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Simulation of Electromagnetic Characteristics of a Terahertz Receiver

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Abstract. Electromagnetic radiation of the terahertz range (THz) is used in various fields of science and technology: medical diagnostics, security and control, sensor and communication technologies, scientific research, etc. Computer simulation in the development and research of THz receivers significantly reduces costs and time-to-market by replacing expensive experiments. Advanced software suites, like HFSS, facilitate the accurate modeling of intricate three-dimensional configurations and the analysis of component electrodynamic performance. This study leveraged HFSS to simulate the performance of a THz receiver across the 0.4–1.4 THz band. The accuracy of the simulations relies on the fidelity of the model, encompassing geometric details, material properties, and chosen simulation parameters. This paper proposes a three-dimensional model of an original selective compact receiver of terahertz electromagnetic radiation (with a conversion efficiency of ~97 %) for two resonance frequencies, consisting of a sensor based on two open apodized periodic microcavity structures with a fill factor changing according to a linear law, a matching element in the form of an asymmetric irregular triangular strip line, and a detecting diode. The design offers key advantages including high conversion efficiency, suitability for matrix architectures, high selectivity to registered radiation, and the potential for simple readout methods, making it an attractive approach for THz sensing, an important tool across various scientific and practical applications.

Keywords: sensor, detecting diode, terahertz radiation, 3D model, resonance frequency, HFSS, conversion efficiency, reflection losses, directivity

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Моделирование электромагнитных характеристик приемника терагерцового излучения

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Реферат. Электромагнитное излучение терагерцового диапазона (ТГц) находит применение в различных областях науки и технологии (медицинская диагностика, безопасность и контроль, сенсорные технологии, коммуникационные технологии, научные исследования и т.д.). Компьютерное моделирование в разработке и исследовании ТГц-приемников значительно сокращает затраты и время вывода продукта на рынок, заменяя дорогостоящие эксперименты. Современные программные комплексы, такие как HFSS, позволяют точно моделировать сложные трехмерные конфигурации и анализировать электродинамические

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характеристики компонентов. В рамках исследования параметров ТГц-приемника в диапазоне 0.4–1.4 ТГц использовалось моделирование в HFSS, где точность результатов зависит от корректности модели, включая детализацию геометрии, свойства материалов и параметры симуляции. В данной работе предложена трехмерная модель оригинального селективного компактного приемника электромагнитного излучения терагерцового диапазона длин волн (с эффективностью преобразования ~97 %) для двух резонансных частот, состоящего из чувствительного элемента, выполненного на основе двух открытых аподизированных периодических микрорезонаторных структур с коэффициентом заполнения, изменяющимся по линейному закону, согласующего элемента в виде несимметричной нерегулярной полосковой линии треугольной формы и детектирующего диода. Конструкция обладает ключевыми преимуществами, включая высокую эффективность преобразования, пригодность для матричной архитектуры, высокую селективность к регистрируемому излучению и возможность простых методов считывания, что делает ее привлекательным подходом для терагерцового зондирования – важного инструмента для различных научных и практических приложений.

Ключевые слова: чувствительный элемент, детектирующий диод, терагерцовое излучение, трехмерная модель, резонансная частота, HFSS, эффективность преобразования, потери на отражение, коэффициент направленного действия

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Introduction

The terahertz (THz) range of electromagnetic radiation, with frequencies from 0.1 THz to 10 THz, corresponds to a wavelength range from 3 mm to 30 μm, situated between millimeter waves and infrared waves. As a result of the rapid development of ultrafast electronics, laser and semiconductor technology, terahertz sensors have found widespread application in various fields of science and technology [1]. Some of these include: non-invasive tissue imaging; baggage and clothing scanning for concealed objects; chemical detection; high-speed wireless communication; the study of molecular dynamics, material properties and interactions at the nanoscale.

Creating a compact and reliable receiver for THz radiation is one of the challenging tasks in modern applied physics [2]. This is because both radio-physical methods (from the long wavelength side) and optical methods (from the short wavelength side) perform poorly in this spectral region [3].

The aim of this article is to develop a simulation model of a selective compact receiver for terahertz electromagnetic radiation, and to calculate and evaluate its main electromagnetic characteristics.

THz receiver design and its operational algorithm

This article discusses a selective THz receiver based on two apodized periodic microcavity structures with a filling factor that varies linearly, coupled through matching elements to a detecting diode [4].

One of the important factors affecting the efficiency of converting electromagnetic wave energy in the THz range into an electrical information signal by the proposed structure is the optimal matching of the sensor with the surrounding space and the detecting diode.

Structurally, the THz receiver consists of sensors 4, located on a substrate 1 and implemented as two apodized metal diffraction gratings (with a linearly varying filling factor), coupled through matching elements 5, which are asymmetrical irregular strip lines of triangular shape, with a detecting diode 6. In the substrate 1, there is an air cavity 8 under the detecting diode 6, and rectangular cutouts 7 under the sensors 4. At the ends of the diagonal of the substrate 1, contact pads 3 are symmetrically located, electrically connected by L-shaped output lines 2 to the bases of the matching elements 5, the apex angle of which is chosen to be 140° (Fig. 1).

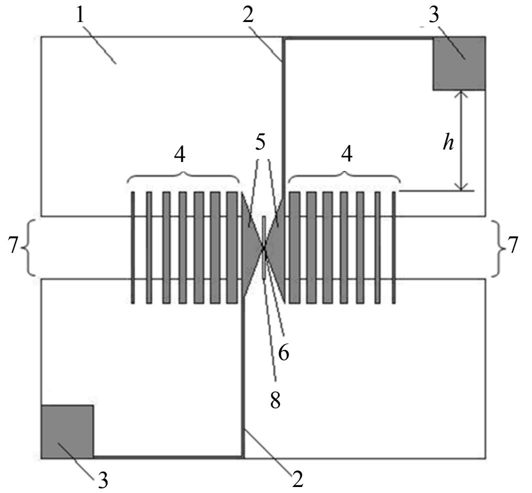

Fig. 1. Structure of the terahertz receiver: 1 – substrate; 2 – output lines; 3 – contact pads; 4 – sensors; 5 – matching elements; 6 – detecting diode; 7 – rectangular cutouts; 8 – air cavity

The device operates as follows. Electromagnetic radiation of the THz wavelength range from the surrounding space is almost completely absorbed by the sensors 4 due to their optimal impedance matching with the surrounding environment. This radiation is fed to the detecting diode 6 through the matching elements 5, which provide optimal matching between the diode and the sensors 4. Thus, high-frequency electrical currents, whose frequency corresponds to the received wavelength range of terahertz radiation, are fed to the detecting diode 6. The electrical information signal from the detecting diode 6, through the matching elements 5 and output lines 2, is fed to the contact pads 3 (the output of the device).

The proposed sensor enables optimal impedance matching between the receiver and the surrounding environment. Furthermore, the varying impedance of the matching element 5 along its length ensures efficient signal transfer to the load (detecting diode 6). The selected locations of the contact pads 3, the configuration of the output lines 2 and the specified optimal distance between the horizontal sections of the output lines 2 also reduce reflection losses in the considered receiver.

A diode 6 with a reduced effective Schottky barrier height was used for highly efficient detection of THz frequency currents corresponding to the range of converted wavelengths. This diode is one of the primary nonlinear elements widely employed today for converting THz radiation. It has virtually no competitors in the electromagnetic wave range under consideration.

Computer simulation and its results

Application of computer simulation in the research and design of THz receivers can largely replace expensive experiments, which leads to a significant reduction in product release times and lower development costs [5]. The modern development of computer technology, the active improvement of known methods and the development of new methods for the analysis and synthesis of receiving devices open up opportunities for quick and high-quality problem solving in this area [6, 7]. Currently, there are a number of universal and sufficiently powerful software packages such as FEKO, CST MicrowaveStudio, Comsol Multiphysics [8–10], MMANA, HFSS, etc. for modeling the electrodynamic characteristics of various elements and devices. A computer experiment to study the main parameters and characteristics of the proposed THz electromagnetic radiation receiver in the frequency range of 0.4…1.4 THz (Fig. 1) was carried out using the modern powerful software package HFSS, which provides modeling of complex three-dimensional configurations of arbitrary shape. The accuracy of the results obtained is determined by the adequacy of the constructed model. This refers to the correct execution of the drawing, the accurate specification of the materials of the analyzed structure, the optimal decomposition of space into decomposition elements and the choice of simulation mode.

The numerical calculation of the THz receiver was carried out within a limited area of space in the studied frequency range (Fig. 2).

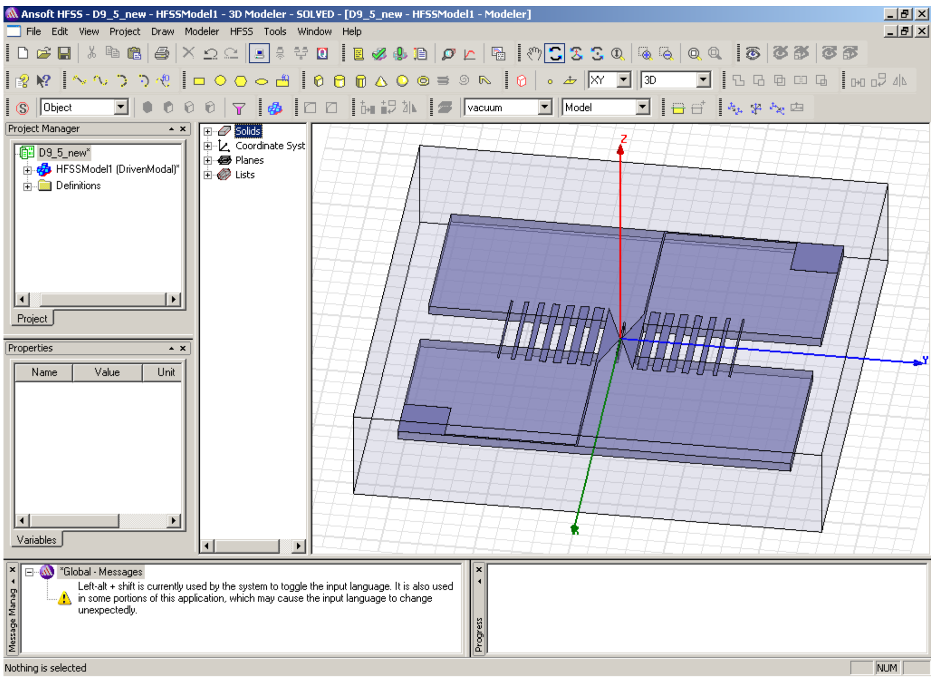

Fig. 2. Screenshot of the developed model of the THz receiver in the HFSS software environment

The period of the apodized grating of the sensor 4 was 15 μm. Gold with a thickness of 80 nm was chosen as the conductive material, and the dielectric of the substrate 1 had a dielectric constant of 2.17, a loss tangent of $9 \cdot 10^{-4}$ and a thickness of 10 μm. The sensor geometric dimensions were 105×105 μm, and the geometric dimensions of the contact pads 3 were 50×50 μm, with a total receiver length of 250 μm. The distance *h* between the contact pads 3 and the sensor 4 varied from 100 μm to 0 μm. The equivalent circuit of the detecting diode 6 was chosen as a parallel connection of an active resistance *R*, which varied in the range from 20 Ohms to 170 Ohms, and an electrical capacitance *C* of 20 fF.

The HFSS postprocessor provides animation for any field and its visualization in the form of vectors, processes static and animated drawings on any surface, including object section surfaces, three-dimensional object surfaces and three-dimensional spatial surfaces. The postprocessor also performs data processing after field calculation. With its help, it is possible to calculate characteristics such as scattering power, absorbed energy, quality factor, *S*-parameters and related characteristics.

Fig. 3 shows the calculated main frequency characteristics of the considered receiver at the extreme values of the specified range h = 100 μm and 0 μm: reflection losses S_{11} (a), standing wave ratio (SWR) (b) and conversion efficiency (c).

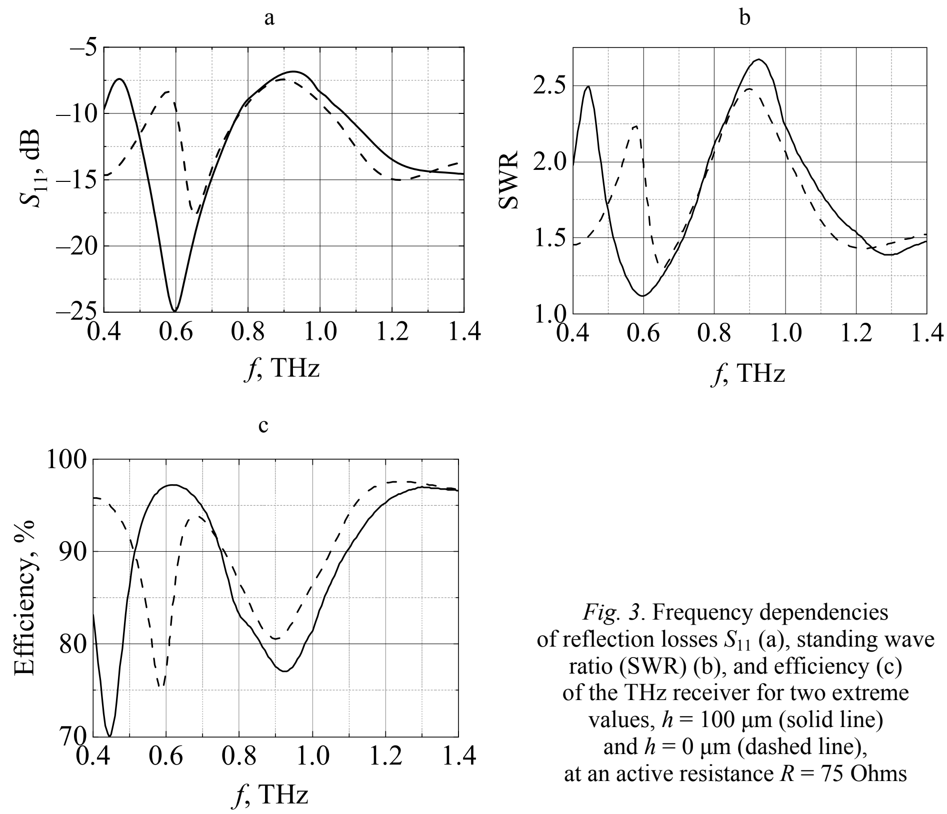

Fig. 3. Frequency dependencies of reflection losses S_{11} (a), standing wave ratio (SWR) (b), and efficiency (c) of the THz receiver for two extreme values, h = 100 μm (solid line) and h = 0 μm (dashed line), at an active resistance R = 75 Ohms

Fig. 4 Shows the dependencies of the directivity factor (DF) of the THz receiver at h = 100 μm and 0 μm for resonance frequencies on the elevation angle θ.

The calculated losses S_{11} of the received radiation due to reflection, depending on the change in the value of the active resistance *R* and the specified value of the capacitance *C* at a fixed h = 100 μm at resonance frequencies of 0.6 and 1.3 THz, are shown in Fig. 5.

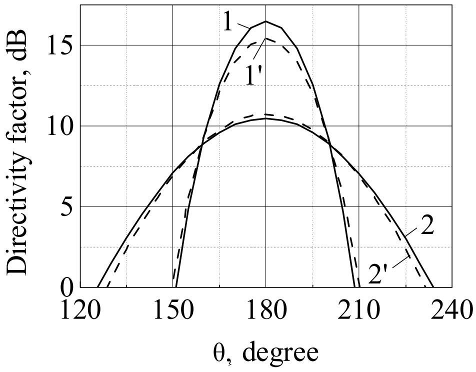

Fig. 4. Dependence of the directivity factors of the terahertz receiver on the elevation angle θ at an azimuthal angle φ = 90 degrees at resonance frequencies of 1.3 (1), 1.25 (1'), 0.65 (2') and 0.6 (2) at h = 100 μm (solid line) and 0 μm (dashed line)

a b

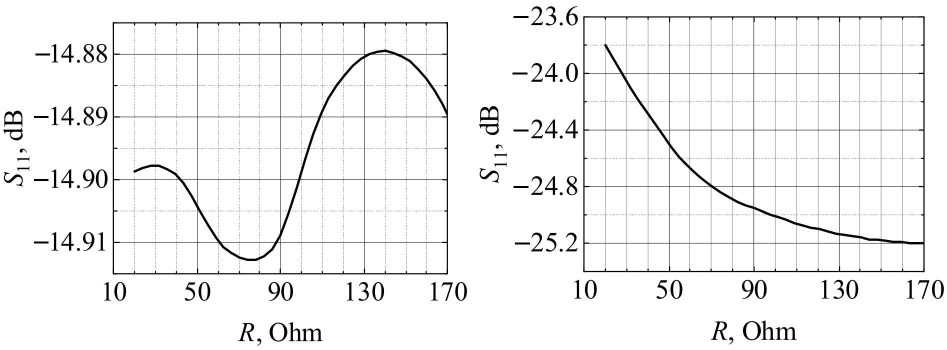

Fig. 5. Dependencies of reflection losses S_{11} of the THz receiver on the resistance R of the detecting diode at resonance frequencies of 0.6 (a) and 1.3 (b) THz at h = 100 μm

The use of the HFSS postprocessor at each point in space made it possible to calculate the magnitude and phase of the E and H vectors of the electromagnetic field and to analyze the field in all possible sections, as well as animate the field distributions by changing the phase of the excitation generator, which creates the impression of the field passing through the structure. The electric field distribution for one of the sections of the THz receiver is shown in Fig. 6.

a b

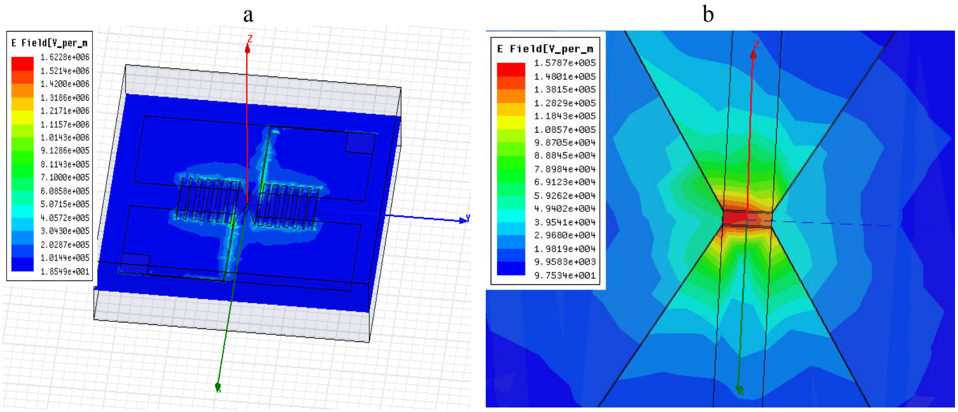

Fig. 6. Electric field distribution in the plane of the upper surface of the substrate (a) and an enlarged fragment of this distribution in the central part of the receiver (at the location of the diode) (b)

Fig. 7 shows the dependencies of the resonance frequencies and reflection losses S_{11} of the THz receiver on the distance h between the output lines and the sensors for an active resistance of the detecting diode of 75 Ohms.

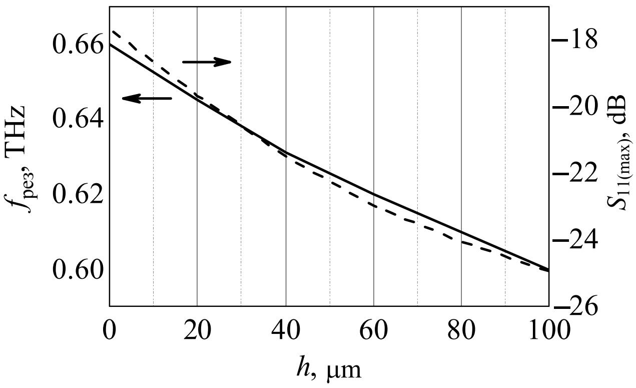

Fig. 7. Dependencies of the resonance frequency (solid line) and reflection losses S_{11} (dashed line) of the THz receiver on the distance between the output lines for an active resistance of the detecting diode of 75 Ohms

The maximum conversion efficiency at frequencies 0.6 THz (at h = 100 μm) and 1.25 THz (at h = 0 μm) is 97.2 and 97.6 %, respectively. Optimal values of reflection losses and standing wave ratio are observed at a frequency of 0.6 THz (at h = 100 μm) and are equal to –24.93 dB and 1.12, respectively.

The results presented in Fig. 5b indicate that the optimal resistance for the detecting diode is R = 75 Ohms at the resonance frequency of 0.6 THz. Fig. 7 shows that as the contact pads 3 approach the sensor 4, the reflection losses S_{11} increase along with an increase in the resonance frequency.

The maximum directivity factor at frequencies 0.6 THz and 1.3 THz is 10.48 dB and 16.5 dB, respectively, at h = 100 μm, and at frequencies 0.65 THz and 1.25 THz, it is 10.74 and 15.42 dB, respectively, at h = 0 μm.

The simulation shows that the proposed THz receiver structure has a high conversion efficiency of up to 97.6 % at two resonance frequencies in the considered range: 0.6 THz (at h = 100 μm) and 1.25 THz (at h = 0 μm), respectively. The directivity factor at frequencies of 0.6 THz and 1.3 THz is 10.48 and 16.5 dB, respectively, at h = 100 μm, and at frequencies of 0.65 THz and 1.25 THz, it is 10.74 and 15.42 dB, respectively, at h = 0 μm.

CONCLUSION

The original design of the receiving part makes the open microcavity structure based on apodized gratings attractive for building integrated high-efficiency compact THz receivers that have a number of distinctive properties:

- ✓ high conversion efficiency;
- ✓ possibility of implementing a matrix design;

✓ high selectivity of the registered radiation;

✓ possibility of implementing a simple readout method.

Terahertz radiation sensors are an important modern tool in various scientific and practical fields.

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