Phase-modulation-combination system for the generation of arbitrarily shaped repetition rate pulses

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We propose a new phase-modulation-combination system for the generation of arbitrarily shaped repetition rate pulses. In this system, the pulses from two electro-optic switches are modulated and interferentially combined, thereby improving the shaping resolution and narrowing the pulse width. This method allows the arbitrary tuning of pulse width, repetition rate, and temporal profile in an all-fiber configuration. The system is compatible with and can be easily embedded in other systems to achieve higher pulse energy and higher pulse repetition rate.

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Pulse energy and pulse peak power are typically the main priorities in laser design. However, temporal characteristics such as pulse shape and repetition rate are also important for several applications, such as high-power amplifiers[1], ultrafast sampling[2], optical combs[3], and ultra-high-speed optical communications[4]. In traditional pulse generation techniques, e.g., mode-locking and Q-switching[5−7], pulse shape and repetition rate are highly dependent on laser configuration (cavity length, dispersion, and modulation depth). Thus, the pulses from these lasers have limited adjustable temporal characteristics in terms of pulse width, repetition rate, and shape. The direct generation of optical pulse by electro-optic (EO) intensity modulation technique has been explored alternatively[8,9]. These techniques entail freedom to adjust the pulse width and repetition rate. Optical pulse can be chopped by an EO switch from a continuous wave (CW) laser; however, the shaping resolution and the narrowest obtainable pulse are limited by the response time of the switch. Much shorter pulses can be generated from the time lens technique[10−12]. This method can generate wide-range width laser pulses from common CW laser sources with high stability and controllability; however, the pulse temporal shape cannot be adjusted. Although pulse shaping and pulse spectral shaping technologies have been extensively studied, difficulty still exists in generating arbitrary temporal-shaped pulses in fibers[13].

This letter demonstrates a new and simple phase-modulation-combination (PMC) method to achieve arbitrarily shaped repetition rate pulse trains. In principle, the method can generate 1-Hz to 40-GHz repetition rate and quasi-CW to several hundred femtoseconds (fs) width pulse with the state-of-the-art EO modulator. This method is suitable for any wavelength and is compatible with diode lasers with integral optical circuit, which are widely applied in several fields, such as communication, plasma, measuring, biology, and medicine.

The basic structure of our system is shown in Fig. 1. A CW laser diode (LD) at 1 053 nm was used as the light source, whose line width was about 50 kHz. The light from the source was chopped into a pulse train by two Mach-Zehnder intensity modulators (MZs). The pulse after MZs was split into two parts by a 50/50 splitter, and then the sub-pulses were separately phase-modulated by the phase modulator (PM). Afterward, the modulated pulses were combined into one pulse through a coupler with 50/50 ratio. An optical delay line was inserted into one arm of the phase modulation for precise alignment of the phase shift between two sub-pulses. All the modulators were controlled by an arbitrary waveform generator (AWG).

Although directly chopping out an arbitrary width pulse by two MZs is possible in theory, the shaping resolution and the narrowest pulse width are limited by the capability of the optical devices. For example, in our experiments, the rise and fall time of MZs were 75 and 45 ps, respectively. The shortest achieved pulse was 200 ps, including the limited bandwidth of AWG, which would induce an additional delay of ∼90 ps. The delay induced by AWG can be compensated by operating two MZs under the offset conditions.

The scheme of offset chopping with two MZs is also shown in Fig. 1. The response delay of AWG is compensated by the ∼20-ps synchronous precision of AWG. Pulses, as short as 150 ps, can be generated using two temporal offset MZs.

The PMC method should be applied to generate a

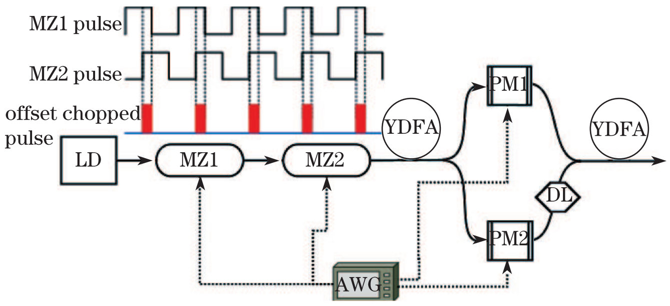


Fig. 1. Experimental setup. YDFA: Yb-doped fiber amplifier; DL: delay line.

shorter pulse with adjustable pulse shape. Supposing the chopped pulse $I_0(t)$ incident to the splitter is evenly separated into two sub-pulses, $I_1(t) = I_2(t) = 1/2I_0(t)$. The sub-pulses in each path are separately modulated by the PMs. The modulated results are given by

$$E_1(t) = \frac{1}{\sqrt{2}}E_0(t)\exp\left[-\mathrm{i}\Phi_1(t)\right], \tag{1}$$

$$E_2(t) = \frac{1}{\sqrt{2}}E_0(t)\exp\left[-\mathrm{i}\Phi_2(t)\right], \tag{2}$$

where $\Phi_1(t)$ and $\Phi_2(t)$ are the modulated phase function of the two PMs, respectively. The modulated pulses are then combined through the coupler. The intensity of the combination pulse is expressed as

$$I(t) = 2I_0(t)\cos^2[\Delta\Phi(t)/2], \tag{3}$$

where $\Delta\Phi(t) = \Phi_1(t) - \Phi_2(t)$ is the phase difference between the PMs. The temporal characteristics of the pulse can be controlled by proper selection of the phase modulation function. Assuming the rise time of PM is the same as that of MZ, the narrowest pulse can be about 1/2 shorter than that of directly chopped pulse because the combined pulse is controlled by $\Delta\Phi$, rather than Φ. In practice, the rise time of PM is faster than that of MZ. Thus, about 1/6 to 1/8 shorter pulses can be achieved by optimizing the modulation function. The shaping resolution is proportional to the narrowest obtainable pulse width.

The types of the phase modulation functions used in the experiments to generate arbitrary widths and repetition pulses in different regions are shown in Fig. 2. For pulses shorter than 150 ps, a fragment phase modulation function was used to suppress the side lobes. The fragment function consisted of five segments of linear function. For pulse widths ranging from 150 ps to 2.5 ns, a sinusoidal or linear phase modulation function was used. When the pulse width was larger than 2.5 ns, phase modulation was not required. In this case, a stage function was applied to the PMs; thus the phase difference $\Delta\Phi(t) \equiv 0$ during the pulse and $\Delta\Phi(t) \equiv \pi$ outside the pulse to improved the signal-to-noise ratio (SNR).

The various pulses generated in the experiments are shown in Figs. 3 and 4. In Fig. 3, we provide examples to generate different width pulses with various repetition rates. The pulse widths are 4, 4, and 2 ns, while the repetition rates are 31.25, 62.5, and 125 MHz, respectively. The adjusted accuracy of the repetition rate is less than 10^{-3}. Figure 4 presents the ability of this system to generate arbitrarily shaped pulses. Flat top, triangular, and multi-peak pulses were generated with 2.5-ns pulse width and 200-MHz repetition rate. For the 2.5-ns pulse width, the shaping resolution can be 100 ps. By contrast, the shaping resolution of directly chopping pulse was 250 ps. The shaping resolution of the multi-peak pulse cannot be demonstrated by the directly chopping method.

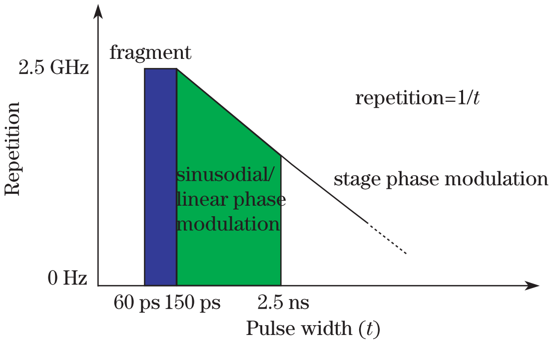
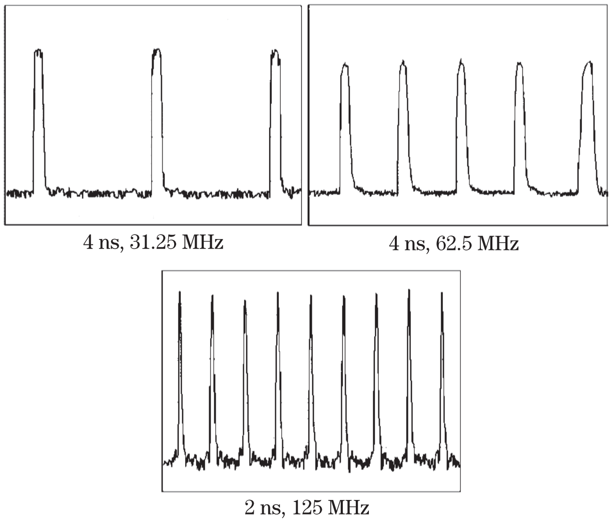


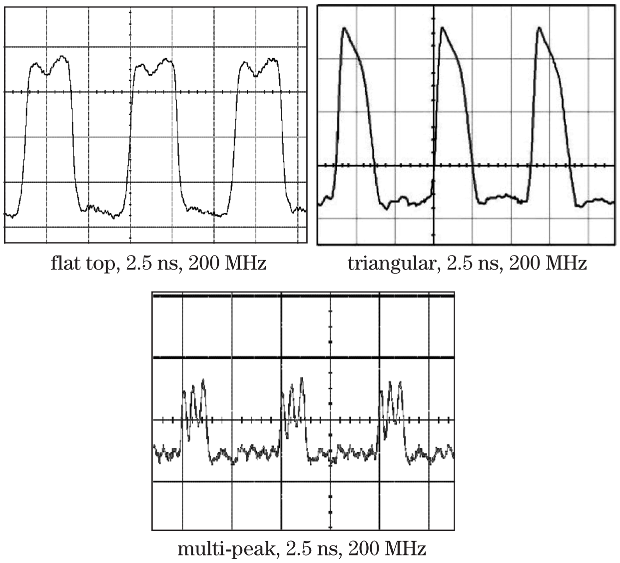
Fig. 2. Ability of our experimental system to generate pulses with arbitrary width (x-axis) and repetition (y-axis) in different regions.


4 ns, 31.25 MHz

4 ns, 62.5 MHz

2 ns, 125 MHz

Fig. 3. Experimental results for various repetition rates.


flat top, 2.5 ns, 200 MHz

triangular, 2.5 ns, 200 MHz

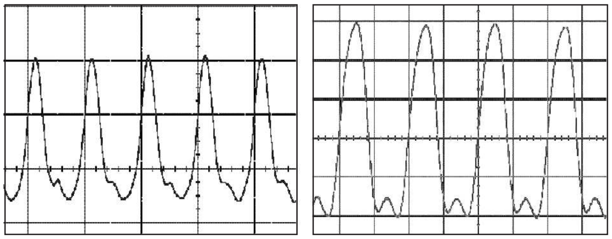
multi-peak, 2.5 ns, 200 MHz

Fig. 4. Experimental results for various pulse temporal profiles.

We demonstrated a higher repetition rate and a shorter pulse train in Fig. 5 to explore the limitation of the system. The highest repetition rate in our system was 2.5 GHz, which was mainly limited by the response time of our AWG. Gaussian pulses of 200-ps width, with 1.25- and 2.5-GHz repetitions are presented in Fig. 5. Pulse distortion was small even at higher repetition rates. The sinusoidal function was the only type of output for high-repetition signal generation. The shorter pulse generated using the PMC system may have big sidebands, thus, improving its SNR was difficult. The shortest pulse width recorded was 60 ps (black line, Fig. 6). The red line represents the shortest pulse generated using two MZs. The curve was re-casted from the oscilloscope in consideration of the response time of the measurement system consisting of an InGaAs photo-detector (rising time 45 ps), transport lines, and an oscilloscope (sample rate 40 Gs/s). Using an ultrafast Ti:sapphire laser, the response time of our measurement was calibrated as 150 ps. When the data was input to the oscilloscope, the time scale was re-calculated by $t = \sqrt{t_{\text{mea}}^2 - \tau_{\text{res}}^2}$, where τ_{res} and τ_{mea} are the response time of the measurement system and the measure result, respectively.

An YDFA was used to compensate for the loss of switches[14,15]. When the 5-dBm pulse train with 1-GHz repetition rate and the 250-ps pulse width were incident to the YDFA, the output average power was about 100 mW. The energy of the single shortest combination pulse was 0.1 nJ. Measuring and displaying the low-power ultra-short pulse is another topic that we will study in the future.

In conclusion, we demonstrate a new fiber-based method to generate arbitrarily shaped repetition rate pulses. The method, which utilizes offset chopping and PMC, can produce several GHz repetitions and shorter pulses of less than 100 ps with high-resolution shaping pulses. The PMC method can be integrated with other techniques such as the optically time-division-multiplex method to generate higher repetition pulse trains of more than 500 GHz[16]. In this method, the pulse width, shape, and repetition rate can be easily controlled by the EO devices. This PMC method is not limited to two-beam combinations because N-beam combinations may also be used to generate much shorter pulses, which can greatly reduce the low limitation of the pulse width.


200 ps, 1.25 GHz

200 ps, 2.5 GHz

Fig. 5. Experimental results for high-repetition rate pulses.

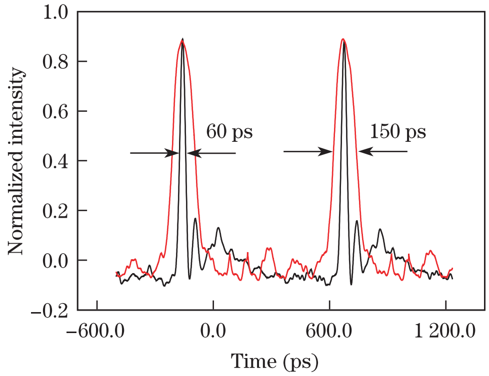


Fig. 6. (Color online) Two MZ chopped pulses and PMC output pulses with repetition of 1 GHz. FWHMs are 150 and 60 ps, respectively. The shaping resolution noticeably improved.

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