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GENERAL EXPERIMENTAL TECHNIQUE

Fabry–Perot Terahertz Scanning Interferometer

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Abstract—A terahertz (THz) Fabry–Perot scanning interferometer designed to measure the wavelength and intensity of narrow-band THz radiation, as well as to filter it, has been developed. Measurements have been carried out confirming the possibility of using the device in the entire THz range. The characteristics of various modifications of FPI are given.

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1. INTRODUCTION

Fabry-Perot interferometers (FPI) are widely used in spectroscopy, quantum electronics, astrophysics, spectral analysis, metrology, and other fields. The classical FPI is a key element in tunable infrared (IR) and terahertz (THz) filters. However, their high resolution can only be realized when the reflectivity of the outer filter plates is close to unity [1]. The disadvantages of FPI include the relative complexity of the design, due to the presence of mechanisms for maintaining strict parallelism of the mirrors, as well as insufficient contrast (sharpness) of the spectral pattern.

The Fabry-Perot interferometer for the THz wavelength range is an effective tool for analyzing radiation in this range; it is widely used in various systems where spectral analysis is required.

FPI is made on the basis of an optical resonator consisting of two parallel plates spaced apart by a distance d, between which there is an optical medium with a refractive index n. By changing the distance d, spectral restructuring of the filter is carried out between the plates. Figure 1 shows the diagram and the transmission dependence T from the wavelength λ of the FPI-based tunable filter. If the absorption of the FPI plates is equal to A and reflection is R, then transmission T is determined by the Airy formula [2] as

$$T = \left[1 + \frac{A}{T_0}\right]^{-2} \left[1 + \frac{4R_0}{(1 - R_0)^2} \sin^2\left(\frac{\delta}{2}\right)\right]^{-1}, \tag{1}$$

where R_0, T_0, and A are coefficient reflection, transmission, and absorption values for one plate (mirrors), respectively. Absorption, supposed small, equals

$$A \approx 1 - T_0 - R_0, \tag{2}$$

$$\delta = 4\pi n d \sigma \cos\theta - 2\varphi(\sigma), \tag{3}$$

where δ is the phase difference, related to optical paths d length at passing one photon there and back. Here, θ is the primary angle of incidence of the rays on the interferometer, φ is the phase shift of reflection, and $\sigma = 1/\lambda$. Distance between neighboring highs makes up half-length waves. Maximum FPI throughput

$$T_0 = \left(1 - \frac{A}{1 - R}\right)^2 = \left(1 + \frac{A}{T}\right)^{-2}, \tag{4}$$

in the q-order at wavelength λ_q is determined from the condition that $\delta = 2\pi q$, where $q = 1, 2, 3, \ldots$.

The resolving power of the interferometer for the first order is defined as

$$Q = \frac{\lambda_q}{\Delta\lambda} = qF, \tag{5}$$

where $\Delta\lambda$ is the half-width of the passband centered at λ_q, while F is the so-called finesse factor of the bandwidth, which, when $R \geq 0.6$, is defined as

$$F = \frac{\pi}{\left(2\arcsin\frac{1 - R}{2R^{1/2}}\right)} \approx \frac{\pi R^{1/2}}{1 - R}, \tag{6}$$

it is the ratio of the distance between two adjacent interference maxima l to the width of the interference maximum w (Fig. 1).

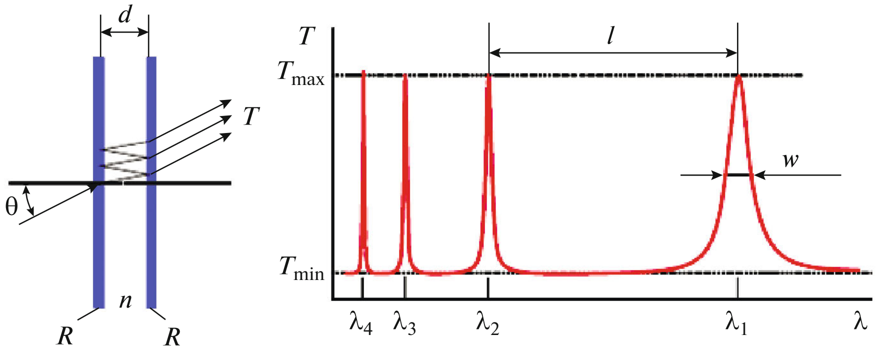

Fig. 1. Schematic representation and transmission spectrum of FPI.

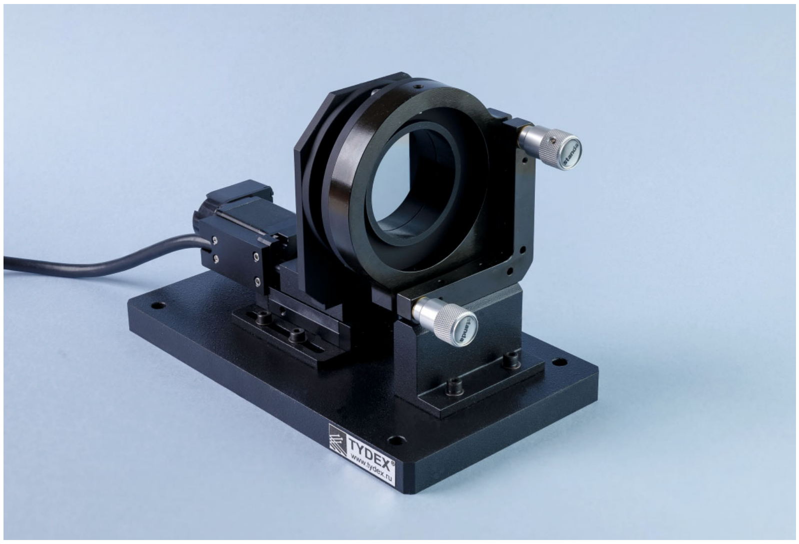

Fig. 2. Scanning FPI of THz radiation from TIDEX.

2. SCANNING FABRY-PEROT INTERFEROMETER FOR THE THz RANGE

The THz scanning FPI developed by TYDEX (Fig. 2) is a high-resolution, high-transmission spectral multibeam interference instrument designed to measure the wavelength and intensity of narrowband THz radiation. It can be used to work with both pulsed and continuous sources of narrowband THz radiation. The device consists of two parallel silicon (Si) mirrors, one of which is mounted on a motorized linear translator [3]. The mirrors are made from zone-melted Si with a resistivity of at least 10 kΩ cm; they have the form of plane-parallel double-sided polished plates. The mirrors provide a transmittance to reflectance ratio of (54/46)% [4]. The advantages of Si mirrors are relative their simplicity in production and the capability to encompass a region spectrum from 30 μm to microwave range total in a couple mirrors. Measurement of THz radiation parameters occurs by moving a movable mirror (scanning). The characteristic value of the sharpness factor for the 30–300 μm range is approximately 10, while that for the 300–3000 μm range is approximately 7.

Figure 3 shows one of the possible device-installation schemes. The given scheme is used to analyze the spectrum of a THz radiation source. Any THz radiation detector suitable for the spectral sensitivity range (for example, a Golay cell [5]) can be used as a receiver. The spectral ranges of the THz radiation source and FPI, as well as the spectral sensitivity range of the receiver, must be mutually consistent, i.e., they must overlap.

The device's software package processes the signal from the receiver and ensures the device operates with

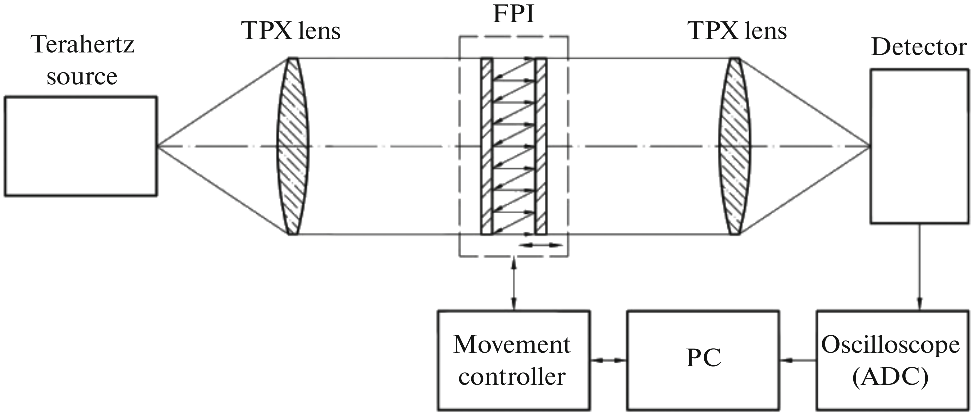

Fig. 3. Schematic diagram of the operation of the scanning FPI.

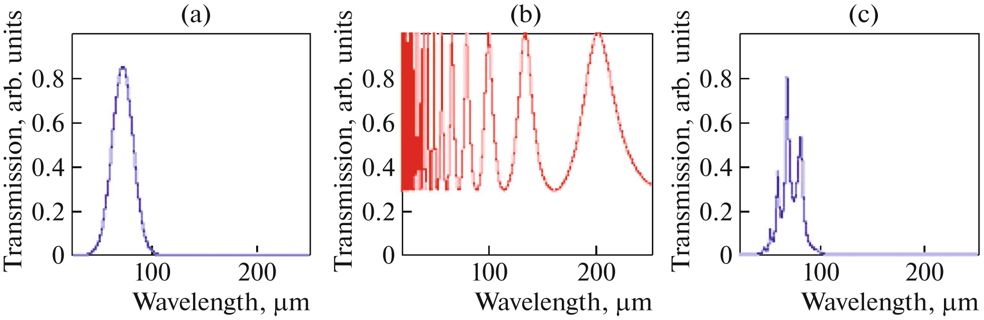

Fig. 4. Transmission spectrum of scanning FPI at a distance between mirrors of 500 μm: (a) spectrum of radiation incident on FPI, (b) transmission spectrum at a fixed distance between the mirrors, (c) radiation spectrum after passing through the device.

and without a PC. The software runs on the Windows 7 or Windows 10 operating system and communicates between the PC and the device via a USB interface.

In general, the response of the interferometer $I(d)$ (the dependence of the signal at the receiver on the distance between the mirrors) is described using a certain integral over the wavelength of the product of the kernel $J(\lambda, d)$ on the desired spectrum $I(\lambda)$ (dependence of spectral amplitude on wavelength):

$$I(d) = \int_0^\infty J(\lambda, d) I(\lambda) d\lambda. \qquad (7)$$

Core (λ, d) is a matrix of values of the FPI hardware contour (HC) function calculated for different wavelengths and distances between FPI mirrors.

The HC of a device is understood as the spectral distribution of the signal at the output of a spectral device with a monochromatic input signal. It differs from the HC of the interferometer itself since the recorded interference pattern bears traces of the influence of all components of the installation. The developed mathematical apparatus allows calculating the spectrum of radiation entering the FPI in an arbitrarily wide range of wavelengths. The imposed restrictions are of a purely technological and production nature. Implementation of the solution to the restoration problem spectrum of THz radiation entering the interferometer is provided by software developed for these purposes.

The device can also be used to measure the wavelength and intensity of broadband THz radiation sources and to filter THz radiation according to the FPI transmission spectrum (Fig. 4).

The position of the transmission peaks (interference maxima) is calculated using the formula

$$\lambda_m = \frac{2d}{q}, \qquad (8)$$

where d is distance between FPI mirrors, q is interference order, and λ_m is position of maximum interference.

The device is controlled by a motorized movement with a built-in decoder; the movement is controlled

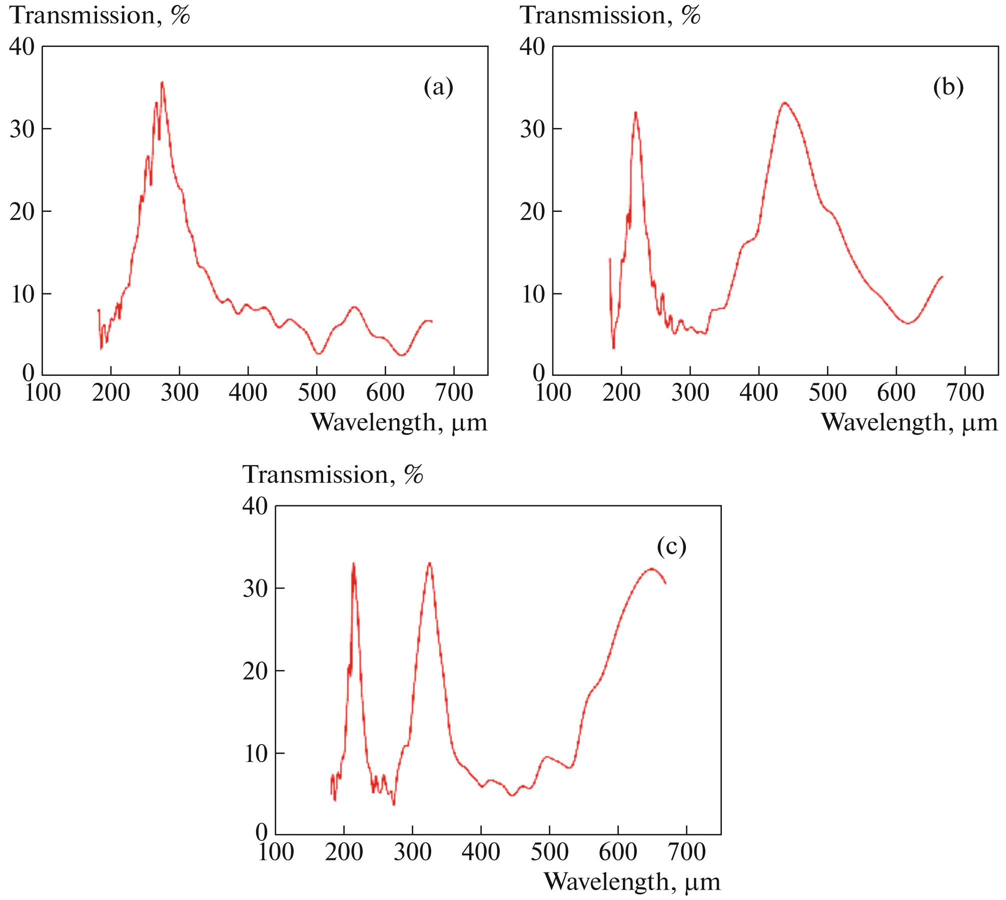

Fig. 5. Transmission spectra of scanning FPI with silicon mirrors: (a) distance between the mirrors is 150 μm, (b) distance between the mirrors is 225 μm, (c) distance between mirrors is 325 μm.

using XILab software. The decoder allows one to accurately set the distance between the FPI mirrors. The device can implement the following options for mirror movement: mirror movement to a given position, mirror shift by a given distance, continuous mirror movement, and cyclic mirror movement. It is also possible to set the speed of the mirror movement, the intervals between movements, and the initial and final positions of the mirror.

Filtering of the incident THz radiation according to the transmission spectrum is carried out by changing the distance between the FPI mirrors. To change the bandwidth, it is necessary to move the interferometer mirrors apart by a given distance, calculated using formula (8). Figure 5 shows a typical dependence of the change in the bandwidth of the scanning FPI on the change in the distance between the mirrors. Transmission spectra were obtained on a Bruker Vertex 70 Fourier transform spectrometer at different distances between mirrors.

The device can also operate in scanning mode. To do this, it is necessary to set the required range of movement of the mirrors and enter the number of repetitions into the motorized movement control program. Figure 6 shows the result of measuring the wavelength of a continuous submillimeter HCOOH laser with optical pumping by tunable CO_2-laser using FPI scanning. During the experiment, the laser operated at a wavelength of 432.6 μm. As follows from the graph, the arithmetic mean distance between adjacent transmission maxima, measured as (433 μm – 216 μm = 217 μm), (647 μm – 433 μm = 214 μm), (865 μm – 647 μm = 218 μm), is (217 + 214 + 218) μm/3 = 216.3 μm, which exactly coincides with half the laser generation wavelength. This result is also consistent with theoretical calculations of the positions of the FPI transmission maxima using formula (8).

To measure the integrated intensity of the THz beam that passed through the interferometer, a series of transmission spectra are measured depending on the position of the mirrors. These spectra are then integrated over a fixed range of wavelengths. The value of the integral corresponds to the integrated intensity measured by a nonselective receiver of any type. Fig-

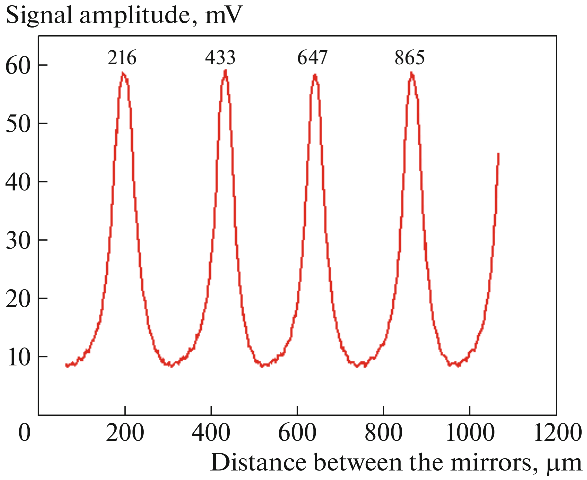

Fig. 6. Dependence of the signal from the THz radiation detector on the distance between the FPI mirrors. Source: submillimeter laser with optical pumping, λ = 432.6 μm.

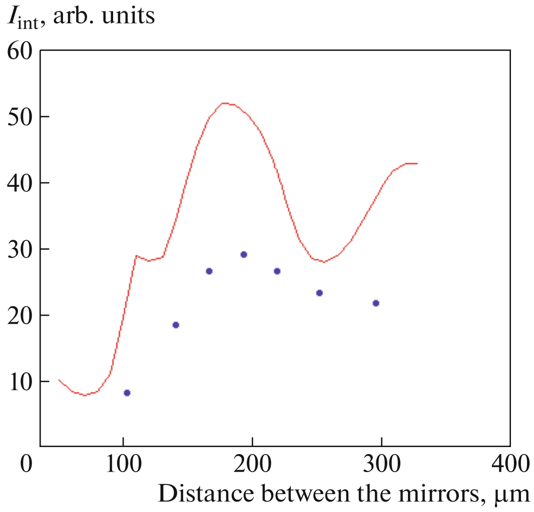

Fig. 7. Integrated intensity of the THz beam that passed through the interferometer, depending on the distance between the mirrors. The series of blue dots are experimentally obtained values. The red curve is the theoretically calculated intensity dependence.

ure 7 shows the dependence of the integrated radiation intensity of the mercury lamp of the Fourier spectrometer on the distance between the FPI mirrors.

The scanning FPI can be used to measure the radiation parameters of gyrotrons, optically pumped submillimeter lasers, backward-wave tubes, free-electron lasers, difference-generation THz radiation sources, photomixing THz radiation sources, quantum cascade lasers, p-Ge lasers, and fundamentally new THz radiation sources.

TYDEX produces four different modifications of FPI, differing from each other in the width of the gap between the mirrors, the height of the optical axis, and the light diameter. Table 1 presents the main parameters of all modifications.

To isolate a specific emission band, bandpass filters can be additionally supplied to the FPI [6] to the desired wavelength in the range from 0.1 to 15 THz.

3. CONCLUSIONS

In the THz range, FPIs have until recently been mainly used in narrow spectral ranges for peak series separation tasks. The novelty of the approach in this device lies in the adaptation of the interferometric scheme to a wide spectral range, covering the entire THz range and further up to a frequency of 20 GHz (λ =1.5 cm). For this purpose, high-resistance Si mirrors are used to manufacture FPI. A mathematical apparatus has also been developed for this purpose,

Table 1. Optical-mechanical parameters of FPI

Parameter	Modification			
	TSFPI-1	TSFPI-2	TSFPI-RF-1	TSFPI-RF-2
Device operating range, THz	0.1–15		0.02–15	
Free dispersion region, THz	0.01–1.8			
Width of the gap between mirrors, mm	0–9.5		0–29.5	
Gap setting accuracy, μm	±1.25			
Optical axis height, mm	53	110	53	110
Light diameter, mm	26	52	26	52

with the help of which the spectroscopic problem of reconstructing the spectrum of a THz signal incident on the interferometer is solved.

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CONFLICT OF INTEREST

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

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