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Millimeter-wave band subsurface sounding module

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Abstract: **Radio-wave devices are used for many environmental and material research tasks. These devices and the development of relatively simple and affordable quasi-optic radio wave receivers and transmitters of millimeter and terahertz bands are important for numerous applications. Results of the design of a terahertz-band quasioptical transmitter-receiver module are presented. The module is intended for the remote detection of various objects and for measuring the depolarized field components backscattered by various long objects hidden behind obstacles (building materials and/or everyday items that prevent visual contact with the objects). These may be interfaces between materials with different dielectric constants, fiber optic cables, electric cables, and other objects. Results of full-scale experimental testing of the module on the detection of electric cables buried under plater in the wall of a building are presented.**

Keywords: **microwave module, millimeter and terahertz bands, quasi-optical devices, waves depolarization effect**

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Contents

1. INTRODUCTION

With the development of solid-state electronics, millimeter and terahertz band waves are being intensively used for solving scientific and engineering problems. The development of relatively simple and inexpensive terahertz-band quasi-optical transmitter-receiver systems is important for many applications. These may be spectroscopy, detection and visualization of various objects hidden in building structures or under clothes, new methods of diagnostics in medicine, atmospheric control, and many other applications. Of great importance is studying the electrodynamic parameters of various materials, detection and localization of small-size objects, not only metallic, but also dielectric ones.

The purpose of this work is to present the results of the development of a receiving-transmitting radio-wave quasi-optical terahertz module for problems of subsurface sensing.

2. PURPOSE OF THE DEVICE

The module is designed for remote detection of reflections and measuring the reflection coefficients of various objects in the millimeter and terahertz wavelength ranges. These can be dielectric or metal objects and interfaces between materials with different dielectric constants. The module can be used both for studying the internal structure of spatially inhomogeneous media and measuring the depolarized field component backscattered by various linear (elongated) objects, including microwires, wires, fiber-optic cables, etc., and for detecting objects hidden behind building structures (drywall, plywood, brick, wallpaper, etc.) or behind fabrics, leather and other non-transparent household materials.

3. OPERATION PRINCIPLE

Metallic or dielectric objects in optically opaque media with dielectric constant different from the dielectric constant of the objects can be detected by radio wave transmission or reflection radio wave methods [1,2]. The thickness of building structures limits the applicability of transmission methods due to the losses in the building materials. To detect hidden anomalies at shallow depths, one can apply the radar method, which significantly reduces the effect of absorption in the environment. However, in such schemes, wave reflections at the interfaces have a great interfering effect. In order to get rid of this, it is proposed to use the phenomenon of radio wave depolarization in the case of scattering by linear inhomogeneities.

The operating principle of this method is described in [2]. It consists in the fact that if the orientation of the linear object differs from the polarization direction of the incident wave, then the reflected wave has a component with polarization orthogonal to the polarization of the incident wave. The receiver of the reflected wave has a polarizing filter that transmits only the depolarized field component. This allows one to get rid of the interference of reflections at the interfaces of building structures, to significantly reduce the noise level, and, accordingly, to increase the signal-to-noise ratio of the signal reflected from objects hidden behind building structures. To substantiate this method of detecting objects behind obstacles, we measured the reflection coefficients and the polarization conversion coefficients of a number of objects [2]. The measurement results showed that the use of the depolarized component of the reflected wave to detect small-diameter wires does not lead to a loss of the energy potential of the device.

The microwave part of the module contains a linearly polarized microwave source (transmitter), as well as a linearly polarized microwave radiation receiver with polarization orthogonal to that of the transmitter [2]. The development of such a module on the basis of ordinary waveguides would lead to a bistatic location system, which significantly complicates the design, or to the use of ferrite microwave elements, which are currently little used in the terahertz range. Therefore, we decided to implement such a module in a quasi-optical version.

4. DESIGN AND COMPOSITION OF THE DEVICE (MICROWAVE MODULE)

The diagram of the device (microwave module) is given in [2]. It consists of a microwave oscillator, a waveguide-to-beam-guide converter (WBC), a beam-guide module, a beam splitter, a lens that forms the output microwave beam, and a receiver. The receiver includes a polarizing filter, waveguide-beam converter, a detector head, and an amplifier. The device also includes a power supply and a microwave modulator. The microwave power is modulated through the feeding circuit of a Gunn oscillator with operating frequency of 1 kHz.

A plane linearly polarized wave from a microwave oscillator formed by a waveguide-beam converter into a quasi-optical beam is incident on a plane grating of linear conducting elements, which is located at an angle of 45° to the direction of wave propagation. The conductors of the grating are parallel to the electric field of the wave and completely reflect the wave toward the boundary of the test medium. The wave of orthogonal polarization arising from scattering by the object is not reflected by the grating, but is completely transmitted to the receiver. The receiver consists of a polarizing filter, a waveguide-beam transducer, and a detector head.

Consider the design features of some elements of the microwave module. The microwave oscillator, detector heads, and power supply are purchased items.

The beam-guiding module or, as we call it, a prism, is made of Plexiglas and is the supporting structure. We called this element (prism) a beam-guiding because it contains cylindrical channels in which a microwave beam propagates. All other elements of the microwave module are mounted to this prism: the oscillator with the WBGC, the beam-splitting grating (in some cases a beam-splitting film), the polarizing filter, the detector head (with the WBGC). The diameter of the quasi-optical beam was chosen to be 16 mm. It is known that the amplitude distribution of the field in the horn opening is similar to the distribution of the field in the feed waveguide, and the phase in the aperture changes according to the quadratic law. Therefore, to form a wave with a plane front, a phase corrector is placed in the horn opening. In our case, this is a Teflon lens. The quasi-optical system should satisfy the condition $ka >> 1$, where $k = 2\pi/\lambda$ and a is the transverse size of the beam. The ratio $C = ka/L$ is a parameter characterizing the diffraction spread of the beam during its propagation in the path [3]. L is the length of the beam or the distance to the working area. At small L, the diffraction losses are also small. These and some minor circumstances forced us to choose a quasi-optical beam diameter of 16 mm.

A variety of devices made of wire gratings or thin dielectric plates to control wave propagation in quasi-optical systems have been described in the literature [4,5]. If a grating is placed at an angle of 45° to the direction of wave propagation and its conductors are parallel to the electric field vector, then the field is completely reflected from the grating, while if the conductors are perpendicular, then the wave completely passes through the grating. In our module, we use a small-period wire grating. It is glued to a special frame inserted into a groove in the prism at an angle of 45° to the incident

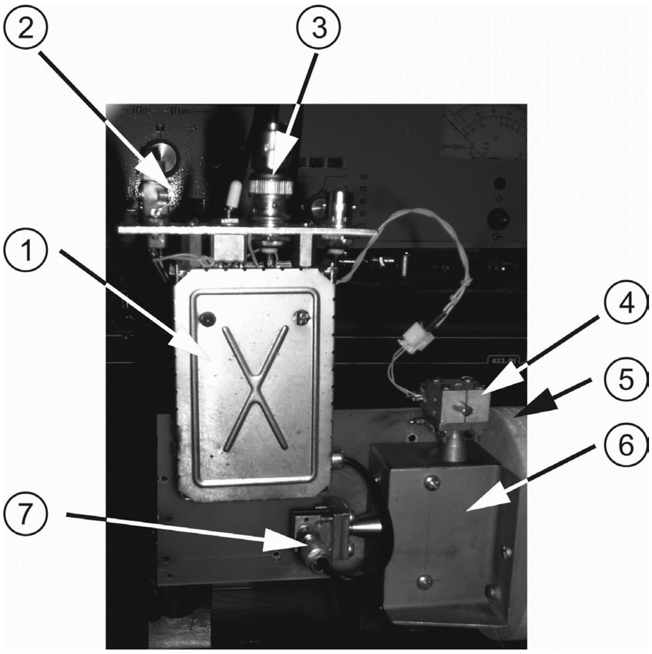

Fig. 1. *Photo of the microwave module with a tube for the lens antenna 1 – amplifier and modulator of the supply voltage, 2 – power connector of the amplifier and the Gunn diode, 3 – amplifier output connector, 4 – Gunn oscillator, 5 – tube for mounting the lens-antenna, 6 – prism, and 7 – detector.*

wave and deflects the beam. **Fig. 1** shows a photograph of the microwave module with all the elements of the module, including the tube on which the lens-objective is mounted. The lens-objective is a receiving-transmitting antenna for a quasi-optical beam and allows focusing the beam at the required distance.

The operation of the module with a lens antenna is discussed below in Section 5.

5. OPERATION OF THE MODULE WITH A LENS-OBJECTIVE

For remote measurements, it is necessary to form a beam focused at a certain distance from the microwave module. **Fig. 2** shows a diagram of a single-channel module operating at a frequency of 100 GHz with a lens-objective (antenna) forming a focused

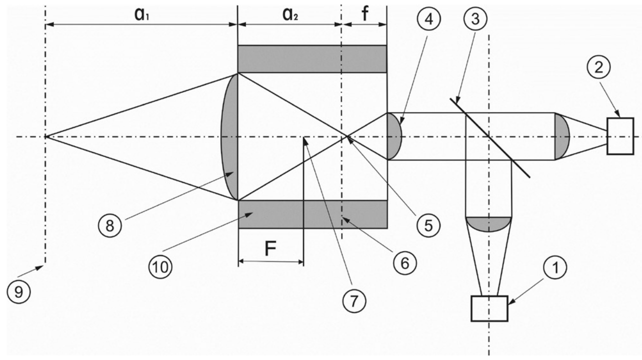

Fig. 2. *Scheme of the microwave module with a lens-antenna (objective). 1- oscillator, 2 - receiver, 3- grating, 4 - ocular lens, 5 - ocular focus, 6 - image plane, 7 - objective focus, 8 - objective, 9 - object plane, and 10 - tube.*

beam. This scheme was implemented in laboratory conditions.

The lens antenna is calculated by the formula [6]:

$$F = \{[D/2\,(n-1) - t](n+1)\}/2t.$$

The antenna is made of Teflon F-4 with a refractive index of n = 1.427. The lens diameter is D = 70 mm. The focal length of the lens F = 90 mm was chosen for the convenience of using the microwave module with the lens. The lens thickness at the center is t = 13.5 mm.

The ocular is a spherical lens made of Teflon F-4 with thickness at the center t = 2.3 mm. The lens diameter is d = 16 mm. The lens was calculated by the formula

$$f = (d/2)/2t(n-1).$$

The focus of the lens is 32.5 mm.

The image plane passes through the focus of the ocular lens (perpendicular to the optical axis). For optimal use of the lens aperture, the latter was placed at a distance a2 from the image plane, which is calculated by the formula

$$a_2 = D \cdot f / d.$$

This distance turned out to be a_2 = 142.2 mm.

Now, we find a_1 – the distance from the lens to the plane of the object:

$a_1 = (a_2 \cdot f)/(a_2 - f)$.

The plane of the object is located at a distance a_1 = 244.4 mm from the objective lens.

Thus, a point of the object is mapped to a point on the image plane, which passes through the ocular focus perpendicular to the optical axis of the system. Then, the signal corresponding to this point is converted into a signal from the detector by the waveguide-optical system of the module.

A point of an object on the optical axis is irradiated by a wave formed by the WBGC, the grating, the ocular lens, and the objective lens (antenna). The tube is a foam plastic tube that structurally integrates the lens and the module. The length of the tube is $a_2 + f$ = 174.2 mm. The optical scheme was tested on the resolution of two conductors. Two conductors 0.5 mm in diameter without insulation and 0.07 mm in diameter (MGTP wire in Teflon insulation with a diameter of 0.5 mm) were attached to the back side of a plate 8-mm-thick foam plastic at a distance of 10 mm from each other. When the foam plate was moved in the plane of the object (at a distance of ~240 mm from the objective), the signal at the receiver output has a two-hump shape, the dip between the humps being about 3 dB. In natural conditions, the device was tested to find electrical wiring hidden behind plaster in the wall of an industrial building. The excess of the signal from the cables of the wiring system was also 3 dB.

If, instead of a polarizing reflective grating placed in the module at an angle of 45° (see Fig. 2), we place a dielectric (Mylar) film in the prism of this microwave module, and turn the receiver to receive the main polarization emitted by the oscillator, then the module can be used as a reflectometer to measure not only external boundaries, but also internal inhomogeneities of various materials.

6. CONCLUSIONS

This design of the device expands the possibilities of its application in detecting linear objects buried in building structure and improves the resolution and other technical characteristics necessary for further modifications of microwave modules for subsurface sounding.

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