Terahertz generator on basis on basis of magnetic system with high localized magnetic field values

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Abstract. In this paper terahertz generator design was proposed. In this THz generator magnetic system on permanent magnets was used to create which create localized magnetic field. Analytical calculation was made for this magnetic system and simulated was done for it. One can obtain point magnetic field with flux magnetic field value over 2.5 T due to the magnetic system. Beyond that analysis of influence of semiconductor crystals properties was done. The semiconductor crystals are used in the magnetic system for terahertz radiation generation.

1. Introduction

At the present time scientific researches in terahertz (THz) frequency range attract more interest. This is due to use of terahertz radiation in different fields of science and to applications in physics, biomedicine, defense and security [1-2] and metamaterials science [3-6]. The special interest is devoted to the terahertz time-domain spectroscopy (THz TDS) since amplitude and a phase may be simultaneously obtained. Scientific application for static THz TDS is spectroscopy of solid-state materials, water and aqueous solutions, semiconductor nanostructures [7]. Terahertz radiation is obtained by variety of ways, which include ultrabroadband THz pulse generation by a femtosecond laser. This method can be realized by photoconductive antennas, optical rectification or optical-induced breakdown [8].

2. Experimental facilities

The theoretical calculation of terahertz generator parameters was implemented for experimental facilities that is shown in figure 1 [9]. The femtoseconds-laser produces the laser beam that is splitted by two ones in the ratio of 10% to 90%. Probe beam transfers 10% energy and pump beam transfers 90% one. Optical delay line controls the pump beam optical path. This beam is modulated by chopper at the frequency of 667 Hz. The generator of THz radiation is based on the crystal in the magnetic system. After passing through IR radiation filter THz beam incidents on the sample. Then, THz radiation induces birefringence in electro-optical crystal. Wollaston prism splits the probe IR beam on two ones with orthogonal polarization, which are detected by balanced photodiodes. THz spectrometer has following parameters: the pump pulse power of 1W, the pump pulse duration of 200 fs, the frequency range is 0.1-1.2 THz, the average THz radiation power is 30 μW [10]. In this setup the Dember effect is used. The Dember effect is one of THz generation methods by illumination of ultrashort laser pulses [11]. It is effect of electric field origination in a semiconductor by illumination it owing to difference in
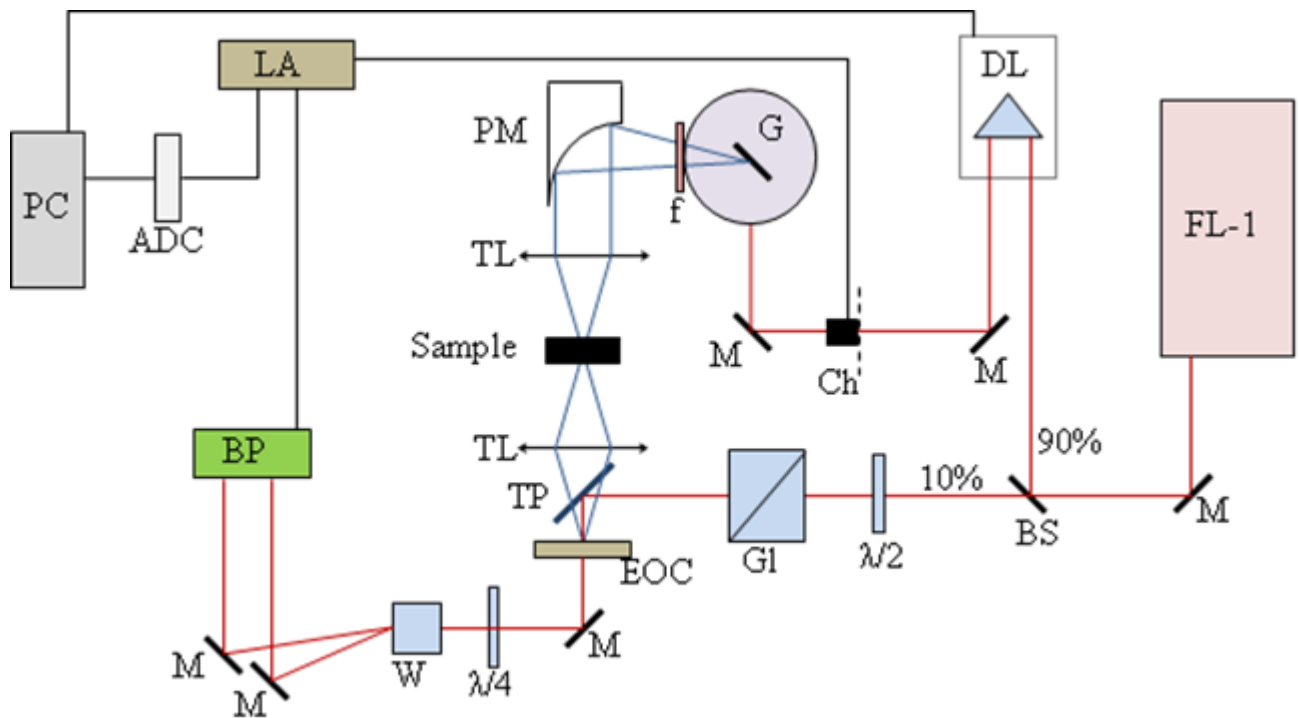
Figure 1. Scheme of the time-domain THz spectrometer in transmission mode. FL-1 is laser of femtosecond pulses, M are mirrors, BS is beam splitter, DL is optical delay line, G is generator of THz radiation based on the crystal InAs, PM are parabolic mirrors, TL are lenses for THz radiation, f is filter of infrared (IR) radiation, TP is translucent silicon plate, Ch is chopper, EOC is electro optical crystal of CdTe, W is Wollaston prism, BP is balanced photodiodes, LA is lock-in amplifier, ADC is analog-to-digital converter, PC is personal computer.

electrons and holes diffusion coefficient. With a strong absorption of laser pulses a strongly nonhomogeneous distribution of electron-hole pairs emerges in a surface layer of semiconductor. Charge carriers diffuse into a material. Inasmuch as electron mobility is more then hole mobility, holes diffuse slowly and in the surface layer charge separation and electromagnetic field occur. The field can be transformed in a free propagating emission. Oscillations of carrier density occur perpendicular to the semiconductor surface and emission effectiveness is not large. For more effective generation one applies matching elements like lenses, prisms or special methods for a turn of a directional radiation pattern of an elementary dipole at a tangent to semiconductor surface. For example, a strong magnetic field can be used as in the described experimental setup.

3. Magnetic systems
The magnetic system produces a magnetic field which is perpendicular to magnet surface. It does not change the magnitude of the carrier acceleration. The B field converts some of the current initially flowing along the normal z to surface to the component parallel to the surface x, when we consider a 3-dimensional space. The p-polarized THz field is described

$$E_p(t) \sim \theta(t)e^{-\frac{t}{\tau}}(\cos \omega_c t + \gamma \sin \omega_c t)\sin \theta, \qquad (1)$$

where θ is angle, under that laser pulse impinges, t is time, τ is the mean scattering time, ω_c is cyclotron frequency, $\gamma = (\epsilon - \sin 2\theta)^{1/2}/\sin\theta$, is a parameter, which relates to the radiation efficiency. For typical photoconductive materials with $\epsilon \gg 1$ parameter $\gamma \gg 1$, the B field enhances THz emission [12]. The enhancement can be explored by defining a power-enhancement factor

$$\eta_p(\gamma, g = \mu_0 B) = \frac{\gamma^2}{2} + \frac{3}{2} + (\frac{1}{2} - \frac{\gamma^2}{2} + \gamma g)/(1 + g^2) - (2 + \gamma g)/(1 + \frac{g^2}{4}), \qquad (2)$$

which depends on the radiation factor $\gamma, g = \mu_0 B = \omega_c t$, where B is field strength and $\mu_0 = e\tau/m^*$ is carrier mobility. A strong enhancement is predicted for the actual THz dielectric constant, for example $\epsilon = 14.6$ for an InAs, but in the same conditionals little effect is expected for a material with $\epsilon = 1$. It is necessary to have a magnetic system with high magnetic field at the room temperature. In our paper the magnetic system was simulated NdFeB [13]. The system consists of two pairs of magnets (type 1 and type 2). The shape of type 1 magnet is represented a cone, and the shape of type 2 magnets is presented a hemisphere with a cut in the form of a cone. Both magnets are divided into eight equal sectors by radial planes passing through the axis of cones. Magnetization vector in each part is parallel to dihedral angle bisector plane and it is directed at the angle to cone axis. The magnetic field strength distribution is described by the formula:

$$H(\alpha, \phi_1, \phi_2) = [2\pi\sigma_{av}\sin 2\alpha + 2n \cdot 2M_s(\sigma_1 \sin\alpha + \sigma_2(1 - \sin\alpha))] \cdot \ln(R/r), \qquad (3)$$

where α is an angle at the cone vertex, φ_1 and φ_2 is the angles between the vector Ms of the first and the second magnets types, correspondingly, and the cone axis. For the segments number $n = 8$ the parameters $\alpha = 54°, \varphi_1 = -107°, \varphi_2 = 14°$ allow to obtain the most effective system design. The outward of the magnetic system and the numerical magnetic field distribution are shown in figure 2 a) and b) respectively. [14] As seen from figure 2, b) we can obtain the magnetic
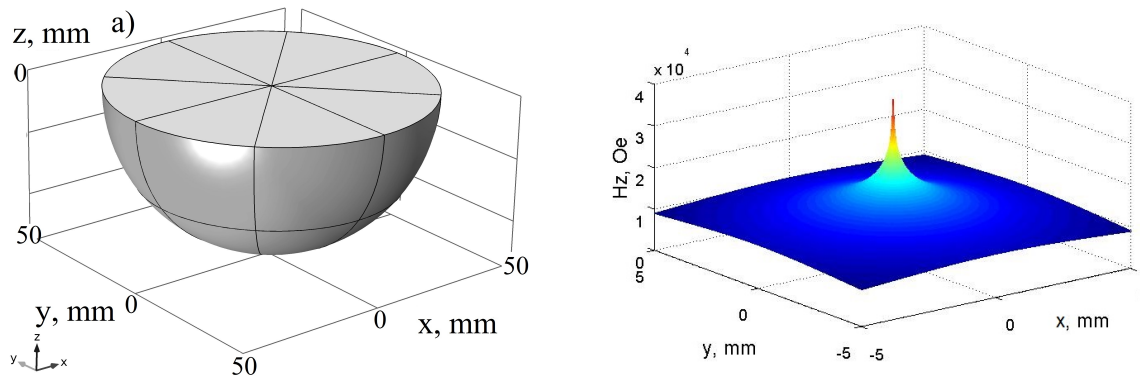

Figure 2. Suggested magnetic system: a) outward and b) analytical magnetic field strength distributions.

field B above 2.5 T by this system design at the room temperature. The magnetic system is a part of a THz radiation generator.

4. Semiconductor crystals in THz generator
The THz radiation generator is shown on figure 3. The pumping beam is generated by the femtosecond laser Yb3+:KYW and goes through a lens that focuses this beam on the semiconductor InAs crystal than THz radiation and reflected IR radiation go through IR-filter and THz collimating lens. InAs crystal is placed into the area of the maximum external
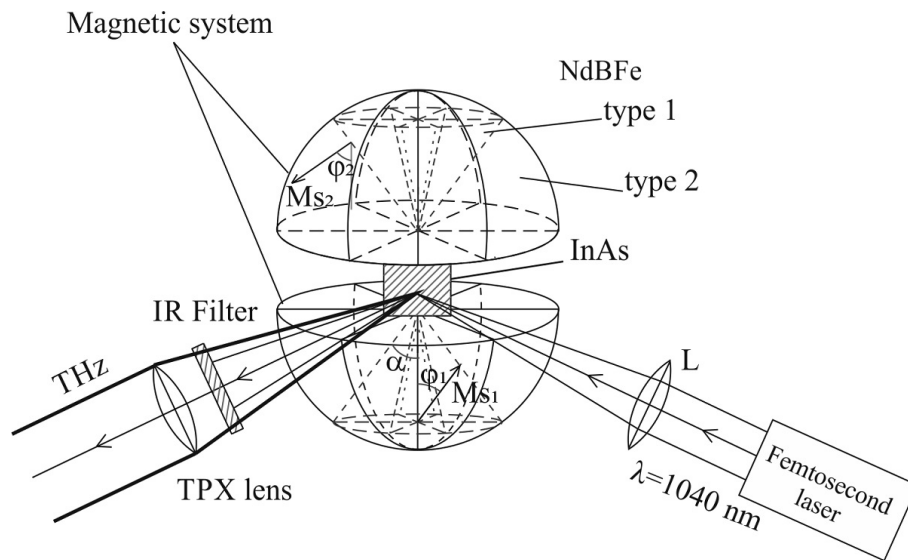
Figure 3. Scheme of the THz radiation generator.

magnetic field that is caused by the magnetic system [15]. The parameters of the THz generator are following: the wavelength of the pump radiation, $\lambda_p = 1040nm$, the THz radiation wavelength generated by the InAs-crystal, $\lambda_g = 0, 3..3mm$, the focus point, f, the diameter of the pump beam, $D_p = 2mm$, the diameter of the spot at the focal point on the InAs-crystal surface $d = 1, 27f\lambda_p/D_p$ (in our setup $d = 1, 5mm$), the diffraction-limited beam divergence, $\theta_d = \frac{1}{\pi}\lambda_g/(d/2)$, the diameter of the generated THz beam at the distance L: $D_g = 2L\theta_d$. As seen from the formula (2), the power-enhancement factor depends not only on B-field but on semiconductor THz dielectric constant, ϵ, and inferred carrier mobility, μ_0. Usually for THz generation one uses semiconductor crystal the following GaSb, InP, GaAs, InAs, InSb. The properties are presented in table 1. The power-enhancement factor dependence is shown on

Table 1. Properties of semiconductors

Property	GaSb	InP	GaAs	InAs	InSb
THz dielectric constant ϵ	15.7	12.4	13.2	14.6	17.7
Inferred carrier mobility, $\mu_0, cm^2/Vs$	2200	5600	9300	8000	19000

figure 4 for the semiconductors. Carrier mobility $\mu0$ differs for each semiconductor, for this reason on the absciss $g = \mu_0 B$ is, points on plots mean value of the power-enhancement factor for magnetic field B 2.5 T. As seen from figure 4, the most effective semiconductor for THz generation is InSb.

5. Conclusions
Therefore, in this paper the development of the magnetic system with point type magnetic field for terahertz time-domain spectroscopy was developed and simulated. The magnetic field approaches to the values higher 2.5 T. It was shown that this system improve efficiency THz
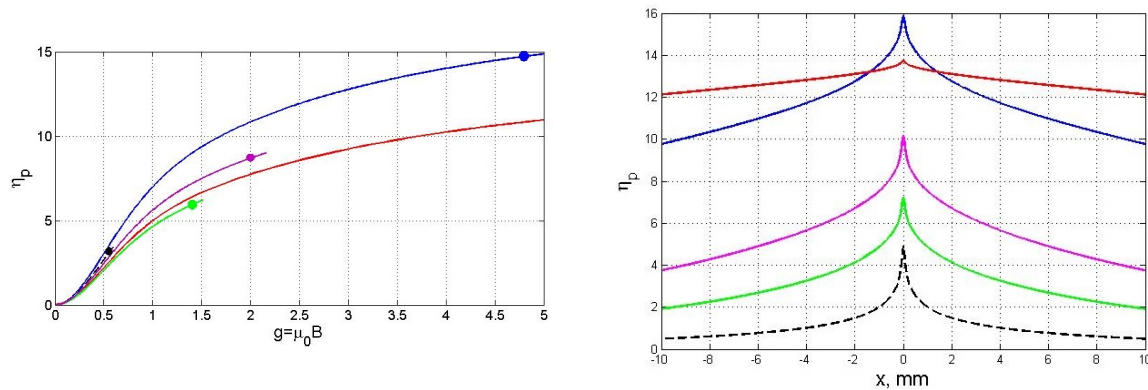
Figure 4. Dependence of the power-enhancement factor a) on magnetic field B and carrier mobility μ_0 and b) on coordinate x at the surface of the magnet; blue line is InSb, black line is GaSb, purple line is InAs, red line is GaAs, green line is InP.

radiation generation. The power-enhancement factor was calculated for typical semiconductors which are often used for the generation. The most efficiency material is InSb.

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