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MULTI-RESONATOR DUAL-BAND FILTERS ON DIELECTRIC RESONATORS

Tatyana V. Pidhurska
National Technical University of Ukraine “KPI”, Kyiv, Ukraine

In the current article the concept of multi-resonator dual-band filter has been described. The dual-band filters based on three and four rectangular dielectric resonators have been synthesized that functionate in $TE_{01\delta}$ and $TE_{02\delta}$ modes. The proposed construction benefits since it doesn’t have additional coupling elements or DR shape complication. The analytical model of dual-band filter has been developed that accounts for two bands simultaneously. The accuracy of the proposed model is verified by the simulation results obtained by applying finite element method and shows insignificant disagreement. The proposed dual-band filter can be applied for satellite systems that require the transmission of several non-contiguous frequency channels in the one beam.

Introduction

With the movement to the mm-wave range [1], the high Q resonator filters are of great importance, particularly on dielectric resonators, since they pro-vide better in-band selectivity.

In order to provide several frequency bands simultaneously the multiband band-pass filters have got a growing attention for satellite and mobile communications [2]. The actual importance of dual-band filter development on dielectric resonators (DR) is this three-dimensional cavity-type of resonators which ensure high unloaded quality factor and consequently lower in-band losses [3]. The drawbacks of the existing constructions include the complication shape of DR as well as additional coupling elements that generally complexify the analytical model of the filter [4], [5] as well as increase the weight and size parameters.

In [6] the dual-band filter design has been researched, operating in lower mode $TE_{01\delta}$ as well as higher $TE_{02\delta}$ [7] mode of rectangular DR. The electromagnetic field distribution of $TE_{02\delta}$ resembles two magnetic dipoles, exited in antiphase, thus providing higher unloaded quality factor.

Statement of the problem

The aim of the article is to synthesize multi-resonator dual-band filter, particularly on three and four resonators while applying the proposed concept [6], namely: by using elongated rectangular DRs with square cross-section, operating in $TE_{01\delta}$ and $TE_{02\delta}$ oscillating modes with approximately equal coupling coefficients. The applied methods include: numerical, realized in the software HFSS [8], analytical [9] that implies the development of analytical scattering model of the filter.

Main part

The construction of three-resonator filter consists of rectangular dielectric resonators, the coaxial lines that are connected to the central conductors, which excite the resonators in $TE_{01\delta}$ and $TE_{02\delta}$ modes. In fig.1 the simulation model of the filter has been illustrated solved by applying finite element method (FEM).

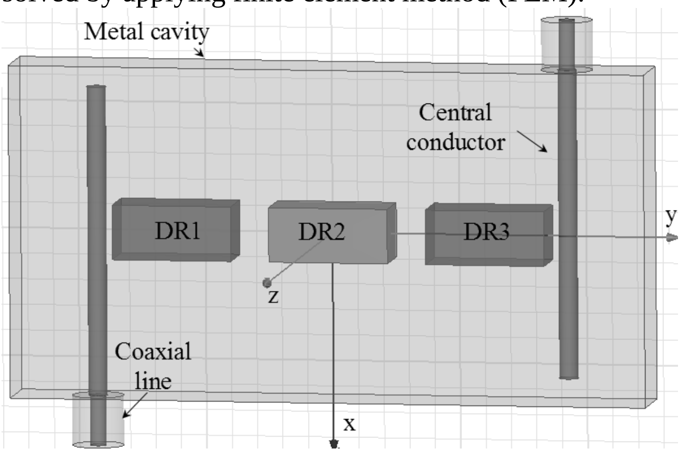

Fig.1. Construction of dual-band filter on three DR

The frequency offset between central frequencies can be tuned by varying the length of DR.

By applying the numerical method to the EMW scattering problem on the system of three resonators the following wide-band amplitude-frequency response (AFR) of dual-band filter has been depicted in fig.2.

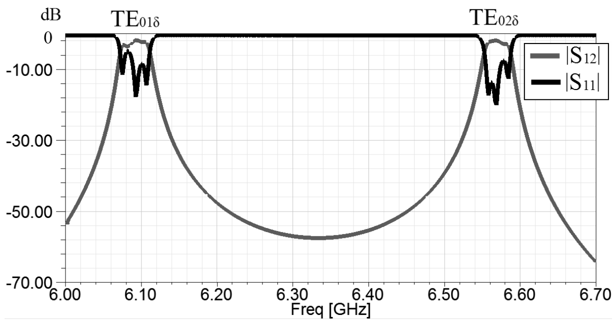

Fig.2 Wideband AFR of dual-band filter based on three DR with the dimensions: $4.26 \cdot 4.26 \cdot 9.33$ mm,

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manufactured from the material $\varepsilon_r = 80$, $tg\delta = 5\cdot 10^{-4}$ and placed in metal cavity with dimensions $26\cdot 50\cdot 5.5$ mm

The analytical scattering model of the three-resonator filter has been developed, that accounts for the behavior of scattering parameters of the three-DR system (fig. 1) in the resonance region [9], enabling to calculate the frequency dependences of both transmission $T_1(f)$ and reflection $R_1(f)$ coefficients in each band:

$$T_1(f) = \sum_{j=1}^{2} \frac{-2\cdot Q_D}{4k_{12\_j}\cdot\lambda_{1\_j} - 4k_{12\_j}\cdot\lambda_{3\_j}} \times \left(\frac{2\tilde{k}_{11\_j}\cdot k_{12\_j}\cdot\lambda_{1\_j}}{Q_{1\_j}(f)} + \frac{2\tilde{k}_{11\_j}\cdot k_{12\_j}\cdot\lambda_{3\_j} - 2\tilde{k}_{11\_j}\cdot k_{12\_j}\cdot\lambda_{1\_j}}{Q_{2\_j}(f)} - \frac{2\tilde{k}_{11\_j}\cdot k_{12\_j}\cdot\lambda_{3\_j}}{Q_{3\_j}(f)} \right), \quad (1)$$

$$R_1(f) = 1 - \sum_{j=1}^{2} \frac{-2\cdot Q_D}{4k_{12\_j}\cdot\lambda_{1\_j} - 4k_{12\_j}\cdot\lambda_{3\_j}} * \left(\frac{2k_{11\_j}\cdot k_{12\_j}\cdot\lambda_{1\_j}}{Q_{1\_j}(f)} + \frac{2k_{11\_j}\cdot k_{12\_j}\cdot\lambda_{1\_j} - 2k_{11\_j}\cdot k_{12\_j}\cdot\lambda_{3\_j}}{Q_{2\_j}(f)} - \frac{2k_{11\_j}\cdot k_{12\_j}\cdot\lambda_{3\_j}}{Q_{3\_j}(f)} \right),$$

where Q_D - Q-factor of dielectric ,

$\tilde{k}_{11\_j}$ – coupling coefficient between the transmission line and DR in j-th operating mode,

k_{12_j}, k_{13_j} – are the cross-coupling coefficients between the first and second DR as well as first and third DR correspondingly in j-th operating mode.

f_{0_j} – the resonance frequency of j-th operating mode;

$$\lambda_{m\_j} = 0.5\cdot\left(i\cdot\tilde{k}_{11\_j} + k_{13\_j}\right) \pm 0.5\cdot\sqrt{d},$$

$\lambda_{2\_j} = i\cdot\tilde{k}_{11\_j} - k_{13\_j}$ - j-th eigenvalues of the coupling operator,

$m = 1{,}3$; $d = \left(i\cdot\tilde{k}_{11\_j} + k_{13\_j}\right)^2 + 8k_{12\_j}^2$,

i – imaginary unit;

$$Q_{n\_j}(f) = \frac{f}{f_{0\_j}} + 2iQ_D\left(\frac{f}{f_{0\_j}} - 1 - \frac{\lambda_{n\_j}}{2}\right),$$

$n = 1{,}2{,}3$.

The coupling coefficients have been calculated for each band according to the results, reported in [9], namely:

$\tilde{k}_{11\_1} = 2.67\cdot 10^{-3}, \tilde{k}_{11\_2} = 2.75\cdot 10^{-3}$,

$k_{12\_1} = 4.41\cdot 10^{-3}, k_{12\_2} = 3.25\cdot 10^{-3}, k_{13\_1} = 5\cdot 10^{-7}$

$k_{13\_2} = 5\cdot 10^{-7}$.

In [10] the coupling coefficients' dependencies have been also researched, namely the coupling parameters between DR and transmission line as well as the cross-coupling coefficients. Moreover, the optimal conditions for the equal alteration of coupling coefficients have been determined that ensure the two bands of the filter.

In fig.3 (a,b) the AFR of dual-band filter calculated by applying two methods, namely FEM and analytical one (1), have been depicted. The phase frequency responses (PFR) have been also illustrated in fig.3 (c,d).

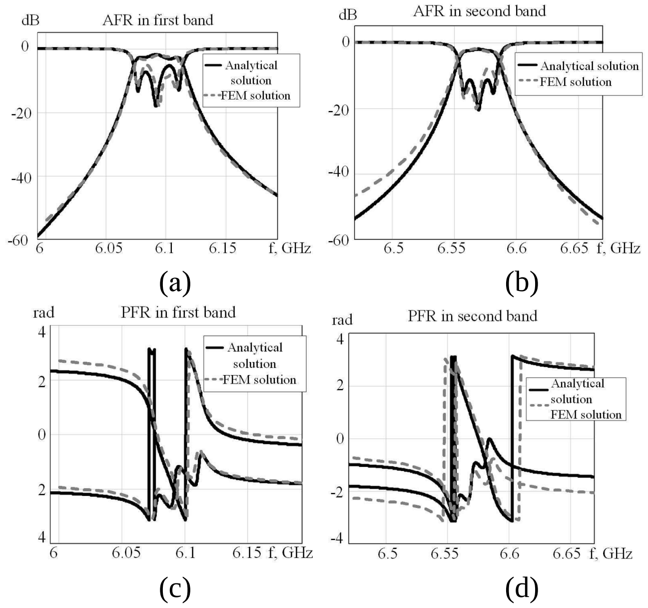

Fig.3 AFR of 3-resonator dual-band filter in each band calculated according to analytical (1) and FEM [8] approaches

According to fig.2, the computed numerical and analytical dependencies have modest disagreement in each band of the filter. This occurs due to the fact that HFSS software environment accounts for the boundary conditions of the construction as well as the effect of non-resonance propagation whilst the presented analytical model considers solely the resonant scattering of electromagnetic wave (EMW) on the system of DR.

From fig. 3 the -3dB level fractional bandwidth of the first passband ($TE_{01\delta}$ mode) is 0.68% at the center frequency of 6.09 GHz with the insertion loss of 1.8 dB while the -3dB level fractional bandwidth of the second passband ($TE_{02\delta}$ mode) is 0.5% at the center frequency of 6.58 GHz with the insertion loss of 2dB in the band. Out-of-band rejection between passbands is about 60dB. The spurious product is located at 7.41GHz.

The four-resonator band-pass filter has been also synthesized. In fig.4 the simulation model of the filter has been illustrated solved by applying finite element method.

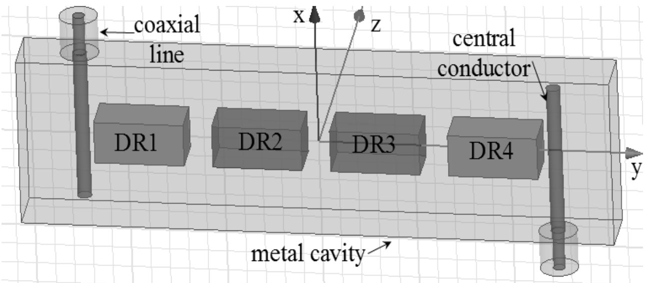

Fig.4. Construction of dual-band filter on four DR

As follows from the numerical solution of the EMW scattering from the four-resonator system the following wideband AFR of dual-band filter has been calculated as indicated in the fig.5.

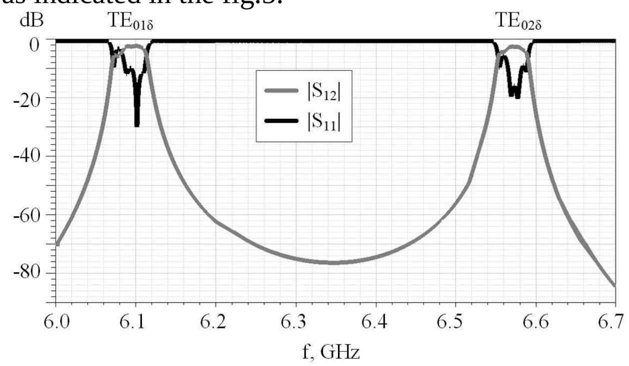

Fig.5 Wideband AFR of dual-band filter based on four DR with the dimensions: $4.26 \cdot 4.26 \cdot 9.33$ mm, manufactured from the material $\varepsilon_r = 80,\ tg\delta = 5 \cdot 10^{-4}$ and placed in metal cavity with dimensions $20 \cdot 62 \cdot 5.5$ mm

As follows from [9] the analytical scattering model of the DRs' system implies the successive determination of both the eigenvalues and eigenvectors of coupling operator, afterwards handling the scattering problem of EMW on the DR system.

In view of awkwardness of the four-resonator filter's analytical model the scattering coefficients have been written in the matrix form through the eigenvectors of coupling operator. The derived eigenvectors for the coupling operator matrix can be given for each band as:

$$B = \begin{pmatrix} 1 & 1 & 1 & 1 \\ \frac{-\left(i \cdot \tilde{k}_{11} - \lambda_1 + k_{14}\right)}{k_{12} + k_{13}} & \frac{-\left(i \cdot \tilde{k}_{11} - \lambda_3 - k_{14}\right)}{k_{12} - k_{13}} & \frac{-\left(i \cdot \tilde{k}_{11} - \lambda_4 - k_{14}\right)}{k_{12} - k_{13}} & \frac{-\left(i \cdot \tilde{k}_{11} - \lambda_2 + k_{14}\right)}{k_{12} + k_{13}} \\ \frac{-\left(i \cdot \tilde{k}_{11} - \lambda_1 + k_{14}\right)}{k_{12} + k_{13}} & \frac{-\left(i \cdot \tilde{k}_{11} - \lambda_3 - k_{14}\right)}{k_{12} - k_{13}} & \frac{-\left(i \cdot \tilde{k}_{11} - \lambda_4 - k_{14}\right)}{k_{12} - k_{13}} & \frac{-\left(i \cdot \tilde{k}_{11} - \lambda_2 + k_{14}\right)}{k_{12} + k_{13}} \\ 1 & -1 & -1 & 1 \end{pmatrix},$$

where eigenvalues of coupling operator are defined as:

$$\lambda_{1,2} = \frac{\left(k_{12} + i \cdot \tilde{k}_{11} + k_{14}\right) \pm \sqrt{\left(k_{12} + i \cdot \tilde{k}_{11} + k_{14}\right)^2 - 4 \cdot \left(k_{12}\left(i \cdot \tilde{k}_{11} + k_{14}\right) + \left(k_{12} + k_{13}\right)^2\right)}}{2},$$

$$\lambda_{3,4} = \frac{\left(k_{12} + i \cdot \tilde{k}_{11} - k_{14}\right) \pm \sqrt{\left(k_{12} + i \cdot \tilde{k}_{11} - k_{14}\right)^2 + 4 * \left(k_{12}\left(i \cdot \tilde{k}_{11} - k_{14}\right) + \left(k_{12} - k_{13}\right)^2\right)}}{2}$$

k_{14} - the cross-coupling coefficient between the first and fourth DR.

By providing summation for each operational band the scattering parameters of dual-band filter on four resonators can be found as:

$$T_2(f) = \sum_{j=1}^{2} \left(\frac{-2 \cdot Q_D}{|B|} \cdot \sum_{t=1}^{4} \frac{|A_t|}{Q(f)_t} \right)_j, \tag{3}$$

$$R_2(f) = 1 - \sum_{j=1}^{2} \left(\frac{2 \cdot Q_D}{|B|} \cdot \sum_{t=1}^{4} \frac{|L_t|}{Q(f)_t} \right)_j,$$

where $t = 1,2,3,4$ since there are four resonators, matrices $|A_t|$, $|L_t|$ are defined through the elements of eigenvector matrix B:

$$A_t = \begin{pmatrix} b_{00} & \cdots & \tilde{k}_{11} \cdot b_{3t} & \cdots & b_{03} \\ b_{10} & \cdots & 0 & \cdots & b_{13} \\ b_{20} & \cdots & 0 & \cdots & b_{23} \\ b_{30} & \cdots & 0 & \cdots & b_{33} \end{pmatrix}, \quad L_t = \begin{pmatrix} b_{00} & \cdots & \tilde{k}_{11} * b_{0t} & \cdots & b_{03} \\ b_{10} & \cdots & 0 & \cdots & b_{13} \\ b_{20} & \cdots & 0 & \cdots & b_{23} \\ b_{30} & \cdots & 0 & \cdots & b_{33} \end{pmatrix},$$

where $\begin{pmatrix} \tilde{k}_{11} \cdot b_{3t} \\ 0 \\ 0 \\ 0 \end{pmatrix}$, $\begin{pmatrix} \tilde{k}_{11} \cdot b_{0t} \\ 0 \\ 0 \\ 0 \end{pmatrix}$ substitute the t-th column of the matrix A_t correspondingly

$$Q(f)_t = \lambda_t \cdot Q_D + \frac{f}{f_0} + 2i \cdot Q_D \cdot \left(\frac{f}{f_0} - 1 \right).$$

The following coupling coefficients have been calculated for each band according to [9]:

$$\tilde{k}_{11\_1} = 3.36 \cdot 10^{-3}, \tilde{k}_{11\_2} = 2.77 \cdot 10^{-3},$$

$$k_{12\_1} = 4.7 \cdot 10^{-3}, k_{12\_2} = 3.27 \cdot 10^{-3},$$

$$k_{13\_1} = 1 \cdot 10^{-4}, k_{13\_2} = 1 \cdot 10^{-4},$$

$$k_{14\_1} = 1 \cdot 10^{-6}, k_{14\_2} = 1 \cdot 10^{-6}.$$

According to the chosen coupling coefficients the AFR of dual-band filter by applying FEM has been compared with the AFR based on analytical model (3) in fig.6 (a,b). The PFR of $|S_{21}|$ in each band have been illustrated in fig.6 (c,d).

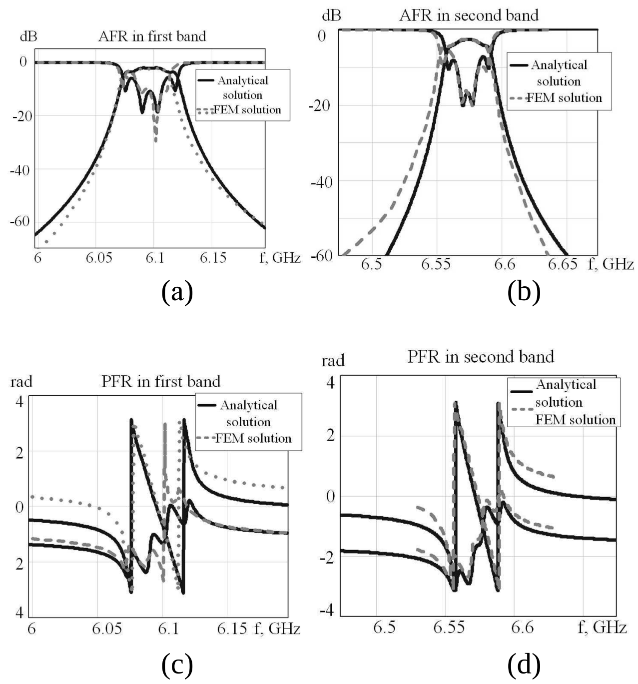

Fig.6 AFR of 4-resonator dual-band filter in each band calculated according to analytical (3) and FEM approaches [7]

According to fig.6, the computed numerical and analytical dependencies have modest disagreement in each band due to the effect of non-resonance scattering that is not accounted by the analytical model. Nevertheless, the applied analytical method is considerably more accurate comparing with the well-known low-frequency prototype approach, since the first one addresses the resonant properties of the system more precisely.

By summarizing the data from fig. 6, the -3dB level fractional bandwidth of the first passband ($TE_{01\delta}$ mode) is 0.64% at the center frequency of 6.1 GHz with the insertion loss of 2.1dB, while the -3dB level fractional bandwidth of the second passband ($TE_{02\delta}$ mode) is 0.55% at the center frequency of 6.58 GHz with the insertion loss of 2.6 dB. Out-of-band rejection between passbands is about 80 dB. The spurious product is located at 7.57 GHz. The future work might be connected with the synthesis of three-band filter, since the four-resonator BPF has shown that there is one more possible band ($TE_{03\delta}$ mode) at 7.6 GHz, close to the spurious product.

Conclusion

The dual-band multi-resonator filter on rectangular DRs has been synthesized, that operates in $TE_{01\delta}$, $TE_{02\delta}$ oscillation modes. The analytical models based on Maxwell equations have been derived for both three- and four-resonator filters accounting for two frequency bands simultaneously as well as their phase-frequency properties. Compared with the finite element method application the scattering parameters derived by applying analytical model, demonstrates insignificant discrepancy due to the fact that the analytical model doesn't consider the effect of non-resonance propagation. The proposed dual-band filter can be used for satellite systems that require noncontiguous in frequency channels to be transmitted to the ground through one beam.

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