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DATA SHEET 716

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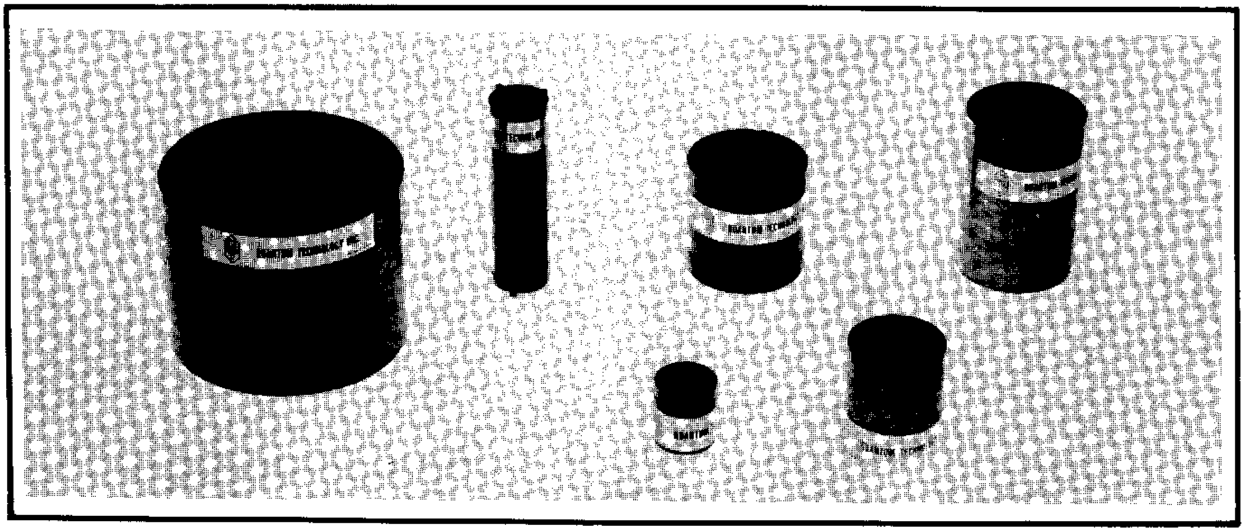
CHOOSING A FREQUENCY DOUBLER FOR A Nd:YAG AND A RUBY LASER



SHG Cells for Angle Tuning

This technical data sheet covers the subject of matching SHG crystals, in order to obtain the best possible doubling efficiency from a Nd:YAG and Ruby laser.

1. Doubling the Output of a Nd:YAG Laser

In order to double the frequency of 1060 nm output from a Nd:YAG laser to 530 nm radiation, there are various SHG crystals available, depending upon the operating characteristics of the laser. The SHG crystal characteristics such as the non-linear susceptibility coefficient and the damage threshold must be matched to the characteristics of the laser. In every case, however, the important phase-matching condition must be so that the SHG crystal is either 90° phase-matched for temperature tuning or angle-matched for angle tuning. The amount of energy converted is a function of peak power, as well as other equally important parameters like mode structure, beam divergence, angular acceptance and other factors. The length of the crystal is important to maintain the proper phase relationship for maximum output.

The most common SHG materials and their properties are shown in Table I.

Table I

Material	Non-Linear Coefficient w.r.t. KDP (d_{36})	Damge Threshold	Phase Match Angle	Temper-ature
$Ba_2NaNb_5O_{15}$	$d_{31} = 32$	1 MW/cm^2	90°	105°C
$LiNbO_3$	$d_{31} = 13$	20 MW/cm2	90°	165°C
$LiIO_3$	$d_{31} = 10.2$	50 MW/cm^2	30°	25°C
KD_2PO_4 (Type I)	$d_{36} = 1.0$	200 MW/cm^2	41°	25°C
KD_2PO_4 (Type II)	$d_{36} = 1.0$	500 MW/cm^2	53.5°	25°C
CsH_2AsO_4 (Type I)	$d_{36} = 0.92$	300 MW/cm^2	85°	25°C
CsD_2AsO_4 (Type I)	$d_{36} = 0.92$	500 MW/cm^2	82°	25°C
$KTiOPO_4$ KTP	$d_{31} = 15.0$	1600 MW/cm^2	21°	25°C

Table II

<table>
<tr><th colspan="3">Continuously Pumped</th></tr>
<tr><td>A. CW Oscillation</td><td>B. Q Switched</td><td>C. Q Switched and Mode-Locked</td></tr>
<tr><td>$Ba_2NaNb_5O_{15}$</td><td>$LiNbO_3$</td><td>$LiIO_3$
KTP</td></tr>
<tr><th colspan="3">Flash Pumped</th></tr>
<tr><td>D. Long Pulse</td><td>E. Q Switched</td><td>F. Q Switched and Mode-Locked</td></tr>
<tr><td>$LiIO_3$</td><td>D-CDA (I)
CDA (I)
D-KDP (I&II)
KTP</td><td>D-CDA (I)
CDA(I)
D-KDP (I&II)
KTP</td></tr>
</table>

A. Continuously Pumped CW Radiation:

Since the output power from a CW laser is low, SHG crystal like $Ba_2NaNb_5O_{15}$ with a high non-linearity and low damage threshold, is normally used intracavity, to obtain efficiences of about 25% for a 1 watt input power.

B. Continuously Pumped, Q Switched Radiation:

Since peak powers of continuously pumped, Q switched Nd:YAG laser is typically in the kilowatt range, $Ba_2NaNb_5O_{15}$ crystals with high non-linearity and low damage threshold cannot be used. The SHG crystals $LiNbO_3$ and $LiIO_3$ are used for this type of laser. $LiNbO_3$ has a higher non-linearity and low damage threshold and is preferred because it can 90° phase- match at 165°C, consequently there is no walk-off between fundamental and SHG beams. The output of this type of laser is most efficiently doubled in frequency with an intracavity crystal. Typical average harmonic output from such a laser is as large as the maximum fundamental output. Peak harmonic power is often higher than peak fundamental power because the harmonic pulse is shorter than fundamental pulse. Such lasers typically emit pulses lasting several hundred nanoseconds, at repetition rates of several kilohertz. Average powers are normally about half watt with peak powers near a kilowatt.

C. Continuously Pumped, Q-Switched and Mode-Locked Radiation:

Peak power of repetitively Q switched laser may be increased by mode-locking the laser during the Q switched pulse. The mode-locked output is a train of Q switched pulses which may have a repetition rate as high as several hundred hertz. Each Q switch pulse may consist of several dozen mode-locked pulses of 50 to 100 picoseconds duration separated from each other by a few nanoseconds. Peak power of each pulse is typically several hundred kilowatts.

A fast E-O switch outside the laser cavity can select a single mode-locked pulse from each Q switched pulse. This produces a series of single very short pulses, with very high energy and a high repetition rate. The output can be doubled in frequency by a $LiIO_3$ crystal, outside the laser cavity, with an efficiency of more than 35%. Recently both KTP and D-CDA crystals are also used for SHG of CW Q switched and mode-locked laser with an efficiency of 20–25%.

D. Flash Pumped, Long Pulsed Radiation:

Flash pumping of Nd:YAG laser can produce a higher energy output than is available from continuously pumped versions with typical pumping rates of 100 Hz. These lasers are used in industrial application like drilling, welding, etc. Frequency doubling is rarely employed for such application. However, $LiIO_3$ crystal may be used to double the frequency in certain applications if the input energy is lowered below the damage threshold of the doubler.

E. Flash Pumped, Q Switch Radiation:

Addition of a Q switch to a flash pumped Nd:YAG laser shortens the pulse from a few hundred microseconds, to about 10 ns. Although the pulse energy from such a laser is typically below 500 millijoules, peak power is 20–50 megawatt. High peak powers can cause permanent optical damage in $Ba_2NaNb_5O_{15}$, $LiNbO_3$ and $LiIO_3$ crystals. The crystals, D-KDP, CDA and D-CDA are most often used with such lasers.

KTP crystal material is grown from the melt. It has a high non-linear coefficient as well as very high damage threshold. SHG efficiency of 30% is reported with a crystal length of 3 mms. This crystal would find a unique position as a doubler for Nd:YAG laser if the present available size of 5mm^3 can be increased.

In Type I D-KDP, the phase matching angle is 41° and doubling efficiencies of about 10% are obtained. In this process walk-off between fundamental and SH beams is present. Also angular alignment and thermal control are more critical than Type II D-KDP frequency doubler. In the latter method, linearly polarized 1060 nm fundamental radiation is incident at an angle of 45° to the projection of the crystal optic axis. The phase-match angle is 53.5°. The Type II process has proven more efficient with typical doubling efficiency of about 30%. The phase matching parameters are summarized in Table III.

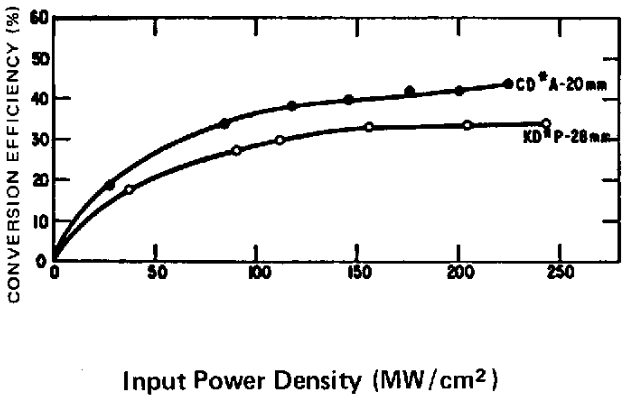
Table III

Parameter	D-KDP Type I	D-KDP Type II	CDA Type I	D-DCA Type I
Phase-matching angle (degree)	41°	53.5°	85°	82°
Angular acceptance (cm-millirad)	1.1	2.2	--	9.0
Spectral acceptance (cm-Å) FWHM	72.5	55.7	--	22.5
Linear absorption (%/cm)	0.6	0.6	1.7	0.6
Beam walk-off (millirad)	27	18	2.5	3.1

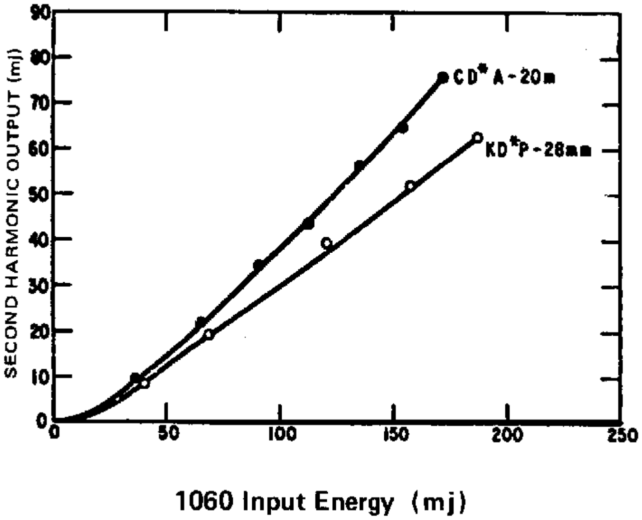
Type II process is not possible for CDA and D-CDA crystals at 1060 nm. These crystals can be angle-tuned, as well as temperature-tuned, at a temperature of 45°C and 110°C for CDA and D-CDA respectively. Temperature tuning of D-CDA gives doubling efficiency of over 40%. However, recent experiments have shown that angle tuning of Type I D-CDA oriented at an angle of 82° for room temperature operation, gives efficiences of the same order, without the problems of slow thermal tuning and of expensive temperature control equipment. The temperature width Δt of the tuning curve is ± 5°C. This feature makes it easier to tune and also makes it less sensitive to thermal detuning due to the absorption of high power radiation. For efficient doubling, a beam with a divergence angle less than the angular phase-matching bandwidth is required. The crystal D-CDA can accept a beam twice as divergent as compared to D-KDP (Type II) crystal. Moreover, with an angle tuned D-CDA doubler, there is no degradation of beam quality. The damage threshold is further increased and the useful life of the frequency doubler is extended. In typical experiment, 500 millijoule 17 ns pulse was converted by the D-CDA frequency doubler to 150 millijoule. Moreover, larger acceptance angle makes this crystal suitable for a multimode high power laser radiation. The crystal CDA is useful for converting 100 millijoule 20 nanoseconds radiation, and produces efficiency of 15–20%. Both CDA and D-CDA crystals are easier to tune than Type II D-KDP crystal.

An angle tuned crystal D-CDA is the best candidate for high average power and high peak power radiation. For some applications, however, as in the case of field work, where the environmental termperature fluctuations are too severe, it is best to use a combination of angle tuning (crystal cut at 85° angle) and temperature tuning at about 60°C. Angular alignment and thermal control of D-CDA doubler are less critical than Type II D-KDP doubler.

In the average power range of 60—70 watts, the available doubling crystals that are most attractive for high efficiency conversion are D-KDP (Type II) and D-CDA (Type I). The crystal D-KDP is known to have an absorption of 0.6% per cm similar to that for D-CDA crystal at 1060 nm. Effects due to thermally induced phase-matching are negligibly small in a D-CDA doubler at incident average powers of 50 watts. When the crystal D-CDA (Type I) is used as an angle-tuned doubler, it is very efficient in doubling the frequency of high power radiation because of its unusually higher degree of angular acceptance than D-KDP (Type II) doubler.



1A) Conversion efficiences measured as a function of input power density at 1060 nm.



1B) The SHG output at 532 nm vs. input energy at 1060 nm.

Figures 1A and 1B show the results of the doubling efficiency in D-KDP (Type II) and D-CDA (Type I), from a YAG:FPL laser. An energy conversion efficiency of 45% is obtained at an input energy level of 150 millijoule. The efficiency of a 20 mm D-CDA doubler is found to be consistently higher than that of a 28 mm D-KDP doubler. The average power handling capability of D-CDA doubler is about 35 watts at 530 nm and is comparable to that of a D-KDP doubler. For very high power YAG:FPL lasers, D-CDA doubler when angle tuned, can withstand 1.9 j/pulse, 50 ns pulse width at 10 pps, corresponding to average power of 19 watts and peak powers of 78 MW/cm^2 without damage. Also, Type II D-KDP doubler is more difficult to use, since the extraction of 532 nm radiation requires expensive optics. The fundamental and SHG radiation cannot be separated by a single linear polarizer, since the two polarizations are not orthogonal.

F. Flash Pumped, Q Switched and Mode-Locked Radiation:

Mode-locking of a flash pumped Nd:YAG oscillator can produce pulses of 30 to 100 ps. Amplification of a single pulse by a chain of Nd:YAG rods can produce an infra-red pulse with energies of hundreds of millijoules and with peak powers of gigawatt (GW). Frequency doubling of these high peak power pulses is typically done, with an angle-tuned D-CDA crystal with efficiencies reaching 60%. For shorter pulse widths, the damage threshold is over 10 GW/cm^2 at energy densities of around 2–3 joules/cm^2.

2. Doubling the Output of a Ruby Laser

High power UV laser source, useful to pump a visible tunable dye laser, is obtained by frequency-doubling of a Ruby laser radiation. The best crystal for achieving this goal is the SHG crystal RDA. This crystal can be 90° phase-matched at a temperature of about 92°C for peak input powers of 100 MW/cm^2, and 20 ns pulse widths. Conversion efficiency of about 20% is obtained with a 20 mm crystal length. The damage threshold is much higher, if the crystal if oriented at an angle of 82° w.r.t. the optic axis, to operate it at room temperature. This crystal is less sensitive to temperature fluctuation and is relatively free from detuning as compared to D-KDP crystal. The non-linear coefficient d_{36} of RDA crystal is about 0.9 times that of KDP crystal.

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