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Optimization Scattering Parameters of Optical Filters With Whispering Gallery Mode Resonators for Interleaver Building

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The frequency dependences of the scattering matrices of known types of optical filters, built on coupled Dielectric Resonators (DR) with whispering gallery oscillations, located in one or more transmission lines taking into account several frequency bands, are considered. New electromagnetic models of notch and add/drop filters of various types, which consist of one and two optical resonators with degenerate types of natural oscillations, have been built. The found solutions are used for calculations and analysis of frequency dependences of filter scattering matrices in several excitation bands of the structure's of resonators. Examples of the calculation of frequency dependences of scattering matrices for the most common structures are given, which can be found as practical relationships when building interleavers. The frequency dispersion characteristics of several types of filters consisting of one and two dielectric resonators were calculated. The frequency dependences of the scattering matrices of two most common types of filters made on the basis of coupled DRs located in parallel between two optical transmission lines are investigated: laterally coupled add/drop filters; parallel-coupled add/drop filters; twisted double-channel SCISSORS. The possibilities of the proposed method are demonstrated on examples of calculation of the dispersion matrices of add/drop filters, taking into account several frequency bands, which can be used to build interleavers. The effect of oscillations of resonators neighboring in frequency on the characteristics of filters was analyzed. Constructed electrodynamics' filter models are the basis for calculating and optimizing the characteristics of a wide class of elements of the newest ultra-high-speed optical communication systems.

Keywords: scattering; dielectric resonator; scattering matrix; notch filter; laterally coupled add/drop filter; parallel-coupled add/drop filter; twisted double-channel SCISSOR; interleaver

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Introduction

Today, one of the popular directions for increasing the speed of optical communication systems is the transition to parallel processing, transmission, and reception of information. As a result, we are witnessing the emergence of new, more complex optical network elements, such as multi-core fibers, comb generators, interleavers, broadband amplifiers, etc. Important elements of modern optical networks are interleavers. As is known, interleavers can be constructed based on the use of several types of different optical devices characterized by a periodic frequency dependence of the scattering coefficients on the frequency, for example, based on Fabry-Perrot resonators [1]; optical interferometers [2, 7, 10, 11, 16]; dielectric microresonators [4–6, 9, 13, 17–22], as well as waveguides [8]; silicon wires [14, 15]; thin films [3]; and also liquid crystals [12]. Devices built using dielectric resonators have the smallest dimensions and are easier to implementing in integrated circuits. In addition, the scattering characteristics of filters on the dielectric resonators have wider possibilities for adjusting their parameters in a given frequency range.

1 Statement of the problem

It is known that dielectric resonators (DRs) with whispering gallery mode (WGM) oscillations are characterized by a quasi-periodic frequency spectrum. This property allows them to be used as elements of optical range interleavers.

The use of DRs allows for a significant reduction in the size of interleaver design. At the same time, it should be noted that the calculation of filters based on DRs, taking into account their periodic amplitude-frequency characteristics, was not carried out.

The purpose of this work is to develop the theory and electrodynamics analysis of the parameters of different notch and add/drop filters of the optical wavelength range, possessing periodic frequency scattering characteristics for the purpose of their possible use as components of interleavers.

This paper presents the results of calculations performed using previously created electrodynamics models of scattering of transmission line waves on complex systems of coupled DRs with degenerate types of WGM natural oscillations [23, 24], describing scattering in the frequency range, and taking into account several bands of their coupled oscillations. The influence of "neighboring" types of oscillations on the frequency distribution of scattering matrix elements in the region of a given filter band was investigated.

To solve the scattering problem, a system of equations derived from perturbation theory was used [24], and modified to describe the scattering problem on DRs with whispering gallery oscillations in a transmission line. The general solution to the scattering problem was expanded in terms of coupled oscillations of the resonator system. At that, for the first time, not only the distribution of the fields of natural oscillations were taken into account in the working frequency band of the filter, but also several types of WGM, adjacent in frequencies from above and below, as well as the degeneracy of the oscillations of each of resonators was taken into account. The obtained frequency dependences of the scattering matrix made it possible for the first time to estimate the degree of "influence" of neighboring oscillations on the operating characteristics of optical filters.

2 Scattering theory on detuned DRs with degenerate oscillations in a transmission lines

It's first considered the case of wave scattering on notch filter made on the basis of one (Fig. 1, a) or two (Fig. 2, a) DRs with WGM oscillations, taking into account several modes adjacent in frequency to the filter's working band.

For simplicity, a system of identical DRs is examined. In general, denoted the number of resonators in the filter as equal to N. Also assumed that we know all the natural oscillations in a given frequency band of each of the resonators. It's supposed that the number of degenerate oscillations of each WGM is equal to two. Each type of oscillations is characterized by a given parity of the field distribution relative to a given plane of symmetry of the resonator in the transmission line: which was denoted as even $(\mathbf{e}_s^e, \mathbf{h}_s^e)$, or odd $(\mathbf{e}_s^o, \mathbf{h}_s^o)$.

When setting a fixed (working) filter band with whispering gallery mode, adjacent oscillations in frequency usually also form additional bands characterized by similar amplitude-frequency characteristics. If the number of such additional bands that fall within a given frequency range of each DR is denoted by N^R, the total number of all resonances, taking into account the assumed degeneration of each mode, becomes equal to $M = 2 \cdot N^R \cdot N$, where N is the DR number in the filter.

The coupling coefficients of every DR with the transmission line $\tilde{k}_s^e$, $\tilde{k}_s^o$ as well as mutual coupling coefficients k_{12}^e; k_{12}^o for non-propagating and propagating waves $\tilde{k}_{12}^e$; $\tilde{k}_{12}^o$ can be calculated using analytical expressions for the field of the line and the field of resonators $(\mathbf{e}_s^e, \mathbf{h}_s^e)$, $(\mathbf{e}_s^o, \mathbf{h}_s^o)$, $(s = 1, 2, \ldots, M)$ [24], for each of the considered types of natural oscillations. It's assumed too that the coupling coefficients with the open space $\tilde{k} = \tilde{k}^{e,o}$ of each of resonators with rotational symmetry are equal for identical oscillations of different parity. It's obvious that such degenerate oscillations are orthogonal to each other and coupling coefficients between them in each resonator are equal to zero.

Constructing the theory, the scattering field expansions in terms of v-th coupled oscillations of the N DR system $(\mathbf{e}^v, \mathbf{h}^v)$ [24] $(v = 1, 2, \ldots, M)$ as a whole in a given frequency band was used:

$$\mathbf{e}(\mathbf{r}) = \sum_{s=1}^{M} b_s \mathbf{e}_s(\mathbf{r}); \quad \mathbf{h}(\mathbf{r}) = \sum_{s=1}^{M} b_s \mathbf{h}_s(\mathbf{r}). \tag{1}$$

Where complex amplitudes b_s and complex frequencies $\tilde{\omega} = \omega' + i\omega''$ of coupled oscillations of detuned DRs system, was obtained by solving the problem of eigenvalues of the coupling operator K:

$$\begin{gathered} \sum_{s \neq t}^{M} \kappa_{st} b_s + (i\tilde{k}_t - \lambda_t) b_t = 0, \\ \lambda_t = 2 \cdot \left(\frac{\tilde{\omega} - \omega_t'}{\omega_t'} \right), \quad (t = 1, 2, \ldots, M), \end{gathered} \tag{2}$$

$\kappa_{st} = \kappa_{st}^{e,o} = k_{st}^{e,o} + i\tilde{k}_{st}^{e,o}$ mutual coupling coefficient of the s–th and t-th DR for even or odd mode; $\tilde{k}$ coupling coefficients with open space; $\tilde{k}_t = \tilde{k}_t^{e,o}$ coupling coefficients with transmission line; $\omega_t' = {\omega'}_t^{e,o} = \omega_t$ is the real part of frequency of t–th isolated DR for even or odd mode.

To constructing a solution to the problem of the $(\mathbf{E}_l^+, \mathbf{H}_l^+)$ wave scattering on a system of coupled detuned DRs with WGM, it's also used the perturbation theory of Maxwell's equations and expansions (1). Here l is the multi index characterizing transmission line mode.

At the same time it's assumed that each of the resonators of the filter may be made of a loss dielectric: $\tilde{\varepsilon}_t = \varepsilon_t' - i\varepsilon_t''$ $(t = 1, 2, \ldots, N)$, where $\varepsilon_t'' \ll \varepsilon_t'$. The solution of the scattering problem was presented in the form [24], and also decomposed into coupled oscillations of the resonators:

$$\begin{gathered} \mathbf{E}(\omega) \approx \mathbf{E}_l^+ + \sum_{s=1}^{M} a^s(\omega) \mathbf{e}^s; \\ \mathbf{H}(\omega) \approx \mathbf{H}_l^+ + \sum_{s=1}^{M} a^s(\omega) \mathbf{h}^s, \end{gathered} \tag{3}$$

where $(\mathbf{e}^s, \mathbf{h}^s)$ is the field of coupled oscillations of a resonator system (1), corresponding to the eigenvalues $\lambda_t = \lambda_t^s$ $(s = 1, 2, \ldots, M)$ (2).

Using expressions of perturbation theory, written for the scattered field, transmission line field, and also the fields of partial resonators of the filters, the equation for amplitudes $a^s(\omega)$ [24] was represented in the form:

$$\sum_{s=1}^{M} a^s(\omega) b_t^s Q_{st}(\omega) = -Q_t^D \left(c_t^+\right)^* / \omega_t w_t, \tag{4}$$

where
$Q_{st}(\omega) = \omega/\omega_t + 2iQ_t^D(\omega/\omega_t - 1 - \lambda^s/2)$;
$Q_t^D = \omega_t w_t / P_t^D$ loss quality factor in the dielectric of the t–th DR, here $P_t^D = \frac{\omega_t}{2}\varepsilon_t'' \int\limits_{V_t} |e_t|^2 dv$ determines the dielectric power loss in the t–th resonator;
$c_t^{\pm}$ – field expansion coefficient of t–th DR by transmission line waves in the region $z > z_t$ (sign +), or $z < z_t$ (sign -), where z_t longitudinal coordinate t–th DR along z–axis of the transmission line.

The transmission T and the reflection coefficient R of the detuned DR system in the transmission line was obtained taking into account simultaneously the natural oscillations of the resonators at all considered frequencies of the structure:

$$\begin{aligned} T(\omega) &= T_0 + \sum_{u=1}^{M}\left(\sum_{s=1}^{M} b_s^u c_s^{g+}\right) a^u(\omega) = \\ &= T_0 - \frac{1}{\mathrm{B}(\omega)} \sum_{s=1}^{M} B_s^+(\omega); \\ R(\omega) &= R_0 + \sum_{u=1}^{M}\left(\sum_{s=1}^{M} b_s^u c_s^{g-}\right) a^u(\omega) = \\ &= R_0 - \frac{1}{\mathrm{B}(\omega)} \sum_{s=1}^{M} B_s^-(\omega), \end{aligned} \tag{5}$$

where T_0, (R_0) are the transmission (reflection) coefficients of the considered structure without DRs.

Then from (4):

$$B_s^{\pm}(\omega) = \det\begin{bmatrix} b_1^1 Q_{11}(\omega) & b_1^2 Q_{21}(\omega) & \ldots & Q_1^D \sum_{u=1}^{M} b_u^s \tilde{k}_{u1}^{\pm+} & \ldots & b_1^M Q_{M1}(\omega) \\ b_2^1 Q_{12}(\omega) & b_2^2 Q_{22}(\omega) & \ldots & Q_1^D \sum_{u=1}^{M} b_u^s \tilde{k}_{u2}^{\pm+} & \ldots & b_2^M Q_{M2}(\omega) \\ . & . & \ldots & . & \ldots & . \\ b_{M-1}^1 Q_{1(M-1)}(\omega) & b_{M-1}^2 Q_{2(M-1)}(\omega) & & Q_N^D \sum_{u=1}^{M} b_u^s \tilde{k}_{u(M-1)}^{\pm+} & & b_{M-1}^M Q_{(M-1)(M-1)}(\omega) \\ & & \ldots & & \ldots & \\ b_M^1 Q_{1M}(\omega) & b_M^2 Q_{2M}(\omega) & & Q_N^D \sum_{u=1}^{M} b_u^s \tilde{k}_{uM}^{\pm+} & & b_M^M Q_{MM}(\omega) \end{bmatrix};$$

$$B(\omega) = \det\begin{bmatrix} b_1^1 Q_{11}(\omega) & b_1^2 Q_{21}(\omega) & \ldots & b_1^M Q_{M1}(\omega) \\ b_2^1 Q_{12}(\omega) & b_2^2 Q_{22}(\omega) & \ldots & b_2^M Q_{M2}(\omega) \\ . & . & \ldots & . \\ b_M^1 Q_{1M}(\omega) & b_M^2 Q_{2M}(\omega) & \ldots & b_M^M Q_{MM}(\omega) \end{bmatrix}, \tag{6}$$

where
$\tilde{k}_{sn}^{++} = (c_s^+ c_n^{+*})/(\omega_n w_n) = (\tilde{k}_{sn})_0 e^{-i\Gamma(z_s - z_n)}$;
$\tilde{k}_{sn}^{-+} = (c_s^- c_n^{+*})/(\omega_n w_n) = (\tilde{k}_{sn})_0 e^{-i\Gamma(z_s + z_n)}$;
$c_s^{\pm}$ are the expansion coefficients of the s–th DR field: $(\mathbf{e}_s^e, \mathbf{h}_s^e)$, or $(\mathbf{e}_s^o, \mathbf{h}_s^o)$ (even or odd mode; $s = 1, 2, \ldots, M$) on the propagation wave field of the line $(\mathbf{E}_l^{\pm}, \mathbf{H}_l^{\pm})$; w_n energy stored in the material of the n–th DR; Γ longitudinal wave number of a line.

3 Scattering on different notch filters of detuned DRs

Using the results of (2)–(6), at the beginning the frequency dependences of the scattering matrix of simplest notch filter, consisting of one DR, located in the transmission line were investigated. For simplicity, it is assumed that the coupling coefficients of the resonator in a given frequency band for all considered oscillations are equal to each other, and also $z_s = 0$. In this case it can be stated that:

$$c_s^{\pm} = \left(\sqrt{\tilde{k}_L^e}\left|\sin\left(s\frac{\pi}{2}\right)\right|^2 \pm i\sqrt{\tilde{k}_L^o}\left|\cos\left(s\frac{\pi}{2}\right)\right|^2\right) e^{\pm im\frac{\pi}{2}}, \quad (s = 1, \ldots, M), \tag{7}$$

where m azimuthal number of the considered type of natural oscillations of the resonator; $\tilde{k}_L^{e,o}$ coupling coefficient of the DR with transmission line for the even (odd) mode, respectively.

Fig. 1, b–e show the frequency dependences of the S-matrix elements obtained by solving equations (2), (5) for one DR and for three natural oscillations adjacent from above and below to the oscillation with f_0=200 THz, taking into account the approximations made. Here $S_{21} = 20\lg|T|$; $S_{11} = 20\lg|R|$.

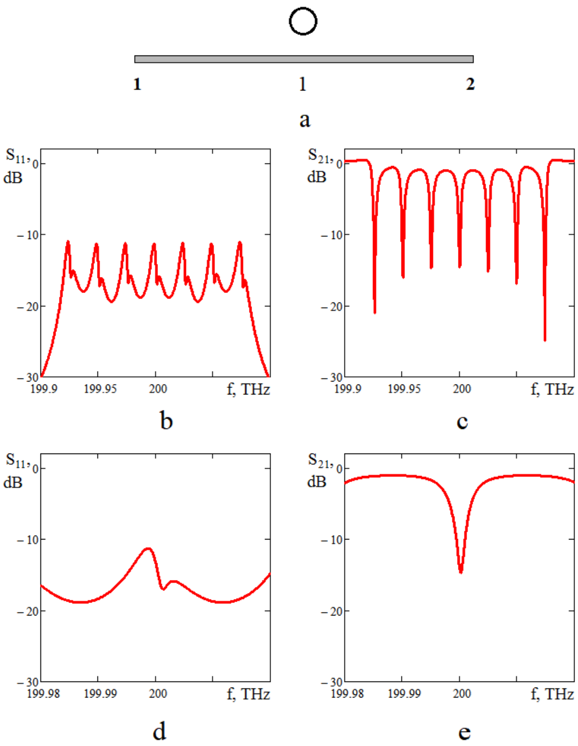

Fig. 1. Scattering characteristics (b-e) of the DR coupled with a transmission line (a) calculated for seven oscillations of WGM: $f_0 = 200\,\mathrm{THz}$; Free Spectral Range (FSR): $FSR = 25\,\mathrm{GHz}$; DR coupling coefficients with a transmission line: for even mode: $\tilde{k}_s^e = 2 \cdot 10^{-5}$, for odd mode: $\tilde{k}_s^o = 1 \cdot 10^{-5}$; coupling coefficients of the resonators with open space: $\tilde{k} = 10^{-7}$; dielectric loss Q-factor $Q^D = 10^5$

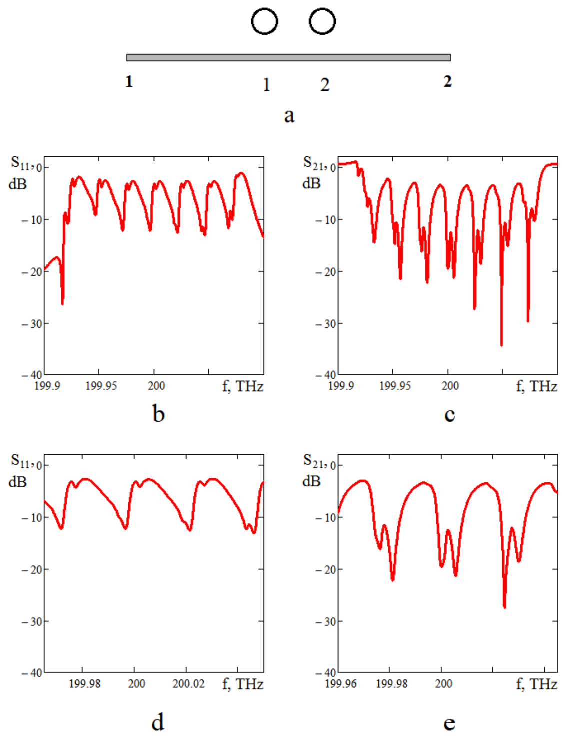

Fig. 2. Scattering characteristics (b–e) of two DR in a transmission line (a) calculated for seven oscillations of degenerate WGM: $f_0 = 200$ THz; $FSR = 25$ GHz; DR coupling coefficients with a transmission line: for even mode: $\tilde{k}_s^e = 3 \cdot 10^{-5}$, for odd mode: $\tilde{k}_s^o = 5 \cdot 10^{-6}$; coupling coefficients of the resonators with open space: $\tilde{k} = 10^{-7}$; coupling coefficients between resonators: for even mode: $k_{12}^e = -6,5 \cdot 10^{-5}$, for odd mode: $k_{12}^o = 2 \cdot 10^{-5}$; dielectric loss Q-factor $Q^D = 10^5$. Relative distance between resonators: $\Gamma \Delta z_{1,2} = \Gamma\,|z_1 - z_2| = 31\pi/2$

An example of calculating the frequency dependences of the scattering matrix of two DR notch filters is shown in Fig. 2. The coupling coefficients of the resonators were selected in such a way as to ensure approximately equal bandwidths of the transmission coefficient pass and rejection S_{21} (Fig. 2, c, e).

As follows from the calculations carried out, the value of the transmission coefficient goes beyond the limits of physically permissible values at the frequencies of the “extreme” oscillations (Fig. 1, 2, c). This phenomenon is simply explained by the fact that real resonators do not have such oscillations; both higher and lower in frequency there are natural oscillations that are not taken into account in this calculation.

In addition, it’s evident (Fig. 1, 2, b, c) that taking into account a finite number of modes in the calculation leads to the appearance of an asymmetry of the extreme values of the scattering matrix even for the same values of the coupling coefficients of all resonators.

4 Scattering on different add/drop filters of detuned DRs

A laterally coupled two DR add/drop filter built on a cascade of resonators with whispering gallery oscillations (Fig. 3, a) was considered in this work.

In general transmission coefficients between 1 and v port of a filter for a more complex structure containing several transmission lines was defined:

$$T_{1v}(\omega) = T_{0v} + \sum_{s=1}^{M} \left(\sum_{u=1}^{L} b_u^s c_u^{g\pm} \right) a^u(\omega) =$$
$$= \delta_{2v} - \frac{1}{\mathrm{B}(\omega)} \sum_{s=1}^{M} B_s^{\pm 1v}(\omega), \quad (8)$$

where T_{0v} is the transmission coefficient without DRs. The $B(\omega)$ function still has the form (7). The coupling matrix K (2) of the resonators is represented in the form [24]. The scattering matrix coefficients: $S_{v1}(\omega) = 20 \lg |T_{1v}(\omega)|$.

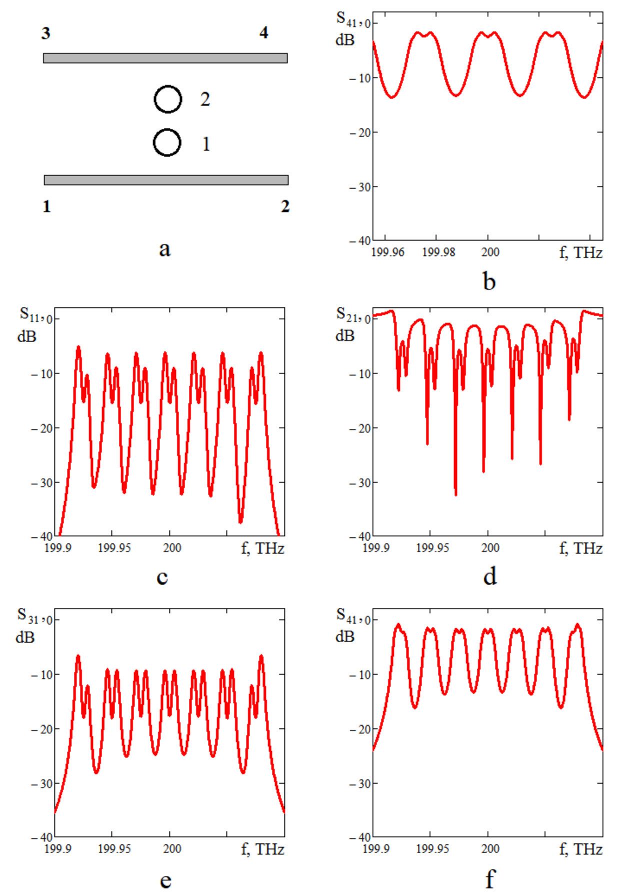

Fig. 3. Scattering characteristics (b–f) of two DR add/drop filter (a) calculated for seven oscillations of degenerate WGM: f_0 = 200 THz; FSR = 25 GHz; DR coupling coefficients with a transmission line: for even mode: $\tilde{k}_s^e = 2 \cdot 10^{-5}$, for odd mode: $\tilde{k}_s^o = 2 \cdot 10^{-5}$; coupling coefficients of the resonators with open space: $\tilde{k} = 10^{-7}$; coupling coefficients between resonators: for even mode: $k_{12}^e = 5 \cdot 10^{-5}$, for odd mode: $k_{12}^o = -3 \cdot 10^{-5}$; dielectric loss Q-factor $Q^D = 10^8$

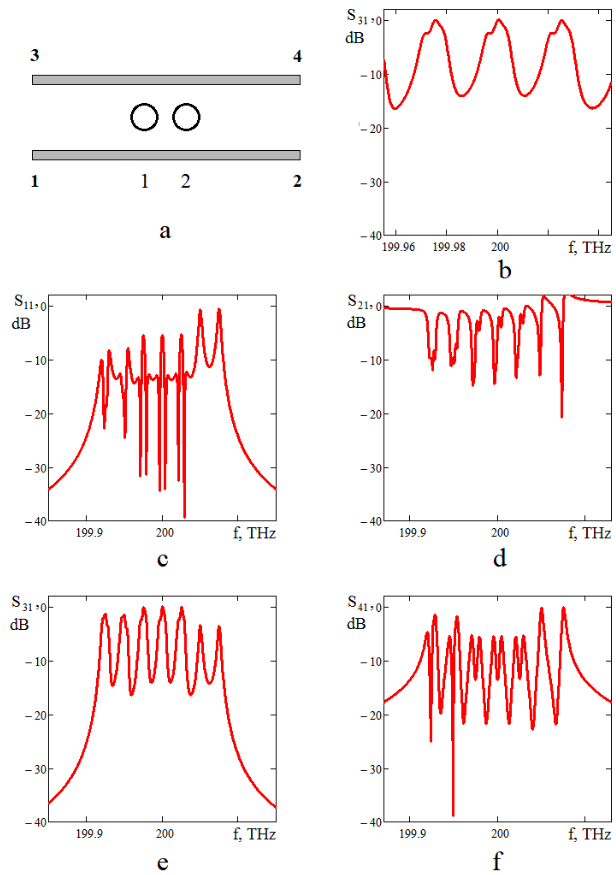

Fig. 4. Two DR SCISSOR (side-coupled integrated spaced sequence of optical resonators) (a). Scattering characteristics (b–e) of two DR filter (a) calculated for seven oscillations of degenerate WGM: $f_0 = 200$ THz; FSR = 25 GHz; DR coupling coefficients with a transmission line: for even mode: $\tilde{k}_s^e = 1 \cdot 10^{-5}$, for odd mode: $\tilde{k}_s^o = 1 \cdot 10^{-5}$; coupling coefficients of the resonators with open space: $\tilde{k} = 10^{-7}$; coupling coefficients between resonators: for even mode: $k_{12}^e = -2,2 \cdot 10^{-5}$, for odd mode: $k_{12}^o = 2 \cdot 10^{-6}$; dielectric loss Q-factor $Q^D = 10^6$

On Fig. 3, b–e shown the frequency characteristics of the scattering matrix of add/drop filter made of two DRs.

In a similar way, can be calculated the frequency characteristics of scattering at parallel-coupled add/drop filters. Fig. 4 shows the scattering characteristics of a 2–resonator filter in 7 pass bands (b). In this case, it's too clear that taking into account a finite number of resonances leads to a noticeable distortion of several extreme frequency bands of the frequency response (Fig. 4, c–f). An additional source of such errors may also be approximations in the magnitude and equality of the coupling coefficients of the resonators in a given structure. In specific filter calculations, this source of error of course should be eliminated.

Figure 5 shows the frequency dependences of the scattering matrix of parallel-coupled add/drop filter, obtained using the relations (4), (6)–(8) also taking into account 3 resonances above and below the operating frequency band.

Further calculations of the filter characteristics taking into account a larger number of bands showed that the uneven distribution of the frequency response of the structures in most designs becomes more uniform. It's obvious that the number of bands lying in frequency above and below the operating band should be selected separately for each specific case, however, as follows from the calculations given, this number must not be less than three.

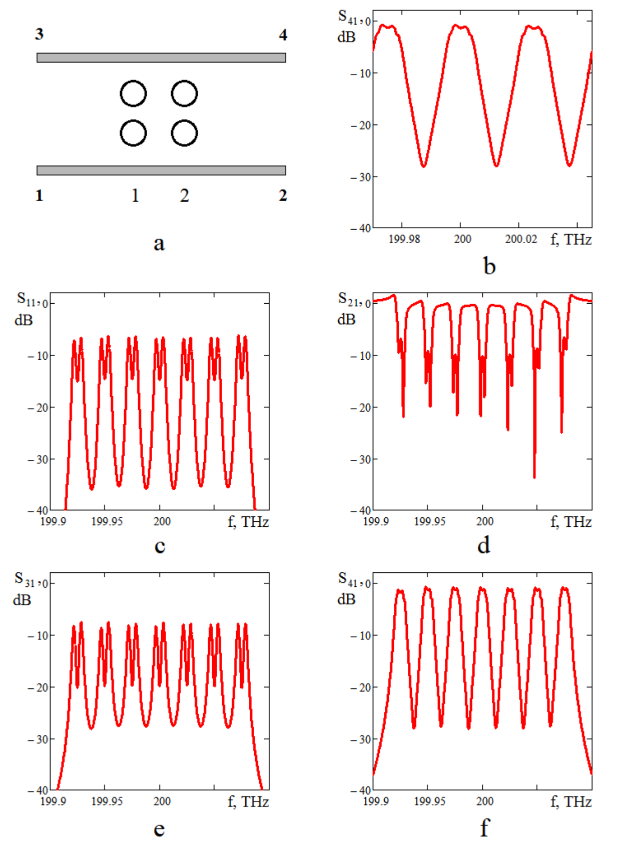

Fig. 5. Twisted double-channel SCISSOR (a). Scattering characteristics (b–f) of fore DR filter (a) calculated for seven oscillations of degenerate WGM: $f_0 = 200\,\text{THz}$; $FSR = 25$ GHz; DR coupling coefficients with a transmission line: for even mode: $\tilde{k}^e_s = 8 \cdot 10^{-6}$, for odd mode: $\tilde{k}^o_s = 8 \cdot 10^{-6}$; coupling coefficients of the resonators with open space: $\tilde{k} = 10^{-7}$; coupling coefficients between series-coupled resonators: for even mode: $k^e_{12} = 1 \cdot 10^{-6}$, for odd mode: $k^o_{12} = -1 \cdot 10^{-6}$; coupling coefficients between vertically-coupled resonators: for even mode: $k^{eV}_{12} = 4 \cdot 10^{-5}$, for odd mode: $k^{oV}_{12} = -2,5 \cdot 10^{-5}$; dielectric loss Q-factor $Q^D = 10^6$

Discussion and Conclusion

A general theory of scattering of electromagnetic waves by systems of detuned in frequency dielectric resonators, proposed in [24], allows constructing correct models of complex systems of add/drop and notch filters, calculated taking into account several resonant bands in a given frequency range. The proposed electromagnetic models of the filters, constructed on the basis of the use of DRs with degenerate whispering gallery oscillations, confirm the main features of the scattering characteristics studied earlier by using direct numerical solutions of Maxwell's equations for similar structures. The theory of calculating the scattering characteristics of optical filters developed in this work gives us a new tool for optimizing the frequency characteristics of the scattering S-matrix in cases of designing interleavers constructed using optical DRs with WGM oscillations.

The conducted research allows to significantly accelerate the design and optimization of scattering characteristics of modern optical communication systems using interleavers in technology WGM. The proposed new scattering models can also be used to calculate the characteristics of a wide class of multiplexers, semiconductor lasers, absorbers and other optical devices built using DRs.

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Оптимізація параметрів розсіювання оптичних фільтрів на діелектричних резонаторах з коливаннями шепочучої галереї для побудови інтерліверів

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Розглядаються частотні залежності матриць розсіювання відомих видів оптичних фільтрів, побудованих на зв'язаних діелектричних резонаторах (ДР) з коливаннями шепочучей галереї, розташованих в одній або кількох лініях передачі з урахуванням декількох смуг частот. Побудовані нові електромагнітні моделі режекторних та фільтрів додавання/виведення різних типів, які складаються із одного та двох оптичних резонаторів з виродженими типами власних коливань. Знайдені рішення використовуються для розрахунків та аналізу частотних залежностей матриць розсіювання фільтрів одночасно в декількох смугах збудження резонаторів структури. Наведено приклади розрахунку частотних залежностей матриць розсіювання для найбільш поширених видів фільтрів, які можуть знайти практичні застосунки при побудові інтерліверів. Розраховано частотні характеристики розсіювання декількох фільтрів, які складаються із одного та двох діелектричних резонаторів. Досліджуються частотні залежності матриць розсіювання двох найбільш поширених типів фільтрів, виконаних на основі зв'язаних між собою ДР, розташованих паралельно між двома оптичними лініями передачі: фільтри додавання/виведення з бічним зв'язком; фільтри додавання/виведення з паралельним зв'язком; двоканальні фільтри додавання/виведення з бічним зв'язком. Можливості запропонованого методу демонструються на прикладах розрахунку матриць розсіювання фільтрів додавання/виведення з урахуванням декількох частотних смуг, які можуть бути використані для побудови інтерліверів. Аналізується вплив сусідніх за частотами коливань резонаторів на характеристики фільтрів. Побудовані електродинамічні моделі фільтрів є основою для розрахунку та оптимізації характеристик широкого класу елементів новітніх систем оптичного зв'язку надвисокої швидкості.

Ключові слова: розсіювання; діелектричний резонатор; матриця розсіювання; режекторний фільтр; фільтр додавання/виведення з бічним зв'язком; фільтр додавання/виведення з паралельним зв'язком; двоканальний фільтр додавання/виведення з бічним зв'язком; інтерлівер