DESIGN OF MICROWAVE MICROSTRIP BANDPASS FILTERS USING DEFECTED GROUND STRUCTURES

N. MILITARU, G. LOJEWSKI*

Articolul prezintă un studiu asupra unor tipuri de filtre trece-bandă (FTB) de microunde în tehnologie microstrip, cu o fantă de cuplaj practicată în planul de masă. Prezența unei fante poate conduce la un cuplaj electric mai strâns, sau la creşterea părții electrice a cuplajului mixt, între cele două rezonatoare planare învecinate. Această structură cu defect de masă („defected ground structure", DGS) permite obținerea unor cuplaje strânse, fără a necesita distanțe foarte mici între rezonatoarele filtrului. Pe baza studiului cuplajelor, în articol este prezentată proiectarea unor FTB de ordin 4 cu rezonatoare tip „ac de păr" cuplate încrucişat, cu una sau două fante de cuplaj în planul de masă. Performanțele filtrelor, obținute prin simulare electromagnetică, indică anumite avantaje față de modelul clasic al unui FTB microstrip (fără fantă în planul de masă).

In this paper a study of some microwave microstrip band-pass filters using defected ground structures (DGS) is presented. It is shown that the presence of a slot in the ground plane can substantially enhance the electric coupling, or the electric part of a mixed coupling, between two adjacent microwave resonators. This technique allows designs of tight couplings without the necessity of using very narrow coupling gaps. Based on the results of the study, some 4-pole cross-coupled planar microwave band-pass filters (BPF) with a single ground slot or with two ground slots were designed. Compared to a similar microstrip filter without defected ground, the simulated performances of these novel structures indicate some advantages.

Keywords: filter, defected ground, attenuation pole, cross-coupling, extended coupling matrix, hairpin resonator.

Introduction

Ground slots have many applications in microwave techniques. Slot antennas [1] and slot coupled antennas [2] have been continuously developed and are widely used in communications. The slot coupling is a convenient way to couple microstrip lines in multilayer circuits [3]. Moreover, stacked filters with slot coupled resonators can provide small-size filter solutions [4].

In this paper are presented investigations on the effects of a ground slot on couplings between hairpin resonators. A slot in the ground plane can enhance the

* Lecturer, Prof., Dept. of Telecommunications, University "Politehnica" of Bucharest, ROMANIA.

electric coupling, or the electric part of a mixed coupling between two adjacent resonators.

The above results were used in the design of some 4-pole cross-coupled planar microwave band-pass filters (BPF) with a pair of attenuation poles at imposed finite frequencies, and with a single or two ground slots.

1. Coupling configurations

The stacked configuration of the investigated microstrip defected-ground structures contains three dielectric layers. 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. On the top and bottom of the microstrip two air layers of 20mm thickness each were considered, for simulation purposes only.

For investigations were used 16.6mm long and 12mm wide microstrip hairpin resonators, in order to develop applications for the 2.4GHz ISM frequency band. The ground slots are rectangular, with lengths l_{slot} and widths w_{slot}.

The geometries of the considered electric and magnetic coupling configurations are shown in Fig. 1 and in Fig. 2.

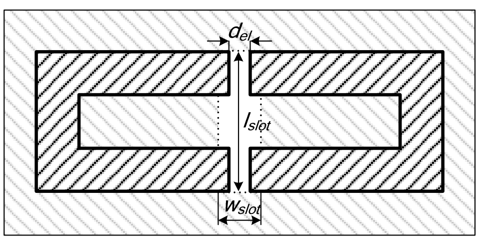


Fig. 1. Electric coupling configuration

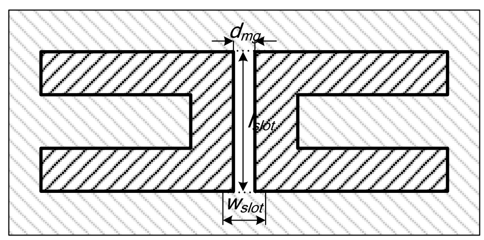


Fig. 2. Magnetic coupling configuration

The geometries of the considered type-I and the type-II mixed couplings are shown in Fig. 3 and in Fig. 4.

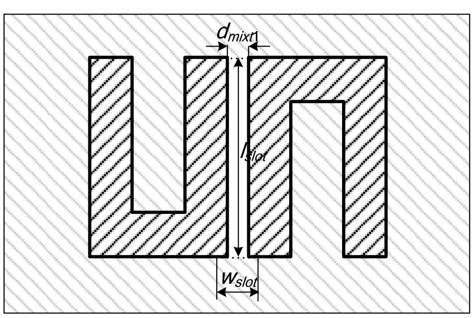


Fig. 3. Type-I mixed coupling configuration

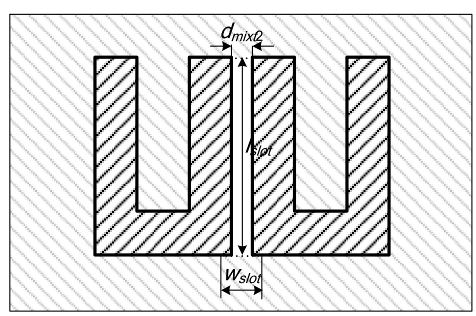


Fig. 4. Type-II mixed coupling configuration

Here 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.

2. Coupling coefficients

The frequency responses of the coupling structures were obtained by using a method of moments (MoM) simulation software [5]. The coupling coefficient was calculated from the two split-resonance frequencies [6].

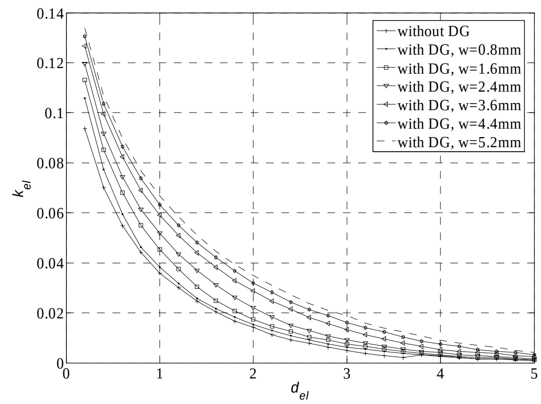


Fig. 5. Electric coupling coefficient, k_{el}, vs. coupling gap, d_{el} (in mm)

Fig. 5 shows the dependence of the electric coupling coefficient k_{el} on the gap d_{el} between resonators, for several widths w of the ground slot. As expected, the electric coupling coefficient k_{el} is increased by the presence of slot.

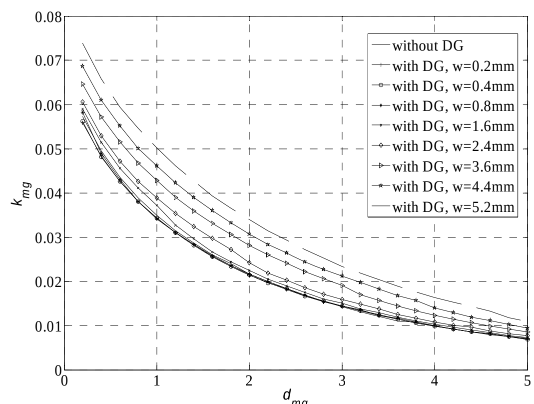


Fig. 6. Magnetic coupling coefficient, k_{mg}, vs. coupling gap, d_{mg} (in mm)

As shown in Fig. 6, for slots of 0.2mm and of 0.4mm width the magnetic coupling coefficient k_{mg} is slightly smaller, while for widths greater than 0.8mm the coefficient is slightly larger, compared to the classical microstrip structure.

From Fig. 7 it can be noticed that the presence of the slot leads to a significantly increased type-I mixed coupling coefficient k_{mixt1}.

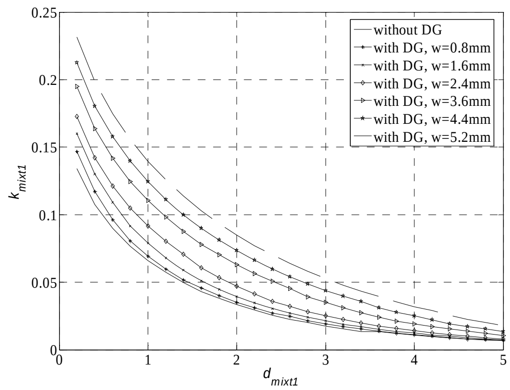


Fig. 7. Type-I mixed coupling coefficient, k_{mixt1}, vs. coupling gap, d_{mixt1} (in mm)

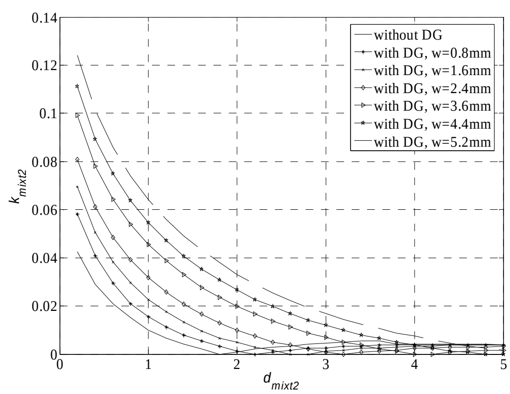


Fig. 8. Type-II mixed coupling coefficient, k_{mixt2}, vs. coupling gap, d_{mixt2} (in mm)

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. 8), a zero and a local maximum of the coupling coefficient k_{mixt2} versus gap occur. 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 d_{mixt2} the electric part of the coupling is predominant, at larger distances this part of the coupling decreases faster than the magnetic part, therefore 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 [7] obtained for microstrip resonators without slots in the ground plane.

3. Band-pass filters design and simulation

Based on the above results, some 4-pole cross-coupled planar microwave band-pass filters with a single or two ground slots were designed. These band-pass filters meet the following specifications: a center frequency of 2400MHz, a frequency bandwidth of 168MHz which corresponds to a 3dB fractionary bandwidth of 7%, and a 4-th order Chebyshev response with a return loss of 20dB in the pass-band. The filters should exhibit two attenuation poles at the frequencies of 2232MHz and 2568MHz.

Using the procedure shown in [8] and an in-house developed program, the extended coupling matrix **M** was computed for a normalized band-pass filter having two attenuation poles at the imposed normalized frequencies:

$$f_{z1} = \frac{1}{FBW}\left(\frac{f_1}{f_0} - \frac{f_0}{f_1}\right) \cong \frac{f_1 - f_0}{\Delta f} = -2\,, \tag{1}$$

$$f_{z2} = \frac{1}{FBW}\left(\frac{f_2}{f_0} - \frac{f_0}{f_2}\right) \cong \frac{f_2 - f_0}{\Delta f} = 2\,. \tag{2}$$

The obtained matrix,

$$\mathbf{M} = \begin{bmatrix} 0 & 0.371111 & 0.62138 & -0.62138 & -0.37111 & 0 \\ 0.371111 & -1.2872 & 0 & 0 & 0 & 0.37111 \\ 0.62138 & 0 & 0.6904 & 0 & 0 & 0.62138 \\ -0.62138 & 0 & 0 & -0.6904 & 0 & 0.62138 \\ -0.37111 & 0 & 0 & 0 & 1.2872 & 0.37111 \\ 0 & 0.37111 & 0.62138 & 0.62138 & 0.37111 & 0 \end{bmatrix}, \tag{3}$$

corresponds to a transversal 4-th order canonical filter satisfying the specified requirements. Such a filter is almost impossible to be fabricated, but starting from this **M** matrix, other $\mathbf{M}'$ matrices corresponding to some topologies suitable for filter realization can be derived, using similitude transformations [9]. Applying some properly chosen similitude transformations on the matrix (3), one gets:

$$
\mathbf{M}' = \begin{bmatrix} 0 & -1.02356 & 0 & 0 & 0 & 0 \\ -1.02356 & 0 & 0 & -0.87057 & -0.17046 & 0 \\ 0 & 0 & 0 & -0.76726 & 0.87057 & 0 \\ 0 & -0.87057 & -0.76726 & 0 & 0 & 0 \\ 0 & -0.17046 & 0.87057 & 0 & 0 & 1.02356 \\ 0 & 0 & 0 & 0 & 1.02356 & 0 \end{bmatrix}. \quad (4)
$$

The matrix (4) corresponds to a filter having a topology easy to be realized in the form of a planar band-pass filter, composed of four identical microstrip resonators [9]. The layout of such a filter with four hairpin resonators is shown in Fig 9. 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.

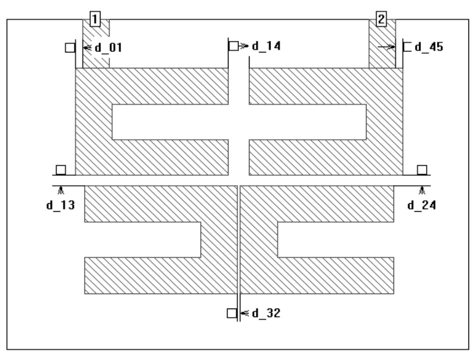


Fig. 9. Layout of the BPF in a classical microstrip technology

The design of the filter from Fig. 9 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 $\mathbf{M}'$ by a de-normalizing procedure [10]. The de-normalized coupling values are shown in Table 1. The corresponding gaps, as resulted from a full-wave EM simulation technique, are presented in Table 2.

Table 1

The values of the external quality factors and of the coupling coefficients between filter resonators

$Q_{e0,1}$	k_{1-3}	k_{2-3}	k_{2-4}	k_{1-4}	$Q_{e4,5}$
13.6	0.0609	0.0537	0.0609	0.0119	13.6

Table 2

The gaps between resonators, as resulted from a full-wave EM-simulation technique

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

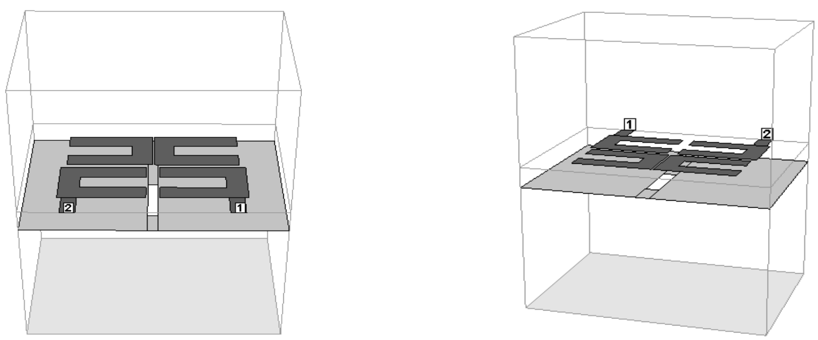
As shown in Table 2, almost all couplings lead to narrow gaps between resonators, technologically hardly to obtain. For a defected ground structure, the same values of the coupling coefficients can be obtained with the configurations from Figs. 1, 2 and 3. The corresponding gaps between two adjacent resonators and the ground slots parameters are shown in Table 3.

Table 3

The gaps between resonators and the DG configurations

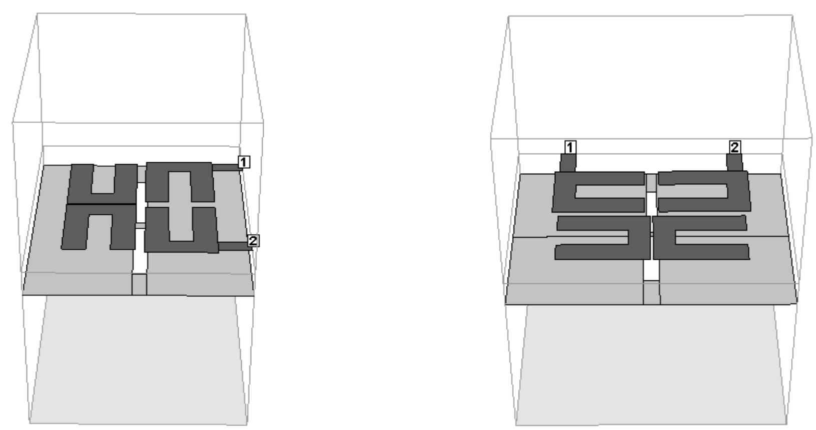
Coupling type	Coupling coefficient	Gaps between resonators [mm]	Slot width w_{slot} [mm]	Slot height l_{slot} [mm]
electric	0.0119	2.6	2	12
magnetic	0.0537	0.42	2.8	12
type-I mixed	0.0609	1.6	2.4	16.6

Several 3D views of the proposed filters with ground slots are shown in Fig. 10 *a*, *b* (single slot) and in Fig. 11 *a*, *b* (two slots).



a) ground slot under electric coupling *b*) ground slot under magnetic coupling

Fig. 10. 3D views of the proposed DG band-pass filters with a single ground slot



a) ground slots under type-I mixed couplings *b*) slots under electric and magnetic couplings

Fig. 11. 3D views of the proposed DG band-pass filters with two ground slots

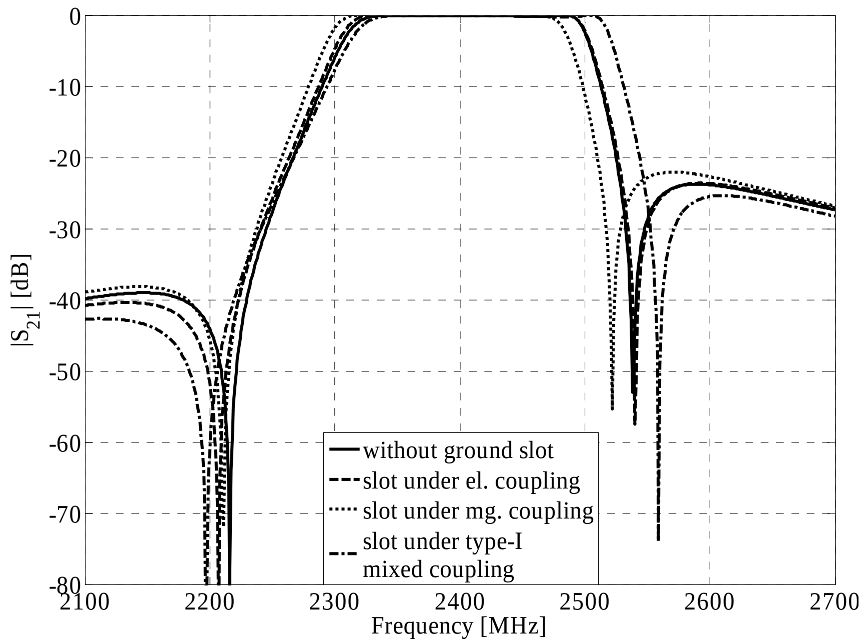


Fig. 12. Simulated $|S_{21}|$ of the filters from Fig. 9, Fig. 10 *a*, *b* and Fig. 11 *a*, vs. frequency

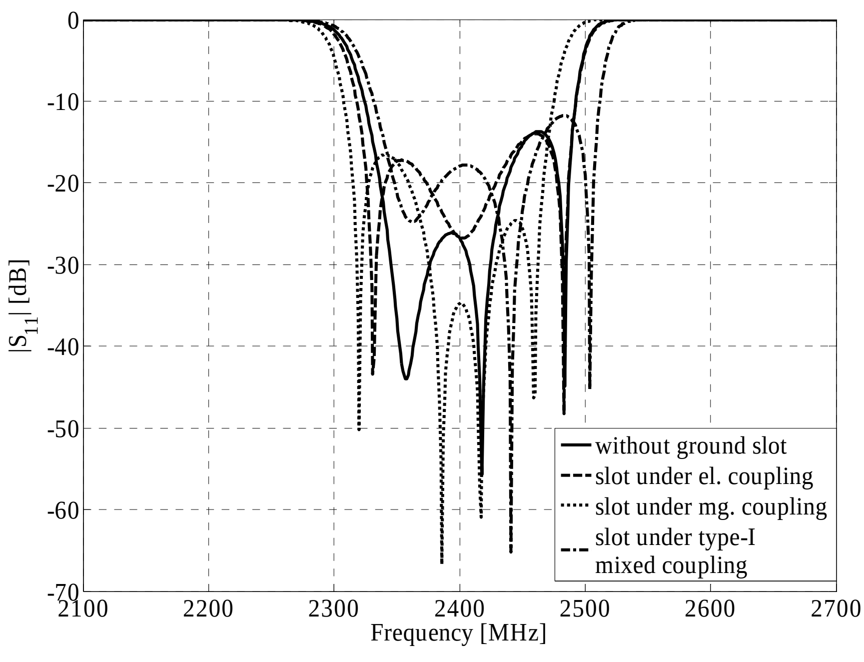


Fig. 13. Simulated $|S_{11}|$ of the filters from Fig. 9, Fig. 10 *a*, *b* and Fig. 11 *a*, vs. frequency

In comparison with the filters depicted in Figs. 10 *a*, *b* and in Fig. 11 *a*, the BPF from Fig. 11 *b* has two ground slots placed under two different couplings (electric and magnetic). The performances of this filter are shown in Fig. 14.

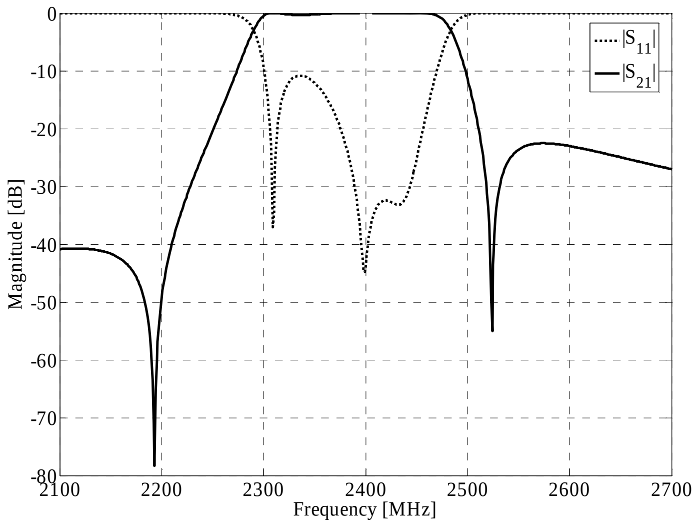


Fig. 14. The performances of the BPF with two slots from Fig. 11 *b*

It can be noticed that the EM-simulated performances of the designed defected ground band-pass filters, plotted in Figs. 12, 13 and 14 are, in general, close enough to the filter requirements. Some relevant parameters of these responses are summarized in Table 4.

Table 4

The main parameters of the responses shown in Figs. 12 – 14

BPF type	Center frequency [MHz]	Frequency bandwidth [MHz]	Return loss [dB]	Frequency of 1st atten. pole [MHz]	Frequency of 2nd atten. pole [MHz]
without ground slot	2400	150	17	2218	2450
with a slot under electric coupling	2404	160	17	2210	2540
with a slot under magnetic coupling	2390	152	20	2212	2523
with two slots under type-I mixed couplings	2425	159	18	2198	2560
with slots under electric and magnetic couplings	2390	151	15	2195	2524

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.

Conclusions

The main advantage of the BPF with ground slots stays in the possibility of using larger gaps between resonators.

The needed couplings were obtained using an in-house developed program.

The filters layouts were designed after a study of the coupling coefficients versus gaps, based on EM-simulation.

The designed defected ground filter structures showed the possibility of using larger gaps between resonators. This solution is especially convenient when tight couplings are needed. The DGS design can be also applied to many other types of band-pass filters, allowing a relaxation of the fabrication tolerances.

R E F E R E N C E S

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