Compact source of continuously and widely-tunable terahertz radiation.

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Abstract: We report a THz radiation source based on the technique of non-collinear phasematched parametric generation. The source, which is compact and operable at room temperature, generates nanosecond pulses of peak power and energy greater than 1W and 5 nJ respectively. The radiation is continuously tunable over the range 1.2–3.05 THz and is of narrow spectral bandwidth (<100 GHz). The use of intersecting pump and parametric wave cavities results in threshold pump pulse energies below 1 mJ (from a Nd:YAG laser excited at 20 W, 500 µsec by a quasi-CW diode-laser) and close to 50% down-conversion efficiency when operated at twice threshold.

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References and links

1. Introduction

The THz spectral region, lying between the microwave and the far infrared, is currently attracting widespread interest in relation to potential applications that span many areas of pure and applied science and technology [1-3]. The development of practical sources of THz radiation, the lack of which has previously inhibited progress, is crucial to the realisation of these applications.

In this communication we report the development of a compact source for the generation of THz radiation which is based on the process of parametric oscillation/generation, in particular using a non-collinear phase-matching geometry in the nonlinear crystal magnesium oxide doped lithium niobate (MgO:LiNbO$_3$), and where wide and continuous tuning is obtained by changing the angle between the resonated idler wave and the pump wave [4, 5]. As well as enabling angle tuning, the use of a non-collinear geometry is essential for ensuring that the generated THz wave (the signal wave) propagates at a large angle to the pump and idler waves, thereby rapidly exiting the nonlinear crystal; an essential requirement since this wave experiences a high absorption in this crystal [6]. In association with an external laser (for example a Nd:YAG laser operating around 1064 nm) to provide the pump wave for the parametric oscillator, this parametric generation approach has been previously demonstrated to be effective for generating THz radiation [7]. However, a particular detraction in this earlier work is the need for high-energy pump lasers; since pump pulses with substantial energies (20-30 mJ) are required in order to exceed the high oscillation thresholds which result from the limited interaction length between the THz wave (signal wave) and the pump/idler waves due to the required rapid walk-off of the former from the latter. In the device reported here, a novel intersecting cavity geometry is employed that allows the nonlinear medium to be placed within the cavity of the pump laser where it is subject to the high circulating intracavity field. Since this field is typically over an order of magnitude greater in intensity than the external field obtainable from the pump laser under optimum output coupling conditions, the need for such a high-energy pump laser is avoided. An additional bonus is that coupling optics between the pump laser and the parametric oscillator are eliminated. Importantly, and unlike conventional intracavity parametric generators, the intersecting cavity geometry incorporates a separate idler wave cavity, the axis of which may be independently rotated, and hence retains the advantages of the wide spectral coverage associated with angle tuning, as well as the rapid walk-off of the THz wave. Further we report significant improvement in the down-conversion efficiency from pump wave to extracted THz wave (signal wave). For example, in a previously reported device [7] employing a separate pump laser, this pump laser was required to deliver pulses with energies in excess of 18 mJ just to exceed oscillation threshold for the parametric process, while pump pulses with energies of 30 mJ were required to generate THz pulses with energies around 200 pJ. Using the intersecting cavity geometry, as detailed below, the pump laser requirement was reduced in the present work to a device that only needed to be capable of delivering output pulses of the order of 0.7 mJ for the parametric process to reach threshold (greater than tenfold reduction in pump energy requirement), and when operating at twice threshold, corresponding to pulses of around 1.3 mJ energy, generated THz pulses with energies around 5 nJ (twenty-five-fold increase in THz pulse energy). A significant advantage ensuing from this reduced pump energy requirement is the ability to employ axial excitation schemes for the Nd:YAG pump laser using diode lasers, as reported below, in place of the much less efficient, more complex, and more bulky side excitation schemes using either lamps or indeed diode-lasers, yet retaining the capability to...
power scale by going to significantly higher pump repetition rates. These various aspects are discussed in more detail below.

Our approach complements existing techniques for the generation of THz radiation including: (i) optical rectification/optically induced photoconductive switching using femtosecond optical pulses [8, 9], (ii) quantum cascade lasers [10], (iii) far infrared molecular lasers [11], and (iv) difference-frequency generation, including internal to the primary generator [12]. The significant advantages of our approach compared to these are: an extensive and continuous tuning range from a single device, unlike (i) and (iii) above; operation in the frequency (spectral) domain as opposed to the time domain, thereby obviating the need for post-detection Fourier transform and averaging techniques, unlike (i) above; operation at or close to ambient temperature, thereby avoiding the need for cryogenic cooling techniques as required in (ii) above; significantly improved powers, energies and efficiencies from simplified device geometries compared to (iv) above; and the generation of close to diffraction limited THz beams, unlike (i) and (ii) above.

2. Experimental system

The experimental set-up for the intersecting cavity, non-collinear phasematched THz OPO is shown schematically in Fig. 1. The pump wave cavity is formed by mirrors M1 (R>98% at 1064 nm & high transmission at 808 nm) and M2 (R=90% at 1064 nm), separated by 37 cm, and includes the laser gain medium (LG), polarisation control optics (QW, QS and POL the function of which is described below) and the optical parametric oscillator nonlinear crystal (NL). The partial transmission of mirror M2 (R=90% at 1064 nm) enables accurate monitoring of the intracavity laser field. The laser gain medium is a neodymium doped (1.3% at wt) yttrium aluminium garnet crystal (Nd:YAG) and is excited by a quasi-continuous-wave laser-diode (QCW-LD). The QCW-LD was supplied and specially selected by LIMO GmbH so as to be of relatively narrow spectral bandwidth centred about the peak of the Nd excitation wavelength of 808 nm. The output from the QCW-LD is fibre delivered and coupled to the laser gain medium via a pair of aspheric lenses (AL). A first aspheric lens, with numerical aperture consistent with the fibre output (NA = 0.22), serves to collimate the fibre output while the second forms an image of the fibre exit aperture. This so called axial excitation scheme has the advantage of providing a gain cross-sectional area within the Nd:YAG crystal that is circularly symmetric, has a near Gaussian radial profile, and has dimensions consistent with, and is thereby efficiently coupled into, the desired pump laser mode size of approximately 1 mm diameter (full width at e^2).

Fig. 1. Schematic diagram of the non-collinear phasematched Thz OPO.

The polarisation state of the resonant pump wave is determined by the insertion in to the pump wave cavity of an air spaced cube polariser (POL). In order to achieve the desired peak power in the pump wave, the pump laser is Q-switched through the insertion of a quarter-waveplate (QW) and an electro-optic Q-switch (QS). The action of these elements in association with the polariser follows a standard quarter-wave Q-switching mode of operation.
In the experimental system a pump pulse duration, in the absence of any parametric generation process, of typically 30 nsec is achieved and at the maximum QCW-LD excitation energy the pump pulse energy is greater than 5 mJ. It will be seen and discussed in the results that at this time the pump pulse energy is limited to around 1 mJ to avoid a surmountable optical damage issue. The modal (spatial) quality of the pump wave in this plane-plane resonator is then determined by a combination of thermal lensing, gain guiding and soft aperturing by the extent of the excited volume in the laser gain medium, the combined effect of which result in a near diffraction limited pump mode.

The nonlinear crystal (NL) has an aperture of dimensions 5 mm x 5 mm, as seen by the pump and idler waves, a crystallographic z-axis parallel to the polarisation of the pump field, and a length 50mm along the x-axis. The OPO (idler-wave) cavity is formed by the plane mirrors M3 (high reflector at the idler wavelength) and M4 (R~98%), through which the idler field is monitored. It is convenient that as the idler wavelength is close to that of the pump these can be standard Nd laser cavity mirrors. The mirrors M3 and M4 are set in adjustable mirror mounts for ease of alignment, but notably these mounts are located on the ends of a common rotatable bar centred above the nonlinear crystal to allow easy angular adjustment of the idler cavity axis relative to the pump wave, and hence tuning of the signal/idler wavelengths through the non-collinear phase matching geometry. The physical length of the idler cavity is 13 cm and forms an intersecting cavity with the pump wave resonator, where the central point of intersection is within the nonlinear crystal. Ideally the idler cavity would be made shorter, however, its minimum length is dictated by the need for the pump and idler waves to be physically separated at the idler cavity mirrors so as not to impede the pump wave. The idler cavity including the nonlinear crystal has an effective optical length of close to 20 cm, so that the time taken for a single-pass transit by the idler radiation is 0.65 ns. The spatial cross-section of the nonlinear gain in the MgO:LiNbO$_3$ crystal induced by the intracavity pump wave and determined by its cross-section within the cavity, has a radius of 0.5 mm, implying an effective Fresnel number for the idler cavity of around 1.7. Calculations using the Fox and Li analysis [14] indicate that such a cavity experiences round-trip diffraction losses of 20% for the TEM$_{00}$ mode rising to 40% for the TEM$_{10}$ mode, being even higher for yet higher order modes. From the trailing edge of the idler pulse as displayed in Fig. 2 we can obtain an estimate of the decay time of the idler radiation in the cavity as around 5 ns (to the $e^{-1}$ point), consistent with an average round trip loss of 30%. In the gain analysis later we will therefore assume that the single pass diffraction loss, the dominant loss, from the plane-parallel cavity is 15%.

As previously discussed, the highly non-collinear phase matching geometry, as it relates to the generated signal (THz) wave, results in the THz wave exiting the nonlinear crystal through a side face. The 5 mm x 50 mm side faces of the nonlinear crystal having their normal perpendicular to the crystallographic z-axis are then fabricated with a good optical polish. Due to the high refractive index of MgO:LiNbO$_3$ at THz wavelengths (~5.2), the total internal reflection angle for a crystal-air interface is close to 11°, as measured from the normal to the interface. In this non-collinear phase match geometry, the THz wave is incident at an angle of around 30° and hence would be totally internally reflected rather than coupled out. To circumvent this problem a prismatic output coupler is used [7]. In this case prisms fabricated from silicon (refractive index ~3.4, resistivity > 10 kΩcm$^{-1}$) are placed against the polished face of the lithium niobate crystal increasing the total internal reflection angle at the now crystal-silicon interface to around 38°, hence allowing output coupling. At the same time, the intermediate refractive index of silicon reduces the Fresnel reflection at this interface to around 6%. If a planar layer of silicon were used, the total internal reflection problem would be shifted to the silicon-air interface, however, the prismatic form of the silicon allows near normal incidence of the THz wave at the outer surface of the prisms, as shown in Fig. 1. Fresnel reflection from this surface remains significant at this time (~29%), but could be reduced in the future by the application of an index matching layer.
3. Results and discussion

The oscillation threshold associated with the previously described idler cavity was observed to correspond to a pump pulse energy of 0.67 mJ measured through mirror M2, corresponding to a diode laser excitation power of only 20 W (over a rectangular pulse of duration 500 µs), when the associated peak intracavity intensity of the pump radiation was 12 MW cm$^{-2}$, in a pulse duration of around 45 ns (FWHM). It will be appreciated that the diode laser excitation power required to reach oscillation threshold may be reduced by specifying mirror M2 to be highly reflecting at 1064 nm (R> 99%). The loss presented to the laser cavity by mirror M2 (R= 90%) is significantly greater than the parasitic losses of the cavity, thus the total measured energy coupled through this mirror is a good approximation to that circulating within the cavity. Note, however, that the intracavity intensity is some ten times greater than that coupled out of the cavity under optimum output coupling conditions, indicative of the advantage of the intersecting cavity approach. A further advantage of the intersecting cavity approach over external pumping is that idler gain is now associated with both the forward and backward transits of the idler cavity by the idler wave. It is noted however, that while this results in a signal (THz) wave being generated in both transit directions, the two signal waves propagate in anti-parallel directions and hence only one is usefully output coupled.

![Figure 2](https://example.com/image.png)

Fig. 2. Undepleted (dashed line) and depleted (solid line) pump pulses for the device operating at twice OPO threshold. The idler pulse is also shown.

Figure 2 displays the temporal behaviour of the idler wave and the pump wave, the latter both in the absence of down-conversion (undepleted pump pulse) and in the presence of down-conversion (depleted pump pulse), for a pump pulse energy of 1.3 mJ (corresponding to pumping at 2x threshold, and requiring only 36 W of diode laser pump power), when the associated peak intracavity intensity is 25 MW cm$^{-2}$ with a pulse duration of the (undepleted) pump pulse of 45 ns (FWHM) as previously. It may be seen from Fig. 2 that under these operating conditions the pump pulse depletion is substantial, being (1.3-0.7) mJ = 0.6 mJ, indicating close to 50% down-conversion of the pump energy into the signal (THz) and idler waves. Further, the pump pulse is significantly depleted by this down-conversion process just after the pump pulse has passed through its maximum intensity. This corresponds to an optimum condition for what can be regarded as the effective “cavity dumping” of the pump field by the nonlinear down conversion process, since at this point the majority of the stored energy in the Nd:YAG gain medium has been extracted, through Q-switching, into the circulating field within the pump cavity. (In the present case the Nd:YAG pump laser is being operated at many times its oscillation threshold, implying that close to all of the stored
inversion has been extracted into the circulating intracavity pump field by the time this “cavity dumping” occurs.) Also, the short build-up time associated with the idler field and the accompanying rapid depletion of the pump field minimises the loss of stored energy from the latter due to unwanted parasitic (i.e. not down-conversion) processes. Since the THz radiation (signal wave) exits the nonlinear medium almost instantaneously following its generation by the nonlinear interaction between the pump wave and the idler wave, then its pulse profile is given by the product of the instantaneous intensity of the pump wave with that of the idler wave. On this basis the duration of the THz pulse will be somewhat shorter than that of the idler pulse, this latter being 8 ns (FWHM). Hence we conclude that when operating at pump pulse energies of the order of twice those required to reach threshold for the down-conversion process the dynamics of the active Q-switching of the pump laser cavity and the passive cavity dumping of the intracavity pump wave by the down-conversion process itself combine so that the overall conversion from the initial stored energy in the population inversion in the Nd:YAG gain medium to down-converted radiation in signal and idler fields is close to optimum.

Figure 2 indicates that the principal determining factor in the efficiency of the down-conversion process is the time taken for an observable signal/idler wave to build-up from initial noise. Brosnan and Byer [14] have modelled this build-up process in the context of pulsed parametric oscillators in general, where a net gain of the order of 140 dB is required for a coherent (observable) output to develop from initial noise. In the case where the signal (THz) wave exits from the nonlinear interaction region in a propagation direction that is close to orthogonal to that of the pump and idler waves, as is necessary in the present case, the gain coefficient experienced by the idler wave is greatly reduced. For the present arrangement we calculate that the single pass idler gain is some 1% of that which would result if all three waves propagated collinearly within the gain medium.

The build-up time associated with the idler pulse shown in Fig. 2 is around 22 ns, corresponding to an estimated 34 single-pass transits of the nonlinear gain medium. Calculations based on the Brosnan and Byer model, in which we now include the gain reduction due to the rapid exit of the signal (THz) wave as discussed previously, indicate an effective nonlinear coefficient of around 150 pm V\(^{-1}\). Such a value is consistent with that expected in the presence of the previously documented [15] enhancement of the usual nonlinear coefficient for lithium niobate (25 pm V\(^{-1}\)) by a polaron resonance associated with the THz wave.

Similar calculations applied to the case of threshold, when the build-up time for the pulse just exceeds the period over which the pump pulse leads to net gain in the nonlinear medium, are consistent with this value of 150 pm V\(^{-1}\) for the effective nonlinear coefficient. (A comprehensive analysis of the dynamics of the intracavity THz generator will form the basis of a future publication.)

Under the conditions above corresponding to pumping at twice threshold where the down-converted energy per pulse was estimated as 0.6 mJ, the externally measured THz pulse energy at 1.6 THz using a calibrated bolometer (QMC Type QFI/XBI) was 5 nJ, indicating a peak pulse power of in excess of 1 W. The quantum efficiency associated with the generation of THz radiation at this frequency is 0.6%, so that the THz energy per pulse generated internal to the nonlinear crystal in the present case is around 4 µJ. The observation that the externally extracted energy is a factor of 1000 below this level is indicative of the widely-known deleterious effects of THz wave absorption in the lithium niobate itself (quoted absorption coefficients are typically in the range 20 cm\(^{-1}\) to 30 cm\(^{-1}\) at 1.5 THz [5]), absorption in the silicon prisms used for extraction and due to both intrinsic impurities and the excitation of free carriers by stray pump/idler wave radiation [7], and residual Fresnel losses. Nonetheless our extracted THz wave energy within a single pulse of the order of 5 nJ is over an order of magnitude greater than that reported previously, even though the pump energies involved in our case were of the order of 1 mJ as opposed to 30 mJ previously. A contributory factor to this improvement in output, but not of course to the significant reduction in threshold, is possibly the reduced absorption resulting from our use of high resistivity silicon prisms.
The present device was continuously tuned over the range 1.2-3.05 THz, corresponding to a wavelength range of 100-250 µm. The THz wavelengths were not measured directly but were inferred from the known pump wavelength (1064 nm) and the changing idler wavelengths measured with an optical spectrum analyser. Figure 3 shows the external angle between pump wave and idler wave as a function of the frequency/wavelength of the generated THz radiation. The solid line is a theoretical curve based on refractive index data for pump/idler waves from Sellmeier equations due to Zelmon et al [16], and for the signal (THz) wave from various sources but compiled in [17]. Our experimental data for various angle/wavelength settings are shown by the boxes, and are seen to be in close agreement with the calculated data. Also to within experimental error our measured angular data are in agreement with the earlier experimental data of Kawase et al [15]. The low frequency end of the tuning range is limited by the geometry of the device in that an angular separation between the resonated idler wave and the pump wave of below 1° results in clipping of the pump beam by the edges of the idler cavity mirrors. On the other hand the high frequency end of the tuning range is limited by loss of gain due to decreasing spatial overlap between the pump wave and the idler wave for external angles above 3°.

The spatial profile of the THz beam has not so far been directly measured, but on the basis of work by Kawase [7] is anticipated to be Gaussian in the far field and close to diffraction limited.

4. Conclusion

We have demonstrated a low threshold parametric generation scheme, based on a diode-laser-pumped Nd:YAG laser and employing an intersecting cavity geometry, for producing THz radiation. We believe that the compactness of the resulting device in association with its wide and continuous tuning in the THz range, improved energy/power levels and efficiency over the current state of the art, room temperature operation and anticipated high spatial beam quality, makes it an attractive source for spectroscopic and related applications. Currently operation has been limited to no greater than 2x threshold, due to optical damage to the coatings on the nonlinear crystal, which occurred at around 30 MWcm⁻², an unacceptably low value in terms of present day coating technology. Since the current pump laser itself is capable of delivering pulse energies some 5x greater than the present damage constraint allows, the removal of this constraint is expected to yield a similar increase in the energy of

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the individual THz pulses generated (25 nJ per pulse). In addition, with improved cooling arrangements for the Nd:YAG gain medium, the repetition rate can be increased from the present 15 Hz up to 100 Hz while staying within the capability of the present diode laser pump module, resulting in an anticipated increase in the mean power overall from the present 75 nW to close to 0.5 µW. Increasing pulse repetition rates to several kilohertz by the use of a higher mean power diode laser pump module will, while still retaining the advantages associated with the end pumping scheme, increase mean powers to the 10µW range, so enhancing opportunities for future applications of the device in THz imaging. Further, we consider that there are opportunities for more closely approaching the quantum limit of the down-conversion process through the elimination of absorption loss in the output coupling arrangements currently used.

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