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Narrow linewidth pulsed optical parametric oscillator

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Abstract. Tunable narrow linewidth radiation by optical parametric oscillation has many applications, particularly in spectroscopic investigation. In this paper, different techniques such as injection seeding, use of spectral selecting element like grating, grating and etalon in combination, grazing angle of incidence, entangled cavity configuration and type-II phase matching have been discussed for generating tunable narrow linewidth radiation by singly resonant optical parametric oscillation process.

Keywords. Optical parametric oscillator; tunable laser; narrow linewidth radiation; optical frequency conversion.

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1. Introduction

Optical frequency mixing techniques (i.e. sum frequency mixing, difference frequency mixing (DFM) and optical parametric oscillation (OPO)) are now well-established techniques for generating tunable coherent radiation in the spectral range where lasers perform poorly or not available. Since the first demonstration of OPO in 1965 by Giordmaine and Miller [1] using a $LiNbO_3$ crystal, the development of OPO was restricted because of the non-availability of suitable crystal and also because of high laser damage threshold coating on mirror as well as on crystal. Now-a-days with the development of coating technology and with the availability of good optical quality crystals having high damage threshold and deep infrared (IR) transparency it is possible to extend the tunability of the OPO. Particularly, we have to mention that the development of periodically poled crystal has revolutionized the OPO technology and there has been a lot of progress made on OPO technology and OPOs are now commercially available. OPOs can generate tunable radiation from UV to far-infrared. OPOs are generally used for long wavelength generation, which can also be generated through DFM process. But OPO is preferred to DFM as it is more user-friendly than DFM because OPO process requires one pump source (which is generally a solid-state laser) whereas in DFM two pump sources are required (one of which should be tunable laser like dye laser). Handling

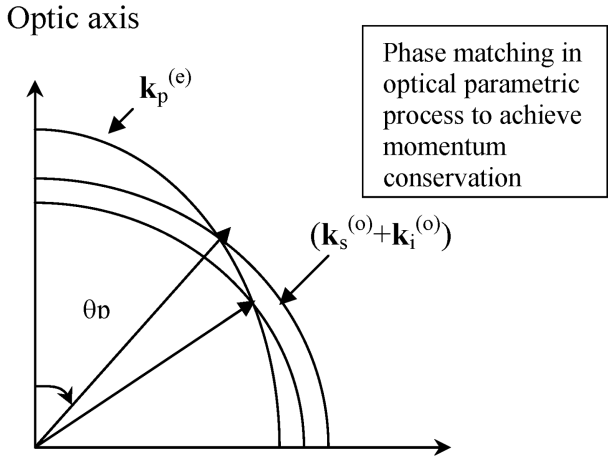

Figure 1. Use of birefringence to offset the material dispersion. Rotating the crystal relative to the direction of propagation of the waves leads to tuning of the frequencies of the signal and idler waves. $\theta_{\rm p}$ is the phase-matched angle.

a system consisting of one laser source is much easier particularly in field application than two laser sources particularly if one of it is a dye laser. As solid-state laser is generally used as a pump source in OPO, it is possible to make an all-solid-state system. Again the conversion efficiency in OPO is much more than that of DFM process, which gives OPO an added advantage over DFM.

2. Factors affecting the linewidth of the generated radiation

The spectral bandwidth of the generated radiation in an optical parametric process is determined by the energy conservation and momentum conservation relation and in a Fabry–Perot-type OPO cavity without any intracavity spectral narrowing elements the spectral bandwidth primarily depends on the linewidth of the pump beam, angular divergence of the pump beam, phase-matched angular acceptance angle, phase matching type, output wavelength, proximity to the degenerate point, number of round trip inside the cavity and crystal length.

Let us consider the case of type-I collinear phase matching in a negative uniaxial crystal. From figure 1 it is clear that the finite beam divergence $\delta\theta_{\rm p}$ of the pump beam will in general lead to a range of $\Delta\mathbf{k}_{\rm p}$ values, which will in turn lead to a range of values for the sum of the propagation vectors of the signal and idler waves $(\mathbf{k}_{\rm s}+\mathbf{k}_{\rm i})$. When the propagation direction of the interacting waves is not along the principal axis of the nonlinear crystal, the linewidth of the signal wave has an order dependence on the beam divergence. For example, in the case of type-I phase matching in a negative uniaxial crystal, the bandwidth of the generated radiation can be determined by the relation given below which is derived from the energy and momentum conservation relation [2].

$$\Delta\omega_{\mathrm{s}} \cong \frac{\omega_{\mathrm{p}}(\partial n_{\mathrm{p}}^{(e)}(\theta)/\partial\theta_{\mathrm{p}})\Delta\theta_{\mathrm{p}}}{[n_{\mathrm{s}} - n_{\mathrm{i}} + (\partial n_{\mathrm{s}}^{(o)}/\partial\omega)\omega_{\mathrm{s}} + (\partial n_{\mathrm{i}}^{(o)}/\partial\omega)\omega_{\mathrm{i}}]}. \tag{1}$$

Under non-critical phase-matching situation, the linewidth arises mainly because of the finite bandwidth of the pump beam and the finite crystal length. But in critical phase-matched condition, a linewidth can be defined in terms of the change in frequency, $\Delta\omega_{1/2}$, from the precise phase matching point to where the phase mismatch over the interaction length L is approximately equal to π [2] or

$$\left[\frac{\partial}{\partial\omega_{\mathrm{s}}}\Delta(k_{\mathrm{p}} - k_{\mathrm{s}} - k_{\mathrm{i}})\right]\Delta\omega_{\mathrm{s}} \cong \frac{\pi}{L} \tag{2}$$

and the corresponding full linewidth is

$$\Delta\omega_{\mathrm{s}} \cong \frac{2\pi c}{L}\left[n_{\mathrm{s}} - n_{\mathrm{i}} + \left(\frac{\partial n_{\mathrm{s}}^{(o)}}{\partial\omega}\right)\omega_{\mathrm{s}} + \left(\frac{\partial n_{\mathrm{i}}^{(o)}}{\partial\omega}\right)\omega_{\mathrm{i}}\right]. \tag{3}$$

Finally the photon energy conservation relation clearly shows that any width in the pump frequency $\Delta\omega_{\mathrm{p}}$ will lead to the corresponding linewidth contribution in the signal frequency $\Delta\omega_{\mathrm{s}}$, which follows the pump beam bandwidth closely. There are a number of mechanisms as stated above that can contribute to the total bandwidth of the parametric process. The principal ones are the pump beam divergence, finite crystal length, the pump beam bandwidth and number of round trips inside the cavity.

3. Techniques of linewidth narrowing

3.1 *Injection seeding*

The spectral linewidth of the generated radiation in an OPO process can be reduced by injection seeding process [3–10]. In this process (figure 2) a very narrow linewidth continuous wave or pulsed source is injected into an oscillator cavity and a few nanojoule of energy or power can control the linewidth of the generated radiation with several millijoule output. The frequency of the injected radiation should (or nearly) match with either the resonating signal or non-resonating idler frequency. With this technique though it is possible to produce very narrow linewidth source but it requires two laser sources which makes the system a little bit bulky and may not be user friendly, particularly in field applications like remote monitoring.

Haub *et al* [3] reported type-I phase-matched BBO OPO tunable from 0.43 μm to 2.3 μm pumped by single third mode 355 nm 3rd harmonic of Nd:YAG (injection seeded) laser radiation and by injection seeding the OPO using pulsed visible dye laser having 0.07 cm^{-1} linewidth, linewidth of the OPO output was reduced to 0.1 cm^{-1}. Fan *et al* [4] also reported BBO OPO pumped by nanosecond pulsed 355 nm, third harmonic of Nd:YAG laser tunable in the spectral range 0.41 μm to 2.55 μm. Through injection seeding at 532 nm the resonant signal wavelength the linewidth was reduced to less than 3 GHz and minimum seeding energy required was 2.5 μJ.

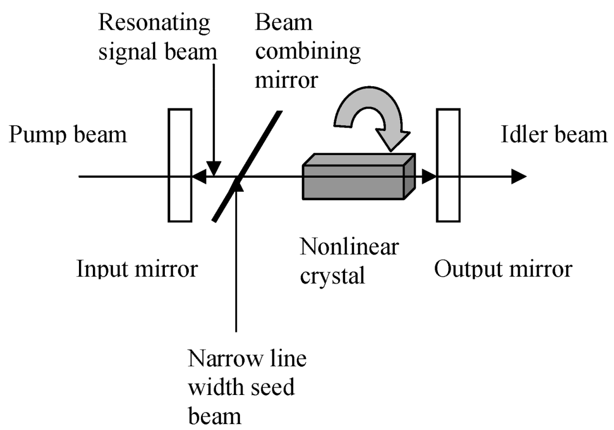

Figure 2. Schematic OPO configuration for narrow linewidth radiation by injection seeding technique.

Barnes *et al* [5] reported narrow linewidth $AgGaSe_2$ OPO pumped by nanosecond Nd:YLF laser at 1.73 μm. The linewidth of the output radiation from free running Fabry–Perot cavity at 3.54 μm was 16 nm at FWHM. It was reduced to 1 nm by injecting 3.39 μm radiation from a CW He–Ne laser. Milton *et al* [7] reported $LiNbO_3$ OPO pumped by an Nd:YAG laser. The OPO was injected with radiation from a grating tuned external cavity tunable diode laser in the signal spectral range 1.49–1.58 μm (linewidth = 150 kHz). The seeded operation using the grating-tuned diode laser was obtained from 1490.6 to 1580.3 nm with a measured linewidth of 135 MHz. Baxter *et al* [9] reported narrow-band PPLN OPO pumped at 1.064 μm from a Q-switched single-mode Nd:YAG laser which was injection seeded by a CW single-mode tunable diode laser tunable from 1.5 to 1.59 μm. The measured linewidth at 1.55 μm was 125 ± 5 MHz (0.0043 cm^{-1}). Srinivasan *et al* [10] also reported narrow bandwidth near-infrared (915–975 nm) KTP optical parametric oscillator and amplifier (OPOA) system. The bandwidth at 960 nm was reduced from the free running mode >100 GHz to less than 150 MHz by using an injection-seeded pump laser (linewidth <8 MHz) and injection seeding the OPO–OPA system by an external cavity diode laser having bandwidth <8 MHz.

Injection-seeded nanosecond optical parametric generator (OPG)-optical parametric amplifier (OPA) was reported by Wu *et al* [11]. Because the OPG-OPA has no cavity modes, it amplifies a whole continuum of frequencies inside its phase-matching acceptance bandwidth, and there is no need of frequency mode matching between the seed and OPG-OPA modes. Pump pulses in this work were provided by the third harmonic from a single longitudinal mode Nd:YAG laser which delivered pulses of 2.5 ns (FWHM) at 355 nm. The OPG-OPA set-up was formed with two walk-off compensated beta-barium borate (BBO) crystal. The OPG-OPA set-up was capable of tuning in the spectral range of 415–2400 nm. But seeding was performed in a much narrower range using a CW single longitudinal mode (SLM) laser with few milliwatt (mW) power tunable around 815 nm. The linewidth of such seeded nanosecond (ns) OPG-OPA was measured to be 650 MHz (0.02 cm^{-1}).

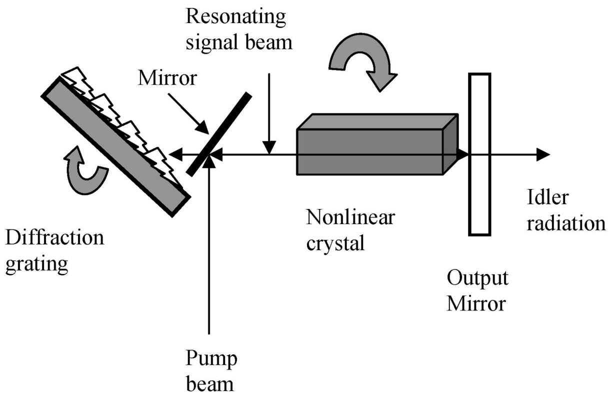

Figure 3. Schematic OPO configuration for narrow linewidth radiation incorporating diffraction grating in the cavity.

3.2 *Intracavity spectral-narrowing element*

Using spectral narrowing elements like diffraction grating in Littrow configuration (figure 3) or Fabry–Perot etalon alone or in combination with grating (figure 4) in the OPO cavity, spectral linewidth of the OPO output can be reduced. By judicial choice of the required number of rulings of the grating, the linewidth of the generated radiation can be reduced to a fraction of centimeter inverse (cm^{-1}). This is perhaps the simplest process in which one of the mirrors of the OPO cavity is replaced with a grating. But for high-resolution spectroscopy sometimes very narrow linewidth radiation is needed and it may not be possible to generate such narrow linewidth radiation using only a grating. Such narrow linewidth radiation can be obtained incorporating a Fabry–Perot etalon alone or along with a grating in combination in the OPO cavity. Though Fabry–Perot etalon in combination with grating produces a very narrow linewidth radiation, this technique requires a very precise alignment of all the optical elements particularly the etalon apart from increasing the threshold of oscillation energy.

Brosnan and Byer [12] achieved linewidth of 0.08 cm^{-1} from a $LiNbO_3$ OPO pumped with Nd:YAG laser using 600 lines/mm grating and the linewidth was reduced further to <0.02 cm^{-1} by introducing a 2 mm thick air-gap Fabry–Perot etalon with the finesse of 7 inside the cavity. Bosenberg *et al* [13] reported OPO in walk-off compensated configuration pumped by 355 nm third harmonic of injection seeded Nd:YAG laser radiation and using a grating having a groove density of 1800 lines/mm in Littman configuration the linewidth of the generated radiation was reduced to 0.3 Å. Raffy *et al* [14] demonstrated $LiNbO_3$ OPO pumped at 930 nm and achieved linewidth of about 0.0009 cm^{-1} at 1650 nm using electrically tunable Fabry–Perot interferometer in the cavity.

Ganikhanov *et al* [15] reported $ZnGeP_2$ OPO pumped by the output of PPLN OPO at 2.55 μm, which was pumped by nanosecond Nd:YAG laser and the achieved linewidth at 4.3 μm and 6.8 μm were 2 cm^{-1} and 3.5 cm^{-1} using diffraction grating having groove density of 240 lines/mm and 120 lines/mm respectively in the cavity. They further reduced the linewidth to 0.12 cm^{-1} and 0.13 cm^{-1} using 2 mm thick

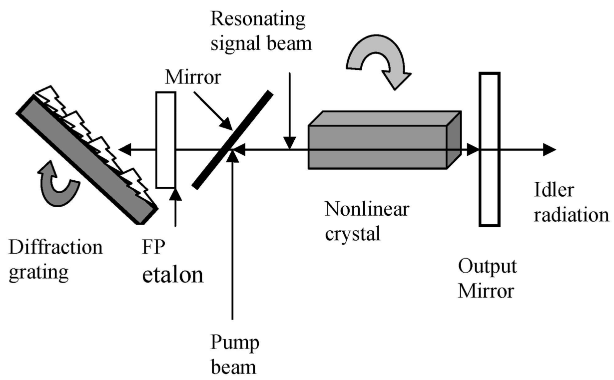

Figure 4. Schematic OPO configuration for narrow linewidth radiation incorporating diffraction grating and Fabry–Perot (FP) etalon in the cavity.

air-spaced Si Fabry–Perot etalon in the cavity though the linewidth of the 2.55 μm pump radiation was about 15 cm^{-1}.

Aniolek *et al* [16] have demonstrated an interesting optical parametric generator (OPG)-optical parametric amplifier (OPA) configuration for getting narrow linewidth radiation. The output of nanosecond Nd:YAG laser pumped PPLN OPG was spectrally filtered through high finesse air-spaced Fabry–Perot etalon and then amplified. The linewidth from the OPG radiation was about 15 cm^{-1}. The spectrally narrowed radiation from the OPG formed a seed to the OPA stage. This spectrally narrowed radiation along with the pump radiation was passed through the PPLN OPA stage and the linewidth of the idler radiation was measured to be 0.05 cm^{-1}.

Recently, Das [17] has demonstrated the KTA OPO in 3–4 μm spectral range pumped by Q-switched Nd:YAG laser and the achieved linewidth of the generated radiation at 3.7 μm is about 0.53 cm^{-1} using a diffraction grating having 600 lines/mm groove density.

3.3 *Grazing angle of incidence configuration*

Grazing angle of incidence technique using a diffraction grating and mirror combination (figure 5) is another process for narrowing the spectral bandwidth of the generated radiation. In this process the cavity length of the OPO system becomes a little bit longer and hence the conversion efficiency is less. Schulp *et al* [18] reported a nanosecond Nd:YAG pumped PPLN OPO and achieved linewidth less than 250 MHz ($\sim$0.01 cm^{-1}) in the spectral range of 1.48–3.82 μm employing angle of incidence of 88.6° using a grating having 900 lines/mm groove density.

Gloster *et al* [19] reported walk-off compensated BBO OPO pumped by third harmonic of Nd:YAG laser radiation having 30 GHz linewidth at grazing angle of incidence configuration. They observed decrease in linewidth of the generated radiation with increasing grating angle. Linewidth of 8.7 GHz was observed at 85° angle of incidence, which was reduced to 5.8 GHz at the angle of incidence of 88.7°

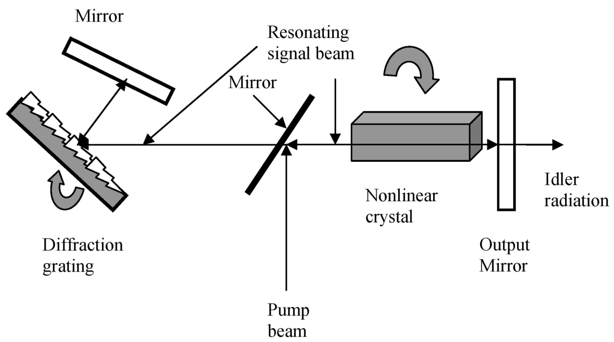

Figure 5. Schematic OPO configuration for narrow linewidth radiation incorporating diffraction grating in Littman or grazing angle of incidence configuration.

measured at a signal wavelength of 600 nm using grating having 2400 lines/mm groove density.

3.4 *Employing type-II phase matching*

Linewidth of the generated radiation can also be reduced to some extent using type-II phase matching due to steepness of the phase matching angle [20,21]. Brosenberg *et al* [20] have demonstrated type-II phase-matched BBO OPO pumped at 355 nm nanosecond radiations. In the spectral range of 0.48–63 μm, without any spectral narrowing element in the cavity, the linewidth of the generated radiation was 0.5–3.0 Å (whereas in type-I phase-matched situation the linewidth was 1.5–22 Å), which was dramatically narrower than type-I phase matching.

Vodopyanov *et al* [21] have also demonstrated type-II phase-matched $AgGaS_2$ OPO pumped by nanosecond pulsed Nd:YAG laser and obtained linewidth of about 1 cm^{-1} in the spectral range of 3.8–11.0 μm.

3.5 *Using a doubly resonant or entangled cavity*

An attractive idea of how to get pulsed narrow linewidth radiation with wide tunability in a doubly resonant cavity was exploited by Scherrer *et al* [22] and Drag *et al* [23]. In a doubly resonant cavity the signal and idler resonant only at a particular wavelength and this is considered to be impractical for spectroscopic application because of cluster hopping effect that preclude continuous frequency tuning. This problem was overcome by constructing a dual or entangled cavity (figure 6). In this cavity configuration the signal and idler were made to oscillate between pairs of mirrors M1–M3 and M2–M4 respectively as shown in figure. The inner mirrors were mounted on the crystal surfaces and the outer mirrors were mounted on two PZT actuators for fine-tuning of the cavity length. By pumping such PPLN crystal-based OPO cavity with a passively Q-switched nanosecond Nd:YAG laser

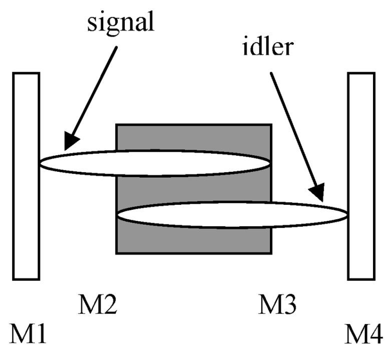

Figure 6. Schematic dual or entangled cavity doubly resonant OPO. Mirrors M1 and M3 form the signal cavity while mirrors M2 and M4 form idler cavity.

the linewidth of the generated radiation was reduced to 80 MHz (0.0027 cm^{-1}) demonstrating stable single-mode operation.

4. Conclusion

Though there are several techniques for reducing linewidth of the generated radiation by OPO, in my opinion grating is the simplest technique because of easiness in alignment and operation. By judicially choosing the groove density of the grating it is possible to generate short linewidth tunable radiation.

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