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Compact and cost-effective scheme for THz generation via optical rectification in GaP and GaAs using novel fs laser oscillators

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Abstract We demonstrate a compact and cost-effective setup to generate broadband THz radiation. As pump source we use a diode-pumped solid-state femtosecond oscillator or a femtosecond fiber laser system, partially in combination with an optical parametric oscillator. For the THz generation we utilize optical rectification in gallium phosphide (GaP) and gallium arsenide (GaAs). The THz power is on the order of 1 µW and we demonstrate imaging and spectral measurements with this setup.

1 Introduction

In recent years many applications for THz radiation were demonstrated. These include security applications, THz imaging, THz spectroscopy, as well as semiconductor characterization [1]. A lot of work has been carried out toward enhancing THz power and toward improving detection schemes. Solutions include photoconductive antennas based on low-temperature grown GaAs pumped by femtosecond oscillators [2], THz quantum cascade lasers [3], cascaded nonlinear processes in optical parametric oscillators [4], difference frequency generation schemes, and optical rectification with femtosecond oscillators [5]. However, all these techniques have their advantages but also show some drawbacks. THz quantum cascade lasers often still need cryogenic cooling, photoconductive emitters require structuring methods and—as well as schemes for optical rectification—high excitation intensities [6]. Therefore, femtosecond laser pulses are used which are often generated by expensive Ti:sapphire systems (for example [7]). Other approaches include femtosecond Yb-doped fiber lasers with output powers up to 14 W for optical rectification in GaP and reaching up to 120 µW of THz output power [8, 9] or Er-doped fiber lasers for optical rectification in GaAs at 1.56 µm wavelength [10]. Also Tm-doped fiber lasers have been employed at 2 µm wavelength in periodically inverted GaAs [11].

We present a THz generation scheme with cost-effective femtosecond laser systems based on optical rectification in GaP. In another approach we use the laser systems in combination with an OPO followed by optical rectification in GaAs. The whole system is compact, cost-effective, easily adjustable, and emits broadband THz radiation at around 1 THz frequency with a bandwidth of 0.5 THz. The key issue for our compactness and cost-effectiveness is the use of extremely cheap high-power pump diodes at 981 nm, as well as a compact oscillator scheme with few optical parts and a cavity with a small footprint.

2 Theory

Optical rectification is a difference frequency generation between the spectral components of a laser pulse [12]. For femtosecond pulses the difference frequencies are located in the THz region of the electromagnetic spectrum. As a simple model we consider two plane waves at the frequencies ω_1 and ω_2 interacting in a $\chi^{(2)}$ nonlinear medium and creating the THz frequency $\Omega_{\mathrm{THz}} = \omega_1 - \omega_2$. The efficiency of difference frequency generation for plane waves in the limit of small conversion, no absorption, and two nearby frequencies (so that their refractive indices n_{pump} are almost equal)

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is given by [13]:

$$\eta = \frac{P_{\mathrm{THz}}}{P_{\mathrm{pump}}} = \frac{8\pi^2 d_{\mathrm{eff}}^2 L^2 I_{\mathrm{pump}}}{\epsilon_0 n_{\mathrm{pump}}^2 n_{\mathrm{THz}} c \lambda_{\mathrm{THz}}^2} \mathrm{sinc}^2\left(\frac{\Delta k L}{2}\right). \quad (1)$$

This easy model already allows one to make a number of predictions. Since the wavelength of THz radiation is very long in comparison to optical wavelengths and λ_{THz}^2 can be found in the denominator, the efficiency of this process is relatively small. Typical values for the efficiency are on the order of 10^{-6} [14]. Since the pump beam intensity I_{pump} can be found in the formula for the efficiency, the actual THz output power will scale quadratically with the pump power, at least for small efficiencies. Even though longer crystals show a smaller bandwidth, due to the L^2 term in (1) they show higher conversion efficiencies. Choosing a material with a high effective nonlinear coefficient d_{eff} is also very important for efficient THz generation. A common material used is lithium niobate [15] having a nonlinear coefficient of $d_{\mathrm{eff}} = (2/\pi) \cdot 152.4$ pm/V [16]. Due to a high refractive index mismatch, resulting in a high Δk, periodic poling is necessary for phase-matching. This structuring makes the crystals rather expensive. As an alternative a tilted pulse front approach has been demonstrated [17] which increases conversion efficiencies up to 5×10^{-4}. Furthermore, due to high THz absorption in the crystal, schemes for extracting the THz radiation at the side facets of the lithium niobate were developed [18].

To preserve simplicity, we decided to use GaAs and GaP in our setup. These crystals still possess a high nonlinear coefficient ($d_{\mathrm{eff}} = (2/\pi) \cdot 46.1$ pm/V for GaAs and $d_{\mathrm{eff}} = (2/\pi) \cdot 21.7$ pm/V for GaP [16]) while showing small THz absorption in the region of about 1 THz. Furthermore phase-matching has to be considered. In order to limit the influence of the sinc^2-term in (1), $\Delta k = 0$ has to be fulfilled, which is equivalent to the condition that the phase refractive index of the THz wave has to be equal to the group refractive index at the wavelength of the pump pulse. These parameters are plotted in Fig. 1 for GaP [19] and GaAs [10]. Obviously, phase-matching in GaP can be achieved around 1020 nm pump wavelength and a THz frequency of 1 THz. This makes our laser systems very well suited for this application (see Table 1). GaAs shows a nonlinear coefficient almost twice as high as GaP, but phase-matching is not possible at the laser wavelength around 1 µm. Thus, we use an optical parametric oscillator which is tunable between 1485 nm and 1820 nm. Efficient phase-matching occurs at around 1.4 µm, but due to a relatively high two-photon absorption coefficient in GaAs, and therefore free charge carriers absorbing THz radiation [20], wavelengths higher than 1.75 µm should be used. So there will be a tradeoff between these two points. Further theoretical investigations concerning pulse duration and focusing can be found for example in [21]. There is also a formula given for the THz spectrum obtained with optical rectification with the slowly varying envelope approximation, and the assumption that the pump pulse has a Gaussian spectrum and is focused loosely on the crystal [21]:

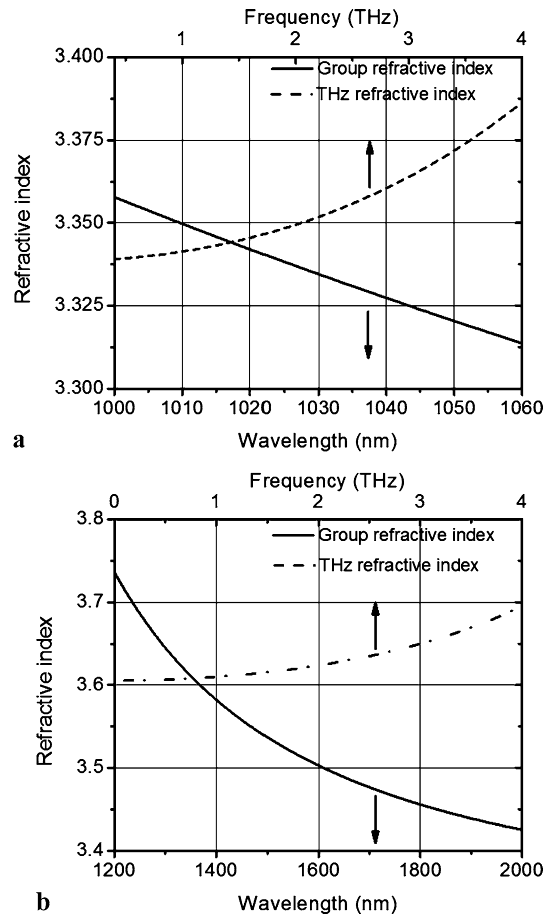


Fig. 1 Group refractive index of the laser pulse and refractive index of the THz wave in (**a**) GaP [19] and (**b**) GaAs [10]

Table 1 Properties of the laser systems we used

System	λ (nm)	P (W)	τ (fs)	f (MHz)
Yb:KGW	1025	4.2	230	44
Fiber laser	1035	3	≤500	37
OPO (PPLN)	1485–1820 (tunable)	0.48	≤750	37

$$\left|E_{\mathrm{THz}}(\Omega_{\mathrm{THz}}, L)\right|^2 = \frac{\Omega_{\mathrm{THz}}^2 d_{\mathrm{eff}}^2 E_0^4 \tau^2 L^2}{8\pi c^2 n_{\mathrm{THz}}^2} \times \exp\left[-\frac{\tau^2 \Omega_{\mathrm{THz}}^2}{4}\right] \mathrm{sinc}^2\left[\frac{\Delta k L}{2}\right]. \quad (2)$$

Here, τ is the FWHM pulse duration and E_0 is the maximum electric field of the laser pulse. This formula will be used later for comparison with our measured spectra.

3 Experimental setup

Figure 2 shows our toolbox for THz generation. We can employ different laser systems as a pump source (details in Table 1).

The Yb:KGW laser was developed in our group and is an inexpensive source of femtosecond laser beams [22]. The high average output power of 4.2 W, the relatively short pulse duration, and its wavelength will give good results for THz generation with GaP. Following (1) we expect that several µW of THz output power should be possible. The fiber laser is a commercial Uranus 005 system by PolarOnyx. Even though its output power of 3 W might not be as high as the Yb:KGW laser's, it is sufficient for THz imaging. The GaP crystal is cut in the (110)-plane, possesses an antireflection coating for 1020 nm wavelength, and has a length of 5 mm.

For the GaAs crystal (also cut in the (110)-plane, antireflection coating for 1800 nm wavelength, and a length of 5 mm) we employ an OPO for frequency conversion. The OPO was pumped by the fiber laser and uses PPLN as the nonlinear conversion medium. Due to different poling periods in the crystal, the OPO is tunable between 1485 nm and 1820 nm. This makes it possible to study the influence of two-photon absorption in the process. The OPO has pulse durations well below 750 fs, which are dependent on the actual wavelength, and shows an output power of about 480 mW.

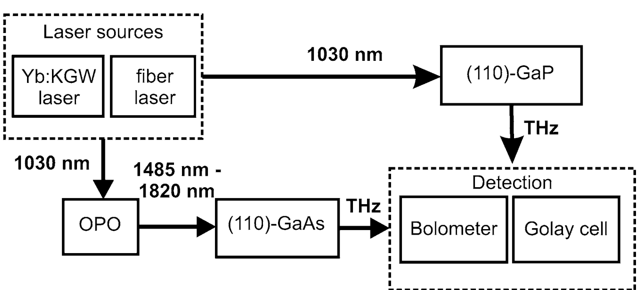


Fig. 2 Our toolbox for the generation and detection of THz radiation

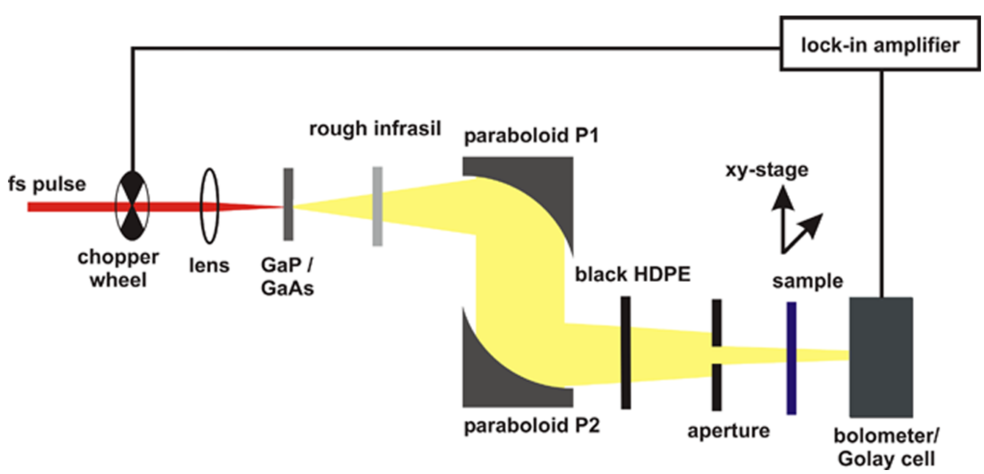
Figure 3 shows a sketch of the setup. It was designed to be simple and easily adjustable. The femtosecond pulse is focused into the nonlinear crystal (40 µm beam radius in the focus), where the THz radiation is created by optical rectification. Since the THz power is expected to be low and the average pump power is still on the order of several Watts, an efficient filter scheme has to be employed. We use black high density polyethylene (HDPE). As this material might burn upon several Watts of incident laser pump power, we use a 0.5 mm thick roughened infrasil plate [23] (bead blasted) which scatters the short pump wavelengths and transmits longer wavelengths, such as THz radiation. The THz radiation is collected and then focused into the detector via two 90 degree off-axis parabolic mirrors. For THz imaging a sample can be mounted on an xy-motorized stage. An aperture cut into black aluminum foil can be used to decrease the beam size at the sample. The THz detection is carried out by a hot electron bolometer by QMC Instruments. With increased THz output power a Golay cell was sufficient for detection. The signal is read out by a lock-in amplifier. Therefore the pump beam is modulated by a chopping wheel. The chopper frequency was set to 800 Hz when using the bolometer for detection, whereas in case of the Golay cell, the chopper frequency was limited to 15 Hz.

4 Results

4.1 THz power

We varied the pump power incident on the crystals and measured the resulting THz signal for different pump powers. Figure 4(a) shows the result for the Yb:KGW laser focused into a GaP crystal of 5 mm length. A quadratic fit, as predicted by theory (see (1)), gives a very good approximation. The same holds for Fig. 4(b), where the fiber laser was

Fig. 3 Experimental setup for generating and detecting THz pulses with the ability for THz imaging



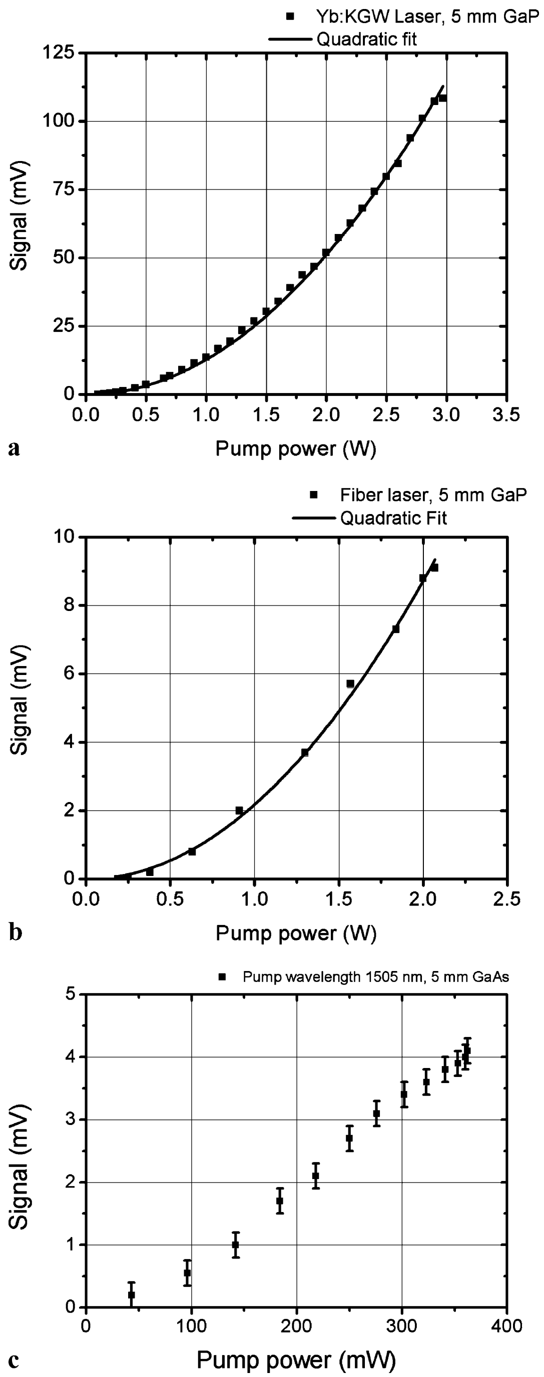


Fig. 4 Signal at the lock-in amplifier measured with the bolometer depending on the pump power for (**a**) the fiber laser and 5 mm GaP, (**b**) the Yb:KGW laser and 5 mm GaP and (**c**) the OPO with an output wavelength of 1505 nm and 5 mm GaAs

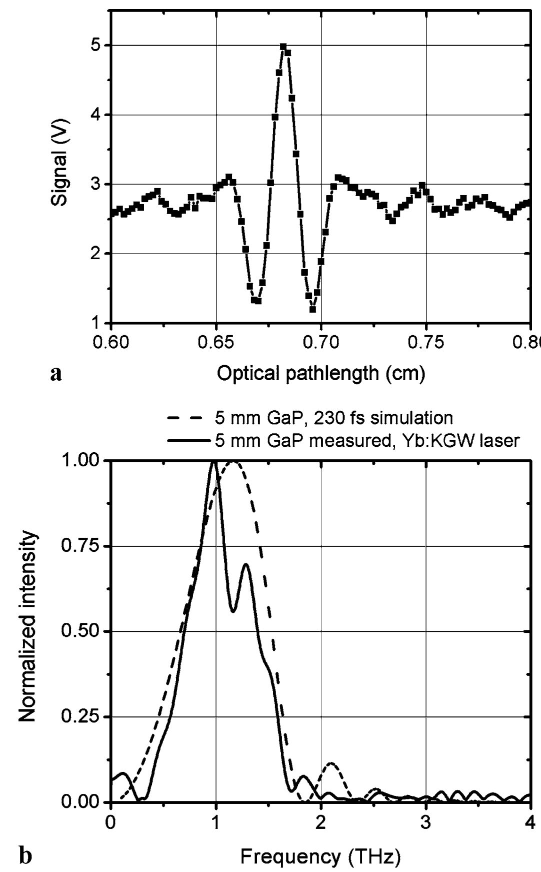


Fig. 5 (**a**) Interferogram measured with a Michelson interferometer setup. The pump source was the Yb:KGW laser. The signal was generated in a 5 mm GaP crystal and measured with the Golay cell. The pulse consists of only a few cycles of the electric field. (**b**) Fourier transform of (**a**) vs. a simulated spectrum

used with the same crystal. Obviously, the Yb:KGW laser gives a much higher THz signal, which was confirmed by the measurements with the Golay cell. This is due to the better phase-matching conditions at 1025 nm wavelength, a higher average output power, and shorter pulses. The calibration by the manufacturers of the Golay cell and the bolometer allows a rough estimate of 1 μW THz output power.

Figure 4(c) shows the same measurement with femtosecond pulses generated in the OPO at a wavelength of 1505 nm focused into a 5 mm long GaAs sample. Compared to the measurements performed with the GaP the signal is much lower. This is due to lower pump powers, longer pulse durations, and worse phase-matching conditions. At small pump powers it shows a quadratic dependence but at higher powers seems to saturate. We interpret this as the onset of two-photon absorption. Measurements at 1780 nm wavelength were also performed but show a much lower signal due to worse phase-matching conditions and the spectral response of the detector.

4.2 THz spectra

In order to measure the spectra of the THz pulses we use a Michelson interferometer instead of the two parabolic mirrors in Fig. 3. The beam splitter is a 1 mm thick silicon wafer with a diameter of 76 mm. One end mirror in the interferometer arm can be moved with a motorized stage. As detector the Golay cell is employed. In such a way interferograms can be recorded. This can be seen in Fig. 5(a) for the

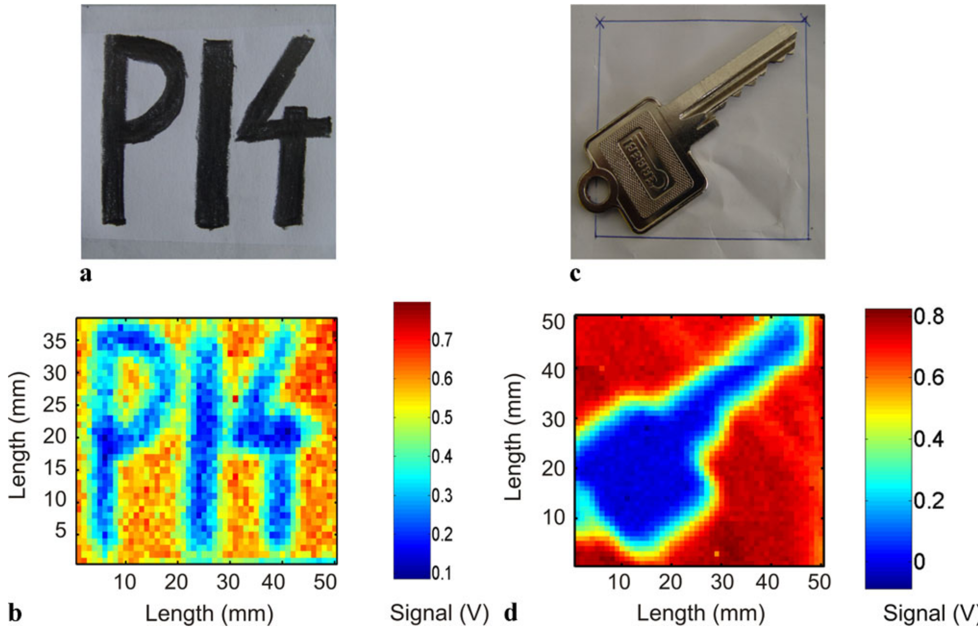


Fig. 6 (**a**) Photograph of a sheet of paper with letters written on it with a soft pencil. (**b**) Transmission scan of the sample through an envelope. (**c**) Photograph of a key. (**d**) Transmission scan of the key in an envelope

Yb:KGW laser and 5 mm GaP. The signal was amplified at the output of the lock-in amplifier, so it is not to scale with the previous measurements. The measured THz pulse consists of only a few cycles of the electric field. Figure 5(b) shows a Fourier transform of the interferogram and a simulated spectrum with (2). Obviously, there is a fairly good agreement. The dip around 1.2 THz might be attributed to water absorption.

4.3 THz imaging

As already mentioned, the setup allows for 2D THz imaging. This was performed using a sheet of paper [24] and the letters "PI4" (name of our institute) written on it with a soft pencil (see Fig. 6(a)). The graphite in the pencil provides free charge carriers, which absorb THz radiation. Therefore there is a huge contrast in transmission compared to the paper. The sheet was placed into an envelope and scanned in the setup with a step size of 1 mm and an aperture of 4 mm × 4 mm. Figure 6(b) shows the result and that the letters are easily readable. The same measurement was performed in Fig. 6(c) and (d) but with a key in the envelope and an aperture of 5 mm × 5 mm. We can scan sample with a size up to 5 cm × 5 cm. The duration for scanning one point is approximately four seconds; so the scans in Fig. 6(b) and (d) took about three hours.

5 Summary

We demonstrated a compact, reliable, and cost-efficient setup for THz generation. This is achieved with femtosecond pump lasers and optical rectification in GaP or via frequency conversion in an optical parametric oscillator followed by optical rectification in GaAs.

Measurements of the THz signal indicate a rough estimate of 1 μW THz power when using the Yb:KGW laser and a 5 mm long GaP crystal. A spectral analysis shows that the measured spectra fit quite well to the simulated ones. We obtain a few-cycle THz pulse with a bandwidth of 0.5 THz centered around 1 THz. Moreover, we demonstrated an easily adjustable setup for THz imaging.

Further upscaling of the THz power can be achieved by using femtosecond laser systems with lower repetition rates and higher pulse energies, for example with cavity dumping schemes [25] and thin-disk oscillators [26]. In the case of GaAs, a periodically oriented crystal could be used to overcome the tradeoff between phase-matching and two-photon absorption; and the pump intensity could be increased by placing this quasi-phase-matched GaAs inside the OPO cavity [27]. We already achieved to place one of our GaAs samples into the cavity with the OPO still running.

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