ISSN 1064-2269, Journal of Communications Technology and Electronics, 2014, Vol. 59, No. 12, pp. 1349–1355. © Pleiades Publishing, Inc., 2014.
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ELECTRODYNAMICS AND WAVE PROPAGATION

Radar Cross Section and the Surface Impedance of a Resonator with Properties of an Artificial Magnetic Conductor

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Received January 31, 2014

Abstract—A flat resonator having properties of an artificial magnetic conductor is analyzed. Frequency dependences of the radar cross sections (RCSs) of such resonators are calculated and measured at microwave frequencies. Surface impedances $|Z|$ of resonators with different thicknesses are calculated numerically. It is demonstrated that the maxima of local RCSs and impedance averaged over the surface $|Z|_{av}$ are shifted towards lower frequencies as the resonator thickness increases. It is found that the maximum values of $|Z|_{av}$ reach 3000 Ω, which many times greater than the value of the free-space impedance 120π Ω. The frequency band in which $|Z|_{av} > 1000$ Ω is wider than 200 MHz.

DOI: 10.1134/S1064226914100040

INTRODUCTION

A number of papers concerned with the study of surfaces with high electrical resistance (artificial magnetic conductors, AMCs) were published in the past decade [1–4]. The reflection coefficient of such surfaces is +1 rather than –1 (as the reflection coefficient of surfaces with high electric conductivities). Artificial magnetic conductors attract great interest due to the possibility of their application in the design of low-profile antennas and screens of electromagnetic radiation. However, relatively large transverse dimensions of such AMCs hinder their application in the technology of small-size antennas and screens. This hindrance was removed in small-size resonators based on AMCs, which were proposed in [5]. An AMC of this type is formed from a pair of closely spaced capacitive gratings placed on a rectangular dielectric layer that is plated at the other side and at two opposite edges.

Small-size resonators based on AMCs and their shielding properties were described in [6, 7]. The AMC structures based on single-periodic and double-periodic gratings are shown in Figs. 1a and 1b, respectively. The external view of a resonator with dimensions of $A \times B \times D$ based on an AMC structure is shown in Fig. 2. The resonator surface from the grating side has properties of an AMC at the resonance frequency and about it. Resonance frequency f_r of a resonator with dimensions much smaller than the wavelength may be estimated using the following formula [6]:

$$f_r = \frac{c}{\pi\sqrt{\frac{2\varepsilon(b-2a)bD}{d}}}, \quad (1)$$

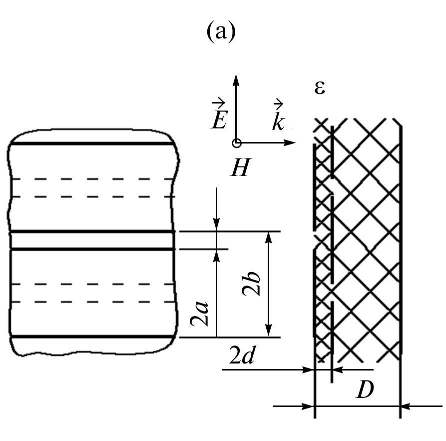

Fig. 1. AMC structures.

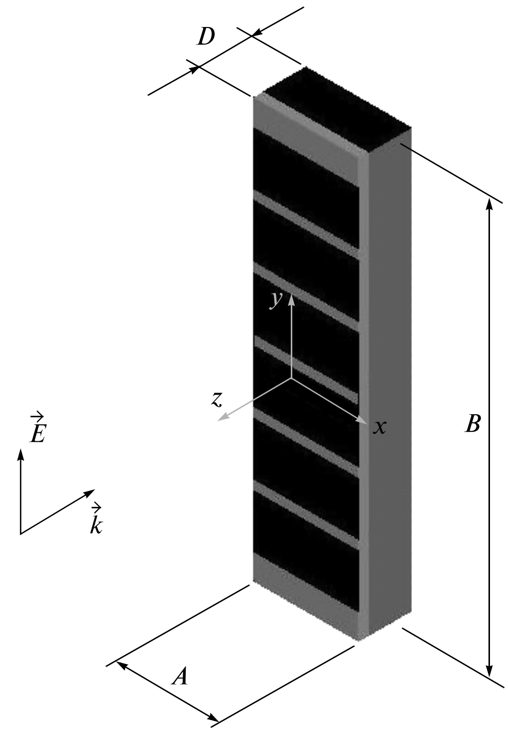

Fig. 2. AMC resonator.

where c is the velocity of light; ε is the permittivity of the material between the gratings; and dimensions a, b, d, and D are shown in Figs. 1a and 1b. It was shown experimentally that the resonator Q factor depends weakly on the resonator width and reduces rapidly with increasing length B. Accordingly, the band in which the resonator surface has AMC properties increases with B. Hence, the study of the properties of AMC resonators with dimensions B that are not negligible compared to the wavelength is of certain interest. In this paper, we analyze the frequency characteristics of the backscattering pattern and the surface impedance for AMC resonators with one and the same length B and different resonance frequencies f_r falling within a wide range of 2–7 GHz. Experimental techniques and numerical calculations were used.

1. SPECIMENS OF AMC RESONATORS

Four resonator specimens based on single-periodic gratings made of aluminum with a thickness of 0.02 mm were manufactured. The samples differed only in their thickness D and had the following dimensions: $A = 10$ mm; $B = 40$ mm; $2b = 6$ mm; $2a = 0.3$ mm; $2d = 0.17$ mm; and $D = 1$ (specimen 1), 2 (specimen 2), 3 (specimen 3), and 4 mm (specimen 4). The material between the gratings was polyethylene (ε = 2.25), and the material between the pair of gratings and the metal surface was polystyrene (ε = 2.55).

2. BACKSCATTERING CHARACTERISTICS

The frequency characteristics of the radar cross sections (RCSs) were measured according to the two-horn method using a vector network analyzer as indicated in the layout shown in Fig. 3.

The results of the measurements performed within a frequency range of 1–5 GHz are shown with solid lines in Figs. 4a–4d. Dotted lines denote the results of numerical calculations performed using the FEKO software. Design features of resonators containing elements with dimensions much smaller than the wavelength necessitated the use of a computational grid that is finer than the standard one. The stability of the solution after further reduction in the size of the grid cell and the quality of approximation of the experimental results were used as the criteria for selection of the most appropriate grid. Dimensions of the grid cell of 0.5 mm met these criteria; standard dimensions of the grid cell for this frequency band are 5 mm.

It can be seen from Fig. 4 that, as the specimen becomes thicker, the low-frequency peak of the RCS moves towards lower frequencies and its width considerably decreases.

Frequencies of the RCS maxima determined in accordance with Figs. 4a–4d and the results of estimation of resonance frequency f_r with the use of formula (1) are listed in the table. It can be seen from the table that resonance frequency f_r lowers with lowering of the frequency of the RCS maximum. These frequencies come closer to each other.

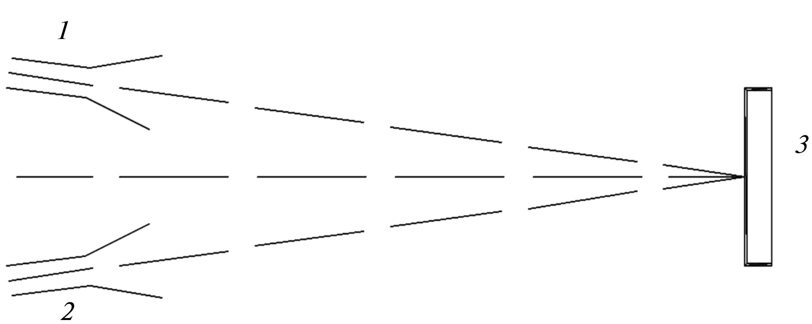

Fig. 3. Measurement setup: (*1*) transmitting and (*2*) receiving horns and (*3*) the tested specimen.

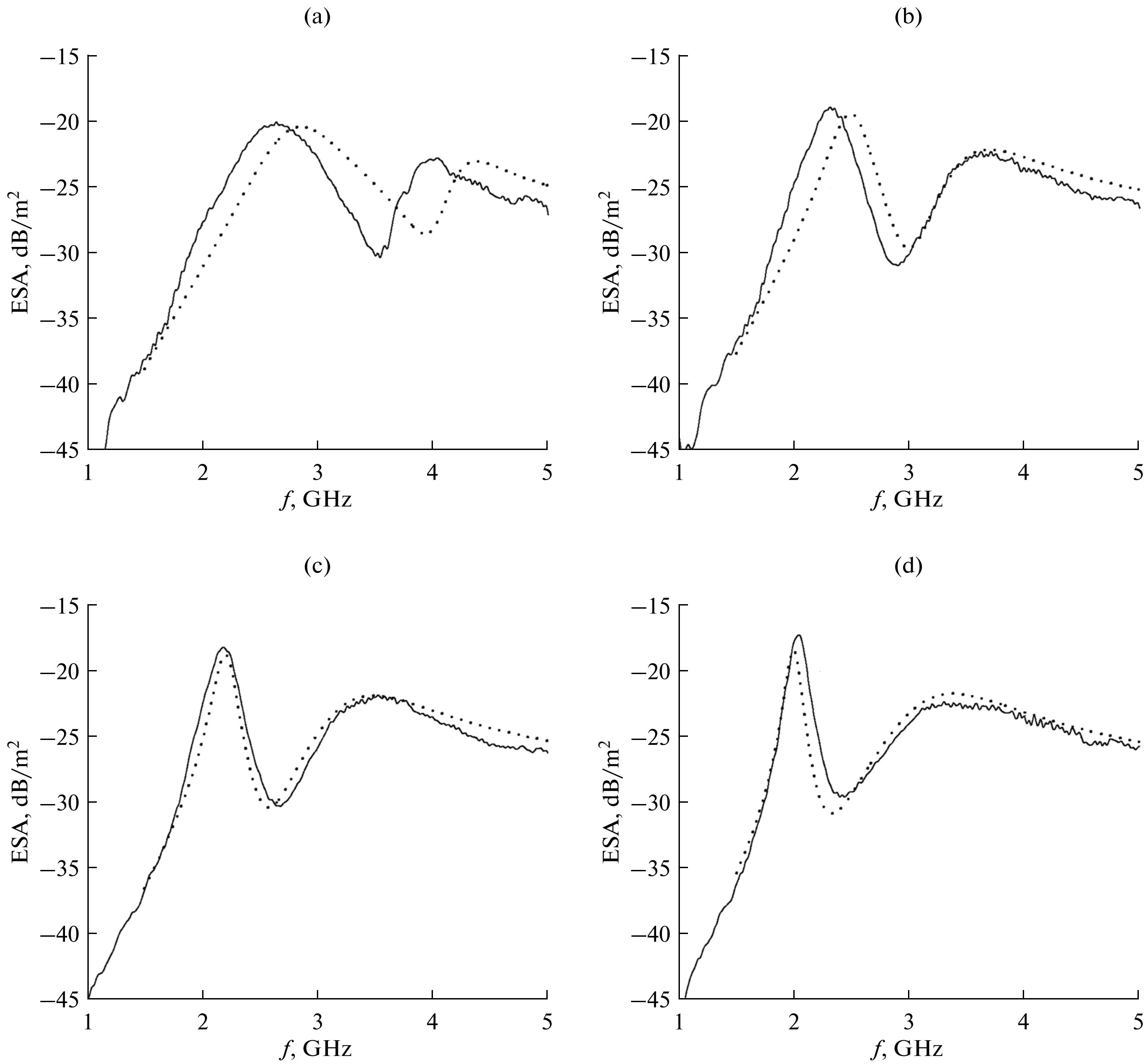

Fig. 4. RCSs of specimens (a) 1, (b) 2, (c) 3, and (d) 4. Dotted lines depict the calculation results, and solid lines correspond to the measured data.

3. IMPEDANCE NEAR THE SURFACE OF THE AMC RESONATOR

Impedance Z in a plane parallel to the pair of gratings of an AMC resonator equals the ratio of tangential components of electric and magnetic fields. It is known that this ratio is 120π Ω in a plane wave and is zero at a metal surface. The impedance in a plane coinciding with the surface of the outer grating is substantially nonuniform in the direction perpendicular to the grating gaps. For example, the impedance is zero in the metal interspaces between the gaps and may be much greater than zero in the gaps. Naturally, the impedance should become more uniform as the distance between the plane in which it is determined and the grating surface increases.

Figures 5a–5f and 6a–6f show calculated dependences of the absolute values of impedances $|Z(z, y)|$ of specimens 1 and 3 at six different frequencies and three distances z from the grating surface. Specifically, Fig. 5a shows function $|Z(z, y)|$ for specimen 1 with a thickness of 1 mm for a frequency at which the value of $|Z|_{av}$ averaged over an interval of -20 mm $< y < 20$ mm is maximal, Figs. 5b–5e show such functions at four neighboring frequencies, and Fig. 5f shows this function for the frequency at which the RCS is maximal. Figures 6a–6f show similar functions $|Z(z, y)|$ for specimen 3 with a thickness of 3 mm.

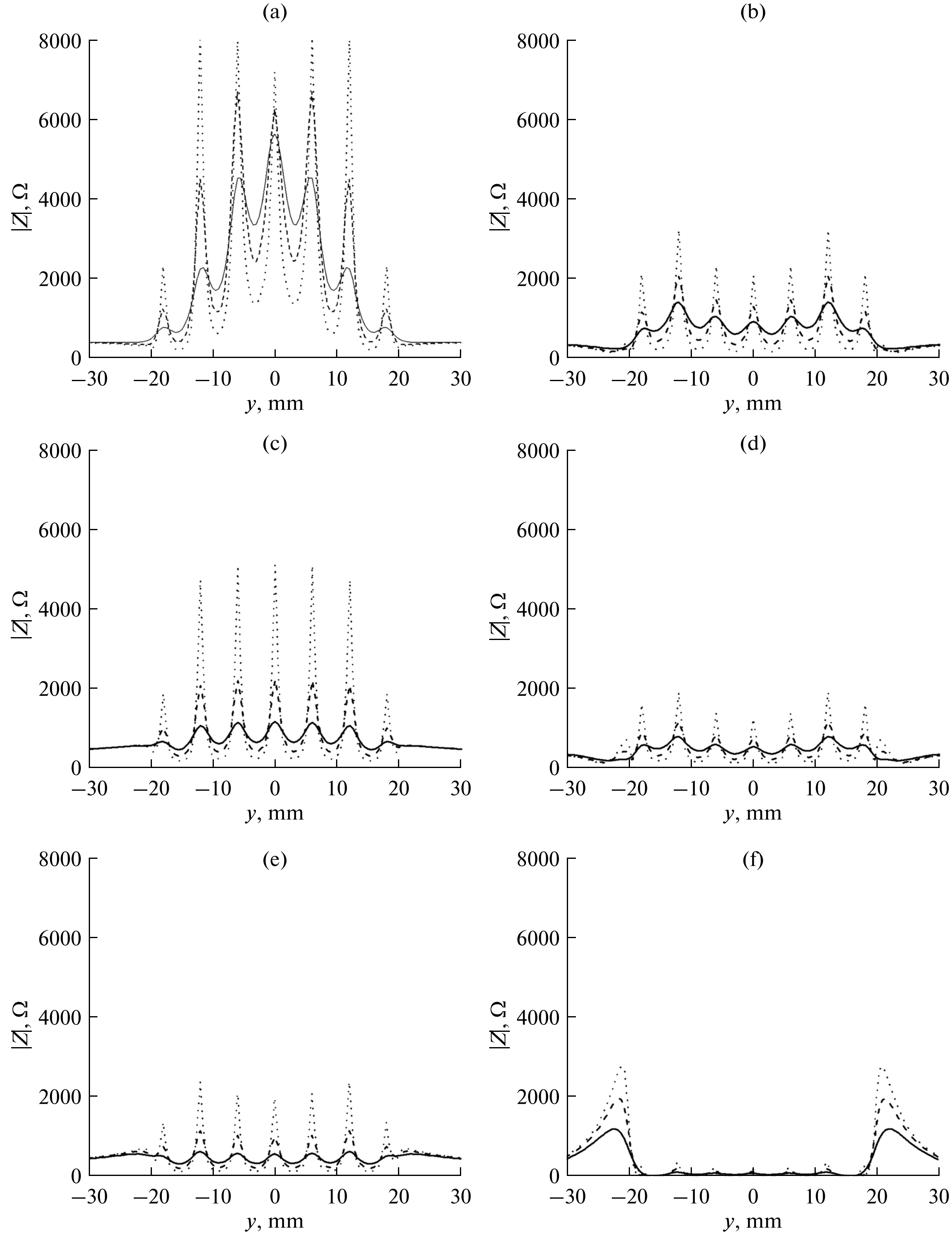

Fig. 5. Calculated dependences of $|Z(z, y)|$ for specimen 1 at frequencies f = (a) 3.9, (b) 3.8, (c) 4, (d) 3.7, (e) 4.1, and (f) 2.9 GHz and z = (dotted lines) 0.5, (dashed lines) 1, and (solid lines) 2 mm.

Maximum values of $|Z|_{av}$ and the corresponding frequencies are listed in the table. It can be seen that, as the specimen becomes thicker, frequencies corresponding to the maxima of $|Z|_{av}$ and RCS come closer to resonance frequency f_r. Note that the impedance at the surface near the resonator varies only slightly in the

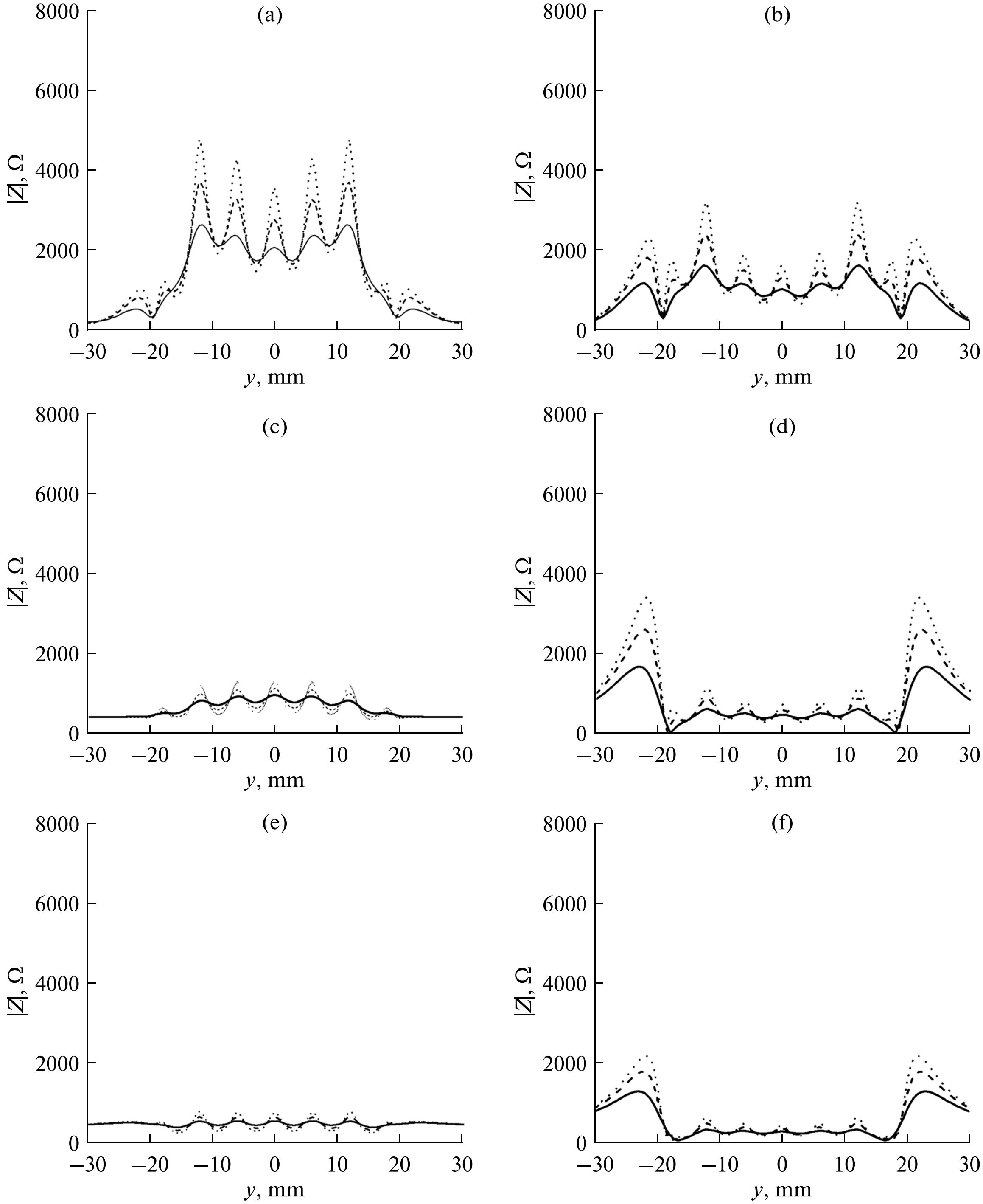

Fig. 6. Calculated dependences of $|Z(z, y)|$ for specimen 3 at frequencies f = (a) 2.35, (b) 2.3, (c) 2.5, (d) 2.2, (e) 2.6, and (f) 2.1 GHz and z = (dotted lines) 0.5, (dashed lines) 1, and (solid lines) 2 mm.

direction parallel to the gaps; therefore, the impedance value averaged over the y coordinate is roughly equal to the impedance averaged over the surface.

Figures 7a and 7b show frequency dependences of $|Z|_{av}$ at three distances z from the grating surface for specimens 1 and 3, respectively. It can be seen that the values of average impedance $|Z|_{av}$ of specimens 1 and 3 are significantly higher than the free-space impedance within frequency bands of 3.8–4 and 2.3–2.5 GHz, respectively.

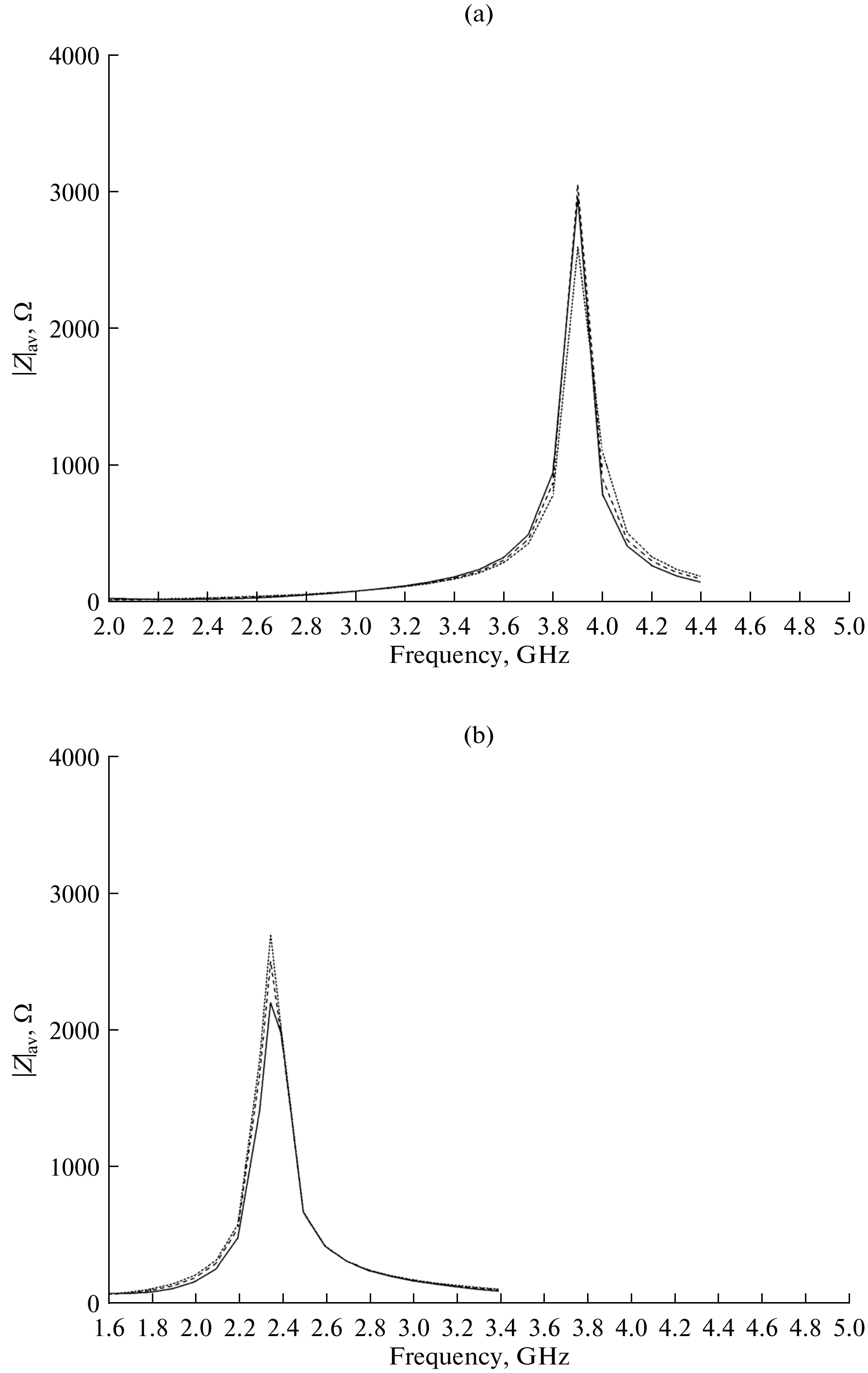

Fig. 7. Frequency dependences of $|Z|_{av}$ for (a) specimen 1 and (b) specimen 3 at z = (dotted lines) 0.5, (dashed lines) 1, and (solid lines) 2 mm.

The electric field patterns near specimens 1 and 3 at the frequencies of the RCS and $|Z|_{av}$ maxima were calculated for the case when a plane wave is incident onto these samples. At the frequency of the RCS maximum, the electric field is concentrated near the resonator ends (i.e., the dipole resonance along the resonator length B is observed). The tangential component of the electric field at the frequency of maximum $|Z|_{av}$ is concentrated near the grating surface. This occurs due to an internal resonance within the

Measured and calculated characteristics of specimens

Specimen no.	Specimen thickness, mm	Measured frequency of the RCS maximum, GHz	Calculated frequency of the RCS maximum, GHz	Resonance frequency f_r, GHz	Frequency of the maximum of impedance $\|Z\|_{av}$, GHz	Maximum value of impedance $\|Z\|_{av}$, Ω
1	1.0	2.65	2.85	4.6	3.9	3000
2	2.0	2.33	2.5	3.2	2.85	2600
3	3.0	2.17	2.2	2.6	2.35	2700
4	4.0	2.05	2.0	2.3	2.1	3500

specimen and is a required property of magnetic conductors.

CONCLUSIONS

Our measurements and calculations have shown that resonance frequency f_r and frequencies of maximum RCS and $|Z|_{av}$ (the averaged value of the surface impedance) decrease and come closer to each other as the AMC resonator becomes thicker. The RCS maximum is associated with the dipole resonance of the AMC resonator and the maximum of $|Z|_{av}$ is attributed to the internal resonance in the region between the gratings and the metal bottom of the resonator. It has been found that maximum values of $|Z|_{av}$ reach 3000 Ω, which is many times greater than the wave impedance of free space. The width of the band in which $|Z|_{av} >$ 1000 Ω is about 200 MHz.

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Translated by D. Safin