The nonlinear optical (NLO) crystals are used in frequency conversion for lasers. The basic NLO crystals include the LBO, BBO, KTP, KD*P, $KNbO_3$, $LiNbO_3$, $MgO:LiNbO_3$, $AgGaS_2$, $AgGaS_2$ etc. The BIBO (BiB_3O_6) 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, efficiency of the nonlinear effect, phase matching range, damage threshold and laser beam quality.

Frequency Conversion

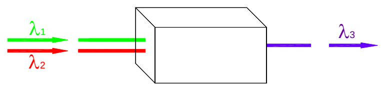
The frequency conversion processes include frequency doubling (which is a special case of sum frequency generation), sum frequency generation (SFG), differential-frequency generation (DFG) and optical parametric generation (OPG) which are demonstrated in the following equations:

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:

1064nm + 532nm → 355nm

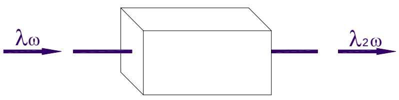


NLO Crystal

Sum Frequency Generation

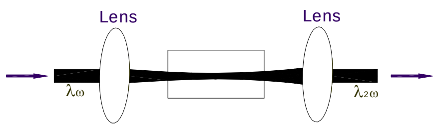
Frequency Doubling

Frequency Doubling or Second Harmonic Generation (SHG) is a special case of sum frequency generation if the two input wavelengths are the same: same: $2\omega_1 = \omega_2$ (or $\lambda_1 = 2\lambda_2$ in wavelength). The simplest scheme for frequency doubling is extra cavity doubling. The laser passes through the nonlinear crystal only once as shown. 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.



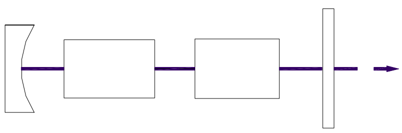
NLO Crystal

Extracavity SHG



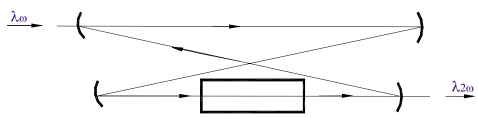
NLO Crystal

SHG with Focused Beam



Laser Crystal NLO Crystal

Intracavity SHG



NLO Crystal

External Resonant Cavity SHG

Frequency Tripling

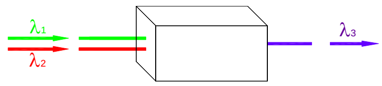
Frequency Tripling or Third Harmonic Generation (THG) is another example of Sum Frequency Generation, where THG of Nd:YAG laser, λ_1 = 1064 nm, λ_2 = 532 nm and generated wavelength λ_1 = 355 nm. By sum frequency of fundamental wavelength and THG of a Ti:Sapphire laser in BBO crystal, it can generate wavelengths as short as 193 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.

532nm - 810nm → 1550nm



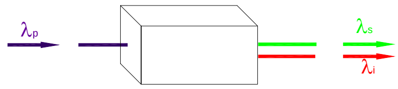
NLO Crystal

Differential Frequency Generation

Optical Parametric Generation (OPG)

$\omega_p - \omega_s = \omega_i$ (or $1/\lambda_p - 1/\lambda_s = 1/\lambda_i$ in wavelength)

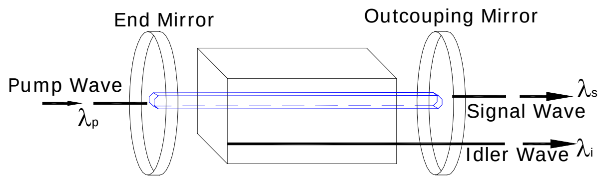
It splits one high energy photon into two low energy photons.



NLO Crystal

Optical Parametric Generation

Optical Parametric Generation (OPG) is an inverse process of sum Frequency Generation. It splits one high-frequency photon (pumping wavelength, λ_p) into two low-frequency photons (signal, λ_s, and idler wavelength, λ_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 $LINbO_3$ are good crystal for OPO and Optical Parametric Amplifier (OPA) applications.



NLO Crystal

Optical Parametric Oscillator

Phase-matching

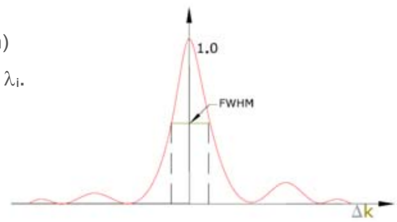
In order to obtain high conversion efficiency, the phase vectors of input beams and generated beams have to be matched:

$\triangle K = k_3 - k_2 - k_1 = 2\pi n_3/\lambda_3 - 2\pi_2/\lambda_2 - 2\pi n_1/\lambda_1) = 0$ (For sum frequency generation)

Where: $\triangle K$ is phase mismatching, k_i is phase vector at λ_i and n_i is refractive index at λ_i.

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

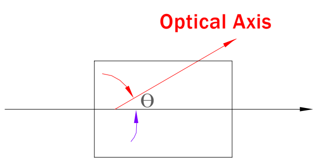
$\eta \propto (\sin(\Delta KL)/\Delta KL)^2$



Conversion Efficiency Vs ΔK

It is clear that the conversion efficiency will drop dramatically if ΔK increases.

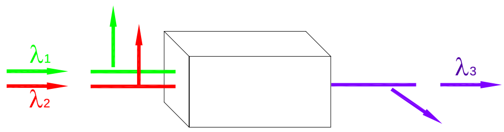
The phase-matching can be obtained by angle tilting, temperature tuning or other methods. The angle tilting is mostly used to obtain phase-matching as shown. If the angle between optical axis and beam propagation (θ) is not equal to 90° or 0°, we call it **Critical phase-matching (CPM). Otherwise, 90° non-critical phase-matching (NCPM)** is for θ = 90° and 0° **NCPM** is for θ = 0°.



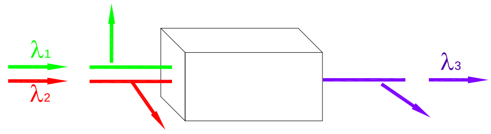
NLO Crystal

Critical Phase matching

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



Type I Phase Matching



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 high conversion efficiency. The conversion efficiency has the following relationship with effective nonlinear coefficient (d_{eff}), crystal length (L), input power density (P) and phase mismatching (ΔK):

$$\eta \propto PL^2 (d_{eff} \sin(\Delta KL)/\Delta KL)^2$$

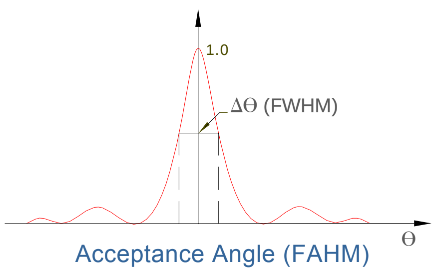
In general, higher power density, longer crystal length, larger nonlinear coefficients and smaller phase mismatching will result higher conversion efficiency. However, there is always some limitation coming from nonlinear crystals and lasers. For example, the d_{eff} is determined by the nonlinear crystal 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.

Parameters for NLO Crystal selection

Laser Parameters	Crystal Parameters
NLO Process	Phase-Matching Type and Angle, d_{eff}
Power or Energy, Repetition Rate	Damage Threshold
Divergence	Acceptance Angle
Bandwidth	Spectral Acceptance
Beam size	Crystal Size, Walk-Off Angle
Pulse Width	Group velocity Mismatching
Environment	Moisture, Temperature Acceptance

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 $\theta = 0°$. is phase-matching direction. For example, the acceptance angle of BBO for type I frequency doubling of Nd:YAG at 1064nm is about 1 mrad-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.

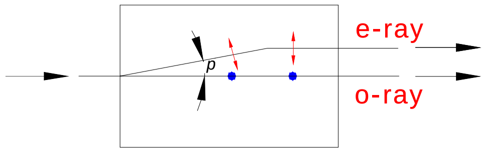


Acceptance Angle (FAHM)

In addition, you have to consider the Spectral acceptance ($\Delta\lambda$) of crystal and the spectral bandwidth of your laser, crystal **temperature acceptance** (ΔT) 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 (ρ) 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.



Walk-Off Angle (ρ)

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 ps/cm at 800nm and $1/V_G$=58.01 ps/cm at 400nm and GVM = 1.92 ps/cm. That means a 1mm long BBO crystal will make 192 fs separation between the pulses at two wavelengths. Therefore, for an 100 fs 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.

The reference parameter of damage threshold

λ	LBO	BBO	KTP	KD*P
266nm	200 MW/cm^2 10ns, 10Hz	120MW/cm^2 8ns 10Hz	—	—
355nm	500MW/cm^2 10ns, 10Hz	400W/cm^2 10ns 10Hz	—	10GW/cm^2 0.03ns 10Hz
532nm	1GW/cm^2 10ns, 50Hz	700W/cm^2 10ns 10Hz	500MW/cm^2, 8ns, 2Hz	8GW/cm^2 0.03ns 10Hz
532nm	400KW/cm^2 cw	40KW/cm^2 cw	10GW/cm^2 0.03ns, 10HZ	—
1064nm	19GW/cm^2 1.3ns, 10Hz	10GW/cm^2 1.3ns, 10Hz	2.4GW/cm^2, 11ns, 2Hz	6GW/cm^2 1ns 10Hz
1064nm	1MW/cm^2 cw	80KW/cm^2 cw	300MW/cm^2 30ns, 10Hz	25MW/cm^2 140ns, 10Hz

How to Handle A NLO Crystal

Keep crystal clean

When you receive the NLO crystals from AOTK, please make sure that only qualified personnel are able to open the inner plastic boxes at clean environment. When the plastic box of a NLO crystal is opened, please prevent finger print, oil and other substances from adhering to the polished or coated surfaces.

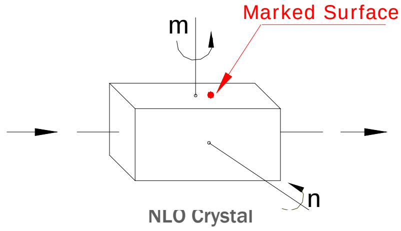
If the surfaces are contaminated, please blow the surface with air ball. If there is still pollution on the crystal surfaces, please clean the surfaces with cleaning liquid and soft silk. For BBO crystal, the mixing liquid of 50% high purity alcohol and 50% high purity ether is recommended as cleaning liquid. Please notify that the contaminated surfaces are very easy to be damaged.

Some NLO crystals have a low susceptibility to moisture, you are advised to provide dry atmosphere conditions for both use and preservation of them. When polished surfaces are fogged or damaged, pleasure ask AOTK for repolishing and coating service.

How to Order A Right crystal

Angle Tilting

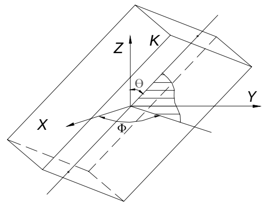
In order to obtain maximum conversion efficiency, angle tilting is normally used to reach phase-matching direction. There are two axes for tilting crystal angles as shown. Because the NLO crystals are normally cut in principal crystal plane, conversion efficiency is not sensitive to the angle tilting 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.



Crystal Angle Tilting

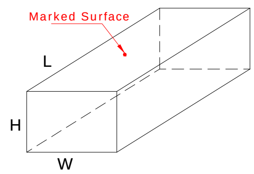
Optimum Crystal Size and Cut

When ordering a nonlinear optical crystal, crystal **orientation** (or crystal cut) and size have to be known. The orientation is solely determined by the nonlinear optical process. For example, for type I frequency-doubling of 1064nm, BBO is cut at θ= 22.8°. and Φ = 0°. Where: θ is the polar angle between the optical axis and the propagation direction, Φ is the azimuthal angle between the projection of propagation direction onto the XY plane and the X axis. If you aren't sure about the crystal orientation and merely provide the nonlinear optical process of your application, AOTK 's salesmen and engineers will help you.



Polar Coordinate System Crystal
(K is the light propagation direction)

The crystal **size** is divided into three dimensions, Width (W), High (H) and Length (L), which is common written as W x H x L mm^3 . The careful design of crystal size is important because the price of crystal varies from crystal sizes. More important, the conversion efficiency has direct relation to crystal length.



Dimension of Crystal

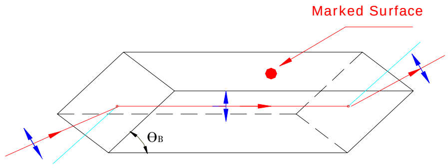
To select the optimum crystal **height** (H), the laser beam diameter upon the crystal should be taken into account. The optimum crystal height should be slightly (for instance, 1 mm to 2mm) larger than the laser beam diameter upon the crystal.

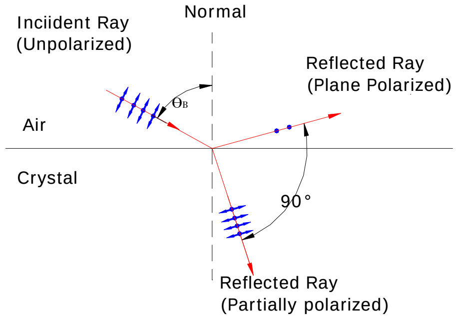
Both of laser beam diameter upon NLO crystal and tunable wavelength range have to be considered when designing the optimum crystal **width** (W). If it is a single NLO process, for example, frequency doubling 532 nm, we select W = H. If it is wide wavelength tuning NLO process, for example, frequency doubling a Dye laser from 440 nm to 660 nm by using BBO crystal, the crystal should be tuned from θ= 36° to θ= 66.6°. The width (W) is set to H + 2xtan((66.6°- 36°)/2)xL. Because if the crystal height (H) is 4 mm and length (L) is 7 mm, the W should be approximately 8 mm long.

Every NLO crystal has a standard **length** (L) for frequency doubling lasers with pulse width longer than nanosecond (ns). For example, the standard crystal lengths for BBO and KTP are 7 mm and 5 mm, respectively. However, OPO and OPA need longer length, for example, > 12 mm for BBO, and the SHG and THG of ultrashort pulse lasers use thin crystals with length of less than 1 mm. AOTK's salesmen and engineers collected a series of standard crystal lengths for various applications. This information is provided free.

Brewster's angle NLO crystals

For laser beam propagates from Air to NLO crystal (with refractive indices n). Brewster's angle is defined as θ_B = arctan(n). At Brewster's angle, the surface reflectance is zero for the light with polarization inside the plane defined by the direction of light propagation and the normal to the surface.





In order to have a low surface reflection, Brewster's angle cut (B-cut) NLO crystals are used. Without special notices, AOTK will fabricate the standard B-cut crystals according to the enclosed drawing. If customers design different sketch from our standard one, please notify AOTK by providing us a drawing

Order Information

Crystal Name	Application Type I or Type II θ = ?, ϕ = ?	Dimension WxHxL	Polished	Coated

For Example:

LBO Crystal	Type I SHG 1064nm $\theta = 90°$, $\phi = 11.36°$	3x3x10 mm	Polished	AR/AR @ 1064&532 nm

- Free services for calculating the parameters of custom NLO processes is provided by AOTK.

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