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SIMULATION OF SENSITIVE ELEMENT FOUND ON PLANAR MUSHROOM-SHAPED METAMATERIAL FOR NONDESTRUCTIVE TESTING AND SEARCHING FOR INHOMOGENEITIES IN TECHNOLOGICAL MEDIA

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A computer model of a sensitive element on a planar mushroom-shaped metamaterial with Maltese cross-type cells is created. Results of a numerical experiment are presented. It is own that this type of electrodynamic structure may be used in nondestructive testing of the geometric and electrophysical parameters of technological media as well as in searching in these media for inhomogeneities relative to variations of the attenuation coefficient and relative to the resonant frequency of the sensitive element.
Keywords: *sensitive element, mushroom-shaped metamaterial, resonance frequency, attenuation coefficient, technological medium, nondestructive testing, search for inhomogenities.*

Introduction. The precipitate development of microwave technologies at the border of the 20th and 21st centuries has led to the emergence of new as regards the development and application of novel electrodynamic structures and instruments based on these trends. The study of physical properties and the creation of structures of metamaterials the existence of which was theoretically demonstrated in [1] are promising directions of this development. A metamaterial is an artificially created medium with periodic structure consisting of elementary cells the dimensions of which are significantly less than the working wavelength of the device. A distinctive feature of metamaterials is the appearance of physical phenomena in these substances that cannot be observed in natural substances and media, for example, negative values of the relative dielectric permittivity and magnetic permeability, the absence of inverse waves in the process of reflection, etc. It is important to note that these physical phenomena arise precisely in a partiucular periodic structure and not as a result of a variation in the chemical composition of the metamaterial.

Practical implementation of structures of metamaterials was first carried out by D. Smith's scientific group [2] based on the earlier studies of J. W. Pendry's group [3]. The first metamaterials constituted a combintion of open annular resonators and rectilinear conductors. Because of the aggregate properties of these two types of cells, it became possible to obtain simultaneously negative dielectric permittivity ε and negative magnetic permeability μ. Over the past 20 years, metamaterials have undergone very active development and today there exist dozens of different types of cells and metastructures.

A planar mushroom-shaped structure that constitutes a dielectric substrate on which elementary cells are situated periodically and connected together by means of capacitative gaps and possessing an intercell ohmic contact with a metallized shield on the reverse side of the substrate is one possible practical realization of a metamaterial. Such a frequency-selective surface, which was first proposed in [4], contains periodically situated mushroom-shaped cells in the form of planar hexagons connected together by their grounding through transitional holes. The structure is a modification of crimped high-impedance delay-time systems [5, 6].

These types of metamaterials are widely used today as elements of microwave and terahertz devices, such as miniature antennas and radiators, suppression filters, switches and circuits of conductor-free devices in telecommunications, etc. [7–10]. Among the advantages of mushroom-shaped metamaterials, we may note the relative simplicity of their fabrication

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along with extensive capabilities for modification and adjustment of their characteristics and parameters. For example, variations in the geometric dimensions of mushroom-shaped cells substantially affects the equivalent linear inductance and capacitance parameters of the entire structure and its resonance frequency. Expansion of the working frequency band of metamaterials and the use of modulated frequency-selective surfaces that combine mushroom-shaped cells with different geometric dimensions is of practical interest [11, 12]. In addition, the incorporation of capacitative gaps situated in parallel in mushroom-shaped structures of variable-capacitance diodes makes it possible to achieve in real time adaptive adjustment of high-impedance surfaces in a specified range of frequencies [13, 14].

The possible use of structures based on planar metamaterials as miniature sensitive elements in different types of sensory devices [15–19] represents yet another promising trend. The advantages of such applications includes the capacity for reflection of inphase waves and restriction of the propagation of surface phases, making it possible to concentrate the electromagnetic field as well as achieve an advantageous concentration or separation of the electrical and magnetic fields in a given controlled region. With the use of such properties, it becomes possible to create effective sensitive elements based on metamaterials for use in monitoring slight deviations of controllable electrophysical parameters of metamaterials and technological media amounting to fractions of a percentage point.

Computer model of sensitive element. On the basis of an analysis of the structure of metamaterial it may be concluded that a model of a frequency-selective surface has the form of a set of *LC* circuits connected in parallel. It is impossible for current to travel on a frequency-selective surface, since the circuits function as filters, moreover, the electromagnetic field is concentrated near the surface of the structure and the movement of an electromagnetic wave is slowed down.

The degree of localization of the electromagnetic field between the structural elements of the cells of a metamaterial forming a frequency-selective surface is directly proportional to their relative length.

The equivalent linear capacitances that are formed between closely situated “hats” of the elements are inversely proportional to the distance d between them:

$$C = \varepsilon\varepsilon_0 S/d,$$

where ε is the relative dielectric permittivity; ε_0, electrical constant of a vacuum; and S, area between the “hats” of the elements.

Equivalent linear capacitances are formed due to the “feet” of the mushroom-shaped elements of the surface:

$$L = \frac{\mu_0}{2\pi} l [\mu_m \ln(l/r) + \mu_i/4],$$

where μ_0 is the magnetic constant of a vacuum; μ_m and μ_i, relative magnetic permeability of the external medium and material of the conductor, respectively; l and $r \ll l$, length and radius of cross-section of conductor, respectively.

Cells of a given configuration, which may form frequency-selective surfaces possessing the required geometric dimensions and areas [20, 21], are of practical interest. Corrections to the area of the surface occupied by the hats of mushroom-shaped elements,

$$F_{surf} = S_{surf}/S_{mush},$$

are introduced in order to compute the parameters of cells of a given configuration in the computer model, where $S_{surf} = xy$ is the total area of the frequency-selective surface; x and y, geometric dimensions of an element of the metamaterial; and S_{mush}, total area of hats of mushroom-shaped elements.

Thus, the required capacitance of the frequency-selective surface of a metamaterial may be calculated by means of the formula

$$C_{surf} = CF_{surf}.$$

The relative variation of the resonance frequency of a sensitive element is determined by the expression

$$\frac{\Delta f}{f_r} = \frac{\int_V (\Delta\varepsilon_m \mathbf{E}_1 \mathbf{E}_0 + \Delta\mu_m \mathbf{H}_1 \mathbf{H}_0)\, dV}{\int_{V_0} (\varepsilon_0 |\mathbf{E}_0|^2 + \mu_0 |\mathbf{H}_0|^2)\, dV},$$

where $\Delta\varepsilon_m = \varepsilon_m - \varepsilon_0$; $\Delta\mu_m = \mu_m - \mu_0$; **E** and **H** – vectors of the electrical and magnetic field strengths, represented with the subscript “0” corresponding to the value of the undisturbed field and the subscript “1,” to a field with distortions due to

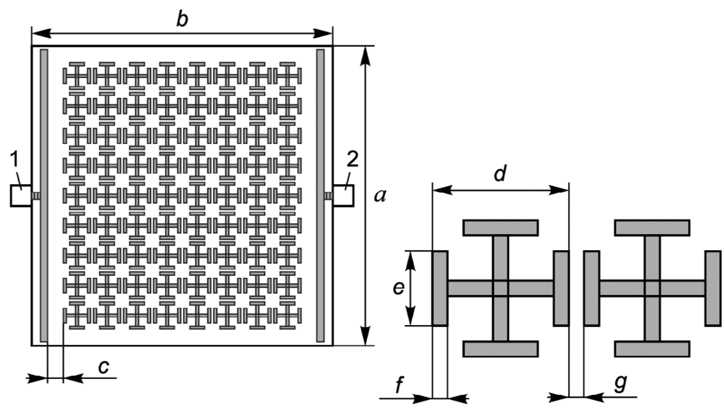

Fig. 1. Model of sensitive element and its geometric dimensions: $a = 2.73$ mm, $b = 3.15$ mm, $c = 0.07$ mm, $d = 0.28$ mm, $e = 0.14$ mm, $f = 0.04$ mm, $g = 0.07$ mm.

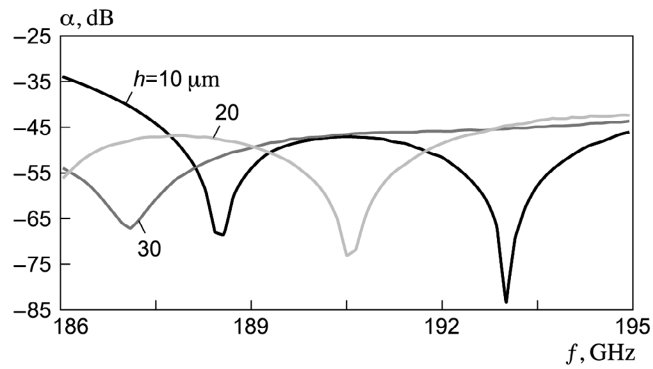

Fig. 2. Attenuation coefficient α as a function of frequency f with variation of the thickness h of a plate produced from Teflon.

variation of the controlled parameter; ε_m and μ_m, relative dielectric permittivity and relative magnetic permeability of the controlled medium; V, volume of controllable medium; V_0, volume occupied by electromagnetic field of resonator (sensitive element); f_r, resonator frequency corresponding to an undisturbed field; $\Delta f = f - f_r$, shift of resonance frequency.

The following approximation is acceptable in the case of small disturbances in the field:

$$\frac{\Delta f}{f_r} = \frac{\int_V (\Delta\varepsilon_m |\mathbf{E}_0|^2 + \Delta\mu_m |\mathbf{H}_0|^2)\, dV}{\int_{V_0} (\varepsilon_0 |\mathbf{E}_0|^2 + \mu_0 |\mathbf{H}_0|^2)\, dV}.$$

It should be emphasized that a mushroom-shaped frequency-selective surface may be created in several different structural variants, for example, in the form of two-layer or three-layer surfaces containing quadratic or hexagonal hats of elements. This is due to the variant of practical implementation of a particular structure in which it is most important to assure that the frequency-selective surface is wide-banded. In this connection, the use of "hats" of mushroom-shaped elements produced in the form of a Maltese cross, which makes it possible to transform the frequency-selective surface of a metamaterial into a resonance network convenient for simulation, proves the most promising approach.

A computer model of the sensitive element based on a mushroom-shaped metamaterial with elements produced in the form of a Maltese cross was created in the CST Studio Suite program. The overall form of the model and the geometric dimensions of the individual cells of the metamaterial are presented in Fig. 1.

Among the practical problems that may be solved by such a sensitive element we may note monitoring of the thickness, dielectric permittivity, and choice of the type of dielectric plate as well as searching for inhomogenities in the plate. Monitoring of these parameters is realized with the introduction of the test object into the electromagnetic field of the sensitive element, which leads to variation of its resonance frequency and attenuation coefficient α.

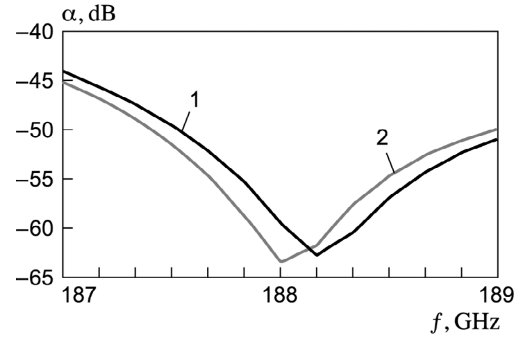

Fig. 3. Attenuation coefficient α as a function of the frequency *f* in the course of monitoring the position of the metallic inhomogeneity at the center (curve *1*) and at the edge (curve *2*) of a dielectric plate.

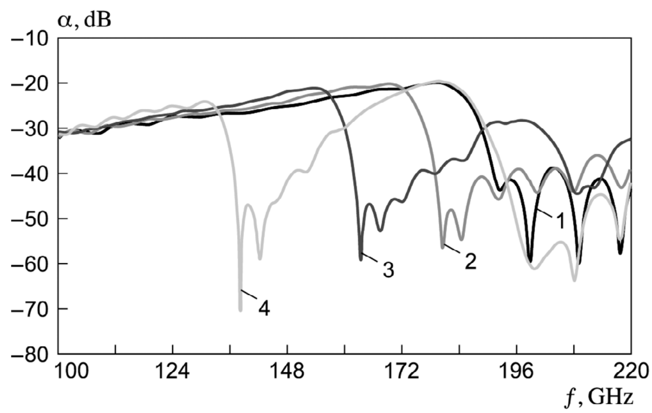

Fig. 4. Attenuation coefficient α as a function of frequency *f* in monitoring of the relative dielectric permittivity of plates of identical thickness: *1*) air; *2*) Teflon; *3*) FR-4; *4*) Policor (alumina).

Analysis of results of simulation. The results of a numerical experiment designed to monitor the thickness of a plate produced from Teflon with relative dielectric permittivity ε = 2.1 are shown in Fig. 2 in the form of dependences of the attenuation coefficient on frequency. As the thickness of the plate varies in the range 10–30 μm, the resonance frequency varies in the range 193.5–187.1 GHz while α = –(83.21–67.14) dB. It should be noted that a successive shift in the resonance frequency in the decreasing direction is observed as the thickness of the plate increases and that this shift is also accompanied by a significant decrease in the attenuation coefficient.

A gasket made of copper with diameter commensurable with a single cell of the metasurface and amounting to 0.3 mm was introduced to simulate inhomogenities in the test sample. The gasket was first placed at the edge of the dielectric plate and then at its center. The results of the simulation are presented in Fig. 3. It follows from the relationships obtained that the resonance frequency varies in the range 188.0–188.3 GHz with α in the range –(63.48–62.77) dB as the position of the metallic inhomogeneity varies. Moreover, a second numerical experiment demonstrated that the nature of the variation of the resonance frequency of the sensitive element is preserved independently of the direction in which the inhomogeneity travels to the center. This simplifies localization of the inhomogeneity.

Results that demonstrate the possibility of monitoring the relative dielectric permittivity of plates of identical thickness and determination of the type of dielectric from which the plate is fabricated are presented in Fig. 4. Thus, the resonance frequency of a sensitive element without a controlled object amounts to 198.6 GHz at α = –59.60 dB. When a dielectric plate made of Teflon with ε = 2.1 is situated right on the surface of the sensitive element, a deviation of the resonance frequency of up to 180.4 GHz with α = –56.45 dB is observed; for a plate produced from FR-4 fiberglass laminate with ε = 4.4, the resonance frequency is equal to163.2 GHz for α = –59.31 dB, and for a plate produced from Policor with ε = 9.8, the resonance frequency reaches 138.0 GHz in the case α = –70.13 dB.

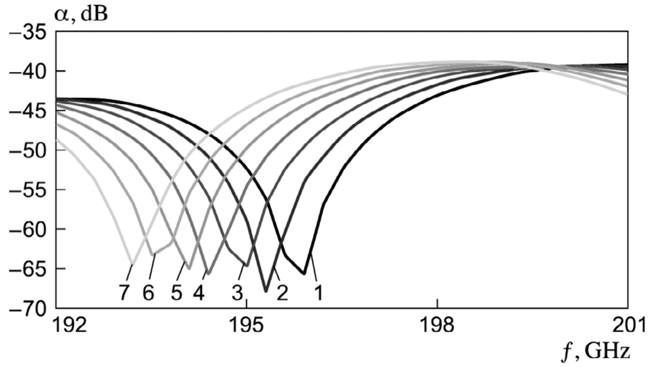

Fig. 5. Attenuation coefficient α as a function of frequency *f* with monitoring of small deviations of the relative dielectric permittivity ε of a plate made of Teflon; ε varies in the range from –15 to +15% of the nominal value in 5% increments: *1–7*) –15; –10; –5; 0; 5; 10; 15%, respectively.

The results of the numerical experiments that have been obtained demonstrate that it is theoretically possible to monitor significantly smaller deviations of the relative dielectric permittivity. Dependences of the attenuation coefficient on frequency for a Teflon plate with ε = 2.1 as its dielectric permittivity varies in the range of several tenths of a percent are shown in Fig. 5.

From the results of the simulation it follows that where the dielectric permittivity of the plate deviates in the positive direction from the nominal value ε = 2.1 (+5%), the resonance frequency varies in the range 194.4–194.1 GHz while α is in the range –(65.70–64.94) dB. With a deviation of the dielectric permittivity in the negative direction (–5%), the resonance frequency varies up to 195.0 GHz in the case α = –4.71 dB. With a further increase in the deviation of the dielectric permittivity of the plate in the negative direction from the nominal value (+15%), we find that the frequency varies up to 193.2 GHz while the variation in the attenuation coefficient reaches –64.58%. With a deviation in ε reaching 15%, the resonance frequency amounts to 195.9 GHz with α = –65.66 dB.

Conclusion. The present results of the numerical simulation show that a sensitive element based on a planar mushroom-shaped metamaterial with cells in the form of a Maltese cross may be used to monitor the geometric and electrophysical parameters of test samples. Moreover, the parameters of the materials and of the technological media may be monitored relative to variations in the resonance frequency of the sensitive element as well as relative to variations in its attenuation coefficient, the latter being more effective for media with high values of the relative dielectric permittivity, amounting to several tenths of a percentage point.

Among the advantages of the present sensitive element we should note the simplicity of its design, small dimensions, and high level of sensitivity due to the use of the physical and structural features of a planar mushroom-shaped metamaterial. Thus, it may be used as an element of automatic quality control systems or classification systems in technological processes of modern industry.

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