UDC 621.382

«QUADRUPOLE» MODE DR FILTER FOR C-BAND APPLICATIONS

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The possibility of reducing the radiation loss of dielectric resonator (DR) to the external environment has been investigated for the first time by applying higher order mode of DR, namely “quadrupole” type, with higher Q factor. The “quadrupole” mode for constructing narrow band-pass filter (<1%) has been studied. The resonant frequencies of dielectric resonator have been calculated on grounds of approximate analytical method as well as finite element method. The coupling coefficients of the rectangular DR with coplanar line have been scrutinized both as a function of the glass substrate’s height, namely b_s, on which the DR is situated, and as a function of the DR’s displacement toward the center line, namely y_0. The synthesized two-resonator band-pass filter has the improved gain slope. The minimum value of insertion loss at the central frequency of 5.9 GHz is -2.4dB, the shape factor is equal to 3.45.

Introduction

Dielectric resonators are made of materials with high values of dielectric constant, low dissipative losses and temperature coefficients. They are widely used for constructing frequency-selective devices, since they provide significant advantages, like higher Q-factor, lower dissipation losses, a steeper gain slope at the edges of the passband etc. In most cases, the feature of energy accumulation inside the material itself is determined by the index of relative dielectric constant: the higher value of this index, the less radiation occurs in external environment [1].

Despite these modern technologies allow producing DRs with large indices of relative permittivity (of about 100), the Q factor of DRs, made of such dielectrics, often decreases due to the increase of dissipation effect of the material loss in the dielectric in microwave frequencies. The usage of materials with reduced dielectric constant is accompanied by growth in radiation loss from the DR to an external environment as well as interaction between the accumulated field in the resonator and structural elements. In order to reduce the above mentioned impact the idea of higher order oscillation modes of DR with higher Q factor is proposed, characterized by high concentration of accumulated field.

The term “higher modes” of DR implies that the electro-magnetic modes with a large amount of half-waves are confined in the dielectric volume, compared with the lowest type of oscillation. It is assumed that the number of mentioned half waves isn’t too large. Thus, the utilization of “higher modes” of DR is considered to increase slightly the size of the structure compared with the main mode, namely $TE_{01\delta}$.

Statement of the problem

The purpose of this study is to investigate the possibility of using of the highest mode of the DR, namely “quadrupole” type, in order to increase the unloaded quality factor, while maintaining an acceptable level of coupling coefficient with the transmission line, as well as the construction of a band-pass filter with improved frequency response slope on the DRs. The transmission line selected for this research is coplanar line. The investigation techniques include numerical and analytical methods for solving Maxwell's equations in order to find the solution to the problem of wave scattering of coplanar transmission line from the DR as well as the problem of filters’ computations with the DR with higher oscillation modes.

“Quadrupole” oscillation mode

The urgency of DR with a rectangular cross-section involves the presence of additional parameters of freedom, comparing to spherical or cylindrical DRs, that allows more flexible choosing of corresponding dimensions while maintaining the appropriate values of Q-factor and bandwidth. It is commonly known that there is no accurate single-wave solution of the boundary conditions for both rectangular and cylindrical DRs [2]. In order to calculate the eigen frequencies of the DR the dielectric waveguide model of the respective cross-section [3,4]has been used.

An approximate solution to the problem of eigen modes is usually examined by submitting the field in the resonator in the form of a standing wave of H- and E- modes in rectangular waveguide, that does not account for the higher oscillation modes. Frequency calculating error of the main magnetic oscillation mode constitutes approximately 5%.

The technique proposed in [5] was used to account for both basic and higher oscillation modes. The field of eigen oscillation mode was obtained in the form of five-component exponentially decaying solutions of Maxwell's equations in the rectangular coordinate system. The fields of eigen oscillation modes outside the dielectric prism were assumed to decay exponentially as the distance increases from the surface of the resonator.

Figure 1 shows the distribution of electro-magnetic field (EMF) of $TE_{21\delta}$ oscillation mode for the DR, characterized by a height *L*, width a_0 and depth b_0. The depicted oscillation mode at fig. 1 is a magnetic quadrupole that resembles two magnetic dipoles excited in opposite phase.

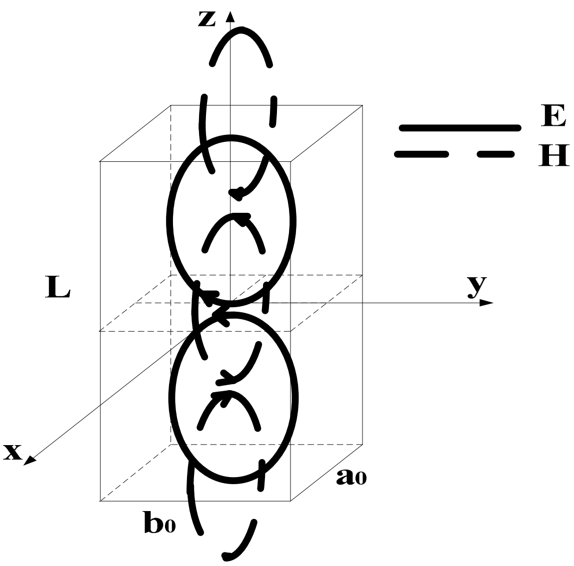


Fig.1. Distribution of electro-magnetic field of $TE_{21\delta}$ oscillation mode

Considering the electric field vectors are tangential and the magnetic are normal to the sidewalls, the Maxwell equations acquire the following form:

$$e_x^{(1)} = \frac{h_1 i\omega\mu_0\beta_z}{k_1^2-\beta_y^2}\cdot\cos\beta_x x\cdot\sin\beta_y y\cdot\cos\beta_z z,$$

$$e_z^{(1)} = \frac{h_1 i\omega\mu_0\beta_x}{k_1^2-\beta_y^2}\cdot\sin\beta_x x\cdot\sin\beta_y y\cdot\sin\beta_z z,$$

$$e_y^{(1)} = 0, \qquad (1)$$

$$h_x^{(1)} = -\frac{h_1\beta_x\beta_y}{k_1^2-\beta_y^2}\cdot\sin\beta_x x\cdot\cos\beta_y y\cdot\sin\beta_z z,$$

$$h_z^{(1)} = \frac{h_1\beta_y\beta_z}{k_1^2-\beta_y^2}\cdot\cos\beta_x x\cdot\sin\beta_y y\cdot\sin\beta_z z,$$

$$h_y^{(1)} = h_1\cdot\cos\beta_x x\cdot\sin\beta_y y\cdot\sin\beta_z z,$$

where $\beta_x, \beta_y, \beta_z$ are wave propagation numbers in the *x*-, *y*- and *z*- directions.

By matching the fields at the boundary conditions, the eigen frequencies are obtained from the following transcendental equation:

$$\beta_y\cdot ctg\left(\beta_y\frac{b_0}{2}\right) = \beta_{0y}, \qquad (2)$$

Based on transcendental equation (2) the normalized frequency dependencies [6] as a function of DR's dimensions have been received and shown at fig.2. Hence, the following dimensions of DR are chosen: $a_0 = 7mm, b_0 = 7mm, L = 15mm$ and $\varepsilon_r = 36$.

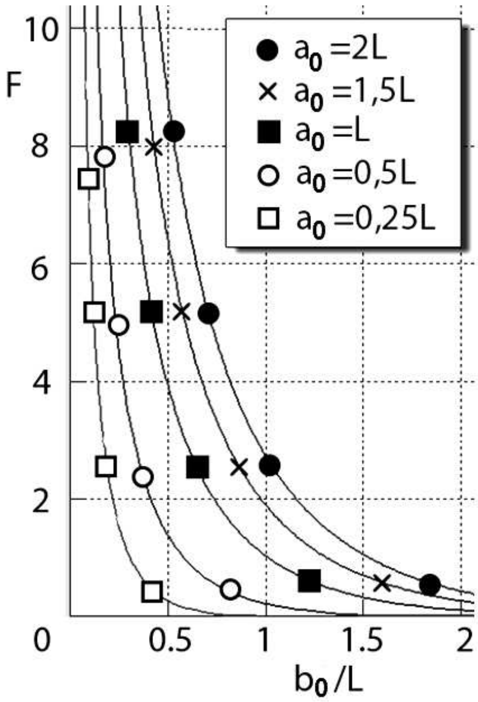
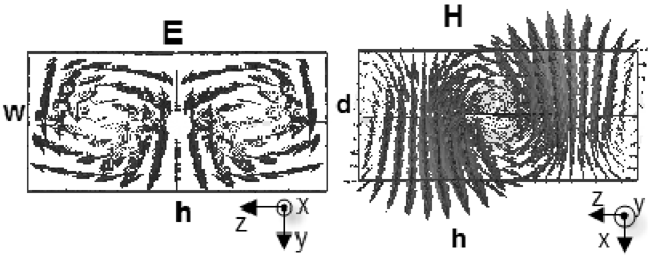


Fig.2. Normalized resonant frequency of the rectangular DR

In order to provide more accurate electrodynamic analysis of eigen oscillation modes of the dielectric resonators the finite element method has been applied, implemented in CAD software HFSS. The result of numerical simulation of the resonance frequency, namely $f_{0\_HFSS} = 5.58$ GHz, shows good agreement with the calculated one according to (2) and makes up $f_{0\_calc} = 5.69$ GHz. The error is 1.9%.

At figure 3 the distribution of electro-magnetic field of $TE_{21\delta}$ oscillation mode at frequency of 5.58 GHz is shown according to the numerical method of computation.



a) b)

Fig.3. Distribution of electro (a) and magnetic (b) fields of $TE_{21\delta}$ at frequency of 5.58 GHz

DR with the “quadrupole” oscillation mode in a coplanar transmission line

Figure 4 illustrates a structure that consists of the DR, disposed on the glass substrate. The last one is placed on a coplanar transmission line. The whole structure is enclosed in a rectangular metal cavity. The geometric dimensions and other parameters of the structure are shown in Table. 1.

Table 1. Parameters of the structure of DR with the $TE_{\delta 21}$ oscillation mode in a coplanar transmission line

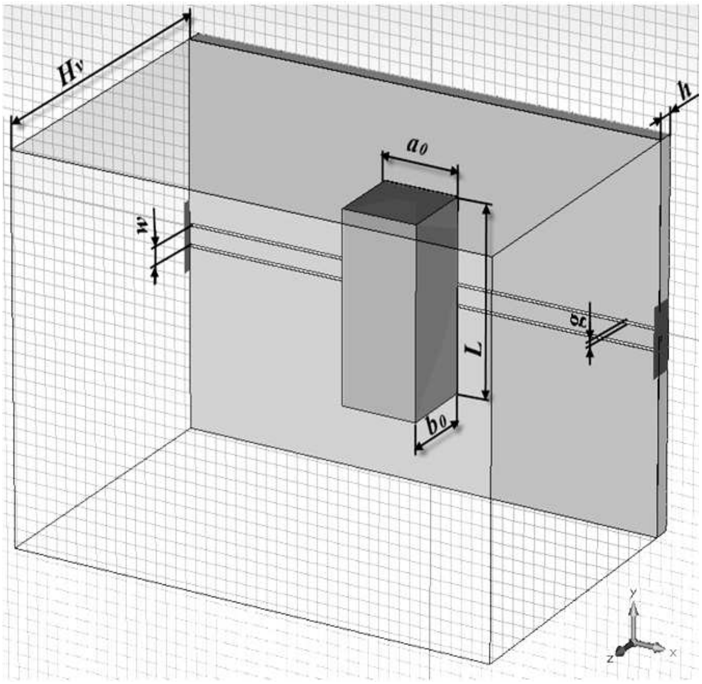
Name	Param.	Value, mm	Material
DR	$a_0;b_0;L$	7; 7; 15	Dielectric (Ɛ=36; tgδ=$5*10^{-4}$)
CPW	$w;g;h$	1,4;0,2; 1,6	FR-4 (Ɛ=4,3; tgδ = 0,025)
	t	0,035	Copper (γ=$5,8*10^{7}$Sm/m;μ=1)
Vac. box	H_v	28	Vacuum (Ɛ=1; μ=1)
Subs. under DR	b_s	0,1	Glass (Ɛ=2,5; tgδ=0,002)

where t denotes the thickness of metallization of coplanar transmission line;

“CPW” stands for coplanar transmission line;

“Vac. box” designates the vacuum box;

“Subs.” signifies the substrate with thickness b_s.



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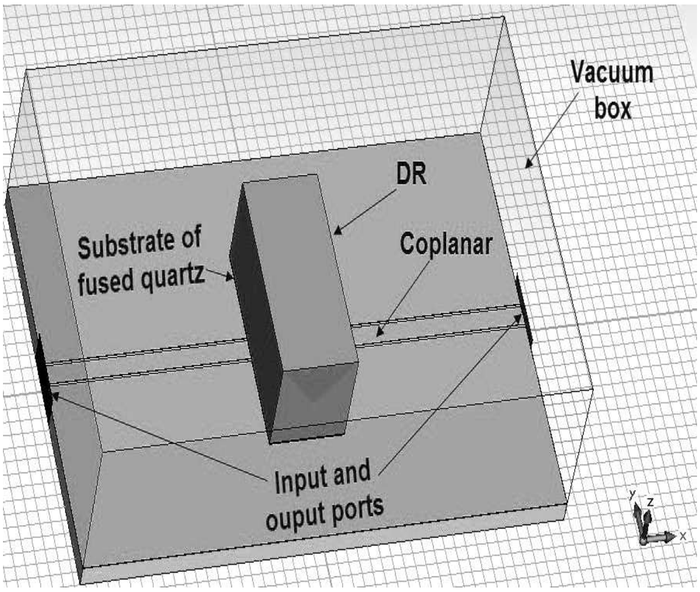


b)

Fig.4. The dimensions (a) and general view (b) of the simulated DR with the $TE_{21\delta}$ oscillation mode in a shielded coplanar transmission line

Figure 5 shows the calculated S-parameters of the structure, according to which the frequency of the $TE_{21\delta}$ oscillation mode is equal to 5.97 GHz. The adjacent parasitic modes of DR are separated from the operating one for 0.63 GHz ($f_l = 5.34$ GHz) and 1.17 GHz ($f_r = 7.13$ GHz).

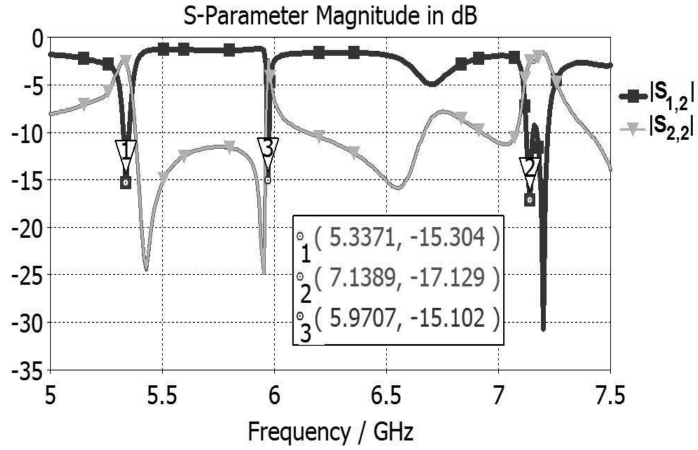
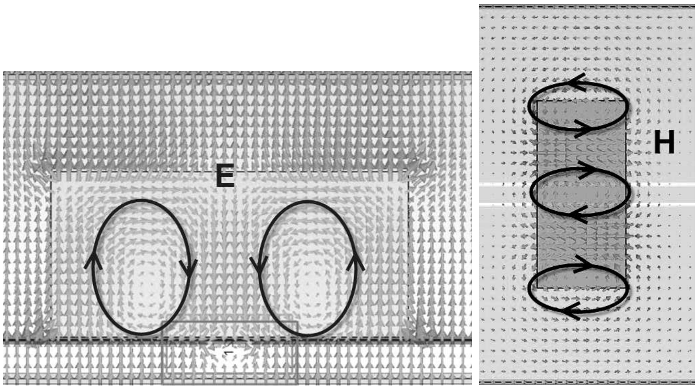


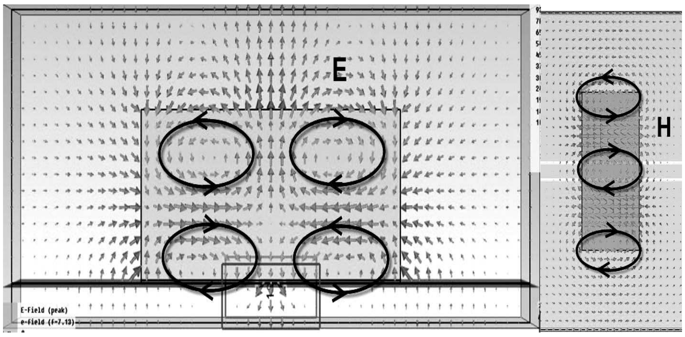
Fig.5. S- parameters of the structure

Fig. 6 and 7 show the distribution of EMF of adjacent parasitic modes of DR.



a) b)

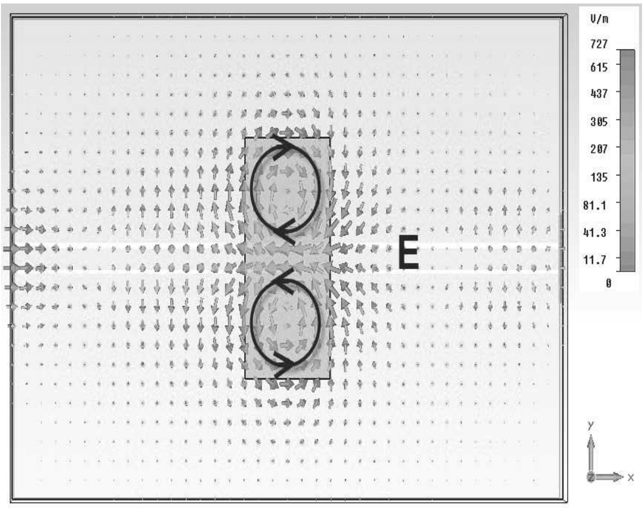
Fig. 6. Distribution of electro (a) and magnetic (b) fields of left adjacent parasitic mode at frequency of 5.34 GHz



a) b)

Fig. 7. Distribution of electro (a) and magnetic (b) fields of right adjacent parasitic mode at frequency of 7.13 GHz

Fig. 8 illustrates the structure of the electromagnetic field of the “quadrupole” oscillation mode at frequency of 5.97 GHz.



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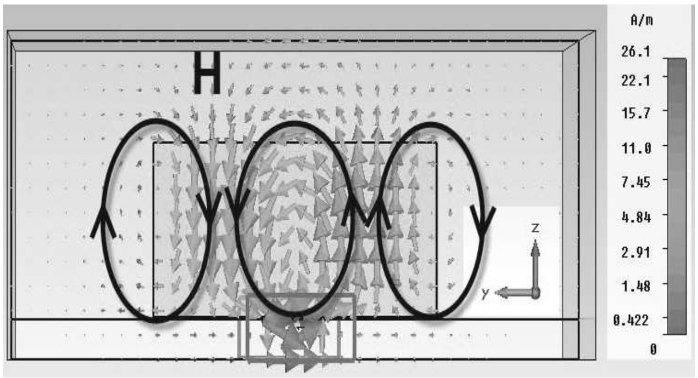


b)

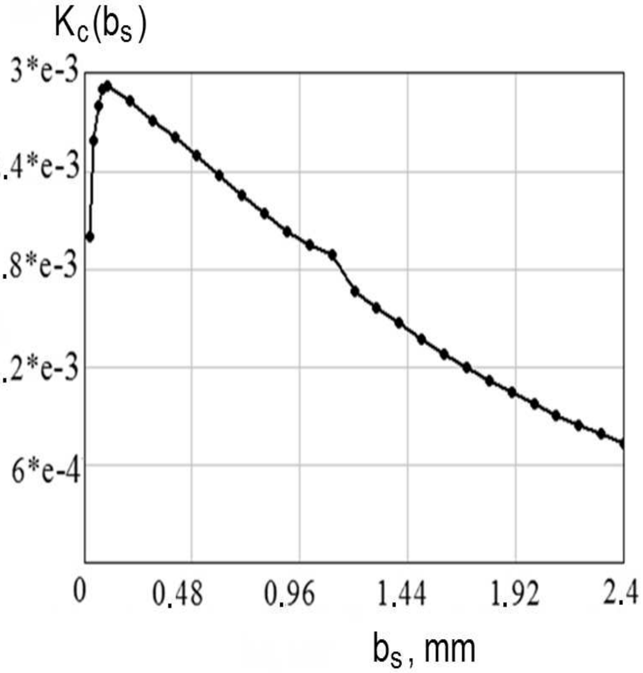
Fig.8. Distribution of EMF of $TE_{21\delta}$ at 5.97 GHz

The construction, shown in fig. 4, has been used for the calculation of the coupling coefficients between the transmission line and the DR [7]. The excitation of DR is carried out by the field of coplanar transmission line [8]. It was assumed that the DR is located on a glass substrate with a thickness of b_s.

Calculation of the coupling coefficients is accomplished using the formula [1]:

$$K_c = tg\delta * (10^{-|S_{2,1}|/20} - 1), \qquad (3)$$

where $tg\delta$ =0.0005 is the loss tangent of dielectric; $|S_{2,1}|$ - coefficient of transmission in dB.



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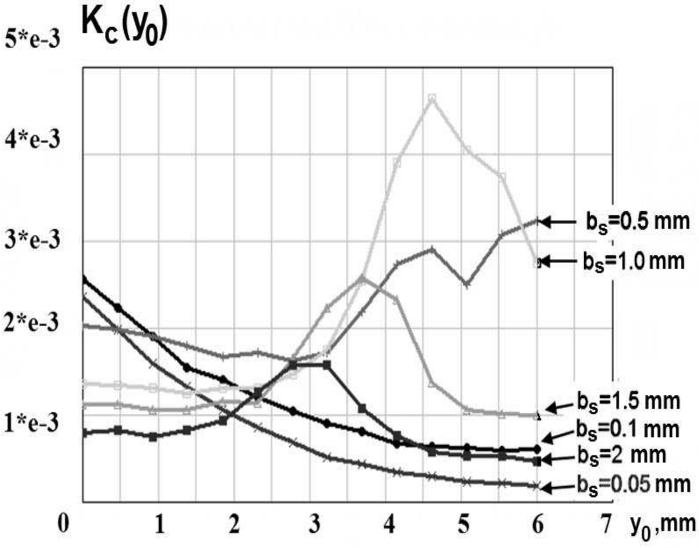

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Fig. 9. Coupling coefficients of DR with the coplanar transmission line as a function of substrate's height *bs* (a) and displacement from the centerline y_0 (b)

The coupling coefficients were calculated for the values of b_s, varying in the range [0.01; 2.4] mm with step 0.1 mm. From fig. 9a it is clear that the peak of the coupling is obtained when b_s is equal to 0.1mm and makes up about 2.9 $*10^{-3}$. The further increase in the height of the glass substrate leads to a gradual reduction of the coupling coefficient.

Coupling coefficients of DR with the coplanar transmission line have been studied as a function of displacement from the centerline y_0 (Fig. 4a) for a range of substrate's height b_s, namely [0.05; 2.0] mm. As it can be seen from the Fig. 9b, the maximum coupling is achieved with the symmetrical placement of DR at the current-carrying strip line, i.e. when y_0 equals 0 mm. It should be noted that the value of y_0 = 0 mm corresponds to the unshifted position of DR, while y_0 = 7 mm corresponds to the maximum possible displacement of the center DR in a rectangular shielding cavity.

Thus, in order to increase the unloaded Q-factor, while maintaining the acceptable value of the coupling coefficient the following values of the substrate's height and displacement from the centerline were chosen, namely b_s equals 0.1 mm and y_0 is 0 mm.

Band-pass filter with "quadrupole" oscillation mode of DRs

Fig. 10 depicts the structure of the two-resonator band-pass filter with an operating oscillation mode of $TE_{21\delta}$. Two resonators with the dimensions of $a_1 = b_1 =$

7 mm; $a_0 = b_0 = 7$ mm and $L_1 = L_0 = 15$ mm are located on a glass substrate with thickness of $b_s = 0{,}1$ mm. The distance *dz* between two resonators equals 2mm.

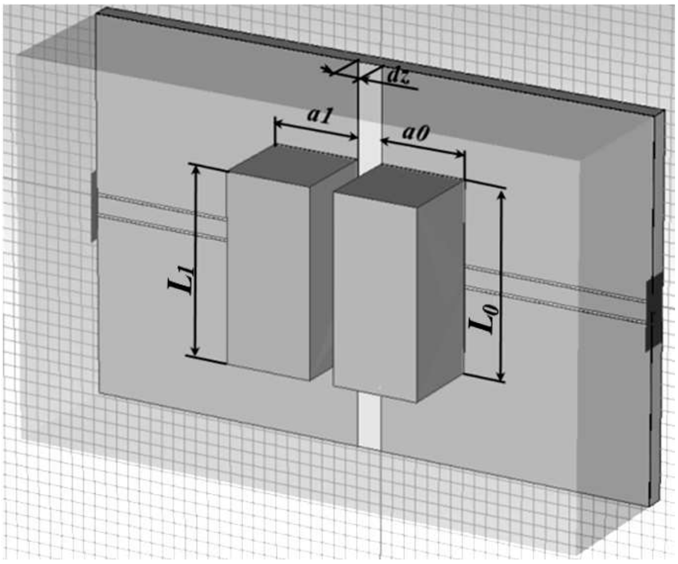
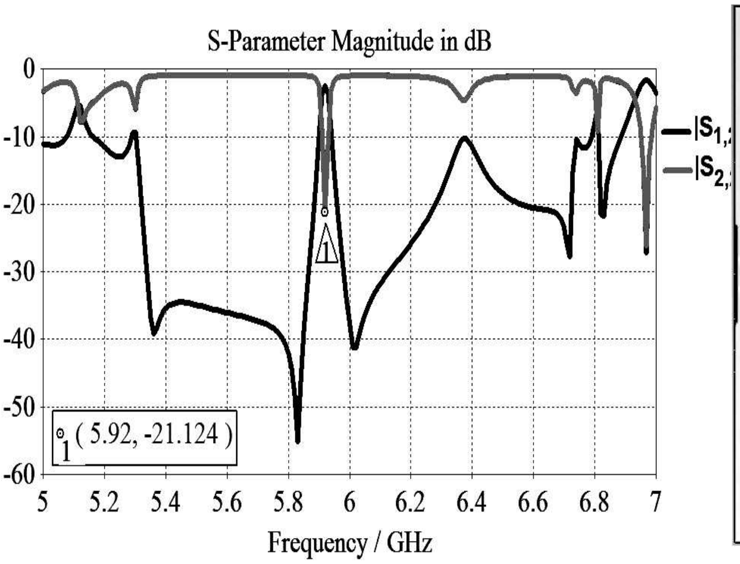


Fig. 10. 3D view of the band-pass filter with "quadrupole" oscillation mode of DRs

Quality indices of band-pass filter are depicted at Fig. 11. In order to provide a better suppression of the nearest neighboring components the following approach was used. The dimensions of one DR (Fig. 10), namely a_1 and b_1 have been varied, while the resonant frequency of it stayed the same, namely 5.9 GHz. However, such measure allowed only slightly suppressing of parasitic components whilst the separation from the operating $TE_{21\delta}$ has decreased with the significant deterioration of $|S_{2,1}|$ at the resonance frequency.



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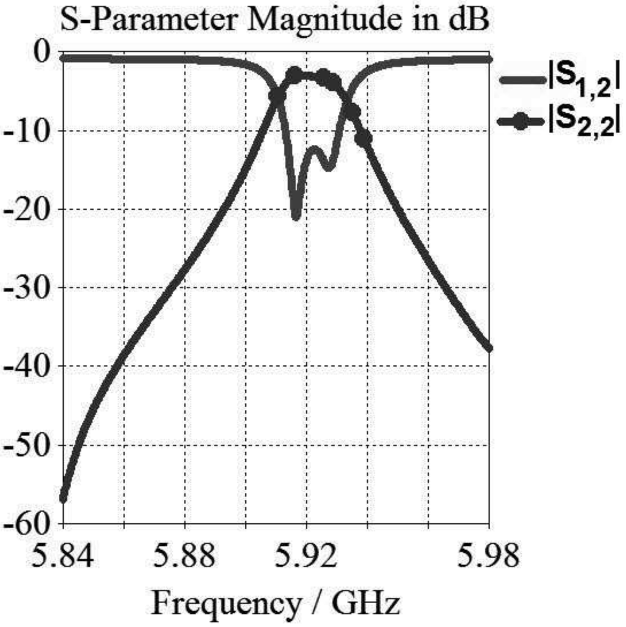

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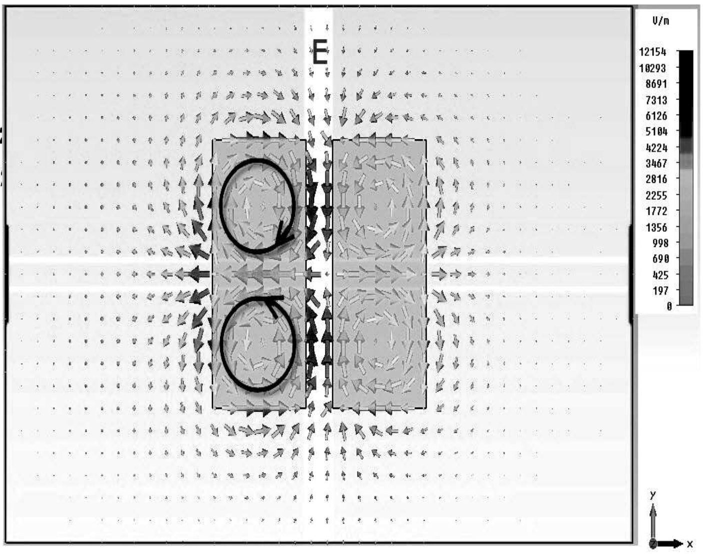
Fig. 11. S-parameters of the band-pass filter with "quadrupole" oscillation mode of DRs

Thus, the minimum amount of insertion loss at the center frequency of 5.9 GHz is equal to -2.4 dB, the bandwidth of band-pass filter at the level of -6dB makes up 0.72% and the shape factor constitutes 3.45.

Electromagnetic field distribution of the band-pass filter with “quadrupole” mode of two DRs is shown at Figure 12. According to it the excitation field, accumulated in the left DR, excites the right DR at 5.9 GHz.



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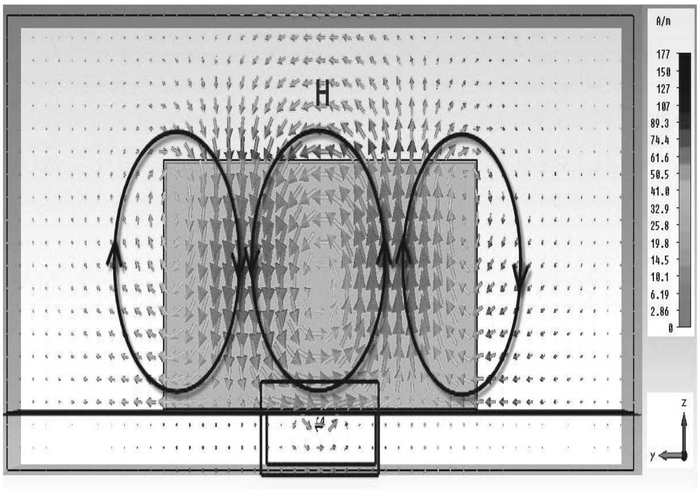

b)

Fig.12. Distribution of electro (a) and magnetic (b) fields of band-pass filter with $TE_{21\delta}$ oscillation mode of DRs at resonant frequency of 5.97 GHz

Table. 2 provides the comparison of quality indices of band-pass filter under research and of two filters from [9], in which the rectangular DRs are placed in rectangular waveguide and operate on the lowest oscillation mode, namely $TE_{11\delta}$.

Table 2. The comparison of quality indices of the developed band-pass filter and the ones from [9]

Parameter	[9]	This work	[9]
f_0, GHz	3	5,92	9
Δf	2,3%	0,72%	0,78%
N	3	2	4
Mode	$TE_{11\delta}$	$TE_{21\delta}$	$TE_{11\delta}$

where f_0 and Δf are the central resonant frequency and the bandwidth correspondingly;

N is the number of resonators.

Thus, the proposed band-pass filter with $TE_{21\delta}$ oscillation mode has a narrower bandwidth (0.72% compared to 0.78% [9]) and utilizes fewer resonators (two against four [9]) comparing to band-pass filter, operating at the lower oscillation mode $TE_{11\delta}$. However, the disadvantage of the proposed structure of band-pass filter is denser spectrum of spurious products, allocated near the $TE_{21\delta}$ operating mode.

Conclusion

1. Using the finite element technique for "quadrupole" oscillation mode the resonant frequencies of rectangular DR have been computed and studied.

2. The "quadrupole" mode has been investigated for the first time. It is characterized by a high concentration of accumulated field near the resonator and provides the improvement of band-pass filter's gain slope.

3. The coupling coefficients of DR with the coplanar transmission line have been investigated as a function of substrate's height b_s and displacement from the centerline y_0. The optimal values were chosen, namely b_s equals 0.1 mm and y_0 is 0 mm.

4. The two-resonator band-pass filter with rectangular DRs is proposed that operates on magnetic quadrupole oscillations mode, thus, having an improved gain slope. The minimum value of insertion loss at the central frequency of 5.9 GHz equals -2.4dB, the shape factor is 3.45.

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Received in final form on May 15, 2013