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Non-Linear Optical properties of β-BBO and LBO

Physical properties of β-BBO:

The non-linear optical (NLO) properties and applications of this crystal β-BBO were studied by Fujian Institute in Fuzhou, PRC China. Crystal β-BBO (Beta Barium Borate, β-BaB_2O_4) is characterised by wide transparency, moderate non-linear optical coefficient and high damage threshold.

The beta phase of crystal BBO is the low temperature phase (< 925 °C.). It belongs to a trigonal system with a point symmetry of 3m. It is a negative uniaxial crystal with unit cell dimensions $a = b = 12.532$ Å and $c = 12.717$ Å. Crystal BBO is characterised by a broad phase-matchable range from 409.6 nm to 3000 nm (Type I), and from 530 nm to 3000 nm (Type II).

BBO has a density of 3.849 gms/cm³. It has a hardness of 4.5 on Mohs scale. Its d_{eff} NLO coefficient for Type I is about 4.4 times that of crystal KDP at 1064 nm. It has a large birefringence ($n_o - n_e = 0.1126$) and low dispersion allowing phase-matching for both Type I and Type II processes. Type I process is most commonly used as it is more efficient than Type II process. It is non-critically phase-matchable (NCPM) at 209.6 nm. It has the largest temperature acceptance width of 55 °C. (about nine times that of crystal KDP). Problems of thermal detuning are extremely small due to its small thermal birefringence.

BBO Refractive Indices:

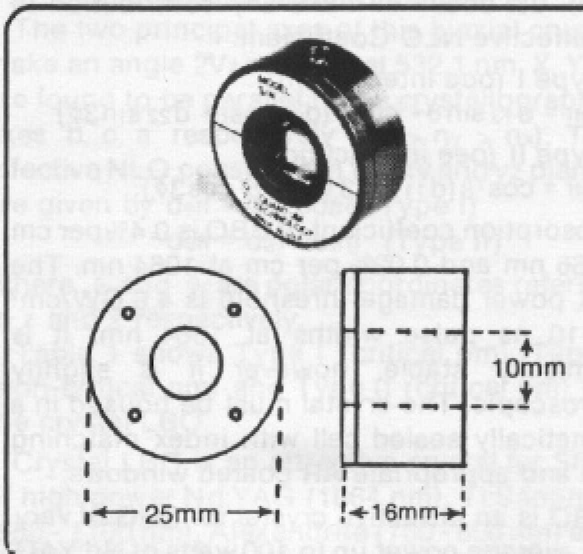
The two principal refractive indices are given by Sellmeier's equations $n^2 = A + \frac{B}{(\lambda^2 - C)} - D\lambda^2$

where

Parameter	A	B	C	D
n_o	2.7359	0.01878	0.01822	0.01354
n_e	2.3753	0.01224	0.01667	0.01516

and λ is expressed in micrometers.

Typical refractive indices for BBO are:



The phase-matching angles for type I process for BBO and LBO are plotted in fig. 1.

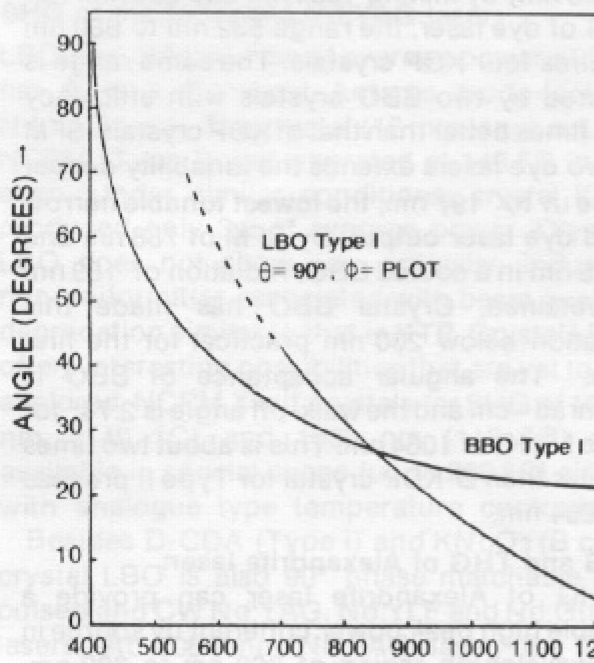


FIGURE 1

λ nm	n_o	n_e
266	1.7571	1.6146
532	1.6741	1.5541
632	1.6673	1.5500
1064	1.6570	1.5390

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Physical properties of LBO:

The non-linear optical (NLO) properties and applications of this crystal LBO were studied by Fujian Institute in Fuzhou, PRC China. Crystal LBO (Lithium Triborate LiB_3O_5 is characterised by wide transparency, moderate NLO coefficient and high laser damage threshold.

Crystal LBO belongs to an orthorhombic system with point group symmetry of mm2. It is a negative biaxial crystal with unit cell dimensions a = 7.3788 Å, b = 8.4473 Å and c = 5.1395 Å. Crystal LBO is characterised by broad phase-matchable range from 550 nm to 3000 nm (Type I) and from 790 nm to 2200 nm (Type II).

LBO has a density of 2.47 gms/cm³. Its d_{eff} NLO coefficient d_{32} for Type I is about 3.1 times d_{36} of KDP crystal. It has a hardness of 6 on Mohs scale, is chemically stable and non-hygroscopic. It decomposes at a transition temperature of 834 °C (±4 °C). It has moderate birefringence ($n_z - n_x = 0.0427$). When it is non-critically phase matched (NCPM) for Type I operation at 1064 nm, it has a moderate temperature acceptance width of 3.9 °C - cm.

Refractive Indices:

The three principal refractive indices of LBO are given by Sellmeier's equation

$$n^2 = A + \frac{B}{(\lambda^2 - C)} - D\lambda^2$$

where λ is expressed in micrometers.

Parameter	A	B	C	D
n_x = b	2.4542	0.01125	0.01135	0.01388
n_y = c	2.5390	0.01277	0.01189	0.01848
n_z = a	2.5865	0.01310	0.01223	0.01861

Typical Refractive Indices are:

λ nm	$n_{b=x}$	$n_{c=y}$	$n_{a=z}$
266	1.6256	1.6597	1.6761
532	1.5785	1.6065	1.6212
633	1.5740	1.6014	1.6164
1064	1.5656	1.5905	1.6055

NLO properties of LBO:

Crystal LBO has five coefficients, namely d_{31} = 1.16 pm/v, d_{32} = 1.24 pm/v, d_{33} = 0.063 pm/v, d_{15} = 1.15 pm/v and d_{24} = 1.24 pm/v.

The two principal axes of this biaxial crystal make an angle $2V_z = 108.5°$ at 532.1 nm. X, Y, Z are found to be parallel to the crystallographic axes b, c, a respectively ($n_z > n_y > n_x$). The effective NLO constants in the xy and yz planes are given by $d_{eff} = d_{32}\cos\phi$ (Type I)

$d_{eff} = d_{31}\cos\theta$ (Type II)

Where θ and ϕ are polar coordinates refering to z and x respectively.

Table 1 shows Type I (critical pm), Type I (non-critical pm) and Type II (critical pm) for the crystal LBO.

Crystal LBO is an attractive crystal for SHG of high power Nd:YAG (1064 nm), Ti:Sapphire (650 - 1100 nm), Alexandrite (700 - 800 nm) and Cu-Vapour (580 nm only) lasers. LBO is angle phase matchable for SFM down to 232.5 nm at 20 °C by mixing 1064 nm with SHG of dye laser.

SHG of mode-locked Nd:YAG laser:

LBO has obtained 6w of average power at 532 nm from a Coherent Antares mode-locked Nd:YAG laser. The crystal (12 mm long) cut for NCPM (Type I) was operated at 149 °C in an oven. Under similar conditions, crystal KTP produced only 3w of average power. Crystal LBO does not show any optically induced non-uniformities associated with beam quality degradation similar to that in KTP. Crystal LBO offers interesting possibilities that are yet to be explored. NCPM X cut crystals for SHG of 1064 nm, (149 °C) and 1080 nm (112 °C) are available in special ovens (up to 200 °C) along with analogue type temperature controllers.

Besides D-CDA (Type I) and $KNbO_3$ (B cut) crystal LBO is also 90° phase matchable for pulsed and CW Nd:YAG, Nd:YLF and Nd:Glass lasers. At 1064 nm Nd:YAG laser, the 90° phase-match temperature is 149 °C and at 1132 nm, it is 77 °C. At 1320 nm, the NCPM temerature is minus 9.5 °C. LBO crystals operated at 90° non-critical phase-matching are highly efficient for SHG by temperature tuning from 1064 nm to 1350 nm. LBO crystal is superior to KTP (Type II) crystal in conversion efficiency and stability. Conversion efficiency of over 70% is obtained for pulsed lasers and 25% for CW lasers. Furthermore LBO crystals are also good NLO crystals for OPO applications.

LBO is available in cross-section of $10 \times 10\ mm^2$. For larger beam diameters, crystals of D-CDA (Type I) or D-KDP (Type II) are available in large cross-sections of $25 \times 25\ mm^2$ or more for SHG of 1064 nm. All these crystals including KTP, $KNbO_3$ and $MgO:LiNbO_3$ are available from Quantum Technology, Inc.

TABLE 1

Parameter	Type I Critical pm	Type I Non-critical pm	Type II Critical pm
Phasematch Angle	$\theta = 90°$, $\phi = 10.7°$ to 'a' axis in xy plane	$\theta = 90°$ $\phi = 0$	$\theta = 90°$, $\phi = 19.7°$ to 'b' axis in yz plane
Acceptance angle (mrad-cm)	$\Delta\theta.L = 57$ $\Delta\phi.L = 9$	$\Delta\theta.L = 35$ $\Delta\phi.L = 42$	$\Delta\theta.L = 82$ $\Delta\phi.L = 24$
Temp. bandwidth	9 °C - cm	3.9 °C - cm (Peaked at 149 °C)	-
Walk-off angle	0 - 43°	small	0.22°
d_{eff} (pm/v)	1.22	1.243	1.08

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NLO properties of BBO:

Crystal BBO has five NLO coefficients d_{11} = 1.6 pm/v, d_{31} = 0.08 pm/v. d_{22} and d_{14} are small. d_{33} does not make any contribution to the effective NLO Coefficient.

In Type I (ooe interaction):

$$d_{eff} = d_{13} \sin\theta + \cos\theta (d_{11} \cos\theta - d_{22} \sin 3\phi)$$

In Type II (oee interaction):

$$d_{eff} = \cos^2\theta (d_{11} \sin 3\phi + d_{22} \cos 3\phi).$$

Absorption coefficient of BBO is 0.4% per cm at 266 nm and 0.02% per cm at 1064 nm. The peak power damage threshold is 4.6 GW/cm^2 for 10 ns pulse widths at 1064 nm. It is chemically stable, however it is slightly hygroscopic. The crystal must be housed in a hermetically sealed cell with index matching fluid and appropriate AR coated windows.

BBO is an attractive crystal for SHG of very high average power up to 100 watts of Nd:YAG laser, Ti:Sapphire laser (650 nm - 1100 nm), Alexandrite laser (700 nm - 800 nm). It can phase-match for 5th harmonic generation (212.8 nm) by mixing 1064 nm and 266 nm. For SHG of dye laser, the range 532 nm to 680 nm requires four KDP crystals. The same range is covered by two BBO crystals with efficiency four times better than that of KDP crystals. SFM of two dye lasers extends the tunability deeper in the uv to 197 nm, the lowest tunable narrow band dye laser output. By SFM of 788 nm and 248.5 nm in a cooled BBO, radiation of 189 nm is obtained. Crystal BBO has made this radiation below 200 nm practical for the first time. The angular acceptance of BBO is 1.4 mrad - cm and the walk-off angle is 2.74° for Type I SHG of 1064 nm. This is about two times greater than D-KDP crystal for Type II process at 1064 nm.

SHG and THG of Alexandrite laser:

SHG of Alexandrite laser can provide a tunable high peak power coherent uv source in the wavelength region of 360 nm to 390 nm. BBO crystal oriented at 31° (Type I SHG) is useful for producing uv pulse energy of 105 mj at 378 nm with 31% efficiency. The measured spectral width is 1.15 nm-cm and angular acceptance width is 0.9 mrad-cm. For THG, BBO crystal oriented at 48.6° (Type I) is used to generate UV in the range 244 nm to 259 nm with 24% efficiency. A half-wave plate is used between SHG and THG to rotate ω_1 in the same plane as ω_2. Even after using a half-wave plate (which produces optical loss) Type I THG is more efficient than Type II process (which does not require a half-wave plate). In a typical THG experiment, 160 mj at 744 nm mixed with 40 mj at 372 nm produced THG output of 6 mj at 248 nm.

SHG of Ti:Sapphire (TS) laser:

In a typical experiment, TS laser generates 130 mj at 780 nm in a 2mm diameter ($^1/e^2$) beam. A single BBO crystal (5 X 5 X 6 mm^3) Type I oriented at 28° is angle tuned to cover the range 710 nm to 940 nm. SHG output of 30 mj is obtained at 390 nm, giving energy conversion efficiency of 23%. In order to improve efficiency, it is necessary to reduce the spectral bandwidth of the TS laser by injection seeding. This improves the internal conversion efficiency to over 50% at the 390 nm SH output.

At present, crystal BBO is unmatched in performance as a doubler or tripler in the wavelength range 409 nm to 800 nm. Other crystals such as $KNbO_3$, KTP, LBO, D-KDP and D-CDA are more efficient than crystal BBO above 800 nm.

For SHG, six BBO crystals of 5 X 5 X 6 mm^3 are required to cover the range 409 nm to 1600 nm. These are oriented at a 80° angle (409 nm - 430 nm), 61° angle (430 nm - 460 nm), 51° angle (460 nm - 550 nm), 41° angle (540 nm - 670 nm), 31° angle (670 nm - 850 nm) and 22° angle (850 nm - 1600 nm).

BBO crystals are available in cross-section of 10 X 10 mm^2 and length 10 - 12 mms. For larger beam diameters, crystals of KDP Type I (518 nm - 800 nm), crystals of D-KDP Type II (740 nm - 1100 nm), crystals of D-CDA Type I (1034 nm - 1100 nm) are available in large cross-sections 40 X 40 mm^2 or more. All these crystals including LBO, KTP, $KNbO_3$ are available with anti-reflection coatings for high performance. Quantum Technology, Inc. keeps a complete stock of these crystals. Please direct your inquiries to **407-333-9348**.