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OPTICAL PARAMETRIC OSCILLATORS :

The frequency conversion processes include **Sum Frequency Generation (SFG), Difference Frequency Generation (DFG) and Optical Parametric Generation (OPG).** Frequency doubling or **Second Harmonic Generation (SHG)** is a special case of **SFG**. The three processes are shown in the following equations.

1. Sum Frequency Generation (SFG).

$$\omega_1 + \omega_2 = \omega_3$$

It combines two low energy photons into one high energy photon (Fig 1). It is a passive device.

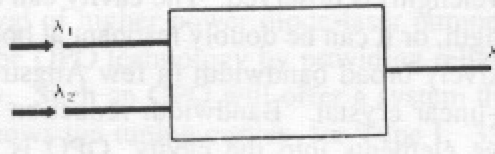

Fig. 1. SFG and DFG

SFG occurs only when a strong external electric field (E >>1 KV/cm) induces an appreciable non-linear response in a crystalline medium. Or in terms of wavelengths, it is expressed as:

$$\frac{1}{\lambda 1} + \frac{1}{\lambda 2} = \frac{1}{\lambda 3} \quad \text{and if } \lambda_1 = \lambda_2, \text{ then } \lambda_3 = \frac{\lambda_1}{2} = \frac{\lambda_2}{2} \text{ for SHG.}$$

Tripling is also a special case of SFG. If $\lambda_1 = 1064$nm, $\lambda_2 = 532$nm, then $\lambda_3 = 355$nm

2. Difference Frequency Generation (DFG).

$$\omega_1 - \omega_2 = \omega_3$$

It combines one high energy photon and one low energy photon into another low energy photon (Fig 1). Or if expressed in wavelengths

$$\frac{1}{\lambda 1} - \frac{1}{\lambda 2} = \frac{1}{\lambda 3}$$

As an example: $\lambda_1 = 532$nm, $\lambda_2 = 810$nm, $\frac{1}{532} - \frac{1}{810} = \frac{1}{\lambda 3}$ or $\lambda_3 = 1550$nm

3. Optical Parametric Generation (OPG).

This process is the inverse of SFG in which two photons are created. One is called signal (ω_s) photon and the second is called idler (ω_i) photon, both created from one pump photon (ω_p) (Fig 2 and 3). The signal and idler frequencies obey the energy-conservation condition.

$$\omega_p = \omega_s + \omega_i$$

A specific phase relationship between the waves must also be maintained throughout the entire crystal length. If the relative phases slip, then SFG will take over, reversing the process. This phase-matching condition is equivalent to the condition of conservation of momentum for three waves, expressed as

$$K_p = K_s + K_i$$

where K is the momentum vector of a wave. Because the relationship between photon momentum and photon energy depends upon the refractive index of the crystal, both conditions can be met simultaneously by manipulating the refractive index. This is usually done in birefringent crystals, by setting the wave polarizations and crystal orientation angle or temperature to establish the phase matching condition. Tunable radiation is then achieved by changing the angle, temperature or the electric field across the crystal to modulate the effective refractive index.

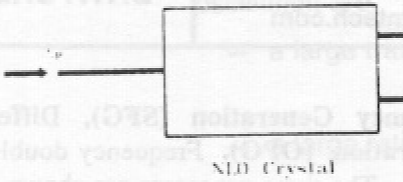

Fig. 2. Optical Parametric Generation

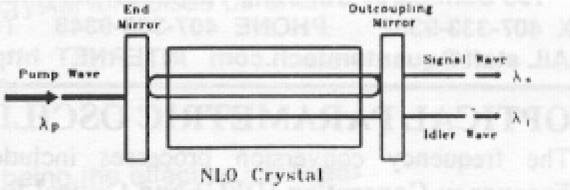

Fig.3 . Optical Parametric Oscillator

If the crystal is placed between two mirrors to form a resonant cavity, then Optical Parametric Oscillation (OPO) is established, and feedback causes gain in the parametric waves similar to build-up in a laser cavity. Thus, output of radiation at the resonated signal wavelength (and the simultaneously produced idler wavelength) is observed. The cavity can either be singly resonant at either the signal or idler wavelength, or it can be doubly resonant at both wavelengths.

A simple OPO will exhibit a relatively broad bandwidth (a few Angstroms) determined by the bandwidth acceptance of the non-linear crystal. Bandwidth reduction can be achieved by the introduction of frequency selective elements into the cavity. OPO is an excellent source for generating wide tunable range coherent radiation.

In general, pulsed lasers are used to pump parametric oscillators, and the gain is sufficient to obtain oscillation with the singly resonant oscillator (where only one of the generated waves is resonant).

Improved Materials:

During the last ten years, the range of new OPO materials has increased dramatically. These materials collectively provide good coverage of the entire wavelength region from the IR (to 15 micron) to the blue (to 410 nm). The parametric tuning range in a given crystal is determined by the pump wavelength, the transparency of the crystal and the range over which phase-matching is possible.

The table I lists the properties of usable Non-Linear Optical (NLO) crystals for OPOs.

Properties of nonlinear materials for OPOs

Material	Transmission range (μm)	Phase-matching range (μm) 0.266-μm pump	0.355-μm pump	0.532-μm pump	1.064-μm pump	2.05-μm pump	Nonlinear figure of merit, $C^2(GW)^{-1}$	Optical damage threshold (GW/cm^2)
BBO (BaB_2O_4)	0.190–2.6	0.3–2.5	0.41–2.5	0.67–2.5			40	~1.5
LBO (LiB_3O_5)	0.16–2.6	0.3–0.41 0.75–2.5	0.41–2.5	0.67–2.5	–	–	5.4	~2.0
KNB ($KNbO_3$)	0.35–4.2	–	–	0.61–4.2	1.43–4.2		44	~1.2
KTP ($KTiOPO_4$)	0.35–4.0	–	–	0.61–4.0	1.45–4.0	–	45	~1.5
LNB ($LiNbO_3$)	0.35–4.3	–	–	0.61–4.3	1.42–4.3	–	15	~0.20
$AgGaS_2$	0.8–9.0	–	–	–	1.2–9.0	2.6–9.0	75	~0.040
$AgGaSe_2$	1.0–15				–	2.4–15	100	~0.040
$ZnGeP_2$	2.0–8.0	–	–	–	–	2.7–8	270	~0.050

Crystal BBO Optical Parametric Oscillator :

The OPO performance can be easily related to NLO coefficient or figure of merit, c^2. The single pass optical gain (g) in the NLO crystal is given by:

$$g = \sqrt{c^2 L^2 Ip}$$

where L = crystal length

Ip = Intensity of pump

The gain mechanism is based upon the stimulation of emission process. The rate of emission through the NLO parametric process is proportional to the photons present. OPO is an inverse process of SFM.

BBO, KTP, LBO, and $AgGaSe_2$ are good NLO crystals for achieving efficiencies greater than 30% to 40%. The arrival of higher power diode-laser pumped, solid-state lasers (used as pump sources) will advance the OPO technology by providing reliability, compact size, high repetition rate and high efficiency. Such an OPO will offer a system that is broadly tunable, narrow-band and efficient. Fig. 4 shows the tuning curves for Type I, 355 nm pumped BBO OPO. Fig. 5 shows a typical OPO experimental set-up.

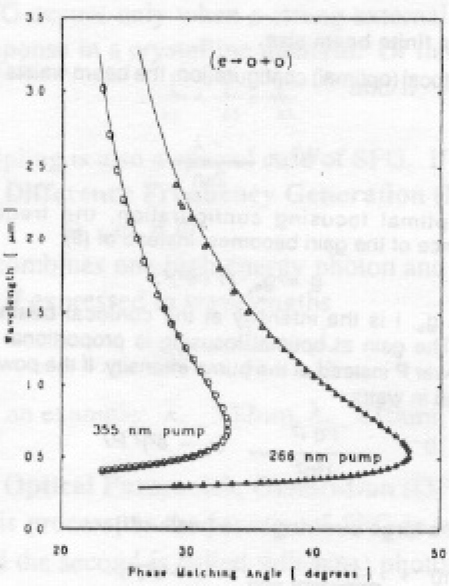

Fig.4 Tuning curves for Type 1 BBO in OPO

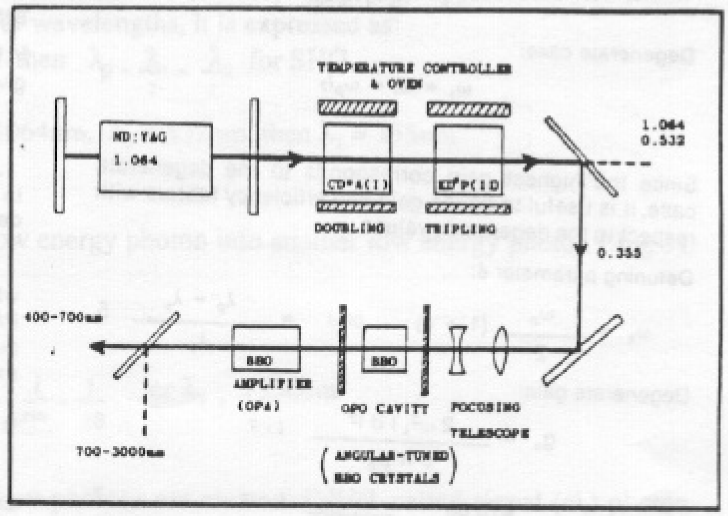

Fig.5 Typical experimental setup for OPO

References:

1. Tang C.L. et. al. Proc. IEEE Vol. 80 No. 3 March 1992 pp. 365-374
2. Bosenburg W. et. al. Laser Focus World May 1992 pp. 165-170
3. Spence D.E. and Tang C.L. IEEE J of Q.E. Vol. 1 No. 1 April 1995 pp. 31-43

The qualities required from a crystal for pulsed parametric oscillation are:

- a large transparency range;
- a large ratio $\frac{|d^2|}{n^3}$ (d being the effective nonlinear coefficient and n the index of refraction);
- phase matchable;
- a good resistance to optical damage.

USEFUL FORMULAE.

Resonance and phase matching conditions:

$$\omega_p = \omega_s + \omega_i \qquad 1.$$

$$\frac{\omega_p}{n(\omega_p)} = \frac{\omega_s}{n(\omega_s)} + \frac{\omega_i}{n(\omega_i)} \qquad 2.$$

Gain for a length ℓ:

$$g = \frac{2\,\omega_s\,\omega_i\,|d|^2\,I\,\ell^2}{n_s\,n_i\,n_p\,\varepsilon_0 c^3} \qquad 3.$$

Degenerate case:

$$\omega_s = \omega_i = \omega_p/2 \qquad 4.$$

Since the highest gain corresponds to the degenerate case, it is useful to define gain and efficiency factors with respect to the degenerate values.

Detuning parameter δ:

$$\omega_s = \frac{\omega_p}{2}(1+\delta) \quad \text{or } \delta = \frac{\lambda_p - \lambda_s}{\lambda_s} \qquad 5.$$

Degenerate gain:

$$g_0 = \frac{2\,\omega^2_s\,|d|^2}{c^3 n^3_s \varepsilon_0}\,I\,\ell^2 \qquad 6.$$

$$= 0.03\,\frac{|d|^2}{\lambda^2_s n^3_s}\,I\,\ell^2 \qquad 7.$$

In Eq. (7), the effective nonlinear coefficient (for the particular crystal orientation of interest) d is in 10^{12}m/V; the pump intensity I in MW/cm^2, the signal wavelength λ_s in μm, and the length ℓ in cm.

If the nonlinear coefficient of KDP (d_{KDP}) is taken as reference:

$$g_0 = 0.015\,\frac{(d/d_{KDP})^2}{\lambda^2_s n^3_s}\,I\,\ell^2 \qquad 8.$$

As the signal frequency is tuned away from degeneracy, the gain decreases according to:

$$g \cong (1-\delta^2)\,g_0 \qquad 9.$$

Effect of a finite beam size.

In the confocal (optimal) configuration, the beam waists W are given by:

$$W^2 = \frac{\ell\,\lambda}{2\pi n} \qquad 10.$$

In the optimal focusing configuration, the frequency dependence of the gain becomes, instead of (9):

$$g = g_0 \cdot (1-\delta^2)^2, \qquad 11.$$

where in g_0, I is the intensity at the confocal beam waist $P/\pi W_0^2$. The gain at optimal focusing is proportional to the pump power P instead of the pump intensity. If the power P is expressed in watts:

$$g = 6\cdot 10^{-4}\,\frac{|d|^2}{\lambda^3 n^2}\,(\ell-\delta^2)^2\,P\,\ell \qquad 12.$$

Effect of a large birefringence [walk-off].

$$g \cong 3\cdot 10^{-8}\,\frac{|d|^2}{\lambda_0^2 n_0^2 n_p}\,\frac{P}{\rho^2}\,(1-\delta^2)^2, \qquad 13.$$

where ρ is the walk-off angle (in radians), P the power in watts, and the subscript $_0$ applies to the degenerate frequency $\omega_p/2$.