Consideration of angular acceptance angle in BBO crystal on a highly efficient second harmonic generation

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Abstract

The angular acceptance angle (phase matching acceptance angle) $D_y$ in BBO crystal is theoretically calculated in milli-radian magnitude. To satisfy a fully phase matching condition of a laser beam and obtain efficient conversion of SHG, an intracavity frequency doubled (IFD) Nd:YAP mode-locked laser with a confocal unstable resonator and a BBO crystal as an SH generator is designed. Thus, fully phase matching of an approximately ideal plane wave can be realized in BBO crystal and an energy conversion efficiency of 81% for SHG from 1.08 to 0.54 $\mu$m has been achieved. The pulse durations of fundamental wave and maximum energy fluctuations are measured and calculated. The results are compared with those of a convex-antiresonant ring (ARR) unstable resonator IFD laser.

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1. Introduction

The technique of second harmonic generation (SHG) converts the fundamental wave $\omega$ to a $2\omega$ coherent beam by means of the nonlinear effect, which is an efficient method commonly employed to extend the output wavelength. Conversion efficiency of frequency doubling in low conversion can be derived from three-wave nonlinear coupled equations and can be expressed as follows [1]:

$$\eta_{\text{SHG}} = \frac{P_{2\omega}}{P_{\omega}} = 8 \left( \frac{\mu_0}{\mu} \right)^{3/2} \omega^2 d_e^2 \left( \frac{P_{\omega}}{A} \right) \frac{n^3}{n^2} \frac{\sin^2(\Delta k l/2)}{(\Delta k l/2)^2}$$

(1)

where $\omega$ is the frequency of the fundamental wave, $d_e$ is the effective nonlinear coefficient (here, it can also be called the effective frequency doubled coefficient), $l$ is the length of the crystal for doubling, $P_{\omega}$ and $P_{2\omega}$ are the power of fundamental and second harmonic waves, respectively, $n$ is the index of refraction of the nonlinear crystal and $\Delta k$ is the mismatching quantity of the wave vectors.

Considering SHG with a depleted input, the conversion efficiency of SHG in high conversion can be expressed by [2]:

$$\eta_{\text{SHG}} = \frac{P_{2\omega}}{P_{\omega}} = \tanh^2 \left[ 2\omega d_e \left( \frac{\mu_0}{\mu} \right)^{3/4} \left( \frac{P_{\omega}}{A} \right)^{1/2} \frac{\sin(\Delta k l/2)}{(\Delta k l/2)} \right]$$

(2)

Eqs. (1) and (2) tell us that, in order to obtain efficient SHG conversion to satisfy the phase matching condition, $\Delta k = 0$ is very important, as is enhancing the fundamental beam power density $P_{\omega}/A$ and seeking the crystal with the largest effective nonlinear coefficient. In practice, it is difficult to satisfy full phase matching in most of the laser beam, because of divergence and other factors. Even the TEM$_{00}$ Gaussian beam, which is not an ideal plane wave, is a Gaussian spherical wave. If the center of the Gaussian beam, meets the phase matching condition, the other part of the beam will deviate from this direction. The mismatching quantity $\Delta k$ will cause a decrease of the conversion efficiency of frequency doubling. Usually, a maximum allowed mismatching quantity $\Delta k = \pm \pi l$ (sin $\Delta k/l = \pm 1$) is set, then a corresponding angular acceptance angle $D_0$ can be calculated [3].
In this paper, the angular acceptance angle $\Delta \theta$ in a BBO crystal is theoretically calculated, and this angle has a magnitude in milli-radians. Therefore, when a laser beam with divergence angle in milli-radians passes through a BBO crystal, a certain phase mismatching is introduced. In our previous experiment [4], we reported an efficient SHG conversion of $\sim 70\%$ from an intracavity frequency doubling (IFD) in a BBO crystal and a colliding pulse mode-locked (CPM) unstable resonator Nd:YAP pulsed laser containing an antiresonant ring (ARR) structure. But this laser beam had a milli-radian divergence angle which limited any further increase of conversion efficiency. To solve this problem, an IFD mode-locked Nd:YAP pulsed laser with a con-focal unstable resonator and using BBO crystal as a SH generator is designed, such that full phase-matching condition is

$$D = y = 4 \text{ mm for a Nd:YAP laser from 1.08 to 0.54 } \mu \text{m.}$$

Therefore, we have, by Eq. (6)

$$\Delta k = \Delta k_{|_{\theta = \theta_m}} + \frac{d(\Delta k)}{d\theta}|_{\theta = \theta_m} \Delta \theta$$

Substituting Eq. (5) into the above equation, the angular acceptance can be expressed as

$$\Delta \theta = \pm \frac{\lambda}{2d}(n_{2e}^{(2)}(\theta_m))^3[(n_{2e}^{(2)})^2 - (n_{0e}^{(2)})^2] \sin 2\theta_m$$

It is easy to calculate the refractive index of BBO crystal at SH wave $\lambda = 0.54$ of a Nd:YAP laser

$$(n_{2e}^{(2)})^2 = 2.812 \rightarrow n_{2e}^{(2)} = 1.677$$

$$(n_{0e}^{(2)})^2 = 2.416 \rightarrow n_{0e}^{(2)} = 1.554$$

according to Sellmeier’s equation of a BBO crystals [5]

$$n_0^2(\lambda) = 1.9595 + 0.7892\lambda^2 / (\lambda^2 - 0.06123)$$

$$n_e^2(\lambda) = 1.6932 + 0.6782\lambda^2 / (\lambda^2 - 0.01816)$$

on the other hand, using the formula of the phase matching angle (in type I) for negative uniaxial crystals

$$\theta_m = \sin^{-1} \left[ \frac{(n_0^2)^2 - (n_{0e}^{(2)})^2 - (n_{0e}^{(2)})^2}{(n_e^{(2)})^2 - (n_{0e}^{(2)})^2} \right]^{1/2}$$

one can solve the phase-matching angle $\theta_m \approx 22^\circ$ for the conversion from 1.08 to 0.54 $\mu$m. Furthermore, $n_{2e}^{(2)}(\theta_m) = 1.657$ is obtained by Eq. (4). Finally, substituting all given parameters into Eq. (7) and taking
l = 4 mm, we obtain the angular acceptance angle 
\[ \Delta \theta = \pm 0.735 \times 10^{-3} \text{ radian}. \] 
This result shows that the angular acceptance angle of the BBO crystal is 
very small and has a magnitude of only milli-radian.

3. Experimental setup and results

Since the BBO crystal has a large SHG coefficient 
(the effective SHG coefficient of BBO is 6 times larger 
than that of KDP) and high damage threshold (>10 
GW/cm² for the mode-locked laser pulse), it is an 
ideal nonlinear crystal for high power frequency 
doubled conversion. In our previous experiments, we 
demonstrated an efficient IFD by using a convex-ARR 
unstable resonator CPM, Nd:YAP pulsed laser with a 
BBO as an SH generator, a 70% conversion efficiency 
was achieved. The diagram of the experimental setup 
is shown in Fig. 1.

This cavity configuration combines the advantages 
of both the CPM antiresonant ring configuration for 
narrow pulsewidth and an unstable resonator for high 
output energy. It also shows a good stability of mode- 
locking and laser output. But since this cavity is equiv- 
alent to a convex-plane unstable resonator (ARR) is 
equivalent to a 100% reflective plane mirror as long as 
the ARR beam-splitter MS has an exact 50/50 ratio 
for energy transmission to reflection [6], the beam in 
this cavity is a spherical wave with about 1 mrad 
divergence angle [7] which corresponds to the accep- 
tance angle of the BBO crystal. This causes a mis-
matching of laser beam when it passes the BBO crystal 
and limits it to the further increase of conversion effi- 
ciency of SHG. It is necessary to improve the beam 
quality to meet the requirement of a fully phase 
matching condition.

According to the above analysis, an IFD with a con- 
focal unstable resonator of a Nd:YAP mode-locked 
laser was designed. Fig. 2 shows the experimental 
setup. In this configuration, a parallel beam reflected 
from total reflective concave mirror M2 passes through 
the BBO crystal satisfying the fully phase matching 
condition; therefore, a high energy conversion of 81% 
from 1.08 to 0.54 μm radiation was achieved. In this 
experiment, the BBO crystal was cut at 22° for type I 
phase matching with a frequency doubling length of 4 
mm (the crystal was supplied by the Fujian Institute of 
Research on the Structure of Matter, Academia 
Sinica). The nonlinear crystal holder provided its 
movement and rotation in all required planes. A dye 
cell (CD) filled with pentamethine cyanine dissolved in 
1,2-dichlorothane as a saturable absorber was attached 
to the concave mirror M2. When the laser was run 
with an optimal coupler mirror at 1.08 μm, without 
the insertion of the BBO crystal, the maximum output 
energy of a single pulse train at the fundamental wave 
was measured. At the same pump energy, when the 
outcoupler had a high transmissivity at 1.08 μm and 
high reflectivity at 0.54 μm, with the BBO crystal 
inside the cavity, by precise and repeated adjustment 
of the crystal, a powerful SH radiation at 0.54 μm was 
obtained. For measuring SH energy, a filter was kept 
in front of the detector to absorb unconverted 1.08 μm 
radiation. Following the definition of conversion effi- 
ciency for intracavity SHG in Ref. [8], we can easily 
calculate the energy conversion efficiency from 1.08 to 
0.54 μm. Table 1 gives the main experimental results

<table>
<thead>
<tr>
<th>Resonator configuration</th>
<th>Radiation wavelength (μm)</th>
<th>Output energy (mJ)</th>
<th>Energy conversion efficiency (%)</th>
<th>Pulse duration (ps)</th>
<th>Maximum energy fluctuation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confocal</td>
<td>1.08</td>
<td>33.8</td>
<td>81</td>
<td>18</td>
<td>8.3</td>
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<tr>
<td></td>
<td>0.54</td>
<td>27.25</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Convex-ARR</td>
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<td>69.3</td>
<td></td>
<td>8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.54</td>
<td>48.3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* All experimental data in this paper have been averaged over ten measurements.
(the experimental data in the convex-ARR configuration are listed for the purpose of comparison). In the experiments, the output energy was measured by a PT-1 energy calorimeter, the pulse duration was determined using the autocorrelation function of non-collinear SHG and the mode-locked pulse train was monitored with a 500 MHz Tex 7834 storage oscilloscope.

4. Conclusions

We have calculated an angular acceptance angle $\Delta \theta$ of a BBO crystal which has a milli-radian magnitude. Small angular acceptance causes phase mismatching when a divergence beam passes through the crystal. It results in a decrease of SHG conversion efficiency. An IFD Nd:YAG mode-locked laser with a confocal unstable resonator and a BBO crystal as the SH generator was designed, therefore, such that full phase matching of an approximately ideal plane wave can be realized in a BBO crystal, and a high efficiency, as high as 81%, energy conversion of frequency doubling was obtained. This cavity is superior to a convex-ARR CPM unstable resonator if we consider more about the conversion efficiency of SHG. On the other hand, experimental results tell us that the CPM unstable resonator IFD laser has a shorter pulse duration and stable output of SHG compared to a confocal unstable resonator IFD laser. Therefore, we can choose the resonator we need according to the application requirement. Furthermore, the elements of ARR in a CPM unstable resonator can be further selected and optimized, and an improved cavity will become an ARR confocal unstable resonator which will combine the advantages of both unstable resonators.

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