Generation of tunable continuous-wave terahertz radiation by photomixing the signal waves of a dual-crystal optical parametric oscillator

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Abstract. We present a continuous-wave dual-crystal optical parametric oscillator that generates signal waves of about 1.4 \( \mu \)m wavelength with a tunable difference frequency \( \Delta \nu \) between 0.64 and 5.3 THz. A model of the parametric gain in such a system indicates that the lowest reachable value for \( \Delta \nu \) depends on the refractive index dispersion of the nonlinear material used. As a proof of principle, we demonstrate the generation of terahertz radiation by photomixing the signal waves. Frequencies between 0.64 and 0.85 THz are created and detected coherently with ion-irradiated InGaAs interdigitated photomixers.

Contents

1. Introduction
2. Experimental setup
3. Dual-crystal optical parametric oscillator
4. Photomixing the signal waves
5. Conclusions
Acknowledgments
References

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1. Introduction

Light sources emitting tunable continuous-wave (CW) terahertz (THz) radiation are of great interest for applications such as high-resolution spectroscopy [1], heterodyne receiver systems [2] and local area networks [3]. One approach to obtain this radiation is photomixing two optical waves and thereby generating their difference frequency. This technique allows a homodyne coherent detection, e.g. permitting the determination of the refractive index as well as the absorption coefficient of a sample [4]. So far commonly two laser diodes generating light at frequencies $\nu_1$ and $\nu_2$, respectively, have been used to excite photomixers. Here, it is crucial to achieve spatial overlap between the two laser beams which requires additional alignment effort. Therefore, it would be favorable to have one light source that generates waves at $\nu_1$ and $\nu_2$ with intrinsically given spatial overlap. For this purpose, two-color laser diodes have been developed. Yet, their tuning range is limited by their gain bandwidth to a few THz or they are not tunable at all [5]. In contrast to this, optical parametric oscillators (OPOs) are known for their wide tunability which can exceed 100 THz [6]. Additionally, they can provide a perfect spatial overlap between the outcoupled waves.

In this paper, we present a CW dual-crystal OPO based on periodically poled lithium niobate (PPLN) generating two signal waves with a tunable difference frequency $\Delta \nu$. We discuss the lowest reachable value for $\Delta \nu$ using a model that describes the parametric gain in such a system. Furthermore, we demonstrate photomixing of the signal waves, i.e. generation and detection of THz radiation.

2. Experimental setup

Our experimental setup, sketched in figure 1, comprises a singly resonant OPO in a bowtie configuration pumped by a Yb : YAG solid-state laser at 1030 nm with an output power of 6 W. The cavity consists of two plane mirrors and two concave ones (curvature radius 100 mm), all reflecting more than 99.9% in a wavelength range of 1400–1800 nm. The optically nonlinear medium is a MgO-doped PPLN crystal (HC Photonics Corp.) measuring $50 \times 7.4 \times 0.5$ mm$^3$. It consists of two quasi phase matching (QPM) regions, each 25 mm in length. The first has a QPM period of $\Lambda_1 = 28.5 \, \mu$m, while the second is divided into sections with $\Lambda_2 = 28.58, 28.68, 28.73, 28.79, 28.87$ and $28.98 \, \mu$m. To minimize intracavity losses and Fabry–Perot effects, the end surfaces are antireflection coated with a residual reflectivity of $<1\%$ at signal and $<5\%$ at pump and idler wavelengths. The crystal temperature can be varied by an oven from room temperature up to 200$^\circ$C. To monitor the spectra of the signal field, we use an Agilent 86140B spectrum analyzer. The frequency stability is measured with a Burleigh WA-650 spectrum analyzer connected to a Burleigh WA-1500 wavemeter.

About 40 mW of the signal fields are coupled out through a curved as well as through a plane mirror. While the first beam is separated from residual pump and idler fields by a dielectric filter, the second beam passes through a movable retroreflector. Finally each beam is focused onto an ion-irradiated InGaAs photomixer with a lens (focal length 12 mm). Both photomixers, one acting as the emitter and one as the detector, have $8 \times 8 \, \mu$m$^2$ interdigitated fingers and self-complementary spiral antennas (see inset of figure 1). The emitter is biased with a voltage of $\pm 250$ mV (frequency 930 Hz) and generates CW THz radiation, which is coupled out of the photomixer by a hyper-hemispherical silicon lens, travels through 5 cm of air, and is finally detected coherently using a lock-in amplifier referenced to the bias modulation. Moving the retroreflector gives an interferogram of the THz electric field [7].

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Figure 1. Sketch of the experimental setup: \( P_p, P_p^*, P_s \) and \( P_i \) represent the powers of the pump, its residual, the signal waves and the idler waves, respectively, while \( \lambda_{s1,s2} \) denotes the signal wavelengths. The inset shows the antenna structure of the photomixers.

Figure 2. Difference frequency of the signal waves versus the crystal temperature. The symbols ■, ○, ⋆, △, • and □ denote the measured data for \( \Lambda_2 = 28.58, 28.68, 28.73, 28.79, 28.87 \) and 28.98 \( \mu \)m, respectively. The QPM period of the other crystal section is constant at \( \Lambda_1 = 28.5 \)\( \mu \)m. The solid lines represent the prediction derived from the dual-crystal gain.

3. Dual-crystal optical parametric oscillator

The main goal of our dual-crystal OPO is to create two signal waves at frequencies of \( \nu_{s1,s2} \) with a tunable value for \( \Delta \nu = \nu_{s1} - \nu_{s2} \). Figure 2 shows the difference frequency versus the crystal temperature \( T \) for various QPM-period differences \( \Delta \Lambda = \Lambda_2 - \Lambda_1 \). Increasing \( T \) at a fixed \( \Delta \Lambda \) or vice versa leads to a larger \( \Delta \nu \). We obtain difference frequencies between 0.64 and 0.85 THz as well as between 1.4 and 5.3 THz at signal wavelengths of 1400–1470 nm. For comparison with theoretical predictions, we simulate the dual-crystal parametric gain [8] using the following parameters: pump wavelength 1030 nm, pump power 1 W, beam radii of the interacting waves 100 \( \mu \)m and effective nonlinear coefficient 17 pm V\(^{-1}\). The refractive indices are calculated from a Sellmeier equation [9] for magnesium-doped lithium niobate combined with the temperature dependence [10] for undoped lithium niobate. Considering the
QPM structures in our experiment, the simulation shows two main maxima as exemplified in figures 3(a) and (b). The difference frequency determined from these peaks is the theoretical prediction in figure 2 and is in good agreement with the experimental data.

One might think that a further reduction of ΔΛ would lead to smaller values for Δν. However, as we have shown previously [8], the bandwidth of the parametric gain, given by the relation |(k_p − k_s − k_i − 2π/Λ)L| ≤ 2π, limits the difference frequency in a dual-crystal OPO. Here, k_p, s, i represent the absolute values of the wave vectors of the pump, signal and idler waves, Λ denotes the QPM period, while L is the crystal length. Since the gain bandwidth depends on the refractive index dispersion, the lowest value for Δν is a function of the signal wavelength. This is illustrated in figure 3(d). We determine the difference frequency limit by the following procedure: for a fixed QPM period Λ_1, leading to a gain maximum at a wavelength λ_s1, we reduce Λ_2 until the dual-crystal parametric gain does not show two distinguishable peaks anymore as displayed in figures 3(a)–(c). This simulation is made for a crystal temperature of 40 °C and indicates that smaller values for Δν are achievable by operating the dual-crystal OPO farther away from degeneracy. In principle, temperatures below 40 °C would result in lower difference frequencies. However, then light-induced refractive index changes (‘optical damage’) occur in lithium niobate causing beam distortions and unstable behavior of the system.

The frequency stability of the two generated signal waves is measured to be better than ±60 MHz over 40 min, which is the accuracy of the Burleigh spectrum analyzer. In this time range, the outcoupled signal power of 40 mW varies by ±5%. These values should be sufficient for stable photomixing of the signal waves.

4. Photomixing the signal waves

As a proof of principle for THz generation, we excite the photomixers with the beat signal coupled out of the dual-crystal OPO and record the output of the lock-in amplifier versus retroreflector position. This measurement has been performed for Λ_1 = 28.5 μm, Λ_2 = 28.58 μm and crystal temperatures of 60, 111 and 198 °C. The observed signal spectra as well as the mapped interferograms are displayed in figure 4.
Figure 4. Left: spectra of the outcoupled signal waves. Right: corresponding signal of the lock-in amplifier versus position of the retroreflector. The measurements have been performed for $\Lambda_1 = 28.5 \, \mu m$ and $\Lambda_2 = 28.58 \, \mu m$ and crystal temperatures of (a) 60 °C, (b) 111 °C and (c) 198 °C.

We determine the wavelengths of the generated THz radiation to be 458, 422 and 357 μm (for increasing $T$) by a sinusoidal fit to the measured data. The corresponding frequencies are in full agreement with the measured $\Delta \nu$ of the signal waves, considering the accuracy of the Agilent spectrum analyzer of ±30 GHz.

In the surveyed frequency range between 0.64 and 0.85 THz the amplitudes of the interferograms and thus the THz output powers do not change significantly. However, for $\Lambda_2 \geq 28.68 \, \mu m$, leading to larger difference frequencies, we could not detect a THz signal. Furthermore, the spectra show that the two components of the signal field have unequal powers $P_{s1, s2}$. Since the efficiency of the photomixing process grows with the product $P_{s1} P_{s2}$ [11], the THz output power could be improved by equalizing the powers of the signal waves.

5. Conclusions

We have presented a CW dual-crystal OPO acting as a source of a tunable beat signal. A model describing the parametric gain of such a system shows that the refractive index dispersion of the nonlinear material determines the lowest achievable beat frequency. Output power and frequency stability are sufficient for the generation of CW THz radiation by photomixing, which
has been demonstrated as well. Such a monochromatic and tunable THz source is ideally suited for a wealth of spectroscopic applications.

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