Numerical analysis of conversion efficiency of second harmonic generation on new crystal $CsLiB_6O_{10}$

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In this paper, a detailed theoretical analysis of the second harmonic generation (SHG) efficiency versus the polarization ratio and the crystal lengths of $CsLiB_6O_{10}$ (CLBO) in the phase matching using a computer simulation are presented. The efficiency of SHG has been up to 80% when the pumped radiation is of a plane wave. The efficiency is 65% and 80% as the pumped wave is of Gaussian beam in type I and type II, respectively. It is useful result that the phase matching of type II be perfectly adopted in the SHG experiment of CLBO.

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1. The new ultraviolet (UV) nonlinear optical (NLO) crystal $CsLiB_6O_{10}$ (CLBO) has been discovered as a high power source of the solid UV lasers by Y. Mori et al in the 1995 [1]. The shortest transparent of CLBO has been found that is 180 nm [2]. In order to obtain higher output energy and shorter laser wavelength in CLBO, many efforts have been invested on up-frequency conversion of the fundamental laser [3 – 5]. The second harmonic generation (SHG) is the special case of the three-wave interaction process in the NLO and the Nd:YAG laser has been utilized, such as the higher (3-rd, 4-th and so on) order harmonic generation [6, 7]. It is important that the numerical analysis of the conversion efficiency of SHG on the NLO CLBO is invested. Whereas BBO is demonstrated to be more effective in recent years and nonlinear frequency conversion in BBO is limited by its large walk-off angle and relatively small acceptance bandwidths. Recently the harmonic generation of the picosecond (ps) or nanosecond (ns) Nd:YAG laser output from the SHG to 5-th is also tested in [9]. In this paper, a detailed computer numerical simulation centering the SHG conversion efficiency versus the polarization ratio and the crystal lengths of the CLBO will be introduced in difference pumped power on the type I and type II. It is based on refractive index data, phase matching (PM) curves and walk-off angles as a function of fundamental wavelength are reported.

2. Theoretical analysis and computer simulation. The SHG is the special case of the three-wave interaction progress in the NLO CLBO. The foundation of SHG is the second order nonlinear interaction between the laser fields in a NLO medium with the propagation of the three waves in direction z. The efficiency of the SHG on CLBO inferred from the Kleinman symmetry and the instantaneous coupled wave equations in the constitutive equations, and the approximations of slowly varied amplitude can be obtained in the incidence of a plane wave and a Gaussian beam.

1. Plane wave. When the loss of the crystal medium is neglected. The $E_j(z,t)$ form of the incident plane wave

$$E_j(z,t) = E_j(z)\exp i[k_j z - \omega_j t - \Phi_j(z)]\ (j = 1,2,3). \quad (1)$$

Where ω_j, k_j, Φ_j is the frequencies, wave vectors and initial phase, respectively. The polarization ratio is written as

$$\gamma = \frac{E_2(0)\sqrt{n_2\cos\alpha_2}}{E_1(0)\sqrt{n_1\cos\alpha_1}}. \quad (2)$$

Where α_i is the walk-off of the corresponding wavelengths. Now let us consider the PM in type I, the conversion efficiency η of as $\gamma = 1$ can be written as following [1]

$$\eta = \mathrm{th}^2(Az), \quad (3)$$

$$A = \left(\frac{8\pi^2 d_{\mathrm{eff}} I_s}{n_1^2 n_2 c\lambda_1^2\varepsilon_0}\right)^{1/2} \quad (4)$$

Where $\mathrm{th}(x)$ is the hyperbolic tangent function, I_s is the intensity of pumping power, n_1, n_2 are refraction index of the pumping wave and the SHG wave respectively. Fig.1 shows the PM efficiency curves versus the crystal lengths that calculated for type I SHG according to the dispersion equations [1], formula (3) and (4) when the pumped peak power is a scale of 100 MW. We can see clearly from Fig.1 that the efficiency is infinity access to 100% when the optical crystal length increases. But this

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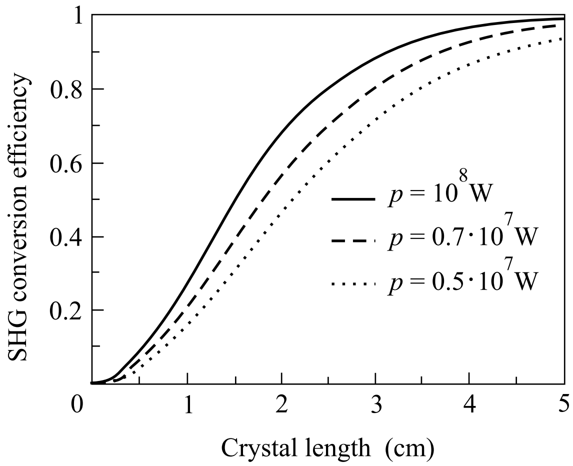

Fig.1. SHG efficiency curves of type I phase-matching for CLBO pumped by the plane wave of 1064 nm

efficiency will be less 100% when the phase matching is not realized because of the beam divergence in different directions. When we consider the PM in type I, the efficiency of as $\gamma \neq 1$ can get [10]

$$\eta = \frac{\omega_3 t^2}{\omega_1 + \omega_2 t^2}\mathrm{sn}^2\left(\sqrt{\frac{1}{\omega_1+\omega_2 t^2}}Bz,\, t\right) \quad (t<1), \quad (5)$$

$$\eta = \frac{\omega_3 t'^2}{\omega_2 + \omega_1 t'^2}\mathrm{sn}^2\left(\sqrt{\frac{1}{\omega_2+\omega_1 t'^2}}Bz,\, t'\right) \quad (t'<1), \quad (6)$$

$$B = \left(\frac{16\pi^3 d_{\mathrm{eff}}^2 I_s}{n_1 n_2 n_3 \lambda_1 \lambda_2 \lambda_3 \varepsilon_0}\right)^{1/2}. \quad (7)$$

Where sn (x, y) is Jacob ellipse function for the first class. The efficiency curves are shown in Fig.2 when

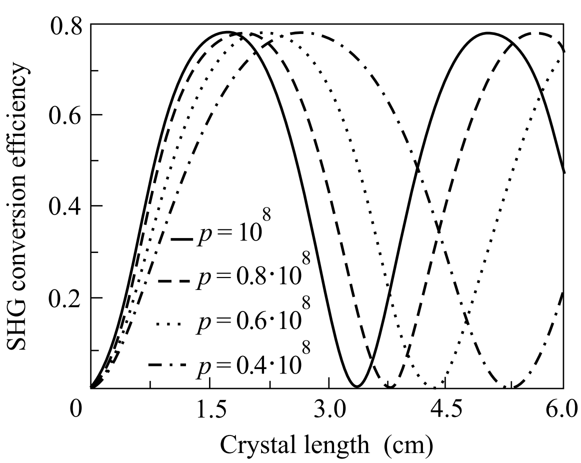

Fig.2. Curves of SHG conversion efficiency as a function of the crystall lenght and for $t = 0.8$

the $\gamma = 0.8$. Which is calculated for type II according to the dispersion equations of the CLBO and the formula

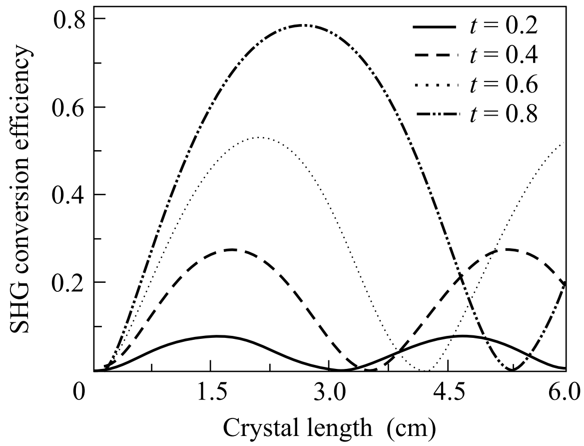

Fig.3. Curves of SHG conversion efficiency as a function of the crystal length and t, and for $p = 0.8\cdot10^8$ W

(5) and (6). As shown in Fig.3, we considered the efficiency curves both the polarization ratio and the crystal lengths with the 80 MW. From Fig.2 and Fig.3 that the polarization ratio of the pumping wave is access to 1, the SHG efficiency has a higher in a range of the crystal lengths and a fixed pump. The efficiency is up to 80% when the $\gamma = 0.8$; A larger pumping intensity and the longer crystal lengths will lead to the higher energy conversion efficiency with the constant polarization ratio of the pumping wave. The higher output and efficiency can be obtained by increasing the crystal lengths and pumping intensity because of the smaller effect nonlinear coefficient [11], the higher damage threshold and the larger of the crystal dimension of the CLBO.

2. *Gaussian distribution.* If a Gaussian beam is written as

$$E_j(z,t) = E_j(z,r)\exp i[K_j z - \omega t - \Phi_j(z)]. \quad (8)$$

Where $E_j(z,t)$ is a symmetry function for the axis z and is used in dissociable variable. Then we can get

$$E_j(z,r) = u_j(z)\omega_j(r) \quad (j = 1,2,3). \quad (9)$$

Now let us insert a form of (9) to the three-coupled wave equations [12] can be developed as

$$\frac{du_1}{d\xi} = -2u_1u_2\omega_2\sin\theta, \quad (10a)$$

$$\frac{du_2}{d\xi} = \frac{u_1^2\omega_1^2}{\omega_2}\sin\theta, \quad (10b)$$

$$\frac{d\theta}{d\xi} - \mathrm{tg}\theta\frac{d}{d\xi}[\ln(u_1^2u_2)] =$$

$$= \frac{\Delta K}{K} + \frac{1}{2Kk_2\gamma}\frac{d}{dr}\left[\ln\left(\frac{\omega_2}{\omega_1^{2K_2/K_1}}\right)\right] = \frac{D}{K}, \quad (10c)$$

$$\xi = \frac{1}{2}\mu_0\varepsilon_0 d_{\text{eff}} \prod_{j=1}^{3} \sqrt{\frac{\omega^2}{k_j \cos\alpha_j}} z = Kz. \tag{10d}$$

Where $\theta = z\Delta k + \Phi_3 - \Phi_2 - \Phi_1$, $\Delta k = k_3 - k_2 - k_1$, n_j is the light wave refractive index, ω_1, ω_2 is angle frequency of the foundation wave and harmonic wave, respectively. $D = \Delta k + (2\Delta k - 5k_1)/\omega_0^2 k_1(\Delta k - 2k_1)$, where ω_0 is the waist radius of a pumping wave, in order to get the SHG efficiency of the type I, we insert $\omega_0 = 4$ mm into the form $D = 0$, which leads Δk to be 0, approximately. Then we can get

$$\eta = \left| \frac{1}{\sqrt{2}} - \frac{\sqrt{2}}{kzu_0}\text{th}(\sqrt{2}kzu_0) + \right.$$
$$\left. + \frac{1}{(kzu_0)^2} \ln\left[\text{ch}\,(\sqrt{2}kzu_0)\right] \right|. \tag{11}$$

Where $u_0 = u_1(0)$. The form of (11) is the energy conversion efficiency of the CLBO in PM type I. As shown in Fig.4, we considered the conversion efficiency versus

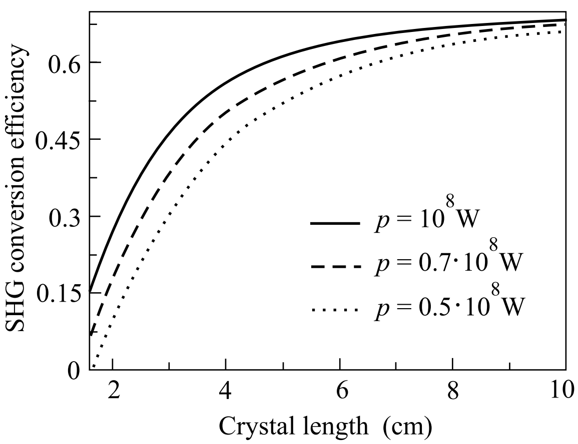

Fig.4. Efficiency curves of type I SHG versus the length of CLBO pumped by the Gaussan fundamental wave

the crystal lengths and used the following typical power parameters: 100 MW, 70 MW and 50 MW. From Fig.4, the efficiency is up to 68% when the pumping intensity is larger and the crystal lengths is increasing for type I PM.

For type II PM CLBO, which will be used the

$$D = \Delta k + \frac{1}{\omega_0^2}\left(\frac{1}{k_1} + \frac{1}{k_2} - \frac{1}{k_3}\right) = 0,$$

in order to get the formula of the efficiency. Then we can get

$$\eta(z) = \frac{g_1\gamma^2}{1+\gamma^2} \times$$

$$\times \frac{\int_0^\infty \text{sn}^2\left[\frac{g_2 E_0(0,r)}{\sqrt{1+\gamma^2}} z, g_3\gamma\right] \exp\left(-\frac{r^2}{\omega_0^2}\right) 2\pi r\, dr}{\int_0^\infty 2\pi r \exp\left(-\frac{r^2}{\omega_0^2}\right) dr} \tag{12a}$$

$$(\gamma < 1),$$

$$\eta(z) = \frac{g_1'}{1+\gamma^2} \times$$

$$\times \frac{\int_0^\infty \text{sn}^2\left[\frac{g_2' E_0(0,r)}{\sqrt{1+\gamma^2}} z, g_3'/\gamma\right] \exp\left(-\frac{r^2}{\omega_0^2}\right) 2\pi r\, dr}{\int_0^\infty \exp\left(-\frac{r^2}{\omega_0^2}\right) 2\pi\, dr} \tag{12b}$$

$$(\gamma > 1),$$

where $\gamma = u_2(0)/u_1(0)$ is a polarization ratio,

$$g_1 = \frac{k_2\omega_3^2 \cos\alpha_2}{k_3\omega_2^2 \cos\alpha_3}, \quad g_1' = \frac{k_1\omega_3^2 \cos\alpha_1}{k_3\omega_1^2 \cos\alpha_3}, \tag{13a}$$

$$g_2 = \frac{1}{2}\mu_0 \frac{d_{\text{eff}}\omega_2\omega_3}{(k_2k_3 \cos\alpha_2 \cos\alpha_3)^{1/2}},$$
$$g_2' = \frac{1}{2}\mu_0 \frac{d_{\text{eff}}\omega_1\omega_3}{(k_1k_3 \cos\alpha_1 \cos\alpha_3)^{1/2}}, \tag{13b}$$

$$g_3 = \frac{\omega_1}{\omega_2}\left(\frac{k_2\cos\alpha_2}{k_1\cos\alpha_1}\right)^{1/2}, \quad g_3' = \frac{\omega_2}{\omega_1}\left(\frac{k_1\cos\alpha_1}{k_2\cos\alpha_2}\right)^{1/2}. \tag{13c}$$

For type II PM CLBO, which will be used in our theory in order to get the SHG efficiency from the form of (12),

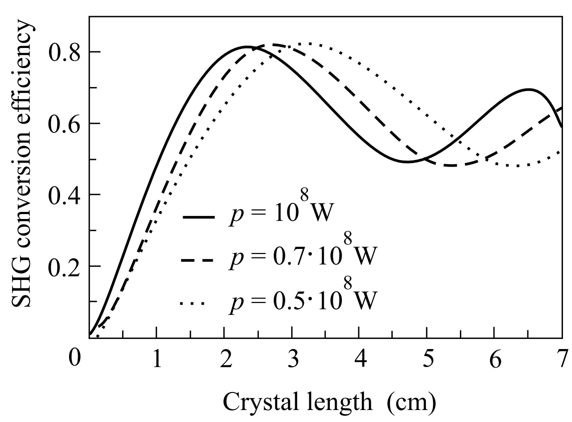

Fig.5. SHG conversion efficiency curves for CLBO pumped by Gaussian beam and $t = 0.893$

we let $g_1 = 2.05$, $g_2 = 0.672 \cdot 10^{-4}$, $g_3 = 1.008$, $g_3\gamma = 0.9$, which leads γ to be 0.89 approximately. Then we let the pumping power 100 MW, 70 MW, 50 MW, which leads the efficiency curves versus the crystal lengths in Fig.5. From Fig.5, the efficiency can be up to 80% for type II PM. From Fig.4 and Fig.5, we can clearly see the efficiency of type II CLBO is larger than that of type I in the same conditions for a Gaussian beam distribution, type II CLBO is considered ideal for high order harmonic generation in our theoretical analysis and computer and simulation.

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