LASER COMPONENTS

# Beta-Barium Borate ($\beta$-$BaB_2O_4$ or BBO)

## Introduction

Beta-Barium Borate ($\beta$-$BaB_2O_4$ or BBO), discovered, developed manufactured in China and marketed by LASER COMPONENTS and its partners. The high-quality crystal boule is steadily available from LASER COMPONENTS, who holds specialized proprietar techniques (flux-method) of the BBO crystal growth.

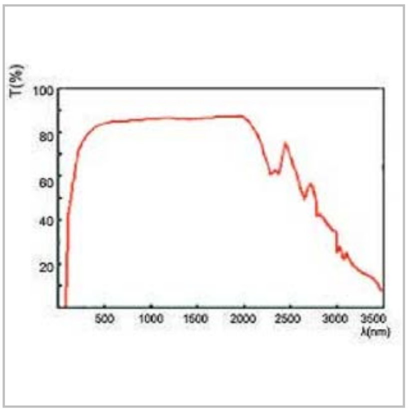


Figure 1:
Transparency curve of BBO

## BBO is featured by

- Broad phase-matchable range from 409.6 nm to 3500 nm;
- Wide transmission region from 190 nm to 3500 nm;
- Large effective second-harmonic-generation (SHG) coefficient about 6 times greater than that of KDP crystal;
- High damage threshold;
- High optical homogeneity with $\delta n \approx 10^{-6}$/cm;
- Wide temperature-bandwidth of about 55 °C.

## LASER COMPONENTS offers:

- Strict quality control;
- Crystal length from 0.01 mm to 25 mm and size up to 20x20x25 $mm^3$;
- P-coatings, AR-coatings, mounts and re-polishing services;
- A large quantity of crystals in stock (in China);
- Fast delivery (10 days for polished only, 15 days for AR-coated – plus transport from China).

## Basic Properties

| | |
|---|---|
| Crystal structure | trigonal, space group R3c |
| Lattice parameter | a=b=12.532Å, c=12.717Å, Z=6 |
| Melting point | about 1095 °C |
| Mohs hardness | 4 |
| Density | 3.85 $g/cm^3$ |
| Thermal conductivity | 1.2 W/m/K(⊥c); 1.6 W/m/K(//c) |
| Thermal expansion coefficient | $\alpha$,$4x10^{-6}$/K; c,$36x10^{-6}$/K |

Table 1:
Chemical and Structural properties



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Beta-Barium Borate
($\beta$-$BaB_2O_4$ or BBO)

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| | |
|---|---|
| Transparency range | 190 – 3500 nm |
| SHG phase matchable range | 409.6 ~ 3500 nm (Type I) 525 ~3500 nm (Type II) |
| Therm-optic coefficient (/°C) | $dn_o/dT = -9.3 \times 10^{-6}$<br>$dn_e/dT = -16.6 \times 10^{-6}$ |
| Absorption coefficient | <0.1%/cm at 1064 nm <1%/cm at 532 nm |
| Angle acceptance | 0.8 mrad-cm ($\theta$, Type I, 1064 SHG)<br>1.27mrad-cm ($\theta$, Type II, 1064 SHG) |
| Temperature acceptance | 55 °C-cm |
| Spectral acceptance | 1.1 nm-cm |
| Walk-off angle | 2.7° (Type I 1064 SHG)<br>3.2° (Type II 1064 SHG) |
| NLO coefficient | $d_{eff}(I)=d_{31}\sin\theta+(d_{11}\cos3\phi - d_{22}\sin3\phi)\cos\theta$<br>$d_{eff}(II)=(d_{11}\sin3\phi + d_{22}\cos3\phi)\cos2\theta$ |
| Non-vanished NLO susceptibilities | $d_{11} = 5.8 \times d_{36}(KDP)$<br>$d_{31} = 0.05 \times d_{11}$<br>$d_{22} < 0.05 \times d_{11}$ |
| Sellmeier equations ($\lambda$ in µm) | $n_o2=2.7359+0.01878/(\lambda2-0.01822)-0.01354\lambda2$<br>$n_e2=2.3753+0.01224/(\lambda2-0.01667)-0.01516\lambda2$ |
| Electro-optic coefficients | $\gamma11 = 2.7$ pm/V, $\gamma_{22}, \gamma_{31} < 0.1\gamma_{11}$ |
| Half-wave voltage | 48 kV (at 1064 nm) |
| Resistivity | $>10^{11}$ ohm-cm |
| Relative dielectric constant | $\varepsilon^S_{11} / \varepsilon_o$ : 6.7<br>$\varepsilon^S_{33} / \varepsilon_o$ : 8.1<br>$\tan\delta<0.001$ |

Table 2. Optical and Nonlinear Optical Properties

BBO is a negative uniaxial crystal, with ordinary refractive-index ($n_o$) larger than extraordinary refractive-index ($n_e$). Both type I and type II phase-matching can be reached by angle-tuning. The phase matching angles of frequency doubling are shown in Fig. 2.

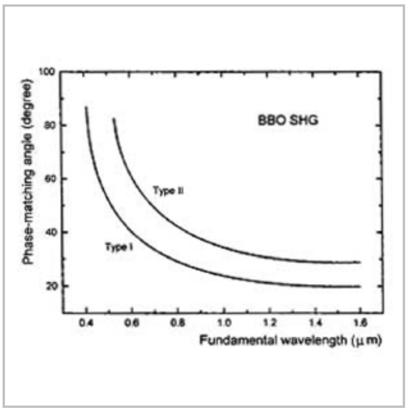


Figure 2:
SHG tuning curves of BBO

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## Application in Nd: YAG LASERS

BBO is an efficient NLO crystal for the second, third and fourth harmonic generation of Nd:YAG lasers, and the best NLO crystal for the fifth harmonic generation at 213 nm. Conversion efficiencies of more than 70% for SHG, 60% for THG and 50% for 4HG, and 200 mW output at 213 nm (5HG) have been obtained, respectively.

BBO is also an efficient crystal for the intracavity SHG of high power Nd:YAG lasers. For the intracavity SHG of an acousto-optic Q-switched Nd:YAG laser, more than 15 W average power at 532 nm was generated in a AR-coated BBO crystal. When it is pumped by the 600 mW SHG output of a mode-locked Nd:YLF laser, 66 mW output at 266 nm was produced from a Brewster-angle-cut BBO in an external enhanced resonant cavity.

Because of a small acceptance angle and large walk-off, good laser beam quality (small divergence, good mode condition, etc.) is the key for BBO to obtain high conversion efficiency. Tightly focusing of laser beam is not recommended by our engineers.

## Applications in Tunable Lasers

### 1. Dye Lasers

Efficient UV output (205 nm – 310 nm) with a SHG efficiency of over 10% at wavelength of >206 nm was obtained in type I BBO, and 36% conversion efficiency was achieved for a XeCl-laser pumped Dye laser with power 150 kW 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. BBO is widely used in the Dye lasers. With type I sum-frequency of 780 – 950 nm and 248.5 nm (SHG output of 495 nm dye laser) in BBO, the shortest UV outputs ranging from 188.9 nm to 197 nm and the pulse energy of 95 mJ at 193 nm and 8 mJ at 189 nm have been obtained, respectively.

### 2. Ultafast Pulse Laser

Frequency-doubling and -tripling of ultrashort-pulse lasers are the applications in which BBO shows superior properties to KDP and ADP crystals. Now, we can provide as thin as 0.02 mm BBO for this purpose. A laser pulse as short as 10 fs can be efficiently frequency-doubled with a thin BBO, in terms of both phase-velocity and group-velocity matching.

### 3. Ti:Sapphire and Alexandrite Lasers

UV output in the region 360 nm – 390 nm with pulse energy of 105 mJ (31% SHG efficiency) at 378 nm, and output in the region 244 nm – 259 nm with 7.5 mJ (24% mixing efficiency) have been obtained for type I SHG and THG of an Alexandrite laser in BBO crystal. More than 50% of SHG conversion efficiency in a Ti:Sapphire laser has been obtained. High conversion efficiencies have been also obtained for the THG and FHG of Ti:Sapphire lasers.

### 4. Argon Ion and Copper-Vapor Lasers

By employing the intracavity frequency-doubling technique in an Argon Ion laser with all lines output power of 2 W, 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 the UV at 255.3 nm with maximum 8.9% conversion efficiency was achieved for the SHG of a Copper-Vapor laser at 510.6 nm.



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## BBO´s OPO and OPA

The OPO and OPA of BBO are powerful tools for generating a widely tunable coherent radiation from the UV to IR. The tuning angles of type I and type II BBO OPO and OPA have been calculated, with the results shown in Fig. 3 and Fig. 4, respectively.

### 1. OPO pumped at 532 nm

An OPO output ranging from 680 nm to 2400 nm with the peak power of 1.6 MW and up to 30% energy conversion efficiency was obtained in a 7.2 mm long type I BBO. The input pump energy was 40 mJ at 532 nm with pulse-width 75 ps. With a longer crystal, higher conversion efficiency is expected.

### 2. OPO and OPA P pumped at 355 nm

In the case of Nd:YAG pumping, BBO's OPOs can generate more than 100 mJ, with wavelength tunable from 400 nm to 2000 nm. Using BBO crystal, the OPO system covers a tuning range from 400 nm to 3100 nm which guarantees a maximum of 30% and more than 18% conversion efficiency, over the wavelength range from 430 nm to 2000 nm.

Type II BBO can be used to decrease linewidth near the degenerate points. A linewidth as narrow as 0.05 nm and usable conversion efficiency of 12% were obtained. However, a longer (>15 mm) BBO should normally be used to decrease the oscillation threshold when employing the type II phase-matching scheme.

Pumping with a picosecond Nd:YAG at 355 nm, a narrow-band (<0.3 nm), high energy (>200 µJ) and wide tunable (400 nm to 2000 nm) pulse has been produced by BBO's OPAs. This OPA can reach as high as more than 50% conversion efficiency, and therefore is superior to common Dye lasers in many respects, including efficiency, tunable range, maintenance, and easiness in design and operation. Furthermore, coherent radiation from 205 nm to 3500 nm can be also generated by BBO's OPO or OPA plus a BBO for SHG.

### 3. Others

A tunable OPO with signal wavelengths between 422 nm and 477 nm has been generated by angle tuning in a type BBO crystal pumped with a XeCl excimer laser at 308 nm. And a BBO's OPO pumped by the fourth harmonic of a Nd:YAG laser (at 266 nm) has been observed to cover the whole range of output wavelengths 330 nm – 1370 nm.

When pumped by a 1 mJ, 80 fs Dye laser at 615 nm, the OPA with two BBO crystals yields more than 50 µJ (maximum 130 µJ), < 200 fs ultrashort pulse, over 800 nm – 2000 nm.

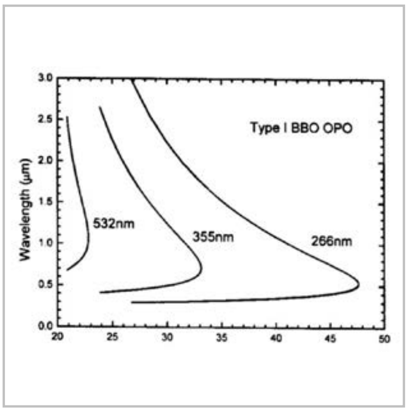


Figure 3:
Type I OPO tuning curves of BBO

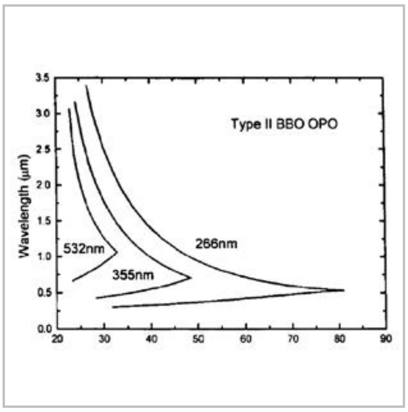


Figure 4:
Type II OPO Tuning curves of BBO



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## BBO´s E-O Applications

BBO can also be used for E-O applications. It has wide transmission range from UV to about 3500 nm. And it has much higher damage threshold than KD*P or $LiNbO_3$. More than 80 W output power and 50 kHz repetition rate have been reached by using E-O BBO crystals and Nd:$YVO_4$ crystals as gain media. At 5 kHz, its pulse has width as short as 6.4 ns, and energy of 5.7 mJ 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 (48 kV at 1064 nm), long and thin BBO can reduce the voltage requirements. LASER COMPONENTS now can supply 20 mm long and 1 mm thin high optical quality of BBO crystal with Z-cut, AR-coated and Gold/Chrome plated on the side faces.

## Coatings

### LASER COMPONENTS provides the following AR-Coatings for BBO:

- Dual Band AR-coating (DBAR) of BBO for SHG of 1064 nm.
- Low reflectance (R<0.2% at 1064 nm and R<0.5% at 532 nm);
- High damage threshold (>300 MW/cm$^2$ at both wavelengths);
- Long durability.
- Broad Band AR-coating (BBAR) of BBO for SHG of tunable lasers.
- Broad Band P-coating of BBO for OPO applications.
- Other coatings are available upon request.

## Warranty on BBO Specifications

- Dimension tolerance: (W ± 0.1 mm) x (H ± 0.1 mm) x (L + 0.5/-0.1 mm) (L ≥2.5 mm)
  (W ± 0.1 mm) x (H ± 0.1 mm) x (L + 0.1/-0.1 mm) (L <2.5 mm)
- Clear aperture: central 90% of the diameter
- No visible scattering paths or centers when inspected by a 50 mW green laser
- Flatness: less than λ/8 @ 633 nm
- Transmitting wavefront distortion: less than λ/8 @ 633 nm
- Chamfer: ≤0.2 mm @ 45°
- Chip: ≤0.1 mm
- Scratch/Dig code: better than 10/5 to MIL-O-13830A
- Parallelism: ≤20 arc seconds
- Perpendicularity: ≤5 arc minutes
- Angle tolerance: ≤0.1°
- Damage threshold [GW/cm$^2$]: >1 for 1064 nm, TEM00, 10 ns, 10 Hz (polished only)
  >0.5 for 1064 nm, TEM00, 10 ns, 10 Hz (AR-coated)
  >0.3 for 532 nm, TEM00, 10 ns, 10 Hz (AR-coated)
- Quality warranty period: one year under proper use.

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## Note

1. BBO has a low susceptibility to the moisture. The user is advised to provide dry conditions for both the use and preservation of BBO.
2. BBO is relatively soft and therefore requires precautions to protect its polished surfaces.
3. When angle adjusting is necessary, keep in mind that the acceptance angle of BBO is small.
4. LASER COMPONENTS engineers can select and design the best crystal, if the main parameters of your laser are provided, such as energy per pulse, pulse width and repetition rate for a ulsed laser, power for a cw laser, laser beam diameter, mode condition, divergence, wavelength tuning range, etc.
5. For thin crystal, we can provide free holder for you.



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