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PHYSICS

Study of an Electromagnetic Wave Transmission Line Based on Coupled Dielectric Resonators

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Abstract—An analog of an optical waveguide in the form of a chain of metallic nanoparticles has been investigated using modified cylindrical dielectric resonators in the microwave band. Similar to the plasma oscillations in spherical nanoparticles, the two lowest resonances of the dielectric resonator correspond to the dipole and quadrupole oscillatory modes. It is shown that a waveguide consisting of seven resonators exhibits high frequency selective properties and relatively low loss if the resonances of the quadrupole oscillatory modes are used to form its passband. The characteristics of the investigated waveguide remain almost unchanged at its bending by 90°, and the cross section of localization of the main part of the energy propagating in the waveguide is smaller than the electromagnetic wavelength by a factor of five, which approximately corresponds to the optical waveguides based on plasma oscillations in nanoparticles.

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It is well-known that optical signals in optoelectronic devices are transmitted by waveguide lines with transverse dimensions much smaller than the light wavelength. Therefore, optical waveguides in the form of chains of electromagnetically interacting spherical or elliptical metallic nanoparticles [1–3] with transverse dimensions orders of magnitude smaller than in conventional fiber optic transmission lines have been investigated intensively. In metallic particles tens of nanometers in size, one can observe the resonances of multipole modes of plasma oscillations at the optical frequencies that have a fairly high Q factor [4], since the mean electron free path in such particles is significantly larger than their size. In designing optical waveguides, researchers use, as a rule, only the resonances of the lowest (dipole) mode of nanoparticle oscillations; it was shown experimentally, however, that the light wave energy in a chain of nanoparticles is transmitted more efficiently at the resonances of the quadrupole, rather than the dipole, oscillatory mode [5].

Despite the great number of studies carried out currently, the analysis of the literature data shows that the characteristics of optical waveguides consisting of nanoparticles do not satisfy the practical requirements and we cannot speak about the wide use of such waveguides yet. The power losses in them are too large; these are tens of decibels even with signal transmission over distances comparable with the wavelength of light, which is accompanied by the strong nonuniformity of the frequency dependence of the passband loss. However, in the microwave band, the waveguide designs based on resonance structures are well-studied [6] and widely used, in particular, as slow-wave systems due to their relatively high characteristics.

In this study, we investigate the analog of an optical waveguide based on cylindrical dielectric resonators made of high-frequency TBNS ceramics with a permittivity of $\varepsilon = 80$ in the microwave band. The established regularities in the behavior of the characteristics of the investigated waveguide representing a chain of coupled dielectric resonators at different design parameters will undoubtedly be useful for tuning real optical waveguides based on chains of interacting nanoparticles.

WAVEGUIDE DESIGN BASED ON DIELECTRIC RESONATORS

A waveguide was a chain of interacting dielectric cylinders with a base diameter of 25 mm and a height of 19 mm made of TBNS ceramics with a permittivity of $\varepsilon = 80$. The electromagnetic oscillation spectrum of such a resonator is shown by the dashed line in Fig. 1. Among the many resonances observed in the spectrum, only two resonances corresponding to the dipole (TE_{011}) and quadrupole (TE_{012}) oscillatory modes are of interest. These modes are analogous to the dipole and quadrupole modes of plasma oscilla-

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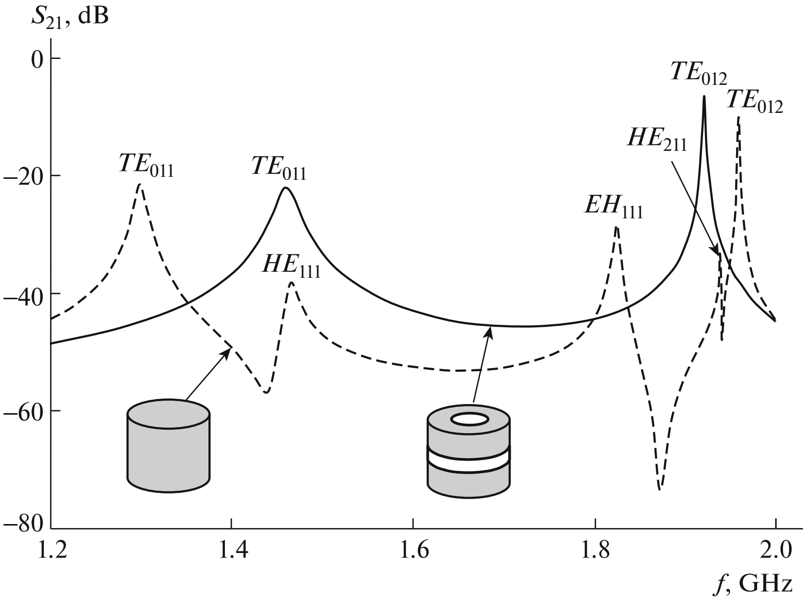


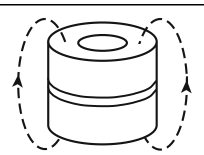
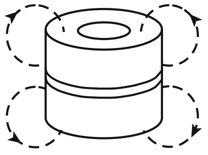
Fig. 1. Electromagnetic oscillation spectrum of the initial (dashed line) and modified (solid line) cylindrical dielectric resonators.

tions in the metallic nanoparticles used, as was mentioned above, in designing optical waveguides.

To eliminate spurious resonances from the spectrum, the initial cylindrical resonator was modified; specifically, a hole 12 mm in diameter was drilled along its axis and, perpendicular to the axis, the resonator was divided into two equal parts and the 2.5-mm gap between them was filled with expanded polystyrene with a permittivity of $\varepsilon = 3$. As a result, the two lowest resonances in the spectrum of such a resonator (the solid line in Fig. 1) correspond to the dipole and quadrupole oscillatory modes. Table 1 gives the structure of the RF magnetic fields of the dipole and quadrupole oscillatory modes for the modified resonator, their resonance frequencies, and the unloaded Q factors obtained by calculating the resonator 3D model in the CST Microwave Studio program. The configuration of the RF fields of the quadrupole oscillatory mode prevents energy emission from the resonator; therefore, its Q factor is much higher than the Q factor on the dipole mode. It should be noted that, in metallic nanospheres [4], the Q factors of the resonances of plasma oscillations of both the dipole and quadrupole modes differ insignificantly from those given in Table 1.

Resonators in a waveguide can be coupled in two ways. In the first case, the dipole moment oriented along the resonator axis is orthogonal to the direction of wave propagation; this coupling is called the TM (transverse-mode) coupling. In the second case, the dipole moment is oriented along the direction of wave propagation; this coupling is called the LM (longitudinal-mode) coupling. The orientation of the resonators in a chain for the TM and LM couplings between them is shown in the insets in Fig. 2. It is noteworthy that the waveguide based on coupled resonators is, in fact, a bandpass filter [12] and its passband is deter-

Table 1. Characteristics of the dipole and quadrupole oscillatory modes of the modified dielectric resonator

Oscillatory mode	RF magnetic field distribution	Eigenfrequency (wavelength)	Resonator unloaded Q factor
TE_{011} (magnetic dipole)		1.55 GHz (194 mm)	50
TE_{012} (magnetic quadrupole)		1.94 GHz (155 mm)	700

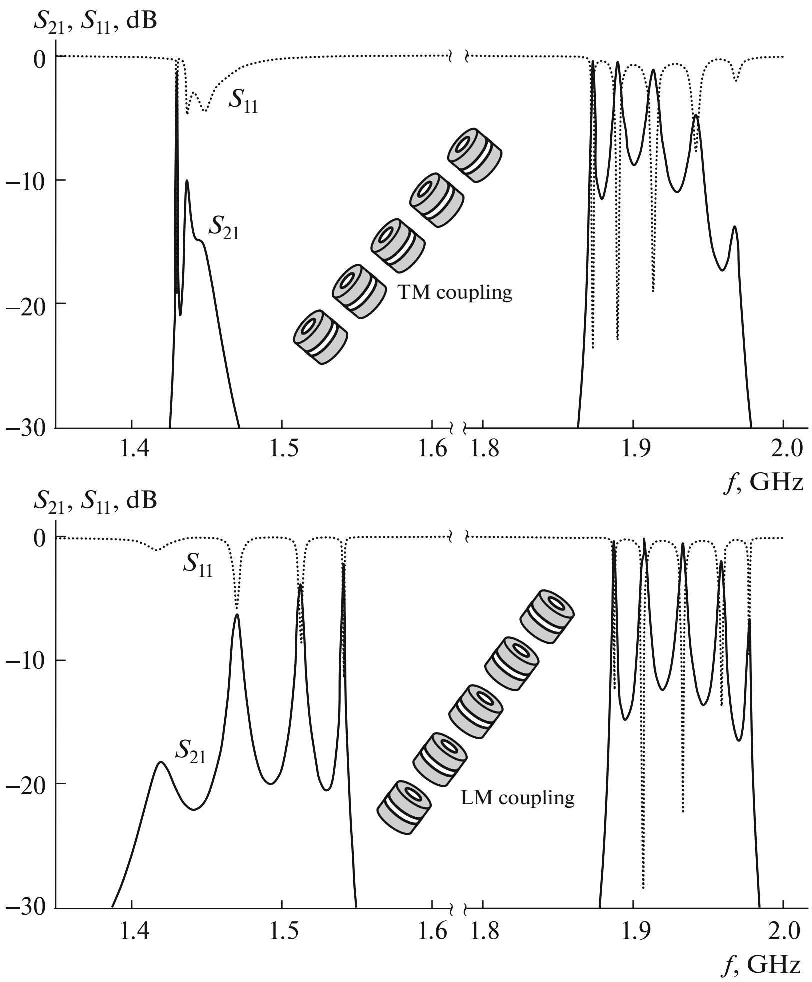


Fig. 2. Frequency responses of the waveguides with the TM and LM coupling between the resonators in a chain and weak coupling between the resonators and the external transmission lines (solid lines show the direct loss and dots show the return loss).

mined by the coupling between the resonators, which is inversely proportional to the gap between them.

Obviously, the frequency response of the waveguide investigated depends on the type of coupling between the resonators in it. For comparison, Fig. 2 shows the frequency response of the TM-and LM-coupled waveguides consisting of five resonators located at the same distance (10 mm) from each other calculated in the CST Microwave Studio electrodynamic analysis program. The numerical calculation was made for a weak coupling of the input and output resonators with external transmission lines for better resolution of individual peaks in the frequency response due to repulsion of the resonance frequencies of the interacting resonators.

It can be seen that, at the TM coupling, the interaction of the resonators on the dipole oscillatory mode is very weak; therefore, the passband is narrow and only includes a part of the resonance peaks. In the quadrupole mode, the interaction between the resonators is much stronger, so all five resonance peaks are observed and the bandwidth is several times greater. In addition, according to the frequency dependences of direct loss S_{21} and return loss S_{11}, to obtain a uniform frequency response in the waveguide passbands, the resonator couplings must be corrected and their resonance frequencies must be tuned. It should be noted that, as a result of the interaction, the resonator frequencies on the dipole oscillatory mode decreased by about 100 MHz (Table 1), while the decrease on the quadrupole mode is much smaller (~20 MHz).

In the case of the LM coupling (Fig. 2), a strong interaction between the resonators is observed on both the dipole and quadrupole oscillatory modes; however, all five resonances are only observed on the quadrupole mode in the passband and the couplings between the resonators are almost balanced. Note that, in the case of the LM coupling, the resonator frequencies decreased by about 50 MHz due to the interaction on the dipole mode (Table 1), while on the quadrupole mode they remained almost unchanged.

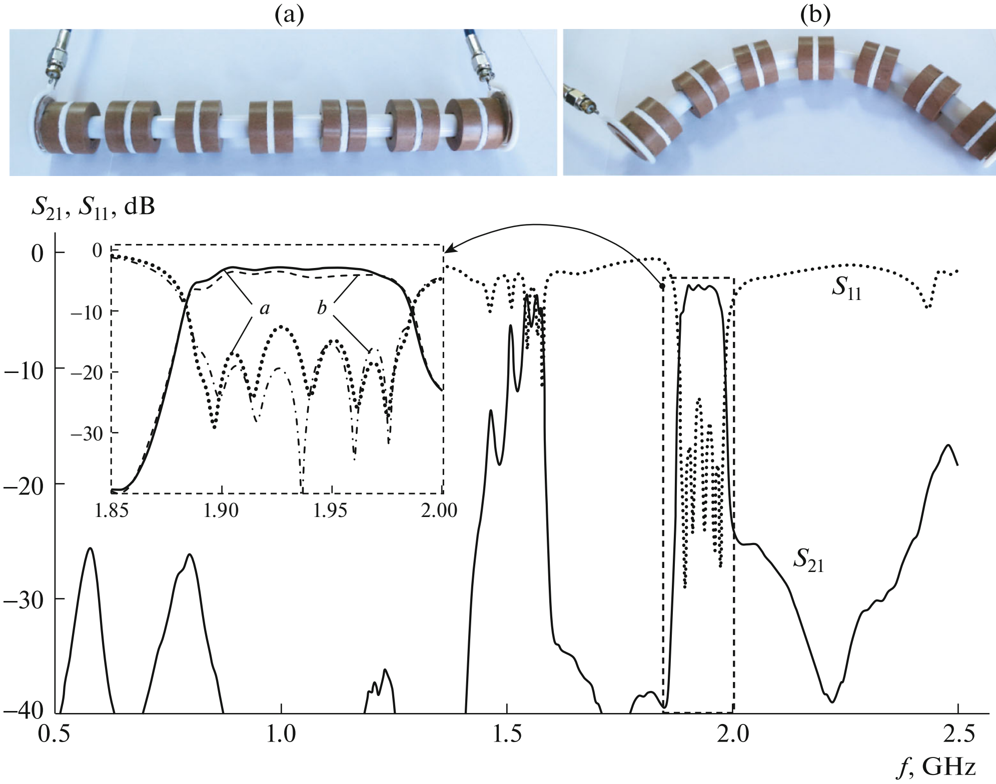


Fig. 3. Frequency responses of the straight waveguide (solid lines show the direct loss and dots show the return loss). Inset: zoomed bandwidth for (*a*) the straight and (*b*) right-angle curved waveguides.

STUDY OF THE DEVELOPED WAVEGUIDE DESIGN

To study the characteristics of the developed waveguide, two prototypes consisting of seven dielectric resonators were fabricated. Taking into account that the resonator Q factor on the quadrupole oscillatory mode is much higher than on the dipole mode, it was the quadrupole mode that was chosen as a working mode for forming the waveguide passband. In the designs shown in the photograph in Fig. 3, the LM coupling between the resonators was used, which made it possible to place them on a flexible Teflon rod with a low permittivity ($\varepsilon = 2.2$), which affected neither the coupling nor the resonance frequencies of the resonators. This design significantly simplified the assembly of prototypes and their tuning. The end waveguide resonators were connected to coaxial ports with an impedance of 50 Ω through coupling elements in the form of inductive loops, in which the structure of RF electromagnetic fields at the central passband frequency corresponded to the structure of the fields in the resonators.

Before fabricating the waveguide, the passband was tuned by manual parametric synthesis of its 3D model in the numerical electrodynamic analysis program using a standard method for tuning microwave filters [7]. For certainty, when tuning the structure, a bandwidth of $\Delta f = 80$ MHz and a central band frequency of $f_0 = 1940$ MHz were fixed, which corresponds to a relative bandwidth of $\Delta f/f_0 = 4.1\%$. The gaps between the resonators were selected to balance the couplings between them, the gaps between the inductive loops and end resonators were selected to form the optimal connection with the ports, and the thickness of the dielectric spacer between ceramic rings of each resonator was selected to correct the resonant frequencies. The waveguide was considered to be tuned when the maximum return loss in its passband was no higher than −14 dB. The gaps obtained after tuning the waveguide were used in the assembly of the prototypes.

Figure 3 presents the frequency dependences of the direct and return loss of the tuned rectilinear waveguide measured on a vector network analyzer in a wide frequency band. As expected, these characteristics for the waveguide curved by an angle of 90° are almost the same and therefore omitted. For comparison, the inset in Fig. 3 shows the frequency responses of both waveguides in the passband region. One can see slight differences; in particular, the minimum passband loss is ~2.5 dB for the direct waveguide and ~3.5 dB for the curved one.

Along with the width of the passband and loss in it, the main characteristics of unshielded waveguides include waveguide length l_λ normalized to the wavelength and cross section S_λ in which the propagating energy of the electromagnetic wave is mainly localized. Taking into account that the waveguide investigated had a length of 220 mm and the wavelength at its passband center frequency is $\lambda \approx 155$ mm, we have $l_\lambda \approx 1.4$. The cross section through which the electromagnetic wave energy propagated had a diameter of ~30 mm, i.e., $S_\lambda \approx 0.2$. The boundary of this cross section was considered to be the distance at which the microwave power level was lower than its maximum value in the resonator by 10 dB. It is important that, in optical waveguides with the use of plasma resonances in a chain of metallic nanoparticles, the localization of the light-wave electromagnetic energy is approximately the same as in the waveguide investigated.

CONCLUSIONS

Using a well-known design of the optical waveguide in the form of a chain of electromagnetically coupled metallic nanoparticles, we designed and investigated in the microwave band its analog based on modified cylindrical dielectric resonators in which the two lowest resonances correspond to the dipole and quadrupole oscillatory modes corresponding to the plasma oscillations in nanoparticles. The waveguide investigated consisted of seven resonators and was tuned as a bandpass filter by selecting resonance frequencies and couplings between resonators and between the end resonators and external transmission lines so that the microwave power reflection maxima in the device passband were no more than –14 dB. In this case, only the quadrupole oscillatory modes were involved in the formation of the passband.

It was shown that the waveguide exhibits high frequency selective properties and relatively small passband loss. Note that when the waveguide is curved by 90°, its characteristics almost do not change. In addition, it is important that, due to the use of ceramics with a high ($\varepsilon = 80$) permittivity for fabricating resonators, the waveguide cross section that includes the main part of the propagating energy is smaller than the electromagnetic wavelength by a factor of five. This characteristic is approximately the same as in the optical waveguides that use plasma resonances in a chain of metallic nanoparticles.

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