**Nanostructured surfaces**

**Anomalously large absorption of electromagnetic radiation by nanometer**

**gold film in the band 26÷37.5 GHz**

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**Abstract.** The experimental data of power reflection and absorption coefficients of electromagnetic radiation in the frequency band 26÷37.5 GHz for a gold film of 10 nm thickness at a distance 1 mm from the reflecting surface of a shorting in a rectangular waveguide are presented. Comparison with theoretical calculations stressed a high level of absorption and a virtual absence of frequency dependence of the reflection coefficient.

**Introdaction.** Reducing the impact of electromagnetic radiation (EMR) on technical devices and biological objects, especially due to the sharp increase in the number of sources of electromagnetic radiation (communication, consumer electronics, information systems, etc.), is an important task in a wide frequency band.

The development of new, improved radar absorbing materials (RAM) is one of the main components of the task of protection from EMR (along with screening, the use of design elements, etc.).

There are resonant absorbers, which are one type of RAM [1]. They use semitransparent metal films. If such film is situated at a distance of *λ*/4 (*λ* - wavelength of electromagnetic radiation) before conductive surface which has to be protected, it is provided the conditions for optimal matching at this wavelength. When several films use, with help of modern computational methods, it is possible to optimize not only the absorption band, but and number of layers, the total thickness and weight of the RAM.

Additional studies are conducted and for studying of the absorbing properties of metal films [2-3]. These works are carried out on the assumption that the film thickness is much smaller than the thickness of the skin layer in the selected band of wavelengths. At a film thickness of 10÷100 nm, this assumption holds for the microwave range.

In this paper it is studied an anomalously large absorption of electromagnetic radiation by a gold film of 10 nm thickness in the band 26÷37.5 GHz.

**Experimental technique.** For research it is used a gold film of 10 nm thickness, obtained by thermal vacuum deposition on a dielectric polymer substrate of 0.1 mm thickness. Control the thickness of the film is implemented by known method of quartz oscillator.

The measurements were made in the band 26÷37.5 GHz with using of a VSWR meter panoramic P2-65 (similar to a scalar network analyzer). The sample - a gold film on polymer substrate - was placed in a segment of the rectangular waveguide with cross section 3.4´7.2 mm2. Measurements were carried out for two cases: the segment of the waveguide with the sample was joined to or the shorting in the form of metal plate (see Figure 1(a)) or the matched load (see Figure 1(b)).

The samples were cut with size slightly smaller than the cross section of the waveguide so that they are easily placed in him. The sample was placed between the layers of foam as shown in Figure 1. The gold film had no galvanic contact with the walls of the waveguide.



**Figure 1.**Placement of the samples in the wave guideline: (a) a segment of the waveguide is connected to shorting, (b) a segment of the waveguide is connected to the matched load; *h* - the distance from the film to the shorting, *h*1 - the thickness of the polymer substrate, *G*–the reflection coefficient of the field when the shorting connecting, *G*1and*T*1–the reflection and transmission coefficients of the field when the matched load connecting.

The complex reflection coefficient of the field from the gold film, when the shorting was connected(*G*),and the complex reflection and transmission coefficients of the field, when the matched load was connected,(*G*1 and *T*1) are indicated in Figure 1additionally.

The measurements of *VSWR* (voltage standing wave ratio) were made in the waveguide line which was connected to the waveguide section with the sample as shown on Figure 1.

Distance *h* was chosen to be 1 mm. The substrate thickness *h*1was 0.1 mm.

The power reflection coefficient *R* from the measured of *VSWR* is calculated by the known formula

$R=\frac{(VSWR-1)^{2}}{(VSWR+1)^{2}}$. (1)

The absorption coefficient *A* is calculated by the formula

$A=1-R$. (2)

**Experimental result and discussion.** Experimental results of the power reflection coefficient *R* obtained from *VSWR* measurements and calculations carried out by means of (1), in two cases: when connected to the shorting (curve with black squares) and when connected to the matched load (curve with red circles), are shown in Figure 2.



**Figure 2.**Experimental (curves with symbols) and theoretical (lines *1*, *2* and curves *3* and *4*) results of power reflection coefficient as a function of frequency for the sample with a gold film thickness of 10 nm. Lines *1*, *2* and curve with red circles - for the case of connection to the matched load; curves *3*, *4* and curve with black squares - for the case of connection to the shorting.

As seen in Figure 2, experimental results of the power reflection coefficient for the case of the shorting (curve with black squares) are almost independent of frequency and are at a level of 0.1 or slightly less.

In this case, in view of formula (2), absorption is about 90% in the whole frequency band of measurements.

The experimental results of the power reflection coefficient for the case of the matched load (curve with red circles) are varied with frequency in the range from 0.32 to 0.42.

Let us compare the experimental results with theory. Relative dielectric constant of the foam is about 1.1 and it of the polymer used for the substrate is about 2. Moreover, the dielectric loss tangents of both of these materials are less than 10-3.

In view of this, and the fact that the thickness of the polymer substrate is 0.1 mm, which is about 1/100 of the wavelength in the waveguide in the band measurements, we neglect reflections of EMR which associated with the presence of both the foam and the polymer substrate.

We assume that the gold filmis in air-filled waveguide. The thickness of the skin layer in the selected band of frequency for gold is more than an order greater than the thickness of the film.

In this case, the EMR penetrates the entire thickness of the film and the reflection coefficient *G*1for the film having a thickness *d* and a conductivity *σ* can be written [3]

$G\_{1}=-{β}/{(1+β)}$, (3)

where $β={σd}/{(ε\_{0}c)}$, *ε*0 – the permittivity of vacuum, *c* – the speed of light in vacuum.

Accordingly, the transmission coefficient is equal to

$T\_{1}=1+G\_{1}={1}/{(1+β)}$. (4)

At a film thickness of 10 nm conductivity *σ* depends both on the thickness and on the method of preparation of the film.

On the other hand, in the case of connecting to the matched load, *G*12correspondsto the power reflection coefficient that is given by the formula (1).

Therefore, to determine the value of *β*, we use the experimental values of the power reflection coefficient for the case of the matched load.

Power reflection coefficient is equal to square of modulus of complex reflection coefficient of the field. In view of the experimental results we can write inequality

$0.32\leq {β^{2}}/{(1+β)^{2}}\leq 0.42$. (5)

From here it is easy to get

$1.3\leq β\leq 1.8$. (6)

In Figure 2, lines *1* and *2* correspond to the two extreme values of the power reflection coefficient (with *β* = 1.3 and *β* = 1.8) for the case of connection to the matched load.

The reflection coefficient of the field *G* for the case of shorting connection, taking into account the multiple reflections between the gold film and the reflecting surface of shorting, can be written as

$G=G\_{1}-\frac{T\_{1}^{2}e^{-i4πh/λ\_{0}}}{1+G\_{1}e^{-i4πh/λ\_{0}}}$, (7)

where$λ\_{0}={λ}/{\sqrt{1-({λ}/{2a})^{2}}}$ – the wavelength in the waveguide, *a* = 7.2 mm – the size of the wide wall of the waveguide.

The power reflection coefficient *R* is equal to square of modulus of the complex reflection coefficient *G*

$R=\left|G\right|^{2}$. (8)

Two theoretical values of *R* as a function of frequency, calculated on the basis of formulas (7) and (8) for the two extreme values of *β* are shown in Figure2 (curve *3*corresponds to *β* = 1.3,curve *4*- corresponds to *β* = 1.8).

As seen in Figure 2, the calculations carried out with the help of formulas (7) and (8), do not give satisfactory agreement with the experimental results. When the sample is placed in the waveguide connected to the shorting, and the distance *h* = 1 mm which corresponds to about 1/10÷1/15 of the wavelength in the waveguide in the selected frequency band, the theoretical power reflection coefficients (curves *3* and *4*) are in 3÷5 times greater than those obtained from the experiment (curve with black squares).In addition for the theoretical curves it is observed a pronounced dependence from the frequency. The theoretical reflection coefficient decreases with frequency increasing what corresponds to the expected reduction of reflection when we approach to the theoretical minimum at the frequency corresponding to *λ*0/4 of the distance *h* between the gold film and the reflecting surface of the shorting.

**Conclusion.** Experimental data of the power reflection coefficient obtained for the gold film thickness of 10 nm at a distance 1 mm from the reflecting surface of the shorting were significantly less than that were calculated according to traditional theory in the frequency band 26÷37.5 GHz.

The absorption is fixed on a level of 90% and almost not depended from frequency that can significantly expand the ability to use such films in practical RAM [4].

**References**

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