Microwave Bandpass Filters Using Couplings With Defected Ground Structures

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Abstract: - In this paper some novel types of microwave bandpass filters using defected ground structures are investigated. In the microstrip technology the use of defected ground structures (DGS) allows designs of filters with tight couplings, without the necessity of using very narrow coupling gaps. In multilayer filters DGS can be used as coupling elements between resonators, allowing very compact filter designs. A study of the couplings between two planar microstrip resonators in the presence of a DGS, and between two planar resonators located on different layers and separated through a DGS in a multilayer structure, is presented. Based on the results of the study some models of planar microwave bandpass filters were designed and simulated, with a single or with two slots etched in the ground plane. These novel filter structures show a good compactness and can offer some technological advantages, compared to the classical.

Key-Words: - microwave filters, defected ground structures, multilayer filters, extended coupling matrix, attenuation poles.

1 Introduction

Ground slots have many applications in microwave techniques. Slot antennas and slot-coupled antennas [1] have been continuously developed and are widely used in communications. The slot coupling is a convenient way to couple microstrip lines in multilayer circuits [2].

In microstrip technology a slot in the common ground plane can enhance the electric coupling, or the electric part of a mixed coupling between two adjacent microstrip resonators. This effect can lead to a relaxation of the fabrication tolerances [3].

In multilayer filters the resonators are placed on different layers, so that defected ground layers can be placed between them [4]. In this position the DGS can act as a convenient, easy-to-control coupling element.

In this paper are presented investigations on the coupling coefficients between two planar resonators, both for microstrip and for multilayer technology. The study is based on full-wave electromagnetic field simulations. Results of the investigations were used in the design of novel types of planar microwave bandpass filters with DGS. As examples, some four-pole cross-coupled planar microwave bandpass filters with a pair of attenuation poles at imposed finite frequencies, with a single or with two ground slots, were designed. Small-size multilayer filters with defected ground plane couplings were also designed and verified by simulation, in order to validate the study of couplings.

2 Derivation of Coupling Coefficients from Simulated Frequency Responses

The coupling coefficient between two resonators can be extracted from the frequency response of a pair of synchronously tuned coupled resonators:

$$k = \frac{\omega_2^2 - \omega_1^2}{\omega_2^2 + \omega_1^2}, \qquad (1)$$

where ω_1 and ω_2 are the two split-resonance frequencies [5].

The coupling between a resonator and its feed line represented by the external quality factor can be derived from the 3dB bandwidth of the frequency response of the circuit [5]:

$$Q_{ext} = \frac{f_0}{B_{3dB}}, \tag{2}$$

where f_o is the resonator's frequency.

The frequency responses can be obtained with a full electromagnetic field simulation software. The results presented in this paper were obtained by using a method of moments (MoM) commercial software [6].

3 Couplings Investigation

3.1 Couplings between resonators in the presence of DGS, in microstrip technology

The microstrip circuit was designed on a FR4 dielectric substrate, with a thickness of 1.6mm, a dielectric constant of 4.6 and a cooper metallization thickness of 0.035mm. Above and below of the microstrip two air layers of 20mm thickness each were considered, for simulation purposes only. In order to develop applications for the 2.4GHz ISM frequency band, 16.6mm long and 12mm wide microstrip hairpin resonators were used. The ground slots are all rectangular, with different lengths l_{slot} and widths w_{slot}.

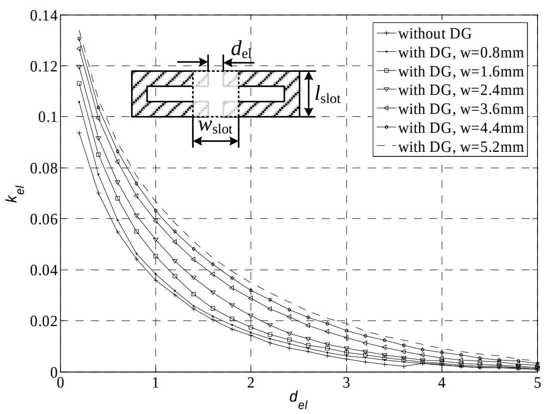


Fig.1. Electric coupling coefficient, k_{el}, vs. coupling gap, d_{el} (in mm)

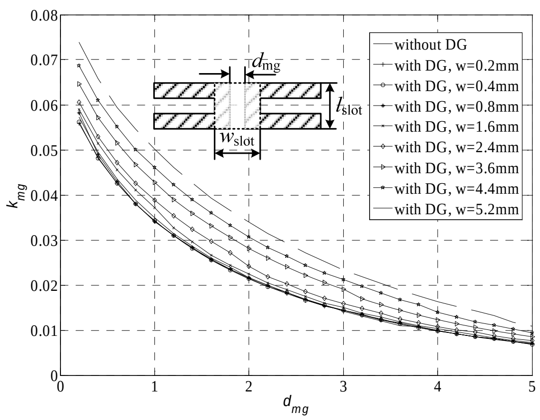


Fig.2. Magnetic coupling coefficient, k_{mg}, vs. coupling gap, d_{mg} (in mm)

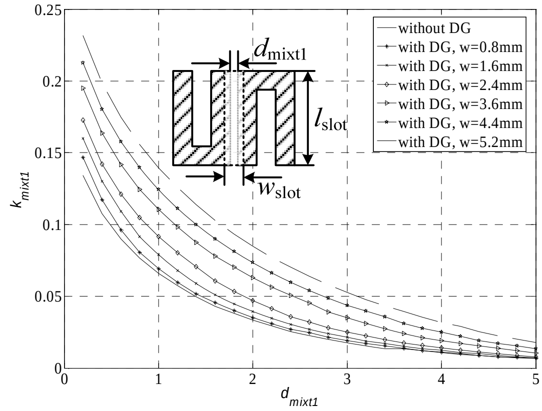


Fig.3. Type-I mixed coupling coefficient, k_{mixt1}, vs. coupling gap, d_{mixt1} (in mm)

In the Figs.1÷4 d_{el}, d_{mg}, d_{mixt1} and d_{mixt2} are the (variable) coupling gaps for the electric, magnetic, type-I and type-II mixed couplings configurations, respectively.

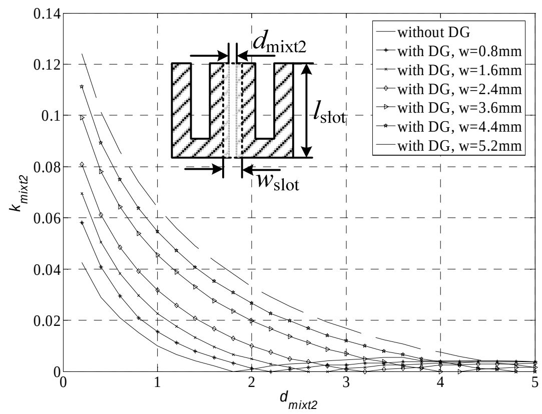


Fig.4. Type-II mixed coupling coefficient, k_{mixt2}, vs. coupling gap, d_{mixt2} (in mm)

The coupling coefficient was calculated using the procedure shown in Chapter 2.

Fig.1 illustrates the dependence of the electric coupling coefficient on the gap between resonators, for several widths of the ground slot. As expected, the electric coupling coefficient is increased by the presence of slot.

As depicted in Fig.2, the magnetic coefficient is slightly larger, compared to the classical microstrip structure.

From Fig.3 it can be noticed that the presence of the slot leads to a significantly increased type-I mixed coupling coefficient.

For the electric and type-I mixed couplings, the dependence of the coefficients on the coupling gaps shows a monotonic variation. However, for the type-II mixed coupling (Fig.4) the coupling coefficient shows a zero and a local maximum. This behavior can be explained by the fact that the electric part of type-II mixed coupling has an opposite sign as its magnetic part. At small gaps the electric part of the coupling is predominant, but at larger distances this part of the coupling decreases faster than the magnetic part, so that there is a gap where the two couplings cancel each other. At large distances, the magnetic coupling predominates. This behavior is in agreement with other previous results [5] obtained for microstrip resonators without ground slots.

3.2 Couplings between resonators in the presence of DGS, in multilayer technology

The structure is composed of two stacked, identical dielectric substrates, with a thickness of 0.508mm, a dielectric constant of 3. All the cooper metallization have a thickness of 0.035mm. Above and below of the structure two air-layers of 30mm thickness each were considered, for simulation purposes only.

The resonators are located on the two external faces of the stacked layers. The dimensions in Fig.5 correspond to a hairpin resonator at 2.4GHz. The couplings between resonators are obtained by using one or two rectangular slots, with different lengths and widths, etched in the common ground plane placed between the two layers.

The coupling configuration of a resonator with its 50Ω microstrip feed line is shown in Fig.5.

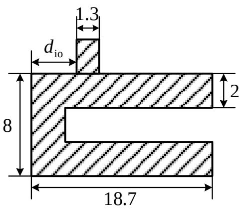
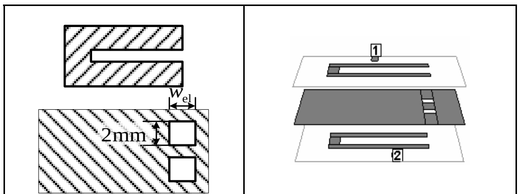


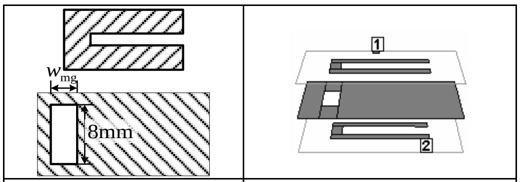
Fig.5. The coupling of a resonator with its feed line (dimensions in mm)

The geometries of the main coupling configurations between two resonators are shown in Figs.6÷9. Here w_{el}, w_{mg} and w_{mx} are the (variable) ground slot widths for the electric, magnetic, and mixed coupling configurations, respectively.



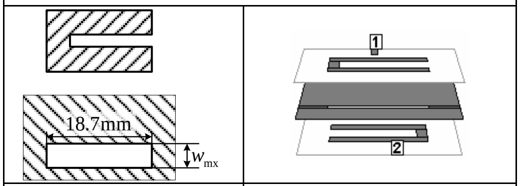
a) b)

Fig.6. Electric coupling configuration: a) slots geometry; b) 3D view



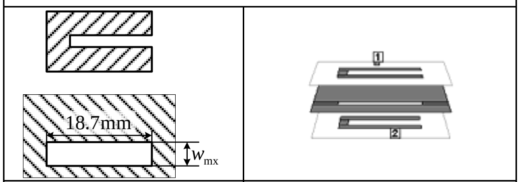
a) b)

Fig.7. Magnetic coupling configuration: a) slot geometry; b) 3D view



a) b)

Fig.8. Mixed coupling configuration: a) slot geometry; b) 3D view



a) b)

Fig.9. Mixed coupling configuration: a) slot geometry; b) 3D view

The simulated frequency responses of the coupling structures from Figs.6÷9 and the values of the corresponding coupling coefficients were obtained using the procedures described in Chapter 2.

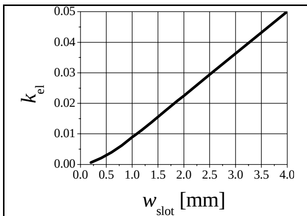


Fig.10. Electric coupling coefficient vs. ground slots width

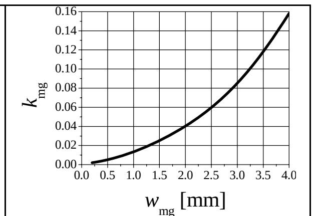


Fig.11. Magnetic coupling coefficient vs. ground slot width

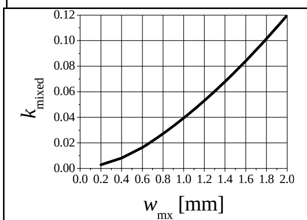


Fig.12. Mixed coupling coefficient vs. ground slot width

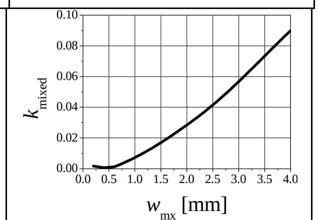


Fig.13. Mixed coupling coefficient vs. ground slot width

From Figs.10÷13 it can be noticed that the coupling k increases monotonically with the slot width w.

The external quality factor Q_{ext} depends on the parameter d_{io}, as shown in Fig.14. The values were extracted using the method presented in Chapter 2.

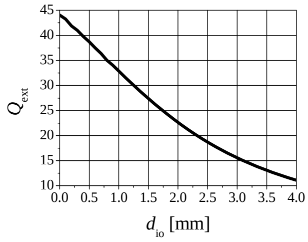


Fig.14. The external quality factor, Q_{ext}, vs. coupling distance, d_{io}

4 Design Examples

4.1 Microstrip bandpass filters with defected ground slots

Based on the results presented in Chapter 3.1, some four-pole cross-coupled planar microwave BPFs with a single or with two ground slots were designed. These filters meet the following requirements: center frequency f_c=2.4GHz, bandwidth B=168MHz, fourth order Chebyshev response with an in-band return loss R_L=20dB. The filters should exhibit two attenuation poles at the frequencies of 2.23GHz and 2.56GHz.

The corresponding extended coupling matrix **M**, obtained using the procedure shown in [7] and an in-house developed program, leads to a filter having a topology easy to be realized in the form of a planar bandpass filter, composed of four identical microstrip resonators [8]:

$$\mathbf{M} = \begin{bmatrix} 0 & -1.0235 & 0 & 0 & 0 & 0 \\ -1.0235 & 0 & 0 & -0.8705 & -0.1704 & 0 \\ 0 & 0 & 0 & -0.7672 & 0.8705 & 0 \\ 0 & -0.8705 & -0.7672 & 0 & 0 & 0 \\ 0 & -0.1704 & 0.8705 & 0 & 0 & 1.0235 \\ 0 & 0 & 0 & 0 & 1.0235 & 0 \end{bmatrix}$$

The layout of such a filter with four hairpin resonators is shown in Fig.15. The input and output lines, directly coupled with resonators no. 1 and 4, have widths of 2.9mm, assuring standard 50Ω terminations for the filter.

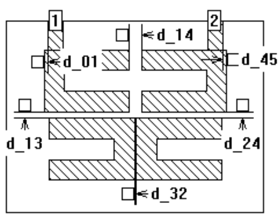


Fig.15. Layout of the BPF in a classical microstrip technology

The design of the filter from Fig.15 stays in finding the gaps d, in order to obtain the needed external and mutual couplings for the resonators, as derived from the extended coupling matrix **M** by a de-normalizing procedure [9]. The de-normalized coupling values are shown in Table 1. The corresponding gaps, as resulted from the study in 3.1, are presented in Table 2.

Table 1

Q_{ext}	k_{1-3}	k_{2-3}	k_{2-4}	k_{1-4}
13.6	0.0609	0.0537	0.0609	0.0119

Table 2

d_01 [mm]	d_13 [mm]	d_23 [mm]	d_24 [mm]	d_14 [mm]	d_45 [mm]
0.8	1.18	0.3	1.18	2.3	0.8

As shown in Table 2, some couplings lead to very narrow gaps between resonators, technologically difficult to obtain.

For a defected ground structure, the same values of the coupling coefficients can be obtained with the configurations from Figs.1÷3, where the gaps are larger. The corresponding gaps between two adjacent resonators and the ground slots parameters are shown in Table 3.

Table 3

Coupling type	Coupling coefficient	Gap [mm]	w_{slot} [mm]	l_{slot} [mm]
electric	0.0119	2.6	2	12
magnetic	0.0537	0.42	2.8	12
type-I mixed	0.0609	1.6	2.4	16.6

Some 3D views of the designed filters with ground slots are shown in Figs.16, 17 (single slot) and in Figs.18, 19 (two slots).

The EM-field simulated performances of the designed defected ground bandpass filters plotted in Figs.20, 21 are, in general, very close to the filter requirements.

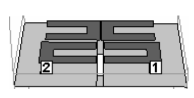


Fig.16. Slot under electric coupling

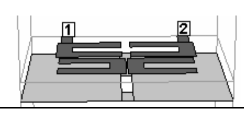


Fig.17. Slot under magnetic coupling

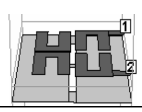


Fig.18. Slots under type-I mixed couplings

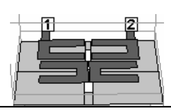


Fig.19. Slots under electric and magnetic couplings

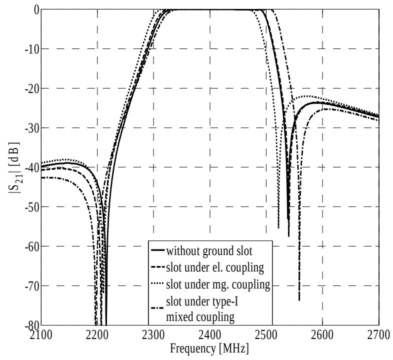


Fig.20. Simulated $|S_{21}|$ of the filters from Figs.16÷18, vs. frequency

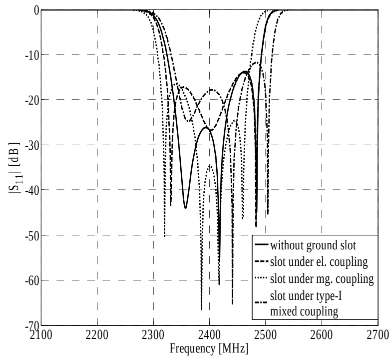


Fig.21. Simulated $|S_{11}|$ of the filters from Figs.16÷18, vs. frequency

Some relevant parameters of these responses are summarized in Table 4.

Table 4

BPF	f_c [MHz]	B [MHz]	R_L [dB]	f_{pole1} [MHz]	f_{pole2} [MHz]
w/o slot	2400	150	17	2218	2450
Fig.16	2404	160	17	2210	2540
Fig.17	2390	152	20	2212	2523
Fig.18	2425	159	18	2198	2560

The increase of couplings in the presence of a ground slot has a simple physical explanation. For a conventional microstrip structure in the electric coupling configuration, many of the electric lines starting from a resonator end on the ground plane. In the presence of the slot, a part of these lines are forced to end on the other resonator, enhancing this way the electric coupling, or the electric part of a mixed coupling.

4.2 Bandpass filters in multilayer technology

Based on the results from 3.2, several simple second-order bandpass filters were designed and simulated. These filters meet the following requirements: center frequency f_c=2.4GHz, bandwidth B=100MHz, a second-order Chebyshev response with an in-band ripple of R=0.1dB.

A second-order Chebyshev lowpass prototype with 0.1dB passband ripple is chosen, whose normalized elements values are g_0=1, g_1=0.843, g_2=0.622 and g_3=1.3554 [8]. Using these normalized values and the 3dB fractionary bandwidth, $w = B/f_c \cong 0.042$, the external quality factors and the coupling coefficient between the two resonators can be found by the usual de-normalization procedure [8]:

$$Q_{\text{ext}1} = \frac{g_0 g_1}{w} = 20.2 = Q_{\text{ext}2} \tag{3}$$

$$k_{1-2} = \frac{w}{\sqrt{g_1 g_2}} = 0.05754 \tag{4}$$

The topology of this filter is easy to be realized in the form of a two-dielectric layer bandpass filter, composed of two identical hairpin resonators, as shown in Figs.22, 23.

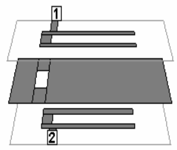


Fig.22. Two-layer 2nd order BPF with magnetic coupling

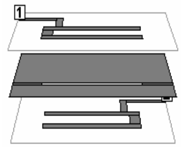


Fig.23. Two-layer 2nd order BPF with mixed coupling

The design of these filters stays in finding the distance d_{io} and the widths w_{mg}, and w_{mx} of the ground slots etched in the common ground plane, in order to obtain the needed external and mutual couplings for the resonators, as derived from the relations (3) and (4). These values, obtained from the study in 3.2, are presented in Table 5.

Table 5

BPF	d_{io} [mm]	Slot width [mm]	
Fig.22	1.6	w_{mg}	2.4
Fig.23	2.3	w_{mx}	1.2

The input and output microstrip feed lines have widths of 1.3mm, assuring the standard 50Ω terminations for the filters.

The EM-field simulated performances of the designed filters, plotted in Fig.24 and in Fig.25 are very close to the specification. Several relevant performances of the designed filters are summarized in Table 6.

Table 6

BPF	f_c [MHz]	B [MHz]	R [dB]	Insertion Loss [dB]
Fig.17	2400	102	0.095	0.9
Fig. 18	2403	108	0.13	1