A Novel Bandpass Filter Using a Combination of Open-Loop Defected Ground Structure and Half-Wavelength Microstrip Resonators

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Abstract. *This paper deals with a defected ground structure (DGS) open-loop resonator analysis and bandpass filter design, using coupled DGS and microstrip resonators. The combination of DGS and microstrip resonators allows using top and bottom sides of the microwave substrate, therefore the resonators can partially overlap and a desired coupling coefficient can be easily achieved. The open-loop DGS resonator properties are investigated, as well as coupling types between the resonators. Finally, two bandpass filters are designed and simulated. The sixth order filter is fabricated and the results are compared with measurement. The introduced structure represents an alternative to a conventional parallel-coupled half wavelength microstrip resonator bandpass filter.*

Keywords

Defected ground structure, bandpass filter, DGS resonator, slot resonator, open-loop resonator, half-wavelength microstrip resonator, Chebyshev prototype filter.

1. Introduction

Microstrip open-loop resonators are commonly used in a coupled resonator bandpass filter (BPF) design. Replacing the microstrip loop by a square-loop shaped slot in the ground plane was introduced in [1], [2]. Excitation of this type of resonator and its properties were investigated in [3], as well as extraction method of equivalent circuit. An interesting possibility is to combine this open-loop DGS resonator and a conventional microstrip half-wavelength resonator. Since the DGS and microstrip can overlap, there are no technical problems with extremely narrow gaps between the resonators, when close coupling is required. The aim of this experiment was to find a combined DGS – microstrip structure, analogous to a conventional parallel-coupled half-wavelength microstrip resonator bandpass filter.

For 3D fullwave simulations software Ansoft HFSS was used. Filters were designed on microwave substrate Arlon DiClad 870 with parameters $\varepsilon_r = 2.33$, $h = 0.508$ mm and $\tan\delta = 0.002$.

2. Open-Loop DGS Slot Resonator

Fig. 1 shows the slot loop used for the experiment (gray color represents etched ground plane). The loop is of a rectangular shape with sides a and $a/2$ long. This shape occupies 89 percent of area in comparison with a square shape with the same circumference (i.e. with equal resonant frequency) [3]. The width of the slot was chosen to be the same as the width of 50 Ohm microstrip line w_{50} (w_{50} = 1.5 mm for the given substrate). The gap between open ends of the loop is marked g.

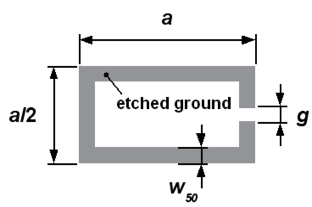

Fig. 1. Open-loop DGS slot resonator – dimensions.

The configuration shown in Fig. 2 was chosen for coupling input and output resonators to the microstrip line. Resonator external quality factor Q_e then depends on the spacing d (d can be either positive or negative) as well as on the width w of the microstrip line. Fig. 2 shows the simulated relation between resonant frequency f_0 and dimension a (where width w = 1.5 mm and gap g = 0.3 mm were constant). Low coupling represents spacing d = 0.55 mm. An external quality factor extracted from simulation is Q_e = 800 in this case. On the other hand close coupling with Q_e = 10 corresponds to spacing d = -0.97 mm. Thus close coupling between the feed line and the resonator results in a lower resonant frequency. Here should be noted that for all simulations the structure was shielded from the top and bottom sides, both 10 mm above the substrate surface. This is very important since the slots radiate and the external quality factor is influenced by the surrounding environment (see Fig. 3). Therefore a proper shielding of the structure is necessary to obtain high Q suitable for BPF design.

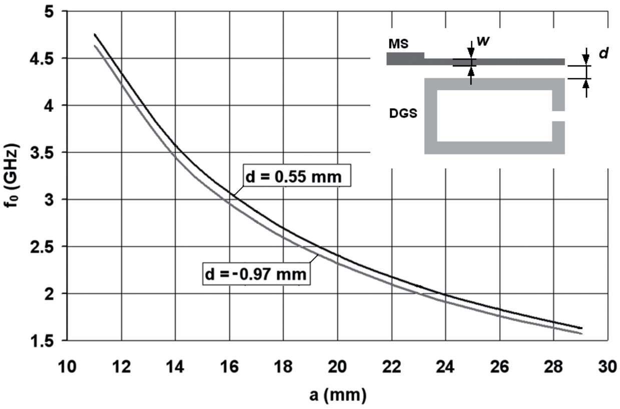

Fig. 2. Resonant frequency f_0 versus dimension a (g = 0.3 mm, w = 1.5 mm). Close coupling Q_e = 10 (i.e. d = -0.97 mm) and weak coupling Q_e = 800 (i.e. d = 0.55 mm).

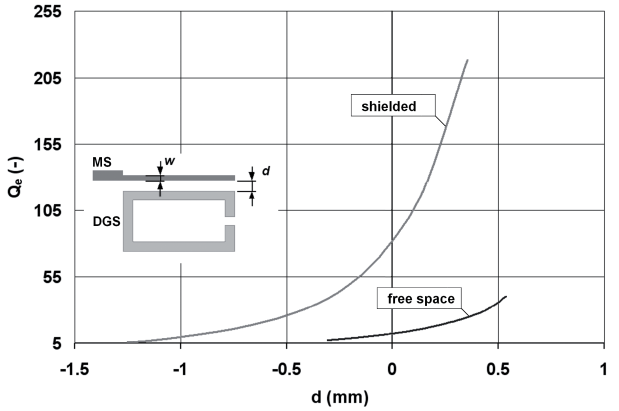

Fig. 3. External quality factor Q_e versus spacing d (a = 20 mm, g = 0.3 mm, w = 1.5 mm).

Fig. 3 shows how external quality factor depends on spacing d in case of resonator side length a = 20 mm. The resonant frequency of the resonator with very weak coupling (Q_e = 800) to the feed microstrip line is 2408 MHz. As was mentioned above, close coupling results in lower resonant frequency than in case of weak coupling. Thus the resulting resonant frequency depends on the spacing d (resp. Q_e), as shown in Fig. 4.

From the following approximation, it is possible to calculate d corresponding to the given Q_e as

$$d = 0.4911 \cdot \ln(Q_e) - 2.1016 \text{ [mm]} \qquad (1)$$

where Q_e = 5 .. 45.

When we design a coupled resonator filter, we have to set exact Q_e value, however the resonant frequency should not change. Fig. 5 shows how the resonant frequency of the resonator can be tuned, without affecting Q_e. Simulations have shown that when changing gap width g, the external quality factor Q_e remains almost constant. This is useful in case of close coupling when we set spacing d to obtain the required Q_e, however the resonant frequency shifts (see Fig. 4). Then the resonant frequency can be tuned by changing gap width g.

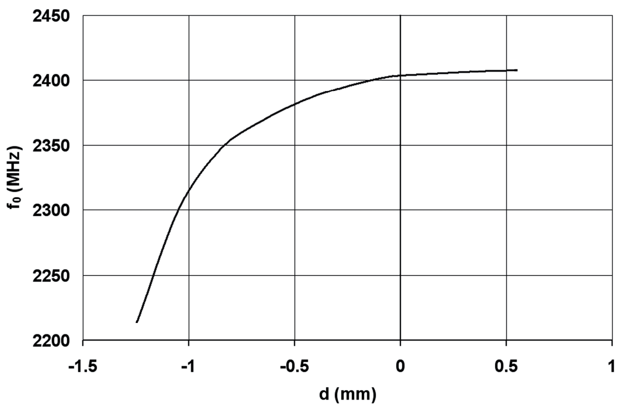

Fig. 4. Resonant frequency f_0 versus spacing d (a = 20 mm, g = 0.3 mm, w = 1.5 mm).

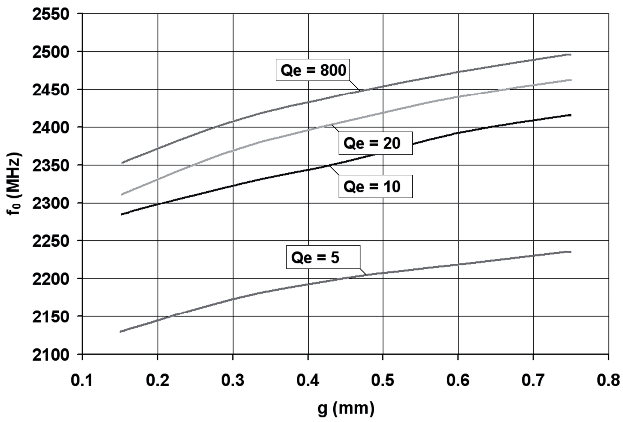

Fig. 5. Resonant frequency shift in dependence on the gap width g (a = 20 mm, w = 1.5 mm).

3. Coupled Resonators

The open-loop DGS slot resonator is a dual structure to the open-loop microstrip resonator, since the electromagnetic field is inversely distributed. The maximal value of electric field is at the center of the slot a. On the other hand, the maximal value of magnetic field is in the gap (between the open ends of the loop). We can differentiate between three types of coupling. Electric coupling (E coupling), magnetic coupling (H coupling), and mixed coupling (EH coupling). In case of mixed coupling there is no dominant component of the EM field – resonators are significantly coupled by both components of the field.

For a coupled resonator BPF design, it is important to determine the relationship between the value of the coupling coefficient and physical dimensions of the coupled resonator structure. Fig. 6 shows coupling coefficient M depending on spacing s between two resonators for each of the three considered coupling types. The values of M were extracted from 3D fullwave simulation using the approach described in [4]. For filter design purposes, the curves were approximated as follows.

E coupling (for M = 0.008 .. 0.040 and s = 3 .. 0.2 mm):

$$s = -1.7197 \cdot \ln(M) - 5.3444 \quad [\text{mm}]. \tag{2}$$

H coupling (for M = 0.090 .. 0.259 and s = 3 .. 0.2 mm):

$$s = 12.716 \cdot e^{-15.706 \cdot M} \quad [\text{mm}]. \tag{3}$$

EH coupling (for M = 0.036 .. 0.106 and s = 3 .. 0.5 mm):

$$s = -2.3241 \cdot \ln(M) - 4.7756 \quad [\text{mm}]. \tag{4}$$

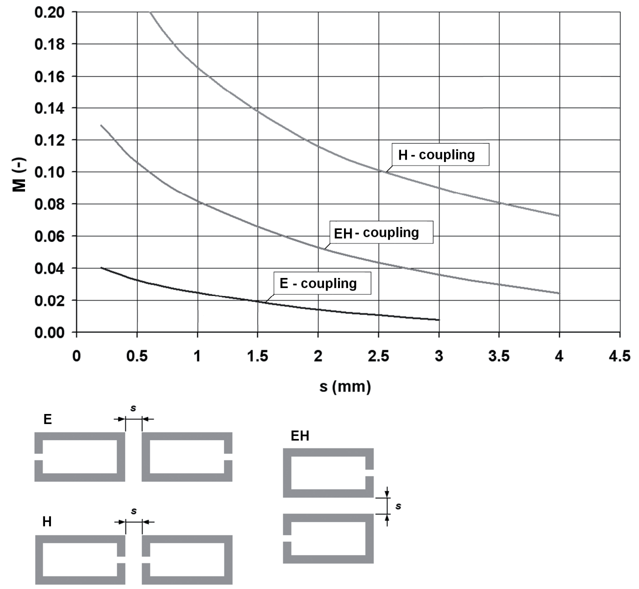

Fig. 6. Different coupling types between open-loop DGS resonators.

For a design combining open loop DGS resonator and conventional half wavelength microstrip resonator, the coupling coefficient of this structure had to be found. Fig. 7 shows the structure configuration. The microstrip length was calculated as a half wavelength at 2400 MHz (considering an open end effect, the microstrip length is 43.8 mm).

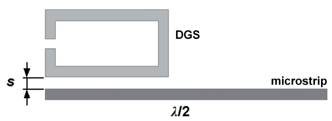

Fig. 7. Coupling between the DGS and the microstrip half-wavelength resonator.

After extracting dependency of the coupling coefficient M on the spacing s, the following approximation was found:

$$s = -0{,}9401 \cdot \ln(M) - 2{,}1997 \quad [\text{mm}] \tag{5}$$

where M = 0.164 .. 0.033 and s = -0.5 .. 1 mm.

4. Bandpass Filter Design Method

Parallel-coupled half-wavelength bandpass filter design equations were introduced in [3]. The same equations were used for the filter with DGS open-loop and microstrip resonator combination.

From the frequency characteristic approximation, the elements g_0, g_1 … g_n of a ladder-type lowpass prototype filter can be calculated. The filter is of order n. Then from a given fractional bandwidth (FBW), the external quality factors of the input and the output resonators Q_{e1} and Q_{en} are calculated as

$$Q_{e1} = \frac{g_0 g_1}{FBW}, \; Q_{en} = \frac{g_n g_{n+1}}{FBW}. \tag{6}$$

The coupling coefficients between the resonators are given as

$$M_{i,i+1} = \frac{FBW}{\sqrt{g_i g_{i+1}}} \quad \text{for } i = 1 \,..\, n-1. \tag{7}$$

In our case, Chebyshev approximation with passband ripple 0.1 dB (i.e. $|s_{11}|_{max}$ = -16.4 dB in the passband) was used. After determining the set of the parameters Q_e and $M_{i,j+1}$ for the given filter order, the physical dimensions of the structure were calculated using (1) – (5).

4.1 Third Order BPF Design

To verify the described design method, a third order bandpass filter was designed. Parameters of the filter were chosen to be as follows: Center frequency 2400 MHz, bandwidth 10 % of the center frequency and passband ripple 0.1 dB. As was mentioned above, the Chebyshev approximation was used. Fig. 8 shows the configuration of the filter.

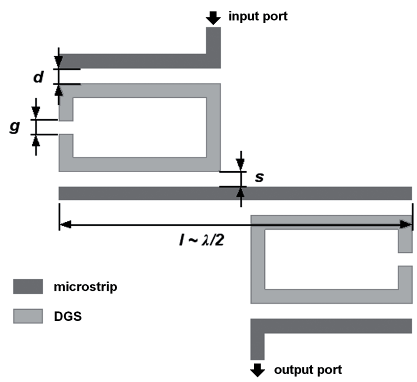

Fig. 8. Third order bandpass filter dimensions.

From the given filter parameters, the external quality factor Q_e and coupling coefficient M_{12} were obtained from (6) and (7). The variables d and s were calculated using equations (1) and (5). The resonant frequency of the DGS resonator loaded by the feed microstrip line was tuned by increasing the gap width from 0.3 mm to the final value g = 0.63 mm. The length of the microstrip half-wavelength resonator was tuned from the calculated value of 43.8 mm to final 43.4 mm, to obtain the required maximum passband ripple. Calculated parameters and dimensions are shown in Tab. 1.

Q_e	M_{12}		
10.32	0.092		
d **(mm)**	***s*** **(mm)**	***g*** **(mm)**	***l*** **(mm)**
-0.96	0.04	0.63	43.4

Tab. 1. Third order filter - calculated parameters and dimensions.

The filter was simulated using Ansoft HFSS (see simulated $|s_{11}|$ and $|s_{22}|$ in Fig. 9). The comparison of ideal and simulated parameters is shown in Tab. 2. There is obviously a good agreement between the design and the simulation, therefore this method can be used for the design of this BPF type.

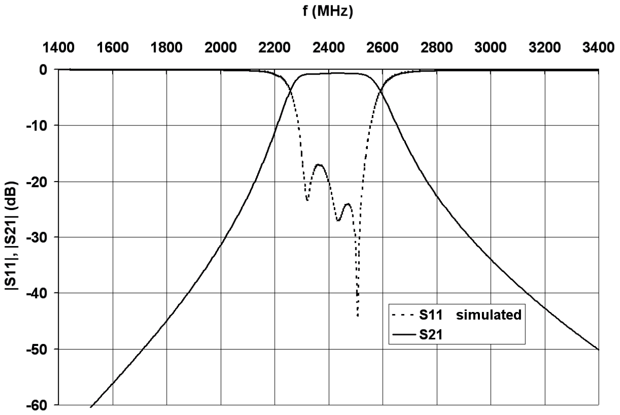

Fig. 9. Third order bandpass filter – simulated characteristic.

	f_0 (MHz)	Δf_0 (%)	f_{c1} (MHz)	f_{c2} (MHz)	BW (%)
design	2400	-	2283	2523	10
simulation	2415	0.6	2302	2534	9.6

Tab. 2. Third order filter – designed and simulated parameters.

4.2 Sixth Order BPF Design

As shown in Fig. 10, a compact bandpass filter with a combination of two microstrip and four DGS resonators was designed. Except dimensions of the structure, Fig. 10 illustrates the coupling diagram of the filter. Dots represent resonators numbered from 1 to 6 and lines symbolize coupling between resonators. The solid line represents coupling between adjacent resonators, while the dashed line represents cross coupling [3] between nonadjacent resonators. The cross coupling between resonators 1, 3 and 4, 6 (M_{13} and M_{46}) is of type E, thus the coupling coefficient is low in case of a sufficient distance x (see how the coupling coefficient depends on spacing - Fig. 6). Then the cross coupling does not affect the resulting frequency characteristic.

The filter was designed to have the center frequency 2300 MHz, bandwidth 15 % and maximal ripple 0.1 dB. External quality factors and coupling coefficients were calculated as was described above. The spacing d between the feed line and input/output resonator was calculated using equation (1), the dimensions s_1 and s_2 were obtained from equation (5). The coupling between resonators 3 and 4 is of type H, thus the spacing s_3 was calculated using approximation (3). The DGS resonators were tuned during simulation to the exact resonant frequency by changing the gap width. This results in values g_1 = 0.4 mm and g_2 = 0.3 mm. All the parameters are resumed in Tab. 3.

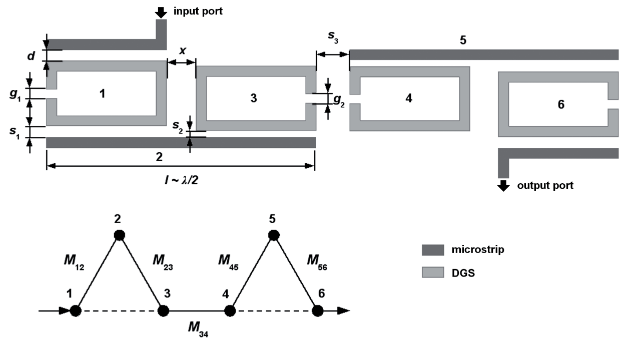

Fig. 10. Sixth order bandpass filter topology and coupling diagram.

Q_e	M_{12}	M_{23}	M_{34}
7.8	0.117	0.088	0.084
d **(mm)**	s_1 **(mm)**	s_2 **(mm)**	s_3 **(mm)**
-1.09	-0.18	0.08	3.35
g_1 **(mm)**	g_2 **(mm)**	***l*** **(mm)**	
0.4	0.3	45.2	

Tab. 3. Sixth order filter - calculated parameters and dimensions.

Parameters obtained from the fullwave simulation are compared with the design assumption in Tab. 4. Since the acceptable agreement was achieved, the filter was fabricated (see Fig. 11) and measured. Simulated and measured frequency characteristics are compared in Fig. 12.

	f_0 (MHz)	Δf_0 (%)	f_{c1} (MHz)	f_{c2} (MHz)	BW (%)
design	2300	-	2134	2479	15
simulation	2322	0.9	2164	2461	14.1

Tab. 4. Sixth order filter – designed and simulated parameters.

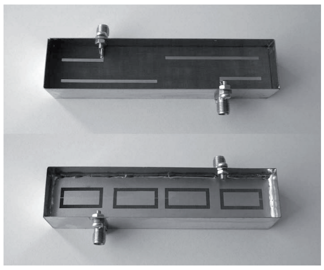

Fig. 11. Fabricated and measured filter - top and bottom view.

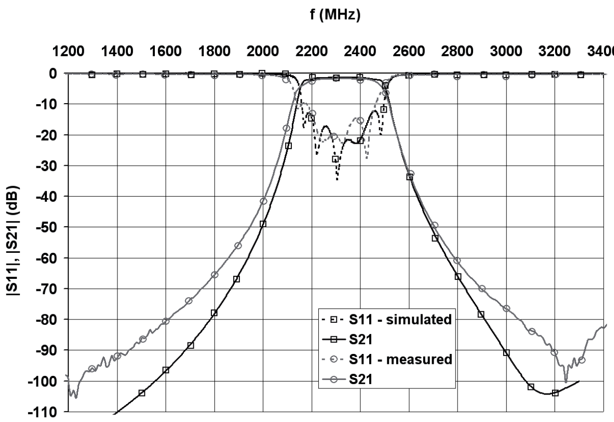

Fig. 12. Simulated and measured frequency characteristic of the sixth order filter.

5. Conclusion

In this paper, a bandpass filter design method was introduced. The method is applicable for the design of planar filters using a combination of microstrip and DGS open-loop resonators. Initially, DGS resonator properties and its dependencies on physical dimensions of the resonator were investigated. Coupling coefficients between the resonators were extracted for each coupling type. Finally, two filters were designed to verify the presented method. The sixth order filter was fabricated and measured. The results have shown that good agreement between the design and measurement was achieved.

Since the resonators occupy top and bottom layer of the microwave substrate, coupling between the resonators is easier than in case of conventional microstrip technique.

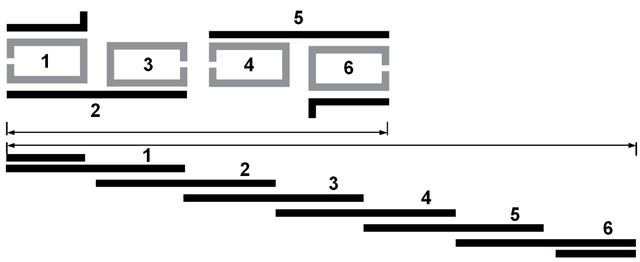

Fig. 13. Dimensions of the proposed structure compared with a conventional microstrip half-wave coupled resonator filter.

Fig. 13 shows, that the filter structure also provides compact dimensions in comparison with microstrip half-wave coupled resonator filter of the same order. On the other hand, the filter structure must be shielded from both sides of the substrate.

Acknowledgements

The research leading to these results has received funding from the European Community's Seventh Framework Programme under grant agreement no. 230126. This work has been supported by the research grant GACR (Grant Agency of the Czech Republic) No. P102/10/1853 *Advanced Microwave Components for Satellite Communication Systems* and by the research program of the Brno University of Technology no. MSM0021630513, *Electronic Communication Systems and New Generation Technology (ELKOM).*

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