Frequency-Tunable Microwave Dielectric Resonator

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***Abstract*—A new type of tunable composite dielectric resonator (DR) has been designed. In the structure of this DR, a controllable insert was used to change the resonance frequency (f_0) in a wide spectral range, while preserving a high quality factor. The simplest of proposed resonance systems for obtaining f_0 control is a microwave DR crossed by an air slot, which is controlled by fast piezoelectric actuator. Analytical and experimental techniques were employed for optimization of the composite DR structure. It has been observed that this device can create a change up to 20%–25% in its resonance frequency.**

***Index Terms*—Dielectric resonator, resonant frequency, tuning.**

I. Introduction

TELECOMMUNICATION systems require a compact size and low-cost electronic equipment. Electronically tuned microwave filters are among them. Moreover, in some specific and important applications, the semiconductor microwave oscillator need fast control of frequency, which is usually realized by the tuned resonator. Application areas of these devices are rapidly tuned panoramic receiver, mobile antenna arrays, and mobile basestations for cellular telephones, etc.

The performance of tuned resonant microwave devices depends on their frequency range, operation speed, and especially on the quality factor Q of the resonator. However, currently available tuned-microwave filters have a low quality factor, which is their limiting property. For this reason, there is an urgent need for high-Q low-cost agile microwave filters for modern radio and communication systems.

YIG types of ferrite resonators are generally used for the frequency-tuned microwave filter applications. Important disadvantages of a YIG resonator are their high cost and operation range (up to 20 GHz) [1]. In microwave communication units, other tuning resonance systems can be also used, but sometimes they are very complicated [2]. Dielectric resonators (DRs) are used in a wide variety of devices; however, most of them have constant resonant frequency f_0. For this reason, microwave DRs based electrically adjustable filters are an intriguing subject.

Existing methods for mechanical tuning of a DR-based filter, such as quasi-static tuning by using a screw, are limited due to a slow operation rate [3]. Material parameters of a filter cannot be changed: the DR must be fabricated from the thermally stable low-loss ceramic materials to have a distinct resonant frequency [4]–[6]. The intrinsic dielectric constant (ε) of these materials cannot be controlled electronically because of their high stability to any environmental influence. Therefore, there is not any other easy way to alter the DR resonance frequency at a substantial scale, except by inserting a tunable material (ε_i) incorporated with a microwave DR (Fig. 1). The final system forms a sort of laminar composite structure. It is apparent that electric-field lines of the DR should pass through the sandwiched materials to maximize the insert influence [7]. Evidently, the inserted material has to be electrically controllable, and performance of the given composite resonance system depends on the properties of the DR and insert material.

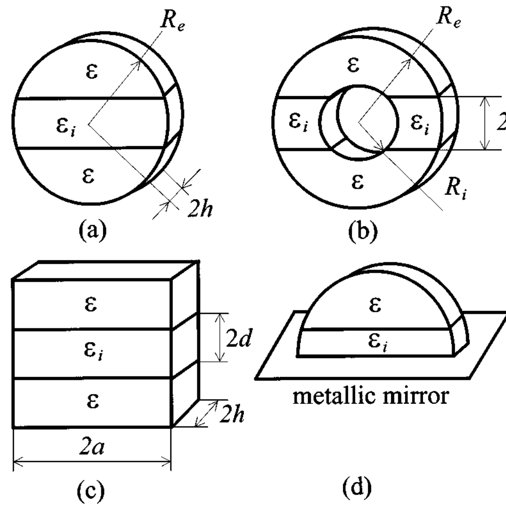

Fig. 1. Composite DRs. (a) Disk. (b) Ring. (c) Rectangular. (d) 1/2 disk reflected in mirror.

The inserted material can be paraelectric ceramics with an electronically controlled dielectric constant [6], as well as a semiconductor with a controlling conductivity (p-i-n diode) or the controlling thickness of a p-n junction (varactor diode). However, at the present state-of-the-art of these materials technology, all of them significantly decrease the quality factor of the DR, and the paraelectric ceramics with their existing quality factors ($\tan\delta = Q^{-1} \sim 0.01$–$0.005$ [8]) cannot provide good enough results for a tuned composite DR.

Electronic methods for adjustment of the DR resonant frequency have a rather low tuning range $\Delta f/f_0$. As an example, for the optical controlling tuning range, it is less than 1%, for the varactor circuit, it is <2% [9], for the ferrite rod inserted in the DR, it can be ~3% [10], for the tunable paraelectric film, it is also ~3% [11]. As it is seen, in all these composite systems, the quality factor essentially decreases.

In this paper, a new method for high-quality electrically tunable and microwave DR-based filters, which are fabricated using

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a new type of frequency tunable DR, is examined. Various types of adjustable DRs were studied to investigate their full characteristics. Schematic of the studied most common type the DRs are shown in Fig. 1(a)–(c). It has been concluded from these calculations that a narrow air slot $(\varepsilon_i = 1)$ is essential for the tunable systems and a fast actuator can be used to control clearance of this slot while preserving the high initial quality factor of the microwave dielectric. As well as two parts of a DR, a reflecting metallic mirror can be also applied to increase the range of frequency control [see Fig. 1(d)].

A fast-acting electromechanical actuator operates successfully only in the case of small deformation. Keeping this in mind, the resonant frequency of the proposed composite system should be strongly dependent on the air slot thickness. It is shown here that resonant frequency of some modes of a composite DR could be essentially changed with the small alteration in air slot. In this investigation, an analogous mode of frequency control was employed. Required displacement among the system components is very small due to the high dielectric constant of the DR. Recently developed electroactive composite ceramic–metal actuators, i.e., the cymbal and moonie, can provide rather large, nonhysteretic, and quickly controlled displacement [12]–[14].

The design of a composite DR was theoretically analyzed to calculate the cardinal parameters and to investigate optimal components and materials. Electromagnetic-field calculations are verified by experimental studies. By using the designed resonance devices, it is possible to alter the resonance frequency up to 20%–25% $(\Delta f/f_0)$, while maintaining the high quality factor.

II. Designing Composite DR Structures

The basic model consists of a DR crossed by an air slot, whose width can be changed by a fast piezoelectric actuator to control resonance frequency. As an alternative to this high-Q resonance system, the image DR has been used. In the structure of this image DR, half of the resonator has been replaced with a reflecting metallic mirror. The surface of the mirror was coated with copper and gold. Meanwhile, DRs were prepared from the microwave ceramics with a thermal stable dielectric constant $(\varepsilon = 40\text{–}100)$ and a very low-loss factor: unloaded $Q = (8\text{–}13) \cdot 10^3$ [3], [6].

Various designs based on a one resonator and multiresonator were studied. One-resonator devices can be used for oscillator frequency control. On the other hand, multiresonator systems can provide a frequency band need for microwave filters. The designs of tuned composite DRs, as well as the operational principles of their frequency control are illustrated in Fig. 2. The control might be a quasi-static (using a micrometry screw) or a dynamic (using piezoelectric actuator)

The first design shown in Fig. 2(a) represents a two-resonator bandpass tuned filter. Two disk-type DRs consist of composite structures including two halves of a disk DR with a slot between them. The clearance of the air slot in the system “1/2DR–slot–1/2DR” is changed by the screw or by the piezoelectric actuator to control the resonance frequency f_0 in

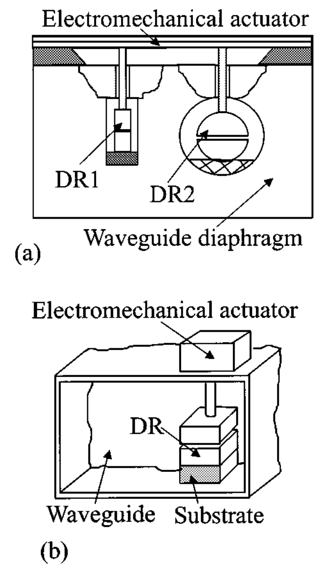

Fig. 2. Simplest design of: (a) bandpass and (b) bandstop filters with DRs in the waveguide.

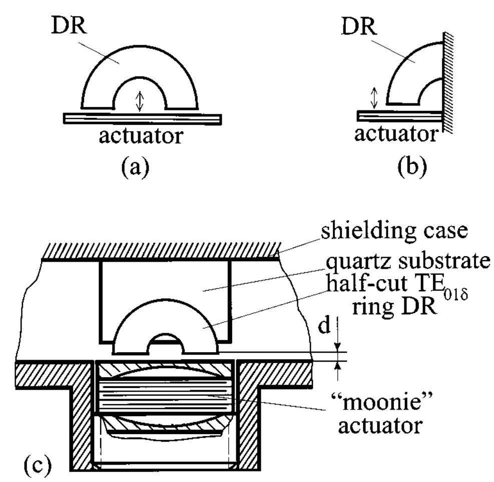

Fig. 3. Electromechanically tuned image DR. (a) 1/2DR reflected in the mirror actuator. (b) 1/4DR reflected in a waveguide wall and mirror actuator. (c) One of single-resonator design.

a wide spectral range while preserving the high initial quality factor of a DR.

The second example shown in Fig. 2(b) is also a composite resonance system, which is designed for a tuned bandstop filter. The rectangular (cubic-shape) DR has a controlling slot inside, and naturally has two types of orthogonal (independent) $\mathrm{TE}_{11\delta}$ modes. The amplitude-frequency characteristics (AFCs) of filter devices shown in Fig. 2 will be discussed later.

The half of the ring DR can be replaced with a metallic mirror to decrease the size of the DR-based design, which is important for UHF applications [see Fig. 3(a)]. Intrinsic frequency f_0 of such an “image DR” practically is not changed from the reflection. In the case of image DR tuning, the clearance of the air slot decreases two times that, and makes the controlling easier. On the other hand, if two mirrors are used for reflection, only 1/4 of the DR can be used for the frequency control, as is shown in Fig. 3(b) (a similar design was used previously for the nontuned DR-based filter [5]). Dielectric-to-mirror contact surface decreases the DR unloaded Q factor to some extent. That is why the faces of the cut surface of the DR should be highly polished, and highly conductive metals should be used as a mirror.

The most important point is that image designs of a 1/2DR and 1/4DR mirrors are very convenient for air–slot thickness controlling by an actuator. The 1/2DR mirror is an adequate design at the microwave range where the DR is a component, despite a rather small size. The 1/4DR mirror composition is better for the UHF band, where the resonance device could be large because of the compact size and reliable operation.

Various types of actuators are examined. The tested bimorph types of a piezoelectric actuator are based on a transverse piezoelectric module d_{31} and have had a reasonable strain, but comparatively small operation speed, in which the resonance frequency Ω_0 is approximately 15 kHz [7]. However, the bimorph actuator is sensitive to the external vibrations. On the contrary, a common type of multilayer actuator using a longitudinal piezoelectric module d_{33} is faster than bimorph ($\Omega_0 > 50$ kHz) and the actuator can reliably withstand the vibrations. However, it exhibits rather small strain.

Recent “moonie” and “cymbal” types of actuators [15] combine the advantages of two aforementioned actuators; they produce large strains with a quick response. Their acoustic resonance frequency Ω_0 might be more than 100 kHz. The brass plate used in the design of these actuators can simultaneously play the part of the metallic mirror [see Fig. 3(c)].

Regarding the composition of the piezoelectric ceramic material, all actuators have had unwanted hysteresis. That is why, to simplify the linear electric control of microwave resonant devices, the nonhysteresis electrostrictive ceramics should be preferred. In addition, with the electrostrictors, it is easy to avoid any uncertainty at the initial part of the strain–electric-voltage characteristic.

Recently developed electroactive composite ceramic actuators, i.e., the cymbal and moonie, can provide rather large, nonhysteretic, and quickly controlled displacement. The cymbal and moonie are flextensional composite actuators that consist of a ceramic driving element sandwiched between two metal endcaps. Under an applied electric field, the lateral motion of the piezoelectric ceramic is converted and amplified to an axial displacement by the endcaps. The cymbal actuator shows a higher displacement and lower position-dependent behavior than the moonie design. It is possible to achieve tens to hundreds of micrometers displacement by tailoring the size and material of the conical cymbal endcap. The cymbal has faster response time ($\Omega_0 > 100$ kHz) and larger generative forces than bimorphs, and higher displacement than a multilayer actuator.

III. Theoretical Analysis

In order to analyze the possibilities of the proposed composite resonant system, the mode-matching (partial-domain) method has been used. The problem is reduced to a set of first-type Fredholm integral equations for the unknown tangential components of electric and magnetic fields at the boundaries of partial domains. The system of integral equations has been reduced to algebraic equations to solve them.

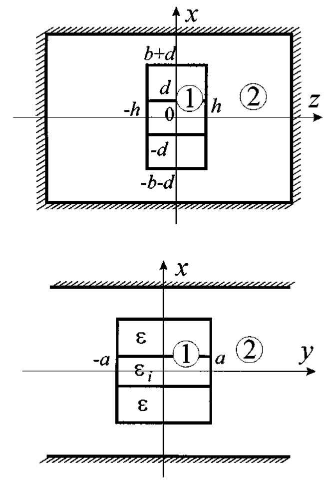

Fig. 4. Schematic representation of the rectangular DR with an insert for theoretical study.

As an example of this method of analysis, a calculation has been done for the rectangular type of DR, as shown in Fig. 1(c), and represented in detail in Fig. 4. Employing the same method, the theoretical analysis has also been performed as well for disk and ring-shaped DRs [see Fig. 1(a)and(b)]. All three types of DRs with a controlling slot were studied experimentally, and the results are compared with the data obtained by the simulation

The electrical Γ^e and magnetic Γ^m hertz vectors of the rectangular DR component can be described as a series of the partial domain's eigenfunctions as

$$\Gamma_i^{e(m)} = \sum_{m=0}^{\infty} A_{mi}^{e(m)} \Gamma_{mni}^{e(m)} = \sum_{m=0}^{\infty} A_{mi}^{e(m)} X_{mi}^{e(m)}(x) Y_{ni}^{e(m)}(y) Z_i^{e(m)}(z). \quad (1)$$

Here, i is a number of the partial domain, m, n are the number of eigenvalues of the partial domain, $A_{mni}^{e(m)}$ are indeterminate coefficients, $\Gamma_{mni}^{e(m)}$ are the partial domain's eigenfunctions. Functions $X_{mi}^{e(m)}(x)$, $Y_n^{e(m)}(y)$, and $Z_i^{e(m)}(z)$ can be derived from Helmholtz equations for each partial domain. Coefficients $A_{mni}^{e(m)}$ are expressed in terms of the partial domain's eigenfunctions as

$$A_{m1}^e = \int_0^b \frac{\varepsilon(x) f^e(x) X_{m1}^e(x)}{Z_1^e(h)(\beta_{yn}^2 + \beta_{z1}^{e^2})} dx$$

$$A_{m2}^e = \int_0^b \frac{f^e(x) X_{m2}^e(x)}{Z_2^e(h)(\beta_{yn}^2 + \beta_{z2}^2)} dx$$

$$A_{m1}^m = \int_0^b -\frac{j}{z_0} \frac{f^m(x) X_{m1}^m(x)}{Z_1^m(h)(\beta_{yn}^2 + \beta_{z1}^{m^2})} dx$$

$$A_{m2}^m = \int_0^b -\frac{j}{z_0} \frac{f^m(x) X_{m1}^m(x)}{Z_2^m(h)(\beta_{yn}^2 + \beta_{z2}^2)} dx \quad (2)$$

were β_{yn}, β_{z1}^e, β_{z1}^m, and β_{z2} are eigenvalues of the eigenfunctions $Y_{n1}(y)$, $Z_1^e(z)$, $Z_1^m(z)$, and $Z_2(z)$, respectively, [16], z_0

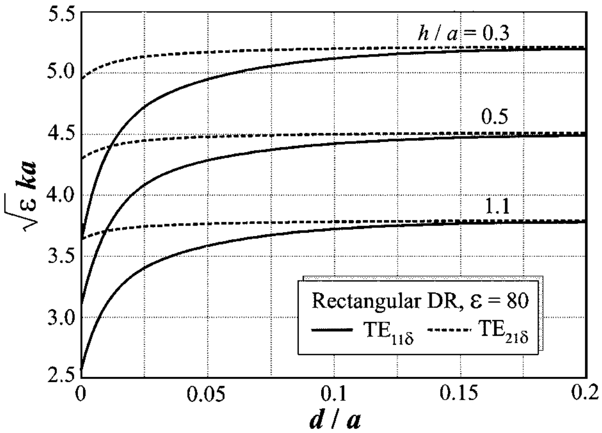

Fig. 5. Normalized resonant wavenumber via normalized width of air clearance d/a at several normalized resonator thickness h/a.

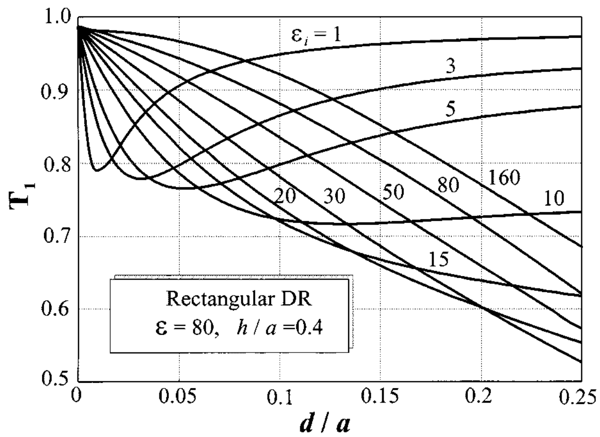

Fig. 6. Energy-filling factor versus normalized thickness of the insert for various insert dielectric constant ε_i.

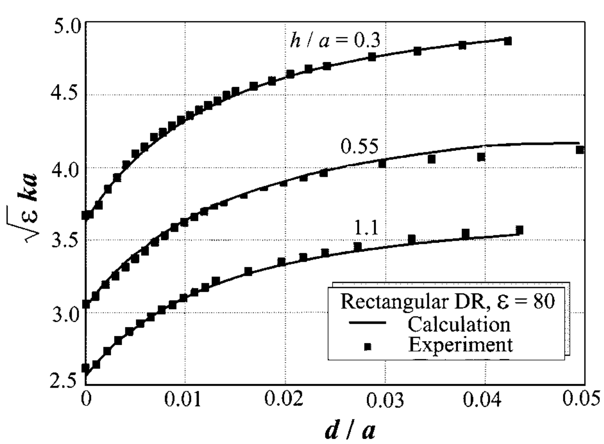

Fig. 7. Calculated and experimental results of a rectangular DR at various h/a ratios.

is the characteristic impedance of free space and $\varepsilon(x)$ is the distribution of dielectric permittivity along the x-axis.

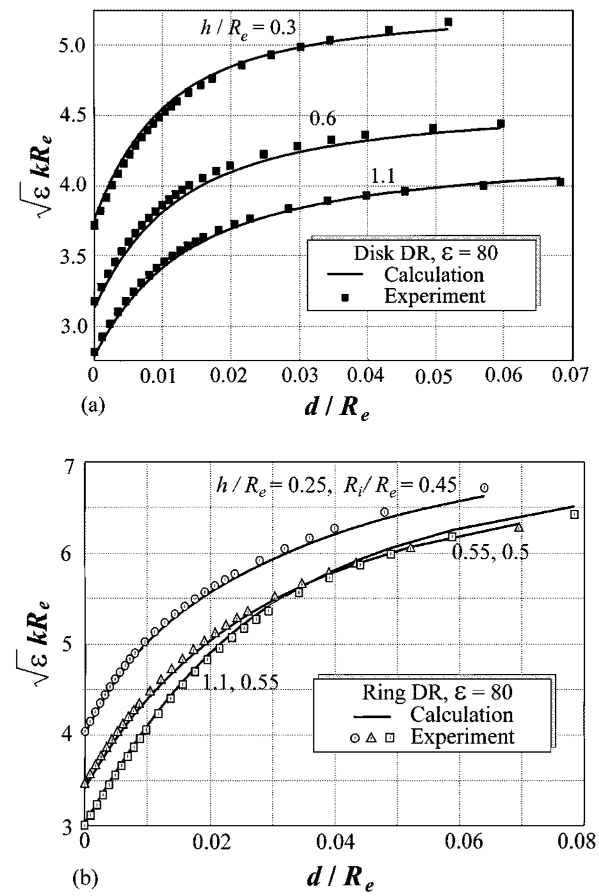

Fig. 8. Experimental and calculated results of: (a) disk and (b) and DRs with air inserts.

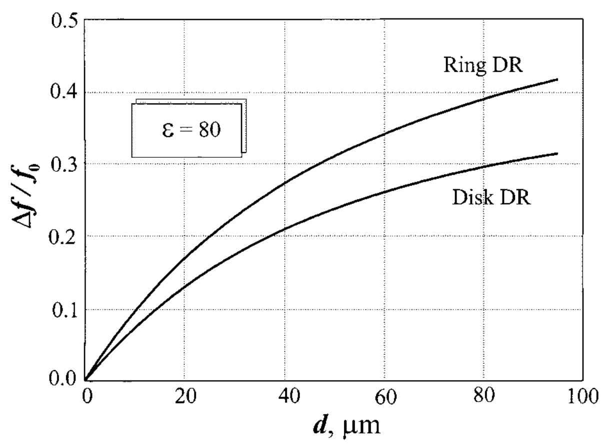

Fig. 9. Composite DR resonant frequency versus the distance between the 1/2DR and metallic mirror.

The reduced set of 1-rst-type Fredholm integral equations for the unknown tangential components of electric and magnetic fields at the boundaries of the partial domains is

$$\int_0^b \left(G_k^e(x,x') f^e(x) + G_k^m(x,x') f^m(x) \right) dx = 0, \qquad k = 1, 2.$$

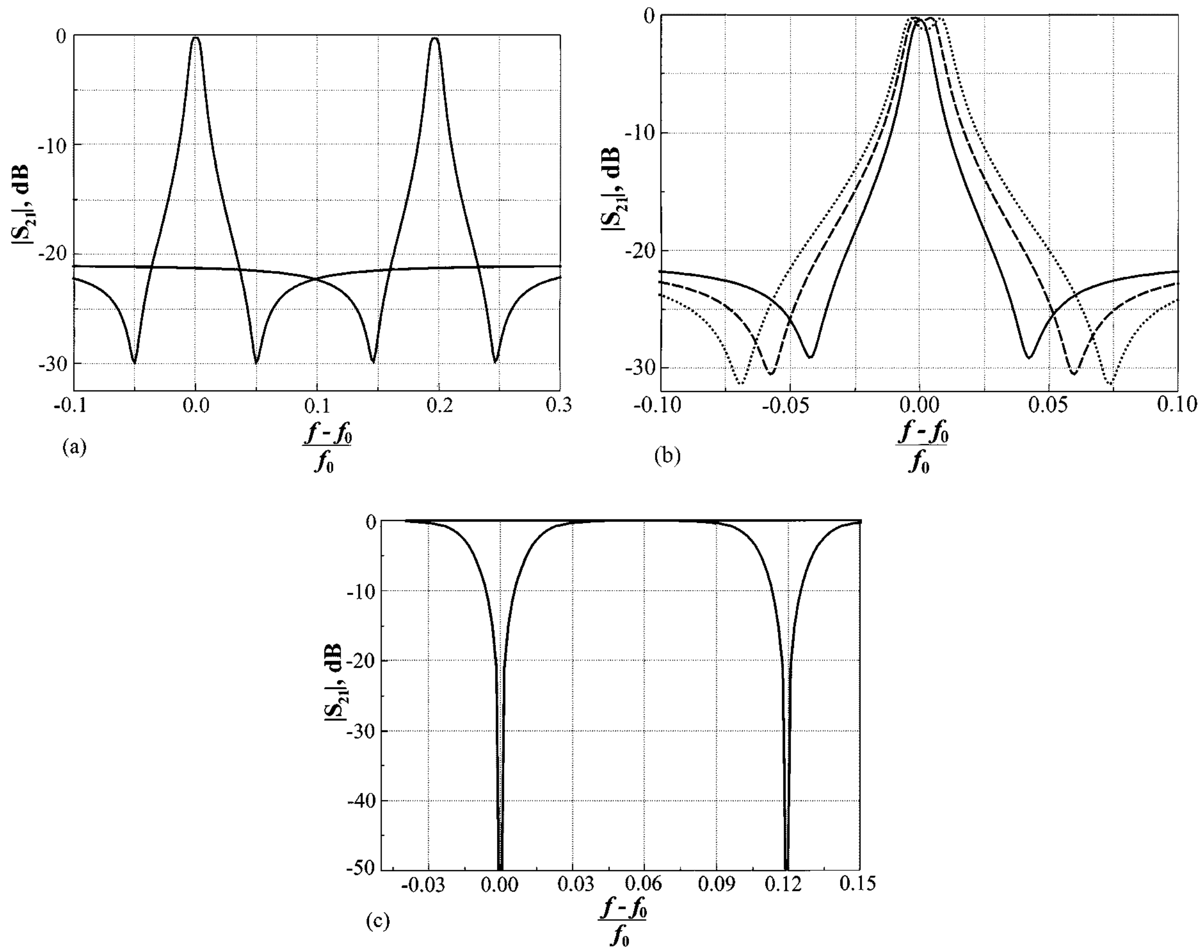

Fig. 10. Tuned filters attenuation-frequency characteristics. (a) AFC of bandpass filter shown in Fig. 2(a) (with two composite DRs). (b) Shape adjustable AFC of the 2-DR filter with only one controlled DR. (c) Bandstop tuned filter based on cut cubic DR shown on Fig. 2(b).

The functions in integral equations are

$$f^e(x) = \frac{E_x}{Y_n^e(y)} = \frac{\frac{\partial^2}{\partial x^2}\Gamma_i^e + \varepsilon(x)k^2\Gamma_i^e}{Y_n^e(y)}$$

$$f^m(x) = \frac{jz_0 H_x}{Y_n^m(y)} = jz_0 \frac{\frac{\partial^2}{\partial x^2}\Gamma_i^m + \varepsilon(x)k^2\Gamma_i^m}{Y_n^m(y)}.$$

Systems of integral equations were used to find eigenvalues and eigenfunctions. Each of them designates the tangential fields in the plane $z = h$ (Fig. 4). Correspondingly, using (1) and (2), the full electromagnetic field for any type of DR vibration could be found by using the frequency of the resonance modes. A system of integral equations was solved by using Galerkin's method to reduce them to linear algebraic equations [17].

Calculations show that the most sensitive to the slot width are the resonant frequencies of those modes in which their electric field $\mathbf{E}$ is perpendicular to the interface between dielectrics with ε and ε_i, as is shown in Fig. 1. As an example, Fig. 5 shows the dependence of a normalized resonant wavenumber $\sqrt{\varepsilon}ka$ on the width of the slot (where $k = 2\pi f_0/c$, c is the light velocity and a is the DR dimension).

For comparison, the two modes have been analyzed: $\mathrm{TE}_{11\delta}$ and $\mathrm{TE}_{21\delta}$. The resonance frequency of the $\mathrm{TE}_{11\delta}$ mode (in which $\mathbf{E}$ is perpendicular to the dielectrics interface) is crucially changed with the slot thickness. On the contrary, the resonant frequency of the $\mathrm{TE}_{21\delta}$ mode, in which $\mathbf{E}$ is parallel to the dielectrics interface, is weakly dependent on the slot width.

An intrinsic Q factor of constituent DRs was computed using common definitions, assuming that the electromagnetic-field distributions of the resonant system with low loss remains the same as for the lossless systems. As a result, it is shown that unloaded Q factor can be expressed as follows: $Q_0^{-1} = \sum T_i \tan\delta_i$, where $i$is a number of the resonant structure domain having a different loss tangent $\tan\delta_i$, and T_i is the energy-filling factor dependent only on the dielectric constant and domain size (Fig. 6). Therefore, the Q factor remains practically the same if active inclusion with a small loss tangent is used for the composite DR.

As a consequence, the analysis shows that the efficiency of resonant frequency control is increased as the DR material dielectric constant increases. Composite DR tunability is growing with the increase of the DR normalized thickness h in comparison with DR transverse dimensions, with the increase of the DR dielectric constant, and with the wavelength decrease.

IV. Experimental Results

Experiments with controlled DRs and filters were performed in the frequency range of 3–40 GHz. To study the AFC and other S-parameters of DR-based resonance systems, several network analyzers were used. In the quasi-static experimental study, the width of the air slot was controlled by a micrometric screw, while the dynamic mode was investigated with microactuators.

A comparison of simulated data and experimental results of a rectangular DR with a slot are shown in Fig. 7 for various d/a rations. The results are presented as a normalized resonant wavenumber $\sqrt{\varepsilon}ka$ with respect to the relative thickness of air slot d/a. The dielectric constant of the resonator ceramics is $\varepsilon = 80$, while k is the free-space wavenumber. Three d/a ratios were studied and, in the all cases, there is a good agreement between theoretical and experimental results (see Fig. 7).

The experimental and calculated results of the disk and ring type of resonators are presented in Fig. 8. Experimental data shown in Figs. 7 and 8 are obtained in the frequency range of 3–18 GHz. The composite DRs were located in the rectangular waveguide, as in Fig. 2. The dimensions of the disk- and ring-shaped resonators are shown in the Fig. 1(a) and (b). R_e is the disk or ring DR external radii, R_i is the ring internal radius, h is the height of the disk or ring DR, and d is the controlled distance between the half-cut of the $\mathrm{TE}_{01\delta}$ image resonator and metallic mirror [see Fig. 1(d)]. Both disk and ring resonator characteristics were studied at three h/R ratios. Experimental and calculated results are in a very good agreement.

The normalized resonant wavenumber $\sqrt{\varepsilon}kR_e$ with respect to the normalized width of the air slot d/R_e shows a curve with saturation at big d/R_e. The change of the wavenumber with the air–slot alteration is most pronounced at the initial part of this characteristic. As an example, a 10% change on the resonant frequency of the DR could be obtained by changing only tens of a micrometer of the distance between parts of the resonant system in the ∼10-GHz frequency range. A workable result is obtained with the disk DR; however, the best result has been achieved with the ring DR (Fig. 9). The realized construction of one-resonator filter with electrically controlled frequency allowed the frequency change $\Delta f/f_0$ up to 20%–25% under the controlling voltage of ∼100 V. The resonator quality factor was $Q > 1000$ and remained practically unchanged during the operations.

DR-based electrically controlled filters have been affected in various designs depending on the wave range and waveguide configurations [18]. In the case of two-resonators bandpass filters, shown schematically in Fig. 2(a), one DR has an electrical dipole mode f_1 (being excited in phase with the transmission line), while another DR represents magnetic dipole mode f_2 (providing excitation in the opposite phase). Due to this design, the modes of both resonators are independent. That is why, under the synchronous change of f_1 and f_2, the form of the filter AFC is preserved, and in spite of its central frequency, is controlled up to ∼20%, as is shown in Fig. 10(a). It is worth noting that if only one of the two DRs would be frequency tuned, it is possible to change the only shape of the AFC while the filter central frequency remains practically unchanged [see Fig. 10(b)]. This type of controlled filter might be of interest for some microwave applications.

An additional example is a frequency-controlled bandstop filter that was realized with the cubic-shape DR with two types of orthogonal $\mathrm{TE}_{11\delta}$ modes. The principle of design is shown in Fig. 2(b). An experiment showed the 12% change of filter frequency under the controlling voltage of ∼100 V. As shown in the examples of Fig. 2, the operation speed of the slot-width control was limited by the actuator system resonance frequency. The last was decreased to ∼10 kHz because the actuator was joined with the push rod. As a result, the mass of the actuator system was increased, which decreased the speed of operation. That is why moonie- or cymbal-type actuators are preferential.

V. Conclusions

An electromechanically controlled air slot located between two parts of a resonant dielectric system has been proposed as a tunable microwave DR. Such a structure is simulated in order to optimize the composite DR device. Constituent structures of 1/2 or 1/4 parts of DRs reflected in the metallic mirrors are proposed and studied as well. By the control of the air slot between parts of the DRs and mirrors, it is possible to change a central frequency of the constituent structure or its attenuation-frequency characteristic.

Experimentally examined resonant devices show a high quality factor and allow the change of their resonant frequency (up to 20%–25%). A composite DR controlled by the actuator provides a model for a high-quality tunable microwave filter, in which central frequency, as well as the shape of the attenuation-frequency characteristics, could be controlled electrically with a rather fast response. Based on these concepts, bandpass and bandstop frequency-tuned filters were realized. These filters differ from the known ones with their wide bandwidth and high quality factor Q, which remains stable under filter electromechanical control.

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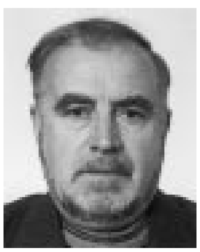

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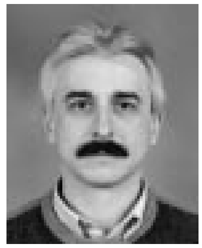

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