A dynamic optical arbitrary waveform generator based on cross phase modulation*

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In this paper, a dynamic optical arbitrary waveform generator (OAWG) based on cross phase modulation (XPM) is proposed. According to the characteristics of XPM, the nonlinear phase shift of signal can be changed along with the pump power. The amplitude of signal can be changed by controlling the phase shift at one arm of a Mach-Zehnder interferometer (MZI) using XPM effect between signal and pump. Therefore, the phase and amplitude of the optical frequency comb (OFC) can be controlled by two pump arrays. As a result, different kinds of waveforms can be synthesized. Due to the ultrafast response of XPM, the generated waveform could be dynamically updated with an ultrafast frequency. The waveform fidelity is affected by the updating frequency.
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An optical arbitrary waveform generator (OAWG) can be used to synthesize arbitrary optical waveforms with a bandwidth up to tens/hundreds of gigahertz, which could find applications in lots of fields, including coherent control over quantum mechanical processes, manipulation of high-field laser-matter interactions, and photonically enabled generation and processing of ultrabroad band radio frequency electrical signals[1]. Over the past few decades, different kinds of methods have been proposed to implement OAWG, such as the wavelength-to-time mapping techniques, space-to-time mapping techniques, temporal pulse shaping system and spectral pulse shaping system[2,3]. Among these reported techniques, spectral pulse shaping is widely used due to its advantage that waveforms can be widely reconfigured by adjusting the amplitude and phase of optical frequency comb (OFC). In real optical networks, the OAWG is usually required to be updated rapidly, which is known as dynamic OAWG. In traditional spectral pulse shapers based on spatial light modulator (SLM), the waveform updating time is limited by the response time of the SLM (~10 ms)[4-6]. This problem can be relieved by replacing the SLM with an electro-optical modulator (EOM) array. A dynamic optical waveform generator with bandwidth up to 30 GHz is reported utilizing gigahertz bandwidth in-phase/quadrature (IQ) modulation[7,8]. However, the electrical modulator is limited by the electronic bottleneck and its updating time is difficult to be shorter than 10 ps.

The main advantage of the nonlinearity of fibers is the ultrafast nature that permits all-optical signal processing at femtosecond scales. The nonlinear response of silica fibers is almost instantaneous (<10 fs)[9]. Therefore, cross phase modulation (XPM), as one of nonlinear effect, can be applied to dynamic OAWG, in which waveforms are updated rapidly.

In this paper, a dynamic OAWG based on XPM is proposed. The amplitude and phase of incident signal are controlled by utilizing the XPM effect in fiber. The generation of arbitrary waveforms and dynamical updating of different waveforms are realized. Furthermore, the factor that limits the waveform fidelity of this scheme is discussed.

The structure of the dynamic OAWG transmitter based on XPM is illustrated in Fig.1. Firstly, the output of an optical frequency comb generator (OFCG) is divided spectrally by an arrayed waveguide grating (AWG). Then each spectral line passes through an amplitude controller followed by a phase controller. The amplitude and phase of each line are changed by the amplitude and phase controllers, respectively, which are controlled by the pump array based on XPM. Finally, all the spectral lines are combined by another AWG and the shaped waveform is launched out at the output of AWG. The waveform of the proposed OAWG can be updated with an ultrafast frequency due to the instantaneous response of XPM.

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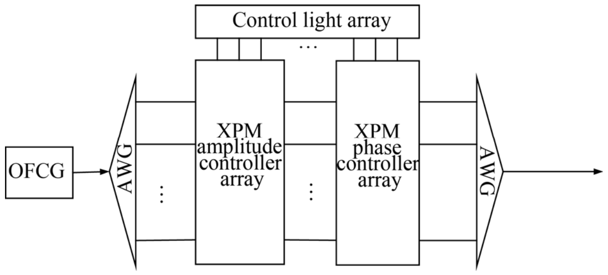


Fig.1 Schematic diagram of the dynamic OAWG transmitter based on XPM

In this scheme, the XPM amplitude controller and XPM phase controller are illustrated in Fig.2(a) and (b), respectively. The XPM effect is used in both phase controller and amplitude controller. According to the theory of XPM, the nonlinear phase shift of the signal could be written as:

$$\varphi_{\mathrm{XPM}} = 2\gamma PL , \tag{1}$$

where γ is the nonlinear coefficient of highly nonlinear fiber (HNLF), P is the pump power and L is the length of HNLF.

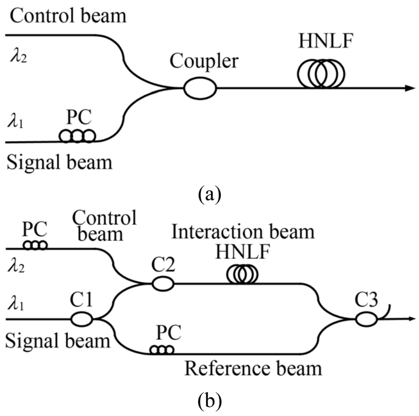


Fig.2 (a) Phase controller based on XPM; (b) Amplitude controller based on XPM (PC: polarization controller; C1/2/3: coupler1/2/3)

Fig.2(a) shows the structure of phase controller in which phase of signal can be changed by adjusting the pump power according to Eq.(1). Fig.2(b) shows the structure of amplitude controller in which the amplitude of signal can be changed by controlling the phase shift at interaction beam of a Mach-Zehnder interferometer (MZI) using XPM effect between signal and pump. Supposing the signal power is far lower than the pump power, the self-phase modulation (SPM) of signal could be neglected. The response of amplitude controller at one port of C3 after the interference can be written as:

$$H_{\mathrm{AM}} = \cos\frac{(\Delta\varphi_{\mathrm{L}} + \varphi_{\mathrm{XPM}} + \pi)}{2} \mathrm{e}^{\mathrm{i}\frac{(2\varphi_{\mathrm{L}} + \Delta\varphi_{\mathrm{L}} + \varphi_{\mathrm{XPM}} + \pi)}{2}} , \tag{2}$$

where φ_{L} is the linear phase shift of interaction beam of MZI, $\Delta\varphi_{\mathrm{L}}$ is linear phase shift difference between two beams of MZI, and φ_{XPM} is the nonlinear phase shift in interaction beam controlled by pump power, shown in Eq.(1).

According to Eq.(1), the nonlinear phase shift φ_{XPM} in phase controller is proportional to the pump power P with the slope of $2\gamma L$. According to Eq.(2), not only the amplitude but also the phase response of amplitude controller is changed by the nonlinear phase shift in interaction beam. Suppose a nonlinear fiber with length of L=1 km and nonlinear coefficient of γ=20 W^{-1}km^{-1} is used in both phase controller and amplitude controller. As shown in Fig.3, when the pump power is changed in the range about 0—320 mW, the response of the phase controller can be adjusted from 0 to 2π. The response of amplitude controller versus pump power is also shown in Fig.3. When the pump power is changed from 0 mW to 160 mW, the nonlinear phase shift caused by XPM is changed from 0 to π. As a result, the response of amplitude controller can be adjusted from 0 to 1.

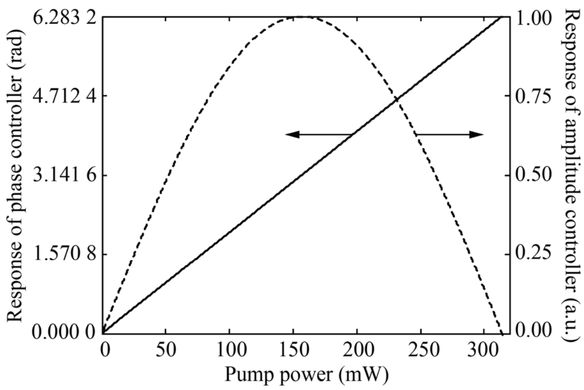


Fig.3 Responses of the phase controller and the amplitude controller based on XPM

In the structure of OAWG shown in Fig.1, each line of OFC firstly passes through the amplitude controller array, which is controlled by a pump array based on XPM. According to Eq.(2), the pump power to control amplitude of the nth comb line should be set as:

$$P_{\mathrm{AM},n} = \frac{2\arccos\left|H_{\mathrm{AM},n}\right| - \pi - \Delta\varphi_{\mathrm{L}} + 2k\pi}{2\gamma L_{1,n}} , k \in Z , \tag{3}$$

where the response of the nth amplitude controller is $H_{\mathrm{AM},n} = \frac{A_{\mathrm{target},n}}{A_{\mathrm{in},n}}$, $A_{\mathrm{target},n}$ is the target complex amplitude of the nth comb line, $A_{\mathrm{in},n}$ is the incident complex amplitude of the nth OFC, and $L_{1,n}$ is the length of HNLF in interaction beam of the nth amplitude controller. The integer k is selected to ensure the numerator on the right of Eq.(3) is in the range of 0—2π, so that $P_{\mathrm{AM},n}$ is as small as possible.

When the amplitude of each line is changed by amplitude controller array, according to Eq.(2), the phase of each line is also changed at the same time, which can be written as:

$$\varphi_{\mathrm{AM},n} = \frac{1}{2}(2\varphi_{\mathrm{L1},n} + \Delta\varphi_{\mathrm{L1},n} + \varphi_{\mathrm{XPM1},n} + \pi) , \tag{4}$$

where $\varphi_{L1,n}$ is the linear phase shift of interaction beam of MZI in the nth amplitude controller, $\Delta\varphi_{L1,n}$ is the linear phase shift difference between two beams of MZI in the nth amplitude controller, and $\varphi_{XPM1,n}$ is proportional to $P_{AM,n}$ with the slope of $2\gamma L_{1,n}$.

And then, the output of amplitude controller array passes through the phase controller array which is controlled by a pump array based on XPM. The phase of each line is compensated to be the same as the target phase by the phase controller array. According to Eq.(1) and Eq.(4), the pump power to control the phase of the nth comb line should be set as:

$$P_{PM,n} = \frac{\varphi_{target,n} - \varphi_{in,n} - \varphi_{L,n} - \varphi_{NL,n}}{2\gamma L_{2,n}}, \qquad (5)$$

where $\varphi_{target,n}$ is the target phase of the nth comb line, $\varphi_{in,n}$ is the phase of the nth incident OFC, and $L_{2,n}$ is the length of HNLF in interaction beam of the nth phase controller. $\varphi_{L,n}=\varphi_{L1,n}+\varphi_{L2,n}+\frac{1}{2}\Delta\varphi_{L1,n}+\frac{\pi}{2}$, where $\varphi_{L2,n}$ is the linear phase shift in the nth phase controller, and $\varphi_{NL,n}=\frac{1}{2}\varphi_{XPM1,n}$.

In the actual structure, the initial phase of OFC and the length of fiber can be arbitrary. By using phase controller array, the phase of output signal can be the same as the target phase no matter what values the initial phase and the fiber length are.

In order to implement dynamic OAWG[10,11], the power of pump array should be dynamically changed. Assume that the pump power has different levels, and each level corresponds to a sort of waveform. At one bit, a group level of pump power synthesizes a waveform according to the theory of static OAWG. At the next bit, due to the almost instantaneous response of XPM, another group level of pump power synthesizes another waveform. Thus, the waveforms can be updated along with the control of pump power dynamically.

The OAWG shown in Fig.1 is set up by using optisystem and there are 21 lines in the incident OFC, which have the same amplitude. The spacing of spectral lines is 100 GHz. HNLF lengths and nonlinear coefficients of different channels are set to be the same respectively for the simulation in Fig.3.

Firstly, in order to synthesize Gaussian waveform, the required pump power is calculated on the basis of Eq.(3) and Eq.(5). The synthesized Gaussian waveform is shown in Fig.4(a) and its period is 10 ps, which corresponds to the 100 GHz spacing of spectral lines. As shown in Fig.4(b), the relationship between response of amplitude controller array and output power of pump array is consistent with Eq.(3). Fig.4(c) demonstrates that the response of phase controller array is proportional to the output power of pump array, which is consistent with Eq.(1). A rectangular pulse with period of 10 ps also can be achieved by tuning the pump power on the basis of Eq.(3) and Eq.(5). The synthesized rectangular waveform by optisystem is shown in Fig.5(a). It is known that the rectangular waveform has a relatively wide spectrum. In this OAWG, only 21 spectral lines of rectangular waveform, which contain most energy, are selected, so there are some ripples in the received rectangular waveform. Fig.5(b) shows the response of amplitude controller array and output power of pump array, which still presents the same relationship as Fig.4(b). Fig.5(c) also indicates the same relationship as Fig.4(c). Fig.6 shows the results of sawtooth pulse. Fig.4, Fig.5 and Fig.6 demonstrate that this pulse shaper has converted a given OFC into three distinct waveforms by only adjusting the pump power.

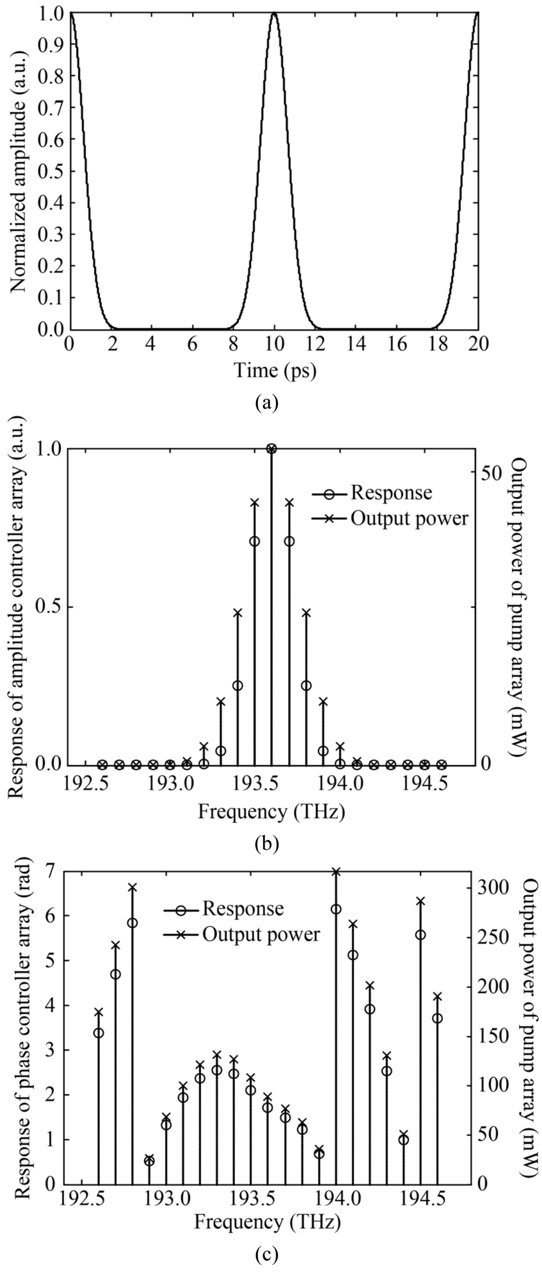


Fig.4 Generation of Gaussian pulse: (a) Sythesized Gaussian waveform by optisystem; (b) Response of amplitude controller array and output power of pump array; (c) Response of phase controller array and output power of pump array

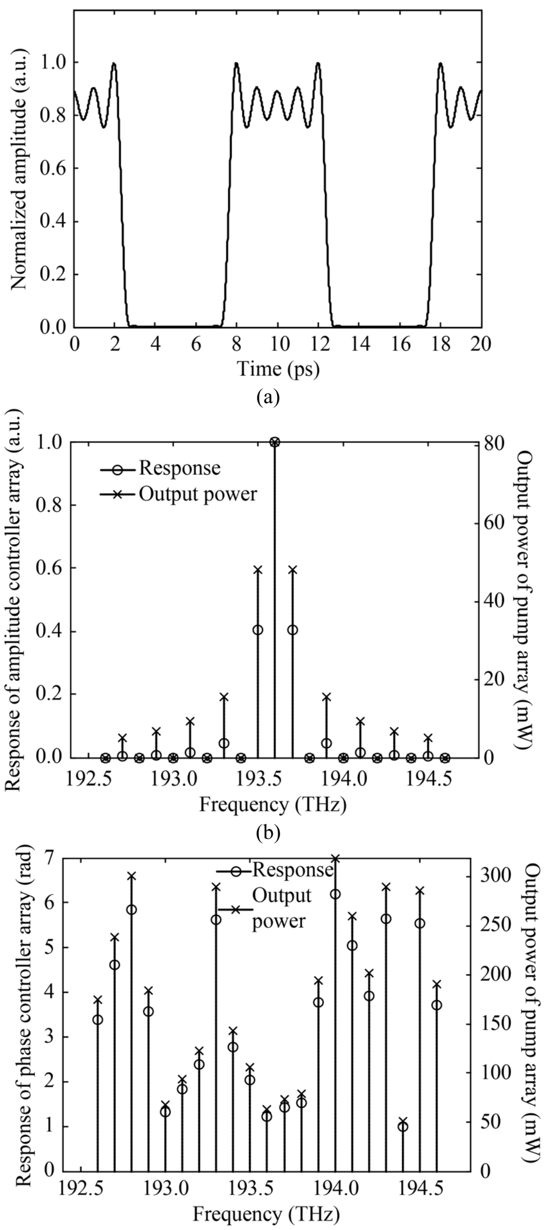
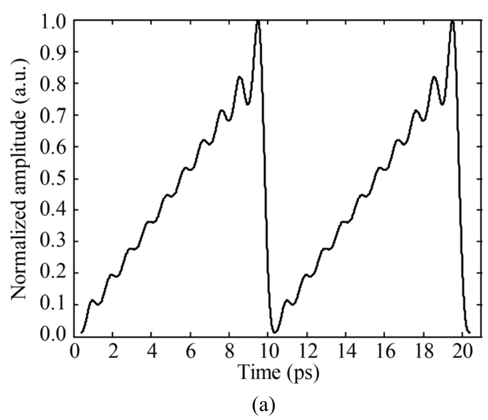


Fig.5 Generation of rectangular pulse: (a) Sythesized rectangular waveform by optisystem; (b) Response of amplitude controller array and output power of pump array; (c) Response of phase controller array and output power of pump array



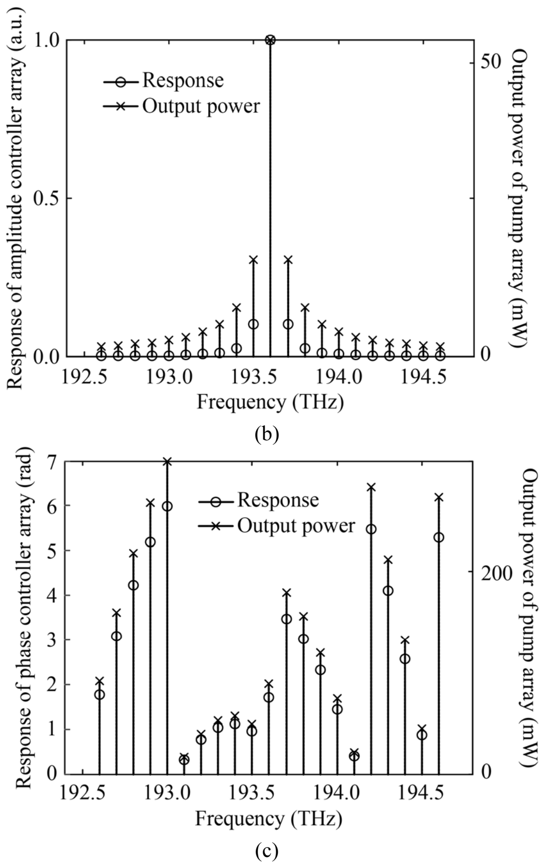


Fig.6 Generation of sawtooth pulse: (a) Sythesized sawtooth waveform by optisystem; (b) Response of amplitude controller array and output power of pump array; (c) Response of phase controller array and output power of pump array

Due to the ultrafast response of XPM, the updating frequency is equal to the repetition rate of pump power. As shown in Fig.7, the generated signal switches between Gaussian pulse and sawtooth pulse with the updating time of 40 ps which corresponds to the pump power repetition rate of 25 GHz, while the fundamental pulse period is 10 ps which corresponds to the spectral lines spacing of 100 GHz.

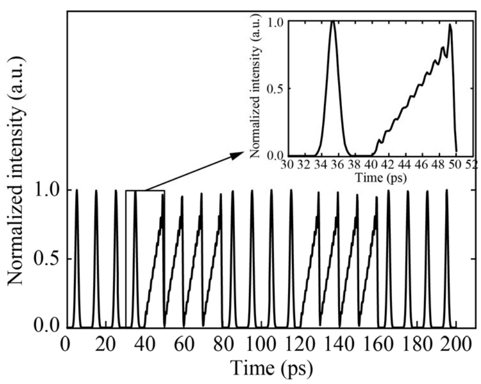


Fig.7 Dynamic OAWG waveform switching between Gaussian pulse and swatooth pulse at the repetition rate of 10 GHz and its local amplification result in the inset

When the updating frequency is increased, the spectra of pumps will be further broadened. After the XPM amplitude and phase controllers, the signal spectra are consequently broadened. The neighboring lines will be overlapped when the lines are broadened to a certain extent, resulting in decrease of waveform fidelity. Here, Pearson correlation coefficient is used to describe the fidelity of the generated waveform compared with the ideal waveform. The Pearson correlation coefficient ρ_{XY} of two variables of X and Y is defined as:

$$\rho_{XY} = \frac{\mathrm{cov}(X,Y)}{\sigma_X \sigma_Y}, \quad (6)$$

where cov(X, Y) is the covariance of X and Y, and σ_X and σ_Y are standard deviations of X and Y, respectively.

The relationship between updating frequency and waveform fidelity is shown in Fig.8. When the updating frequency is lower than 33 GHz, the correlation coefficient of generated and ideal waveforms is very close to 1, and it declines sharply when the updating frequency is increased to more than 33 GHz. Therefore, in this OAWG, the updating frequency should be lower than 33 GHz.

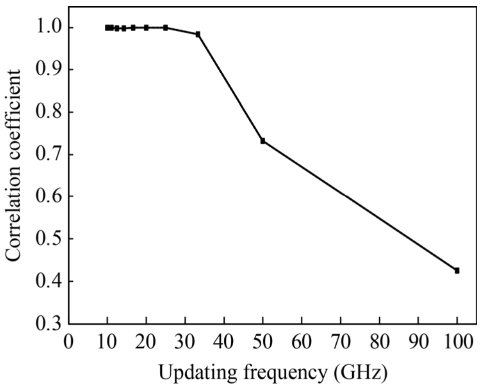


Fig.8 Influence of updating frequency on the waveform fidelity

In this paper, a dynamic OAWG based on XPM is proposed. The phase and amplitude of each spectral line are adjusted by changing the pump power according to the XPM effect. The generation of several waveforms is demonstrated, and different waveforms can be updated rapidly. The waveform fidelity is affected by the updating frequency. This OAWG shows a higher updating frequency due to the ultrafast response of XPM. Furthermore, assisted with light-controlled properties, this OAWG presents a prospect for all-optical networks in future.

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