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Microwave Diffraction Dependencies of a Conductor Cylinder Coated with Twelve Glass and Semiconductor Layers on the *n*-Si Specific Resistivity

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Introduction

Boundary problems of microwave scattering and absorption by cylinders made of conductor, dielectric or semiconductor have been studied for a long period of time because the problems are very important in radar, telecommunication and other technologies [1, 2]. Electromagnetic (EM) wave scattering and absorption from a cylinder is a hot research topic of different areas such as a microwave remote sensing, a cylindrical object influence on the electromagnetic wave propagation, theory of photonic crystals especially when the distance between cylindrical obstacles is large enough compare to a wavelength of incident microwaves, atmospheric sciences, and so on [3, 4]. The different microwave elements like a conductor cylindrical plate or other material scattering bodies located close to an antenna can improve the total antenna characteristics, e.g., enhance antenna bandwidth and reduce antenna size [5].

Innovative physical properties of multiwall carbon nanotubes caused their intensive investigation by macroscopic electrodynamics methods. The research results of multilayer cylinders as nanotubes and other sandwich structures in modern electronic devices are in [6–9]. In article [7] is given the rigorous electrodynamical solution of diffraction problem about the microwave scattering and absorption by a multilayered cylinder. This method is suitable for the analysis of a cylinder, consisting of any number of layers with an actually arbitrary thickness and made of materials with any complex permittivity and permeability. In the article is presented numerical analysis of two layered metamaterial–glass cylinder. Some important electrodynamical investigations of the semiconductor cylindrical rod and other structures are presented in [10–12].

The calculated scattered and absorbed powers of a conductor cylinder coated with a sandwich of *n*-Si semiconductor and glass layers are presented in our current article. There are twelve layers of the cover here. There are layers of glass between the semiconductor layers. We did not find other authors' appropriate articles where would be considered a conductor cylinder coated with so many layers. The cylindrical sandwich structure that presented in our article can be used as a microwave sensor because the structure is very sensitive to the specific resistivity of semiconductor material, as well as a scattering body located close to an antenna in order to improve the antenna characteristics and etc. Our computer code was written on the FORTRAN programming langue.

Problem formulation and parameters

Here we present our calculations that based on the rigorous electrodynamical solution of diffraction problem about the microwave scattering by an infinite multilayered cylinder [7]. The central core of multilayered cylinder made of an ideal conductor. The conductor core is coated by a sandwich semiconductor-glass cover. The multilayered cylinder consists of thirteen concentric surfaces with radii R_j, $j = 1, 2, ..., N$ (Fig. 1).

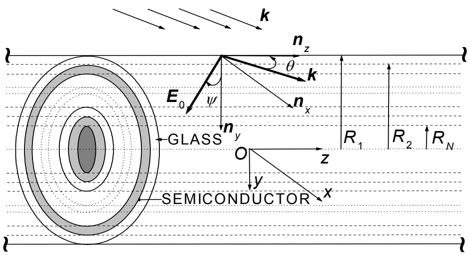

Fig. 1. *N*-layered conductor–semiconductor-glass cylinder model and designations

The every j-th region is filled with a material having the permittivity ε_j and the permeability μ_j. Numbering of layers is going from outside layer to the inner one. Thus R_1 is the outside radius of the cylinder. In our calculations $N = 13$, i.e. the conductor core with radius R_{13} is coated with 12 layers of glass and n-Si materials alternately. The radius of conductor core is R_{13} = 0.5 mm. The outer radius of the multilayered cylindrical structure is R_1 = 2 mm. The thickness of every layer is equal to 0.125 mm. The first layer that coated the conductor cylinder is a semiconductor one and the outer layer is a glass one.

We assumed that a glass material is the non-dispersive and weakly lossy material with the complex permittivity $\varepsilon_g = 3.8 - \mathrm{i}\ 0.0005$ in our calculations. As it is known, a semiconductor material with some relatively small specific resistivity is the dispersive lossy material. The imaginary part of semiconductor permittivity dependent on the frequency. And the n-Si permittivity ε_s is determined by the expression

$$\varepsilon_s = 11.8 - \mathrm{i}/(\omega\varepsilon_0\rho), \qquad (1)$$

where $\omega = 2\pi f$ is an angular frequency of incident microwave, f is the operating frequency, ε_0 is the electric constant, ρ is the semiconductor material' specific resistivity. The semiconductor losses depend on the frequency and this fact strongly affects on the absorbed power into semiconductor layers. The glass and the semiconductor permeabilities are equal to $\mu_g = \mu_s = 1$.

The incident plane harmonic monochromatic microwave

$$\boldsymbol{E}^{in} = \boldsymbol{E}_0 \exp\left(\mathrm{i}\omega t - \mathrm{i}\sqrt{\varepsilon\mu}\,\boldsymbol{kr}\right) \qquad (2)$$

propagates in the plane $x0z$ and the direction of propagation describes by an angle θ between the z-axis and the wave vector $\boldsymbol{k}$. Here $\boldsymbol{E}_0$ is an amplitude of electric field of the incident microwave. The vector $\boldsymbol{E}_0$ determines the polarization of the incident microwave. The direction of vector $\boldsymbol{E}_0$ defined by the angle ψ this one is between the vector $\boldsymbol{E}_0$ and the y-axis. The EM wave has the parallel polarization when the angle ψ is equal to 90°. The EM wave has the perpendicular polarization when ψ is equal to 0°. The module of the amplitude of incident microwave $|\boldsymbol{E}_0| = 1$. Here $(\boldsymbol{E}_0\ \boldsymbol{k}) = 0$, $(\boldsymbol{E}_0\ \boldsymbol{n}_y) = \cos\psi$, $\boldsymbol{k} = k_x\,\boldsymbol{n}_x + k_z\,\boldsymbol{n}_z$, where $\boldsymbol{n}_x$, $\boldsymbol{n}_y$, $\boldsymbol{n}_z$ are the unit vectors. The cylinder is placed in an air medium with the permittivity and the permeability $\varepsilon = \mu = 1$. Boundary conditions on all surfaces separating different media are the standard ones, i.e. the equality of tangent components of the electric and magnetic fields on the every semiconductor - glass surface is required and the tangent component of electric field is equal to zero on the ideal conductor surface.

Results and discussion

The calculated scattered and absorbed powers per unit length for frequencies f from 1 to 101 GHz with the step equal to 0.1 GHz are presented here. Formulae for the calculation of scattered and absorbed powers are given in [7]. The maximum number of members in the sums of scattered and absorbed power expressions are taken equal to 49, i.e. 25 cylindrical harmonics are participated here. The number of curve indicates the magnitude of the semiconductor material' specific resistivity: 1 – ρ = 100 Ω·m, 2 – ρ = 30 Ω·m, 3 – ρ = 10 Ω·m in Figs 2–9.

The investigations of scattered and absorbed powers at two impinge directions of the incident microwave when θ = 90° (Figs 2–5) and θ = 60° (Figs 6–9) are shown in the current article. The scattered power and the absorbed power for the incident perpendicular polarized microwave (ψ = 0°) are presented in Figs 2, 4, 6, 8. The calculations for the incident parallel polarized wave (ψ = 90°) are shown in Figs 3, 5, 7, 9. We can see in Figs 2, 3, 6 and 7 that the scattered power for all three magnitudes of the semiconductor specific resistivity (curves 1–3) with graphical accuracy is the same. The identity of last characteristics is explained by the fact that the real parts of permittivities of all layers are invariable and the modules of the permittivities change insignificantly at the frequency range 1–101 GHz.

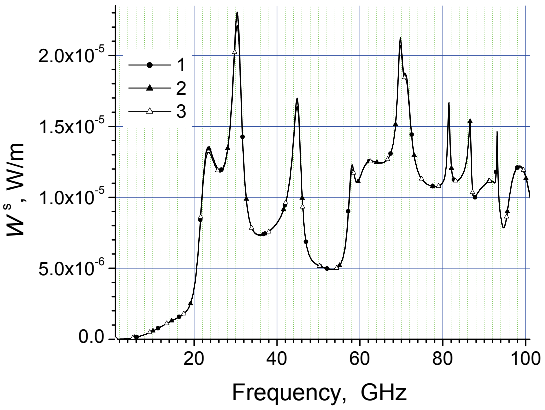

Fig. 2. Scattered power dependency on the incident microwave frequency for θ = 90°, ψ = 0°

The dependencies of the scattered power on frequencies for the perpendicular (Fig. 2) and the parallel (Fig. 3) microwave polarizations are essentially different.

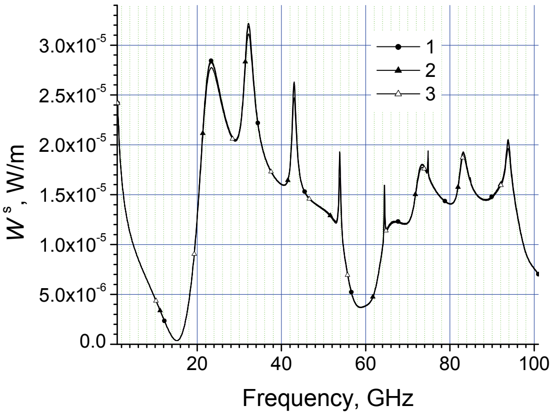

Fig. 3. Scattered power dependency on incident microwave frequency for θ = 90°, ψ = 90°

The place of extremums on the f – axis and their magnitudes in Figs 2 and 3 are dissimilar. We see that the EM wave is not reflected from the cylinder in the vicinity of frequency 17 GHz for the parallel polarized microwave (Fig. 3). There is an interval of transparency for the microwave at and around of 17 GHz. The comparison of scattered power dependencies for the perpendicular polarized microwave at two incident angles θ = 90^o (Fig. 2) and θ = 60^o (Fig. 6) shows that the features of both curves are different.

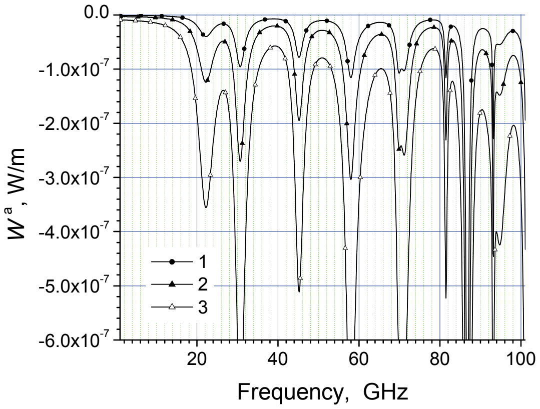

Fig. 4. Absorbed power dependency on incident microwave frequency for $\theta = 90^o$, $\psi = 0^o$

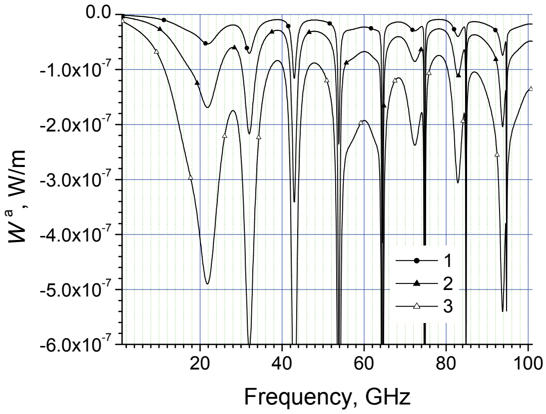

Fig. 5. Absorbed power dependency on incident microwave frequency for $\theta = 90^o$, $\psi = 90^o$

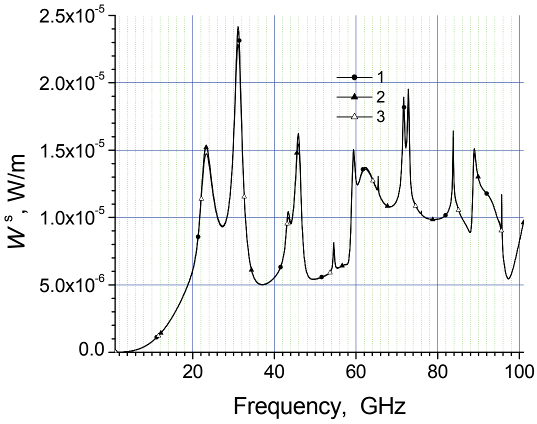

Fig. 6. Scattered power dependency on incident microwave frequency for $\theta = 60^o$, $\psi = 0^o$

For example, a shape of smooth minimum at f~46 – 58 GHz in Fig. 2 has a more complicated shape with an additional local maximum at f ~ 56 GHz in Fig. 6. A comparison of scattered power dependencies for the parallel polarized microwave at two incident angles $\theta = 90^o$ (Fig. 3) and $\theta = 60^o$ (Fig. 7) shows that the both curve extremums have the same position on the f–axis and they have different values.

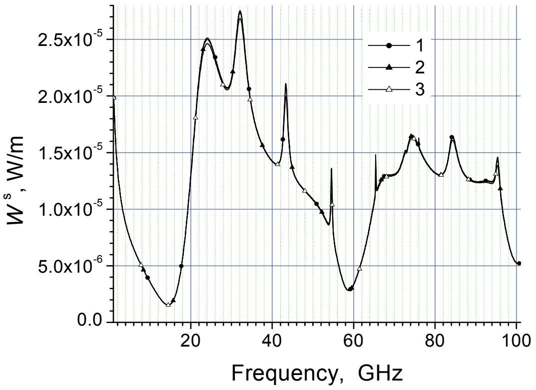

Fig. 7. Scattered power dependency on incident microwave frequency for $\theta = 60^o$, $\psi = 90^o$

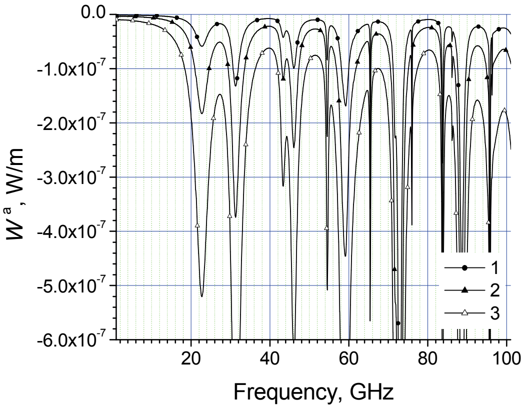

Fig. 8. Absorbed power dependency on incident microwave frequency for $\theta = 60^o$, $\psi = 0^o$

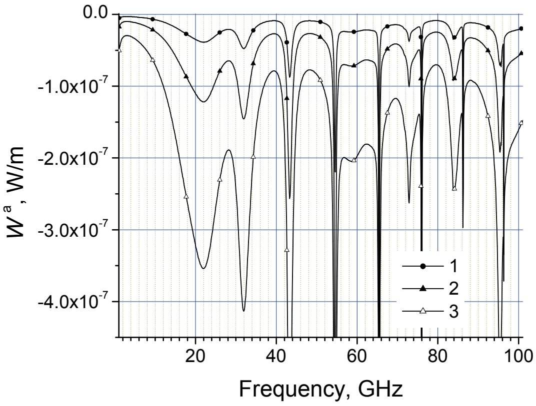

Fig. 9. Absorbed power dependency on incident microwave frequency for $\theta = 60^o$, $\psi = 90^o$

When the angle θ decreases then the scattered power dependency changes qualitatively. For example the scattered power dependencies for both microwave polarizations at angles $\theta = 60^o$ and 90^o were a strong different and these dependencies became very alike for both polarizations at small angles as $\theta = 5^o$.

The absorbed powers of both microwave polarizations depend on the semiconductor specific resistivity noticeably. We see in Figs 4, 5, 8, 9 that the absorbed power is the largest when the ρ magnitude is the smallest. The largest absorption is at the specific resistivity $\rho = 10\ \Omega\cdot\mathrm{m}$ of *n*-Si material.

EM energy of the incident microwave is reflected and absorbed by every layer of cylinder and the energy can be strongly absorbed at certain wavelengths of incident microwave. It means that in a multilayered cylinder can be observed the dimensional resonances.

Conclusions

1. Analyses of scattered and absorbed microwave powers of conductor cylinder coated with twelve lossy semiconductor-glass layers is carried out on the base of the rigorous solution of the boundary diffraction problem.
2. The microwave power dependencies on the *n*-Si specific resistivity, the incident microwave frequency, polarization and direction of it propagation are implemented. The dispersion dependency of semiconductor material losses is taken into account.
3. A magnitude of absorbed power is strongly dependent on the *n*-Si material specific resistivity at the frequency range 1-101 GHz. The dependence on the specific resistivity shows that this multilayered cylindrical structure can be used for creating of microwave semiconductor sensors.

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The analysis of absorption and scattering dependencies of a multilayer cylinder on the incident plane wave frequency is presented. The cylinder consists of ideal conductor cylinder coated with twelve lossy n-Si semiconductor – glass layers alternatively. The calculation of the scattered and absorbed powers per unit length is based on the rigorous solution of scattering boundary problem. Calculations take into account the dispersion properties of n-Si material. Dependences are calculated for different values of semiconductor specific resistivity when the incident microwave propagates in the normal ($\theta = 90^o$) and oblique ($\theta = 60^o$) directions to the z-axis. Here are presented dependencies for the two polarizations of the incident microwave, i.e. the perpendicular ($\psi = 0^o$) and parallel ($\psi = 90^o$) ones. We discovered that there is a strong dependency of the absorbed power on the n-Si specific resistivity. There are intervals on the frequency f -axis where the scattered and absorbed powers have some small values, i.e., the microwave doesn't "see" the multilayer cylinder (Invisible Cloak) at some frequency bands. Ill. 9, bibl. 12 (in English; abstracts in English and Lithuanian).

L. Nickelson, J. Bučinskas. Laidaus cilindro, padengto dvylika stiklo ir puslaidininkio su n-Si savitąja varža sluoksnių, difrakcinės savybės mikrobangų diapazone // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 9(115). – P. 47–50.

Tiriamos sklaidos ir sugerties priklausomybės nuo bangos dažnio, kai idealiai laidus cilindras, pakaitomis padengtas dvylika puslaidininkio ir stiklo sluoksnių, yra plokščiosios bangos lauke. Cilindro ilgio vienete sugeriama ir išsklaidoma galia apskaičiuojama naudojantis griežtu sklaidos kraštinio uždavinio sprendiniu. Skaičiuojant atsižvelgiama į dispersiją n-Si puslaidininkyje. Priklausomybės apskaičiuotos esant įvairioms puslaidininkio savitosios varžos vertėms, kai krintančiosios bangos kryptis yra statmena cilindro ašiai $\theta = 90^o$ ir kai su ašimi sudaro $\theta=60^o$ laipsnių kampą, o bangos poliarizacijos vektorius yra statmenas cilindro ašiai ($\psi = 0^o$), taip pat kai poliarizacijos vektorius yra cilindro ašies ir banginio vektoriaus plokštumoje ($\psi = 90^o$). Skaičiavimai rodo, kad sugertis labai priklauso nuo silicio savitosios varžos. Nustatyta, kad tirtamam daugiasluoksniam cilindrui būdingos mažos sklaidos ir kartu mažos sugerties dažnių juostos, kuriose mikrobanga „nemato“ daugiasluoksnio cilindro. Il. 9, bibl. 12 (anglų kalba; santraukos anglų ir lietuvių k.).