

Performance curves comparison of THG efficiency in CsLiB₆O₁₀ on flattened Gaussian and Gaussian beams

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The conversion efficiency of THG on the flattened Gaussian and Gaussian beams is obtained in detail numerical stimulation for CsLiB₆O₁₀. The conversion efficiencies of 86.7% and 96% of the flattened Gaussian are larger than those of Gaussian beams of 72.6% and 88% under type I and type II(1) phase matching. The efficiencies affected by the pump intensity, polarization rate, crystal lengths and orders of the flattened Gaussian beams were presented.

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The result development in flattened Gaussian beams (FGBs)^[1], with the comparison of the coherent and incoherent for FGBs has been researched^[2,3]. Several researchers have tried to control the shapes of laser pulses^[4,5], with pulse stretching being achieved successfully by a Q-switched Nd:YAG laser^[6]. The energy conversion efficiency has been studied for Gaussian beams, but not for third harmonic generation (THG) of FGBs. Recently the development of large, high quality crystal CsLiB₆O₁₀ (CLBO) has provided a high power source for ultraviolet (UV) laser^[7-9], and THG theoretical analysis of CLBO crystal has simulated for Gaussian beams^[10]. In order to obtain higher output energy conversion efficiency and a shorter laser wavelength based on CLBO, several efforts have been demonstrated based on FGBs in this paper. The conversion efficiency of THG of FGBs is still a new subject field. The efficiency curves versus the crystal lengths, the pumping wave polarization ratio, the order of the FGBs and the pump power intensity have been calculated by computer simulation. The conversion efficiency of THG of the FGBs and Gaussian beams is obtained in detail numerical stimulation for CLBO. The efficiencies of 86.7% and 96% of the FGBs are larger than those of Gaussian beams of 72.6% and 88% under type I and type II(1) phase matching (PM), respectively, and in good agreement with the experimental results^[11].

The efficiency theory of THG on FGBs and Gaussian beams is based on the three waves coupling equations and the dispersion equation of new UV material CLBO. The electric field component in THG FGBs and Gaussian beams now regarded as $E_{20}(0, r) > E_{10}(0, r)$, is written by

$$E_3(z, r) = \sqrt{g_1} E_{20}(0, r) sn [g_2 E_{10}(0, r) z, g_3 E_{20}(0, r) / E_{10}(0, r)], \quad (1)$$

where

$$g_1 = \frac{k_2 \omega_3^2 \cos \alpha_2}{k_3 \omega_2^2 \cos \alpha_3}, \quad (2a)$$

$$g_2 = \frac{1}{2} \varepsilon_0 \mu_0 d_{\text{eff}} \frac{\omega_2 \omega_3}{(k_2 k_3 \cos \alpha_2 \cos \alpha_3)^{1/2}}, \quad (2b)$$

$$g_3 = \frac{\omega_1}{\omega_2} \left(\frac{k_2 \cos \alpha_2}{k_1 \alpha_1} \right)^{1/2}, \quad (2c)$$

and as $E_{20}(0, r) < E_{10}(0, r)$ is considered, the THG field is derived by

$$E_3(z, r) = \sqrt{g'_1} E_{10}(0, r) sn [g'_2 E_{20}(0, r) z, g'_3 E_{10}(0, r) / E_{20}(0, r)], \quad (3)$$

where

$$g'_1 = \frac{k_1 \omega_3^2 \cos \alpha_1}{k_3 \omega_1^2 \cos \alpha_3}, \quad (4a)$$

$$g'_2 = \frac{1}{2} \varepsilon_0 \mu_0 d_{\text{eff}} \frac{\omega_1 \omega_3}{(k_1 k_3 \cos \alpha_1 \cos \alpha_3)^{1/2}}, \quad (4b)$$

$$g'_3 = \frac{\omega_2}{\omega_1} \left(\frac{k_1 \cos \alpha_1}{k_2 \alpha_2} \right)^{1/2}. \quad (4c)$$

We assume $d = \frac{E_{20}(0, r)}{E_{10}(0, r)}$ is the fundamental polarization rate. We obtain the relation of $E_{20}(0, r)$, $E_{10}(0, r)$ and $E_0(0, r)$ by

$$E_0^2(0, r) = E_{10}^2(0, r) + E_{20}^2(0, r), \quad (5a)$$

$$E_{10}^2(0, r) = E_0^2(0, r) / (1 + d^2), \quad (5b)$$

$$E_{20}^2(0, r) = E_0^2(0, r) d^2 / (1 + d^2). \quad (5c)$$

$E_N(0, r)$ of FGBs^[1] is

$$E_N^2(0, r) = E_0 \exp \left[\frac{(N+1)r^2}{\omega_0^2} \right] \cdot \sum_{m=0}^N \frac{1}{m!} \left[\frac{(N+1)r^2}{\omega_0^2} \right]^2 \quad (N = 1, 2, 3, \dots), \quad (6)$$

where $E_0(0, r)$ of Gaussian beams that is $N = 0$ in Eq. (6), and the substitutions of Eqs. (5) and (6) into Eqs. (1) and (3) give the efficiency of THG of FGBs as

$$\eta(z) = \frac{g_1 d^2 \int_0^\infty sn^2 \left[\frac{g_2 z E_0(0, r)}{\sqrt{1+d^2}}, g_3 d \right] E_0^2(0, r) 2\pi r dr}{\int_0^\infty E_0^2(0, r) 2\pi r dr}, \quad (7a)$$

$$g_3 d < 1,$$

$$\eta(z) = \frac{g'_1 \int_0^\infty sn^2 \left[\frac{g'_2 z E_0(0, r)}{\sqrt{1+d^2}}, g'_3 / d \right] E_0^2(0, r) 2\pi r dr}{\int_0^\infty E_0^2(0, r) 2\pi r dr}, \quad (7b)$$

$$g'_3 d < 1.$$

From Eqs. (7), it is clearly demonstrated that the efficiency of THG of FGBs depends on the factors of fundamental orders N , pump intensity, crystal lengths z and polarization rate d .

To optimize the efficiency performance, we aligned THG FGBs and Gaussian beams that are propagated through a CLBO crystal at a type I PM ($o + o \rightarrow e$). The efficiency curves versus the crystal lengths and the polarization rate at the different orders, and the pump intensity as shown in Figs. 1 – 3. From Figs. 1 – 3, the results of efficiencies on FGBs and Gaussian beams are got at the following numerical parameters: PM angles $\theta = 39.15^\circ$, cutting angles $\Phi = 45^\circ$, effective nonlinear coefficient $d_{\text{eff}} = 0.6 \text{ Pm/V}^{[8]}$, fundamental wavelength $\lambda_1 = 1064 \text{ nm}$, frequency $\omega_1 = 1.78 \times 10^{15} \text{ Hz}$, walk-off angle $\alpha_1 = 0^\circ$, refractive index $n_1 = 1.4854$, wave vector $K_1 = 8.81 \times 10^6$; the SHG $\lambda_2 = 532 \text{ nm}$, $\omega_2 = 3.56 \times 10^{15} \text{ Hz}$, $\alpha_2 = 0^\circ$, $n_2 = 1.498$, $K_2 = 1.78 \times 10^7$; the THG $\lambda_3 = 355 \text{ nm}$, $\omega_3 = 5.34 \times 10^{15} \text{ Hz}$, $\alpha_3 = 2^\circ$, $n_3 = 1.494$. Substituting above parameters into Eqs. (2) and (4), we obtain $g_1 = 1.51$, $g_2 = 2.92 \times 10^{-6}$, $g_3 = 0.710$, $g'_1 = 2.98$, $g'_2 = 2.07 \times 10^{-6}$, $g'_3 = 1.41$, and for any N , with Eqs. (7) and the radius of waist spot-size $w_0 = 4 \text{ mm}$ to be used. Figure 1 shows the curves of THG efficiency versus crystal length z in $E_0 = 0.5 \times 10^6 \text{ V/mm}$, and $d = 1.2$. From Figs. 1 and 2, for the maximum efficiency of 87.1% on FGBs which is larger than that of 78.1% on Gaussian beams, the crystal length 2.64 mm for FGBs is smaller than that of 3.5 mm for Gaussian beams at the same conditions, and the efficiencies of THG FGBs are higher than those of Gaussian beams at any orders of N and E_0 . The results shown in Fig. 3 demonstrate that the curves of the efficiencies versus the fundamental polarized rate d at $E_0 = 0.25 \times 10^6 \text{ V/mm}$, $z = 5 \text{ mm}$ and $N = 4$. In Fig. 3, the FGBs maximum efficiency of 86.7% is higher than that of 72.6% of Gaussian beams for $d = 1.41$.

The efficiencies of FGBs and Gaussian beams of THG at type II(1) PM ($e + o \rightarrow e$) are discussed next using the following parameters: $\theta = 48.3^\circ$, $\Phi = 0^\circ$, $d_{\text{eff}} = 0.9441 \text{ pm/V}$, fundamental $\lambda_1 = 1064 \text{ nm}$, $\omega_1 = 1.78 \times 10^{15} \text{ Hz}$, $\alpha_1 = 1.72^\circ$, $n_1 = 1.4568$, $K_1 = 8.64 \times 10^6$; the SHG $\lambda_2 = 532 \text{ nm}$, $\omega_2 = 3.56 \times 10^{15} \text{ Hz}$, $\alpha_2 = 0^\circ$, $n_2 = 1.498$, $K_2 = 1.78 \times 10^7$; the THG $\lambda_3 = 355 \text{ nm}$, $\omega_3 = 5.34 \times 10^{15} \text{ Hz}$, $\alpha_3 = 1.60^\circ$,

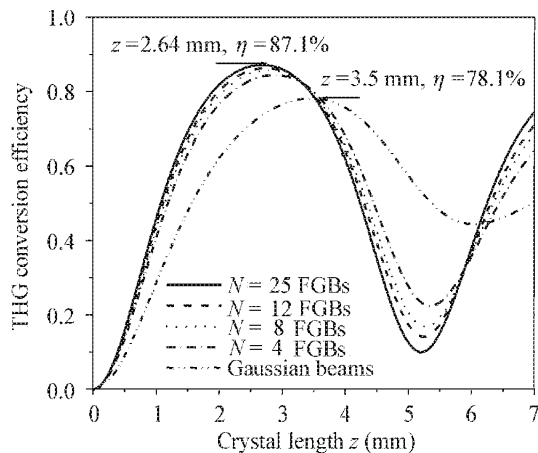


Fig. 1. Efficiency of FGBs and Gaussian beams in type I ($E_0 = 0.5 \times 10^6 \text{ V/mm}$, $d = 1.2$).

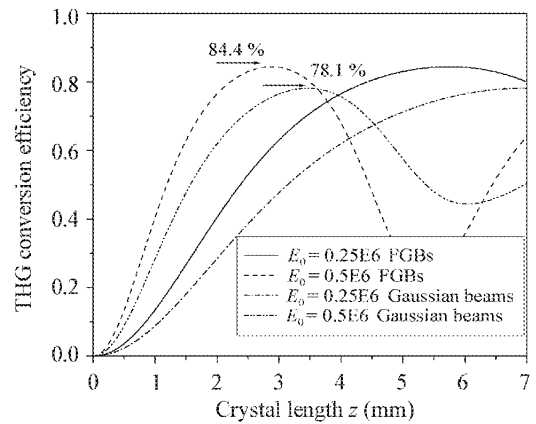


Fig. 2. Efficiency of FGBs and Gaussian beams in type I ($d = 1.2$, $N = 4$).

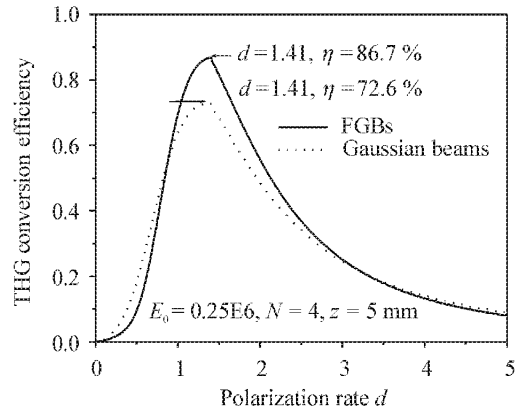


Fig. 3. Curves of efficiency versus d on FGBs and Gaussian beams in type I.

$n_3 = 1.4844$, which are inserted of Eqs. (2) and (4), and the parameters: $g_1 = 1.517$, $g_2 = 4.60 \times 10^{-6}$, $g_3 = 0.717$, $g'_1 = 2.94$, $g'_2 = 3.30 \times 10^{-6}$, and $g'_3 = 1.39$ are obtained by calculation for any N and E_0 . Figure 4 shows the curves of THG efficiency versus the crystal length z under $E_0 = 0.5 \times 10^6 \text{ V/mm}$, $d = 1.2$, and Fig. 5 at $d = 1.5$, $N = 4$ by Eq. (7). In the case of the efficiency of 87.1% of FGBs on THG, which is larger than that of 78.7% of Gaussian beams, and the larger of the orders N of FGBs for THG, the efficiency is higher. Figure 5

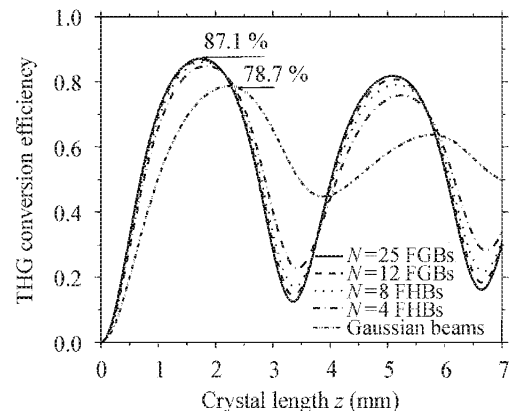


Fig. 4. Curves of efficiency versus crystal lengths in type II ($E_0 = 0.5 \times 10^6 \text{ V/mm}$, $d = 1.2$, $N = 4, 8, 12, 25$ FGBs).

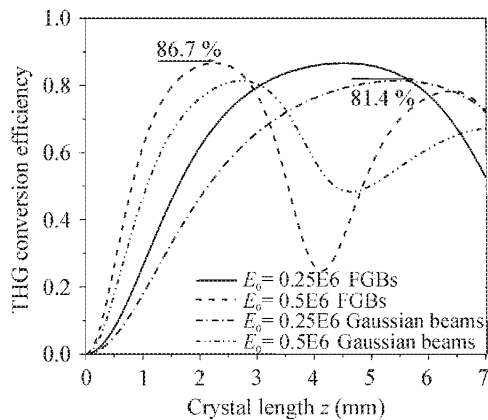


Fig. 5. Efficiency curves of FGBs and Gaussian beams in type II(1) ($d = 1.5$, $N = 4$, $E_0 = 0.25 \times 10^6$, 0.5×10^6 V/mm).

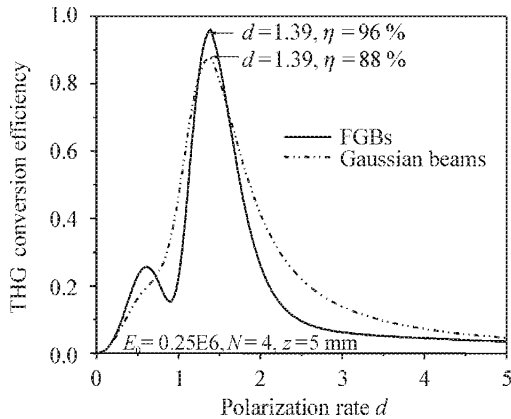


Fig. 6. Efficiency curves of FGBs and Gaussian beams in type II(1).

plots the efficiency of 86.7%, which is larger than that of 81.4% of Gaussian beams at $E_0 = 0.5 \times 10^6$ V/mm, and the curves of efficiency versus the polarization rate d are shown in Fig. 6. It is clear that the maximum efficiency of 96% on FGBs is larger than that of 88% of Gaussian beams at $d = 1.39$, $z = 5$ mm, and $E_0 = 0.25 \times 10^6$

V/mm, and it is demonstrated that the polarization rate d depends on the material properties and pump intensity.

We have simulated the THG conversion efficiency of FGBs and Gaussian beams based on a three-wave coupling equations and the dispersion equation of UV material CLBO. The analyses demonstrate that the efficiency has significant affect on the pump intensity, polarization rate, crystal lengths and orders of FGBs when it is in different condition. We obtained the conversion efficiencies of 86.7% and 96% of the FGBs are larger than those of Gaussian beams of 72.6% and 88% under type I and type II(1) PM, but this effect is clearly to get higher when N is increased for FGBs.

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