

Indirectly-seeded optical parametric generation in periodically poled lithium niobate

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Abstract: We report a technique for injection-seeding optical parametric generation (OPG) in periodically poled lithium niobate in which the wavelength of the seed is neither that of the signal nor of the idler waves; instead, it is the wavelength resulting from the sum-frequency mixing of the pump and signal waves. We show that pulsed OPG can be appropriately seeded in this way even if the sum-frequency process is not quasi-phase-matched if a pulsed laser is used as a seed, and if it is quasi-phase-matched even a low power (15 mW) HeNe beam can substantially reduce the bandwidth of the generated signal wave.

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Quasi-phase-matched optical parametric generation (OPG) and optical parametric oscillation (OPO) are nonlinear frequency conversion techniques commonly used in spectroscopy [1] due

to their ability to produce tunable, narrow bandwidth light in a spectral region that is difficult to access by other means. In these techniques a pump beam interacts with a medium in which the nonlinearity changes sign with a spatial periodicity Λ , creating two new beams, a signal and an idler beam, whose wavelengths are related by

$$\frac{1}{\lambda_p} = \frac{1}{\lambda_s} + \frac{1}{\lambda_i} \quad (1)$$

and

$$\frac{n_p}{\lambda_p} = \frac{n_s}{\lambda_s} + \frac{n_i}{\lambda_i} \pm \frac{2\pi}{\Lambda}, \quad (2)$$

where λ_p , λ_s and λ_i are the pump, signal and idler wavelengths, respectively, and n_p , n_s and n_i are the corresponding indexes of refraction.

Ideally, for a given Λ , the signal and idler beams have well-defined wavelengths λ_s and λ_i ; nevertheless, in reality the finite size of the crystal, fluctuations of the periodicity Λ and the finite pump beam bandwidth broaden the spectrum of these beams. There are basically two techniques to reduce the bandwidth; in the case of OPO, an additional wavelength selecting element, such as a birefringent filter [2], a grating [3] or a prism [4] is introduced into the cavity. In the second technique, called injection-seeded, a weak, narrow bandwidth seed beam with a wavelength equal to λ_s (or λ_i) is introduced simultaneously with the pump beam into the nonlinear crystal where it is subsequently amplified through optical parametric amplification [5-7]. Provided that the source used to seed the process is continuously tunable over the bandwidth of the amplifier, a high power, continuously tunable, narrow bandwidth source can be obtained, in contrast with the OPO techniques in which the modes of the cavity introduce discrete spectral lines. Injection-seeding obviously requires having a highly monochromatic source with the same wavelength that is to be amplified through OPG to be used as the seed, which in some cases may not be available.

On the other hand, if the nonlinearity of the medium or the intensity of the pump beam is large enough, other nonlinear processes occur in the crystal even without quasi-phase-matching. One of these processes is the sum-frequency mixing between the pump and the signal beams [8], which gives rise to another beam with a wavelength λ_m given by

$$\frac{1}{\lambda_m} = \frac{1}{\lambda_s} + \frac{1}{\lambda_p}. \quad (3)$$

We propose to use the inverse effect to control the spectral characteristics of the signal beam generated through quasi-phase-matching. A seed beam of wavelength λ_m given by Eq. (3) is mixed with the pump beam in a sample of periodically poled lithium niobate (PPLN), generating through difference-frequency mixing a signal beam that inherits the spectral properties of the seed, which is then amplified in the PPLN sample by quasi-phase-matched optical parametric amplification (OPA). We call this technique indirect seeding since the wavelength of the seed beam is different from the wavelength of the signal that is finally generated. The advantage of this technique is that the seed source is not restricted to have the same wavelength λ_s of the output signal beam.

In this paper we show that the wavelength of the output signal beam can be tuned using this indirect seeding technique even when the difference-frequency mixing process is not quasi-phase-matched. In addition, we show that if two regions in the PPLN sample with different periodicities Λ_1 and Λ_2 are created, where Λ_1 is chosen to produce quasi-phase-

matching between the pump, the indirect seed and the signal beam, and Λ_2 is chosen to quasi-phase-match the mixing between the pump, the signal and the idler beam [9], then indirect seeding can be achieved by using a low power cw (<15 mW) indirect seed beam.

Figure 1 shows the experimental set-up. The pump beam was derived from a Q-switched, 1064 nm Nd:YAG laser with a 7 ns FWHM pulse duration and 10 Hz repetition rate. The energy and polarization of the pump beam were controlled by a $\lambda/2$ plate and a polarizer. The indirect seed was superimposed on the pump beam using a dichroic mirror, and in order to match the spatial modes of the pump and seed beams inside the PPLN sample, the cross-section of the seed beam was controlled by an additional converging lens mounted on a translation stage, as shown in Fig. 1. The beams were focused with an $f=250$ mm singlet lens to a $160 \mu\text{m}$ diameter spot inside the PPLN crystal, which was enclosed in an oven with a temperature stability of 0.1°C .

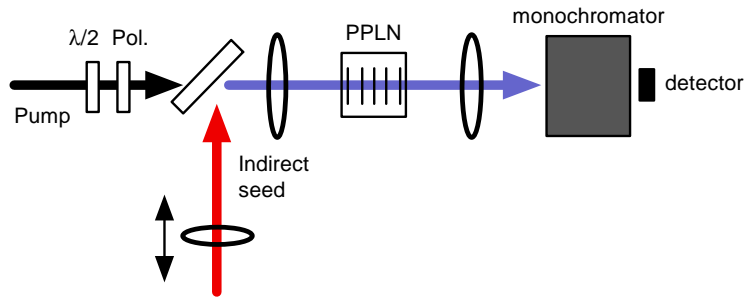


Fig 1. Experimental setup. For the non-quasi-phase-matched indirect seed experiments a pulsed, tunable Rhodamine 6G dye laser was used as the seed and a 20 mm long, $\Lambda = 28.5 \mu\text{m}$ as the nonlinear crystal, and for the quasi-phase-matched indirect seed experiments a 15 mW HeNe was used as the seed and a $\Lambda_1 = 11.5 \mu\text{m}$, $\Lambda_2 = 29.9 \mu\text{m}$ as the nonlinear crystal.

The first experiments were performed with a 20 mm long PPLN sample with a single $\Lambda = 28.5 \mu\text{m}$ periodicity. At a crystal temperature of 100°C and $\lambda_p = 1064.2$ nm, using the Sellmeier equation for the extraordinary refractive index given in Ref. [8], the signal wavelength calculated with Eqs. (1-2) is 1460 nm. For this value, using Eq. (3) we calculate that the seed wavelength $\lambda_m = 615.5$ nm. As a seed source we used a pulsed Rhodamine 6G dye laser that could be tuned around the calculated seed wavelength. To insure a good temporal overlap between the pump and seed beams inside the PPLN sample, these beams were synchronized by pumping the dye laser with the second harmonic of the same Nd:YAG laser used as the OPG pump. The energy of the pump and seed beams were 160 and $\sim 20 \mu\text{J/pulse}$, respectively.

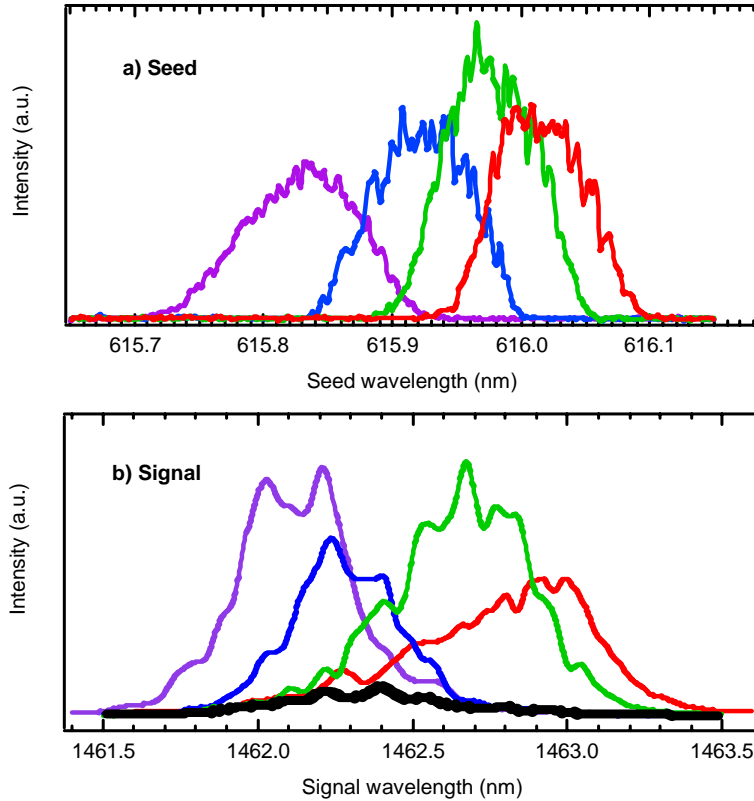


Fig. 2. Indirect seeding without quasi-phase-matching. a) Spectra of the tunable indirect seed. b) Spectra of the corresponding (color-coded) signal beams. The black curve is the spectrum of the signal obtained without the indirect seed beam.

The results obtained with this set-up are shown in Fig. 2. Figure 2a shows four separate spectra of the indirect seed obtained by tuning the dye laser. In each case the bandwidth is approximately 0.1 nm, which is very close to the resolution limit of the spectrometer used to obtain the spectra. Figure 2b shows the four spectra of the output signal that are produced by the corresponding seeds shown in Fig. 2a. For comparison, Fig. 2b also shows the spectrum obtained when the indirect seed was blocked (black line). Notice how the peak of the signal spectrum follows the peak of the spectrum of the indirect seed. We also tuned the indirect seed over a broader range; however, injection-seeded amplification was only observed when the wavelength of the indirect seed was between approximately 615.8 and 616.0 nm.

In order to find out if we could indirectly seed with a low power cw beam using a crystal with two periodicities, for simplicity we chose a 15 mW, 632.8 nm HeNe laser as the indirect seed. For this wavelength the signal and idler wavelengths determined by Eqs. (1) and (3) are $\lambda = 1561.0$ and $\lambda = 3343.7$ nm, respectively. Using the Sellmeier equation given in Ref. [8] and assuming a temperature of 90°C, we find that for the first region $\Lambda_1 = 11.5 \mu m$ and for the second region $\Lambda_1 = 29.9 \mu m$. Using a technique similar to that reported in Ref. [10-12], we made a PPLN sample with these periodicities where the first, seed-pump mixing region was 1 cm long while the last, amplifying region was 1.5 cm long.

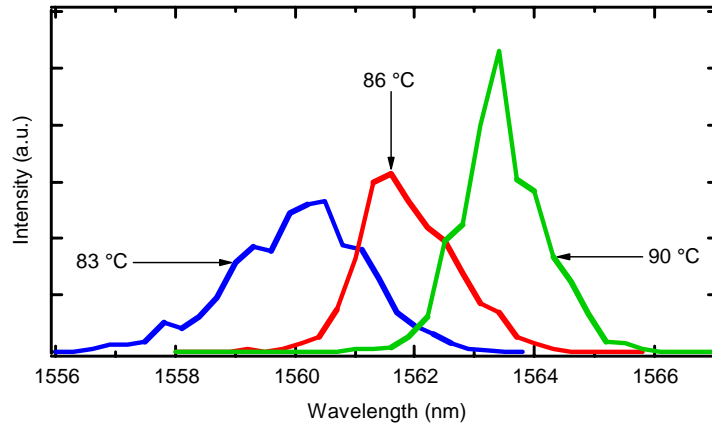


Fig. 3. Spectra of the signal beam at 83.5 °C, 86.2 °C, and 90.5 °C. The seed beam is blocked.

Figure 3 shows the signal obtained at three different temperatures when the seed beam is blocked. As expected, the maximum of the spectrum shifts with temperature. From this figure we see that the temperature at which the spectrum reaches its peak at $\lambda = 1561.0$ is ~ 86 °C. Notice that for this crystal the effective interaction region that produces this signal through OPG is only 1.5 cm long since only the last region has the correct periodicity for quasi-phase-matching, and therefore the bandwidth obtained without indirect seeding is larger than the previous case, approximately 2 nm.

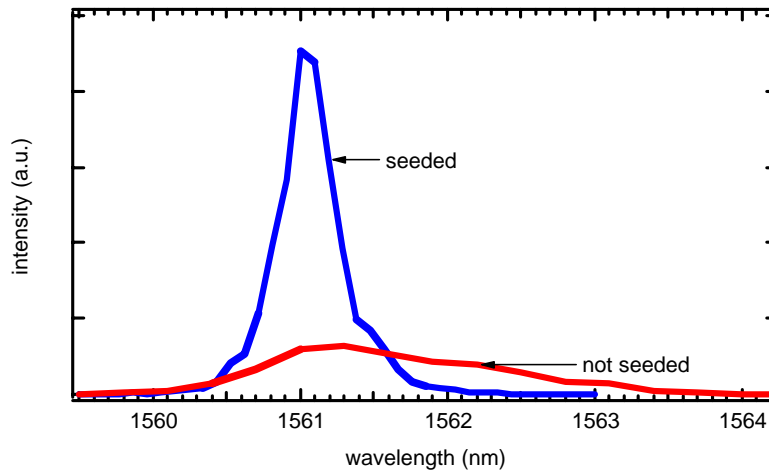


Fig. 4. Indirect seeding with quasi-phase-matching. $T = 86.2$ °C. Incident indirect seed power: 15mW.

The effect of indirect seeding with the HeNe laser is shown in Fig. 4. The temperature of the crystal was set to 86.2 °C in order to maximize the effect of the indirect seed. Notice that the intensity of the pulse is amplified and the bandwidth is reduced when the indirect seed is used. Also, the peak of the signal is at exactly $\lambda = 1561.0$ nm, as expected. The same experiment was done at other temperatures between 83 and 90 °C, and the peak of the signal was always obtained at $\lambda = 1561.0$ nm, although with a lower intensity. The output energy of the signal beam as a function of the input pump beam energy is shown in Fig. 5.

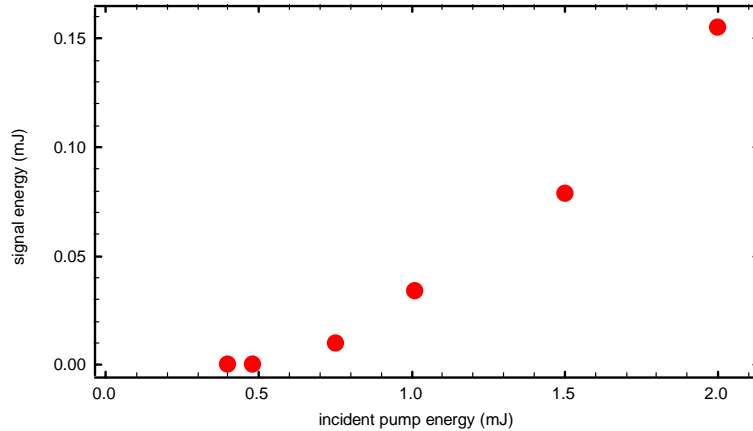


Fig. 5. Output signal energy vs. incident pump energy.

The narrowness of the bandwidth of the signal beam is limited by the finite bandwidths of both the indirect seed and the pump. In these experiments the bandwidth of the HeNe laser is negligible compared to the bandwidth $\Delta\lambda_p$ of the Nd:YAG. A simple calculation shows that in this case the bandwidth $\Delta\lambda_s$ of the (direct) signal seed produced by the first region of the PPLN crystal is given by

$$\Delta\lambda_s \approx \frac{\lambda_s^2}{\lambda_p^2} \Delta\lambda_p. \quad (4)$$

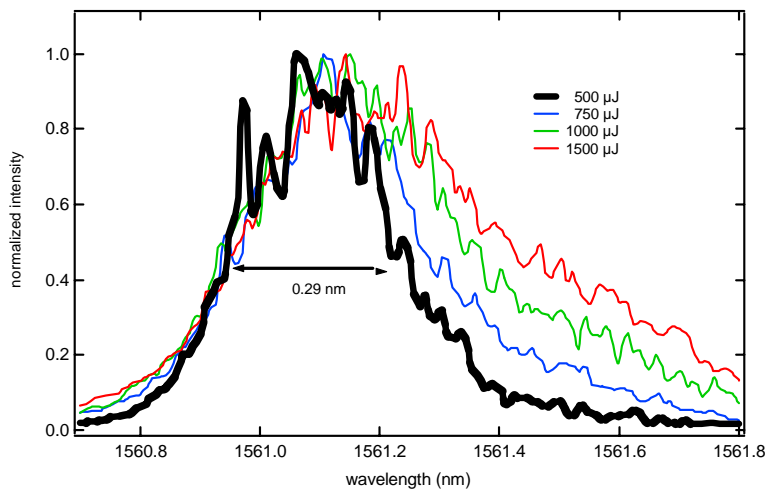


Fig. 6. Normalized spectra of the indirectly-seeded signal beam at different pump energies. Resolution of the spectrum analyzer: 0.1 nm. T=86.2 °C. Incident indirect seed power: 15mW. The fine structure below this resolution limit is an artifact due to pulse-to-pulse fluctuations of the pump beam energy.

We measured the bandwidth of the Nd:YAG pump laser using a Michelson interferometer, and determined that $\Delta\lambda_p \approx 0.1$ nm FWHM, so we can expect to obtain $\Delta\lambda_s \approx 0.2$ nm. We measured the bandwidth of the signal beam under different conditions using a spectrum analyzer with a 0.1 nm resolution. For a pump energy of 0.3 mJ, which is approximately the minimum energy at which we can detect OPG, the FWHM bandwidth was approximately

0.25 nm, which agrees more or less with the predicted value of $\Delta\lambda_s \approx 0.2$ nm. However, the bandwidth of the signal beam increases with the pump energy, as shown in Fig. 6. We believe the broadening of the bandwidth at high pump energies is due to incomplete saturation of the parametric amplification gain by the seed, akin to the broadening that occurs in pulsed lasers due to amplified spontaneous emission.

In summary, we have shown that it is possible to seed OPG in PPLN at a wavelength different from either the signal or the idler wavelengths. If two separate periodicities are used, the OPG can be seeded by a low power cw source, in this case six orders of magnitude less intense than the pump. Although we demonstrated the feasibility of indirect seeding using a fixed-wavelength HeNe laser, this technique can be used with other readily available low power sources, such as tunable diode lasers.

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