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ELECTRONICS AND RADIO ENGINEERING

Terahertz Devices

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Abstract—The results of the development of terahertz (THz) passive devices for various applications are presented. The main principles of the development and manufacturing technology and the technical characteristics of the developed devices are discussed. The possibilities of using passive THz devices in various systems are considered.

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1. INTRODUCTION

Terahertz (THz) devices are currently successfully used in various fields of science and medicine; they are becoming an integral part of industrial applications as well as in communication systems, security, and measuring equipment. Along with active devices for generating and controlling THz radiation, special passive devices, which make it possible to use the capabilities of THz radiation in research and applied tasks, are also finding practical application. Such devices include diffraction gratings, attenuators, objectives, beam expanders, etc. The design and operating principles of such devices have specific features that distinguish them from similar devices for other frequency ranges.

2. DIFFRACTION THz GRATINGS

THz diffraction gratings are designed to perform spectral measurements in the THz range. A distinction is made between transmissive (clear) and reflective diffraction gratings. THz diffraction gratings can be used in the following areas:

1. THz spectroscopy,
2. THz diagnostic devices,
3. electro–optical installations,
4. astronomy and astrophysics,
5. research into the properties of matter.

The TYDEX company manufactures relief-phase gratings [1] operating in transmission, which allow obtaining the maximum concentration of diffracted radiation energy in a certain spectral order. The periodic structure of such gratings is created by cutting parallel lines—grooves of a triangular profile on a transparent substrate. THz-transparent materials, such as TPX (polymethylpentene) and ZEONEX (cycloolefin polymer), are used as substrates.

The gratings are manufactured in four overlapping bandwidths ranging from 0.28 to 3.12 THz: 0.28–0.55, 0.49–0.98, 0.87–1.75, and 1.56–3.12 THz. The choice of the operating ranges of the gratings is determined by the condition of obtaining optimal characteristics for them (angular dispersion and resolution) as well as the technological capabilities of manufacturing this type of grating.

Calculations of the grating parameters, diffracted wave intensities, and first-order peak positions for individual monochromatic waves were performed within the Fraunhofer approximation. To test the operation and compare the calculated and experimental data, measurements of the characteristics of the gratings were carried out in various optical schemes with different THz radiation generators. The radiation sources were SLOP, a submillimeter methanol vapor laser with optical pumping by tunable CO_2-laser (at St. Petersburg State Technical University), and a free-electron laser FEL (at the Siberian THz Synchrotron Radiation Center at Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences). Figure 1 shows a graph of the dependence of the intensity of a monochromatic wave with $\lambda = 118$ μm on the diffraction angle for TPX gratings with a period $d = 250$ μm, where SLOP was used as a radiation source. Figure 2 shows a graph of the dependence of the intensity of a monochromatic wave with $\lambda = 141$ μm on the diffraction angle for the same grating using FEL. In the second case, a collecting lens was installed between the grating and the radiation detector during measurements. When comparing these graphs, it is

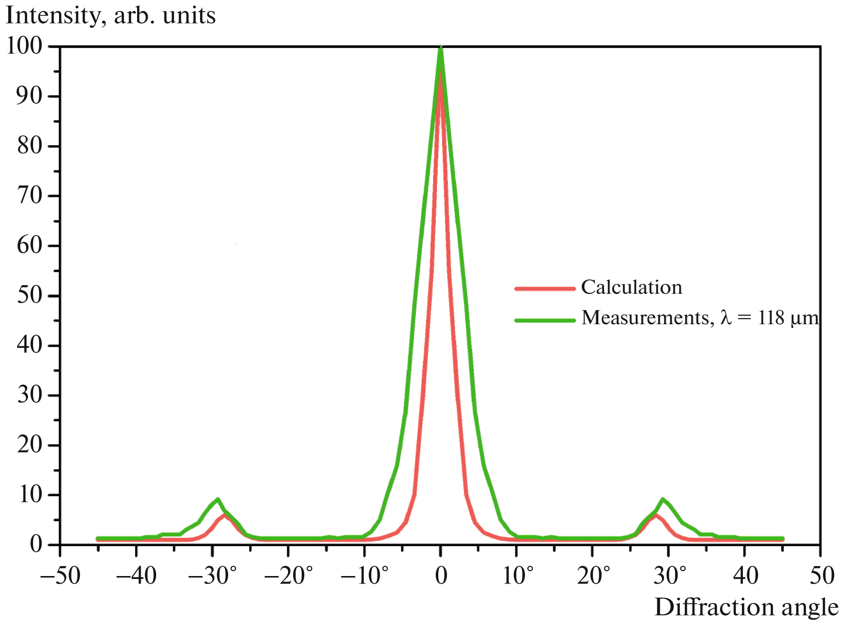

Fig. 1. Dependence of the intensity of the diffracted monochromatic wave with λ = 118 μm on the diffraction angle for TPX diffraction gratings with a period $d = 250$ μm. The radiation source is a submillimeter laser with optical pumping.

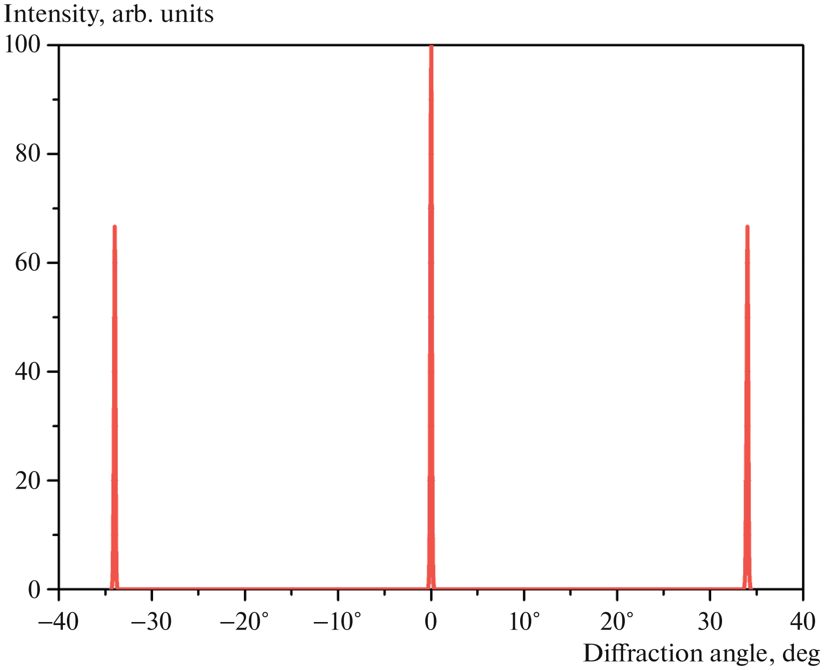

Fig. 2. Dependence of the intensity of the diffracted monochromatic wave with λ = 141 μm on the diffraction angle for a diffraction grating made of TPX with a period $d = 250$ μm. The radiation source is a free-electron laser. A collecting TRX lens was used to record the signal.

clear that, in the first case, the lines of the zero and first order maxima are wider than in the scheme with a lens. This is due to the fact that the converging lens focuses rays traveling parallel. The obtained data should be taken into account by users when preparing experiments depending on the tasks at hand: in the case where the grating is used to study radiation sources (power, beam shape, energy distribution,

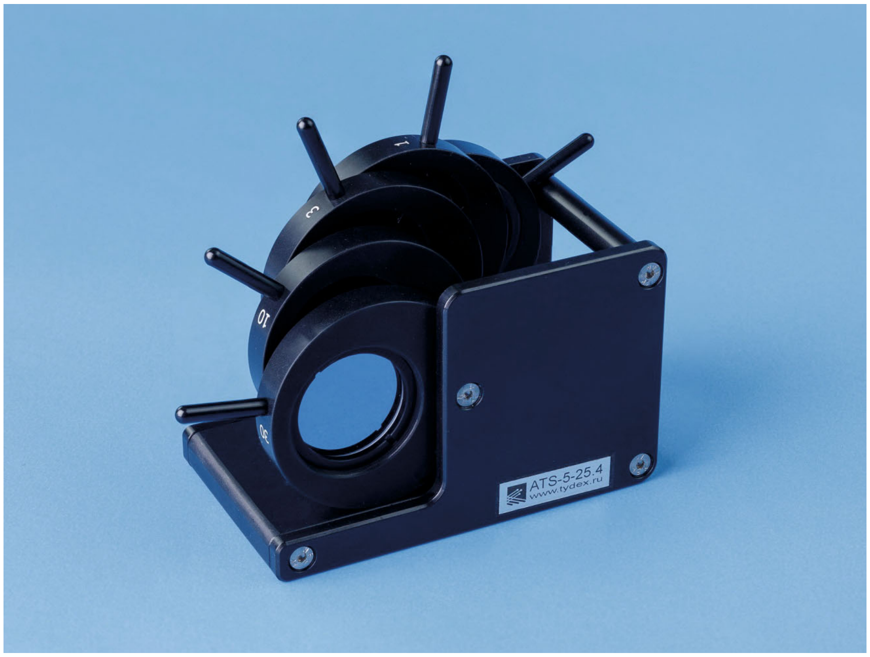

Fig. 3. Device consisting of four attenuators with different attenuation levels.

etc.), a lens may not be used in experiments, but when the task is to resolve spectral lines, a lens must be used.

For a diffraction grating of a specific bandwidth range, which is determined taking into account the Rayleigh criterion, the intensity of diffracted monochromatic waves depends on the wavelength: it is maximum in the middle of the range and decreases as it approaches the edges. For example, for a diffraction grating made of TPX with a period of 250 μm (transmission range of 1.56–3.12 THz or 96–192 μm) for a monochromatic wave with $\lambda = 141$ μm (the middle of the operating range of the grating), the intensity at the first-order maxima is several times greater than for a monochromatic wave with $\lambda = 118$ μm (closer to the edge of the range). This corresponds to theoretical calculations of the intensity of diffracted waves and the position of the first-order maxima for individual monochromatic waves within the Fraunhofer approximation. Since different radiation sources and optical schemes were used during testing of the gratings, the intensity values in the graphs are expressed in relative units.

Measurements of THz relief-phase gratings show that they have high luminosity and resolution of operating maxima. This allows such gratings to be successfully used in the analysis of the spectra of radiation sources, including low-power ones, which is important for research in the THz range.

3. THz ATTENUATORS

Attenuators are designed to attenuate powerful THz radiation. They are used in THz spectroscopy, metrology, and high-frequency communications and imaging systems to regulate radiation intensity over a wide frequency range, while maintaining the temporal shape of pulses and preventing spectral distortions.

The company TYDEX produces devices consisting of four THz attenuators with different attenuation levels mounted in a cassette holder (Fig. 3) [1]. The holder is a structure of five connected ring frames. Each of the four attenuators is inserted into a frame, and one frame is left empty. Another element, such as a cut-off or band-pass filter, can be installed in the empty frame.

THz attenuators are wedge-shaped, silicon wafers coated with a thin metallic film of chromium. The attenuator transmission is 30, 10, 3, and 1%. Some of them are shown in Fig. 4. The operating range of attenuators is 40–3000 μm and more (in accordance with the transmission spectrum of high-resistance silicon HRFZ-Si) [2]. They can be used individually or in combination, allowing for varying levels of attenuation.

4. TUNABLE PRECISION THz ATTENUATOR

Tunable precision THz attenuators are used to precisely control radiation intensity over a wide frequency range. Unlike attenuators with a constant attenuation

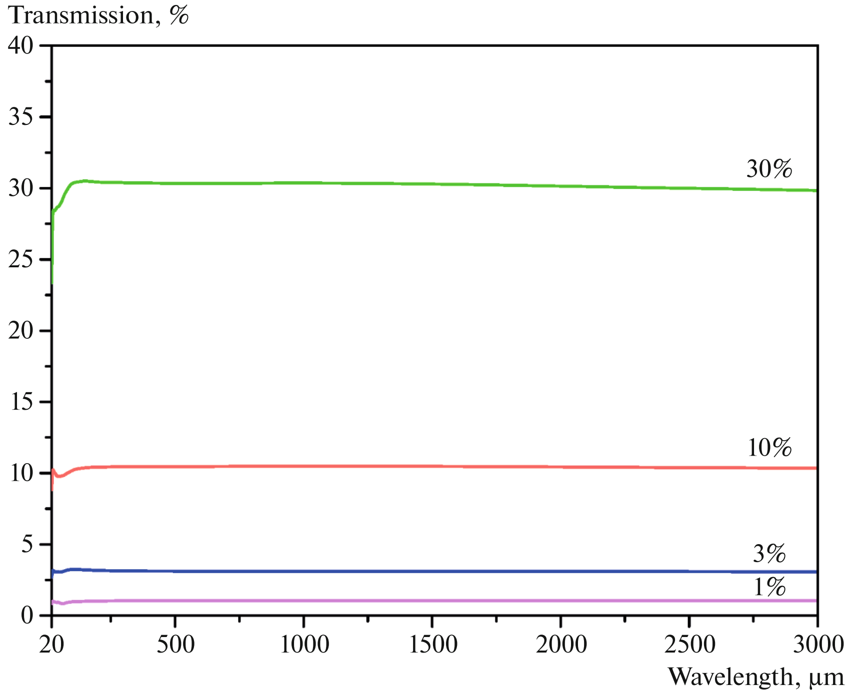

Fig. 4. Transmission spectra of THz attenuators.

level made from silicon wafers, a tunable attenuator is a module of two wire or film polarizers installed in series one after another [3]. Polarizers are installed in rotators that provide 360° rotation and are fixed on a single base. The first polarizer in the radiation path is called the master polarizer, and the second is called the analyzer. The degree of attenuation of the THz radiation intensity, as well as the direction of its linear polarization, is regulated by changing the angle between the axes of the master polarizer and the analyzer.

The advantage of a variable precision attenuator is the ability to smoothly change and precisely set the required attenuation up to 30–40 dB. The design provides the ability to deviate the plane of the polarizers from a parallel position to reduce the effect of reflection and interference.

Depending on the operating wavelength range, the following types of attenuators are offered [4]:

1. an attenuator for microwave radiation for wavelengths of 600 μm and more,
2. an attenuator for THz radiation for wavelengths of 150 μm and more,
3. an attenuator for IR-THz radiation for wavelengths from 15 μm.

Figure 5 shows the dependence of the transmission of the second type attenuator on the orientation angle of the analyzer relative to the reference polarizer, measured on a continuous source with $f = 140$ GHz ($\lambda = 2143$ μm).

Figure 6 shows the spectral calibration characteristic for different analyzer orientation angles.

5. THz LENSES

Terahertz objectives are used to obtain high-quality images when solving visualization problems in the THz range. TYDEX has developed two types of lenses designed to operate in the 4.25–0.094 THz (70–3189 μm) range with a sensor: a matrix of uncooled microbolometers with an aspect ratio of 4 × 3 and a diagonal of 10.4 mm [1]. High-resistance silicon HRFZ-Si is used as lens material. The calculation of the structural diagram of the lenses was carried out on the basis of the calculation method for a thermal-imaging lens [5].

The lenses were tested using a microbolometer matrix with a resolution of 320 × 240 pixels (the pixel pitch is 23.5 μm) in the range of 150–300 μm according to the diagram shown in Fig. 7.

Broadband (150–3000 μm) THz radiation is generated in a 0.5-mm-thick ZnTe crystal by optical rectification using a femtosecond laser with a wavelength of 780 nm and a pulse duration of 25 fs. The pump beam width (FWHM) is 6 mm and the THz beam

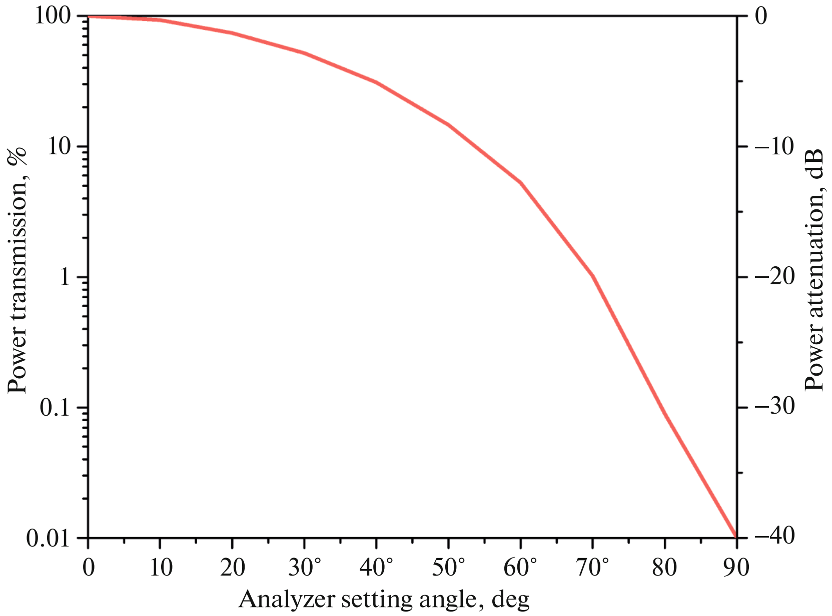

Fig. 5. Dependence of the attenuator transmission on the analyzer orientation angle relative to the reference polarizer, measured on a continuous source with $f = 140$ GHz ($\lambda = 2143$ μm).

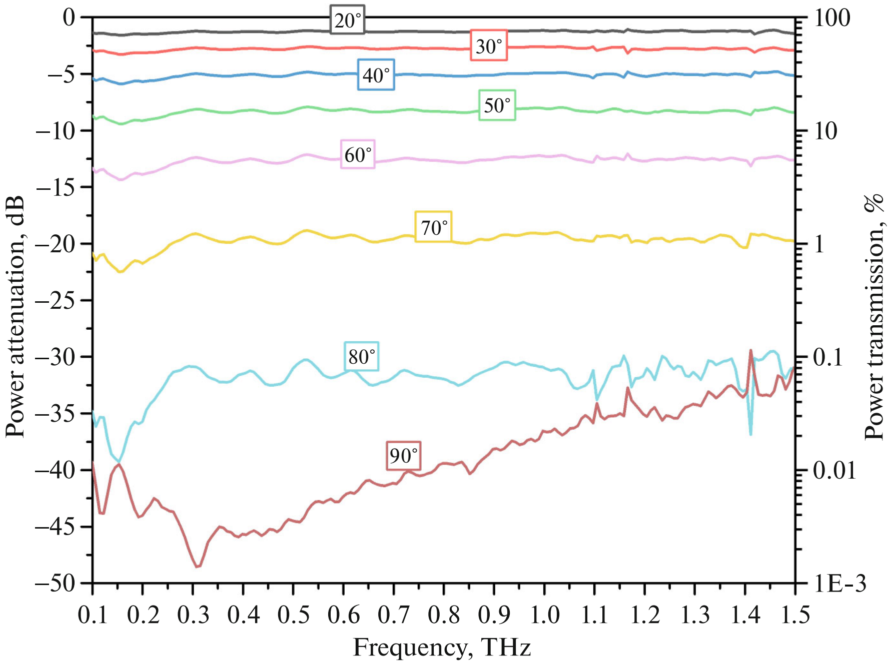

Fig. 6. Typical spectral calibration response of the attenuator for different analyzer orientation angles, measured on a Menlo Systems K-8 pulsed THz spectrometer.

width is √2 times smaller, i.e., 4.2 mm. At a distance L from the crystal, a THz lens is located coaxially, and a THz camera is located behind it at a distance f. The THz camera matrix is located at a distance of 12.9 mm from the input end. The THz camera matrix is sensitive in the range from 30 to 300 μm. Figure 8 shows the THz beam waist profiles for $L = 200$ mm, $f = 15$ mm, and $k = 0.95$ (number k is defined as F/D, where F is back focal length and D is diameter of the entrance pupil of the lens). The constriction width was 260 μm.

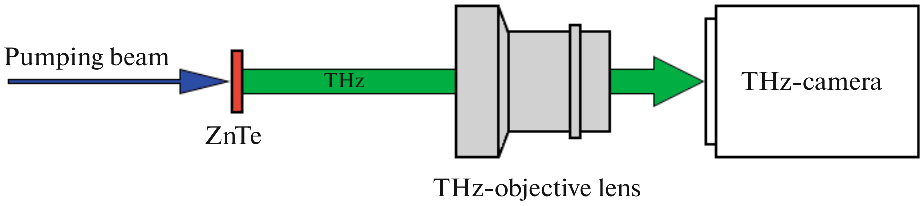

Fig. 7. Scheme of the experiment for testing THz lenses.

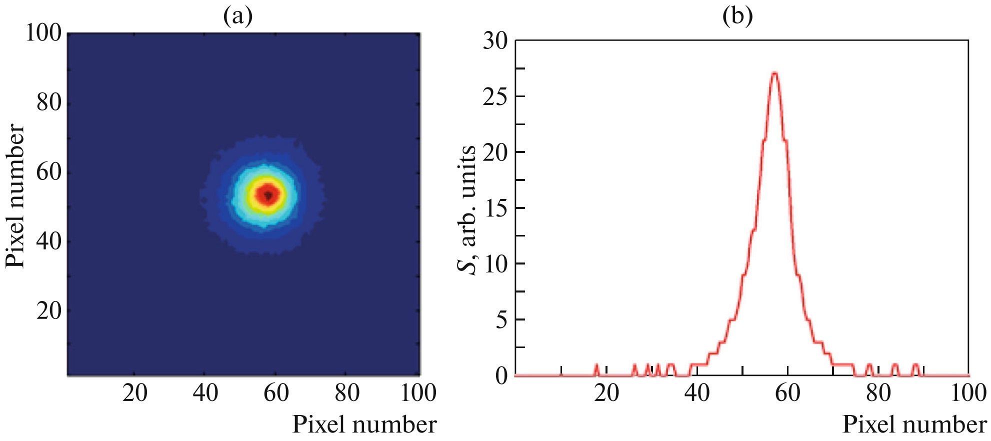

Fig. 8. THz beam waist: (a) picture of a THz radiation beam, (b) dependence of the signal on the pixel number in the matrix row.

The results of the experiment confirm the correct operation of the lens.

6. THz BEAM EXPANDERS

Terahertz beam expanders are designed to increase or decrease the diameter of parallel THz beams. Some of them are shown in Fig. 9. The two-lens THz expanders are based on the Galilean design and provide low-aberration operation. They are diffraction-limited systems that reduce the influence of the divergence of the expanding beam. Beam expansion allows focusing of THz radiation into a diffraction-limited focal spot. In this way, the highest power density can be achieved in the system.

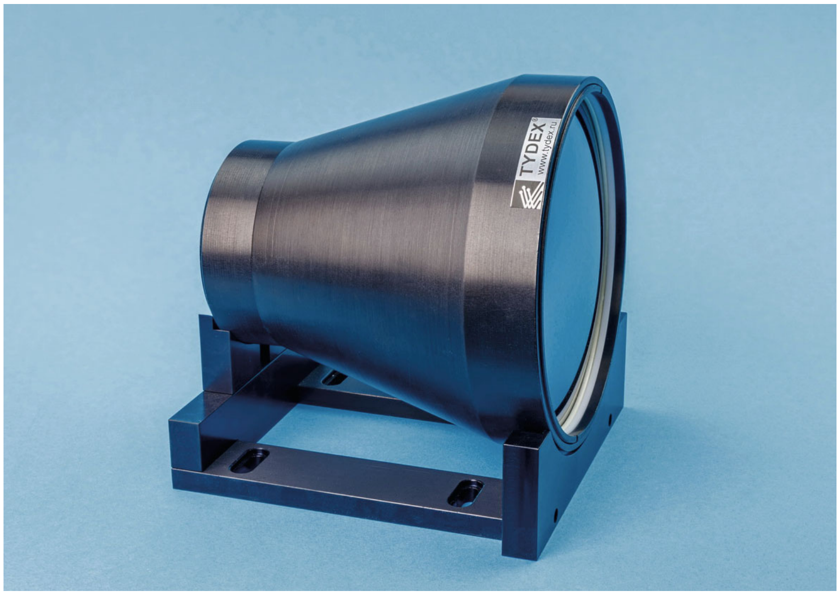

Fig. 9. THz beam expander.

Table 1. Characteristics of THz lenses

Parameters	Lens type	
	44/0.95	44/0.7
Focal length, mm	44	
Working range, μm	50–8000 (6 THz–37 GHz)	
Aperture number	44/0.95	44/0.7
Distance to the object, cm	≥90	≥60
Dimensions (clear aperture/diameter × length), mm^2	Ø57/Ø90 × 74.5	Ø71/Ø105 × 74.5

Table 2. Main parameters of THz expanders

Expansion (compression) coefficients	×2	×5	×10
Lens material	HRFZ-Si		
Operating range, μm	50–8000 (6 THz–37 GHz)		
Maximum input beam diameter, mm	72	28.8	14.4
Total transmittance*	65%		
Wavefront distortion ~50 μm	0.03λ	0.06λ	0.04λ
Overall dimensions, mm^3	156 × 156 × 186	166 × 154 × 203	166 × 154 × 257

The asterisk indicates transmission with double-sided anti-reflective coating on both lenses.

Terahertz beam expanders can be used with both continuous and pulsed radiation sources. These expanders have large input and output apertures, allowing them to be used with a variety of input beam diameters.

To suit the required operating range, a THz antireflective coating can be applied to the expander lenses.

The TYDEX company manufactures expanders with expansion (compression) coefficients: ×2, ×5, and ×10 [1]. The Zemax optical system computer simulation software was used to calculate the expansion. The main parameters of these expanders are presented in Table 2.

Figure 10 shows the experimental scheme for testing THz expanders. A ferrite circulator emitting at a frequency of 100 GHz ($\lambda = 3$ mm) was used as a source of THz radiation. The THz camera MICROXCAM-384I-THZ manufactured by INO with a lens manufactured by TYDEX LLC (*f*/0.7) was used as a radiation receiver. The source generates a parallel beam with a diameter of 10 mm (Fig. 11a). The beam diameter is measured at level $1/e^2$. The camera records the image obtained without the expander and with the expander.

The results of testing the expander with an expansion coefficient of ×2 are shown in Fig. 11. It follows

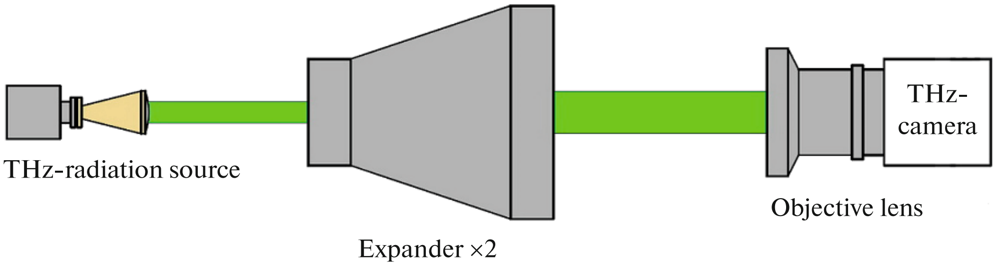

Fig. 10. Experimental scheme for testing THz expanders.

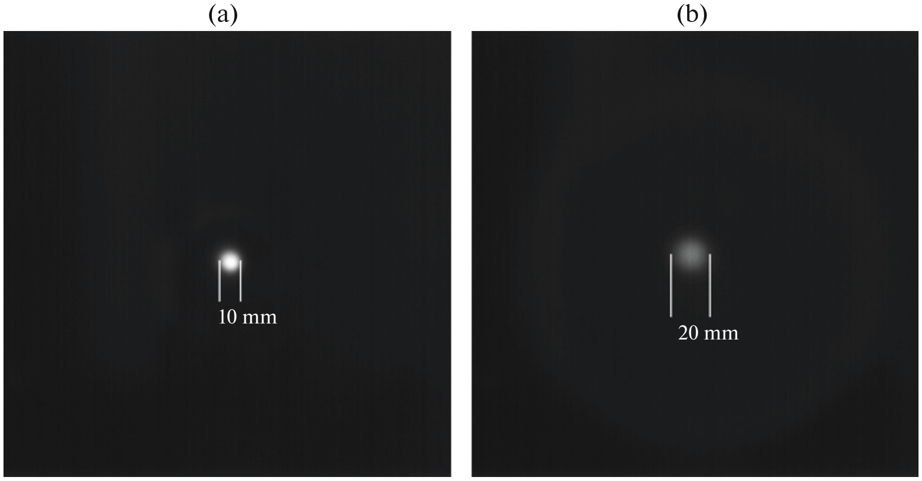

Fig. 11. (a) Image of the beam without the expander. (b) Image of a beam that has passed through the expander.

from the obtained results that the expander increases the beam diameter by two times.

To increase the overall transmittance, the THz expander lenses can also be made of TPX.

7. CONCLUSIONS

Until recently, the limited use of THz radiation in science, and especially in applications used in medicine, industry, and security systems, was due to the lack of inexpensive optical components and devices. The devices considered in this paper make it possible to solve various problems associated with the use of THz radiation. These devices are relatively inexpensive and reliable when working with virtually any THz radiation source, and they provide high technical characteristics for the devices and systems in which they are used.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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