Quasi phase-matched terahertz detector

J. Darmo, M. Martl and K. Unterrainer

A detector of the terahertz (THz) electric field with a quasi phase-matched electro-optic crystal is presented. This detector exhibits enhanced sensitivity in comparison to the standard detector design. The detector performance is demonstrated using broad- and narrow-band coherent THz sources.

Introduction: Recent progress in terahertz (THz) technology has shown a huge potential of electro-optic detection of coherent radiation [1, 2]. Unlike standard THz detectors, the electro-optic detector response is severely limited by the coherence length [3]. This parameter defines the effective interaction length between the detected THz wave and the probing near-infrared (NIR) light pulse, and depends inversely on their propagation velocity mismatch. A larger mismatch causes a shorter coherence length and thus a short usable length of the electro-optic crystal. Since the detector responsivity scales with the crystal length, an approach to overcome the coherence length limit has to be explored. Recently, the optimisation of the coherence length by selection of convenient NIR probe light wavelength has been presented [4]. However, this solution is limited to certain combinations of wavelengths and electro-optical crystals.

In this Letter we report on an enhanced electro-optic detector of coherent THz radiation using a quasi phase-matched (QPM) electro-optic crystal. The operation principle of the detector is demonstrated on a multilayer gallium-phosphide crystal using broadband as well as single frequency THz coherent sources.

The problem of the propagation velocity mismatch of two different frequencies can be solved by periodically inverting the sign of the nonlinear coefficient of the crystal [5]. We have, for the first time, applied this approach to the crystal design of an electro-optic detector. The inversion of the nonlinear coefficient, is in our case achieved by changing orientations of the fundamental crystallographic axis. The electro-optic detector with such modified crystal is schematically shown in Fig. 1.

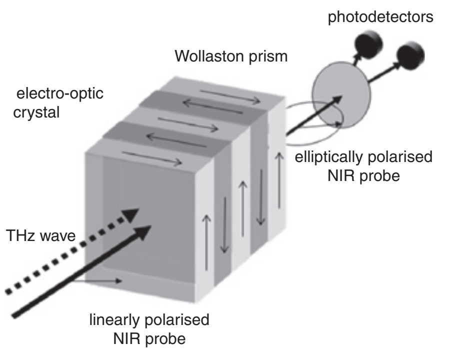

Fig. 1 *Schematic drawing of detection principle for THz radiation by quasi phase-matched electro-optic sensor (NIR – near infrared)*

Arrows indicate orientation of C-axis of crystal

The response function of the electro-optic crystal with the periodically inverted crystalline orientation of individual layers is given by

$$g(\omega, \Omega) = \frac{\exp[i\Delta k(\omega, \Omega)L] - 1}{i\Delta k(\omega, \Omega)} \times \frac{1 - (-1)^N \exp[i\Delta k(\omega, \Omega)NL]}{1 + \exp[i\Delta k(\omega, \Omega)L]} \quad (1)$$

where

$$\Delta k(\omega, \Omega) = \frac{\Omega}{c}\left[n^{\text{NIR}}_{\text{group}}(\omega) - n^{\text{THz}}_{\text{phase}}(\Omega)\right] \quad (2)$$

is the mismatch factor between NIR and THz pulses ($n^{\text{NIR}}_{\text{group}}(\omega)$ and $n^{\text{THz}}_{\text{phase}}(\Omega)$ are NIR probe pulse group velocity and THz phase velocity, respectively, N number of layers). The first term in (1) represents the response of the single layer and sets the frequency range for which the phase matching is optimised. The second term of (2) accounts for the total number of inverted crystal layers in the sensor. We have calculated the response function for a gallium-phosphide (GaP) crystal with ⟨110⟩ orientation and for a NIR pulse with a centre wavelength at 810 nm and a bandwidth of 12 nm. We have used GaP NIR and THz data from [6]. Fig. 2*a* shows the simulated response of the electro-optic detector with a 400 μm-thick GaP and detectors having the quasi phase-matched crystal with two, three and four 200 μm-thick layers. Owing to achieved phase matching, the crystal periodicity enhances the responsivity for frequencies centred around 2.0 THz. As expected from (1), the peak responsivity scales proportionally with a number of layers, while its bandwidth is gradually decreasing.

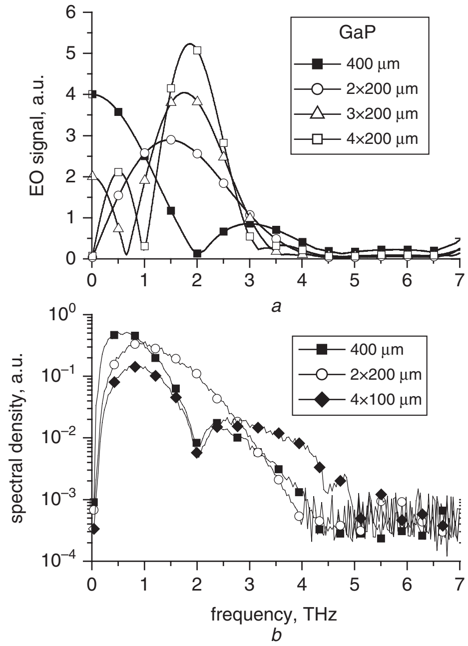

Fig. 2 *GaP quasi phased-matched electro-optic detector*

a Simulation of response function for different crystal thicknesses
b Emission spectrum from photoconductive THz emitter measured by three different detector designs

Experiment: To provide an experimental proof of the detector principle, a GaP electro-optic crystal has been chosen because its lowest phonon associated absorption band is at 10.98 THz [4]. Therefore, the crystal dispersion is not severely compromised in the frequency range from hundreds of GHz up to almost 10 THz. The quasi phase-matched crystal was assembled from ⟨110⟩ oriented GaP layers 100 μm-thick. Individual layers were mounted together using an optical adhesive with a refractive index at 800 nm of 1.68. The response function of each detector has been accessed using a standard time-domain THz setup with a photoconductive THz emitter [6] and has been compared to the response of a GaP bulk crystal of the same nominal thickness.

The results of measurements with QPM detectors with 2 × 200 μm, and 4 × 100 μm GaP crystal design, and the standard detector with 400 μm-thick crystal are shown in the Fig. 2*b*. The 2 × 200 μm QPM detector shows an order of magnitude increased responsivity around 2.0 THz compared to the 400 μm-thick detector, while the 4 × 100 μm QPM detector exhibits increased responsivity at frequencies above 3.0 THz. These observed tendencies in the responsivity match theory predictions very well. Overall shape of the spectrum with the roll-off towards a zero at low and high frequency sides is typical for the photoconductive THz emitter since the most of its energy is radiated around 1 THz.

We have applied the QPM electro-optic sensor also to the measurement of the THz output radiation of quantum cascade laser (THz-QCL). With respect to the response curve of the detectors (Fig. 2), we have chosen a THz-QCL emitting at 2.06 THz [7] and the detector crystal with 2 × 200 μm layers configuration. The coherent THz radiation from the QCL was sampled asynchronously by NIR pulses centred at 810 nm (pulse length of 90 fs, energy of 0.12 nJ, repetition rate of 80 MHz) in the configuration with two crossed polarisers [2]. Fig. 3 shows the measured light-current characteristics for the QCL operating at 8 K. The laser was driven in the pulsed mode with pulse frequency of 5 kHz with duty cycle 5–15%. For the sake of comparison, we have simultaneously measured the laser output also with a pyroelectric detector (LME300 of InfraTec) having the responsivity of

7×10^3 V/W and the intrinsic noise of 20 $\mu V/\sqrt{Hz}$. Owing to the very slow response (~30 ms) of this detector, the THz beam was modulated at 20 Hz. The sensitivity of a QPM electro-optic detector comparable to a standard THz power detector is achieved. However, owing to the construction principle, the electro-optic detector is more robust, and it features significantly shorter response time (~10 µs) and excellent signal-to-noise figure (>5000 at 5 kHz modulation frequency).

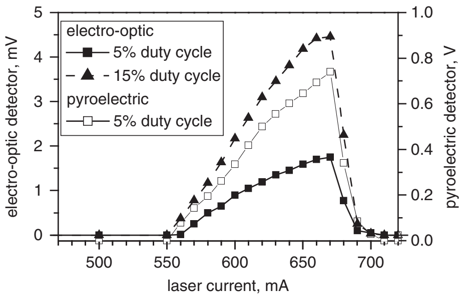

Fig. 3 *THz QCL power against laser current measured by GaP quasi phase-matched electro-optic detector (closed symbols) and by pyroelectric detector (open symbols)*

Conclusions: An electro-optic THz detector with a quasi phase-matched crystal has been presented for the first time. This detector exhibits improved sensitivity in the chosen frequency range. When applied to the detection of continuous wave radiation from a THz-QCL, the performance comparable to a standard pyroelectric detector was demonstrated, but the response time is superior of that detector. The presented detector type is useful for a broad range of emerging THz and mid-infrared applications.

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J. Darmo, M. Martl and K. Unterrainer (*Institut für Photonik and Zentrum für Mikro- und Nanostrukturen, Technische Universität Wien, Vienna, Austria*)

E-mail: juraj.darmo@tuwien.ac.at

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