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Resonances in microwave photonic crystals with an interface layer in the form of structure containing continuous water layer

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The resonant characteristics of microwave photonic crystals associated with the effect of the appearance of photonic Tamm states in the bandgap in the case of using electromagnetic radiation absorber in the form of structure with continuous water layer as an interface layer have been theoretically described and experimentally studied. It has been established that an increase in the thickness of the distilled water layer leads to damped oscillations of the frequency and amplitude of the Tamm resonance.

Keywords: photonic Tamm states, absorbers, water-containing structures, microwave range.

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Layers of an electromagnetic radiation absorber in the form of a continuous conducting (metallic or heavily doped semiconducting) layer or in the form of an array of ordered conducting (metallic) nanometer strips are used as an interface in the study of microwave photonic crystals characterized by the presence of photonic Tamm states in the bandgap [1,2]. The complex permittivity of such layers has a negative real part and a significant imaginary part.

However, the interest in potential application of structures containing water in the form of both continuous layers and individual periodically arranged droplets in microwave technology as absorbers of electromagnetic energy has been on the rise lately [3], since water is characterized by significant values of both real and imaginary parts of complex permittivity in the microwave range. It is noted that absorbers of microwave electromagnetic radiation based on water-containing structures have a number of advantages, such as biocompatibility, availability, ease of adjustment, and optical transparency [3,9], over more traditional materials based on layers with a high electrical conductivity [4–8].

In the present study, the resonant characteristics of microwave photonic crystals associated with the emergence of photonic Tamm states in the bandgap are examined theoretically and experimentally with an absorber of microwave electromagnetic radiation based on a structure containing water in the form of a continuous layer used as an interface layer.

Microwave photonic crystals based on a rectangular waveguide with dielectric filling in the form of alternating Al_2O_3 ceramic (odd layers, $\varepsilon = 9.6$, 0.5 mm in thickness) and polytetrafluoroethylene (even layers, $\varepsilon = 2.0$, 18 mm in thickness) layers were studied within the $7-13$ GHz frequency range. These crystals were composed of 11 layers that filled the entire cross section of the waveguide.

A waveguide section filled with a continuous layer of distilled water with thickness d was adjacent to a photonic crystal. The water layer was separated from the last layer of the photonic crystal by a thin polytetrafluoroethylene film ($\varepsilon = 2.0$) with a thickness of 30 μm. An air gap was also created between the film and the last photonic crystal layer; width L of this gap was adjustable (Fig. 1).

The transfer matrix of a layered structure [10–13] 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 dependence of reflection coefficient $S_{11}(f)$ for an electromagnetic wave.

The frequency dependence of complex permittivity $\varepsilon^*(\nu)$ of distilled water was determined based on the two-frequency Debye relaxation model [14–17]:

$$\varepsilon^*(\nu) = \varepsilon_\infty + \frac{\Delta\varepsilon_1}{1 + i2\pi\nu\tau_1} + \frac{\Delta\varepsilon_3}{1 + i2\pi\nu\tau_3},$$

where $\varepsilon_\infty = 3.96$ is the optical permittivity, $\Delta\varepsilon_1 = 72.15$ and $\Delta\varepsilon_3 = 2.14$ are the relaxation amplitudes, and $\tau_1 = 8.32$ ps and $\tau_3 = 0.39$ ps are the relaxation times [14].

A calculation of the reflection coefficient within the $7-13$ GHz frequency range was performed in order to clarify the specifics of photonic Tamm resonances in the structure of a one-dimensional microwave photonic crystal with an interface layer in the form of a microwave radiation absorber based on a structure containing a continuous water layer. The structure of a microwave photonic crystal with a layer of distilled water was analyzed at different values of water layer thickness d and width L of the air gap between the film and the last photonic crystal layer.

It follows from the calculation results that Tamm resonances emerge in the amplitude-frequency characteristics (AFCs) of photonic crystals in both the first and second bandgaps at frequencies f_{Tamm1} and f_{Tamm2}. Their position varies with thickness of the distilled water layer.

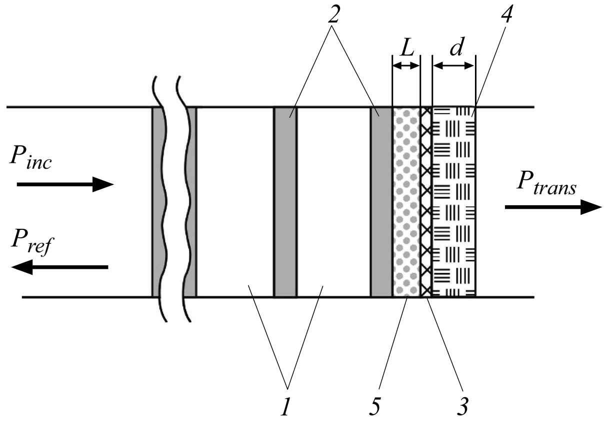

Figure 1. Design of a one-dimensional microwave photonic crystal with an interface layer in the form of a microwave radiation absorber based on a structure containing a continuous water layer. *1* — Polytetrafluoroethylene layer, *2* — Al_2O_3 layer, *3* — polytetrafluoroethylene film, *4* — distilled water layer, and *5* — air gap.

Figure 2 presents the results of calculations in the form of a 3D map of frequencies f_{Tamm1} and amplitudes $S_{11Tamm1}$ of the reflection coefficient for the Tamm resonance in the first bandgap.

As the distilled water layer thickness increases, the Tamm resonance frequency in the first bandgap decreases monotonically within the range of thickness d from 0 to 2.0 mm (Fig. 2, a). A further increase in the water layer thickness leads to damped oscillations of the Tamm resonance frequency.

It follows from the presented data that an increase in thickness d of the water layer also leads to oscillations of the amplitude of Tamm resonances, which are damped at large thickness values (Fig. 2, b).

The amplitude and frequency of the reflection coefficient for the Tamm resonance in the second bandgap vary in much the same way. At large water layer thicknesses, damping of amplitude and frequency oscillations is also observed.

The frequency and amplitude of Tamm resonances could be adjusted by altering the structure of the interface: creating an air gap between the polytetrafluoroethylene film and the last photonic crystal layer.

It follows from the results of calculations of the photonic crystal AFCs (Figs. 2, a, b) that an increase in width L of the air gap between the film and the last photonic crystal layer at fixed thickness d of the water layer induces a downward shift of the Tamm resonance frequency.

The depth of the Tamm resonance may be adjusted in this case by varying width L of the air gap. At small gap widths L, the dependence of the Tamm resonance amplitude on the water layer thickness within the range from 0.1 to 2.0 mm features two sharp deep minima, which merge into one smoother minimum as gap width L increases.

The calculation results also indicate that, depending on thickness d of the water layer (at small thickness values), the creation of an air gap with a subsequent increase of its width L leads either to a monotonic reduction in the amplitude of Tamm resonances or to a non-monotonic variation of their amplitude; the amplitude of Tamm resonances may increase by more than 10 dB in the latter case.

The amplitude and frequency of the reflection coefficient for the Tamm resonance in the second bandgap vary in much the same way. Note that the change in frequency in the second bandgap induced by an enhancement of air gap width L is more than 2 times greater than a similar change in the first bandgap.

A photonic crystal fabricated in accordance with the above model was examined experimentally. Measurements were performed using an Agilent N5242A PNA-X vector network analyzer within the 7–13 GHz frequency range. To isolate water, a polytetrafluoroethylene film was placed between the photonic crystal and the water layer.

The influence of thickness d of the distilled water layer on the characteristics of the Tamm resonance was examined experimentally (Fig. 3). As the water layer thickness increases, the Tamm resonance frequency decreases monotonically in the first bandgap within the thickness range of $d = 0{-}1.74$ mm (Fig. 3, a) and in the second bandgap within the thickness range of $d = 0{-}1.2$ mm (Fig. 3, b). A further increase in thickness d of the water layer leads to damped oscillations of the Tamm resonance frequency.

It follows from the experimental data that an increase in the water layer thickness also leads to oscillations of the amplitude of Tamm resonances, which are damped at large thickness values. A significant change in the amplitude of the Tamm resonance is observed in the first bandgap in this case.

An air gap was created in experiments by positioning thin metal diaphragms of variable thickness (with an aperture matching the cross section of the waveguide used to produce the photonic crystal) between the photonic crystal and the water layer. The creation of an air gap and the growth of its width at a fixed water layer thickness induce a downward shift of the Tamm resonance frequency in both the first and second bandgaps. This is consistent with the calculation results.

The dependence of amplitudes of Tamm resonances on the air gap width was measured at a fixed water layer thickness. The obtained results verified the possibility of adjustment of the Tamm resonance amplitude.

Thus, the studies of resonance characteristics of microwave photonic crystals with an electromagnetic energy absorber in the form of a structure containing a continuous water layer used as an interface revealed the emergence of photonic Tamm states in the bandgap and allowed us to establish that an increase in thickness of the distilled water layer leads to damped oscillations of the frequency and amplitude of the Tamm resonance, while an increase in width of the air gap leads to a downward shift of the Tamm resonance frequency.

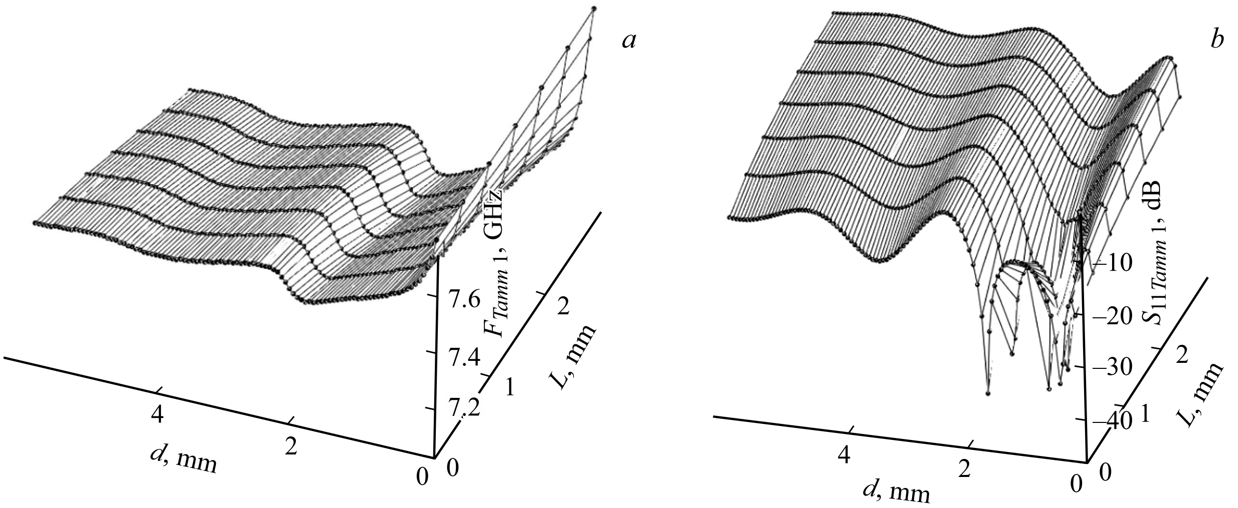

Figure 2. Calculated 3D map of frequencies f_{Tamm1} (*a*) and amplitudes $S_{11Tamm1}$ (*b*) of the reflection coefficient for the Tamm resonance in the first bandgap of a photonic crystal as functions of water layer thickness d and air gap width L.

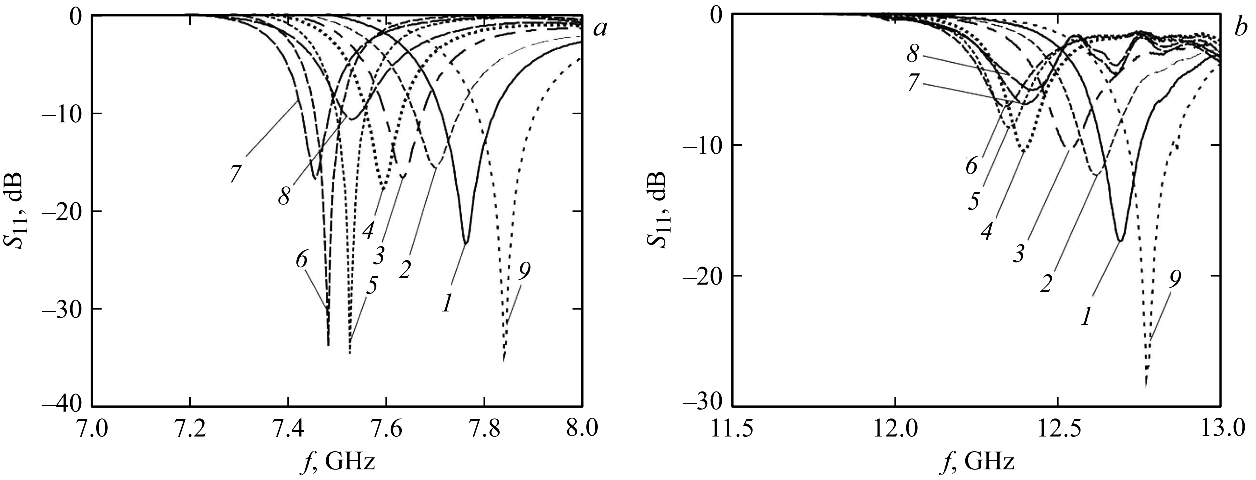

Figure 3. Experimental frequency dependences of reflection coefficient S_{11} in the first (*a*) and second (*b*) bandgaps of an 11-layer photonic crystal with an interface layer represented by a microwave radiation absorber in the form of a layer of distilled water with thickness $d = 0.06$ (*1*), 0.15 (*2*), 0.3 (*3*), 0.6 (*4*), 1.0 (*5*), 1.2 (*6*), 1.74 (*7*), 3.05 (*8*), and 0 mm (*9*). $L = 0$ mm.

The obtained results may be applied, e.g., in the design of narrow-band tunable microwave reflection filters and microwave attenuators based on photonic crystals with a water layer used as an absorber and in the characterization of metastructures containing water inclusions in the form of a continuous layer.

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Conflict of interest

The authors declare that they have no conflict of interest.

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