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Theoretical investigation of phase-mismatched second-harmonic conversion efficiency in BBO crystal

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ABSTRACT

We report a modified general relation of nanosecond second harmonic conversion efficiency relation to determine efficiency at any value of power density, laser wavelength, crystal length and beam divergence when transmission value are relative high >90%, which make it a reference for practical study comparison. We apply this study on BBO crystal and study the efficiency as function of both crystal length (0–0.7 cm) and laser wavelength (460–1400 nm), (527–1400 nm) in 3-D plot for phase matching types I and II respectively. Finally, we study the effect of crystal length and power density at generated deep-ultraviolet cut-off type I wavelength 205 nm.

1. Introduction

Deep-ultraviolet (DUV) lasers attract great interest in many areas such as optical data storage, semiconductor wafer inspection, fiber Bragg grating fabrication, UV photolithography, holography, biomedicine, as well as absorption and fluorescence spectroscopy [1]. Although there are various techniques to produce DUV sources such as excimer lasers [2], high order harmonic generation in gases [3], synchrotron radiation and free electron lasers [4,5], However, DUV solid-state lasers generated through direct second harmonic generation (SHG) present great application merits and markets for its simpler, more compact, narrower spectral bandwidth, better beam quality, easier maintenance and robust setup compared with the other DUV sources [6,7]. Until now, β-BaB_2O_4 (BBO) crystal offers the highest nonlinearity compared to all other birefringent crystal including $KBe_2BO_3F_2$ (KBBF), $RbBe_2BO_3F_2$ (RBBF) and $CsLiB_6O_{10}$ (CLBO) [7]. Table 1 shows some optical properties and relations of BBO crystal. However, to our knowledge, all the publications on the BBO-SHG DUV laser were only focused on experiments in CW [7], nanosecond [8,9], picosecond regimes [6] or on numerical study of second harmonic power [10,11] or when pump depletion is not too large [12]. Especially no one has report so far about the theoretical investigation on generation of 205 nm. On the other side, many publications which works on concluding the relation of second harmonic generation conversion efficiency fall in mistakes which lead to wrong final relation [13–15].

In this report, we have carried out the detailed theoretical investigation about exact solution of phase-mismatched conversion efficiency in lossless nonlinear medium with taking the effect of beam divergence for the first time, we determine the crystal length and wavelength ranges which achieved transmission >90% to close to our assumption ‘lossless medium’, then we study the conversion efficiency as function of both laser wavelength and crystal length for both phase matching types. Finally, we determine the SHG efficiency at generated wavelength 205 nm.

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Table 1
Some optical properties and relations of BBO crystal.

Second-order nonlinear coefficient [16]	$d_{22}(1.064\,\mu\mathrm{m}) = 2.2\,\mathrm{pm/v}$ $d_{31}(1.064\,\mu\mathrm{m}) = 0.04\,\mathrm{pm/v}$
Sellmeier equations [17]	$n_o = \left(A_1 + \frac{B_1}{\lambda^2 - C_1} - D_1\lambda^2\right)^{1/2}$ $n_e = \left(A_2 + \frac{B_2}{\lambda^2 - C_2} - D_2\lambda^2\right)^{1/2}$ [a] $A_1 = 2.7359, B_1 = 0.01878, C_1 = 0.01822, D_1 = 0.01354$ $A_2 = 2.3753, B_2 = 0.01224, C_2 = 0.01667, D_2 = 0.01516$
Phase matching angle relations [18]	$\theta_{mI} = a\sin\left[\frac{n_{o\omega}^{-2} - n_{o2\omega}^{-2}}{n_{e2\omega}^{-2} - n_{o2\omega}^{-2}}\right]^{1/2}$ $\theta_{mII} \cong a\tan\left[\frac{1 - \left(\frac{n_{o\omega}}{n_{o2\omega}}\right)^2}{\left(\frac{n_{o\omega}}{n_{e2\omega}}\right)^2 - 1}\right]^{1/2}$ [b]
Walk-off angle relations [19]	$\rho_{I,II} = a\tan\left(\frac{\left(n_{e2\omega}^{-2} - n_{o2\omega}^{-2}\right)\sin 2\theta_{mI,II}}{2\left(n_{e2\omega}^{-2} - n_{o2\omega}^{-2}\right)\sin^2\theta_{mI,II} + 2n_{o2\omega}^{-2}}\right)$
Effective nonlinearity relations [16]	$d_{effI} = d_{22}\cos\left(\theta_{mI} + \rho_I\right)$ [c,d] $d_{effII} = d_{22}\cos^2\left(\theta_{mII} + \rho_{II}\right)$
Laser damage threshold [20]	$2.3\,\mathrm{GW/cm^2}\,(532\,\mathrm{nm},\ 9\,\mathrm{ns})$ $0.90\,\mathrm{GW/cm^2}\,(355\,\mathrm{nm},\ 8\,\mathrm{ns})$

I and II refers to phase matching types.
[a] $\lambda in \mu$m.
[b] Accuracy determination of $0.1 - 0.2^\circ$.
[c] The azimuth angle taken as $\phi = 90^\circ$ and $\phi = 0^\circ$ for phase matching types I and II respectively.
[d] d_{31} was neglected in the relation of d_{eff} (value of d_{31} is less than 2% of d_{22}).

2. Theoretical investigation

The coupled-wave equations of two plane monochromatic waves at frequencies ω_1 and ω_2 propagates in lossless nonlinear medium at z-direction in SI system are given by [21]:

$$\frac{dA_1}{dz} = \frac{2i\omega_1^2 d_{eff}}{k_1 c^2} A_1^* A_2 \exp(-i\Delta kz) \tag{1}$$

$$\frac{dA_2}{dz} = \frac{2i\omega_2^2 d_{eff}}{k_2 c^2} A_1^2 \exp(i\Delta kz) \tag{2}$$

Where $\Delta k = 2k_1 - k_2$ refer to phase mismatch. The amplitude in Eqs. (1) and (2) can be written as:

$$A_n = \rho_n(z)\exp[i\varphi_n(z)]\,;\, n = 1, 2 \tag{3}$$

Substituting Eqs. (3) in (1) and (2) with define variable $\vartheta = 2\varphi_1 - \varphi_2 + \Delta kz$ and $\exp(i\vartheta) = \cos(\vartheta) + i\sin(\vartheta)$ will make the complex Eqs. (1) and (2) be written in their real and imaginary parts as:

$$\frac{d\rho_1}{dz} = \frac{2\omega_1^2 d_{eff}}{k_1 c^2}\rho_1\rho_2\sin(\vartheta) \tag{4}$$

$$\frac{d\rho_2}{dz} = -\frac{\omega_2^2 d_{eff}}{k_2 c^2}\rho_1^2\sin(\vartheta) \tag{5}$$

$$\frac{d\vartheta}{dz} = \Delta k + \left(\frac{4\omega_1^2 d_{eff}}{k_1 c^2}\rho_2 - \frac{\omega_2^2 d_{eff}}{k_2 c^2}\frac{\rho_1^2}{\rho_2}\right)\cos(\vartheta) \tag{6}$$