Miniaturized Hairpin Defected Ground Structure Filter Design

Marin Nedelchev, Alexander Kolev

Abstract – **The paper presents research of miniaturized hairpin defected ground structure resonator, corresponding coupling topologies and filter design. The resonance frequency dependence of the resonator according to the length of the coupled linesis investigated. The coupling topologies are simulated in fullwave electromagnetic simulator and the coupling coefficient is derived. Using curve-fitting technique, useful design formulas are proposed for filter synthesis. In order to verify the proposed synthesis procedure, an example filter design is performed. There is a good agreement between the simulated and theoretical results.**

Keywords – **Microstrip, Defected ground resonator, Coupling coefficient, Filter design.**

I. Introduction

The bandpass filters used in modern microwave communication systems have to meet very strict requirements for their performance, size and volume. The manufacturing of such filters has to be alsotechnological and easy for adjustments. Bandpass filters can be realized by cascading or configuring of coupled resonators. Many compact microstrip resonators are reported in the references [1], [2]. Additional degree of freedom in the filter synthesis can be added by introduction of intentionally added slots in the ground plane of the microstrip line. These are also known as defected ground structures (DGS). Defected ground structures can be periodic or non-periodic disturbance in the ground plane of the microstrip line. Their shape can be adopted from microstrip resonators described in [2] and appear to be dual to them.

The usage of halfwave square open loop resonator and miniaturized hairpin type of resonators in DGS is researched in [3]. Mixed combination of microstrip resonator and DGS resonators as building blocks of microwave filters are used in [4]. Both applications of slot resonators are a promising way for adding extra degrees of freedom in filter design. The usage of DGS resonators can solve a substantial problem in microstrip filter design-the minimum gap between coupled lines for realizing strong coupling.

One of the problems facing the wideband and ultra-wideband filters is the realization of very small gaps between the coupled resonators and the fabrication tolerances connected with their manufacturing. The filter response is also affected by the precision of the manufacturing process of the small gaps. By utilizing different shaped slots in the ground plane of the microstrip line-defected ground structures [1]-[3], and [5], it is possible to enhance the coupling coefficient.

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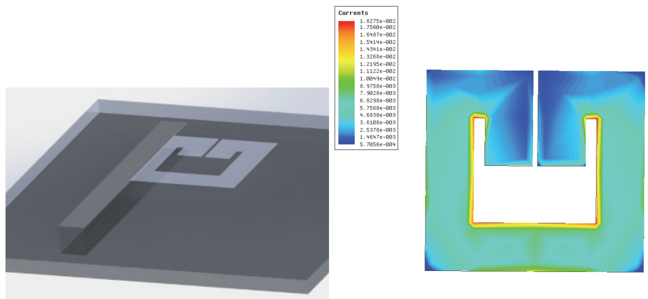
This paper researches miniaturized hairpin DGS resonator and the coupling structures formed by close situated resonator. The resonance frequency of the DGS resonator is investigated and a design formula is proposed. Topologies of coupled DGS resonators are researched and based on the simulations simple formulas are proposed based on curve fitting technique. A three resonator filter is synthesized in order to verify the design equations. A good agreement between the simulated and theoretical results is observed.

II. Miniaturized Hairpin DGS Resonator

All the simulations, design procedures in the paper are performed for dielectric substrate FR-4 with height 1.5 *mm*, relative dielectric constant $\varepsilon_r = 4.4$ and loss tangent $tg\delta = 0.02$.

The miniaturized hairpin microstrip resonator and its synthesis method are proposed in the paper [3]. The dual miniaturized hairpin resonator etched in the ground plane, is introduced as shown on Fig. 1. The resonator consists of main slot line loaded with two parallel coupled slots with a small gap between them. The etched resonator is symmetrical around the axis and the open end is in the middle of the main line.



(*a*) (*b*)

Fig. 1. Topology (*a*) and electric field (*b*) distribution of miniaturized hairpin DGS resonator

The magnetic field is concentrated in the coupled lines and the electric filed is at its maximum near the open end of the resonator. The field concentration allows the realization of three main coupling topologies-electric, magnetic and mixed coupling. The miniaturized hairpin DGS resonator occupies less area than the conventional hairpin or slow wave resonators.

This makes the application of the miniaturized hairpin DGS resonator applicable in the lower microwave bands, where the physical dimensions of the transmission lines are relatively large and the miniaturization is not possible. Another advantage of the DGS resonator is its rectangular form in order to design canonical and pseudo-elliptic filters with cross couplings.

The coupled slot lines can be used for control of the resonant frequency of the resonator. The dimensions of the resonator tuned to central frequency $f_0 = 2.4GHz$ are shown on Fig. 1*a*. The main slot has the width of 50Ω microstrip line $w = 2.8mm$. Using electromagnetic simulation the resonance frequency is obtained. Fig. 2 shows the dependence of the first resonant frequency to the length of the parallel coupled lines *p*.

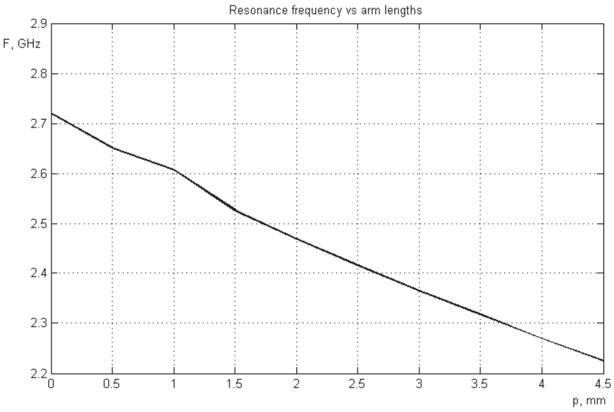


Fig. 2. Dependence of the resonance frequency of the length of the coupled lines

Following the results from the simulations, the resonance frequency of the DGS resonator is easily tuned by adding or removing of metal to the ground plane. The dependence is almost linear. Using curve fitting a useful design expression is derived for the length of the coupled arms:

$$p = 103.8e^{-0.9858 f_0[\mathrm{GHz}]}, [mm] \quad (1)$$

The accuracy of Eq.1 compared to the electromagnetic simulations is better than 2.5 % and prevents errors caused by wrong read of the graphic results shown on Fig. 2.

III. Coupling Coefficients and External Quality Factor Simulations

The coupling coefficient for synchronously tuned resonators can be calculated easily by finding the eigenfrequencies associated with the coupling between a pair of coupled resonators of even (f_{even}) and odd (f_{odd}) mode [2], when the coupled resonators are overcoupled:

$$k = \frac{f_{even}^2 - f_{odd}^2}{f_{even}^2 + f_{odd}^2}. \quad (2)$$

A full wave EM simulator based on the Finite element method (FEM) is used to identify the resonance frequencies in the response [2].

The coupling topologies used to realize the coupling coefficients are shown on Fig. 3. The miniaturized hairpin slot resonators shown on Fig. 3 are dual to the miniaturized hairpin resonator and the electromagnetic field is inversely distributed in it. The maximum value of the magnetic field is in the connection point of the coupled lines with the main transmission line and the maximum value of the electric field is in the center of the main slot line. There are three main types of coupling typologies - electric, magnetic and mixed. In Fig. 3*a* is shown electric coupling, where the electric field has a maximum and dominates over the magnetic field. In this way the sign of the coupling coefficient is negative and can be used for cross coupled filters.

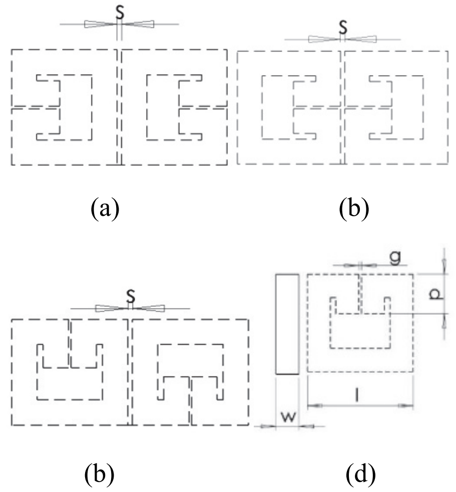


Fig. 3. Coupling topologies of miniaturized hairpin DGS resonators: (a) electric, (b) magnetic, (c) mixed, and (d) external quality factor

Fig. 3*b* shows the magnetic coupling, where the magnetic field is predominant over the electric field. The sign of the coupling coefficient is positive.

An important part of the synthesis of microstrip filters is to determine the gap between the coupled resonators according to the value of the coupling coefficient found from the approximation. There are three main approaches to find out the space between the resonators - analytic formulas [2], approximate formulas from curve-fitting [4] and extraction from EM simulations using the method described in [2], and [3].

Using full-wave EM simulations of the coupling structures, which are very weekly coupled to 50Ω microstrip feed line, the coupling coefficients are extracted using Eq. (2).

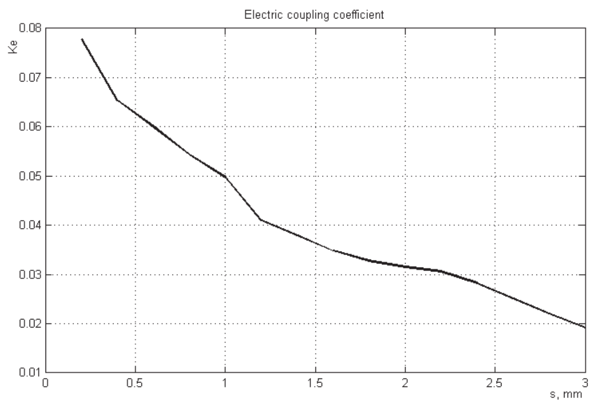


Fig. 4. (*a*) Dependence of the coupling coefficient for electric coupling

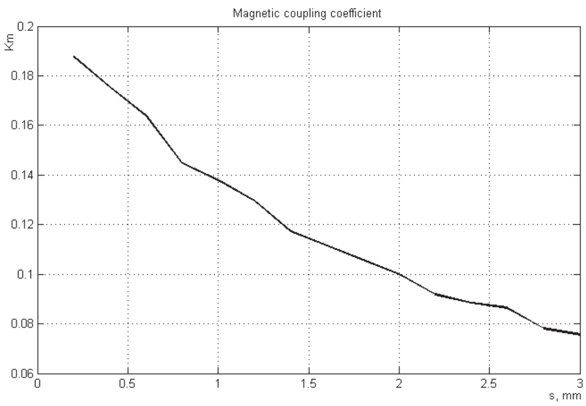


Fig. 4. (*b*) Dependence of the coupling coefficient for magnetic coupling

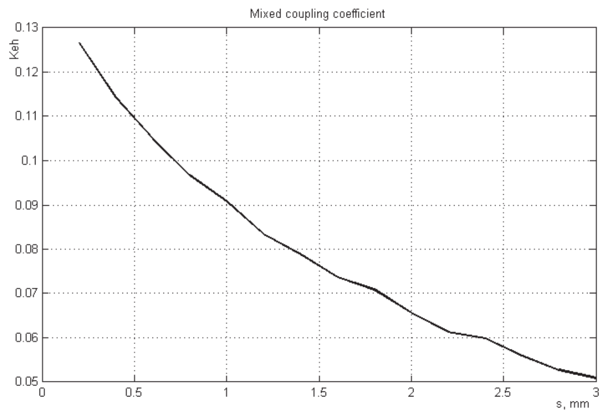


Fig. 4 (*c*) Dependence of the coupling coefficient for mixed coupling

Fig. 4 *a-c* shows the coupling coefficient for all three types of coupling in dependence of the gap between the resonators ***s***.

The dependence of the coupling coefficient for electrical coupling is exponential with respect to the spacing between the resonators. Using curve fitting method, for the design purposes it is derived the following dependence.

For electric coupling and electric coupling coefficient M_e:

$$s_e = 6.88e^{-40.26M_e} \quad (3)$$

For magnetic coupling and magnetic coupling coefficient M_m:

$$s_m = 12.26e^{-18.45M_m} \quad (4)$$

And for mixed coupling and electric coupling coefficient M_{mix}:

$$s_{mix} = 13.05e^{-28.73M_{mix}} \quad (5)$$

Using Eq.(3)-(5) it is easy to compute the spacing between the coupled lines. The main constraint for the equations is $s \in (0.2, 3)\,mm$ and their accuracy toward the simulations is better than 5 %.

The position of the input/output lines is defined by the external quality factor. The external quality factor is realized by a 50Ω microstrip line on the top layer of the substrate, shown on Fig. 3(*d*).

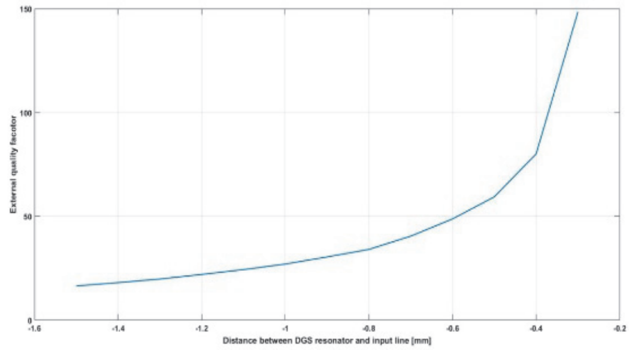


Fig. 5. Dependence of the external coupling to the position of the input/output microstrip line

The external quality factor is very sensitive to close placement of the microstrip line. The input/output microstrip line influences on the resonance frequency of the slot resonator and shifts it to lower values. This effect have to be compensated in the filter design by reduction of the coupled lines in the middle of input/output resonators. As the input/output line is on the top layer, it can overlap the resonator or can be placed aside it.

IV. Bandpass Filter Synthesis and Simulations

In order to verify the proposed topologies of coupled resonators and formulas for coupling coefficients a three resonator Chebyshev filter is designed. Therefore the required coupling coefficients have to be computed using standard technique described in [2]

$$M_{n,n+1} = \frac{FBW}{\sqrt{g_n g_{n+1}}}, \quad (6)$$

where FBW is the fractional bandwidth and g_n, $n = 0,1,2,3$ are the values of the element of the lowpass filter prototype.

There are various sources of precomputed values for the elements for different pass band ripple. The current design is for center frequency $f_0 = 2400\,MHz$, bandwidth $\Delta f = 200\,MHz$ and return loss in the passband $RL = -20dB$. The values for the coupling coefficients are $M_{12} = M_{23} = 0.086$ and the external quality factor is $Q_e = 25.98$. The corresponding gaps are $s_{12} = s_{23} = 1.13\,mm$ and overlapping between the input/output line and the resonator is $d = -1.25\,mm$.

The filter is simulated in fullwave EM simulator and the results are shown on Fig.6. The passband losses are -3 *dB* and the maximum return loss in the pass band is -13.26 *dB*.

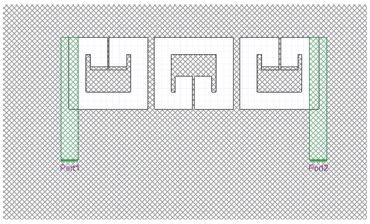


Fig. 6. (*a*) Topology of the synthesized three resonator Chebyshev filter

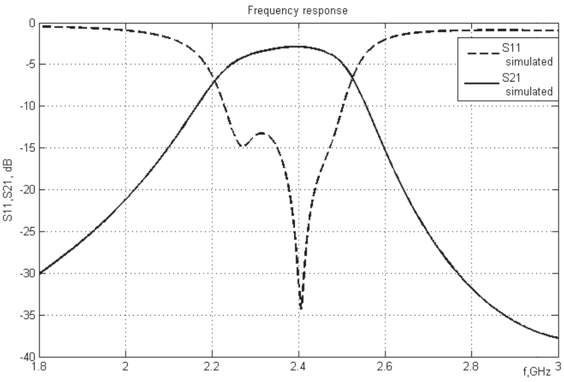


Fig. 6. (*b*) Narrowband frequency response of the synthesized filter

The bandwidth of the simulated filter is 280 MHz and the coupling appear to be stronger than the designed. The resonance frequency of the first and third resonators are affected by the input/output lines and needs to be adjusted with shortening the length of the coupled lines. The length of the coupled lines is shortened with 0.6 *mm* in order to achieve the required resonance frequency. Fig. 7 shows the wideband frequency response of the designed filter.

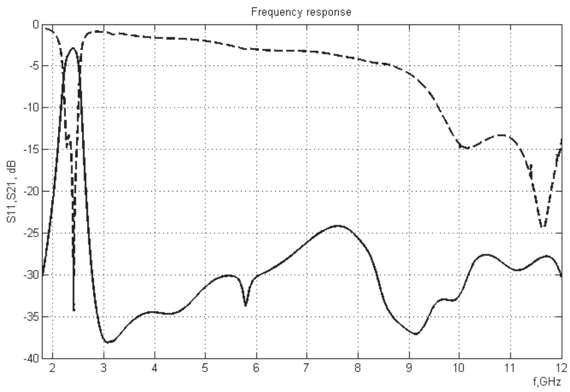


Fig. 7. Wideband frequency response of the synthesized filter

As it is clearly seen, the filter has no spurious passband in the response up to 12 GHz.

V. CONCLUSION

This paper presents design of a miniaturized hairpin DGS resonator and the corresponding coupling structures. Topologies of coupled DGS resonators are researched andsimple formulas are proposed for new designs. They arederived using on curve fitting technique. A three resonatorfilter is synthesized in order to verify the design equations. Agood agreement between the simulated and theoretical resultsis observed. It can be used in microstrip filter design in the ISM band on 2.4 GHz on FR-4 substrate.

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