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Resonance characteristics of microwave photonic crystals with inclusions in the form of conducting nanolayers

© A.V. Skripal, D.V. Ponomarev, V.E. Sharonov

Saratov National Research State University, Saratov, Russia
E-mail: skripala_v@info.sgu.ru

Received June 1, 2023
Revised July 24, 2023
Accepted August 4, 2023

The resonant characteristics of one-dimensional photonic crystals with the defect of periodicity associated with the effect of microwave radiation resonant tunneling through a conducting nanolayer at frequencies lower than the plasma resonance frequency have been theoretically described and experimentally investigated. The effect of transparency at the defect mode frequency is achieved due to the minimum level of electromagnetic radiation interaction with the conductive nanolayer placed in the electric field strength node of the standing electromagnetic wave inside the defect of the photonic crystal.

Keywords: Photonic crystal, nanolayer, resonant tunneling.

DOI: 10.61011/TPL.2023.10.57051.19645

Thin conducting nanolayers are used in various fields of microwave engineering. Microwave matched loads, bolometric power meters for millimeter and subterahertz ranges, electromagnetic screens, components of integrated microwave circuits, and components of flexible large-area electronics and photonics are fabricated based on them [1–3].

The application potential of thin conducting layers in microwave engineering stems largely from their capacity to both absorb electromagnetic energy and become transparent.

Absorbers based on conducting layers are normally constructed as multilayer structures with alternating conducting and dielectric layers. Conducting layers may take the form of metallic and heavily doped semiconductor layers based on graphene and carbon films and metallic and graphene metasurfaces [4–6].

The effect of transparency of conducting layers in the microwave range at frequencies below the plasma resonance one may be regarded as the effect of tunneling of an electromagnetic wave, which is equivalent to tunneling of an elementary particle through a potential barrier with its height exceeding the particle energy [7]. Thin plasma layers, sandwich plasma–dielectric structures, interleaved metal–dielectric structures, and multilayer structures made of metamaterials with a negative permittivity and dielectric layers with high permittivity values have been considered as candidate structures exhibiting the tunneling effect [8–10]. Structures containing ultrathin conducting layers are made highly transparent by resonance tunneling of microwave radiation, which occurs due to resonance reflection in dielectric layers that surround the conducting ones and form Fabry–Pérot cavities. A volume defect of periodicity in a microwave photonic crystal (PC), which induces a defect mode in the band gap in the amplitude–frequency characteristic, is one of the many types of Fabry–Pérot cavities [11].

In the present study, the resonance characteristics of a PC related to the effect of resonance tunneling of microwave radiation at the defect mode frequency are examined theoretically and experimentally with conducting nanolayers introduced into the defect.

A microwave PC based on a rectangular waveguide with dielectric filling in the form of alternating Al_2O_3 ceramic (odd layers, $\varepsilon = 9.6$, 1.0 mm in thickness) and polytetrafluoroethylene (even layers, $\varepsilon = 2.0$, 9 mm in thickness) layers was studied within the range of frequencies $f = 7-13$ GHz. This crystal was composed of 11 layers that filled the entire cross section of the waveguide. A periodicity defect was produced by substituting the central polytetrafluoroethylene layer with an air gap (Fig. 1). The longitudinal size of the defect was $d_6 = 22.0$ mm. The studied metal–dielectric structure was a nanometer metallic layer deposited onto a ceramic substrate (Al_2O_3). It was positioned within the PC defect and filled the entire cross section of the waveguide (Fig. 1).

The PC structure parameters were chosen so as to produce a band gap within the 8–12 GHz frequency range.

The transfer matrix of a layered structure [12–14] with different values of electromagnetic wave propagation constants γ_i and γ_{i+1} (i is the layer number) and the propagation of just the primary wave type H_{10} in the waveguide taken into account was used to calculate the frequency dependences of reflection $S_{11}(f)$ and transmission $S_{21}(f)$ coefficients for an electromagnetic wave.

The distribution of electric field $E(z)$ in the one-dimensional PC [10] was characterized by the wave equation that takes the following form within each homogeneous

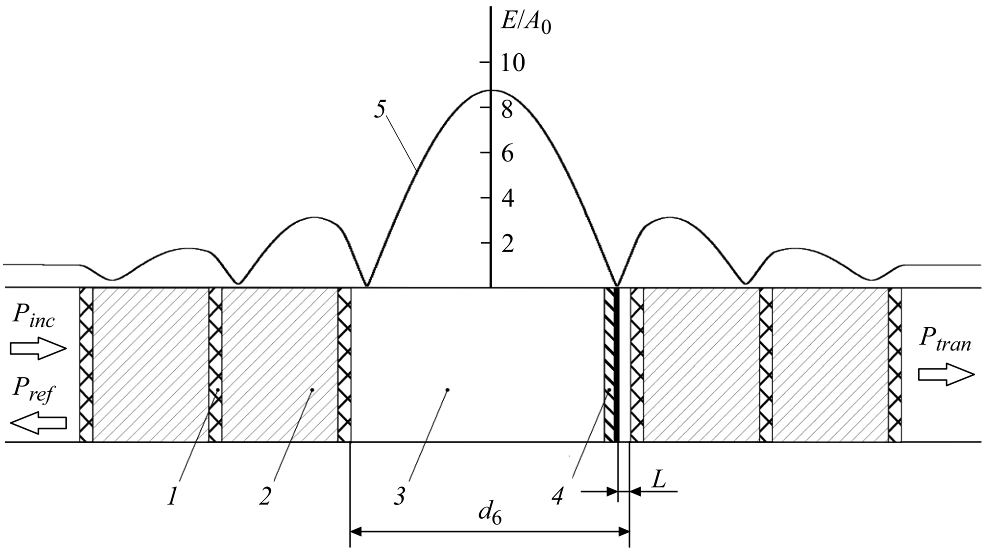

Figure 1. Longitudinal section of a PC with the structure of a ceramic substrate (Al_2O_3) 0.5 mm in thickness with a conducting layer deposited onto it and longitudinal distribution of electric field E of a standing electromagnetic wave in the PC at the defect mode frequency (curve *5*). *1* — Polycor layers, *2* — fluoropolymer layers, *3* — defect, *4* — studied structure. The longitudinal PC size is 64 mm. A_0 — amplitude of the electric field of an electromagnetic wave incident on the PC. P_{inc}, P_{tran}, and P_{ref} — incident, transmitted, and reflected waves.

PC layer:

$$\frac{\partial^2 E(z)}{\partial z^2} + \gamma_i^2(z)E(z) = 0,$$

where $\gamma_i(z)$ is the electromagnetic wave propagation constant in layer i.

The defect size was chosen so that the defect mode emerged in the middle of the band gap and an antinode of the electric field of a standing electromagnetic wave was observed at the center of the defect at the defect mode frequency. Standing wave nodes were observed in this case within the defect near its boundaries (Fig. 1). Positioning the studied structure close to a node or an antinode of a standing wave, one could adjust the level of interaction between the electromagnetic wave and the structure.

Samples in the form of a ceramic (Al_2O_3) substrate 0.5 mm in thickness with a deposited conducting layer with thickness $d = 20$ nm and specific conductivity $\sigma = 2.5 \cdot 10^6\,\Omega^{-1} \cdot \mathrm{m}^{-1}$ were examined.

It follows from the results of calculation of $S_{21}(f)$ and $S_{11}(f)$ presented in Fig. 2, a that transmission coefficient S_{21} at the defect mode frequency of 10.132 GHz is -1.4 dB if the metal–dielectric structure is positioned at the node of a standing wave at distance $L = 1.4$ mm from the right boundary of the defect. This corresponds to a considerable (72%) transmission of microwave power at the defect mode frequency of the PC (curve *5* in Fig. 2, a). This transmission may be regarded as a manifestation of the effect of resonance tunneling through a conducting medium at frequencies lower than the plasma resonance one.

The observed incomplete transmission of microwave power is attributable to its absorption in the conducting layer. Treating metallic nanolayers in the microwave range as media with a negative real part of complex permittivity, one needs to take into account its significant imaginary part $\varepsilon'' = 10^4 - 10^6$. Under resonance tunneling conditions, the reflection coefficient becomes insignificant (below 1%; curve *2* in Fig. 2, a).

Note that an isolated metal–dielectric structure with parameters indicated above transmits less than 1% of power in the three-centimeter wavelength range.

When the sample is positioned far from a node (e.g., at the very boundary of the defect ($L = 0$ mm) or at distance greater than $L = 1.4$ mm from the defect boundary), S_{21} drops sharply to levels below -20 dB (curves *4* and *6* in Fig. 2, a); i.e., the effect of resonance tunneling through the highly conducting layer vanishes almost completely.

Note that the degree of transparency of the conducting layer at the defect mode frequency increases with increasing number of PC layers and multiplicity of their permittivity values.

It follows from the results of calculation of $S_{21}(f)$ and $S_{11}(f)$ for the PC with the sample without a conducting nanolayer within the defect (see Fig. 2, b) that a change in the sample positioning within the defect in the vicinity of the node of a standing wave results in a shift of the resonance defect mode frequency and an insignificant S_{21} reduction due to a slight S_{11} increase.

A PC fabricated in accordance with the above model was examined experimentally at frequencies $f = 7-13$ GHz. A sample in the form of a polycor (Al_2O_3) plate 0.5 mm in thickness with a deposited continuous conducting TaAlN nanolayer 140 nm in thickness with sheet resistance $\rho_l = 19.5\,\Omega$/sq was positioned within the defect. The thickness of the conducting nanolayer was measured with an

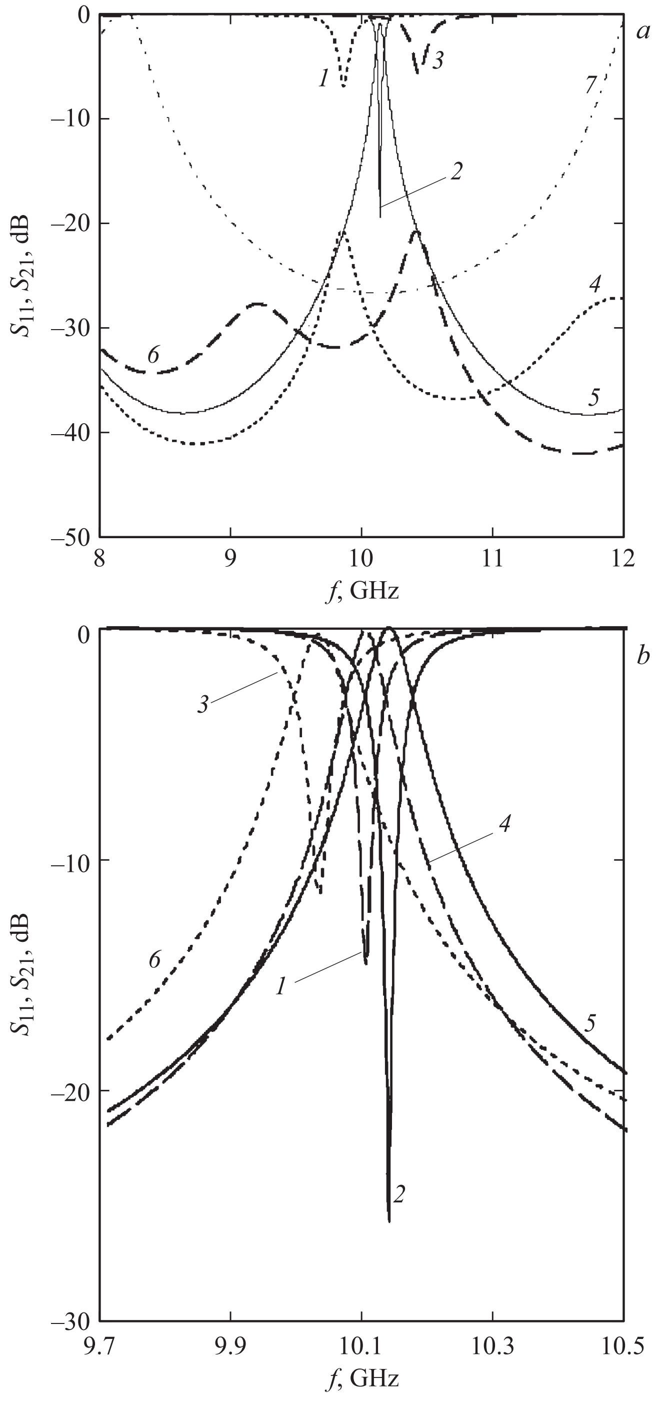

Figure 2. Calculated amplitude–frequency characteristics of reflection $S_{11}(f)$ $(1–3)$ and transmission $S_{21}(f)$ $(4–6)$ coefficients of the PC corresponding to different positions of the sample within the defect. $L = 0$ $(1, 4)$, 1.4 $(2, 5)$, and 2.5 mm $(3, 6)$. *7* — Amplitude–frequency characteristic of the transmission coefficient of the photonic crystal with no defects of periodicity. *a* — With a conducting nanolayer; *b* — without a conducting nanolayer.

Agilent 5600 atomic force microscope. The sheet resistance was measured using the four-point probe method and a Jandel RMS-EL-Z probe station. An Agilent N5242A PNA-X network analyzer was used to examine amplitude–frequency characteristics $S_{21}(f)$ and $S_{11}(f)$ of the PC at different positions of structures with a nanolayer within the defect.

In accordance with the results of theoretical analysis, the effect of enhanced transparency of the metal–dielectric structure was observed experimentally with the metallic layer positioned within the PC defect at a distance of 1.5 mm from the defect boundary (curve *5* in Fig. 3). When the sample is positioned at the very boundary of the defect ($L = 0$ mm) or at distance greater than $L = 1.5$ mm from the defect boundary, S_{21} drops sharply to levels on the order of -20 dB (curves *4* and *6* in Fig. 3); i.e., the effect of resonance tunneling becomes insignificant in these cases.

Thus, the examination of resonance characteristics of microwave PCs with a defect of periodicity containing a nanometer metallic layer revealed the effect of enhanced transparency of the metal–dielectric structure at frequencies lower than the plasma resonance one and demonstrated that the effect of resonance tunneling at the defect mode frequency is induced by the minimization of interaction between electromagnetic radiation and the conducting layer positioned at the node of a standing wave within the PC defect.

The obtained results may be applied both in the design of narrow-band tunable microwave filters and attenuators based on photonic crystals, which contain semiconductor elements with a controllable level of injection of free carriers, and in the characterization of heavily doped semi-

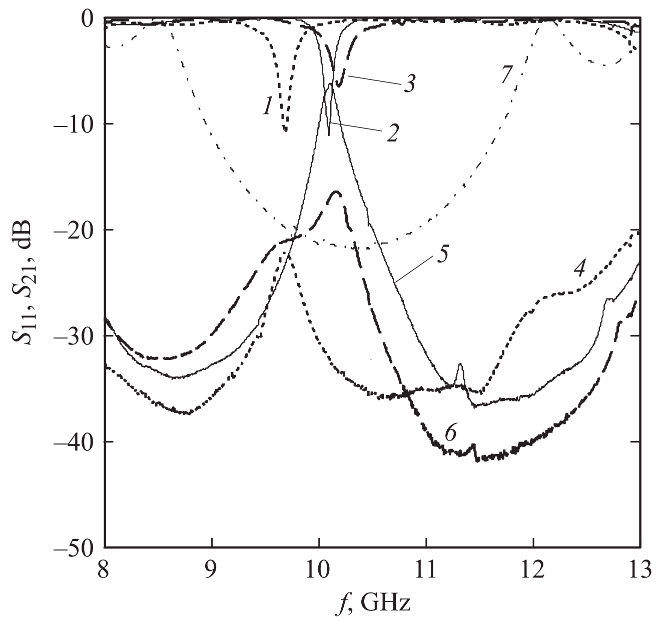

Figure 3. Experimental amplitude–frequency characteristics of reflection $S_{11}(f)$ $(1–3)$ and transmission $S_{21}(f)$ $(4–6)$ coefficients of the PC corresponding to different positions of the sample with a conducting nanolayer within the defect. $L = 0$ $(1, 4)$, 1.5 $(2, 5)$, and 2.5 mm $(3, 6)$. *7* — Amplitude–frequency characteristic of the transmission coefficient of the photonic crystal with no defects of periodicity.

conductor and metallic nanolayers, graphene nanostructures, and metal–dielectric metasurfaces.

Funding

The study was supported financially by the Innovation Promotion Fund (project 17308GU/2022 dated April 12, 2022) and the Ministry of Education and Science of the Russian Federation (as part of the strategic academic leadership program „Priority-2030").

Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by D.Safin