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Novel microwave bandpass filters using defected-ground structures

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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 with a single and with two ground slots are designed, fabricated and measured. The performances of these novel structures indicate some technological advantages, compared to classical microstrip filters, without defected ground.

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Keywords: Filter, Defected ground, Transmission zeros, Cross-coupling, Extended coupling matrix, Hairpin resonator

1. Introduction

Many microwave design techniques make use of defected ground structures in order to improve the device performance. In multilayer circuits, the microstrip lines can be easily coupled through the ground slots [1]. Furthermore, slot antennas and slot-coupled antennas have been continuously improved and are extensively used in communications [2].

In this paper investigations on ground slot effects on the planar device characteristics are presented. For example, a slot in the ground plane can enhance the electric coupling, or the electric part of a mixed coupling between two adjacent hairpin 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 transmission zeros at imposed finite frequencies, with a single or with two ground slots. Two of these filtering structures were fabricated and measured.

2. Coupling configurations

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.

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

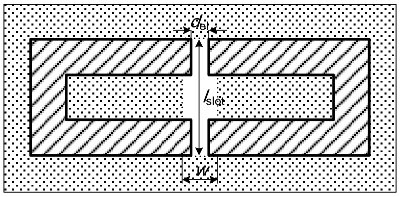


Fig. 1. Electric coupling configuration.

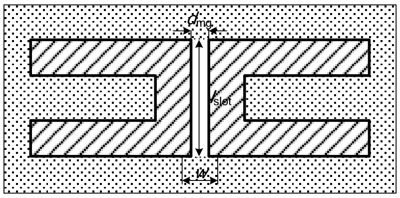


Fig. 2. Magnetic coupling configuration.

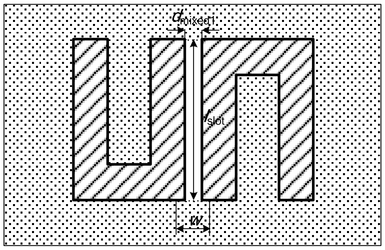


Fig. 3. Type-I mixed coupling configuration.

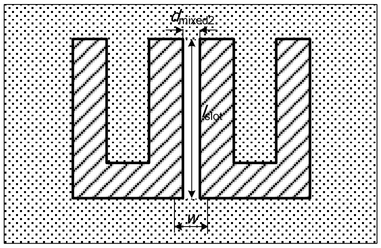


Fig. 4. Type-II mixed coupling configuration.

Here d_{el}, d_{mg}, d_{mixed1} and d_{mixed2} 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].

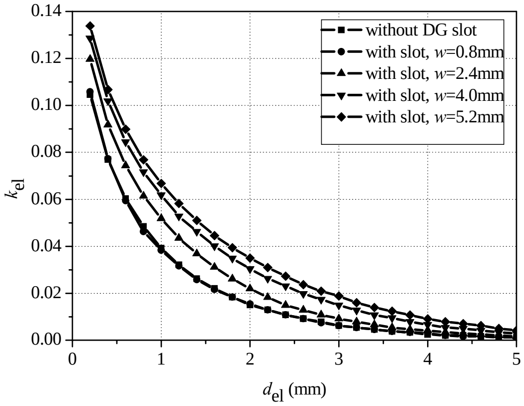


Fig. 5. Electric coupling coefficient vs. coupling gap.

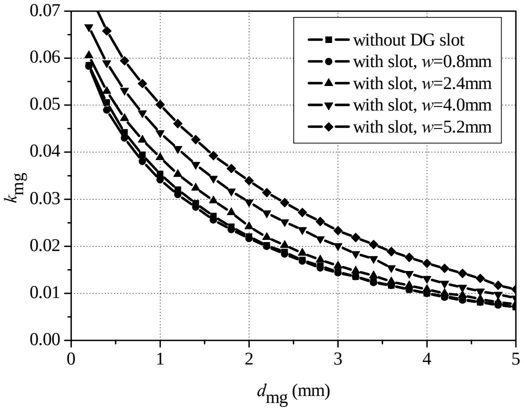


Fig. 6. Magnetic coupling coefficient vs. coupling gap.

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

Furthermore, as shown in Fig. 6, the magnetic coupling coefficient k_{mg} 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_{mixed1}.

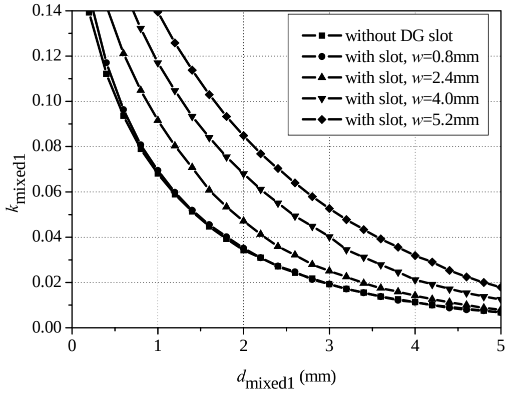


Fig. 7. Type-I mixed coupling coefficient vs. coupling gap.

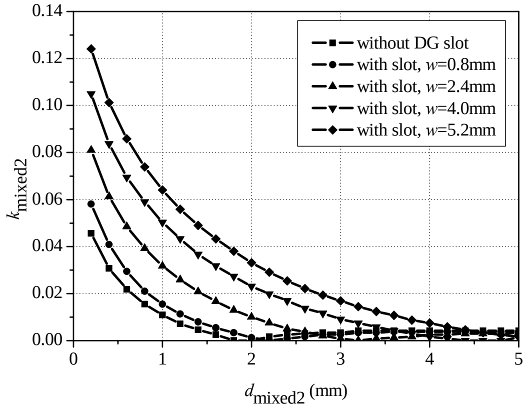


Fig. 8. Type-II mixed coupling coefficient vs. coupling gap.

The coupling coefficients decrease monotonically with the increase of the coupling gap for the electric, magnetic and type-I mixed couplings. However, for the type-II mixed coupling (Fig. 8), the dependence of the coupling coefficient k_{mixed2} on the coupling gap d_{mixed2} 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_{mixed2} 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. In view of the fact that, with the gap increase, the electric part of the coupling decreases faster than the magnetic part, the overall coupling coefficient exhibits a maximum, followed by a monotonic decrease. 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: 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 transmission zeros at the frequencies of 2.23GHz and 2.56GHz.

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 no. 4, have widths of 2.9 mm, assuring standard 50Ω terminations for the filter.

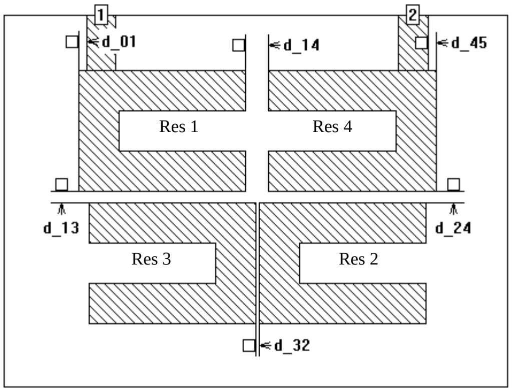


Fig. 9. Layout of the bandpass filter in a classical microstrip technology.

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-field simulation technique, are presented in Table 2.

Table 1.

Q_{ext}	$k_{1\text{-}3}$	$k_{2\text{-}3}$	$k_{2\text{-}4}$	$k_{1\text{-}4}$
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, 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.

Coupling type	Coupling coefficient	Gap (mm)	w (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

The EM-field simulated performances of the designed defected ground bandpass filters plotted in Figs. 10÷12 are, in general, very close to the filter requirements. Some relevant parameters of these frequency responses are summarized in Table 4.

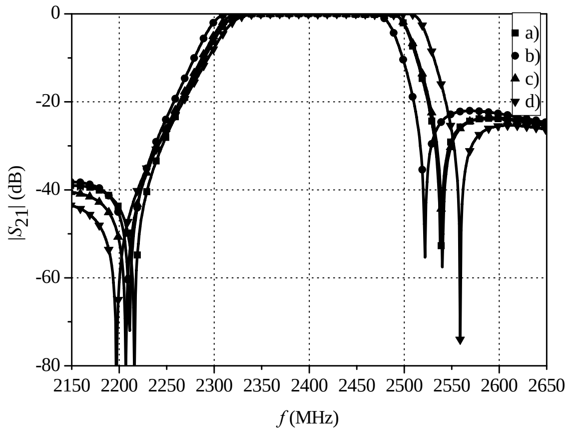


Fig. 10. Simulated $|S_{21}|$ of the filters, vs. frequency a) BPF without slot; b) with slot under the magnetic coupling; c) with slot under the electric coupling; d) with slots under the mixed couplings.

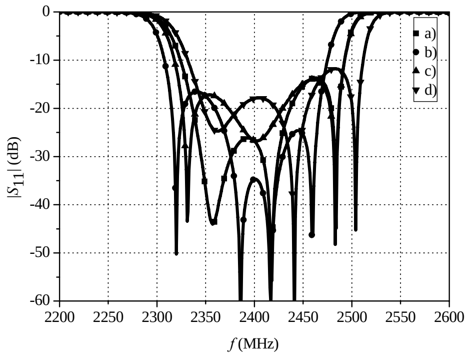


Fig. 11. Simulated $|S_{11}|$ of the filters, vs. frequency a) BPF without slot; b) with slot under the magnetic coupling; c) with slot under the electric coupling; d) with slots under the mixed couplings.

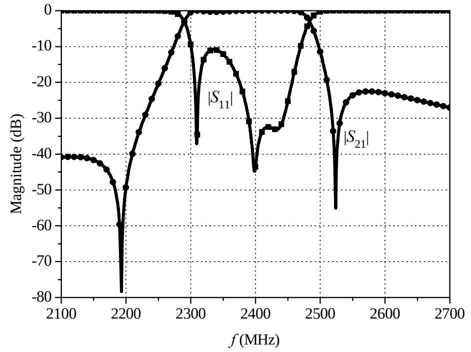


Fig. 12. The simulated performances of the filter with two ground slots placed under two different (electric and magnetic) couplings, vs. frequency.

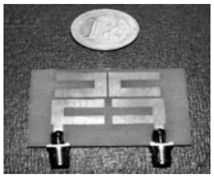
Table 4.

Bandpass filter	f_c (MHz)	B (MHz)	R_L (dB)	f_{pole1} (MHz)	f_{pole2} (MHz)
Fig.10,11.a	2400	150	17	2218	2450
Fig.10,11.c	2404	160	17	2210	2540
Fig.10,11.b	2390	152	20	2212	2523
Fig.10,11.d	2425	159	18	2198	2560
Fig. 12	2390	151	15	2195	2524

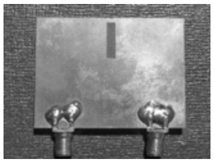
The increase of couplings in the presence of a ground slot has a simple physical explanation. For a conventional microstrip structure in the electric coupling configuration, many of the electric lines starting from a resonator end on the ground plane. In the presence of the slot, a part of these lines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

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. 13 and in Fig. 14. All experimental models have SMA connectors. For measurements, an HP8753C vector network analyzer was used.

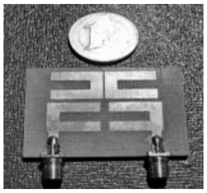


a) top view

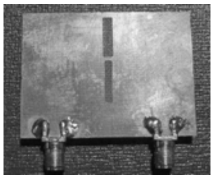


b) bottom view

Fig. 13. BPF with a slot under the magnetic coupling.



a) top view



b) bottom view

Fig. 14. BPF with slots under the electric and magnetic couplings.

The measured performances are plotted in Fig. 15 and in Fig. 16.

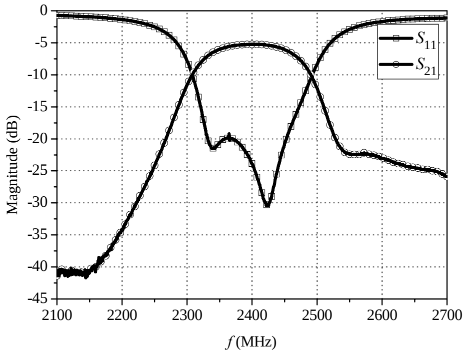


Fig. 15. Measured frequency response of the BPF from Fig. 13.

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

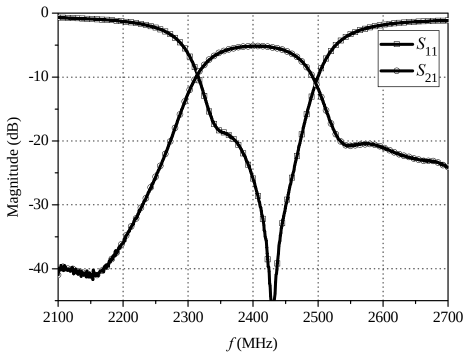


Fig. 16. Measured frequency response of the filter from Fig. 14.

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

6. Conclusions

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

The theoretical couplings for the designed filters 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-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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