August 16, 2002

Application Note:

Generation of four wavelengths from a Nd:YAG laser through the non-linear process.

Nd:YAG laser operating at 1064nm is very versatile and well engineered for generation of four different wavelengths because of the ability to generate high peak powers. This is a requirement for the non-linear process to occur.

For generation of second harmonic of 1064nm, there are many non-linear crystals, which may be used. These can be further divided into two types depending on phasematching condition whether type I or type II. Typically this depends upon the crystal symmetry and how the optic axis is oriented with respect to the input plane of polarization of the laser.

Type I crystals:

1) KD*P Type I angle 36.8° (250mW/cm^2)
2) CD*A Type I angle 81° (250mW/cm^2)
3) LBO Type I angle 11.8° (4Gw/cm^2)
4) BBO Type I angle 22.3° (2Gw/cm^2)
5) $LiI0_3$ Type I angle 30° (100mW/cm^2)
6) $KNb0_3$ Type I poor damage (_____)

Useful for cW diode lasers.

The above damage threshold is for 1ns pulse width at 1064nm. It is important to note that the damage threshold is dependent upon the polishing techniques and the cleaning methods as well as the assembly procedure of the cell.

Type II crystals:

1) KD*P Type II angle 53.5° (250mW/cm^2)
2) KTP Type II angle 24° (1GW/cm^2)
   (This is KTP (H) Hydrolhermally grown)
3) KTP (flux grown) Type II angle 23° (500mW/cm^2)
   Flux grown has low damage and slightly different phase matching angle
4) $LiIO_3$ Type II low efficiency & low damage.

The best type I crystal is LBO temp phase matched at 75° with a phase matching angle of around 9.1° max size available is 15x15x20mm in flux grown material 50 to 60% efficiencies are obtainable at 250mW/cm^2 (1ns pulse width). BBO is the second best and can handle average powers of 100 Watts, generating 37 watts of average green power. LBO has generated about 50 watts of green. It must be operated at 75°C (at elevated temps for best performance). LBO is the most durable SHG crystal, available commercially and as much as seven times more damage resistant than KTP (H) crystal. Diode pumping has made high repetition rates and higher average power operation practical for Nd:YAG laser. CD*A thermally detunes above 5 watts of average power and KD*P around 20 watts average power. Therefore, these crystals must be operated above 60°C for stable SHG performance. Lithium Iodates is good up to 1.5 watt average power at 532nm (intracavity) and KTP up to 3.5 watts. Crystal KTP suffers from photorefractive damage. KTP (H) is better than KTP (F) material. Each material has limitations and the parameters need to be studied before any SHG

experiment. Recent flux grown material KTP is more resistant to gray track damage. The advantage of flux grown KTP is that it is less expensive and GTR grade (gray track resistant) has a damage threshold of 400 mW/cm^2 for 10ns pulse width. It is tested for practically zero laser induced absorption after exposure to 10,000 shots of 3J, 20ns, SHG pulses at rep rates of 20 Hz. Under these conditions, other KTP grades suffer from laser induced absorption.

Type I LBO is always better since there is practically no beam walk-off. Type II KTP produces beam walk-off and some compensation techniques are required for tripling or mixing processes. LBO is again an excellent crystal for CW modelocked and A/O Q-Switched system. Maximum efficiency is about 30%, i.e. with about 18 watts input @ 1064nm; about 5 watt output @ 532 is obtained.

KTP is a hard crystal and non-hygroscopic and the AR coating is very well perfected with double V coat. All other crystals are basically water-soluble or slightly affected by moisture (LBO and BBO). ADP, KDP type crystals can only be coated with a single layer MgF_2 type coating with a damage threshold of about 100 mW/cm^2 at 10ns pulse width, for LBO and BBO, the problem is further complicated by the peculiar property of X_x and X_y and X_z, the temperature coefficient of expansion. X_x is nine times that of X_z and depositing chemicals with proper indices of refraction are not available. So when LBO and BBO are heated at 200°C in a vacuum chamber, the material film does not adhere to the crystal surface with the consequence that the film forms a wrinkle on cooling the crystal.

In effect, the AR coatings of good quality with high damage are not available. If the coating has a lower damage than the crystal, then it produces crystal failure. Both LBO and BBO have very high damage than any coating material or index matching fluid, so careful thought has to be given to the experimental parameters. Both LBO and BBO have an index of 1.6 and the surface reflection is about 6% per surface. For reliability and longevity of the crystal, the crystals may be continuously heated to 60°C without windows and without AR coatings and accept a loss of 12% and obtain 30 to 40% efficiency in the SHG experiment.

The damage of LBO and BBO also depends upon the polishing techniques, cleaning techniques and storing immediately after polish. If iron oxide is used in polishing, a small residue of iron on the surface may cause catastrophic failure. Again any trace of moisture on the surface may reduce the damage threshold.

Regarding AR coatings, which are perfected on fused quartz or BK7 or KTP crystals, the damage threshold is 4 Gw/cm^2 (1ns pulse width at 1064nm). The damage threshold of AR coatings is lower at 755nm and is 1 Gw/cm^2 (1ns pulse width). Bulk peak damage of fused silica is more than 5 Gw/cm^2 and energy damage is $10J/cm^2$. Good AR coatings depends upon index match. Since KTP has index higher than fused quartz, AR coatings on KTP have R less than 0.1%, the same coating on quartz produce R of 0.25%. Single layer MgF_2 coating or polycoating has an R of about 1%. Polycoat is a proprietory vacuum coating

developed by Quantum Technology and has a very high damage of 27Gw/cm^2 peak irradiance at 16.7 picosecond pulse width or 0.78 J/cm^2 peak fluence damage. This is the highest damage of any coating available. However, it does not match the coefficients of expansion of BBO crystal. It is not a serious problem because deposition is carried out at room temperature in a sputter-free boat of molybdenum. It must be stressed that excellent vacuum is required and the rate of deposition must be properly controlled. The thickness is controlled by monitoring the optical intensity of the insitu reflection during the process. These coatings of MgF_2 or polymer material are soft and can be easily damaged if the crystal faces are not handled properly.

Some of these crystals are used for autocorelation at 1064nm, where picosecond or femtosecond pulses are used to produce SHG and two outputs are compared. For this work, BBO, $LiI0_3$ and KDP are often used. Since the group velocity dispersion is highest in BBO and lowest in KDP, for 100 femtosecond pulse separation, the thickness of BBO is about 0.5mm and that of KDP is about 0.1mm. These are the thinnest unsupported thickness that can be fabricated. For 50 femtosecond separation, 0.25mm and 0.05mm thickness is required and these thin crystals are glued on a fused quartz window with UV curing cement. The next wavelength that can be generated is 355nm by mixing

This is called sum frequency mixing or SFM or simply tripling.

Monolithic tripler is a proprietory Nd:YAG tripler where CD*A Type I (angle 81°) is used as a doubler and Type II (angle 58.5°) is used as a tripler. These two crystals are housed in one cell. This is a refreshingly new solution to the problem of adjusting two separate cells, one for the doubler and other for the tripler. By placing two crystals in one cell, there is a saving of cost of two windows and one cell. The turning for optimum efficiency is much simpler because the sensitive axis of the doubler during generation of 532nm is in the plane of the insensitive axis of the tripler. The 40% doubler energy is mixed with 60% of the fundamental energy, with 150 mJ at 1064 is mixed with 60 mJ at 532nm to produce 30 to 40 mj per pulse at 355nm, under optimum tuning conditions. For stable output, it is recommended that the monolithic tripler be operated at about 40° to 50°C with somewhat different tuning angles.

For higher energy per pulse, LBO type I (angle 11.8°) and BBO (Type II 39° angle) are recommended. They can also be mounted in a monolithic tripler configuration. These two crystals have higher damage threshold and are more efficient, LBO is twice more non-linear as compared to CD*A and BBO is four times better than KD*P in non-linearity. These crystals can handle 600 mj per pulse, 10 nanosec at 10 Hz. NASA has used BBO to produce 1 joule/pulse at 532nm from a 1.8 joule/pulse at 1064nm from 1 cm diameter Nd:YAG rod.

The problem with KTP is that it is only Type II phasematchable at 1064nm and there is beam jogging. There are two 1064nm at the output and the beam is

elliptically polarized. One component has to be eliminated by a phase plate in order to use the second component at 1064nm to be mixed with a linearly polarized 532nm to get the tripler output at 355nm. So monolithic configuration is not available.

BBO and LBO crystals are grown by flux method and for tripler application, crystals need to be selected UV grade material and energies greater than 100 mj per pulse (UV) can damage the BBO. Recently a new crystal CLBO is available for tripling, and Quadrupling. However, it is very hygrocopic, although it has better UV transmission.

Quantum Technology has also a monolithic quadrupler where CD*A (Type I angle 81°) and KD*P Type I angle 90° is housed in one cell. With 160 mJ per pulse at 1064nm, 150mJ/per pulse at 266nm can be generated. For higher energy levels, LBO Type I (angle 11.8°) and BBO (Type I angle 47.6°) is used in one cell and 50-60 mJ at 266nm can be generated without damage.

The process of generating fifth harmonic at 212.8nm can be achieved with higher efficiency using 4 + 1 in a BBO crystal Type I at 51.5° angle. This can also be achieved by mixing 3 + 2 in a BBO Type I crystal with angle of 69.3°. This process is less efficient, since the energies in 3 + 2 are lower than 4 +1 process. Cell for generation of fifth harmonic will be a separate cell with a monolithic quadrupler cell.

The technology of UV generation at 212.8nm, 266nm and 355nm is made possible by development of crystals of LBO and BBO. These crystals have damage of 2GW/cm^2 (BBO) and 4GW/cm^2 (LBO) at 1064nm at 1ns pulse width. UV damage is lower by a factor of ten at 355nm upto 10 mj per pulse is possible at 212.8nm and 30 mj per pulse at 266nm is practical without UV damage, 212.8nm is very close to the transmission limit of BBO crystal (200nm). Below 210nm the absorption is around 5% per cm with unstable resonator Q-Switched Nd:YAG laser, 600mj per pulse at 1064 produces 350 mj per pulse at 532nm, 140 mj per pulse at 266nm and 70 mj per pulse at 212.6nm. In KD*P, much lower energies are obtained, typically 270 mj per pulse at 532nm, 113 mj at 266nm and 45 mj per pulse at 212.6nm.

BBO crystal has a very small angular acceptance (about 10% of KD*P), and very wide temperature acceptance width (about 10 times better than KD*P and 15 times greater than KTP.) The non-linear coefficient of BBO (d_{22}) is 4.1 times that (d_{36}) of KD*P. This makes the effective figure of merit 3 to 14 times that of KD*P for SHG. The crystal LBO is not phase matchable below 555nm Type I and is not practical for any UV generation while Type II BBO phasematching is not practical below 525nm. However, Type I BBO is more efficient as well than Type II BBO. The effective figure of merit (F_{eff}) takes into account the effects of beam divergence E $(\Delta\partial.L)^2$, and at 1064nm KD*P Type II (eo-e interaction) it is 2.3 times larger than Type I (oo-e interaction). In all these non-linear process, the

beam divergence of the pump beam must be taken into account as it has a marked effect on the process. The largest size BBO available is around $15x15x15mm^3$ while KD*P is around $50x50x50mm^3$.