and (b) optical spectrum of the experimentally generated optical pulses at 10 GHz.

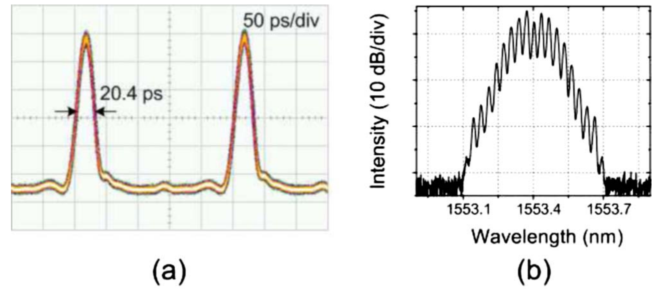

Fig. 4. (Color online) (a) Waveform and (b) optical spectrum of the experimentally generated optical pulses at 4 GHz.

wave signal with a higher microwave power to the PolM will lead to a much shorter pulse train. In our experiment, when the microwave power applied to the PolM is 25 dBm at 10 GHz, a pulse train with a duty cycle of 16.2% is generated. When a higher microwave power at 4 GHz is applied (no high power amplifier at 10 GHz is available), the phase-modulation index is estimated to be 1.85π, and a pulse train with a significantly smaller duty cycle of 8.16% is generated, with the waveform and the optical spectrum shown in Fig. 4. By carefully selecting the bias voltage and the power of the microwave signal to the IM, an extinction ratio of 10.1 dB is obtained.

In conclusion, a simple method for generating a chirp-free short optical pulse train using a PolM and an IM was proposed and experimentally demonstrated. The proposed approach features a compact structure and stable operation with tunable pulse width, which can find applications in optical communications and modern instrumentation.

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