Module 2 : Nonlinear Frequency Mixing

Lecture 14 : Frequency Conversion Devices

Objectives

In this lecture we will look at

Some example of frequency conversion devices:

- Lasers for laser plasma interaction research.
- Frequency doubling of diode laser using periodically poled crystals.
- Optical parametric oscillator(OPO).

Nonlinear optical frequency conversion is the oldest and the most enduring application of nonlinear optics. By now, many such devices are commercially available. We have seen in earlier chapters that very high conversion efficiencies are theoretically expected in phase matched or quasi-phase matched nonlinear optical wave propagation. In this lecture we describe some of the landmark experiments with a view to illustrate the main design criteria for various devices

1. **Frequency conversion of high power lasers for fusion research:**
   In late 1970's it became clear that it would be advantageous to use short wavelength lasers for laser-plasma research. A novel scheme was devised by Craxton (Optics Com 34, 474 (1980)) and demonstrated by Seka et al. in 1980 (Optics Com 34, 469 (1981)). In this scheme, shown schematically in Figure 14.1, the third harmonic of a high power Nd: glass laser was generated in two steps. In the first step about 2/3 of the incident power in the Nd:glass laser was converted into second harmonic. In the second step, the remaining power in the ω-wave was combined with the generated 2ω-wave to produce 3ω-wave. In the second step of THG by SFG of ω and 2ω beam the Manley Rowe relations tell us that the third harmonic power is limited by the beam with the smaller number of photons. To avoid this limitation one requires equal number of photons in the ω and 2ω waves. To achieve this, Seta et al used type II phase matched SHG in step one such that the number of photon generated in the second harmonic were nearly the same as those remaining in the fundamental. As already discussed in the previous lectures Type 2 phase matched SHG is described by a 3 wave mixing process.

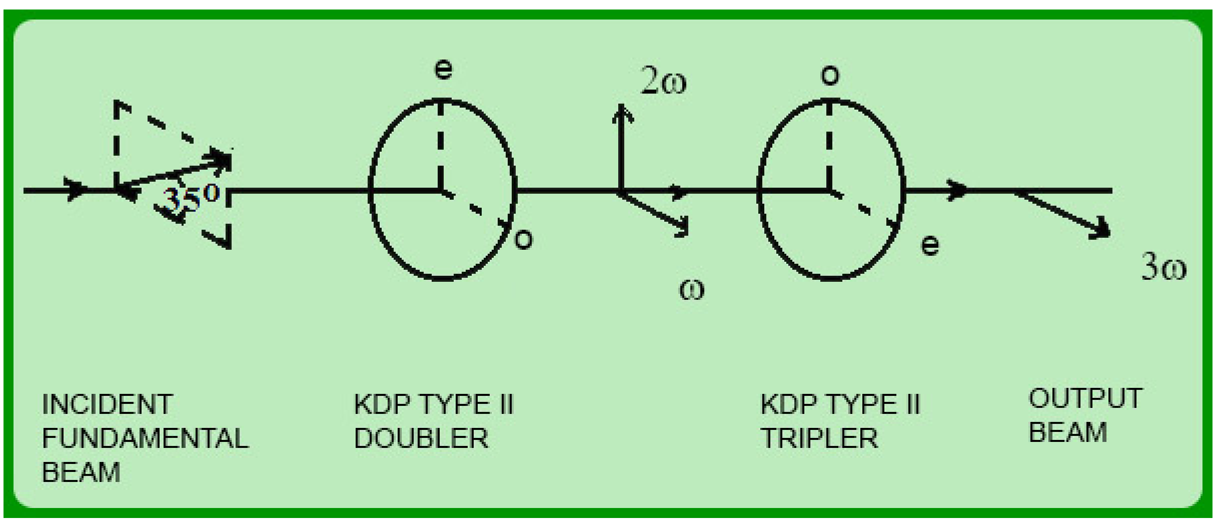

Figure 14.1 Polarization configuration used by Seka etal for high efficiency Third Harmonic generation of a high power Nd:glass laser

In type II phase matching for SHG generally the fundamental beam is polarized at 45° to the direction for o-wave i.e. the incident wave energy is equally divided between the ordinary and the extra ordinary waves. (In this case the number of photons in the two fundamental waves is equal, and) a second harmonic photon is produced using one for each of the two fundamental beams and since the number of photons is equal they deplete equally. The phase matching angle for type II phase matching is 59°, compared to 41° for type I phase matching. So the walk off angle is slightly smaller. To minimize the refractivity losses, the crystal is cut so that the incident/output beams enter/exit the crystal at normal incidence. In principle one could first divide the incident laser in two parts – convert one into SH and then mix the SH with the fundamental in the second crystal. But this requires several beam splitters and plane reflectors. Instead Seka et al. made the polarization of the incident beam at an angle of 35°

to the direction polarization required for o-ray. So the incident fundamental wave has an amplitude $E_0 \mathrm{Cos}\ 35°$ for the ordinary wave and $E_0 \mathrm{Sin}\ 35°$ for the e-wave. Corresponding ratio of photons in the two components is $\frac{N_o}{N_e} \approx \mathrm{Cot}^2\ 35° = 2.0396$, where we assume that the reflectivity for the two waves is nearly the same.

If the crystal is oriented to obtain type II phase matching e + o → e, the maximum conversion would occur in a crystal length *l* which can be calculated as follows

Let the incident wave be linearly polarized at an angle α ≤ 45° to the polarization direction for the ordinary wave. Then, initial values of the three amplitudes are

$$v_p^2 = 0,\ v_s^2 = \cos^2 \alpha, v_i^2 = \sin^2 \alpha$$

Using equation (12.4), this gives Γ = 0

The three roots of equation (12.7) are:

$$v_{pa}^2 = 0,\ v_{pb}^2 = 2\sin^2 \alpha, v_{pc}^2 = 2\cos^2 \alpha \qquad (14.1)$$

Then $\gamma = \tan \alpha$

Thus from equation (14.1) we get the result that a fraction $2\ \mathrm{Sin}^2\alpha$ of the initial power will be converted to the second harmonic wave after a normalized distance ζ= K (γ), where K is the quarter period of the Jacobi elliptic function sn (u, γ). So, for $\mathrm{Sin}^2\alpha = 1/3$, two third of the fundamental wave will be converted to second harmonic and it will be polarized as the e-wave.

At the start of the second crystal, which is phase matched for the conversion process 2ω (o) + ω (e) → 3 ω (e) i. e. ordinary wave photon of second harmonic combining with extraordinary wave photon of fundamental wave to produce an extra ordinary wave photon at the third harmonic. For plane waves in this scheme full conversion is possible from fundamental wave to the third harmonic. Seka et al. obtained 80 % conversion to the third harmonic after correcting for reflection losses. The other factors limiting the conversion to 80 % are mostly because of the averaging over the spatial and temporal profile of the incident pulse.

2. **High efficiency second harmonic generation of a diode laser:**
   The low power available in semiconductor diode lasers makes it challenging to generate second harmonic with substantial conversion efficiency. Several ideas were needed to overcome these challenges. Some of the possibilities are:

- Use waveguide mode for propagation to keep the beam to increase the interaction length over which the intensity remains large.
- Use the crystal inside the resonant cavity of the laser whose frequency is to be doubled.
- Enhance the effective intensity by performing the conversion inside a separate resonator cavity.

use quasi-phase-matching and periodically poled crystal so that the largest available component of $\chi^{(2)}$ can be used

In one such experiment Le Targat et al(Optics Comm 247, 471(2005)) were able to convert a MOPA(master oscillator power amplifier) diode laser at 922 nm with 75% efficiency to second harmonic with source at 461 nm for laser cooling of Sr atoms.

Their experimental set up is shown schematically in the Figure 14.2. The frequency conversion was performed in a resonant ring cavity formed by 4 mirrors M1,M2,M3 and M4. Fine adjustments could be made to the position of the mirror M2 which was mounted on a piezo-drive. The inner surface of mirror M1 was partially reflecting while M2 and M3 were highly coated for high reflectivity for the fundamental wave at 922nm. The mirror M4 was coated for reflectivity >99.9% at 922nm and transmission~98% at the second harmonic at 461nm. The second surfaces of all the four mirrors were antireflection coated at both wave lengths. The crystal periodically poled KTP was also similarly antireflection coated at both the wavelengths and it was periodically poled with a period 5.5 µm. The phase matching temperature was ~30°C and once optimized it was maintained to $\pm 10\mathrm{mK}$. The length of the crystal was 20 mm. The curvature (not shown in figure) the mirrors was designed to produce an optimally focused beams at the crystal.

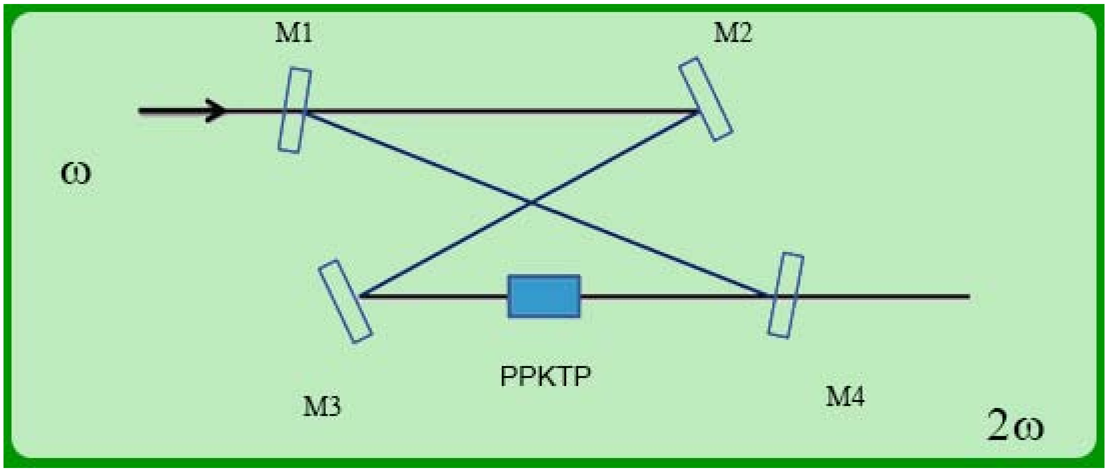

Figure 14.2 Schematic arrangement used by Le Taragat et al for high efficiency second harmonic generation

An alternative method is to enhance the intensity by tighter focusing and using a waveguide to maintain the size of the beams. For example, Jeckow et al (Optics letters 32,3035(2007)) obtained a conversion efficiency of 52% in a periodically poled waveguide of $LiNbO_3$. The waveguide cross-section was $3\mu m \times 5\mu m$ and the length was 10mm.

3. **Optical Parametric Oscillators**

Finally, we look at a recent paper describing a high repetition rate pulsed (10KHz, 17.8ns) OPO exploiting Periodically poled MgO doped $LiNbO_3$. The experimental setup used in this experiment by Dixit et al [Optics & Laser Technology **42**,18 (2010)] sketched in Figure 14.3. They used a relatively long nonlinear crystal with length 50mm with multiple periodically poled gratings with periods ranging from 26.5µm to 30.5µm. The spot size at the crystal was ~500 µm which implies a relatively loose focusing. This is necessary in view of the large crystal length. The input laser was focused using a lens to match the beam with mode size in the resonator. The radii of curvature of the two mirrors was 200 mm and the distance between them was 140 mm. The input coupler mirror M1 was coated to have a high transmission (>90%) for the 1.064mm pump laser.

(Nd:YVO 4) and high reflectivity (~97%) for the signal wave in the entire range 1.37–1.64 µm. The output mirror M2 was partially transmitting (50–75%) for the signal and high transmission for both pump & idler waves. The temperature of the crystal could be varied for fine tuning and it was moved across the laser beam to bring different periods into play. In this way broad coverage of spectrum between 1.37 to 1.64µm and from 3 to 4.8µm could be obtained

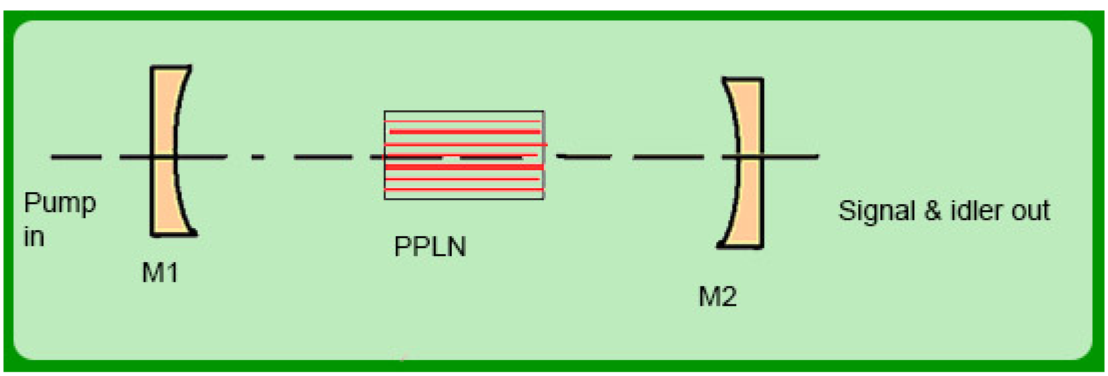

Figure 14.3 OPO configuration used by Dixit et al [Optics & Laser Technology 42,18 (2010)]Further improvements could be obtained by antireflection coatings on the crystal

The variety of nonlinear optical frequency conversion devices is really limitless. This lecture only highlights some aspects that go into designing such devices.

RECAP:

Three examples of high efficiency nonlinear frequency conversion are presented

- Third harmonic generation of high power pulsed lasers for fusion research.
- Cw diode laser second harmonic generation using PPKTP crystal.
- Nanosecond pulsed OPO using a multigrating PPLN crystal covering a broad range.