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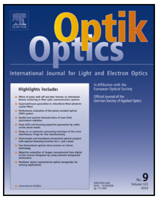

Impact of spatial modulation on the third harmonic wave propagation and far-field focal spot in frequency conversion system

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ABSTRACT

Third harmonic generation (THG) of high power laser is discussed in KDP crystals utilized in frequency conversion systems of large laser facilities. The far-field focal spot of the third harmonic wave is presented based on numerical simulation of the nonlinear coupled-wave equations, in which the walk-off and paraxial diffraction are taken into account and the electric field of the fundamental wave (1053 nm, 1ω) pulse is phase and amplitude modulated in spatial domain. Impact of the modulation depth and frequency on the focal spot energy, the side lobes location and conversion efficiency are analyzed in detail. The results show that the side lobes location is equivalently determined by the modulation frequency of both phase modulation and amplitude modulation, while the energy-concentration is decreased mostly because of the 1ω modulation depth. Relatively, the phase modulation plays a more important role than the amplitude modulation in decreasing main lobe energy for different reasons. The phase modulation makes the energy flowing from the main lobe to side lobes, while amplitude modulation not only makes the energy flowing but also decreases tripling efficiency significantly.

1. Introduction

In the large laser facilities to realize inertial confinement fusion (ICF), the 1ω pulses are required to be up-frequency-converted to 526.5 nm (2ω) and 351 nm (3ω) to improve the target coupling efficiency [1]. It makes the frequency conversion system a crucial part of the final optics assembly (FOA). The conversion efficiency is defined as the ratio of the output 3ω pulse energy to the input 1ω pulse energy. As a result, it is one of the most important goals to get higher conversion efficiency. On the other hand, deformable mirror and phase plate are utilized for wave-front correction to get better near field beam quality, which will enhance the far-field focal spot so that the majority of 3ω pulse energy can be concentrated on the target [2,3]. Many physical effects like the nonlinear refractive-index effects, two-photo absorption, SBS, and bulk losses can reduce the conversion efficiency. Such effects are taken into consideration as various terms in the coupled-wave equations [4,5]. What is more, other effects including phase mismatching, stress deformation, crystal internal defects, as well as the subsurface damage resulting from fabrication process will affect the conversion efficiency as well as the far field focal spot [4–7]. They are taken into account by the momentum mismatch factor or by composing the amplitude and phase modulations on the incident beam in spatial domain so that the frequency conversion crystals would be considered ideal [5,8,9]. The work builds on earlier work performed at Lawrence Livermore National Labs, in which the propagation of 1ω near-field perturbations through the frequency tripling process was simulated, but effects on the far-field distribution were not explored (or at least not published) to our knowledge [9–11]. In this paper, the impact of the spatially modulated 1ω electric field on the propagation of the 3ω electric field is researched theoretically and the far-field focal spot property is presented with frequency conversion system in the No.9 System of SG-II facility as the prototype [12]. The conclusions can be useful for the experimental data analysis and the FOA optimization.

2. Numerical model of THG with spatial modulations

As indicated in Refs. [4,13], the tripling efficiency is severely affected by the nonlinear crystal lengths, fundamental wave intensity and phase matching angles. For various experimental demands, targeting pulses are of different energy from the laser driver so that laser intensity through the conversion system changes in a wide range. On the condition that the nonlinear crystal lengths are fixed, the frequency-doubling converter of type I phase matching ($o + o \rightarrow e$) and frequency-tripling converters of type II phase

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Table 1
Laser parameters of the incident beam [12].

Parameters	Energy	Aperture	Pulse width	Profile
Values	4045 J	310 mm	3 ns	6th super Gauss

matching (o + e → e) are always set detuning angles round the phase matching angles so that the second harmonic conversion efficiency would keep little excursion from the ratio of 66.7% to insure that the TH conversion efficiency is maximized [5,6]. It is reported that the efficiency is up to ∼70% in SG-II No.9 System and >80% in NIF [12,14,15].

To show the prominent influence of 1ω spatial modulations on the 3ω propagation, the bulk losses, group velocity dispersion (GVD), two-photo absorption and nonlinear refractive-index effects are neglected. Considering walk-off and paraxial diffraction, THG nonlinear coupled-wave equations in negative uniaxial crystals are given by [16]

$$\begin{cases} \dfrac{\partial A_1}{\partial z} = \tan\rho_1 \dfrac{\partial A_1}{\partial y} - \dfrac{1}{i2k_1\cos^2\rho_1}\nabla_\perp^2 A_1 + \dfrac{i\omega_1 d_{eff}}{cn_1\cos^2\rho_1} A_3 A_2^* \exp(i\Delta kz) \\ \dfrac{\partial A_2}{\partial z} = -\dfrac{1}{i2k_2}\nabla_\perp^2 A_2 + \dfrac{i\omega_2 d_{eff}}{cn_2} A_3 A_1^* \exp(i\Delta kz) \\ \dfrac{\partial A_3}{\partial z} = \tan\rho_3 \dfrac{\partial A_3}{\partial y} - \dfrac{1}{i2k_3\cos^2\rho_3}\nabla_\perp^2 A_3 + \dfrac{i\omega_3 d_{eff}}{2cn_3\cos^2\rho_3} A_1 A_2 \exp(-i\Delta kz) \end{cases} \quad (1)$$

where subscripts 1, 2 and 3 represent fundamental wave, SH wave and TH wave, respectively. A is the electric field; ω, the angular frequency; n, the refractive index; d_{eff}, the effective nonlinear coefficient; ρ, the walk-off angle; c, the light velocity in vacuum; k, the wave vector in crystal and the phase mismatch factor for type-II tripling $\Delta k = k_3 - k_2 - k_1$. $\nabla_\perp^2$ is the transverse laplacian. The KDP crystals for frequency doubler and tripler are 12.5 mm and 10.5 mm in length and phase matched at 41.18° and 59.02°, respectively. The laser parameters of the incident beam reported in Ref. [12] are listed in Table 1.

To calculate the influence of the fundamental wave modulations on the TH wave far-field focal spot quantitatively, the small ripples of amplitude and phase modulation are given by [9]

$$a(x,y) = 2\pi\sigma_{ax}\sin(2\pi f_{ax}x) + 2\pi\sigma_{ay}\sin(2\pi f_{ay}y) \quad (2)$$

$$\phi(x,y) = 2\pi\sigma_{px}\sin(2\pi f_{px}x) + 2\pi\sigma_{py}\sin(2\pi f_{py}y) \quad (3)$$

where $(\sigma_{ax}, \sigma_{ay})$ and $(\sigma_{px}, \sigma_{py})$ are amplitude and phase modulation depths along x-axis and y-axis, (f_{ax}, f_{ay}) and (f_{px}, f_{py}) are amplitude and phase modulation frequency. In this paper, we take $\sigma_{ax} = \sigma_{ay}$, $\sigma_{px} = \sigma_{py}$, $f_{ax} = f_{ay}$ and $f_{px} = f_{py}$. If electric field without modulations is $A_0(x, y, z, t)$, the fields of amplitude modulated and phase modulated are expressed as $[1 + a(x, y)]A_0(x, y, z, t)$ and $A_0(x, y, z, t)\exp[i\varphi(x, y)]$, respectively.

Calculations with nonlinear coupled-wave equations can provide the TH wave near field, which is focused by lens of focal length 2234 mm. That is to say, the far field focal spot is achieved by the Fourier transform of TH wave near field. The focusing effect is not the topic of this paper and is not taken into account. The energy-concentration can be used to describe TH wave far-field focal spot [17]. Energy-concentration is defined as the ratio of the energy round a certain region to the total energy. In Eq. (4), s is the cross-sectional area for integral region, and is fixed as the radius of 3 μm circular aperture, almost the spatial Fourier-transform limit

$$\eta = \iint_s E dxdy \Big/ \iint_\infty E dxdy \quad (4)$$

We use Strehl Ratio to describe the modulation influence on the main lobe energy of far-field focal spot and it is defined as the ratio of the main lobe energy with fixed modulations to that without modulations:

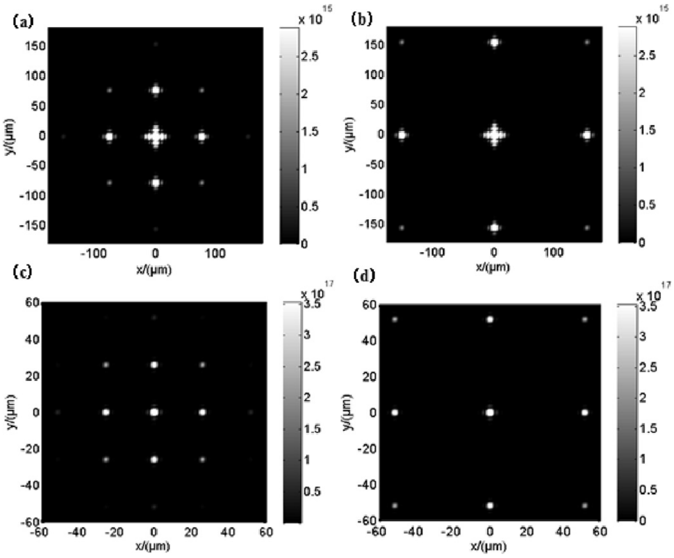

Fig. 1. Fundamental wave (a and b) and TH wave (c and d) far-field focal spots under various phase modulation frequencies of 500 m^{-1} (a and c) and 1000 m^{-1} (b and d).

$$SR = \iint_s E_{\mathrm{modu.}} dxdy \Big/ \iint_s E_{\mathrm{unmodu.}} dxdy \quad (5)$$

Based on the definitions above, the THG conversion efficiency ξ can be expressed by

$$\xi(\sigma, f) = [\eta(0,0)\cdot \mathrm{SR}(\sigma, f)/\eta(\sigma, f)]\cdot \xi(0,0) \quad (6)$$

For the certain fundamental wave in conversion systems, the tripling efficiency and energy-concentration without modulations are constants $[\xi(0,0), \eta(0,0)]$, so the conversion efficiency with modulation $\xi(\sigma,f)$ is determined by the ratio $\mathrm{SR}(\sigma,f)/\eta(\sigma,f)$. On condition of paraxial diffraction, $\eta(0,0) \approx 1$. Eq. (6) indicates that the 3ω total energy with modulations is equal to the main lobe energy without modulations when $\eta = \mathrm{SR}$ is fulfilled, and the conversion efficiency is decreased by the ratio $\eta(0,0)$ because of modulations. For various modulations, the conversion efficiency would be kept round a certain level when $\eta \le \mathrm{SR}$ is fulfilled, and it will be decreased to a large extent when $\eta \gg \mathrm{SR}$ is fulfilled. Strehl Ratio, energy-concentration and tripling efficiency can be used to describe the energy conversion either between the 1ω and the 3ω electric field or between the 3ω main lobe and side lobes, and the different mechanisms of the influence of amplitude and phase modulations can be analyzed with this method.

3. Influence of fundamental wave modulations on TH wave propagation

3.1. Phase modulation

Fig. 1(a)–(d) shows the 1ω and 3ω far-field focal spots when the phase modulation depth σ_p and frequency f_p are assigned (0.05, 500) and (0.05, 1000). It must be noted that, in order to display the fine structure of the far-field focal spot, a maximal intensity ($I_{\max}$) is defined as 10^{19} W/cm^2 and data used to draw Fig. 1(a) and (b) is processed by assigning the actual data larger than 0.01% $I_{\max}$ to be 0.01% $I_{\max}$, and as a result, the magnitude orders in Fig. 1(a) and (b) color bars are 10^{15} W/cm^2. Similar as above, data used to draw Fig. 1(c) and (d) is processed by assigning the actual data larger than 1% $I_{\max}$ to be 1% $I_{\max}$, and the magnitude orders in Fig. 1(c)