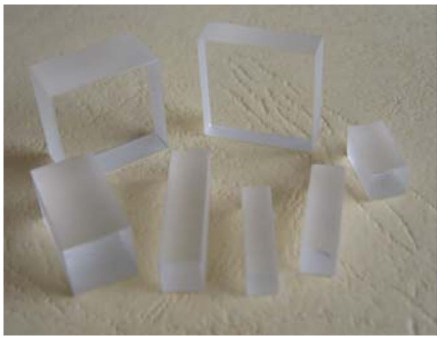
BBO

Beta-Barium Borate (β-BaB_2O_4 or **BBO**) is one of the most excellent NLO crystals. Using a newly improved flux method, AOTK now produces high-quality BBO crystal with high optical homogeneity, no inclusion and lower defects, lower absorption, high damage threshold and better laser performance. AOTK supplies the crystal length from 0.005mm to 20mm with various aperture and coating.



AOTK's BBO advanced properties

- Broad phase-matchable range from 409.6 nm to 3500 nm
- Wide transmission region from 190 nm to 3500 nm
- High damage threshold of 10 GW/cm^2 for 100 ps pulse-width at 1064 nm
- Large effective second-harmonic-generation (SHG) coefficient
- Wide temperature-bandwidth of about 55°C
- High optical homogeneity with $\Delta n > 10^{-6}$/cm
- Good mechanical and physical properties

Typical applications of BBO

- SHG, THG, 4HG and 5HG harmonic generations of Nd: lasers
- SHG, THG, and 4HG harmonic generations of Ti:Sapphire and Alexandrite lasers
- Frequency-doubling, -tripling and -mixing of Dye lasers
- Frequency-doubling and -tripling of ultrashort pulse Ti:Sapphire and Dye lasers
- Frequency-doubling of Argon ion, Cu-vapor and Ruby lasers
- Optical parametric amplifiers (OPA) and optical parametric oscillators (OPO)

Basic Properties

1. Structural and Physical Properties

Crystal Structure	Trigonal Point group 3m, Space group R_{3c}
Lattice Parameters	a=b=12.532Å, c=12.717Å, z=6
Density	3.84 g/cm^3
Mohs Hardness	4.0
Melting Point	1095 ± 5°C
Transition Temperature	925 ± 5°C
Resistivity	>10^{11} ohm-cm
Absorption Coefficient	α<0.1%/cm @1064 nm; α<1%/cm @532 nm
Optical Homogeneity	$\Delta n \approx 10^{-6}$/cm
Hygroscopic Susceptibility	low
Thermal Conductivity Coefficient	$\perp$c, 1.2W/m/K; //C, 1.6W/m/K
Thermal Expansion Coefficient	$\alpha_1=\alpha_2=4\times10^{-6}/°C$, $\alpha_3=36\times10^{-6}/°C$
Relative Dielectric Constant	$\varepsilon^T_{11}/\varepsilon_0=6.7$, $\varepsilon^T_{33}/\varepsilon_0=8.1$; Tan $\delta<0.001$

2. Linear Optical Properties

Transparency Region	189 - 3500 nm	
Refractive Indexes		
at 1064 nm	n_o = 1.6551	n_e = 1.5425
at 532 nm	n_o = 1.6750	n_e = 1.5555
at 355 nm	n_o = 1.7055	n_e = 1.5775
at 266 nm	n_o = 1.7571	n_e = 1.6146
at 213 nm	n_o = 1.8465	n_e = 1.6742
Therm-Optic Coefficients	$dn_o/dT = -9.3\times10^{-6}/°C$ $dn_e/dT = -16.6\times10^{-6}/°C$	
Sellmeier Equations (λ in μm, T=20 °C)	$n_o^2=2.7359+0.01878/(\lambda^2-0.01822)-0.01354\lambda^2$ $n_e^2=2.3753+0.01224/(\lambda^2-0.01667)-0.01516\lambda^2$	

3. NonLinear Optical Properties

Phase Matching Output Wavelength	189 - 1750 nm
Nonlinear Coefficients	$d_{11} = 5.8 \times d_{36}$(KDP) $d_{31} = 0.05 \times d_{11}$ $d_{22} < 0.05 \times d_{11}$
Effective SHG Coefficients	Type I: $d_{eff} = d_{31}\sin\theta+(d_{11}\cos3\phi-d_{22}\sin3\phi)\cos\theta$ Type II: $d_{eff} = (d_{11}\sin3\phi+d_{22}\cos3\phi)\cos2\theta$ (where θ & ϕ are polar angles referring to Z & X axis respectively)
Electro-Optic Coefficients	γ_{11} = 2.7 pm/V, γ_{22}, $\gamma_{31} < 0.1\ \gamma_{11}$
Half-Wave Voltage	48 KV (at 1064 nm)
Damage Threshold at 1064 nm at 532 nm at 266 nm	 5GW/cm² (10 ns), 10GW/ cm² (1.3 ns) 1GW/cm² (10 ns), 7GW/ cm² (250 ps) 120MW/cm² (8 ns)

Main Applications

I. Applications in Nd:YAG Lasers

Base on its superior optical and NLO properties, BBO is the most efficient NLO crystal used for SHG, THG, 4HG of Nd:YAG lasers. Moreover, BBO is the ONLY NLO crystal which can produce 5HG at 213 nm. More than 70% for SHG, 60% for THG and 50% for 4HG conversion efficiencies have been obtained respectively, and output 200 mW at 213 nm. Basic NLO properties from SHG to 5HG of Type I BBO crystal are shown in Table 1, and Table 2 shown the harmonic generation results of BBO and KD*P crystals.

Table 1. Relevant NLO Properties of Type I BBO crystal

Fundamental Wavelength: 1064 nm	SHG	THG	4HG	5HG
Effective NLO Coefficient (d_{36}(KDP))	5.3	4.9	3.8	3.4
Angular Acceptance (mrad-cm)	1.0	0.5	0.3	0.2
Walk-off Angle (Degree)	3.2	4.1	4.9	5.5
Temperature Acceptance (°C)	51	16	4	/

Table 2. Harmonic Generations using BBO and KD*P crystal

Crystal	1ω (mJ)	SHG (mJ)	THG (mJ)	4HG (mJ)	5HG (mJ)
BBO	220	105	39	18.5	5
	600	350	40	70	20
KD*P	600	270	112.5	45	/

Both type I and type II phase-matching can be reached by angle-tuning. The phase matching angles of frequency doubling determined by input radiation wavelength is shown in Fig. 1.

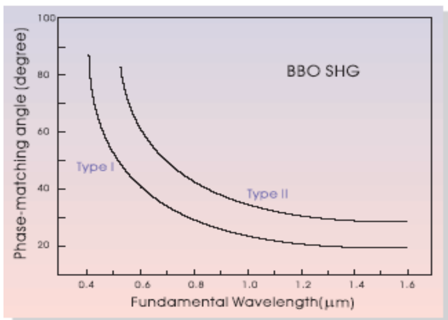


Fig. 1. SHG Turing curves of BBO

BBO is a very efficient crystal for intracavity SHG of high power Nd:YAG lasers. For example, greater than 15 W average power at 532 nm was obtained in intracavity SHG of an acousto-optic Q-switched Nd:YAG laser with AR-coated BBO crystal.

66 mW output was obtained when pumped by 600 mW SHG output of a mode-locked Nd:YLF laser in an external resonant cavity with a Brewster-angle-cut BBO.

Good laser beam quality (such as: small divergence, good mode condition, etc.) is the key for BBO to obtain high conversion efficiency, due to BBO's small acceptance angle and large walk-off. Tight focus of laser beam is not recommended.

II. Applications in Tunable Lasers

♦Dye lasers

Efficient UV output (205 - 310 nm) with a SHG efficiency of over 10% at wavelength of more than 206 nm was obtained in type I BBO, and 36% conversion efficiency have been achieved for a XeCl-laser pumped Dye laser (for example, Lambda Physik's Model

LDP3000 and FL 3000) with power 150KW. The conversion efficiency is about 4 - 6 times higher than that of ADP. Furthermore, the shortest SHG wavelength which is about 4 - 6 times higher than that in ADP. The shortest SHG wavelength of 204.97 nm with efficiency of about 1% has been generated.

With sum-frequency of 780 - 950 nm and 248.5 nm (SHG output of 495 nm dye laser) in Type I BBO, the shortest UV outputs ranging from 188.9nm to 197 nm and the pulse energy of 95 mJ at 193 nm and 8 mJ at 189 nm have been obtained respectively.

♦Ultrafast Pulse Laser

A laser pulse as short as 10 fs pulse can be efficiently frequency-doubled with very thin BBO wafer which shows its superior properties compared with KDP and ADP crystals, considering both phase-velocity and group-velocity matching. It has been reported that 10fs 438 nm ultrafast laser has been achieved by 0.01 mm doubling BBO crystal wafer. Now as thin as 0.01 mm thickness BBO wafers fabricated and supplied by AOTK are widely used in frequency-doubling, -tripling and autocorrelation measurient of ultrafast pulse lasers.

♦Alexandrite and Ti:Sapphire lasers

UV output in the region of 360 - 390 nm with pulse energy of 105mJ (31% SHG efficiency) at 378 nm, and output in the region 244 -259 nm with 7.5 mJ (24% mixing efficiency) have been obtained for type I BBO SHG and THG of an Alexandrite laser.

Greater than 50% of SHG conversion efficiency in a Ti:Sapphire laser has been obtained. High conversion efficiencies were also obtained for THG and 4HG of Ti:Sapphire lasers.

♦Argon Ion and Copper-Vapor lasers

By using the intracavity frequency-doubling technique in an Argon Ion laser with all lines output power of 2W, maximum 33 mW at 250.4 nm and thirty-six lines of deep UV wavelengths ranging from 228.9 nm to 257.2 nm were generated in a Brewster-angle-cut BBO crystal.

Up to 230 mW average power in UV at 255.3 nm with maximum 8.9% conversion efficiency has been obtained for the SHG of Copper-Vapor laser at 510.6 nm.

III. Applications in OPO and OPA

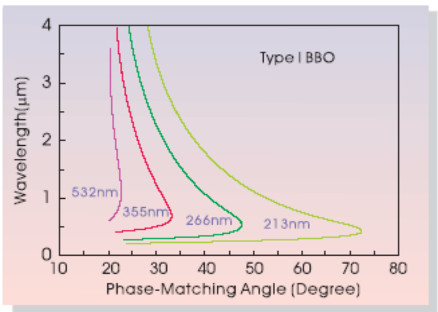


Fig. 2. Type I OPO Turing curves of BBO

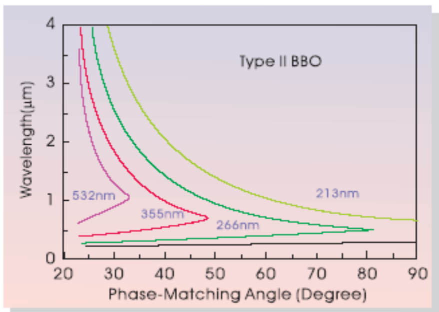


Fig. 3. Type II OPO Turing curves of BBO

BBO is one of the most suitable materials for optical parametric oscillators (OPO) and optical parametric amplifiers (OPA), to generate the widely tunable coherent radiation from UV to IR. Type I and Type II phase matching are applied in BBO's OPO and OPA shown in Fig. 2 and Fig. 3.

Generally long BBO (>15mm) shall be used to decrease the oscillation threshold when employing the type II phase-matching scheme. In order to obtain high efficient conversion, input laser radiation with good beam quality and low divergence is required because of small acceptance angle and large walk-off. Type I gives a larger tuning range and higher parametric amplification rate comparing to Type II, However, Type II interaction can produce narrower bandwidth (0.05 nm) output near degenerate points.

BBO OPO can generate more than 100mJ with wavelength tunable from 400nm to 2000nm by Nd:YAG laser. Meanwhile, BBO OPO system cover the tuning range from 400nm to 3100nm. A maximum of 30% conversion efficiency can be obtained from 400nm to 3100nm, and more than 18% conversion efficiency over the wavelength range from 430nm to 2000nm.

Pumped by picosecond Nd:YAG at 355 nm, narrow-band (< 0.3 nm), high energy (> 200mJ) and wide tunable (400nm ~ 2000nm) pulse have been produced by BBO's OPA. With > 50% conversion efficiency, BBO's OPA is superior to common Dye lasers in efficiency, tunable range and maintenance, and is easy to design and operate.

More than 30% energy conversion efficiency has been got by using 12 mm length BBO in OPO device synchronously pumped at 532 nm, which outputs at 406 nm ~ 3170 nm.

With a 1 mJ, 80 fs Dye laser at 615 nm pumping, OPA using two BBO crystals yields more than 50 μJ (maximum 130 mJ), < 200 fs ultrashort pulse over 800 nm ~2000 nm.

Parametric gain of BBO is over ten times higher than that of KDP at 355 nm pump for Type I interaction.

Tunable OPO with signal wavelengths between 422 nm and 477 nm has been generated by angle tuning a type I BBO crystal pumped with XeCl excimer laser at 308 nm.

BBO's OPO pumped by fourth harmonic of a Nd:YAG laser (at 266 nm) has been observed to cover the whole range of 330 - 1370 nm.

IV. BBO's E-O Applications

BBO can also be used for E-O applications. It has wide transmission range from UV to about 3500nm and it has much higher damage threshold than KD*P or $LiNbO_3$, More than 80W output power and 50KHz repetition rate have been reached by using AOTK's E-O BBO crystals and $Nd:YVO_4$ crystals as gain media. At 5KHz, its pulse has width as short as 6.4ns,and energy of 5.7mJ or peak power of 900 KW. It has advantages over the commercial A-O Q-switched one, including a very short pulse, high beam quality and size compact as well. Although it has a relative small electro-optic coefficient, the Half-wave voltage is very high (48KV at 1064nm), long and thin BBO can reduce the voltage requirements. AOTK now can supply 20mm long and 1mm thin high optical quality of BBO crystal with Z-cut, AR-coated and Gold/Chrome plated on the side faces.

Standard Size

The standard size crystals recommended by AOTK's engineers for various applications are listed as follows (assuming the laser beam diameter upon crystal is ϕ2mm to ϕ3mm):

1. Harmonic generations of Nd:YAG lasers

1064nm SHG –> 532nm	Type I, 4x4x7mm, $\theta = 22.8°$, $\phi = 0°$
1064nm THG –> 355nm	Type I, 4x4x7mm, $\theta = 31.3°$, $\phi = 0°$ Type II, 4x4x7mm, $\theta = 38.6°$, $\phi = 30°$
1064nm 4HG –> 266nm	Type I, 4x4x7mm, $\theta = 47.6°$, $\phi = 0°$
1064nm 5HG –> 213nm	Type I, 4x4x7mm, $\theta = 51.1°$, $\phi = 0°$

2. OPO and OPA pumped by harmonics of Nd:YAG lasers

532nm Pump –> 680-2600nm	Type I, 6x4x12 -15mm, $\theta = 21°$, $\phi = 0°$
355nm Pump –> 410-2600nm	Type I, 6x4x12 - 15mm, $\theta = 30°$, $\phi = 0°$ Type II, 7x4x15 - 20mm, $\theta = 37°$, $\phi = 30°$
266nm Pump –> 295-2600nm	Type I, 6x4x12 - 15mm, $\theta =39°$, $\phi = 0°$

3. Frequency doubling of Dye lasers

670-530nm SHG –> 335-260nm	Type I, 8x4x7mm, θ = 36.3°, ϕ = 0°
600-440nm SHG –> 300-220nm	Type I, 8x4x7mm, θ = 55.0°, ϕ = 0°
444-410nm SHG –> 222-205nm	Type I, 8x4x7mm, θ = 80.0°, ϕ = 0°

4. Harmonic generations of Ti:Sapphire lasers

700-1000nm SHG –> 350-500nm	Type I, 7x4x7mm, θ = 28°, ϕ = 0°
700-1000nm THG –> 240-330nm	Type I, 8x4x7mm, θ = 42°, ϕ = 0°
700-1000nm FHG –> 210-240nm	Type I, 8x4x7mm, θ = 66°, ϕ = 0°

5. Frequency doubling and tripling of Alexandrite lasers

720-775nm SHG –> 360-400nm	Type I, 6x4x7mm, θ = 31°, ϕ = 0°
720-775nm THG –> 240-265nm	Type I, 6x4x7mm, θ = 48°, ϕ = 0°

6. Intracavity SHG of Ar+ laser with Brewster-angle-cut BBO

514nm SHG –> 257nm	Type I, 4x4x7mm, θ = 51°, ϕ = 0°, B-cut
488nm SHG –> 244nm	Type I, 4x4x7mm, θ = 55°, ϕ = 0°, B-cut

Ultra-Thin BBO for Ultra-fast Laser Application

Frequency Conversion of Ultrafast Lasers

For frequency conversion of ultrafast lasers with femtosecond (fs) pulse width, the main concern is fs pulse broadening induced by group velocity mismatching (GVM) or group velocity dispersion of NLO crystal. In order to keep efficiency frequency conversion without significant pulse broadening, the suggested thickness (LGVM) of crystals is less than Pulse Width divides GVM.

Based on advanced crystal technology, AOTK is proud to provide as thin as 0.01 mm BBO crystals for frequency conversion of ultrafast lasers.

Application (Type I) BBO Crystals	SHG of 700 nm	SHG of 800 nm	SHG of 900 nm	THG of 700 nm	THG of 800 nm	THG of 900 nm
d_{eff} (pm/V)	1.296	1.365	1.408	0.893	1.101	1.221
GVM (ps/cm)	2.721	1.922	1.401	8.497	5.676	4.079
LGVM @ 10fs (micron)	40	50	70	10	20	30
Damage threshold @ 10fs (GW/cm^2)	20	25	30	10	15	20

Ultra - thin BBO Wafers

Frequency Doubling Crystal

Crystal	Clear Aperture	Thickness	Part No.
BBO	> ϕ3.5 (mm)	0.01 (mm)	BUT6211
BBO	> ϕ3.5 (mm)	0.02 (mm)	BUT6212
BBO	> ϕ3.5 (mm)	0.03 (mm)	BUT6213
BBO	> ϕ3.5 (mm)	0.05 (mm)	BUT6215
BBO	> ϕ3.5 (mm)	0.1 (mm)	BUT6210
BBO	> ϕ3.5 (mm)	0.2 (mm)	BUT6220
BBO	> ϕ3.5 (mm)	0.5 (mm)	BUT6250
BBO	> ϕ3.5 (mm)	1.0 (mm)	BUT6290

Frequency Tripling Crystal

Crystal	Clear Aperture	Thickness	Part No.
BBO	> ϕ3.5 (mm)	0.01 (mm)	BUT6311
BBO	> ϕ3.5 (mm)	0.02 (mm)	BUT6312
BBO	> ϕ3.5 (mm)	0.03 (mm)	BUT6313
BBO	> ϕ3.5 (mm)	0.05 (mm)	BUT6315

BBO	> ϕ3.5 (mm)	0.1 (mm)	BUT6310
BBO	> ϕ3.5 (mm)	0.2 (mm)	BUT6320
BBO	> ϕ3.5 (mm)	0.5 (mm)	BUT6350
BBO	> ϕ3.5 (mm)	1.0 (mm)	BUT6390

Frequency Quadrupling Crystal

Crystal	Clear Aperture	Thickness	Part No.
BBO	> ϕ3.5 (mm)	0.01 (mm)	BUT6411
BBO	> ϕ3.5 (mm)	0.02 (mm)	BUT6412
BBO	> ϕ3.5 (mm)	0.03 (mm)	BUT6413
BBO	> ϕ3.5 (mm)	0.05 (mm)	BUT6415
BBO	> ϕ3.5 (mm)	0.1 (mm)	BUT6410
BBO	> ϕ3.5 (mm)	0.2 (mm)	BUT6420
BBO	> ϕ3.5 (mm)	0.5 (mm)	BUT6450
BBO	> ϕ3.5 (mm)	1.0 (mm)	BUT6490

Mounting

Super polished or coated crystal surfaces are very easy to be damaged during transportation or handling when needed, especially for thin crystals. In order to prevent crystals from damaging or to be easily operated, AOTK provides three kinds of mount to install different dimension crystals. Custom made mounts or holders are also available. Please contact our sales for more information.

Part No.	Out Diameter (mm)	Thickness (mm)	Crystal Aperture (mm)	Crystal Length (mm)
BH101	25.4	5.0	4x4-10x10	0.1-2
BH102	25.4	9.5, 13.5	4x4-10x10	4-10
BH103	25.4	9.5	8x8-10x10	3-6

Standard Fabrication Specifications

Dimensional Tolerance	(W $\pm$ 0.1mm) x (H $\pm$ 0.1mm) x (L +0.2/-0.1 mm)
Wavefront Distortion	< $\lambda/8$ @633 nm
Angle Tolerance	$\Delta\theta < \pm 0.2°$, $\Delta\phi < \pm 0.2°$
Flatness	$\lambda/10$ @633 nm
Surface Quality	10/5 Scratch/Dig per MIL-O-13830A
Parallelism	< 10 arc seconds
Perpendicularity	< 5 arc minutes
Clear Aperture	> 90% central area
Quality Warranty Period	one year under proper use

Coatings

1. Protective Coating (P-coating)

The polished surfaces of BBO are relatively easy to be fogged in humid air because of its low hygroscopic susceptibility. The protective coating (P-coating) was developed by AOTK to prevent BBO from exposure to moisture. The P-coated BBO with a mount is simpler and better than BBO with housing.

Significant advantages of P-coating show as following:

Better transmittance: Transmittance of P-coated BBO is better than that of uncoated BBO over a wide wavelength range from 200 nm-3500 nm.

High damage threshold: Over 7 GW/cm2 with laser pulse-width 30ps at 1064nm.

Long Lifetime: More than 6 months at 95% humidity and much longer at lower humidity.

2. Anti-Reflective Coatings (AR-coatings)

AOTK supplies single-band and dual-band AR-coatings for BBO at 1064 nm and 532 nm (at 800nm and 400 nm). The AR-coatings are characterized by low reflectance (less than 0.15% at 1064 nm and 0.4% at 532 nm), high damage threshold, anti-moisture and long durability. High damage threshold AR-coatings for 4HG of Nd:YAG or Nd:YLF laser are developed with R < 0.2% at 532 nm and R < 0.4% at 266 nm. AR-coatings at other wavelengths are also available upon request.

Note

- BBO has a low susceptibility to moisture. Users are advised to provide dry conditions for both use and preservation of BBO.
- BBO is soft and therefore the protection of its polished surfaces requires precautions.
- When angle adjusting is necessary, keep in mind that the acceptance angle of BBO is small.
- AOTK's engineers can select and design the best crystal for you if parameters of your laser are provided, for example, energy per pulse, pulse width and repetition rate for a pulsed laser, power for a CW laser, laser beam diameter, mode condition, divergence and wavelength tuning range, etc.
- Keep BBO crystals in a certain temperature, it will increase the damage threshold.

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