

Second-Harmonic Generation of Super Powerful Femtosecond Pulses Under Strong Influence of Cubic Nonlinearity

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Abstract—A theoretical model of second-harmonic generation (SHG) under strong influence of cubic nonlinearity was verified in experiment. Effective energy conversion in thin potassium dihydrogen phosphate crystals at peak intensity up to 5 TW/cm^2 (B-integral equaled 6.4) was demonstrated and no crystal damage was observed. Comparative analysis of SHG of radiation at the fundamental wavelengths of 910 and 800 nm showed the major advantages of the first one. The double-pass geometry of SHG in an ultrathin crystal on a substrate is discussed in detail. Additional correction of parabolic spectral phase of the SH radiation allows pulse duration to be shortened from 20 to 9 fs for 910 nm fundamental wavelength and from 20 to 12 fs for 800 nm.

Index Terms—Frequency conversion, nonlinear optics, nonlinearities, self-focusing.

I. INTRODUCTION

SECOND-HARMONIC generation (SHG) is known to be a classical example of second-order nonlinearity effect. It was discovered in 1961 [1] and initiated the nonlinear optics science development. The process finds applications in different spheres of modern optics. At the present time, the SHG of superstrong ultrashort (tens of femtoseconds) laser pulses is a very important task, because the process can be used not only for wavelength shortening, but for significant improvement of temporal intensity contrast ratio and pulse duration decreasing also. It is especially important for petawatt laser facilities operating at 800 nm (Ti:sapphire) [2]–[4] or 910 nm (optical parametrical amplification) [5]. To avoid optical breakdown, a frequency-doubling crystal should be at least 10 cm in diameter; a potassium dihydrogen phosphate (KDP) crystal is the most suitable candidate. But even in such large aperture crystals, in-

tensity of a petawatt laser pulse is in the range of 10 TW/cm^2 and cubic (third-order) nonlinearity plays an essential role.

The theory of SHG is developed and carefully discussed in the literature [1], [6]–[11]. But the classical approach to description of the phenomena [7] is not suitable for the task because cubic nonlinearity and linear dispersion effects are needed to be taken into consideration. Dispersion effects and especially group velocities mismatch are very important for SHG of ultrashort laser pulses. The influence of the phenomena depends significantly on pulse duration, central wavelength, and dispersion properties.

The cubic polarization of the frequency-doubling crystal leads to at least two adverse effects. The first one is nonlinear-phase mismatch, which decreases SHG efficiency. The second one is small-scale self-focusing [12]–[15], which results in beam filamentation. The nonlinear-phase mismatch was thoroughly investigated theoretically and described in [6], [8]–[11]. According to these works, the phase can be compensated by changing the direction of the fundamental beam propagation. But to the best of our knowledge, this result was not verified in experiments [9].

In Section II, we present the first experimental confirmation of the nonlinear phase compensation in the process of SHG of superstrong femtosecond laser pulses. The influence of the cubic polarization effects was significant in the experiments. In these experiments, we observed no damage of 1-mm-thick KDP crystal at incident peak intensity of 5 TW/cm^2 (B-integral 6.4). This phenomenon is explained in Section III. SHG at 910 and 800 nm fundamental central wavelengths are compared in Section IV. The double-pass geometry for SHG in ultrathin crystals on a substrate is proposed and discussed in detail in Section V. Finally, in Section VI, we describe reduction of SH pulse duration and enhancement of contrast ratio.

II. COMPENSATION OF NONLINEAR-PHASE MISMATCH

Let us briefly remind the major features of SHG in a medium with quadratic and cubic nonlinearities in the case when diffraction and dispersion effects are neglected. Fundamental and SH waves propagating through a frequency-doubling crystal accumulate a nonlinear phase. The additional phase leads to an additional nonlinear-phase mismatch and, hence, decreases SHG efficiency. In order to avoid this effect, the acquired mismatch should be compensated [6], [8]–[11]. The simplest way is to

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detune the beam propagation direction from the phase match angle. For the *oo-e* type of interaction, the optimal detuning angle $\Delta\theta$ was found analytically [11]

$$\Delta\theta = \frac{\Delta n}{n_1^3 (n_1^{-2} - n_o^{-2})} \sqrt{\frac{n_1^{-2} - n_o^{-2}}{n_e^{-2} - n_1^{-2}}} \quad (1)$$

where $\Delta n = \lambda A_{10}^2 \cdot (2\gamma_{11} + 2\gamma_{12} - \gamma_{21} - \gamma_{22}) / (8\pi)$ and γ_{ij} ($i, j = 1, 2$) are the coefficients of third-order nonlinear wave coupling, n_1 is the refractive index of an ordinary fundamental wave, n_o and n_e are the main values of refractive indexes for the SH, and A_{10} is the amplitude of incident fundamental field. For the wavelength of the fundamental harmonic $\lambda_1 = 910$ nm, the coefficients of nonlinear wave coupling in electrostatic units in a KDP crystal are the following: $\gamma_{11} = 2.3 \times 10^{-9}$, $\gamma_{12} = 1.7 \times 10^{-9}$, $\gamma_{21} = 1.4 \times 10^{-9}$, $\gamma_{22} = 2.9 \times 10^{-9}$, and $\beta = 3.329 \times 10^{-4}$ [11]. As apply to input fundamental intensity 5 TW/cm² and 910 nm central wavelength, the detuning angle in a KDP crystal is $\Delta\theta = -0.5^\circ$ [11]. The angle depends on cubic nonlinearity coefficients, refractive indexes, and linearly on fundamental wave intensity. The latter is very important for crystal adjustment during the experiments. In this way, the nonlinear phase can be compensated for each intensity level. Our experiments confirmed this prediction for the first time.

In experiments, we used the output radiation of the front-end system [16] of the petawatt femtosecond optical parametric chirped pulse amplification (OPCPA) laser [5]. The parameters of the radiation incident on the SHG crystal (100 mm diameter, 0.6 or 1.0 mm thickness) were the following: beam diameter 4.3 mm, pulse duration 65 fs (in assumption of Gaussian temporal profile), energy range 1/18 mJ, and central wavelength 910 nm. Transversal structure of the fundamental beam was inhomogeneous due to optical breakdowns on the beam path. It is necessary to point out that the beam quality was not good, as a result at 18 mJ energy, the average over cross-section intensity was 2 TW/cm² and the peak intensity was 5 TW/cm². All measurements were done in vacuum because at such intensity nonlinear beam self-action in air is important, even at several centimeters of propagation distance.

We have measured the energy efficiency of SHG in 0.6-mm-thick KDP crystal at different detuning external angles $\Delta\theta$, see Fig. 1. The main goal was to experimentally verify the fact that for efficient SHG different intensities require different optimal angles of beam propagation.

Note that the fundamental central wavelength of the laser pulse used in the experiments was slightly pulse-to-pulse unstable. This spectrum fluctuation leads to fluctuation of SHG conversion efficiency. We depicted in Fig. 1, the points with central wavelength lying between 900 and 920 nm.

As can be seen from Fig. 1, a perfect phase matching (i.e., $\Delta\theta = 0$ mrad) is optimal for SHG efficiency at low (2/4 mJ) and medium (10 mJ) input energies. But at high energies (18 mJ), SHG is more efficient at the optimal detuning angle $\Delta\theta = -3.1$ mrad, because the phase induced by third-order nonlinearity and linear-phase mismatching compensate each other. A negative value of optimal detuning angle is also clearly seen from comparison of data for $\Delta\theta = -6.2$ and 6.2 mrad: SHG ef-

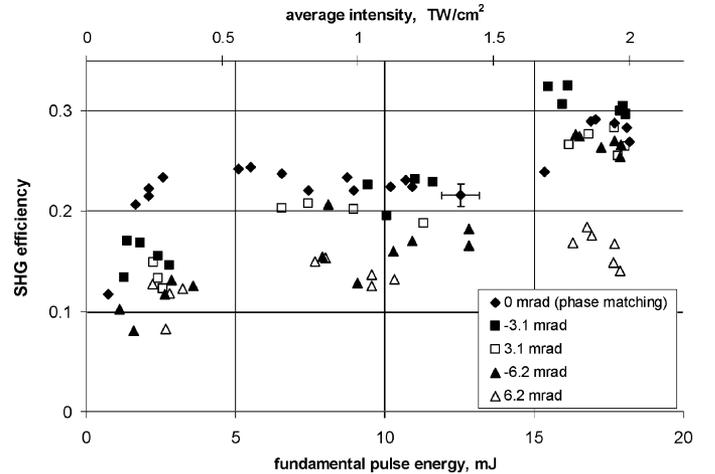


Fig. 1. Dependence of energy conversion efficiency *versus* input fundamental pulse energy at different detuning (external angles) from linear phase matching direction.

iciency is almost the same at 2–4 mJ and is noticeably different at 16–18 mJ. The experimental results are in a good agreement with formula (1), which gives for 18 mJ energy (average intensity 2 TW/cm²) $\Delta\theta = -3.5$ mrad. The optimal detuning angle for the intensities is more than the experimental beam divergency. It is necessary to emphasize that the results are the first experimental confirmation of the theoretical model of SHG under strong influence of cubic nonlinearity.

Relatively low SHG efficiency and large spread of the experimental data are explained by poor quality of both the beam and the ultrathin KDP crystal. In a 1-mm-thick KDP crystal, we reached 41% of SHG energy efficiency at such high intensities.

III. SUPPRESSION OF SMALL-SCALE SELF-FOCUSING

The theory of small-scale self-focusing in a cubic nonlinear medium [12]–[15] was generalized for the case of both quadratic and cubic nonlinearities in [17]. In this paper, we derived the effective B-integral $B_{\text{eff}} = \int_0^L (\gamma_{21}|A_1(z)|^2 + \gamma_{22}|A_2(z)|^2) dz$, which takes into account not only self-action of both harmonics (γ_{11} and γ_{22}), but their cross action (γ_{12} and γ_{21}) as well. B-integral is accumulated nonlinear phase, which appears from influence of cubic polarization. It is the main parameter in the theory of small-scale self-focusing. The one is responsible for gain factors of harmonic disturbances of powerful beams. Consequently, at $B > 2.5$, small-scale self-focusing should lead to strong filamentation and inevitable optical breakdown.

Nevertheless, in our experiments, there were no manifestations of any damage of KDP crystals 0.6 and 1 mm thick at the incident peak intensity of 5 TW/cm² ($B = 3.8$ and 6.4, correspondingly). We believe, this effect is explained by a low level of high-spatial-mode noises because of beam self-filtering during free propagation before the crystal.

The point is that cubic nonlinearity leads to high amplification of spatial noise propagating at an optimal angle to the z -axis [12]–[15]. Strictly speaking, these “dangerous” angles depend on incident intensity, central wavelength, crystal thickness, quadratic, and cubic nonlinearities. But the most important

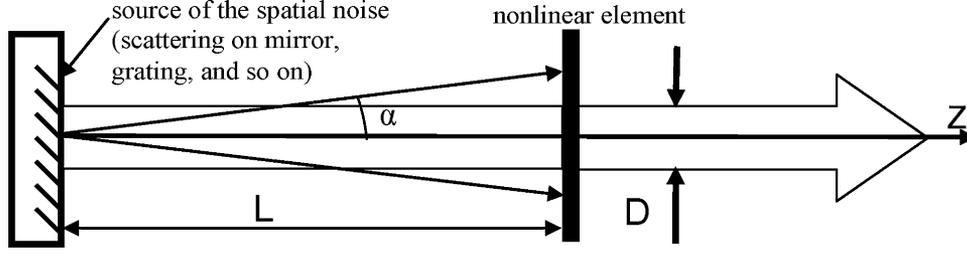


Fig. 2. Idea of small-scale self-focusing suppression. d is beam diameter, D is free-space propagation distance, and α is angle of propagation of noise wave.

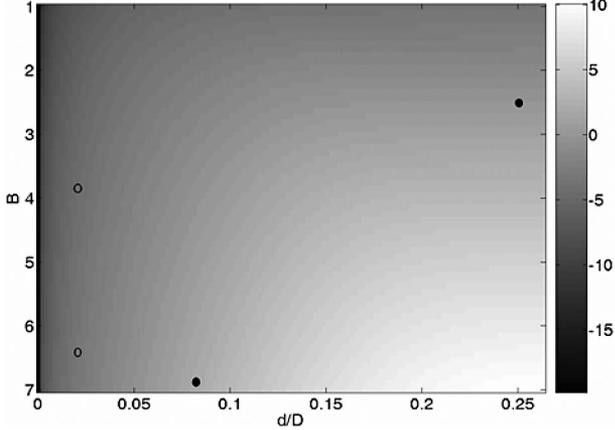


Fig. 3. Logarithm of normalized power of noise $\ln(F)$ versus B-integral and angle of view d/D at intensity 5 TW/cm^2 . Open circles show experiments without filamentation and fill circles show experiment with filamentation.

is intensity dependence: the angle is proportional to the square root of intensity. For the intensity of order 5 TW/cm^2 , the typical value of the “dangerous” angles is 40 mrad [17]. This means that the most “dangerous” (from the small-scale self-focusing viewpoint) noise escapes from the beam aperture (4.3 mm) after propagation of just 11 cm distance. Noise propagating at lower angles is also amplified due to cubic nonlinearity, but its gain is much smaller and filamentation takes place at very high values of B-integral. The principal scheme of small-scale self-focusing suppression is shown in Fig. 2.

This idea to suppress small-scale self-focusing by beam self-filtering due to free propagation before SHG may be used in any high-intensity laser. Full analysis of small-scale self-focusing at SHG is based on the classical theory [12]–[15] and is described in [17]. Here, let us omit bulky math and illustrate the idea by results of calculation and comparison with experiments. The geometry is shown in Fig. 2. The key parameters of the task are B-integral and angle of view d/D .

The dependence of normalized power of the spatial noise $F = P_{\text{out}}(B, d/D)/P_{\text{out}}(B = 2.5, d/D = 1)$ at the output of nonlinear element is presented in Fig. 3. At a large angle of view d/D (no self-filtering), all noise waves reach the nonlinear element and noise power at its output is the highest. In this case, filamentation appears at $B \approx 2.5$ ($F \approx 1$), the fact was observed in our experiments. When d/D reduces to about 0.2 , the noise power decreases as well. It drops sharply when $d/D <$

0.1 . As one can see from Fig. 3, experimental points with 0.6 - and 1 -mm-thick crystal ($d/D = 0.02$) are in a safety region: $F \ll 1$ even though $B = 3.8$ and 6.4 , correspondingly. On the other hand for experimental points, where filamentation was observed ($d/D = 0.08$), the F parameter is above unity, see Fig. 3.

Note that in nanosecond lasers, the typical intensity is 1 GW/cm^2 , hence, self-filtering takes place at the angle of view $d/D < 0.003$, because the angle is proportional to the square root of laser beam intensity. Such a small value limits practical use of self-filtering for 1 GW/cm^2 intensity laser pulses.

IV. INFLUENCE OF DISPERSION ON SHG OF ULTRASHORT PULSES

For correct description of the ultrashort laser pulse SHG, in addition to cubic nonlinearity, the dispersion effects should be taken into consideration. Group velocity mismatch and group velocity dispersion are the most important linear dispersion phenomena. To diminish their influence on SHG, the crystal length L should be minimized. It should be smaller than the characteristic length of group velocity mismatch L_{12} and group velocity dispersion lengths L_1 and L_2 , but larger than nonlinear length L_{nl}

$$L_{nl} < L < L_{12}, L_1, L_2$$

where $L_{12} = T |1/u_1 - 1/u_2|^{-1}$, $L_i = T^2/4 \ln(2) |D_i|$, $u_i = dk/d\omega|_{\omega_i}$ is group velocity, $D_i = d^2k/d\omega^2|_{\omega_i}$, $L_{nl} = (\beta A_{10})^{-1}$, β is the coefficient of second-order nonlinear wave coupling, and T is input pulse duration (full-width at half-maximum (FWHM), Gaussian pulse).

Experimental implementation of the SHG of femtosecond petawatt pulses requires large aperture (more than 10 cm) ultrathin (hundreds of micrometers) nonlinear elements with wide-band phase matching at 800 nm (Ti:sapphire lasers) and 910 nm (optical parametrical amplification lasers). At present, KDP and deuterated KDP (DKDP) crystals are the only crystals satisfying these requirements. Further analysis will be done for the KDP crystal at these two wavelengths.

Taking KDP parameters from [18], we summarize characteristic lengths in Table I.

It is clear from Table I that L_{12} is always smaller than L_1 and L_2 . This means that group velocity mismatch is the most important dispersion effect. Its negative influence on SHG is twice as large at 800 nm fundamental wavelength as at 910 nm . Hence, at 800 nm , the KDP crystal must be thinner for the same

TABLE I
CHARACTERISTIC LENGTHS FOR KDP CRYSTAL

λ_1 nm	$T=20\text{fs}$			$T=50\text{fs}$			T/L_{12} , fs/mm	L_{nl} , mm ($5\text{TW}/\text{cm}^2$)
	L_1 , mm	L_2 , mm	L_{12} , mm	L_1 , mm	L_2 , mm	L_{12} , mm		
800	5.3	1.36	0.26	33	8.52	0.65	77	0.15
910	12.7	1.65	0.55	79.4	10.4	1.38	36	0.18

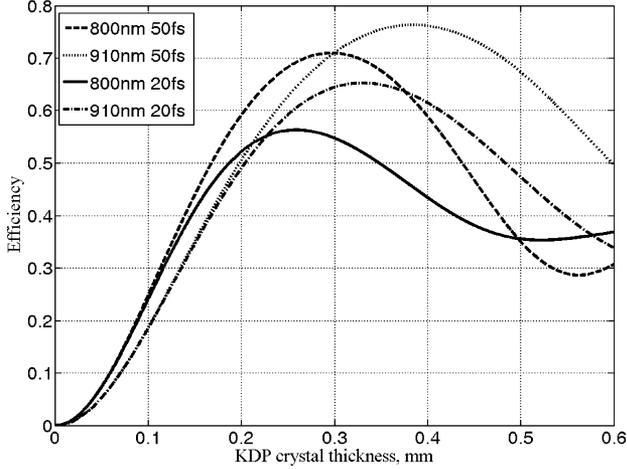


Fig. 4. SHG energy conversion efficiency versus KDP thickness for 20 and 50 fs FWHM pulse at 800 and 910 nm fundamental wavelengths.

pulse duration and the pulse must be longer for the same KDP thickness.

For quantitative characterization of the influence of dispersion effects and for finding optimal KDP thickness, we solve numerically the following equations [7], [11]:

$$\begin{aligned} \frac{\partial A_1}{\partial z} + \frac{1}{u_1} \frac{\partial A_1}{\partial t} - \frac{ik_2^{(1)}}{2} \frac{\partial^2 A_1}{\partial t^2} \\ = -i\beta A_1 A_2^* e^{-i\Delta k z} - i\gamma_{11} |A_1|^2 A_1 - i\gamma_{12} |A_2|^2 A_1 \\ \frac{\partial A_2}{\partial z} + \frac{1}{u_2} \frac{\partial A_2}{\partial t} - \frac{ik_2^{(2)}}{2} \frac{\partial^2 A_2}{\partial t^2} \\ = -i\beta A_1^2 e^{i\Delta k z} - i\gamma_{21} |A_1|^2 A_2 - i\gamma_{22} |A_2|^2 A_2 \end{aligned}$$

where A_1 and A_2 are the complex amplitudes of the fundamental and the SH fields, z is the longitudinal coordinate of wave propagation, and $\Delta k = k(\omega_2) - 2k(\omega_1)$ is the linear wave vector-phase mismatch. The inertia of cubic nonlinearity is not taken into consideration in the equations, because in our work, the pulses durations are more than 5–10 fs [7].

The calculations were done for the input peak intensity of $5 \text{ TW}/\text{cm}^2$ and for the optimal detuning angle $\Delta\theta$ in compliance with (1). SHG energy conversion efficiency versus KDP thickness is presented in Fig. 4. The pulses profiles at the output of 0.4-mm-thick KDP crystal are shown in Fig. 5.

Figs. 4 and 5 clearly confirm advantages of 910 nm fundamental wavelength over 800 nm. First of all, the maximum energy conversion efficiency is higher: 65% versus 56% for 20 fs

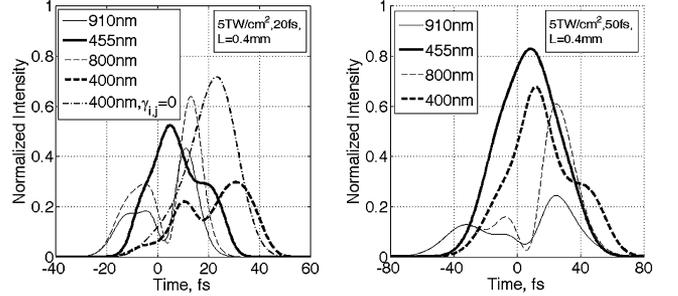


Fig. 5. Output temporal intensity profiles of fundamental and SH. KDP thickness is 0.4 mm, input pulse intensity $5 \text{ TW}/\text{cm}^2$, input pulse duration is (a) 20 and (b) 50 fs, central wavelength of fundamental radiation 800 and 910 nm. The intensity profiles are normalized to peak intensity of fundamental radiation.

pulses. Even more important is the crystal thickness limitation. The thickness of 0.4 mm is sufficient for 910 nm wavelength even for 20 fs pulses. As to 800 nm wavelength, the 0.4-mm-thick KDP crystal still may be used for 50 fs pulse, but it is too thick for 20 fs pulse because group velocity mismatch reduces efficiency to 44% (see Fig. 4) and the SH pulse profile is not suitable for most applications [see Fig. 5(a)].

It is necessary to underline the fact that dispersion effects lead to such drastic SH pulse profile modulation only when cubic nonlinearity is significant. In accordance with Fig. 5(a), when there are no cubic polarization effects ($\gamma_{ij} = 0$), there is no crucial pulse modulation, even if the crystal length is about two times more than the length of group velocity mismatch. The fact is that the cubic polarization produces the nonlinear-phase mismatch and the angle detuning of fundamental beam propagation cannot compensate it entirely in the frame of the model. The phase is conducive to backward energy conversion and, as a consequence, the strong SH pulse modulation appears. The presented approach to the increasing of energy conversion efficiency in quasi-static regime by means of detuning of the fundamental beam propagation direction to the angle, which is correspond to peak intensity is valid as long as self-phase modulation effects are not disastrous for optical pulses.

The cubic polarization cannot be excluded in the experiments. Thus, 20 fs pulses at 800 nm wavelength may be frequency doubled in the 0.2–0.3 mm KDP crystal. The thicker crystals usage at such high intensities ($5 \text{ TW}/\text{cm}^2$) leads to small energy conversion efficiency and significant SH pulse modulation. At present, there is no technology to produce such a thin crystal with an aperture of about 10 cm. A possible way to overcome the bottleneck is to use ultrathin KDP double-pass geometry crystal glued on a substrate.

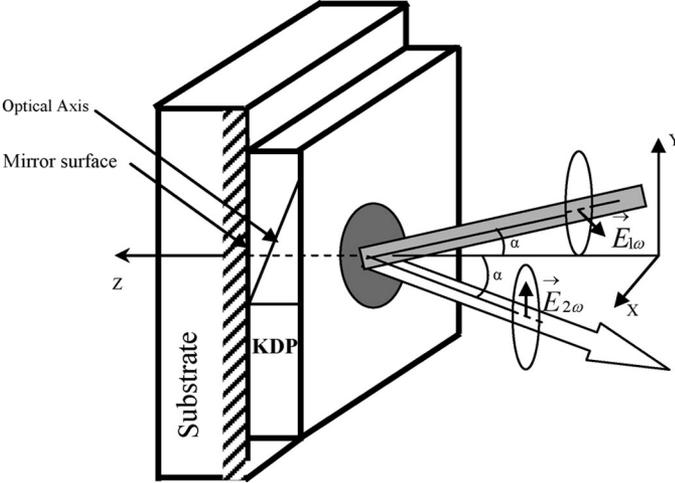


Fig. 6. Double-pass SHG geometry. The incident and reflected beams lie in noncritical xz -plane.

High-aperture crystals with a thickness below 0.4 mm probably may be produced only on a substrate. In this case, the thickness can be controlled during polishing. If there is high-reflectivity mirror between the crystal and the substrate, such a sandwich may be used for SHG of ultrashort pulses, as shown in Fig. 6.

If the angle of incidence $\alpha = 0$, the phase matching takes place for both forward and backward passes because the angle θ between optical axis and both wave vectors is the same. In practice, to pick up a reflected beam without any optics placed in the incident beam, the angle of incidence α should be large enough. Even though both wave vectors lie in the noncritical xz -plane, an increase of α slightly violates the phase matching condition changing the angle θ . But this violation may be easily compensated by changing the crystal axis angle in the critical plane (yz) by $\Delta\theta_2$

$$\Delta\theta_2 = 2 \sin\left(\frac{\alpha}{2}\right)^2 \text{ctg}(\theta)$$

The proposed scheme can be used for SHG of high-power ultrashort femtosecond pulses in spite of group velocity dispersion. But it is necessary to point out the fact that fundamental and SH waves are orthogonally polarized. The fact is very important because during reflection, these waves acquire phase shift resulting in a decrease of SHG efficiency, as depicted in Fig. 7.

Different periods in Fig. 7 for two harmonics can be explained in terms of physics by the fact that SHG is fully determined by generalized phase $\psi = 2\varphi_1 - \varphi_2 + \Delta kz$, where φ_i is harmonic phase [6], [11]. From this expression, period π for fundamental harmonic and period 2π for the second one are clear.

According to Fig. 7, the SHG efficiency significantly depends on the phase shifts induced by the mirror. The amount of the phase shift depends on the intrinsic properties of the mirror. In order to exclude the negative effect, it is necessary to know mirror design and acquired phase shifts. For example, metal mirrors are not suitable at all. The point is that during the reflection from an ideal metal TE-wave (SH radiation in our case) acquires π

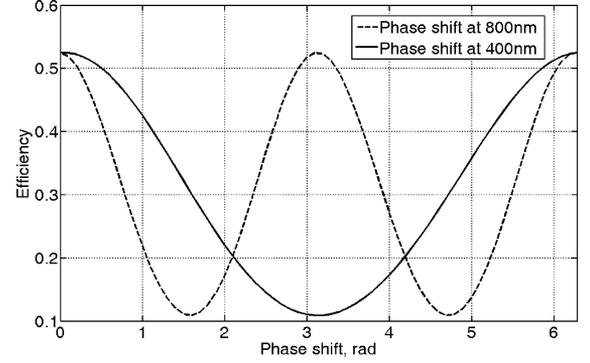


Fig. 7. Dependences of energy conversion efficiency on the phase shift induced by a mirror coated on 0.1-mm-thick KDP crystal. Phase is induced in fundamental or SH. Incident pulse parameters are: pulse duration 20 fs (FWHM, Gaussian), intensity 5 TW/cm², and central wavelength 800 nm.

phase shift, but at the same time, TM-wave (fundamental radiation) does not obtain it [19]. In accordance with Fig. 5, this fact leads to significant decreasing of energy conversion efficiency.

V. PULSE SHORTENING AND CONTRAST ENHANCEMENT AT SHG

The cubic polarization of the frequency-doubling crystal leads not only to negative effects described in Sections II and III, but to spectrum broadening as well. The output SH pulse is not Fourier transform limited; its duration approximately equals input pulse duration. The spectrum phase correction is known to be an excellent approach to pulse compression. The effect is widely used in the optical fibers and was suggested to reduce the duration of SH radiation [11]. For instance, it can be achieved outside the nonlinear crystal by chirped mirrors. Even quadratic spectral phase correction only significantly reduces pulse duration. Mathematically, this operation may be written as follows:

$$A_{2\text{comp}}(t) = F^{-1}[e^{iS\omega^2} F[A_2(z = L, t)]]$$

Here, F and F^{-1} are the direct and inverse Fourier transforms, $A_2(z = L, t)$, $A_{2\text{comp}}(t)$ are the electric fields of SH radiation before and after phase correction, and S is the coefficient of quadratic spectral phase correction. The electric field $A_2(z = L, t)$ is obtained by the numerical solution of (2). The results are presented in Fig. 8 for optimal detuning angle $\Delta\theta$ (1) and for 5-TW/cm² fundamental Gaussian pulse (20 fs FWHM). The coefficient S was chosen to minimize the pulse duration. Maxima of all the three pulses were shifted to zero time for clarity.

According to Fig. 8, SHG allows contrast ratio to be improved significantly. Although the dispersion effects lead to pulse broadening, the second-order spectrum phase correction gives an opportunity to compress SH pulse considerably. For instances, for fundamental wavelength Gaussian pulse with duration 20 fs (FWHM) and intensity 5 TW/cm², the SH pulse may be compressed to 12 fs (800 nm and 0.2-mm-thick KDP) and to 9 fs (910 nm and 0.4-mm-thick KDP). The 50-fs input pulse may be compressed even more efficiently in a 0.4-mm-thick KDP: to 18 fs at 800 nm and to 16 fs at 910 nm.

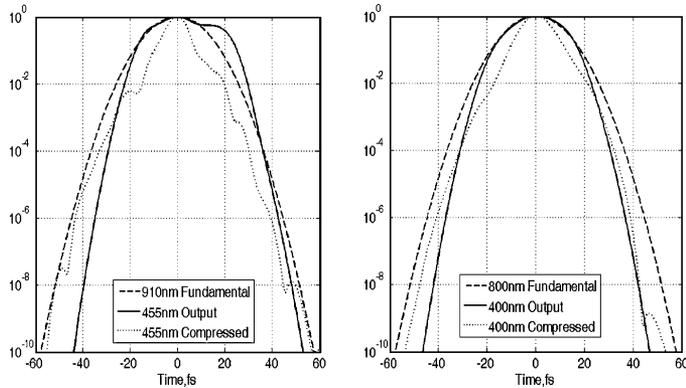


Fig. 8. Shapes of incident (dashed line) and SH pulses before (solid line) and after (dotted line) spectral phase correction. (Left) Fundamental wavelength 910 nm and KDP thickness 0.4 mm. (Right) Fundamental wavelength 800 nm and KDP thickness 0.2 mm.

Note that the contrast of the compressed pulse is lower than the contrast of the uncompressed one, but is still higher than the contrast of the fundamental wavelength pulse (see Fig. 8).

VI. CONCLUSION

The theory of SHG under strong influence of cubic polarization was verified experimentally. Despite the poor quality of the fundamental beam, the energy conversion efficiency of 35% (41%) was achieved in 0.6 (1.0)-mm-thick KDP crystal.

The experiments were done at peak intensity 5 TW/cm², which corresponds to B-integral 6.4 in 1.0-mm-thick KDP. Nevertheless, there were no manifestations of any damage of the crystal. This effect is explained by low level of high-spatial-mode noises because of beam self-filtering during its free propagation before the doubling crystal.

The comparative analysis of SHG of radiation at fundamental wavelengths 910 and 800 nm clearly showed the major advantage of the first one, because group velocity dispersion at 910 nm is lower by a factor of two. The KDP thickness of 0.4 mm is sufficient for 910 nm even for 20 fs pulses. As to 800 nm wavelength, the 0.4-mm-thick KDP crystal may still be used for 50 fs pulse, but for 20 fs pulse 0.25 mm thickness is required.

The double-pass scheme of SHG in an ultrathin KDP crystal on a substrate was proposed and analyzed.

SHG clearly enhances the pulse contrast ratio. Additional correction of parabolic spectral phase of the SH radiation reduces the pulse duration from 20 to 12 fs for 800 nm fundamental wavelength (0.2-mm-thick KDP) and down to 9 fs for 910 nm (0.4-mm-thick KDP).

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