Detection of THz waves in GaSe:S crystals by femtosecond laser radiation with a telecom wavelength of 1.55 μm

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Abstract. In this work, we study Ga_{x+y}Se_{50-x}S_{x} crystals (where x = 0, 1.5, 6, 8, 11) as an electrooptic detector of terahertz pulses using probing femtosecond laser radiation with the wavelength of 1.55 μm. It was found that the sample with x = 6 provides the highest detection efficiency. The efficient value of the electrooptic coefficient of GaSe:S crystals is estimated to be about twice higher than those of GaAs in the same conditions.

1. Introduction
The progress in the technologies of optical telecommunication systems is accompanied by an increase in the modulation frequencies up to hundreds of GHz related to the so-called millimeter-wave or subterahertz range. New concepts based on the optical-to-optical conversion (nonlinear interaction) are proposed for detecting these frequencies as opposed to the classical approach of conventional electronics. Thus, the search and study of suitable nonlinear media are currently of great interest.

In recent years gallium selenide (GaSe) is attracting more attention as a material for integrated optics [1]. It is a well-known nonlinear medium and has been actively studied for the interaction of IR with millimeter- and terahertz waves including generation and detection [2-10]. A significant number of publications devoted to these tasks dedicated to the conversion of wavelengths in the vicinity of 0.8 μm [2-5], 1 μm [6-7], 2 μm [8] and 10 μm [9-10]. However, to the best of our knowledge, there are no reports devoted to the telecom wavelength of about 1.5 μm.

In this work, we present the study of GaSe crystals doped with a sulfur element (GaSe:S) as the detector of the THz waves gated by femtosecond laser pulses at a wavelength of 1.55 μm.

2. Experimental Setup
The study of the detection efficiency in GaSe:S crystals was carried out in the terahertz-time domain spectroscopy setup (THz-TDS) (figure 1). An Er-fiber laser acts as a source of femtosecond pulses at the wavelength of 1.55 μm. The pulse duration and the repetition rate are 80 fs and 77 MHz correspondingly. The output laser beam having the power of about 220 mW is divided into a pump (90%) and a probe (10%) beams using a beam-splitting cube. The pump beam passes through the acousto-optical modulator (AOM). The modulation frequency is locked with the internal generator of the lock-in amplifier. The modulated signal is transmitted to a THz generator represented by a p-InAs...
crystal in a magnetic field of 0.8 T. Generated terahertz pulses are collimated by an off-axis parabolic mirror and pass through a low-frequency filter that cuts off residual laser radiation. The probe beam passes through an optical delay line consisting of a motorized linear stage with a retroreflector mounted on it and enters the electrooptic crystal detector GaAs simultaneously with the THz pulse.

Figure 1. The scheme of the experimental setup.

The detection is based on the electro-optical Pockels effect [11]. The signal from the optoelectronic unit is acquired using the lock-in amplifier. The digitized signal is recorded by a PC.

3. Samples preparation
The Ga_{50-x}Se_{50-x}S_x samples (where x takes the values: 0, 1.5, 6, 8, 11) were grown from melts using the vertical Bridgman method using the rotation of the thermal field. The atomic concentration of sulfur was determined by the energy dispersive X-ray spectrometer combined with the scanning electron microscope. Samples were prepared by cleaving of two thicknesses: ~ 1 mm to measure the terahertz refractive index and ~ 0.3 mm to measure the detection efficiency of terahertz radiation following the estimated coherence length.

4. Selected results

4.1. IR and terahertz optical properties
Measurements of the optical refractive index of GaSe:S samples of various degrees of doping were carried out on the Metricon system at a wavelength of 1547 nm. The claimed measurement error is 0.003. The measurement results are presented in Table 1.

Table 1. The measured refractive index of Ga_{50-x}Se_{50-x}S_x crystals at the wavelength of 1547 nm.

| x   | \(n_{1547}\) |
|-----|-------------|
| 0   | 2.75        |
| 1.5 | 2.744       |
| 6   | 2.733       |
| 8   | 2.713       |
| 11  | 2.703       |
The terahertz refractive index of the samples was measured on a THz-TDS with a high dynamic range. The description of the spectrometer can be found elsewhere [12-13]. The results are shown in figure 2.

![Figure 2](image.png)

**Figure 2.** Terahertz refractive index of Ga\textsubscript{50}Se\textsubscript{50-x}S\textsubscript{x} samples for the ordinary wave, where x = 0, 1.5, 6, 8, 11.

Presented results show that the inclusion of sulfur elements in the structure of the GaSe crystal leads to the decrease of the refractive index in the IR and THz range.

4.2. *Terahertz waves detection efficiency*

GaAs detection crystal (figure 1) was replaced by the GaSe:S samples to study the efficiency of terahertz radiation detection. Figure 3 shows the acquired waveforms of THz pulses. It can be seen that the sample with x = 6 shows the highest signal amplitude.

![Figure 3](image.png)

**Figure 3.** Detected terahertz pulses waveforms in the GaSe:S samples with different sulfur atomic concentrations.

![Figure 4](image.png)

**Figure 4.** The peak amplitude of the THz signal dependence on the sulfur atomic concentration.

A Scatter plot of the THz peak amplitude dependence (figure 4) on sulfur atomic concentration shows that 6% is most likely not the optimal value which most probably is in the range from 3% to 6%.
4.3. Electrooptical coefficient of GaSe:S samples

Since we only change the crystal in the detection system and the terahertz wave with probing IR pulse are remains the same amplitude and energy, we can compare the electrooptic coefficient of the GaSe:S crystals with those of GaAs for which it is well-known. Considering the length of the crystals, THz, and IR refractive index we can estimate the electrooptical coefficient:

\[ r_{\text{GaSe}} = \frac{L_{\text{GaAs}} n_{\text{GaAs}} (1 - \rho_{\text{GaAs}})}{L_{\text{GaSe}} n_{\text{GaSe}} (1 - \rho_{\text{GaSe}})}, \]

where \( L \) – crystal thickness, \( n_{\text{GaSe}}, n_{\text{GaAs}} \) – IR refractive indices, \( \rho_{\text{opt}} \text{ and } \rho_{\text{THz}} \) – optical and terahertz reflection coefficients, respectively. In our case \( r_{\text{GaAs}} = 1.5 \text{ pm/V} \), \( n_{\text{GaAs}} = 3.4 \), and \( n_{\text{GaSe}} \) is taken from the table 1. The results are shown in Table 2.

Table 2. Electrooptical coefficient of GaSe:S crystals.

| x   | \( r_{22} \) [pm/V] |
|-----|-------------------|
| 0   | 2.80              |
| 1.5 | 2.86              |
| 6   | 2.93              |
| 8   | 3.06              |
| 11  | 3.11              |

5. Summary

In this paper, the efficiency of terahertz waves detection in Ga\(_{50}\)Se\(_{50-x}\)S\(_{x}\%) crystals (where \( x \) takes the values 0, 1.5, 6, 8, and 11) is investigated using femtosecond laser pulses at the wavelength of 1.5 \( \mu \)m. The refractive indices of the samples in the IR and terahertz ranges were measured. It was found that the sample with \( x = 6 \) provides the highest detection efficiency. The efficient value of the electrooptic coefficient of GaSe:S crystals is estimated to be about twice higher than those of GaAs in the same conditions. Thus, it is shown that gallium selenide nonlinear crystals are a promising material for the manufacturing of future-generation telecommunication devices operating at the wavelengths of 1.5 \( \mu \)m.

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