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Enhanced Couplings in Broadband Planar Filters with Defected Ground Structures

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Abstract. In this paper a study of some microwave microstrip bandpass filters (BPF) using defected ground structures (DGS) is presented. This technique allows designs of tight couplings without the necessity of using very narrow coupling gaps. Based on the results of the study, four-pole cross-coupled planar microwave bandpass filters were designed, with a single or with two ground slots. Compared to similar microstrip filters without defected ground, the simulated performances of these novel structures indicate some technological advantages.

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 this paper are presented investigations on the effects of a ground slot on the couplings between hairpin resonators. A slot in the ground plane can enhance the electric coupling, or the electric part of a mixed coupling between two adjacent resonators.

The results of these investigations were used in the design of some four-pole cross-coupled planar microwave bandpass filters with a pair of attenuation poles at imposed finite frequencies. The filters were designed with a single or two ground slots.

2. Coupling configurations

The microstrip circuit was designed on a FR4 dielectric substrate, with a thickness of 1.6 mm, a dielectric constant of 4.6 and a cooper metallization thickness of 0.035 mm. Above and below of the microstrip two air layers of 20 mm thickness each were considered, for simulation purposes only.

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

The geometries of the main coupling configurations are shown in Figs. 1–4.

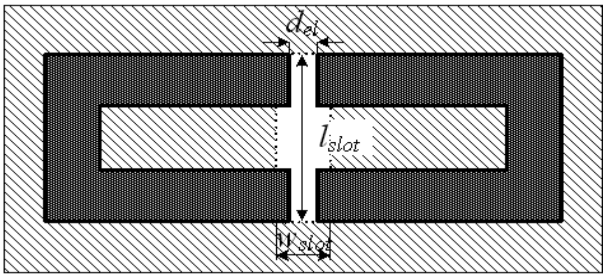


Fig. 1. Electric coupling configuration.

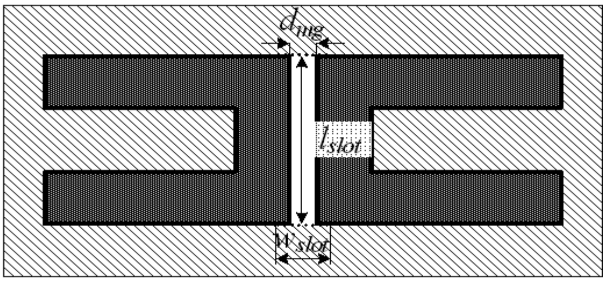


Fig. 2. Magnetic coupling configuration.

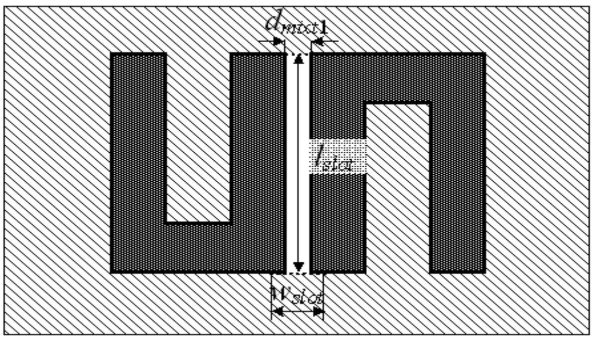


Fig. 3. Type-I mixed coupling configuration.

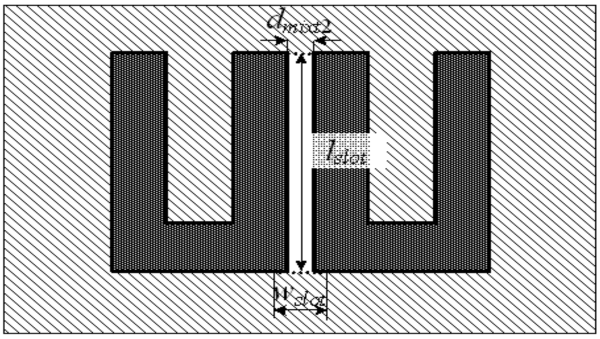


Fig. 4. Type-II mixed coupling configuration.

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.

3. Coupling coefficients

The frequency responses of the coupling structures were obtained by using a method of moments (MoM) commercial simulation software [3]. The coupling coefficient was calculated from the two split-resonance frequencies [4].

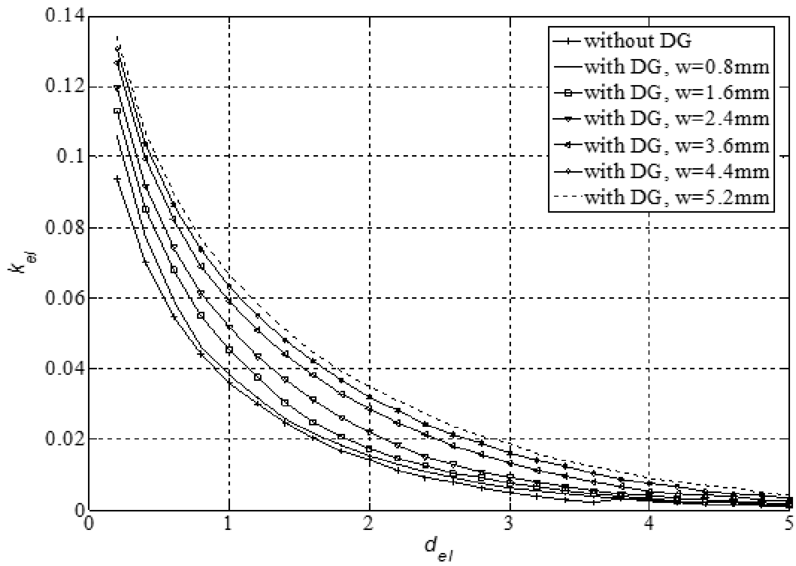


Fig. 5. Electric coupling coefficient, k_{el}, *vs.* coupling gap, d_{el} (in mm).

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 is increased by the presence of slot.

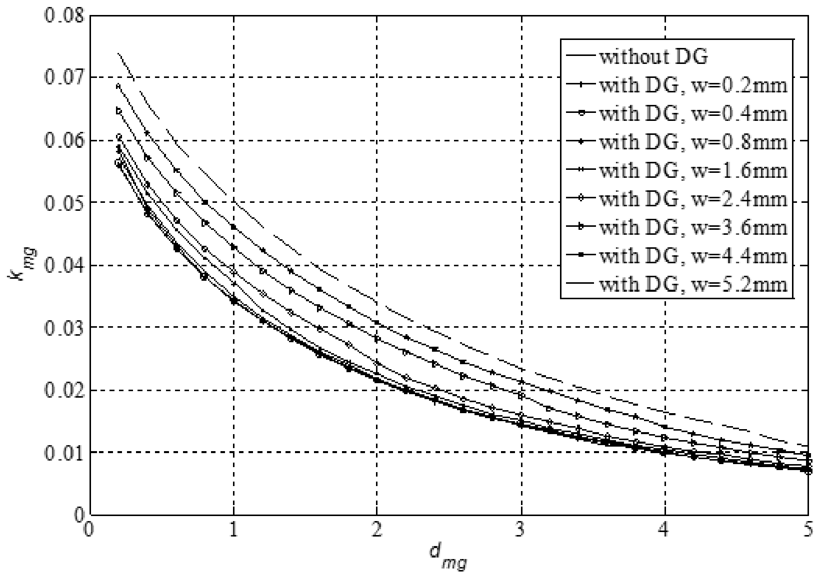


Fig. 6. Magnetic coupling coefficient, k_{mg}, *vs.* coupling gap, d_{mg} (in mm).

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

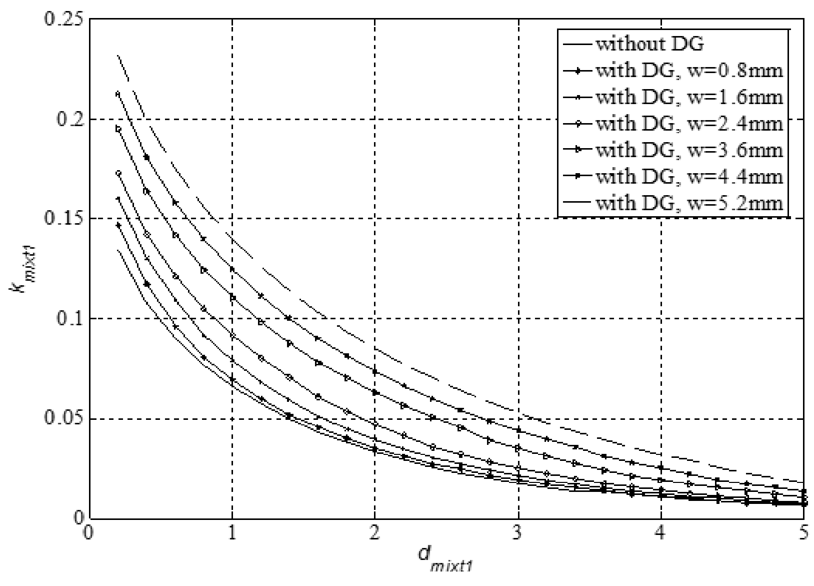


Fig. 7. Type-I mixed coupling coefficient, k_{mixt1}, *vs.* coupling gap, d_{mixt1} (in mm).

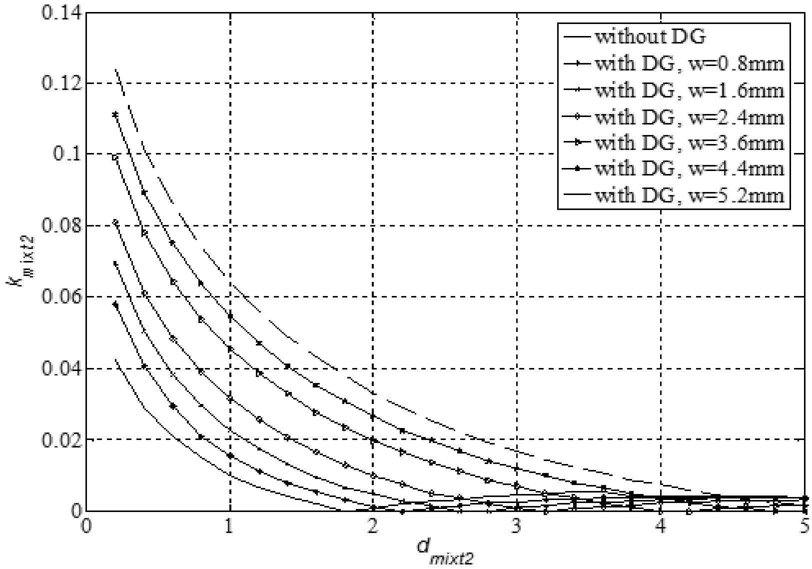


Fig. 8. Type-II mixed coupling coefficient, k_{mixt2}, *vs.* coupling gap, d_{mixt2} (in mm).

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}.

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) the coupling coefficient k_{mixt2} 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 d_{mixt2} 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.

4. Bandpass filters design and simulation

Based on the above results, some 4-pole cross-coupled planar microwave BPFs with a single or with two ground slots were designed. These filters meet the following requirements: a center frequency $f_c = 2.4$ GHz, a bandwidth $B = 168$ MHz, fourth order Chebyshev response with an in-band return loss $R_L = 20$ dB. The filters should exhibit two attenuation poles at the frequencies of 2.23 GHz and 2.56 GHz.

The extended coupling matrix **M**, obtained using the procedure shown in [6] and an in-house developed program, corresponds to a filter having a topology easy to be realized in the form of a planar bandpass filter, composed of four identical microstrip resonators [7]:

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

The layout of such a filter with four hairpin resonators is shown in Fig 9. The input and output lines, directly coupled with resonators no. 1 and 4, have widths of 2.9 mm, assuring standard 50 Ω terminations for the filter.

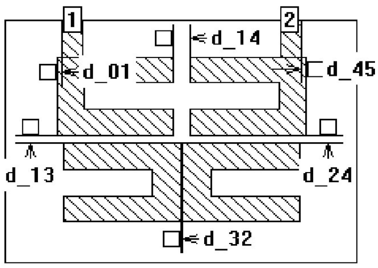


Fig. 9. Layout of the BPF
in a classical microstrip technology.

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 **M** by a de-normalizing procedure [8]. The de-normalized coupling values are shown in Table 1. The corresponding gaps, as resulted from the 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_{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. 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, 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, 2 and 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. The gaps between resonators and the dimensions of the DG configuration

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. 10, 11 (single slot) and in Figs. 12, 13 (two slots).

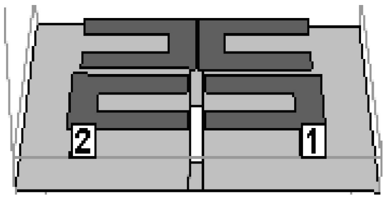


Fig. 10. Slot under electric coupling.

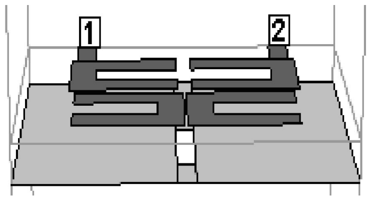


Fig. 11. Slot under magnetic coupling.

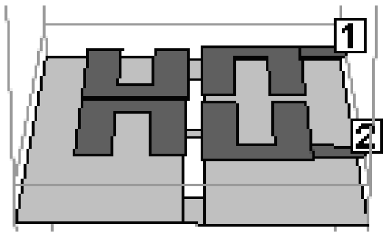


Fig. 12. Slots under type-I mixed couplings.

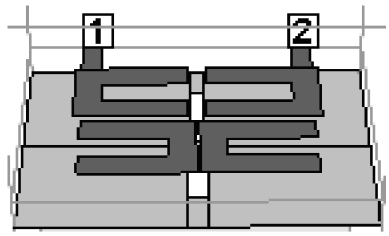


Fig. 13. Slots under electric and magnetic couplings.

In comparison with the filters shown in Figs. 10–12, the BPF from Fig. 13 has two ground slots placed under two different (electric and magnetic) couplings. The performances of this filter are shown in Fig. 16.

The EM-simulated performances of the designed defected ground bandpass filters plotted in Figs. 14–16 are, in general, very close 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. 14–16

BPF	f_c [MHz]	B [MHz]	R_L [dB]	f_{pole1} [MHz]	f_{pole2} [MHz]
w/o slot	2400	150	17	2218	2450
Fig. 10	2404	160	17	2210	2540
Fig. 11	2390	152	20	2212	2523
Fig. 12	2425	159	18	2198	2560
Fig. 13	2390	151	15	2195	2524

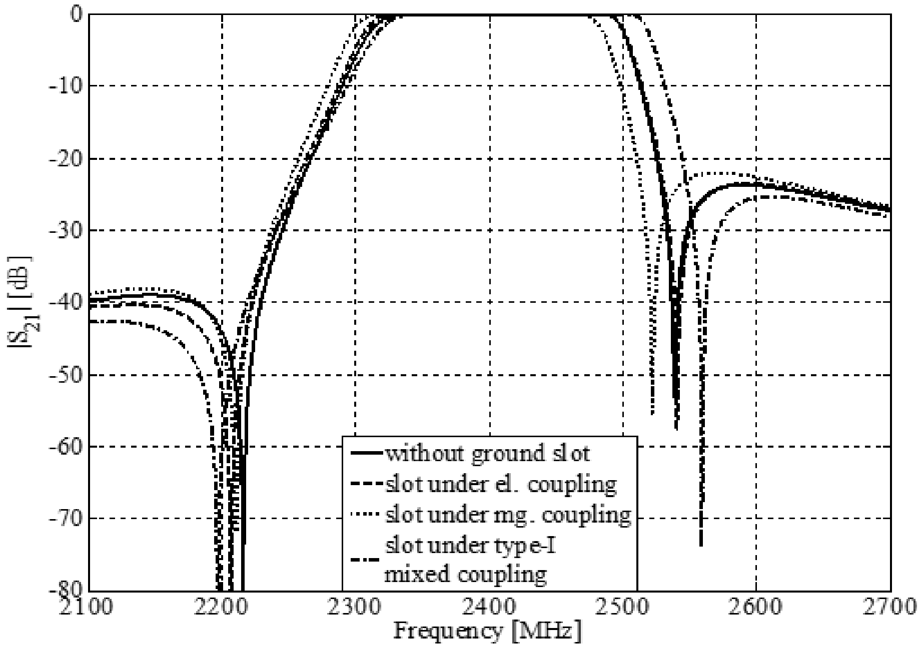


Fig. 14. Simulated $|S_{21}|$ of the filters from Fig. 9, Figs. 10, 11 and Fig. 12, *vs.* frequency.

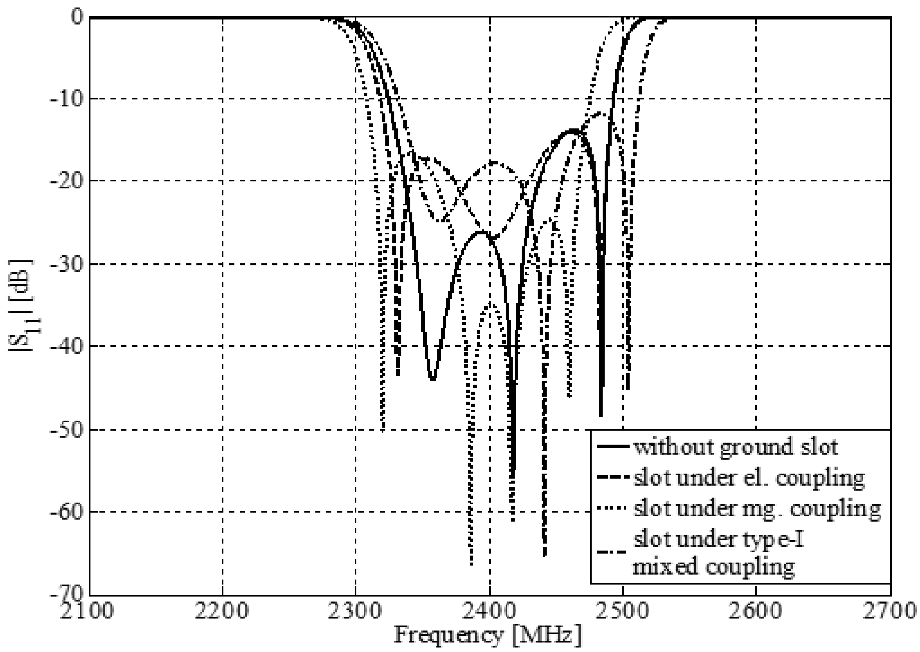


Fig. 15. Simulated $|S_{11}|$ of the filters from Fig. 9, Figs. 10, 11 and Fig. 12, *vs.* frequency.

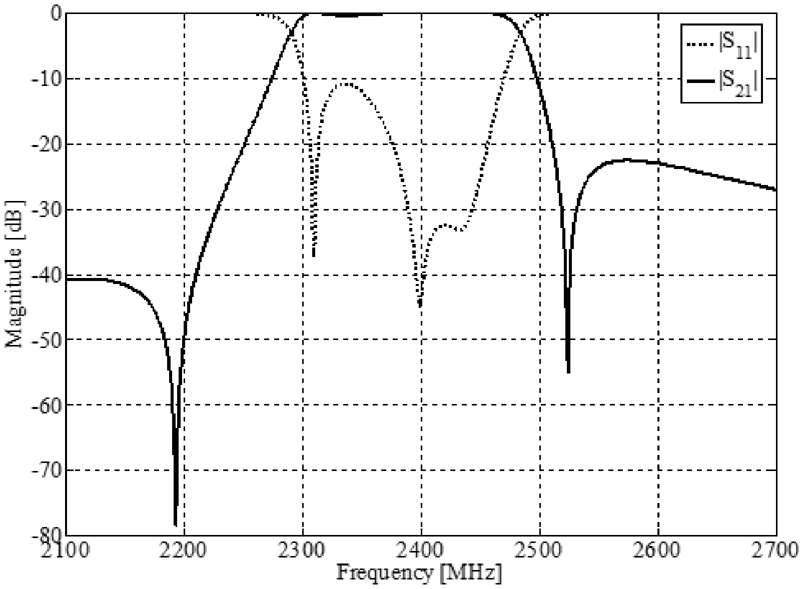
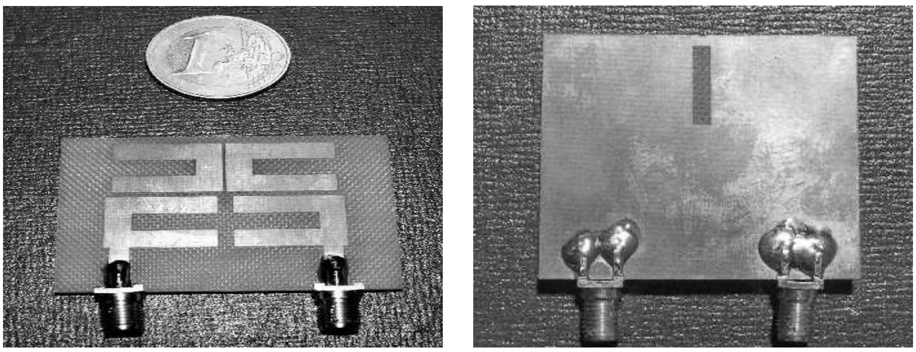


Fig. 16. The performances of the BPF with two slots from Fig. 13.

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.

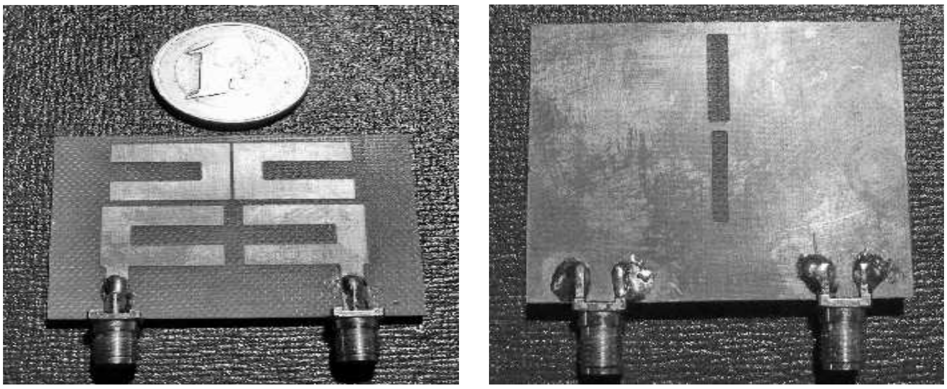
5. Experimental results

Based on the EM-field simulation results, two bandpass filters have been fabricated and measured. Photographs of these structures are shown in Fig. 17 and in Fig. 18.



a) top view b) bottom view

Fig. 17. Photograph of the bandpass filter with a slot under the magnetic coupling.



a) top view b) bottom view

Fig. 18. Photograph of the bandpass filter with two slots, under the electric and magnetic couplings.

The measured performances are plotted in Fig.19 and in Fig. 20.

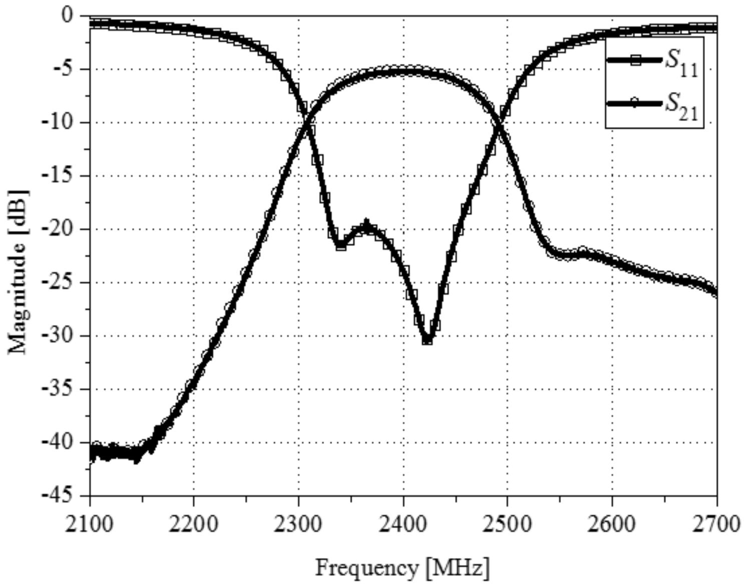


Fig. 19. Measured frequency response of the BPF from Fig. 17.

Both filters exhibit a center frequency of 2.4 GHz and a relatively high in-band insertion loss of 5.2 dB, mainly due to the use of the low-cost substrate FR4.

The 3dB bandwidth is of about 160 MHz for the BPF with a slot under the magnetic coupling, and of 156 MHz for the filter with slots under both electric and magnetic couplings.

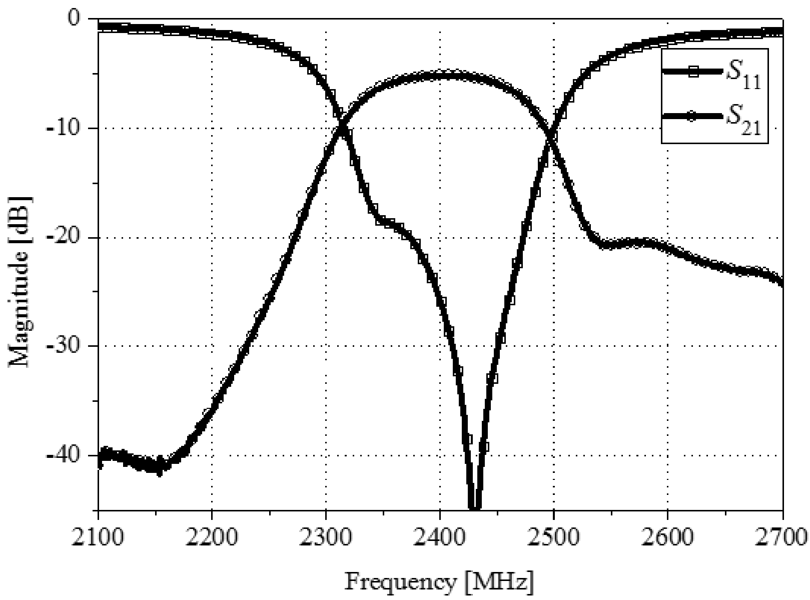


Fig. 20. Measured frequency response of the BPF from Fig. 18.

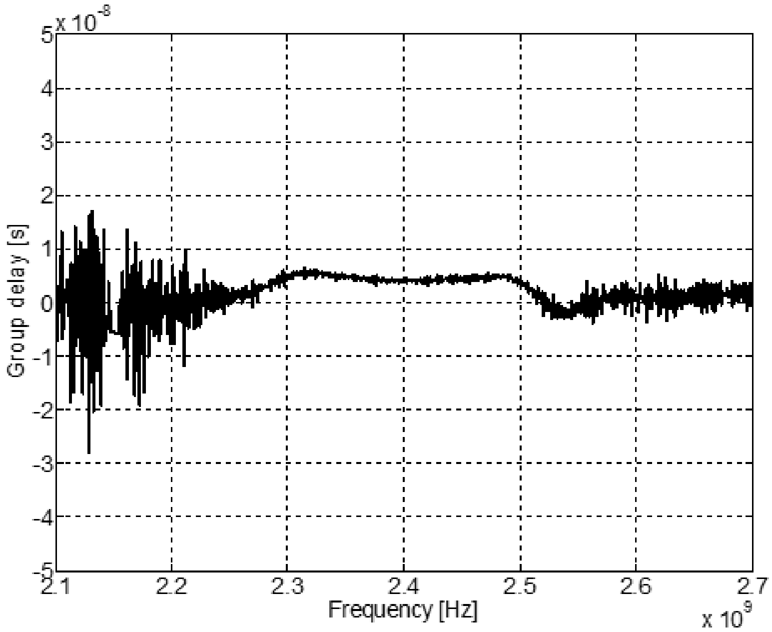


Fig. 21. Measured group delay of the bandpass filter from Fig. 17.

The measured group delay characteristics for both filters, shown in Fig. 21 and in Fig. 22, are approximately constant in the filters' passband.

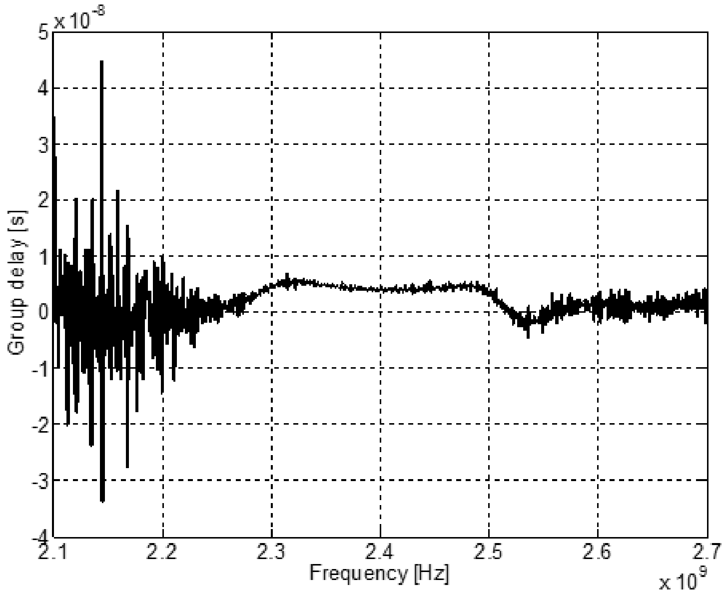


Fig. 22. Measured group delay of the bandpass filter from Fig. 18.

6. Conclusions

The main advantage of the BPF with ground slots stays in the possibility of using larger gaps between resonators. This solution is especially convenient when tight couplings are needed.

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

The designed filters – one with a ground slot under the magnetic coupling and the other with two slots under electric and magnetic couplings – were fabricated and tested. The measured frequency responses of these filtering structures demonstrated the validity of the design and of the EM-field simulations.

The DGS design can be also applied to many other types of bandpass filters, allowing a relaxation of the fabrication tolerances.

If better performances are required, lower loss substrates should be used.

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