The general information for NLO crystals

The nonlinear optical (NLO) crystals are used in frequency conversion for lasers. The basic NLO crystals include the KTP, LBO, BBO, KD*P, KNbO₃, LiNbO₃, AgGaS₂, AgGaSe₂ etc. The BIBO (BiB₃O₆) is a new good NLO crystal for the UV and visible range wavelength. The right NLO crystals should be chosen taking into consideration the criteria transmission, damage threshold, efficiency of the nonlinear effect, phase matching range and laser beam quality.

Frequency Conversion

The frequency conversion processes include frequency doubling (which is a special case of sum frequency generation), sum frequency generation (SFG), differential-frequency generation (DFG) and optical parametric generation (OPG) which are demonstrated in the following equations:

**Sum Frequency Generation (SFG):**

\[ \omega_1 + \omega_2 = \omega_3 \]

(or \(1/\lambda_1 + 1/\lambda_2 = 1/\lambda_3\) in wavelength)

It combines two low energy (or low frequency) photons into a high energy photon. For example:

\[ 1064\text{nm} + 1064\text{nm} \rightarrow 532\text{nm} \]

**Differential-Frequency Generation (DFG):**

\[ \omega_1 - \omega_2 = \omega_3 \]

(or \(1/\lambda_1 - 1/\lambda_2 = 1/\lambda_3\) in wavelength)

It combines two high energy photons into a low energy photon. For example:

\[ 532\text{nm} - 810\text{nm} \rightarrow 1550\text{nm} \]

**Optical Parametric Generation (OPG):**

\[ \omega_p - \omega_s = \omega_i \]

(or \(1/\lambda_p = 1/\lambda_s + 1/\lambda_i\) in wavelength)

It splits one high energy photon into two low energy photons.
**Frequency Doubling**

Frequency Doubling or Second Harmonic Generation (SHG) is a special case of sum frequency generation if the two input wavelengths are the same. The simplest scheme for frequency doubling is extra cavity doubling. The laser passes through the nonlinear crystal only once. However, if the power density of laser is low, focused beam, intracavity doubling and external resonant cavity are normally used to increase the power density on the crystals, for example, for doubling of cw Nd:YAG laser and Argon Ion lasers.

![Extracavity SHG](image1)

**Extracavity SHG**

![SHG With Focused Beam](image2)

**SHG With Focused Beam**

![Intracavity SHG](image3)

**Intracavity SHG**

![External Resonant Cavity SHG](image4)

**External Resonant Cavity SHG**

**Sum Frequency Generation**

Frequency Tripling or Third Harmonic Generation (THG) is an example of Sum Frequency Generation where, for THG of Nd:YAG laser, $\omega_1=1064\text{nm}$, $\omega_2=532\text{nm}$ and THG of a Ti:Sapphire laser in BBO crystal, it can generate wavelength as short as 193 nm.

**Optical Parametric Oscillation**

Optical Parametric Generation (OPG) is an inverse process of sum Frequency Generation. It splits one high-frequency photon (pumping wavelength, $\lambda_p$) into two low-frequency photons (signal, $\lambda_s$, and idler wavelength, $\lambda_i$). If two mirrors are added to from a cavity, an Optical Parametric Oscillator (OPO) is established. For a fixed pump wavelength, an infinite number of signal and idler wavelengths can be generated by tilting a crystal. Therefore, OPO is an excellent source for generating wide tunable range coherent radiation. BBO, KTP, LBO and LINbO3 are good crystal for OPO and Optical Parametric Amplifier (OPA) Applications.
Phase-matching

In order to obtain high conversion efficiency, the phase vectors of input beams and generated beams have to be matched:

\[ \Delta K = k_3 - k_2 - k_1 = 2\pi(n_3/\lambda_3 - n_2/\lambda_2 - n_1/\lambda_1) = 0 \]

(For sum frequency generation)

Where: \( \Delta K \) is phase mismatching, \( k_i \) is phase vector at \( \lambda_i \) and \( n_i \) is refractive index at \( \lambda_i \).

In low power case, the relationship between conversion efficiency and phase mismatching is:

\[ \eta \propto \left( \sin(\Delta K L) / \Delta K L \right)^2 \]

It is clear that the conversion efficiency will drop dramatically if \( \Delta K \) increases. The phase-matching can be obtained by angle tilting, temperature tuning or other methods. The angle tilting is mostly used to obtain phase-matching as shown. If the angle between optical axis and beam propagation (\( \theta \)) is not equal to 90 deg. or 0 deg., we call it Critical phase-matching (CPM). Otherwise, 90deg. non-critical phase-matching (NCPM) is for \( \theta = 90 \)deg. and 0 deg. NCPM is for \( \theta = 0 \)deg.

Two types of phase-matching are classified consideration of polarization of lasers. If the polarizations of two input beams (for sum frequency) are parallel to each other, it is type I phase-matching. If the polarizations are perpendicular to each other, it is called type II phase-matching.

Conversion Efficiency

How to select a NLO crystal for a frequency conversion process with a certain laser? The most important thing is to obtain a high conversion efficiency. The conversion efficiency has the following relationship with effective nonlinear coefficient (Deff), crystal length(L), input power density (P) and phase
mismatching (ΔK):
\[ \eta \propto P \sin(\Delta KL)/\Delta KL \]

In general, higher power density, longer crystal length, larger nonlinear coefficients and smaller phase mismatching will result higher conversion efficiency. However, there is always some limitation coming from nonlinear crystals and lasers. For example, the \( D_{\text{eff}} \) is determined by the nonlinear crystal itself and the input power density has to be lower than the damage threshold of crystal. Therefore, it is important to select a right crystal for your applications. In the following Table, we list the laser and crystal parameters for selecting right crystals.

<table>
<thead>
<tr>
<th>Parameter For NLO Crystal Selection</th>
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</thead>
<tbody>
<tr>
<td>Laser Parameters</td>
</tr>
<tr>
<td>NLO Process</td>
</tr>
<tr>
<td>Power or Energy</td>
</tr>
<tr>
<td>Divergence</td>
</tr>
<tr>
<td>Bandwidth</td>
</tr>
<tr>
<td>Beam Size</td>
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<tr>
<td>Pulse Width</td>
</tr>
<tr>
<td>Repetition Rate</td>
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<tr>
<td>Environment</td>
</tr>
</tbody>
</table>

**Crystal Acceptance**

If a laser light propagates in the direction with angle \( \Delta \theta \) to phase matching direction, the conversion efficiency will reduce dramatically. We define the acceptance angle (\( \Delta \theta \)) as full angle at half maximum (FAHM), where \( \theta = 0 \) deg. is phase-matching direction. For example, the acceptance angle of BBO for type I frequency doubling of Nd:YAG at 1064nm is about 1mrad-cm. Therefore, if a Nd:YAG laser has beam divergence of 3mrad for frequency-doubling, over half of the input power is useless. In this case, LBO may be better because of its larger acceptance angle, about 8 mrad-cm. For NCMP, the acceptance angle is normally much bigger than that for CPM, for example, 52 mrad-cm\(^{1/2}\) for type I NCPM LBO.

In addition, you have to consider the Spectral acceptance (\( \Delta \lambda \)) of crystal and the spectral bandwidth of your laser; crystal temperature acceptance (\( \Delta T \)) and the temperature change of environment.

**Walk-Off**
Due to the birefringence of NLO crystals, the extraordinary wave \( (n_e) \) will experience Poynting vector walk-off as shown. If the beam size of input beam will be separated at walk-off angle \( (\rho) \) in the crystal and it will cause low conversion efficiency. Therefore, for focused beam or intracavity doubling, the walk-off is a main limitation to high conversion efficiency.

**Group Velocity Mismatching**

For NLO processes of ultrafast lasers such as Ti:Sapphire and Dye lasers with femtosecond (fs) pulse width, the main limitation to conversion efficiency is group velocity mismatching (GVM). The GVM is caused by group velocity dispersion of NLO crystal. For frequency doubling a Ti:sapphire laser at 800nm, for example, the inverse group velocities \( (1/V_G) \) of BBO are respectively \( 1/V_G=56.09\text{ps/cm} \) at 800nm and \( 1/V_G=58.01\text{ps/cm} \) at 400nm and GVM=1.92\text{ps/cm}. That means an 1mm long BBO crystal will make 192fs separation between the pulses at two wavelengths. Therefore, for an 100fs Ti:sapphire laser, we normally recommend a 0.5mm long BBO crystal (with 96 fs separation) in order to obtain high efficiency without dramatic pulse broadening.

**Damage Threshold**

The damage threshold is a function of the wavelength of fundamental and harmonic radiation, pulse duration, beam profile and other parameters.

<table>
<thead>
<tr>
<th>( \lambda )</th>
<th>LBO</th>
<th>BBO</th>
<th>KTP</th>
<th>KD*P</th>
</tr>
</thead>
<tbody>
<tr>
<td>266nm</td>
<td>200 MW/cm(^2), 10ns, 10HZ</td>
<td>120MW/cm(^2), 8ns 10HZ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>355nm</td>
<td>500MW/cm(^2), 10ns, 10HZ</td>
<td>400W/cm(^2), 10ns 10HZ</td>
<td></td>
<td>10GW/cm(^2), 0.03ns 10HZ</td>
</tr>
<tr>
<td>532nm</td>
<td>1GW/cm(^2), 10ns, 50HZ</td>
<td>700W/cm(^2), 10ns 10HZ</td>
<td>500MW/cm(^2), 8ns, 2HZ</td>
<td>8GW/cm(^2), 0.03ns 10HZ</td>
</tr>
<tr>
<td>532nm</td>
<td>400KW/cm(^2), cw</td>
<td>40KW/cm(^2), cw</td>
<td>10GW/cm(^2), 0.03ns, 10HZ</td>
<td></td>
</tr>
<tr>
<td>1064nm</td>
<td>19GW/cm(^2), 1.3ns, 10HZ</td>
<td>10GW/cm(^2), 1.3ns, 10HZ</td>
<td>2.4GW/cm(^2), 11ns, 2HZ</td>
<td>6GW/cm(^2), 1ns 10HZ</td>
</tr>
<tr>
<td>1064nm</td>
<td>1MW/cm(^2), cw</td>
<td>80KW/cm(^2), cw</td>
<td>300MW/cm(^2), 30ns, 10HZ</td>
<td>25MW/cm(^2), 140ns, 10HZ</td>
</tr>
</tbody>
</table>
How to Handle A NLO Crystal

Keep crystal clean
When you receive the NLO crystals, please look at the polished or coated crystal surface first. If the surface are contaminated, please blow the surface with air ball. If there is still pollution on the crystal surfaces, please clean the surfaces with cleaning liquid and soft silk. For BBO crystal, the mixing liquid of 50% high purity alcohol and 50% high purity ether is recommended as cleaning liquid. Please note that the contaminated surfaces are very easy to be damaged.

Angle Tilting
In order to obtain maximum conversion efficiency, angle tilting is normally used to reach phase-matching direction. There are two axis for tilting crystal angles as show. Because the NLO crystals are normally cut in principal crystal plane, conversion efficiency is not sensitive to the angle tilting around b-axis. Customers have to pay attention when rotating the crystal around a-axis. A crystal mount with angle accuracy of about 5 arc second is recommended.

Optimum Crystal Size and Cut
When ordering a nonlinear optical crystal, crystal orientation and size have to be known. The orientation is solely determined by the nonlinear optical process. The crystal size is divided into three dimensions noted as WxHXLmm3. The careful design of crystal size is important because the conversion efficiency has direct relation to crystal length.
To select the optimum crystal height (H), the laser beam diameter upon the crystal should be taken into account. The optimum crystal height should slightly (1-2mm) larger than the laser beam diameter upon the crystal. Both of laser beam Diameter upon NLO crystal and tunable wavelength range have to be considered when designing the optimum crystal width(W). The crystal length is decided by the application. The different crystals and different application will be required the different length's crystals.