Visnyk NTUU KPI Seriia – Radiotekhnika Radioaparatobuduvannia, 2017, Iss. 71, pp. 5–10

УДК 621.372

Scattering of Electromagnetic Waves on Different Dielectric Resonators of the Microwave Filters

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The theory of scattering of electromagnetic waves by systems of various coupled the different shape and variant permittivity dielectric resonators is expanded. A new definition of the coupling coefficients of different dielectric resonators is given. The analytical expressions of coupling coefficient of different cylindrical and spherical dielectric resonators made from different dielectrics are obtained. The main regularities of the change in the coupling with the variation of the structure's parameters are considered. The results of calculation of the transmission and the reflection coefficients for bandpass and bandstop filters on various dielectric resonators in the rectangular and circular waveguides are presented. Most optimal configurations, allowing to achieve the best scattering characteristics are determined.

Key words: different dielectric resonator; coupling coefficient; S-matrix; bandstop filter; bandpass filter

Introduction

It is well-known that in addition to a very high Q factors the dielectric resonators (DR) have a number of disadvantages, such as increased density of the spectrum, in some cases non-optimal coupling. The scattering parameters of a variety of devices can be significantly improved by using different forms of DR [1–8]. For the purposes of theory development all resonators are generally supposed to have the same shape and manufactured of the same dielectric [9]. In order to improve the parameters in some cases there is need to build filters on DRs with different shapes made of variant dielectrics. However, in this case the theory describing scattering processes becomes more complicated. In this article we developed electrodynamic theory for describing different DRs. The equation system for the unknown amplitudes of the DR coupled oscillations have been obtained. Total analytical solutions have been found. The research of electromagnetic wave scattering on different cylindrical and spherical DR structures have been conducted in the propagating waveguide and evanescent waveguide segment. In special case of identical resonators obtained solutions are simplified to the known ones [9].

1 Statement of the problem

The goal of the current article is the development of the theory of microwave filters, consisting of different DRs, that can be used in the modern communication systems.

2 Scattering theory

Consider the system of different DRs, consisting of different materials. We assume that the eigenoscillation field of each isolated DR is known: $(\vec{e}_s, \vec{h}_s)$, $(s = 1, 2, ..., N)$. Here $\vec{e}_s$ — is the electric field and $\vec{h}_s$ — is the magnetic field intensity of the s-th isolated DR. The eigenoscillation field of the N-DR system $(\vec{e}, \vec{h})$ can be found as a superposition of fields of the isolated resonators:

$$\vec{e} = \sum_{s=1}^{N} b_s \vec{e}_s; \quad \vec{h} = \sum_{s=1}^{N} b_s \vec{h}_s \tag{1}$$

As shown, the DR amplitudes b_s should satisfy the equation system [10]:

$$\sum_{s=1}^{N} (k_{sn} + i\tilde{k}_{sn}) b_s - \lambda b_n = 0, \quad (n = 1, 2, ..., N) \tag{2}$$

where

$$\lambda = 2 \cdot (\delta\omega/\omega_0 + i\omega''/\omega_0), \tag{3}$$

$\omega_0 = \mathrm{Re}[\omega_s]$ is the real part of frequencies of isolated partial resonators $(s = 1, 2, ..., N)$; $\delta\omega = \mathrm{Re}(\tilde{\omega} - \omega_0)$; $\omega'' = \mathrm{Im}(\tilde{\omega})$; $\tilde{\omega}$ — is the complex resonance frequency of the DR system; k_{sn}, $\tilde{k}_{sn}$ are the coupling coefficients of the s-th and n-th DRs on damped and expanding waves of the transmission line [10] respectively:

$$\begin{aligned} k_{sn} &= \tfrac{-1}{\omega_0 w_n} \sum_{t \geq t_M} (c_t^{s\pm})_0 (c_t^{n\mp})_0^* e^{-\Gamma \Delta z}; \\ \tilde{k}_{sn} &= \tfrac{1}{\omega_0 w_n} \sum_{t \leq t_M} (c_t^{s\pm})_0 (c_t^{n\pm})_0^* e^{-i\Gamma \Delta z}. \end{aligned} \tag{4}$$

Here t_M — is the ultimate multi index, determining the numbers of the expanding waves in the line, and a

$(c_t^{s\pm})_0$ — is the expansion coefficient of the s-th DR field on the t-th wave of the transmission line [10], calculated in the coordinate system, associated with s-th resonator center; $\Delta z = |z_s - z_n|$; z_s — is the longitudinal coordinate of the s-th DR; Γ — is the longitudinal wave number of the transmission line; and $w_n = \frac{1}{4}\int\limits_{V_n}\left(\varepsilon_n|\vec{e}_{1n}|^2 + \mu_0|\vec{h}_{1n}|^2\right)dv$ — is the energy, stored in the dielectric of the s-th DR; $\varepsilon_n = \mathrm{Re}\tilde{\varepsilon}_n$; $\tilde{\varepsilon}_n = \varepsilon_n - i\varepsilon''_n$ — is the complex dielectric permittivity and the μ_0 is the permeability of the n-th DR.

In the case of different DRs the coupling coefficients (4) take different views: $k_{sn} \neq k_{ns}$ and $\tilde{k}_{sn} \neq \tilde{k}_{ns}$.

Generally, by providing the solution to the equation systems (2) for each obtained λ_v, it is possible both to calculate approximately the complex frequency $\tilde{\omega}^v$ of the system coupling oscillation and to determine all amplitudes of partial resonators $\vec{b}^v = (b_1^v, b_2^v, ..., b_N^v)$, $(v = 1, 2, ..., N)$.

The problem solution of the waveguide wave $\left(\vec{E}_l^+, \vec{H}_l^+\right)$ scattering on the DR system will be searched in the form of expansion on coupling modes of the DR lattices (1):

$$\vec{E} \approx \vec{E}_l^+ + \sum_{s=1}^{N} a^s \vec{e}^s; \quad \vec{H} \approx \vec{H}_l^+ + \sum_{s=1}^{N} a^s \vec{h}^s, \tag{5}$$

where $(\vec{e}^s, \vec{h}^s)$ is the field of the N-DR systems (1), corresponding to the eigenvalue λ_s (3).

By using perturbation theory, after the volume integration of each partial resonator, the equation system with the unknown coefficients a^s has been obtained in the form:

$$\sum_{s=1}^{N} a^s b_t^s Q_{st}(\omega) = -\frac{\left(c_l^{t+}\right)^*}{P_t^D}, \quad (t = 1, 2, ..., N), \tag{6}$$

where for different resonators, the functions $Q_{st}(\omega)$ are dependent on the partial DR and the coupled oscillation numbers:

$$Q_{st}(\omega) = 2i\frac{\omega - \tilde{\omega}^s}{\omega_0}Q_t^D + \frac{\omega}{\omega_0}, \tag{7}$$

$Q_t^D = \omega_0 w_t / P_t^D$; $P_t^D = \omega_0 \frac{\varepsilon''_t}{2}\int\limits_{V_t}|\vec{e}_t|^2 dv$ — is the loss power in the dielectric of t-th DR.

The transmission T and the reflection coefficient R of different DR system in the transmission line can be obtained froms (5), s (1) in the form:

$$\begin{cases} T = T_0 + \sum\limits_{u=1}^{N}\left(\sum\limits_{s=1}^{N} b_s^u c_s^+\right)a_u = T_0 - \frac{1}{B(\omega)}\sum\limits_{s=1}^{N} B_s^+(\omega) \\ R = R_0 + \sum\limits_{u=1}^{N}\left(\sum\limits_{s=1}^{N} b_s^u c_s^-\right)a_u = R_0 - \frac{1}{B(\omega)}\sum\limits_{s=1}^{N} B_s^-(\omega) \end{cases} \tag{8}$$

Here T_0, R_0 are the transmission and reflection coefficients of the transmission line without DRs;

$$B_s^{\pm}(\omega) = $$

$$= \det\begin{bmatrix} b_1^1 Q_{11}(\omega) & ... & Q_1^D \sum\limits_{u=1}^{N} b_u^s \tilde{k}_{u1}^{\mp+} & ... & b_1^N Q_{N1}(\omega) \\ b_2^1 Q_{12}(\omega) & ... & Q_2^D \sum\limits_{u=1}^{N} b_u^s \tilde{k}_{u2}^{\mp+} & ... & b_2^N Q_{N2}(\omega) \\ . & ... & . & ... & . \\ b_N^1 Q_{1N}(\omega) & ... & Q_N^D \sum\limits_{u=1}^{N} b_u^s \tilde{k}_{uN}^{\mp+} & ... & b_N^N Q_{NN}(\omega) \end{bmatrix}$$

$$B(\omega) = \det\begin{bmatrix} b_1^1 Q_{11}(\omega) & ... & b_1^N Q_{N1}(\omega) \\ b_2^1 Q_{12}(\omega) & ... & b_2^N Q_{N2}(\omega) \\ . & ... & . \\ b_N^1 Q_{1N}(\omega) & ... & b_N^N Q_{NN}(\omega) \end{bmatrix}, \tag{9}$$

$\tilde{k}_{sn}^{++} = (c_s^+ c_n^{+*})/(\omega_0 w_n) = (\tilde{k}_{sn})_0 e^{-i\Gamma(z_s - z_n)}$; $\tilde{k}_{sn}^{-+} = (c_s^- c_n^{+*})/(\omega_0 w_n) = (\tilde{k}_{sn})_0 e^{-i\Gamma(z_s + z_n)}$; $(\tilde{k}_{sn})_0$ — is the coupling coefficients (4), for the propagating wave, expressed without phase difference accounting in the transmission line $(s, n = 1, 2, ..., N)$.

3 Coupling coefficients of the different DRs calculation

In order to determining the S-matrix parameters: $S_{21} = S_{21}(\omega) = 20\lg|T(\omega)|$; $G_{21} = G_{21}(\omega) = \arg[T(\omega)]$; $S_{11} = S_{11}(\omega) = 20\lg|R(\omega)|$; $G_{11} = G_{11}(\omega) = \arg[R(\omega)]$, we have to calculate coupling coefficients of different DRs in the transmission line. Suppose we have two DRs of cylindrical shape with radius r_1 and r_2, height of L_1 and L_2, respectively. Assume that each resonator is excited in the fundamental magnetic oscillation H_{101}^+ [10]. In this case, the coupling coefficient is of the form:

$$k_{12} = \frac{64\pi\beta_{2z}}{v_2}\cdot\frac{r_1}{r_2}\cdot\frac{\beta_2}{\beta_1}\cdot\frac{(k_1^2 - k_0^2)(k_2^2 - k_0^2)}{k_2^2 ab}\cdot$$
$$\cdot\left\{\sum_{s,u=0}^{\infty}\left(\frac{|\Gamma|\,\chi_{sx}^2}{1+\delta_{u0}} - \frac{k_0^2\chi_{uy}^2}{|\Gamma|}\right)e^{-\Gamma\Delta z}\cdot\frac{1}{\chi^2(\chi_{uy}^2 - \Gamma^2)}\cdot\right.$$
$$\cdot\prod_{t=1}^{2}\frac{\sin\chi_{sx}x_t\cos\chi_{uy}y_t}{(\beta_t^2 - \chi_{uy}^2 + \Gamma^2)}\cdot\left[\beta_t J_0(p_{t\perp})J_1\left(r_t\sqrt{\chi_{uy}^2 - \Gamma^2}\right) - \right.$$
$$\left. - \sqrt{\chi_{uy}^2 - \Gamma^2}J_1(p_{t\perp})J_0(r_t\sqrt{\chi_{uy}^2 - \Gamma^2})\right]\frac{1}{\beta_{tz}^2 - \chi_{sx}^2}\cdot$$
$$\left.\cdot\left[\beta_{tz}\sin p_{tz}\cos\chi_{sx}\frac{L_t}{2} - \chi_{sx}\cos p_{tz}\sin\chi_{sx}\frac{L_t}{2}\right]\right\}. \tag{10}$$

In the case of coupling on propagating rectangular waveguide wave H_{10}:

$$\tilde{k}_{12} = \frac{32\pi\beta_{2z}}{\upsilon_2} \cdot \frac{r_1}{r_2} \cdot \frac{\beta_2}{\beta_1} \cdot \frac{(k_1^2 - k_0^2)(k_2^2 - k_0^2)}{k_2^2 ab} \cdot \\ \cdot \frac{e^{-i\Gamma\Delta z}}{\Gamma} \cdot \prod_{t=1}^{2} \left\{ \frac{\sin\chi_{sx}x_t}{(\beta_t^2 - \Gamma^2)} \left[\beta_t J_0(p_{t\perp})J_1(\Gamma r_t) - \right.\right. \\ \left. - \Gamma J_1(p_{t\perp})J_0(\Gamma r_t)\right] \cdot \frac{1}{\beta_{tz}^2 - \chi_{1x}^2} \cdot \\ \left. \cdot \left[\beta_{tz}\sin p_{tz}\cos\chi_{sx}\frac{L_t}{2} - \chi_{sx}\cos p_{tz}\sin\chi_{sx}\frac{L_t}{2}\right] \right\}, \tag{11}$$

where $\upsilon_2 = [J_1^2(p_{2\perp}) - J_0(p_{2\perp})J_2(p_{2\perp})](2p_{2z} + \sin 2p_{2z})$; $p_{t\perp} = \beta_t r_t$; $p_{tz} = \beta_{tz}L_t/2$; $k_t = \omega\sqrt{\varepsilon_t\mu_0}$; ε_t — is the dielectric permittivity; μ_0 is the permeability and (β_t, β_{tz}) are the wave numbers of the t-th DR [10]; $\chi_{sx} = s\pi/a$; $\chi_{uy} = u\pi/b$; $\chi = \sqrt{\chi_{sx}^2 + \chi_{uy}^2}$; Γ — is the longitudinal wave number; $a \times b$ — is the cross-sectional dimensions of the waveguide; (x_t, y_t, z_t) — are rectangular coordinates of the t-th DR ($t = 1, 2$); here $\Delta z = |z_1 - z_2|$.

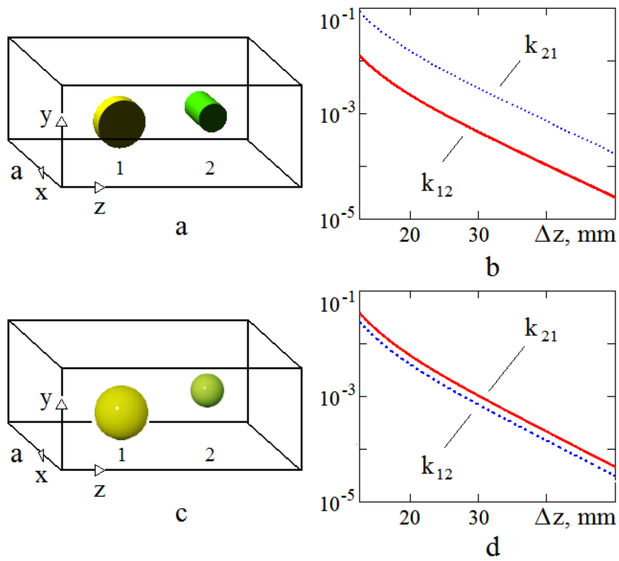

Fig. 1. Two different cylindrical (a) spherical (c) DRs in the propagating metal rectangular waveguide ($\varepsilon_{1r} = 36$;$\varepsilon_{2r} = 82$). Dependence of mutual coupling coefficients versus the distance between the cylindrical (b) or the spherical (d) DR centers ($x_1 = x_2 = a/2$; $y_1 = y_2 = b/2$; $a = 58\,\text{mm}$; $b = 25\,\text{mm}$; $f_0 = 4\,\text{GHz}$): $\Delta_1 = L_1/2r_1 = 0,2$; $\Delta_2 = L_2/2r_2 = 0,8$ (b).

Example of mutual coupling coefficients calculations for two different cylindrical DRs in the rectangular waveguide, obtained on a basis of (10), (11), is showed in fig. 1 a-b. As follows from (10), the difference between the values of the coupling coefficients is mainly due to the different value of stored energy in the resonator material.

The use of different spherical DRs in some cases allow to improve the filter parameters. We have represented the coupling coefficients of different spherical DRs with magnetic oscillations H_{111} in the form:

$$k_{12} = \alpha_1^H(p_1, q_1; p_2, q_2)T_1^1, \tag{12}$$

where

$$\alpha_1^H(p_1, q_1; p_2, q_2) = \frac{j_1(p_1)}{y_1(q_1)} \cdot \frac{j_1(p_2)}{q_2 y_1(q_2)} \cdot \\ \cdot \frac{1}{\{[p_2^2 - 2)]j_1^2(p_2) + [j_1(p_2) - p_2 j_0(p_2)]^2\}};$$

$$T_1^1 = \frac{24\pi}{k_0^2 ab} \cdot \left\{ \sum_{s,u=(0)}^{\infty} \left[\frac{|\Gamma|\,\chi_{sx}^2}{k_0(1 + \delta_{u0})} - \frac{k_0\chi_{uy}^2}{|\Gamma|}\right] \cdot \right. \\ \left. \cdot e^{-\Gamma\Delta z} \cdot \frac{1}{\chi^2} \cdot \prod_{t=1}^{2} \sin\chi_{sx}x_t \cos\chi_{uy}y_t \right\}, \tag{13}$$

(x_t, y_t, z_t) — are rectangular coordinates of the t-th spherical DR centers in the waveguide: $\Delta z = |z_1 - z_2|$; $j_n(z)$; $y_n(z)$ are the spherical Bessel and the Neumann functions, respectively [11]. The characteristic parameters $p_t = k_t r_t$, $q_t = k_0 r_t$ can be obtained from the equations for natural oscillations of the t-th spherical DR [12]. Here r_t — is the radius of the t-th spherical DR.

For the coupling on propagating wave H_{10}:

$$\tilde{k}_{12} = \frac{12}{k_0 b}\frac{\chi_{1x}\Gamma}{k_0^2}\alpha_1^H(p_1, q_1; p_2, q_2) \cdot \\ \cdot e^{-i\Gamma\Delta z}\sin\chi_{1x}x_1 \sin\chi_{1x}x_2. \tag{14}$$

The mutual coupling coefficients, calculated for two different spherical DRs in the rectangular waveguide, obtained from (12) - (14), are showed in fig. 1 c-d. As can be seen, the difference between the values of k_{12} and k_{21} in this case is small.

If two different spherical DRs located on the axis of the cylindrical metal waveguide [12], the mutual coupling coefficients becomes:

$$k_{12} = \alpha_1^H(p_1, q_1; p_2, q_2)F_1^1, \tag{15}$$

where

$$F_1^1 = 3\sum_{s=1}^{\infty} \left\{ \frac{\Gamma_H}{k_0} \left[1 + \left(\frac{\Gamma_H}{k_0}\right)^2\right] \cdot \right. \\ \left. \cdot \frac{e^{-\Gamma_H\Delta z}}{(j'^2_{1,s} - 1)J_1(j'_{1,s})^2} - \frac{[1 + (\Gamma_E/k_0)^2]}{|\Gamma_E/k_0|}\frac{e^{-\Gamma_E\Delta z}}{[j_{1,s}J'_1(j_{1,s})]^2} \right\},$$

$\Gamma_{H,E}$ — is the longitudinal wave number for the magnetic, electrical cylindrical waveguide waves, respectively; $j_{m,s}$, $(j'_{m,s})$ is the s-th root of the Bessel $J_m(z)$ (derivative of the Bessel $J'_m(z)$) function [8].

4 Bandstop Filters on different DRs

DRs in regular transmission lines represent the most interesting case from the point of view of the theory, because in this case all the resonators at the same time exchange fluctuations both propagating and by not extending waves.

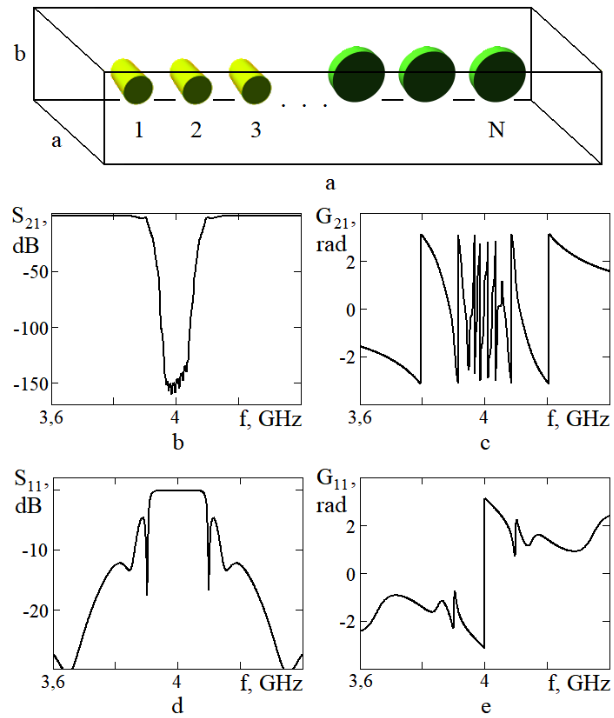

Fig. 2. The structure of different cylindrical DRs on the symmetry axis of propagating rectangular metal waveguide (a). Scattering parameters (b - e) of 5 cylindrical DRs with $\varepsilon_{1r} = 36$; $Q_1^D = 2000$; $\Delta_1 = L_1/2r_1 = 0,4$; and 6 cylindrical DRs with $\varepsilon_{2r} = 82$; $Q_2^D = 1500$; $\Delta_2 = L_2/2r_2 = 0,8$.

Fig. 2 shows scattering parameters of the bandstop filter, consisting of 5 cylindrical DRs characterized by the dielectric permittivity $\varepsilon_{1r} = 36$; $Q_1^D = 2000$ and by the relative sizes $\Delta_1 = L_1/2r_1 = 0,4$ as well as 6 DRs with $\varepsilon_{2r} = 82$; $Q_2^D = 1500$; $\Delta_2 = L_2/2r_2 = 0,8$, calculated by the formula (2),(7), (8), (9) with help of the (10), (11). All resonators placed on the waveguide axis. The distance between adjacent DR centers was equal to $\lambda_w/4$, where λ_w — is the guided wavelength.

The result of the scattering of the rectangular waveguide waves H_{10} on the structure of 9 different spherical DRs is shown in fig. 3 b - e. The coupling coefficients of the DRs were calculated by the formulas (12)-(15).

As can be seen, the use of different alternating DRs in this case gives acceptable results for the frequency distribution of scattering parameters.

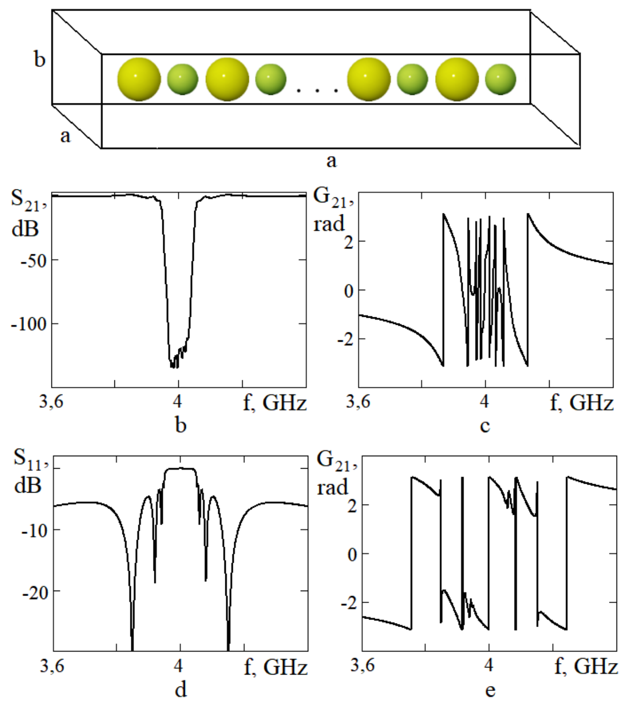

Fig. 3. The structure of different spherical DRs on the symmetry axis of propagating rectangular metal waveguide (a). Scattering parameters (b-e) of 9 DRs bandstop filter with $\varepsilon_{1r} = 36$; $Q_1^D = 2000$; $\varepsilon_{2r} = 82$; $Q_2^D = 1000$.

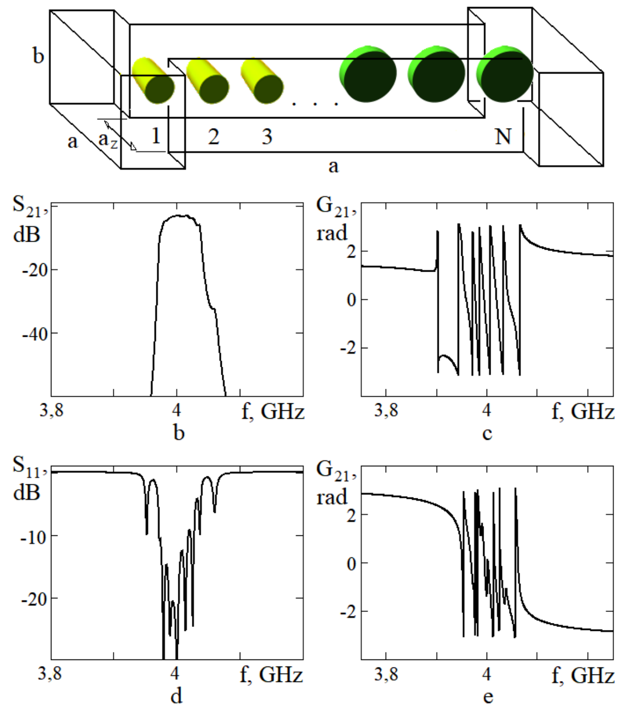

Fig. 4. Cylindrical DR on the symmetry axis of evanescent rectangular metal waveguide segment (a). Scattering parameters of the bandpass filter on 11 cylindrical DRs with $\varepsilon_{1r} = 36$; $Q_1^D = 2000$; $\varepsilon_{2r} = 82$; $Q_2^D = 1500$.

5 Bandpass filters on different DRs

The best results were obtained for the DR structures, located in the evanescent waveguide segment and forming bandpass filters. The filters containing the DRs should have bands free of spurious oscillations. A known solution to this problem is to use different forms of DR.

Fig. 4. shows scattering parameters of the filter, consisting of two lattices with different cylindrical DRs. First lattice contains 4 DR with $\varepsilon_{1r} = 36$, $\Delta_1 = 0,8$, the second lattice consists of 7 DR with $\varepsilon_{2r} = 81$, $\Delta_2 = 0,4$. The distance between the centers of adjacent first type DRs was equal to 17 mm; for the second type DRs 21 mm. All resonators placed on the waveguide axis.

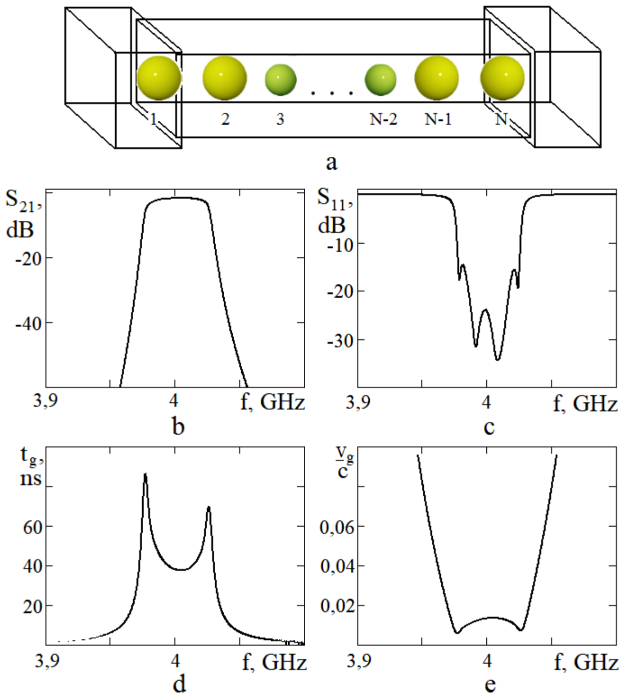

Fig. 5. Different spherical DRs in the evanescent rectangular metal waveguide segment (a). Scattering parameters of the bandpass filter on 11 cylindrical DRs with $\varepsilon_{1r} = 36$; $Q_1^D = 3000$; $\varepsilon_{2r} = 82$; $Q_2^D = 2000$ (b, c). Group delay (d) of the filter and comparative group velocity (e) as a function of the frequency.

Application of spherical DR with different dielectric permittivity allows us to increase the coupling coefficients of the outside resonators in different structures of bandpass filters and thereby reduce the loss in the pass band.

Fig. 5 shows 8 spherical DR bandpass filter scattering parameters. Recent resonators of the filter made of dielectric with $\varepsilon_{1r} = 36$; $Q_1^D = 3000$, the rest are made of dielectric $\varepsilon_{2r} = 81$; $Q_2^D = 2000$. All resonators form symmetrical structure. The distance between the centers of first and second DR is 23,5 mm, between other DRs is 20 mm. The cross section of the input and output waveguides $a \times b = 58 \times 25\,\mathrm{mm}^2$; the cross section of the evanescent waveguide $az \times bz = 20 \times 25\,\mathrm{mm}^2$.

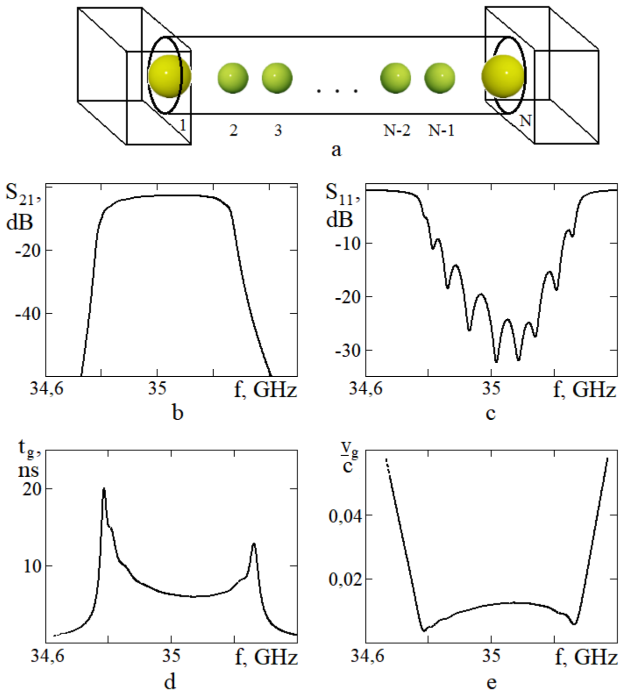

Fig. 6. Different spherical DRs in the evanescent cylindrical metal waveguide segment (a). Scattering parameters of the bandpass filter on 11 spherical DRs with $\varepsilon_{1r} = 36$; $Q_1^D = 3000$; $\varepsilon_{2r} = 82$; $Q_2^D = 2000$ (b, c). Group delay (d) and comparative group velocity (e) as a function of the frequency.

Fig. 6 shows 11 spherical DR bandpass filter arrangement in circular cylindrical metal waveguide. The cross section of the input and output waveguides $a \times b = 7 \times 3\,\mathrm{mm}^2$, the radius of the evanescent waveguide $Rz = 1,5$ mm. We have calculated the dependence of group delay $t_g = -d/d\omega[G_{21}(\omega)]$ and comparative group velocity: $v_g/c = |z_N - z_1|/ct_g$ (fig. 1, fig. 6 d, e), where c — is the velocity of light; $|z_N - z_1|$ — is the longitudinal length of the filter. As can be seen from Fig. 6 d, e, the results demonstrate a remarkable slowing of signal propagation, characteristic of the filters on DRs.

Proposed enhancement of the electrodynamic theory for the scattering electromagnetic waves on different dielectric resonators greatly enhances design of the filters and other devices. As shown from calculations, the developed model correctly describes the scattering processes in the system of different DRs for a variety of transmission lines. The obtained solutions makes it possible to calculate all scattering parameters of the filters, made in various DR. Such design has several advantages compared with identical resonators for filters, in particular the filters have a more clean stop band, and in the case of spherical cavities, produce better scattering characteristics due to the wider coupling bands variations. The frequency dependence of the scattering S-matrix can be further improved even more after a fine optimization of the filter parameters.

Conclusion

A scattering theory on different dielectric resonator systems, based on perturbation theory, has been expanded.

Given new definitions of coupling coefficients for the different dielectric resonators in the transmission line.

New analytical relationships for the coupling coefficients of different spherical and cylindrical dielectric resonators has been obtained.

A new design of the bandstop and bandpass filters on different DRs are proposed.

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Розсіювання електромагнітних хвиль на різних діелектричних резонаторах мікрохвильових фільтрів

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Розширена теорія розсіювання електромагнітних хвиль лінії передачи на системах зв'язаних діелектричних резонаторів різної форми та діелектричної проникності. Дано нове визначення коефіцієнтів зв'язку різних діелектричних резонаторів. Отримані аналітичні вирази для коефіцієнтів взаємного зв'язку діелектричних резонаторів циліндричної та сферичної форми, виконаних із різних матеріалів. Розглянуті основні закономірності зміни зв'язку при варіації параметрів структури. Приведені результати розрахунків коефіцієнтів передачи та відбиття смугових та режекторних фільтрів, побудованих на різних діелектричних резонаторах в прямокутному та круглому хвилеводах. Встановлено найбільш оптимальні конфігурації, які дозволяють досягати найкращих характеристик розсіювання.

Ключові слова: діелектричний резонатор; коефіцієнт зв'язку; S-матрица; режекторний фільтр; смуговий фільтр

Рассеяние электромагнитных волн на разных диэлектрических резонаторах микроволновых фильтров

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Расширена теория рассеяния электромагнитных волн линии передачи на системах связанных диэлектрических резонаторов разной формы и диэлектрической проницаемости. Дано новое определение коэффициентов связи различных диэлектрических резонаторов. Получены аналитические выражения для коэффициентов связи диэлектрических резонаторов цилиндрической и сферической формы, выполненных из различных материалов. Рассмотрены основные закономерности изменения связи при вариации параметров структуры. Приведены результаты расчета коэффициентов передачи и отражения полосовых и режекторных фильтров, построенных на различных диэлектрических резонаторах в прямоугольном и круглом волноводах. Установлены наиболее оптимальные конфигурации, позволяющие достигать наилучших характеристик рассеяния.

Ключевые слова: диэлектрический резонатор; коэффициент связи; S-матрица; режекторный фильтр; полосовой фильтр