Nanosecond terahertz optical parametric oscillator with a novel quasi phase matching scheme in lithium niobate

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Abstract: We present an optical parametric oscillator pumped by a single mode Q-switched nanosecond Nd:YVO_4 laser for terahertz generation in periodically poled lithium niobate with a new phase matching scheme. This new method leads to an emission of terahertz radiation close to the Cherenkov angle and to a parallel propagation of the pump and signal wave. The emission frequency of this novel source is chosen by the poling period to 1.5 THz. For spectral narrowing the signal wave of the OPO is injection seeded. In the optical spectrum also cascaded processes are observed demonstrating a powerful generation of terahertz waves.

OCIS codes: (190.4970) Parametric oscillators and amplifiers; (230.6080) Sources.

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1. Introduction

The generation of terahertz (THz) radiation by optical parametric oscillation (OPO) has been proven and well developed in the past decade [1, 2]. So far, the nonlinear medium for nanosecond pumped devices was mostly bulk lithium niobate ($LiNbO_3$) and not periodically poled for THz generation. This implies a phase matching scheme often related to the Cherenkov-radiation, which is a totally non-collinear phase matching method. Totally means that no pair of the three mixing waves (pump, signal and idler) are parallel, and the interaction of them is lowered due to the reduced spatial overlap. Our approach to make at least the pump and (optical) signal waves parallel is a new phase matching scheme in the lithium niobate crystal. This scheme has not been proposed so far.

2. Phase matching schemes

Phase matching in nonlinear optics is neccessary to avoid destructive interference of the desired wave that is produced by the process. In this section only phase matching schemes are considered which lead to an emission of THz out of the side facet to minimize the propagation and therefore the high absorption inside the crystal (see Section 5). As the pump and THz waves have widely separated refractive indices ($n_{THz} \approx 5.1, n_{IR} \approx 2.15$) a phase matching using the birefringence of the crystal is not applicable in this case. One possibility that has been used by several groups in various experiments is the use of non-collinear phase matching related to Cherenkov-radiation. The principle is shown in Fig. 1(a). In this case no pair of the three mixing waves is collinear, so the interaction is limited by the caused walk-off. An alternative to achieve phase matching is to introduce a periodic poling to the crystal resulting in an alternating second order nonlinear susceptibility $\chi^{(2)}$. Conventional periodic poling, applied for e.g. second harmonic generation (SHG), where the grating vector is parallel to the optical pump wave is only a limited option to achieve THz output to the side facet of the crystal, as there is still a need of hard focussing to achieve a perpendicular momentum component labeled $\Delta\mathbf{k}$ as shown in Fig. 1(b) (the hard focussing leads to an angular distribution of the mixing optical waves, so the phase matching is again totally non-collinear. The $\Delta\mathbf{k}$-notation is only another description for this fact). This type of phase matching has been used in femtosecond TDS-systems [3, 4]. The perpendicular emission of THz radiation without the need of tight focussing in nanosecond

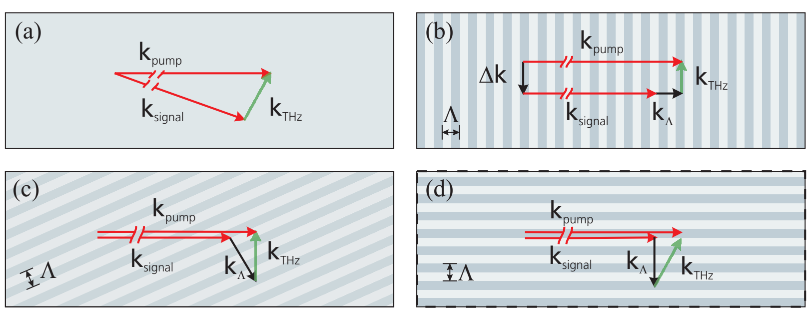

Fig. 1. Phase matching schemes. (a) Non-collinear phase matching also known as Cherenkov-phase matching. (b) “Conventional” quasi phase matching, grating vector parallel to pump wave propagation. (c) Slant-stripe periodic poling for quasi phase matching. (d) Novel quasi phase matching scheme with grating vector perpendicular to pump wave propagation.

difference frequency generation (DFG) experiments has been shown by Sasaki et al. by the use of so-called slant-stripe periodic poled material [5]. The principle of this scheme is shown in

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Fig. 1(c). Here the pump and signal wave (or the mixed optical waves in DFG experiments) are collinear, resulting in a higher interaction of them, but the THz wave propagates perpendicular to the optical waves propagation direction. So the interplay of the THz wave with the optical waves is limited. Our approach of achieving a parallel propagation of the pump and the (optical) signal wave and still having an interaction of the THz and the optical waves comparable to the Cherenkov phase matching is shown in Fig. 1(d). The grating vector of this novel scheme is perpendicular to the pump and signal wave, resulting in domain walls along the propagation direction of these waves. By applying this scheme the THz wave is emitted under an angle close to the so called Cherenkov angle. In comparison to the slant-stripe periodic poling scheme this is expected to have a higher interaction between the THz and the optical waves. With respect to the direction of propagation of the pump wave the THz wave is emitted under an angle of

$$\theta = \arccos\left[\left(\frac{n_P}{\lambda_P} - n_S\left(\lambda_P^{-1} - \lambda_{THz}^{-1}\right)\right)\left(\frac{\lambda_{THz}}{n_{THz}}\right)\right] \tag{1}$$

where λ_P, λ_S, λ_{THz}, n_P, n_S and n_{THz} are the pump wavelength, the signal wavelength, the Terahertz wavelength, the refractive indices of the pump, signal and Terahertz wave, respectively. This angle is almost equivalent to the so called Cherenkov angle of

$$\theta_{Cherenkov} = \arccos\left(\frac{n_{IR}}{n_{THz}}\right) \tag{2}$$

with the condition $n_P \approx n_S (= n_{IR})$ [6]. Therefore outcoupling techniques for THz waves emitted in this specific direction are already well known (e.g. Cherenkov-cut or Si-prisms, see also [6]).

The grating period as a function of the pump wavelength and the desired THz output frequency is given by

$$\Lambda = \left[\left(\frac{n_{THz}}{\lambda_{THz}}\right)^2 - \left(\frac{n_P}{\lambda_P} - n_S\left(\lambda_P^{-1} - \lambda_{THz}^{-1}\right)\right)^2\right]^{-\frac{1}{2}}. \tag{3}$$

3. Pump enhancement of nanosecond pulses

In order to build a cavity which is pumped at 1064 nm and highly reflective at the signal wave (1070 nm for THz generation at 1.5 THz), no standard dichroic mirrors are available. Our solution to overcome this problem is the application of a pump enhancement cavity. The effect is, that a stabilization of the length of a highly reflective cavity on a multiple of the pump wavelength leads to an effective transmission of the pump field through the incoupling cavity mirror. Further, the pump intensity inside the cavity can exceed the incoming intensity. For the signal wave the cavity is still highly reflective. A requirement needed to obtain a pump enhancement of pulses is that the pulse length is larger than the roundtrip time inside the cavity (a further possibility is synchronous pumping, which is only applicable at high repetition rate systems, e.g. enhancement of Ti:Sapphire laser pulses). Then each pump pulse is enhanced by itself. Although the maximum enhancement factor achievable in this case is lowered in comparison to the maximum enhancement in the case of a continuous wave pump field, this scheme is still helpful to build a cavity which allows for a collinear overlap of the pump and signal wave. The stabilization of a cavity to a special wavelength is a well known and solved problem [7, 8]. One convenient solution is the stabilization scheme by Hänsch-Couillaud which analyzes the ellipticity of the reflected pump wave. This reflection consists of two contributions. One is the direct reflection from the input coupler, the other one is the transmission through this mirror after the wave has taken one roundtrip inside the cavity. If the cavity is detuned (length is not a multiple of the wavelength) these two waves have a phase difference. The wave that has

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taken one roundtrip inside the cavity suffers a polarisation rotation caused by different nonlinear losses or conversions of the different polarization contributions. The overlap of the two waves outside the cavity results in an elliptically polarized wave, whose chirality is proportional to the length detuning of the cavity.

4. Experimental setup

As pump source a Q-switched single mode Nd:YVO_4 laser (Xiton Photonics GmbH) is used. It emits pulses with a length of about 33 ns at a repetition rate of 10 kHz. This high repetition rate is the most significant difference to THz-OPOs reported by other groups. So far mostly 10 Hz and once 350 Hz repetition rate systems have been reported [1, 2]. The average output power of the laser is up to 7 W, thus a pulse energy of 0.7 mJ is available at the laser output. Single mode operation of the laser is achieved by injection seeding with a MISER leading to a bandwidth below 60 MHz. The OPO itself is also seeded by a grating stabilized diode laser tunable from 1064 nm to at least 1076 nm. Therefore this seed laser is in principle useful to build OPOs for THz frequencies up to 3 THz when pumped at 1064 nm. For the purpose of cavity length stabilization we apply the Hänsch-Couillaud stabilization scheme and a commercially available locking system. The OPO cavity itself is built by two curved mirrors with a radius of curvature of 200 mm each. The transmittance of the mirrors is 5 % for both optical wavelengths. The dimensions of the used 5% MgO-doped congruent $LiNbO_3$ crystal are 50x3x1 mm^3. The crystal is poled as shown in Fig. 1(d) with a periodicity Λ of 43.7 µm. With the refractive index of lithium niobate at the pump wavelength of 2.15 the cavity roundtrip time is 0.85 ns, which is significantly less than the pulse duration. Output coupling of the THz radiation was achieved by use of five high resistivity Si prisms. The base of each prism is 10 mm, the height is 7 mm and the angles 40 and 50 degrees. So the direction of emission of the THz radiation is perpendicular to one surface of the Si prisms.

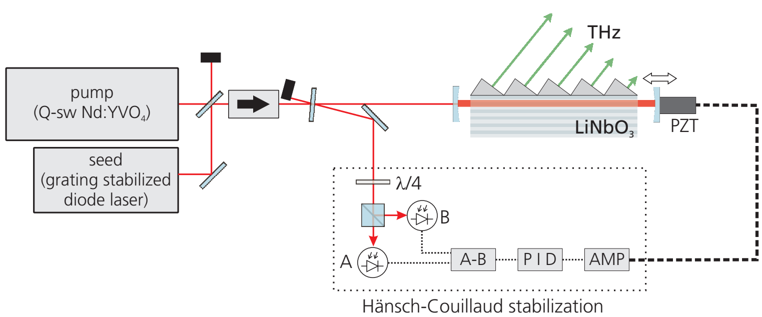

Fig. 2. Experimental setup of the OPO including the pump laser (Nd:YVO_4), the grating stabilized seed laser and the Hänsch-Couillaud stabilization scheme.

5. Considerable losses

The extraction of the generated THz out of the nonlinear crystal is a nontrivial problem. Several restrictions and sources of loss lead to a limitation of the extractable THz power.

The phase matching scheme and the fact that a linear cavity in combination with asymmetric Si prisms is used lead to a reduction of the extractable THz power by a factor of four: A factor of two is contributed by the fact, that the poling is symmetric and leads to emission of THz into the direction of both y-facets of the crystal. The linear setup of the cavity results in a further factor of two. In our setup with the used asymmetric Si prisms only one direction of emission can be accessed.

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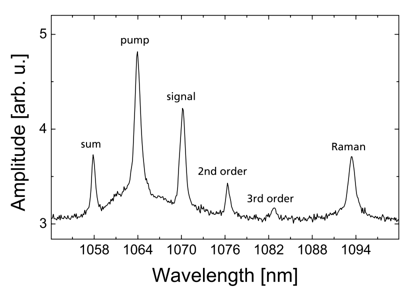
One of the major problems of THz generation inside $LiNbO_3$ crystals is the high absorption coefficient in the THz region [9]. At the frequency of 1.5 THz the absorption is about 45 cm^{-1}. Assuming the generation position inside the crystal being 500 µm from the exit facet this results in an absorption of 91 %.

With our outcoupling scheme two interfaces on the way from the inside of the crystal to the outside have to be overcome which lead to inevitable Fresnel losses. The interface $LiNbO_3$-Si leads to a loss of about 7 %, the interface Si-air to a loss of about 30 %.

The generation of THz radiation in a nonlinear crystal suffers from considerable diffraction, when the beam waist inside the crystal is small. The divergency angle of the emitted beam is enhanced by refraction at the interface $LiNbO_3$-Si as well as at the interface Si-air. The limited collection angle of the following mirror leads to a decrease of the fraction of collectable THz power.

6. Results

A typical optical spectrum of the OPO is shown in Fig. 3. Peak height or area is not to be taken as a measure of intensity. Besides the pump wavelength at 1064 nm and the signal wavelength of 1070 nm further generated wavelengths are observed. The additional peak at 1076 nm is caused by a cascaded process, where a photon at 1070 nm decays in a further THz photon and a 1076 nm photon. This is a very useful process to overcome the Manley-Rowe limit, because, in principle, one pump photon can decay in more than one THz photon by passing through this cascaded process (see also [10]). The highest cascaded process observed so far is of the third order. An unintended process which occurs is the sum frequency generation (SFG) of the pump and the THz wave leading to a peak at 1058 nm. This is a further indication of the high efficiency of this source, but unfortunately it is also a source of loss of THz photons. However, the power of the SFG wave observed in our experiment is negligible so far. The lowest A_1-symmetry polariton mode of the $LiNbO_3$ crystal leads to a Raman peak at 7.6 THz and is therefore the reason for the Raman lasing process at 1093.5 nm. This peak is only observed when the OPO is not seeded and can be seen in the shown spectrum because of the chopped seed laser (so the spectrum is the superposition of the seeded OPO and the Raman laser).



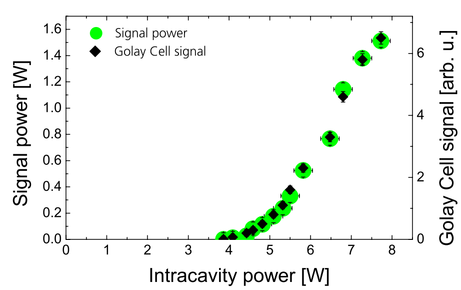


Fig. 3. Left: Typical optical spectrum including cascaded, SFG and Raman processes. Right: Threshold behavior and correlation between signal power and THz (Golay cell-) signal.

The THz output was detected with a Golay cell and the lock-in technique. The power of the generated signal wave was measured after the separation from the pump wave using a grating behind the OPO. On the right side of Fig. 3 the threshold behavior and the good correlation between the signal and the THz power is obvious. The measured intracavity signal power of

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about 1.5 W corresponds to a total THz power inside the crystal of about 8 mW. It is evident that only a fraction of this power can be extracted out of the crystal for reasons already discussed.

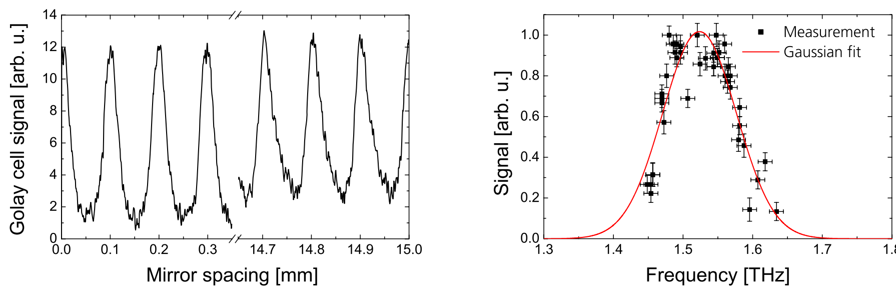

Fig. 4. Left: Fabry Perot scan of the THz output. Right: Tunability of the OPO measured by the peak wavelength of the signal wave and the Golay cell signal.

A FPI-scan of the THz-wave performed with a FPI consisting of two silicon wafers is shown on the left side of Fig. 4. The scan range was limited to about 15 mm, thus, only an upper bandwidth limit of about 3 GHz can be estimated, but is expected to be much less as the two input waves (pump and seed) are single mode. Further experiments to determine the THz linewidth with more sophisticated measurement equipment will be carried out in the near future.

By measuring the signal output wavelength with a high resolution optical spectrometer, the tuning characteristics of the OPO were measured as can be seen on the right graph of Fig. 4. The seed laser was tuned by tilting the grating and the Golay cell signal was taken to measure the relative power of the THz output. The peak wavelength of the signal wave was used to calculate the THz frequency. The OPO tuning bandwidth was found to be about 100 GHz, limited by the finite bandwidth of the QPM-scheme.

7. Conclusion

We have presented the generation of monochromatic THz radiation in an OPO by applying a novel QPM-scheme in $LiNbO_3$. This new scheme leads to a parallel propagation of the optical waves (pump and signal) and therefore to a better interaction of these two. The pump and signal resonant cavity was achieved by applying a pump enhancement with a Hänsch-Couillaud stabilization scheme. A tunability of about 100 GHz and an upper bandwidth limit of 3 GHz was shown. Further, cascaded processes of higher orders were observed which is an important result for future experiments to overcome the Manley-Rowe limit.

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