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Impact of Optical Illumination on Transmission of Subterahertz Electromagnetic Waves by $Bi_{12}GeO_{20}$ Crystals

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In this paper, we have investigated the impact of optical illumination on the transmission of subterahertz waves through $Bi_{12}GeO_{20}$ crystals. At the investigated frequency range (220–330 GHz) at different intensities of optical illumination (440–465 nm), we received a change in transmittance of the $Bi_{12}GeO_{20}$ crystal of about 0.6 dB. The transmission recovery time after the optical illumination stops was 2 min. The optical illumination with the intensity $I = 3.0$ W/cm^2 leads to changes in the resistance of the test sample by three orders of magnitude, i.e., to the values of $\simeq 10^4$ Ω, and hence to the conductivity $\sigma = 10^{-5}$ $(\Omega\ \text{cm})^{-1}$. Using light illumination with the photon energy > 3.2 eV and the intensity $I \geq 1$ W/cm^2, it is possible to achieve a concentration of free carriers (electrons and holes) that will lead to a more significant modulation of terahertz illumination by $Bi_{12}GeO_{20}$ crystals. The obtained results were analyzed and compared with the results of other scientific groups.

topics: transmission, optical illumination, $Bi_{12}GeO_{20}$ crystals, subterahertz waves

1. Introduction

The rapid change in the manufacturing processes of new electro–optical devices and devices for the terahertz/subterahertz frequency range has forced scientists to investigate better quality materials to produce more efficient, cheaper, and environmentally friendly devices. Various types of materials that may be suitable for this type of application have now been studied in terms of their structural, optical, and electrical properties. One of the most widely used materials for such application is the bismuth germanate crystals $Bi_{12}GeO_{20}$ (BGO), grown and produced on an industrial scale due to their active use in electro–optical and ultra-high frequency devices.

High-resistance photorefractive $Bi_{12}GeO_{20}$ crystals reveal the following effects: piezoelectric, linear electro–optical, bulk photovoltaic, and high optical activity. BGO samples can be used in various applications such as hologram recording, surface wave amplifiers, resonators, light modulators, signal processing, photocatalysts [1–4]. Furthermore, BGO samples have photorefractive, photoconductive, piezoelectric and electro–optical properties, making such samples suitable for use in holographic storage, image enhancement, real-time interferometry, optical data processing, and as a spatial light modulator [5–7]. BGO crystals are also used in devices on surface acoustic waves [8] and space-time light modulators of the PROM and PRI3 type [9, 10]. The operation of these light modulators is based on the photorefractive effect, i.e., a change in the refractive index due to excitation of the investigated sample by intense laser illumination.

It should be noted that the action of optical illumination leads to photogeneration of carriers in BGO and BSO ($Bi_{12}SiO_{20}$) crystals [11, 12], which can be used to achieve modulation of terahertz radiation [13, 14]. In [15], the effect of optical radiation with the wavelength $\lambda = 0.365$ μm on the transmission of subterahertz radiation by the BSO crystal was investigated. Maximum changes in the transmittance of terahertz radiation of 0.095 dB were detected.

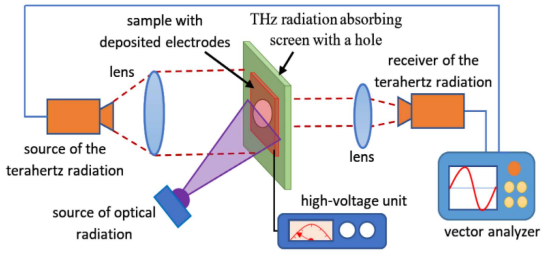

Fig. 1. A block diagram of the setup for investigation of the influence of photogeneration of carriers on the parameters of the selected materials.

In this paper, the effect of illumination of the sample with a source of the wavelength $\lambda = 0.44$ μm on the transmission of subterahertz electromagnetic waves by BGO crystals was investigated. It is taken into account that the BGO crystals have a much higher light absorption coefficient α in the wavelength range λ = 365–440 nm [16]. To study the effect of illumination on the BGO transmission parameters of the sample, a much more powerful source of optical illumination was chosen.

2. Experimental part

2.1. Samples preparation and measurement

The $Bi_{12}GeO_{20}$ crystals we used for the investigation were grown using the Czochralski method with the orientation along the direction [111]. Monocrystalline plates of this material were cut parallel to the plane (111). Correspondingly, the working surfaces of these samples were surfaces parallel to the plane (111). The cut plates were 0.65 mm thick, and the working surfaces' dimensions were 20×20 mm^2. Grinding and polishing of $Bi_{12}GeO_{20}$ samples were performed on Logitech machines (England). The flatness control was performed using a laser interferometer and the measurement of non-parallelism was performed using an autocollimator. The deviations of plane parallelism of the manufactured samples were in the range of 1–2'.

To perform the measurements of the photogeneration effect on the value of the electrical resistance of the sample, on both sides of the manufactured $Bi_{12}GeO_{20}$ sample, transparent conductive films of In_2O_3+ SnO_2) (ITO) were sputtered using the magnetron sputtering technique.

The investigation of the manufactured samples of $Bi_{12}GeO_{20}$ crystals at the subterahertz frequency range was carried out with a setup, the block diagram of which is shown in Fig. 1.

The setup consists of a sequentially placed source of the terahertz radiation, a teflon lens, a screen that absorb terahertz radiation with a hole in which the tested sample is placed with the applied electrodes, a second teflon lens and a receiver of terahertz radiation. The receiver and transmitter are connected to a vector network analyzer. Voltage can be applied to the test sample using a high-voltage power supply. The source of optical radiation was used to investigate the generation of photocarriers in the experimental samples. As the source of optical radiation, the optical diode CLU048-1812C4-B455-XX from Citizen Electronics Co., LTD (Japan) was used. The list of optical diode characteristics is shown in Table I.

TABLE I

Electro–optical characteristics of the diode.

Parameter	Value
product code	CLU048-1812C4-B455-XX
color of light	blue
wavelength [nm]	
λ_{min}	445
λ_{max}	465
forward current [mA]	1.080
voltage [V]	
V_{min}	49.3
V_{typical}	53.6
V_{max}	57.9
thermal resistance [C/W]	0.25
Radiant flux [W]	25

Using the setup shown in Fig. 1, the effect of photocarrier generation on the transmission of the $Bi_{12}GeO_{20}$ sample with sputtered transparent electrodes with ITO in the 220–330 GHz frequency range was investigated. Results of experimental measurements are shown in Figs. 2–4. It is worth emphasizing that the possibility of modulation of terahertz radiation by generating photocarriers was carried out in [13] for Si, Ge, and GaAs crystals, which allows us to utilize the proposed approach on our samples.

In Fig. 2, it was shown the change in the transmittance of a $Bi_{12}GeO_{20}$ crystal sample, when subterahertz radiation with a frequency of 250 GHz passing through it under the illumination with the light diode CLU048-1812C4-B455-XX (see Table I) depending on the illumination time. The intensities of the incident light flux were $I = 3$ W/cm^2 (Fig. 2a) and $I = 0.3$ W/cm^2 (Fig. 2b).

2.2. Transmittance of the $Bi_{12}GeO_{20}$ sample with different applied voltages

Since the transmittance of terahertz radiation of the sample $Bi_{12}GeO_{20}$ also depends on the electric field, we investigated the influence of the electric field on the transmittance during the photocarriers generation (see Fig. 3).

The dependence of the transmission of subterahertz radiation of the $Bi_{12}GeO_{20}$ sample on the applied voltage was investigated at the illumination intensity $I = 0.3$ W/cm^2.

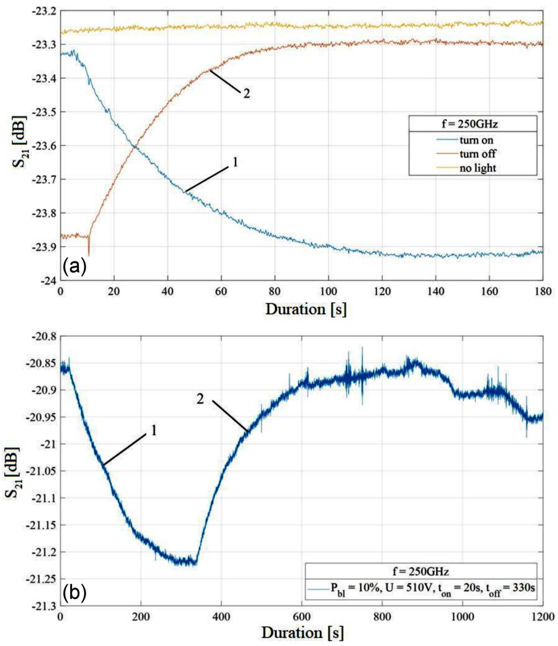

Fig. 2. The transmission through the $Bi_{12}GeO_{20}$ sample of subterahertz radiation at the frequency $f = 250$ GHz when the sample is illuminated (curve 1) and when this illumination is switched off (curve 2) at the intensity of incident light flux (a) $I = 3$ W/cm^2 and (b)$I = 0.3$ W/cm^2.

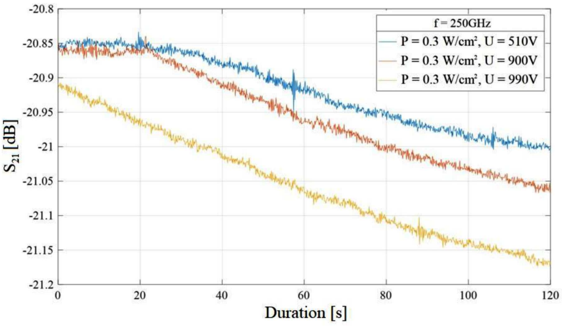

Fig. 3. The transmission through the $Bi_{12}GeO_{20}$ sample at a frequency of 250 GHz with the illumination of light and with the applied different voltages.

As shown in Figs. 2 and 3, the transmission of subterahertz radiation at frequency of 250 GHz for the $Bi_{12}GeO_{20}$ crystal depends on the power of the illumination, duration of illumination and voltage applied to the $Bi_{12}GeO_{20}$ sample.

Furthermore, as shown in Fig. 4, the changes in the transmission spectra of subterahertz radiation in the frequency range 249–250.6 GHz for the $Bi_{12}GeO_{20}$ crystal occur under the influence of illuminating light.

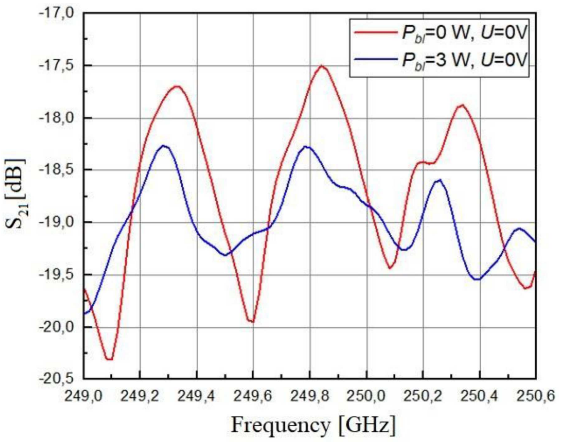

Fig. 4. The transmission spectrum of the $Bi_{12}GeO_{20}$ sample in the subTHz frequency range 249–250.6 GHz depending on the illumination power.

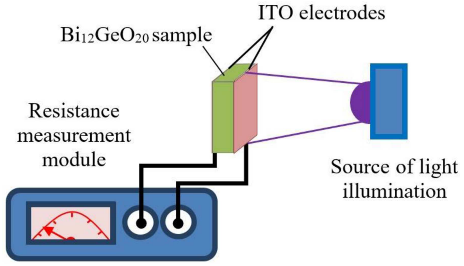

Fig. 5. Block diagram of the setup for measuring the resistance of the $Bi_{12}GeO_{20}$ sample from the intensity.

Observing the behavior of the transmission dependences on the external electric field and the intensity of illumination, it can be concluded that the formation of moving pairs of electrons and holes during the absorption of light, which causes transitions between the energy bands of the crystal, as well as transitions between the impurity level and the conduction band, leads to an increase in the concentration of carriers of both types.

2.3. Measuring the resistance of the sample under illumination

The dependence of $Bi_{12}GeO_{20}$ sample resistance on the illumination intensity was determined for the setup, the block diagram of which is presented in Fig. 5.

In Fig. 6, it is shown the dependence of the resistance of the $Bi_{12}GeO_{20}$ crystal sample on the intensity of illumination as a percentage of the maximum value of $I = 3$ W/cm^2.

3. Discussion (analysis) of experimental results

The loss of terahertz radiation during its passage through the crystal is mainly due to two reasons, namely absorption on the lattice oscillations (phonon absorption) and absorption on free media. Free carriers in the studied BGO crystal are generated by illuminating samples with the light of the

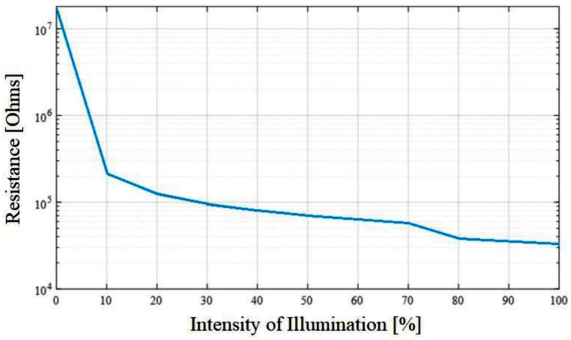

Fig. 6. Dependence of $Bi_{12}GeO_{20}$ resistance on intensity of illumination.

wavelength $\lambda = 0.44$–0.465 μm (see Table I). This corresponds to the photon energy in the range of 2.8–2.65 eV [16]. Since the bandgap in the BGO crystal is 3.2 eV, the main absorption mechanism in our case, which leads to the appearance of mobile charge carriers', is the transitions between the impurity levels and the conduction band. While considering the linear recombination of carriers and their photogeneration, the exit to the steady-state is carried out with a characteristic time. The maximum concentration of photogenerated carriers ΔN at $\alpha \gg 1$, which takes place in our case, is equal to [17]

$$\Delta N = g\tau_e = \beta \frac{\alpha I(1-R)\,\mathrm{e}^{-\alpha x}}{h\nu}\tau_e, \qquad (1)$$

where x is the thickness of the sample and the thickness of the absorbing layer, τ_e is the lifetime of the electron, g is the rate of generation of moving media under light intensity I with the quantum energy hv, α is the absorption coefficient, β is the quantum yield, and

$$R = \left(\frac{n-1}{n+1}\right)^2$$

is a reflection coefficient.

Therefore, as follows from (1), the greater the intensity of photoelectric excitation radiation and the absorption coefficient α, the higher the generation rate of mobile media g and the concentration of mobile media in the steady-state due to photogeneration of media ΔN. As it can bee seen in Fig. 2 (curve 1), the maximum change in the transmission of a subTHz wave with a frequency of 250 GHz through the BGO crystal illuminated with a luminous flux $I = 3.0$ W/cm^2 from a diode with the characteristics given in Table I, is $\simeq 0.6$ dB. Such a small change in transmittance indicates an insufficient concentration of free carriers in the studied BGO crystal.

It should be noted that the lifetime of free electrons τ_e in BGO crystals is of the order of 1 ms [9], which, as follows from [13], should lead to low intensities of photogenerating radiation for a significant modulation of terahertz radiation. However, the Si and Ge semiconductor materials considered in [13] have much smaller bandgap widths than BGO. For Ge and Si crystals, the bandgap is 0.66 and 1.12 eV [16], respectively. Therefore, their dark conductivity (without illumination) is much higher compared to the dark conductivity of the BGO crystal. In Fig. 6, it can be seen that the dark resistance of the BGO crystal is slightly higher than 10^7 Ω. The dark conductivity of the investigated BGO crystal is $\sim 10^{-9}$ $(\Omega\ \mathrm{cm})^{-1}$, while the dark conductivities of Ge and Si are $\sigma = 10^{-1}$–10^{-2} $(\Omega\ \mathrm{cm})^{-1}$ and $\sigma = 10^{-5}$–10^{-6} $(\Omega\ \mathrm{cm})^{-1}$, respectively [9].

In Fig. 6, it can be seen that optical radiation with the intensity $I = 3.0$ W/cm^2 leads to changes in the resistance of the investigated sample by three orders of magnitude, i.e., from 10^7 to $\simeq 10^4$ Ω, and hence to the conductivity $\sigma = 10^{-5}$ $(\Omega\ \mathrm{cm})^{-1}$. This conductivity coincides in order of magnitude with the dark conductivity of the Si semiconductor crystal. It is obvious that to achieve more significant changes in the transmission of terahertz radiation of the BGO crystal, it is necessary to use optical illumination with photon energy greater than 3.2 eV, because the concentration of the state density in the valence band is much higher than the concentration of impurities and defects. Therefore, using illumination with photon energy > 3.2 eV and intensity $I \geq 1$ W/cm^2, it is possible to achieve a concentration of free carriers (electrons and holes), leading to more significant modulation terahertz radiation through BGO crystals.

Another important parameter of terahertz waves modulation is the recovery time of the initial transmission of the crystals after the illumination is finished. In our case, the recovery time for the transmittance of terahertz wave through the BGO crystal, as seen in Fig. 2 (curve 2), is $\simeq 2$ min. This is commensurate with the storage time of the information recorded in the "PRIZ" modulator and results in the presence of adhesion levels in the bottom of the conduction band [9, 10]. Changes in transmittance of a $Bi_{12}GeO_{20}$ sample depending on the illumination time and the applied voltage are shown in Fig. 3. They can be explained by the change (increase) of the absorption coefficient when an electric field is applied. This in turn leads to a rise in the generation rate of mobile media according to (1) [17].

4. Conclusions

The effect of optical radiation with a wavelength 0.44–0.465 μm and intensity $I = 3.0$ W/cm^2 on the transmission of subterahertz waves through the $Bi_{12}GeO_{20}$ crystal was investigated. It was found that at these wavelengths and optical illumination intensities, the change in transmission by the BGO crystal is $\simeq 0.6$ dB, and the transmission recovery time after the illumination is finished is $\simeq 2$ min. The obtained results are analyzed in comparison with the results carried out in [13].

Acknowledgments

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