Quasi-phase matched electro-optic terahertz detector

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Abstract: An enhanced electro-optic detector of the far and mid-infrared radiation is presented. A quasi-phase matching approach is used to address low sensitivity of the detector at multi-terahertz frequencies. Demonstrated concept enables to increase the sensitivity especially for the high frequencies by order of magnitude.

OCIS codes: (040.2235) Detectors, far infrared or terahertz; (190.4360) Nonlinear optics, devices; (300.6495) Spectroscopy, terahertz

1. Introduction

Deployment of the electro-optic detector of the coherent free space terahertz waves has boosted the development of the terahertz technology [1]. Unlike other THz detectors, this detector type operates at room temperature and utilizes a Pockels effect, an electric field induced birefringence of the optical crystal. Induced birefringence is monitored by an ultrashort near-infrared pulse and provides information about the instant vector of the THz electric field. The spectral responsivity of the electro-optic sensor is limited by a mismatch between the group velocity of the near-infrared probe pulse and the phase velocity of the THz wave [2]. Typically, detection of the multi-terahertz frequencies requires a thin electro-optic crystal that in turn means a low sensitivity of detector, since the detector signal is proportional to the interaction (crystal) length.

In this contribution we present the results of study of the electro-optic detector based on the quasi-phase matching between the probe light and terahertz wave. The quasi-phase matching is achieved periodically changing the crystallographic orientation of the electro-optic crystal which leads to a modulation of the birefringence sign. The spatial period of the modulation and the number of periods determine the center wavelength and spectral bandwidth of the spectral range, respectively, in which the detector responsivity can increased more than an order of magnitude. We demonstrate the presented detector concept on GaP and GaAs crystals at probe light wavelength of 800 and 1550 nm, respectively.

2. Results and discussion

Spectral response of an electro-optic crystal is given by the interaction of the probe pulse with the THz wave during co-propagation through the crystal. Mismatch between the probe pulse velocity and phase velocity of the THz wave leads to a pulse walk-off and to an averaging effect of the THz wave electric field. When the walk-off is more than a half of the wavelength of the THz wave, detector signal decreases and reaches zero for the walk-off equal to a wavelength. The electric field of THz wave changes orientation with respect to the crystal axis when the walk-off is larger than half of the wavelength. Therefore, the induced birefringence has changed sign and cancels previous birefringence contributions. The convenient flip of the electro-optic crystal orientation can solve this problem similar to a quasi-phase matched optical device used for the parametric optical generation [3].

The concept of the quasi phase-matched electro-optic detector is shown in Fig. 1(a). The detector crystal consists of several layers of the non-linear optical crystal. Optical axis of individual layers is oriented alternatively to provide the opposite birefringence for the same electric field vector. The principle of operation of this novel detector is identical to the standard electro-optic THz sensor. The linearly polarized near-infrared probe is sensing the birefringence induced by the THz wave copropagating with probe. The birefringence leads to an elliptical polarization of the probe that is subsequently analyzed with a convenient combination of polarizers and optical detectors [2]. The spectral response of the detector crystal in the Fig. 1 is described by expression

$$g(\omega,\Omega) = \frac{\exp(i*\Delta k(\omega,\Omega)*L)-1}{i*\Delta k(\omega,\Omega)} * \frac{1-(-1)^{\mathrm{N}}*\exp(i*\Delta k(\omega,\Omega)*L*N)}{1+\exp(i*\Delta k(\omega,\Omega)*L)}$$

$$and \quad \Delta k(\omega,\Omega) = \frac{\Omega^{THz}}{c} * \left[n_{gr}^{NIR}(\omega) - n_{ph}^{THz}(\omega)\right],$$

where ω and Ω are angular frequencies of the near-infrared probe and THz wave, respectively; L and N are thickness and number of layers; c is speed of light in the vacuum. First term of spectral response function $g(\omega,\Omega)$ is the standard response function of a single layer of the electro-optic crystal (see e.g. [2]), while the multilayer character of the detector is reflected by the second term. In the Fig. 2 we show a model calculation of the spectral response of the detector similar to GaP based detector. Comparing response of thick, thin and multilayer detector

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with the total thickness equal to a thick one, we see that our concept provides strikingly large sensitivity in the selected frequency region. An increase of the number of layers leads to an increased sensitivity, but the bandwidth is reduced. The center of the enhanced response region is controlled by a layer thickness and can cover whole usable range of the used electro-optic crystal.

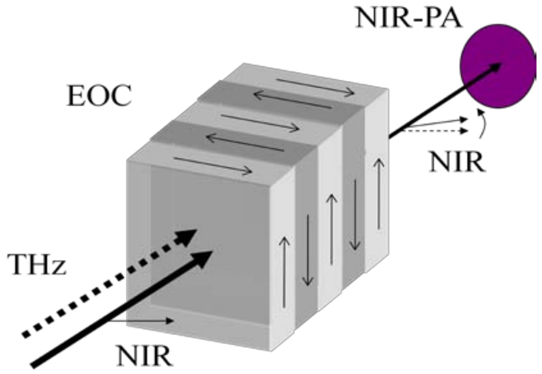

Fig. 1: Schematic drawing of the electro-optic terahertz detector with quasi-phase matched crystal (EOC – electro-optic crystal with periodically inverted orientation of layers, NIR-PA – NIR polarization analyzer, NIR & THz – copropagating probe and terahertz pulse). Crystallographic orientation is indicated by arrow.

We verify the detector concept on the two electro-optic crystal – gallium phosphide (GaP) and gallium arsenide (GaAs). Both crystal are isotropic and are operating well at 800 and 1550 nm, respectively [4]. The GaP based detector consists of 4 layers, each 300 μm thick, while GaAs detector is built of 5 layers, each 350 μm thick. All layers are diffusion bonded [5] to create compact crystal with a periodically inverted crystalline orientation. Detector performance is verified in the standard time-domain terahertz spectroscopic setup as well as with the terahertz quantum cascade lasers emitting between 2.0 – 3.8 THz.

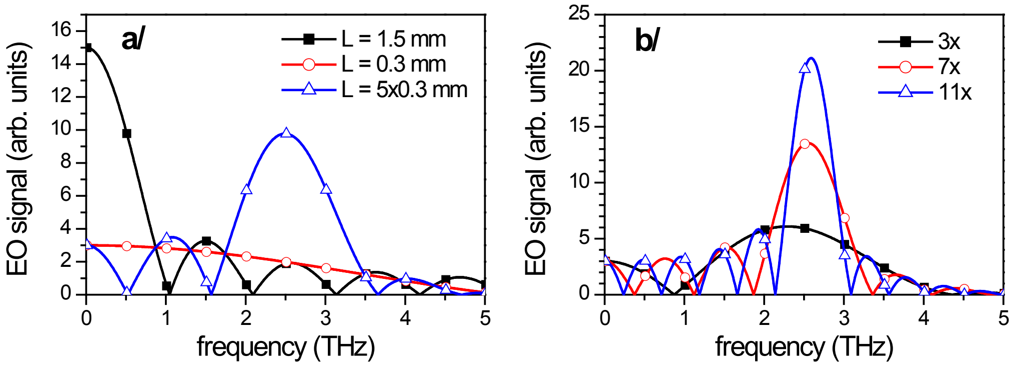

Fig. 2: Spectral response of the model electro-optic crystal with (a) different thickness (full square: 1.5 mm thick, open circle: 300 μm thick, open triangle: 5 layers of 300 μm thick crystal with periodically inverted crystalline orientation); (b) different number of 300 μm thick layers.

3. Conclusions

We proposed and demonstrate an electro-optic terahertz detector with periodically inverted crystalline orientation. The choice of the periodicity and number of inverted layers allows to reach an order of magnitude increased responsivity in the targeted spectral region. Character of the detector operation favors this detector type for the sensing of terahertz radiation from coherent sources such as the terahertz quantum cascade laser.

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4. References

[1] Q. Wu, A. Litz, and X.-C. Zhang, 'Broadband detection capability of ZnTe electro-optic field detectors,' Appl. Phys. Letters 68, 2924-2926 (1996).
[2] G. Gallot and D. Grischkowsky, 'Electro-optic detection of terahertz radiation,' J. Opt. Soc. Am. B 16, 1204-1212 (1999).
[3] R.W. Boyd, 'Nonlinear Optics,' (Academic Press, San Diego 2003) p. 107.
[4] P. Pradarutti, G. Matthäus, S. Riehemann, G. Notni, S. Nolte, and A. Tünnermann, 'Highly efficient terahertz electro-optic sampling by material optimization at 1060 nm,' Optics Comm. 281, 5031-5035 (2008).
[5] L.A. Gordon, G.L. Woods, R.C. Eckartd, R.K. Route, R.S. Feigelson, M.M. Fejer, and R.L: Byer, 'Diffusion bonded stacked GaAs for quasi-phase-matched second-harmonic generation of a carbon dioxide laser,' Electron. Lett. 29, 1942-1944 (1993).