All Electrical Detection of the Stokes Parameters of IR/THz Radiation

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***Abstract*—A fast room temperature pure photoelectrical detection scheme for obtaining the information about polarization ellipticity of laser radiation (described by the Stokes parameters) with a bandwidth from the infrared to the terahertz range is reported. The device consists of two elements, back-to-back, which detect the polarization ellipticity and the ellipse azimuthal angle. The first element utilizes the circular photogalvanic effect in a narrow gap semiconductor and the second the linear photogalvanic effect in a bulk piezoelectric semiconductor. In contrast to optical methods we propose an all-electric approach, which is demonstrated by applying a large number of different laser sources.**

I. Introduction and Background

FAST and easy measurements of the Stokes parameters of a radiation field is of great importance for various applications. The established method for the detection of the polarization state of light is the use of optical elements to determine optical path differences. Recently we presented a technique that allows an all-electric room temperature detection of the polarization state providing full characterization of laser beams at terahertz frequencies[1,2]. The operation of the detector system is based on photogalvanic effects[3] in semiconductor quantum well (QW) structures of suitable low symmetry. The time constant of photogalvanic currents is determined by the momentum relaxation time of free carriers, which is in the range of picoseconds at room temperature. This makes possible to measure the state of polarization of laser radiation with subnanosecond time resolution.

Here we report a substantial improvement of the sensitivity of the method by about two orders of magnitude higher than previously reported and the extension of the detector's spectral range from terahertz to mid-infrared in a single device.

To realize the detection concept we studied photogalvanic effects in HgTe-based QWs as well as in bulk single-crystalline GaAs. The detection is demonstrated for various low power *cw* and high power pulsed laser systems.

HgTe QWs are promising narrow gap materials characterized by high electron mobilities, low effective masses, an inverted band structure, large *g* factors, and spin-orbit splittings of subbands in the momentum space. Because of these features low dimensional HgTe/CdHgTe structures hold a great potential for detection of terahertz radiation and for the rapidly developing field of spintronics. The most important property of the materials relevant for the detection of the radiation ellipticity is the magnitude of the circular photogalvanic effect (CPGE), which gives access to the helicity of a radiation field. Therefore we focus our work on the study of the CPGE. We show that HgTe QWs can be used for all-electric detection of radiation ellipticity in a wide spectral range from terahertz radiation to midinfrared wavelengths.

II. Results

The experiments were carried out on $Cd_{0.7}Hg_{0.3}Te/HgTe/Cd_{0.7}Hg_{0.3}Te$ single QWs of 21 nm width. The structures were grown on GaAs substrates with surface orientation (013) by means of a modified molecular beam epitaxy method. A large spectral range from 9 μm to 500 μm was covered by low-pressure cw, pulsed, and Q-switched CO_2 lasers and high-power pulsed TEA CO_2 lasers, which are used directly in the infrared range or as pump sources for terahertz molecular lasers. Besides gas lasers we used the output from the free electron laser "FELIX" at FOM Institute Rijnhuizen in the Netherlands at wavelengths between 5 and 17 μm and power about 100 kW. Making use of the frequency tunability and short pulse duration of this laser, we obtain the spectral behavior of the detector responsivity and demonstrated its time resolution.

To vary the ellipticity of the laser beam we used λ/4 plates made of *x*-cut crystalline quartz in the terahertz range and a Fresnel rhomb in the midinfrared. The light polarization was varied from linear to elliptical. Rotating the polarizer varies the helicity of the light, $P_{circ} = \sin 2\varphi$, from $P_{circ} = -1$ (left-handed circular, σ_-) to $P_{circ} = +1$ (right-handed circular, σ_+) where φ is the angle between the initial linear polarization and the optical axis (*c*-axis) of the polarizer. In Fig. 1 (top) the shape of the polarization ellipse and the handedness of the radiation are shown for various angles φ.

With illumination of HgTe samples at normal incidence we detected in the in-plane *x*-direction a helicity dependent current signal. This is shown in Fig. 1 for a measurement at room temperature obtained at 77 μm wavelength and power P ~ 10 kW of a pulsed NH_3 laser. Note that the measurement is dc coupled and no background subtraction has occurred.

The signal changes direction if the circular polarization is switched from left- to right-handed and vice versa. The dependence on the helicity P_{circ} and in particular the change in

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sign demonstrate that the observed current j_x is due to the CPGE.

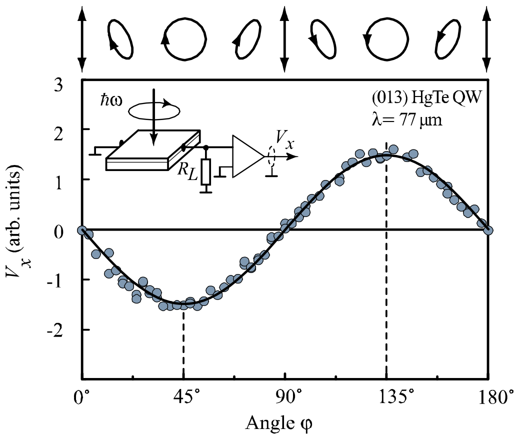

Fig. 1. Helicity dependence of the photoresponse normalized by the radiation power in a (013)-grown HgTe QW at room temperature. The signals are obtained at $\lambda = 77$ μm applying pulsed radiation of NH_3 terahertz laser. The inset shows the experimental geometry. On top of the figure polarization ellipses corresponding to various phase angles φ are plotted viewing from the direction toward which the wave approaches.

Our results show that in the terahertz range the magnitude of the circular photogalvanic effect (CPGE), which provides information on the radiation helicity, in HgTe-based QWs is substantially larger than that in GaAs QWs investigated previously[1,2]. Moreover, due to the narrow band structure of HgTe-based QWs we detected a large CPGE response also in the mid-infrared spectral range. The spectral behavior is shown in Fig. 2. Time-resolved measurements demonstrated that the detector has subnanosecond time resolution (Fig. 2).

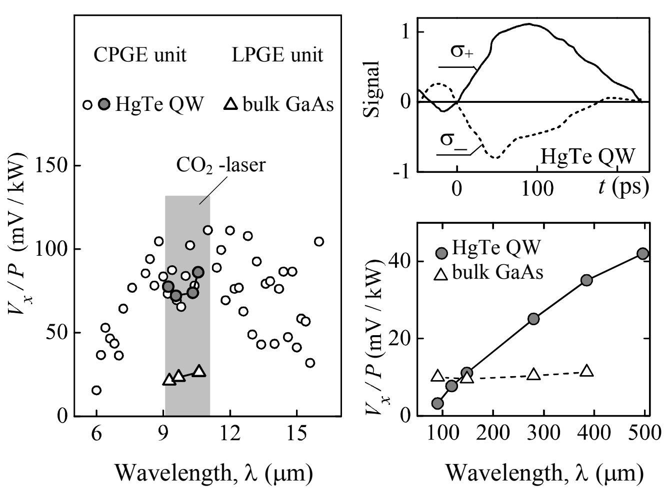

Fig. 2. Spectral behavior of the CPGE and LPGE.

The voltage signal resulting from the photocurrent $V_x \propto j_x$ is well described by $V_{x\mathrm{HgTe}} = S(\omega)P\cdot P_{circ}$, where $S(\omega)$ denotes the strength of CPGE and the sensitivity of this detector unit. The photogalvanic current is described by the phenomenological theory. It can be written as a function of the electric component of the radiation field $\boldsymbol{E}$ and the propagation direction $\hat{\mathbf{e}}$ in the following form[4]:

$$j_\lambda = \sum_\rho \gamma_{\lambda\rho}\hat{e}_\rho P_{circ}|E|^2 + \sum_{\mu,\nu}\chi_{\lambda\mu\nu}\left(E_\mu E_\nu^* + E_\mu^* E_\nu\right)$$

where the first term being proportional to the helicity or circular polarization degree P_{circ} of the radiation represents the CPGE, while the second term corresponds to the linear photogalvanic effect[3] (LPGE), which may be superimposed to the CPGE.

To get all Stokes parameters an additional element is needed to determine the ellipse azimuthal angle. This information we obtained, by analysing the linear photogalvanic effect (LPGE) in bulk GaAs crystals. The irradiation with polarized radiation propagating in the [111] direction in GaAs yields signals (see Fig. 3):

$$V_{[11\bar{2}]}/P = C(\omega)\,(|E_x|^2 - |E_y|^2)/|E|^2 \propto (1+\cos 4\varphi)/2$$

$$V_{[1\bar{1}0]}/P = C(\omega)\left(E_x E_y^* + E_y E_x^*\right)/|E|^2 \propto \sin 4\varphi/2$$

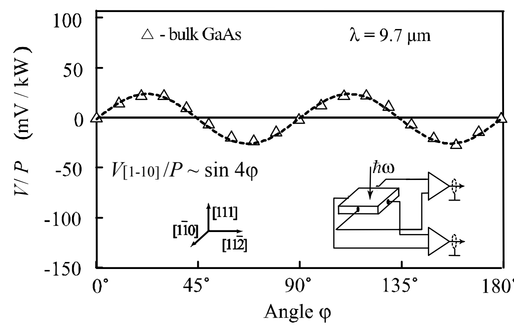

Fig. 3. Helicity dependence of the photoresponse normalized by the radiation power in bulk GaAs at room temperature. The signals are obtained applying pulsed TEA CO_2 laser radiation. Inset shows the experimental geometry. In the GaAs-detector unit the signal of each contact pair is fed into a differential amplifier floating against ground.

Simultaneous measurements of signals caused by the CPGE unit (HgTe QW) and the LPGE unit (bulk GaAs), allow us the determination of the Stokes parameters:

$$s_0 = |E|^2\ ; \quad \frac{s_1}{s_0} = \frac{|E_x|^2 - |E_y|^2}{|E|^2} = \frac{V^{GaAs}_{[11\bar{2}]}}{PC(\omega)}\ ;$$

$$\frac{s_2}{s_0} = \frac{E_x E_y^* + E_y E_x^*}{|E|^2} = \frac{V^{GaAs}_{[1\bar{1}0]}}{PC(\omega)}\ ;$$

$$\frac{s_3}{s_0} = \frac{i\left(E_y E_x^* - E_x E_y^*\right)}{|E|^2} = P_{circ} = \frac{V_x^{HgTe}}{PC(\omega)}\ ,$$

which completely characterize the polarization state of the radiation.

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