Optimized Second Harmonic Generation of Femtosecond Pulse by Phase-Blanking Effect in Aperiodically Optical Superlattice *

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In order to minimize the effect of the unconsidered frequency components on the generated compression pulse, phasing-blanking effect is taken into account of designing the one-dimension aperiodic domain reversal structure. Hierarchic genetic algorithm for the design of a domain reversal grating to modulate the spectrum and phase of the generated SH pulse simultaneously are presented. Our simulation shows that the quality of an output pulse is fairly improved.

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Optical parametric processes are of importance for creating laser sources at new frequencies and have been widely applied to nonlinear optics.[1] Due to the restriction of the birefringence of a nonlinear crystal, a quasi-phase-matching (QPM) was introduced in nonlinear optics as an alternative technique to birefringence phase matching.[2,3] With the development of room-temperature poling technology, it is possible to achieve domain-inverting structures in ferroelectric crystals such as $LiNbO_3$, $LiTaO_3$, $KTiOPO_4$ and so on. Recently, these microstructured QPM materials have been used in ultrafast frequency conversion. QPM provides extra degrees of freedom in engineering the amplitude and phase responses for ultrafast application, a function not available with conventional birefringent phase matching. More importantly, QPM SHG devices have been used to combine such ultrafast techniques as pulse shaping and compression.[4−6] The initial progress towards arbitrary pulse shaping using QPM second-harmonic generation (SHG) crystals was in work by Arbore *et al.*,[7] who theoretically demonstrated that by using a QPM crystal containing a linearly-chirped gating, it is possible to generate a compressed SHG output pulse from a chirped input fundamental pulse (FP). Subsequently, many researches about the pulse shaping and pulse compression during SHG by the linearly and nonlinearly one-dimensional aperiodic QPM gratings are reported.[6,8−10] A procedure of designing aperiodic QPM gratings for compression optical ultrashort pulse during second-harmonic generation is provided.[11] In this method, the length of domain block is fixed and can be selected artificially, so the difficulty of poling can be alleviated compared with that of chirped domain inversion gratings. Furthermore, this method can be employed when the input fundamental pulse with arbitrary amplitude and phase. In the simulations, only some limited frequency components were considered, their phases almost have the same value, but the phase of other frequency components is irregular. Because only phases of being given frequencies are optimized in calculations, the arbitrary distributions of SHG phases in the whole wavelength region may cause the output pulses to be distorted and accompanied by pedestal. Although great progress has been made in producing of ultrashort pulse recently, the ultrashort pulse by compression sometimes has very wide pedestals. In addition, not only the width of ultrashort laser pulse but also the shape of laser pulse are requested in many applications.[12] Thus the quality of the compression pulse is also important.

In this Letter, phasing-blanking method is employed to minimize the influence of the unconsidered frequency components during that SHG, so that the performance of compressed SHG pulse can be well improved.

QPM gratings generally use sign reversal of the nonlinear coefficient $d(z)$ along the crystal length in a periodic or aperiodic fashion. Generally, as an example, a lithium niobate grating with aperiodic optical superlattice (AOS) structure is shown in Fig. 1. The AOS device consists of nonlinear crystal blocks, each with a length of l. Adjacent crystal blocks have the same or the opposite nonlinear polarization direction. The choices of polarization directions are determined by the genetic algorithms.

We begin the analysis with the coupled wave equations expressed in the frequency domain by considering an aperiodic QPM grating of length L with longitudinally optionally modulated nonlinear coefficient $d(z)$. The frequency-domain envelops $\widehat{A}_m(z,\Omega_m)$ are defined by[6]

$$\widehat{E}_m(z,\omega) = \widehat{A}_m(z,\Omega_m)\exp[-ik(\omega_m+\Omega_m)z], \tag{1}$$

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where the wave vector $\boldsymbol{k}$ is a function of frequency, $\Omega_m = \omega - \omega_m$ is the frequency detuning from the optical carrier angular frequency ω_m. This definition explicitly accounts for the effect on each frequency component of the interacting waves.

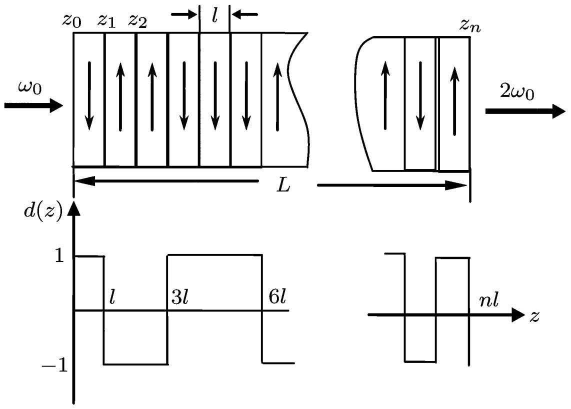

Fig. 1. Schematic of the pulse compression by SHG in aperiodically poled lithium niobate.

By the assumption of the slowly varying amplitude approximation, an undepleted pump, and a plane-wave interaction, we can obtain the solution of the coupled wave equations, as

$$\widehat{A}_1(z,\Omega) = \widehat{A}_1(z=0,\Omega), \tag{2}$$

$$\widehat{A}_2(L,\Omega) = \int_{-\infty}^{+\infty} \widehat{A}_1(\Omega')\widehat{A}_1(\Omega-\Omega')\widehat{d} \cdot [\Delta k(\Omega,\Omega')]d\Omega', \tag{3}$$

where $\widehat{A}_1(z,\Omega)$ and $\widehat{A}_2(z,\Omega)$ is the FH envelope and SH envelope, respectively (hereafter we use the subscript 1 to denote the FH and the subscript 2 to denote the SH); and $\widehat{d}(\Delta k) = -i\gamma \int_{-\infty}^{+\infty} d(z)\exp(-i\Delta k z)dz$, we extend the limits of integration from $[0, L]$ to [-∞, +∞] by the reason that $d(z) \equiv 0$ outside the grating, $\gamma = 2\pi/\lambda_1 n_2$, λ_1 is the free-space FH wavelength, and n_2 is the refractive index at the SH frequency. The k-vector mismatch $\Delta k(\Omega,\Omega')$ is defined as

$$\Delta k(\Omega,\Omega') = k(\omega_1+\Omega') + k(\omega_1+\Omega-\Omega') - k(\omega_2+\Omega). \tag{4}$$

It is noted that Eqs. (2) and (3) are valid for materials with arbitrary dispersion. It is difficult to calculate $\widehat{A}_2(L,\Omega)$ for arbitrary input pulse and arbitrary material dispersion. Assuming that GVD and higher-order dispersion terms at the FH and SH wave-pulse can be ignored, the grating can act as a transfer function.

Considering second harmonic generation interaction $\omega_1 + \Omega/2 + \omega_1 + \Omega/2 \rightarrow 2\omega_1 + \Omega$ to $\widehat{A}_2(\Omega)$ in Eq. (3), then Eq. (3) is simplified to

$$\widehat{A}_2(L,\Omega) = -i\gamma \widehat{A}_1^2\Big(\frac{\Omega}{2}\Big)\int_{-\infty}^{+\infty} d(z) \cdot \exp\Big[-i\Big(2k\Big(\omega_1+\frac{\Omega}{2}\Big) - k\Big(2\omega_1+\Omega'\Big)\Big)z\Big]dz. \tag{5}$$

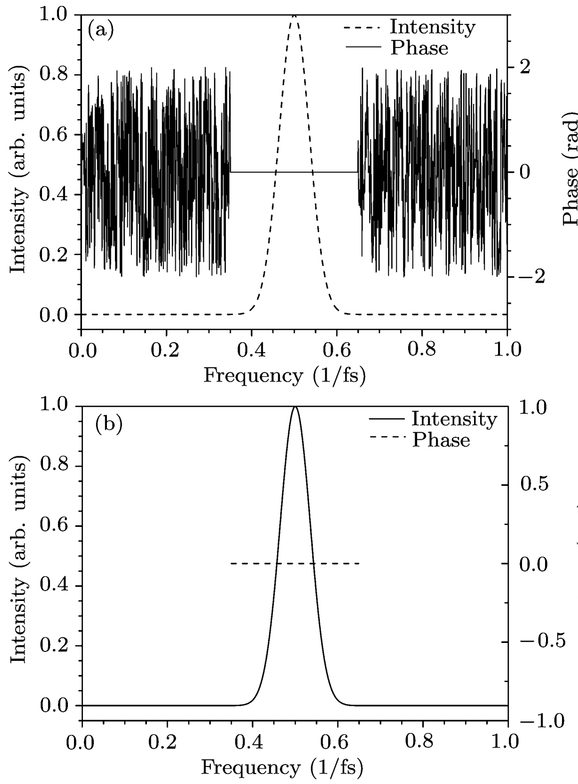

Fig. 2. Intensity and phase of the pulse in different cases: (a) without phase blanking (b) with phase blanking.

It is well known that the phase is meaningless when the amplitude of light-wave in frequency domain is approximates zero. This effect is called the phase blanking. Figure 2 shows the cases without phase-blanking and with the phase blanking. In the simulations of the referencehe,[11] the selected frequency components are discrete, that is to say, only some limited frequency components were considered, and their phase almost have the same value (circle), but the other phases are irregular (line). The spectral phase of all the frequency components is shown in Fig. 3. Because only phases of being selected frequencies are optimized in calculations, the arbitrary distributions of SHG amplitudes in the whole wavelength region may cause the output pulses to be distorted and accompanied by pedestal. In order to minimize the effect of the unconsidered frequency components on the generated compression pulse, we will design a spectrum. In the spectrum, when the amplitudes are large, their phase values are almost the same; when the amplitudes are very small (approximating zero), their phase values are irregular. Such a kind of generated spectrum of laser pulse by SHG is carried out in the engineered aperiodic optical superlattice (AOS).

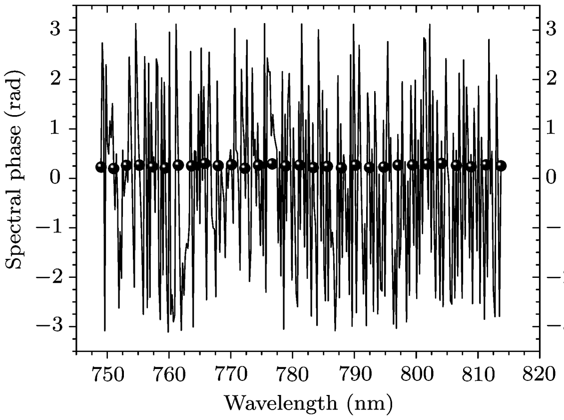

Fig. 3. Spectral phase of the unconsidered frequency components (line) and the being selected frequency components (circles).

In our simulations, we adopt the length of the grating L is 16 mm, the length of each block l is 5 μm. Certainly you can choose the length of L and l arbitrarily as long as you want. Moreover, the refractive indices of the fundamental and second harmonic depend on the Sellmerier equation[13] and the operation temperature of the lithium niobate sample is assigned to be 25°C. We take the case of SHG pumped by a linearly chirped Gaussian FH pulse with optical carrier frequency ω_0 (the central wavelength of FH is 1560 nm).

The frequency-domain enveloped of the electric field the corresponds to this pulse is

$$\widehat{A}_1(\Omega) = \frac{1}{\sqrt{2\pi}} E_0 \tau_0 \exp\Big[-\frac{1}{2}(\tau_0^2 + iC_1)\Omega^2\Big], \qquad (6)$$

where the parameters of the input FH pulse are taken as $\tau_0 = 42.0$ fs (FWHM is 70.0 fs), $C_1 = 20\tau_0^2$, and real (temporal peak) amplitude E_0 is a relatively arbitrary value.

In our simulations, the crystal length L and the block numbers n is fixed, so $\widehat{A}_2(\Omega)$ is determined by the modulated nonlinear coefficient $d(z)$ according to Eq. (5). If the amplitude and phase of the input Gaussian pulse are known, we will seek for the optimal distribution of the nonlinear coefficient of the grating. In this simulation, we make the phase response same for the frequency components of SH waves that we assigned and the corresponding amplitude is as high as possible. At the same time, the amplitude should be as low as possible in the other frequency regions. It will not only lead the output SH pulse to be compressed but also can eliminate the influence of the unwanted amplitude and phase involved in synthesizing pulse.

Our goal is to obtain the best distribution of the modulated nonlinear coefficient by genetic algorithm (GA) with prescribed SH target pulse. In the simulations, not only the amplitude but also the phase of SH pulse in frequency domain has the special request, so an improved genetic algorithm—Hierarchic genetic algorithm (HGA) is proposed. We summarize the main lines of the HGA as follows:

(1) Randomly generate two initial populations.

(2) One runs of GA independently with object-amplitude as fitness function, and the other runs of GA independently with object-phase as fitness function.

(3) After running several genetions (genetions need to be pre-determined), the two ending-populations are combined into one new population. The new population's evaluation function is a synthetical fitness including amplitude and phase.

(4) Selection, crossover and mutation are operated in the new population, the elitist model is adopted at the same time.

(5) Regenerate two populations from the outcome population, repeat steps 2–5 until the satisfying is obtained.

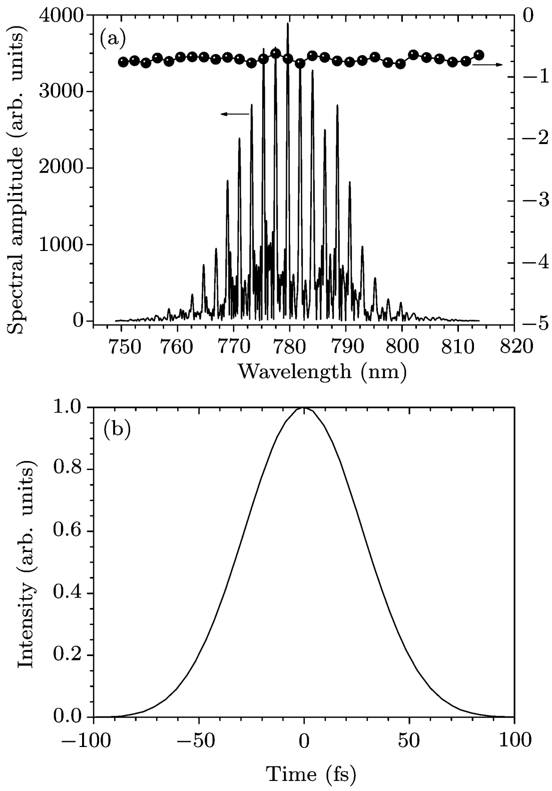

Fig. 4. (a) Spectral amplitude and spectral phase of SHG pulse in frequency domain, and (b) intensity of the output SHG pulse in time domain.

After optimization of the domain inversion structure, the amplitude of SHG at the wavelength we assigned are large, whereas the others is relatively low, and the phase of being assigned frequency components becomes relative uniform for the wavelengths from 749 nm to 814 nm, as shown in Fig. 4(a). The synthesized SH pulses intensity are plotted in Fig. 4(b), the calculated SH pulse duration (FWHM) is 65.69 fs.

In order to certify the advantage of the method we proposed above, we compare the quality of the output SH pulses by using the primary method[11] and the current method. The grating structure is optimized by the two methods with the same initialized data, such as the spectral width, the input FH and the number of being assigned frequency dots. In order to investigate the influence of phase-blanking effect, the generated SH pulse intensity are reconstructed by adding as much as 15 times frequency components between two adjacent assigned wavelengths. For example, we choose 30 frequency dots from 749 nm to 814 nm in searching the best distribution of the sign of the nonlinear coefficient, but we will choose 480 frequency dots in synthesizing SHG pulse, as shown in Fig. 5. We find that the generated SH pulse profiles by the current method is almost unchanged, as those synthesis SHG pulse with the being assigned frequency dots as shown in Fig. 4(b). We also find that the generated pulse has no obvious pedestals and asymmetrical pulse wing, whereas by the primary method, the pulse has pedestals and becomes asymmetric, which show that if there is no phase-blanking effect, the real pulse will be distorted apart from the original theoretical calculations.

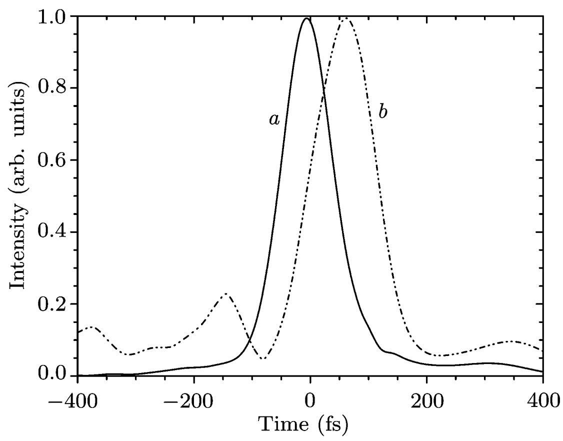

Fig. 5. Reconstructed intensity of the output SHG pulse from the end of the crystal: (a) the simulation result by the new method, and (b) the simulation result by the primary method.

In the fabrication process, the ideal boundary position of the crystal block may depart from the original position, which is due to some typical but uncontrollable factors in the fabrication process. The poling error is inevitable and is only introduced into the boundaries between the original and the invert domain block. In our simulation when an error domain length is added to the boundary of an invert domain block, an equal amount of the length is subtracted from its adjacent original domain block. Figure 6 shows the simulation result for a grating that has a overpoled domain error of $\Delta l = l \cdot 10\%$ and $\Delta l = l \cdot 20\%$ with the block length $l = 5\,\mu$m. The error we set is reasonable by the current room temperature poling technology. It can be seen from the figure that the spectral amplitude and phase of the generated second harmonic pulse is highly insensitive to the fabrication errors. This characteristic makes our proposed method more practical for applications in frequency conversion of femtosecond laser.

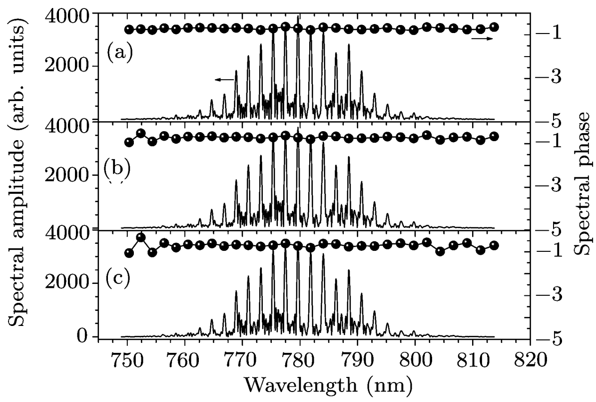

Fig. 6. Simulation results for the grating with overpoled domain errors: (a) ideal, (b) $\Delta l = l \cdot 10\%$, and (c) $\Delta l = l \cdot 20\%$. The block length of grating is $l = 5\,\mu$m.

In summary, we investigate the practical approach to achieve SH waves compression pumped by a chirped femtosecond laser based on phase-blanking effect in aperiodic QPM grating. This method is attractive because of its ability to eliminate the pedestals and to reduce the influence of unwanted frequency components. We have also simulated the effect of typical fabrication errors on a grating and found that compressed pulse is fairly insensitive to the errors. This method can fairly improve the quality of the compression pulse, and can also be applied for pulse shaping with arbitrary object pulse.

References

[1] Gu B Y, Dong B Z, Zhang Y and Yang G Z 1999 *Appl. Phys. Lett.* **75** 2175
[2] Myers L E, Eckardt R C, Fejer M M, Byer R L, Bosenberg W R and Pierce J W 1995 *J. Opt. Soc. Am.* B **12** 2102
[3] Shoji I, Kondo T, Kitamoto A, Shiraneand M and Ito R 1997 *J. Opt. Soc. Am.* B **14** 2268
[4] Imeshev G, Galvanauskas A and Fejer M M 1998 *Opt. Lett.* **23** 864
[5] Loza-Alvarez P, Reid D T and Sibbett W 1999 *J. Opt. Soc. Am* B **16** 1553
[6] Imeshev G, Arbore M A and Fejer M M 2000 *J. Opt. Soc. Am.* B **17** 304
[7] Arbore M A, Macro O and Fejer M M 1997 *Opt. Lett.* **22** 865
[8] Loza-Alvarez P, Ebrahimzaseh M and Sibbett W 2001 *J. Opt. Soc. Am.* B **18** 1212
[9] Liu H T, Mu G G and Lin L 2006 *J. Opt. Soc. Am.* A **23** 848
[10] Sapaev U K and Reid D T 2005 *Opt. Exp.* **13** 3264
[11] Li P C, Chen X F, Chen Y P and Xia Y X 2005 *Opt. Exp.* **13** 6807
[12] Goswami D 2003 *Phys. Rep.* **374** 385
[13] Jundt D H 1997 *Opt. Lett.* **22** 1553