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DATA SHEET 715

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TYPE II PHASE-MATCHING PROCESS

1. Frequency Doubling by Type II Process in Non-Linear Crystals:

Type II process requires an angle of orientation different from type I process. This process is very efficient, especially for doubling 1064 nm radiation due to a more favourable angle in the most popular crystal KDP, used in laser fusion. In type I process, the crystal orientation is obtained by rotation about the Z axis through an angle of 45° and then rotating again about the new X or Y axis through the phase-matching angle. In type II process, crystal orientation is obtained by rotating only about the X or Y axis through the phase-matching angle. The orientation for type II process is shown in Figure 1. The phase-matching angles for type I as well as for type II processes are described by equations in our data sheet 706. For a crystal KDP, type I phase-matching angle is 41° and type II phase-matching angle is 58° for doubling 1064 nm radiation. Since type II conversion efficiency is proportional to $\sin^2 2\theta_m$, this process is preferred when

$$\sin^2 2\theta_m \text{ (II)} > \sin^2 \theta_m \text{ (I)}$$

For KDP crystal,

$$\sin^2 2\theta_m \text{ (II)} = 1.8 \sin^2 \theta_m \text{ (I)}.$$

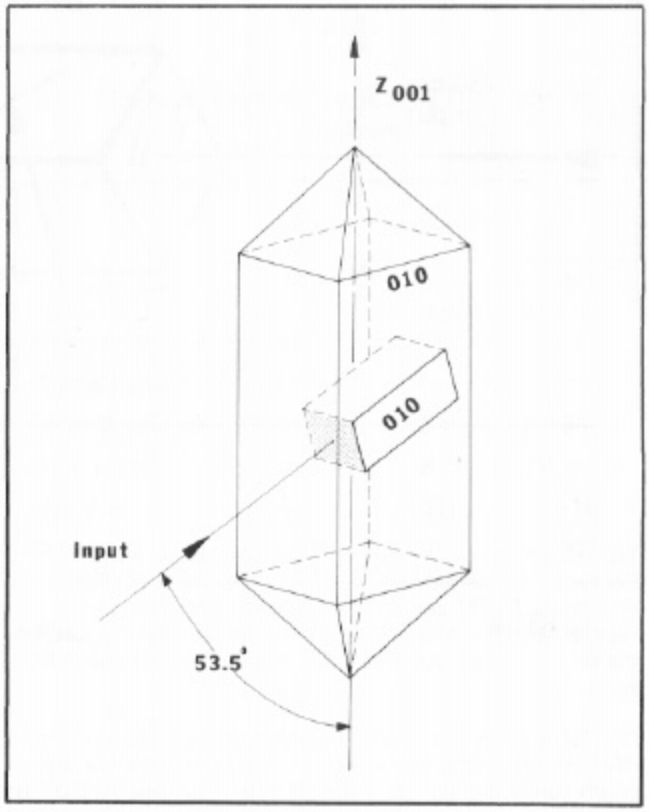


Figure 1
Orientation for Type II Process in D-KDP Crystal

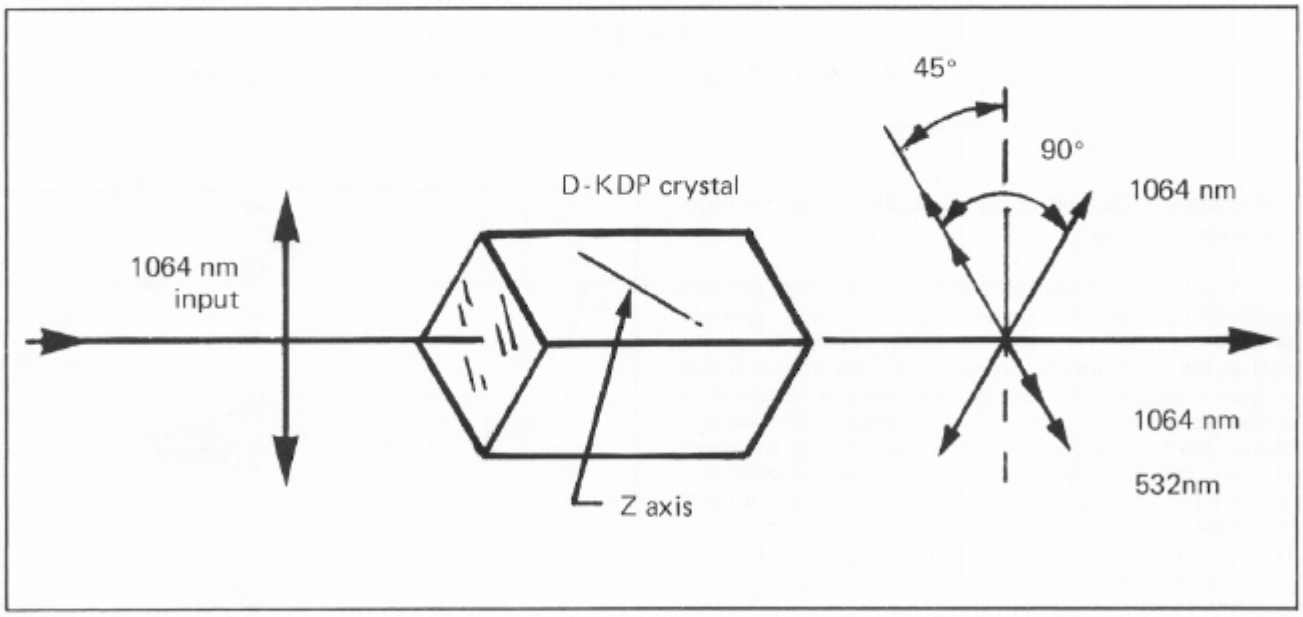
A second advantage in type II process is that the mismatch due to the angular divergence from the phase-matched direction is reduced by a factor of 2 in a KDP crystal. The smaller mismatch means that the acceptance angle is wider and angular alignment is less critical. As a result, thermal control in type II process is less critical than in type I process.

While type I process requires a plane polarized input beam, type II process can be achieved from either an unpolarized or a linearly polarized input beam. In type II process, this incident beam is split within the crystal into an O-ray and E-ray of equal amplitude. The second harmonic output is polarized as an E-ray. In type I process, the incident interacting beam propagates as an O-ray and the second harmonic output is polarized as an E-ray. Because there are two orthogonal beams interacting within the crystal, the SHG efficiency in type II process is higher than in type I process. In high peak power low beam divergence SHG, of 1064 nm radiation with type II D-KDP crystal, efficiencies as high as 75% are achieved. Mode structure, beam divergence, crystal length, angular acceptance of the crystal material and thermally induced gradients are the factors that greatly affect the conversion efficiency.

The two most popular crystals for 1064 nm Nd:Yag and 1054 nm Nd:Glass laser are (a) D-CDA crystal (b) D-KDP crystal. These lasers are capable of producing very high peak powers in excess of 100 Gigawatt/cm^2 for subnanosecond pulses or average powers in excess of 60 watts. Type II process is not possible for D-CDA crystals for 1064 nm radiation and type I process in D-CDA crystal is fully compared with type I process in D-KDP crystal in our data sheet 716. Fortunately both type I and type II processes are possible in D-KDP material at 1064 nm radiation. Crystal D-KDP is very expensive since it requires growing in a heavy water solution of KDP material over a period of three months. The substitution of deuterium for hydrogen in KH_2PO_4 crystal lattice gives D-KDP crystal a lower absorption, typically 0.5% per cm at 1064 nm radiation. This lower absorption of D-KDP crystal means that thermal detuning is less of a problem as compared to that in KDP material. Second harmonic polarization vectors for type II KDP and D-KDP crystal are shown in Figure 2.

Figure 2

Polarization Vectors for Type II D-KDP Doubler



The most popular crystals for dye lasers are Lithium Formate Monohydrate (LFM), Potassium Dihydrogen Phosphate (KDP) and Lithium Iodate (LI). The type I and type II angles for KDP and Lithium Iodate crystals are shown in Table I. All these crystals are grown in our laboratory.

This table shows that even though type II process is more efficient than type I process, it has a limited visible wavelength tuning range. For example type I process in KDP is not possible below the wavelength of 517.4 nm while type II process is not obtainable below the wavelength of 732 nm. Similarly, type I process in LI crystal is obtainable above the wavelength of 600 nm while type II is not possible below 707 nm. Limitation of angle tuning at room temperature can be overcome by operating the crystal at a lower temperature and by taking advantage of the property of thermal birefringence. For example, the lower wavelength limit for KDP can be pushed to 514 nm by operating the KDP crystal at −13°C.

Table I

Type I and Type II Angles of KDP and Lithium Iodate Crystals

Wavelength nm	KDP		LI	
	Type I Degrees	Type II Degrees	Type I Degrees	Type II Degrees
517.4	90	Not	Not Transparent	
524.5	81.5	Obtainable		
600.0	60	↓	62.8	Not
694.3	50.4		50.3	Obtainable
707.0	49.6		50	90
732.0	47.5	90	45	81
800.0	46.0	72	40	68
890.0	44	63.6	37	54.2
1058.0	40.3	59.1	29.7	43.1
1065.0	40.3	59.1	29.7	43.1
1700.0	Not Transparent		14	–
6000.0			5.0	7.0

The orientation of type II process in a KDP crystal is so attractive that many harmonic generator rods or plates can be cut from a large crystal boule and all of the clear crystal material is used without any waste as compared to that of type I process. This results in the reduction of the cost of a doubler by as much as 30%. This is particularly important in laser fusion experiments where large numbers of doublers and triplers with apertures in excess of 250 mm are required in large quantities.

For crystals of KDP type (uniaxial and negative crystals), the SH beam is always an E ray for both type I and type II processes. After generating the SH output, one is usually confronted with the problem of separating the output fundamental and SH beams. Since these beams are orthogonally polarized in type I process, the SH beam can be separated by the use of a calcite or a glan-thomson or a thin film polarizer. In type II process, dispersive prisms or narrow band optical filters are used to achieve this separation.

Non-linear coefficient of a LI crystal is about ten times larger than a KDP crystal while its damage threshold is only about 50 Mw/cm². Crystal D-KDP has a non-linear coefficient 4% smaller than KDP while its absorption is about 30% of that of a KDP crystal. For high peak powers, crystal D-KDP (type II cut) is a better choice provided the optical quality of laser is excellent, and the beam divergence is lower than 1 to 2 milliradian. Typical conversion efficiencies with type II D-KDP crystal are shown in Table II.

Table II

D-KDP Crystal (Type II) Efficiency at 1064 nm

Parameters	Peak Power TEM_{oo}		
	10 Mw/cm²	100 Mw/cm²	1000 Mw/cm²
Crystal Length	30 mm	30 mm	40 mm
Beam Divergence	1 mr	0.8 mr	0.2 mr
Pulse Width	40 ns	18 ns	0.25 ns
Rep. Rate	10 Hz	10 Hz	5 Hz
Efficiency	40%	50%	70%

For multimode beam, the efficiency is only 20 to 30% under similar conditions.

CW radiation tunable from 257 to 357 nm has been obtained, using a Rh6G laser, by extracavity SFM in angle tuned crystals of KDP, ADP, ADA and rubidium dihydrogen phosphate.[24] Given the output powers available from Rh6G and ion lasers, this technique provides output powers $\gtrsim 0.1$ mW over much of this tuning range. Tunable radiation at ~ 247 nm has been generated by mixing the 413 nm line from a krypton ion laser with radiation from a Rh6G laser in a temperature tuned ADP crystal. UV output powers of ~ 1 mW were obtained,[25] much greater than could be realized by extracavity SHG using a Coumarin dye laser. Radiation tunable from 211 to 215 nm has been obtained by mixing, in KB5, the output of a Rh6G laser with the 334.5 nm line of an argon ion laser.[26] Radiation extending to about 233 nm can be produced by mixing with other UV argon ion laser lines. Although the conversion efficiencies are low, they are sufficient to provide output powers of $\sim 50-100$ nanowatt.

Significant increases in output power can be obtained by use of intracavity SFM, the mixing crystal being located either in the primary laser cavity itself[27] or in an external, frequency-locked passive ring cavity.[28] Although these techniques have not, as yet, been widely applied, intracavity SFM in a temperature tuned ADP crystal has already been exploited to provide several milliwatts of UV power in the range of 254 to 268 nm.

Summary

As is evident from the foregoing discussion, tunable radiation can be obtained over an extended range of UV wavelengths by use of SHG and SFM techniques. Frequently a given pump laser/dye laser combination will afford a number of options as regards generation of a particular UV wavelength. In selecting which option to adopt several factors must be considered including:

i) the conversion efficiencies that can be realized in existing non-linear materials[29] either using SHG or using SFM with different possible combinations of input wavelengths,

ii) the efficiency of utilization of the output(s) of the pump laser, and

iii) the efficiency of the dye laser.

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