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Microwave planar band-pass filters using defected ground microstrip structures

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Abstract – 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 microwave resonators. This technique allows designs of tight couplings without the necessity of using very narrow coupling gaps. Based on the results of this study, a 4-pole cross-coupled planar microwave band-pass filter (BPF) with a slot in the ground plane was designed. Compared to a similar microstrip filter without defected ground, its simulated performances indicate some advantages.

Keywords: filter, cross-coupling, defected ground

I. 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 investigations on the effects of a ground slot on couplings between hairpin resonators are presented. A slot in the ground plane can enhance the electric coupling, or the electric part of a mixed coupling between two resonators. The above results were used in the design of a 4-pole cross-coupled planar microwave band-pass filter (BPF) with a pair of attenuation poles at finite frequencies, and with a slot in its ground plane.

II. COUPLING CONFIGURATIONS

The configuration of the investigated microstrip defected-ground (DG) structures, presented in Fig.1., 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.

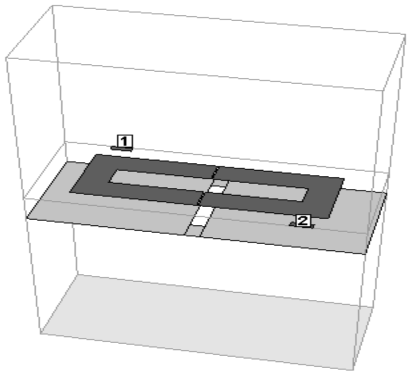

Fig. 1. Geometry of the investigated microstrip DGS

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

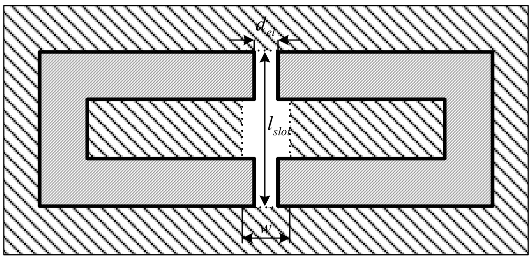

Fig. 2. Electric coupling configuration

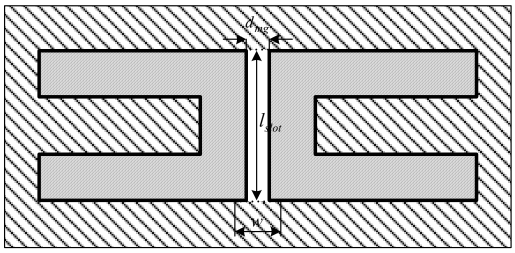

Fig. 3. Magnetic coupling configuration

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The slot length l_{slot} was of 12mm for the electric and magnetic coupling configurations, and 16.6mm for the mixed couplings. The width w was considered as a parameter, in order to study the effect of the ground slot on coupling between resonators.

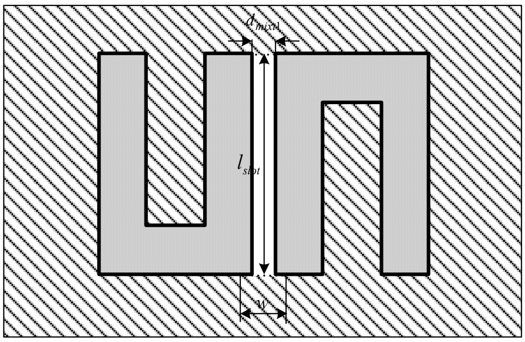

Fig. 4. Type-I mixed coupling configuration

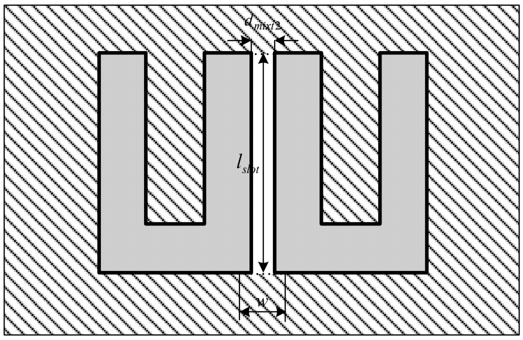

Fig. 5. Type-II mixed coupling configuration

The geometries of the electric and magnetic coupling configurations are shown in Fig.2. and in Fig.3. The geometries of the type-I and the type-II mixed couplings are shown in Fig.4. and Fig.5. 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, respectively.

III. 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 relation

$$k = \frac{f_{p2}^2 - f_{p1}^2}{f_{p2}^2 + f_{p1}^2}, \tag{1}$$

where f_{p1} and f_{p2} are the two split-resonance frequencies [6].

Fig.6. 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 the defected ground slot.

As shown in Fig.7., the magnetic coupling coefficient k_{mg} is slightly larger, compared to the classical microstrip structure.

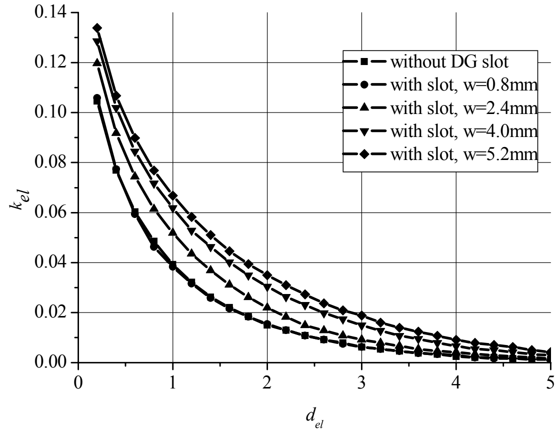

Fig. 6. Electric coupling coefficient, vs. coupling gap (in mm)

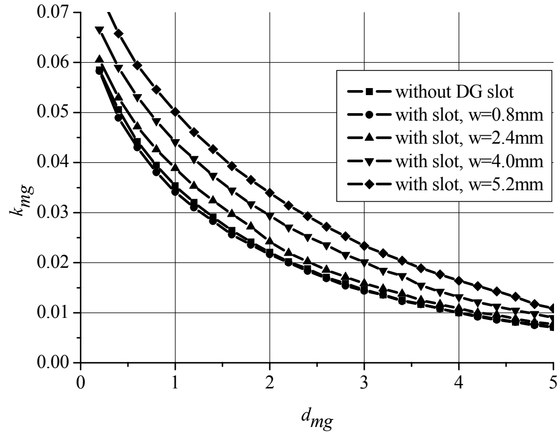

Fig. 7. Magnetic coupling coefficient, vs. coupling gap (in mm)

From Fig.8., it can be noticed that the presence of the slot leads to a significantly increased type-I mixed coupling coefficient k_{mixed1}.

For the electric and type-I mixed coupling coefficients versus the coupling gaps, a monotonic variation was obtained. However, for the type-II mixed coupling, a zero and a local maximum of the coupling coefficient k_{mixed2} 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_{mixed2}, 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.

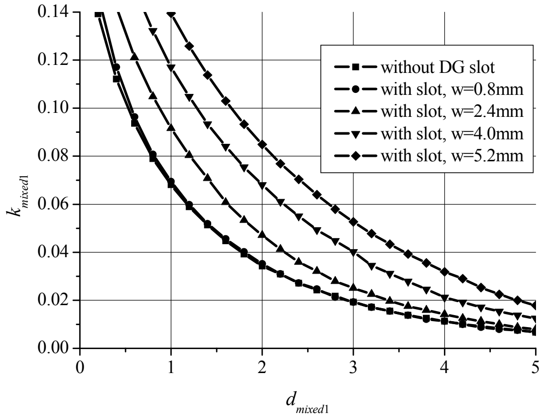

Fig. 8. Type-I mixed coupling coefficient, vs. coupling gap (in mm)

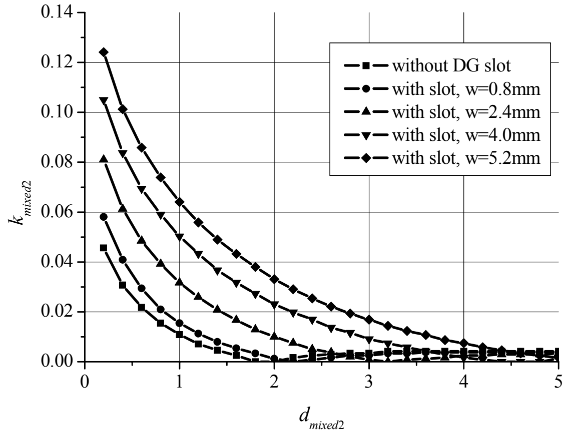

Fig. 9. Type-II of mixed coupling coefficient, vs. coupling gap (in mm)

This behavior is in agreement with other previous results [7] obtained for microstrip resonators without slots in the ground plane.
The results shown in Fig.9. can be used in designing planar band-pass filters with topologies containing type-II mixed couplings.

IV. BAND-PASS FILTER DESIGN AND SIMULATION

Based on the above results, a 4-pole cross-coupled planar microwave band-pass filter with a slot in the ground plane was designed. This band-pass filter meets the following specifications: a center frequency of 2400MHz, a frequency bandwidth of 168MHz, (a 3dB fractionary bandwidth of 7%), and a 4-th order Chebyshev response with a return loss of 20dB in the pass-band. The filter should exhibit two attenuation poles at the frequencies of 2232MHz and 2568MHz.
Using the procedure developed 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 normalized frequencies:

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

$$f_{z1} = \frac{1}{FBW}\left(\frac{f_2}{f_0} - \frac{f_0}{f_2}\right) \cong \frac{f_2 - f_0}{\Delta f} = 2 \qquad (3)$$

The obtained matrix,

$$\mathbf{M} = \begin{bmatrix} 0 & 0.371111 & 0.62138 & -0.62138 & -0.37111 & 0 \\ 0.371111 & -1.2872 & 0 & 0 & 0 & 0.37111 \\ 0.62138 & 0 & 0.6904 & 0 & 0 & 0.62138 \\ -0.62138 & 0 & 0 & -0.6904 & 0 & 0.62138 \\ -0.37111 & 0 & 0 & 0 & 1.2872 & 0.37111 \\ 0 & 0.37111 & 0.62138 & 0.62138 & 0.37111 & 0 \end{bmatrix} \qquad (4)$$

corresponds to a transversal 4-th order canonical filter satisfying the specified requirements. Such a filter is almost impossible to be fabricated. However, starting from this **M** matrix, other **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 (4), one gets:

$$\mathbf{M}' = \begin{bmatrix} 0 & -1.02356 & 0 & 0 & 0 & 0 \\ -1.02356 & 0 & 0 & -0.87057 & -0.17046 & 0 \\ 0 & 0 & 0 & -0.76726 & 0.87057 & 0 \\ 0 & -0.87057 & -0.76726 & 0 & 0 & 0 \\ 0 & -0.17046 & 0.87057 & 0 & 0 & 1.02356 \\ 0 & 0 & 0 & 0 & 1.02356 & 0 \end{bmatrix} \qquad (5)$$

The matrix (5) 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. The layout of such a filter with four hairpin resonators is shown in Fig.10. 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.

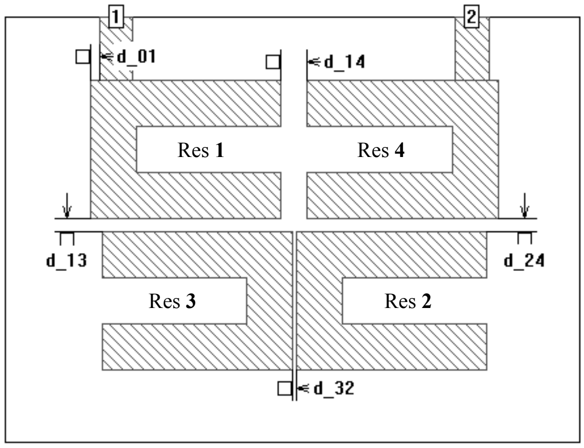

Fig. 10. Layout of the BPF in a classical microstrip technology

The design of the filter from Fig.10. stays in finding the gaps *d*, in order to obtain the necessary 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 a full-wave EM-field simulation technique, are presented in Table 2.

Table 1

$Q_{ext0\text{-}1}$	$k_{1\text{-}3}$ (type I mixed)	$k_{1\text{-}4}$ (electric)	$k_{2\text{-}3}$ (magnetic)	$k_{2\text{-}4}$ (type-I mixed)
13.6	0.0609	0.0119	0.0537	0.0609

Table 2

$d_{0\text{-}1}$ [mm]	$d_{1\text{-}3}$ [mm]	$d_{1\text{-}4}$ [mm]	$d_{2\text{-}3}$ [mm]	$d_{2\text{-}4}$ [mm]
0.8	1.18	2.3	0.3	1.18

The necessary magnetic coupling coefficient $k_{2\text{-}3}$ needs a very narrow gap $d_{2\text{-}3}$, of only 0.3mm, technologically hardly to obtain. For a defected ground structure, the same value of the magnetic coupling coefficient can be obtained with the configuration from Fig.3., for a ground slot of 2.8mm width and 12mm length, and for a gap $d_{2\text{-}3}$ between the resonators 2 and 3 of 0.4mm.

The 3D view of the complete structure of the BPF with a slot in the ground plane is shown in Fig.11.

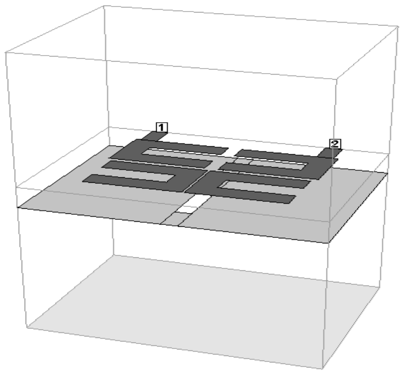

Fig. 11. 3D view of the DG band-pass filter

The EM-simulated performances of the designed band-pass filters are plotted in Fig.12. and Fig.13.

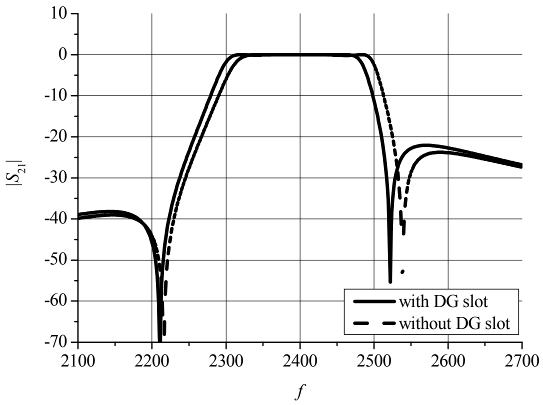

Fig. 12. $|S_{21}|$ (in dB) of the filters from Fig. 10. and Fig. 11., vs. frequency f (in MHz)

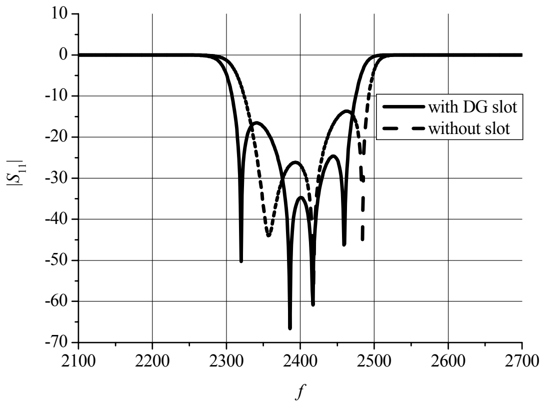

Fig. 13. $|S_{11}|$ (in dB) of the filters from Fig. 10. and Fig. 11., vs. frequency f (in MHz)

It can be noticed that these simulated characteristics are, in general, close enough to the filter requirements.

The filter from Fig.10. exhibits its first attenuation pole at a frequency of 2220MHz, very close to the specification, while the second attenuation pole is located at a frequency of 2540MHz, slightly different to the requirement. The resulted bandwidth is of 150MHz, slightly inferior to the specifications.

The frequency characteristics of the filter with a ground slot are also in good agreement with the specifications.

The presence of the slot leads to a frequency shift of almost 10MHz for $|S_{21}|$, while the in-band return loss seems to be improved, in comparison to the filter without ground slot.

The main advantage of the BPF with a slot stays in the possibility of using a larger gap between resonators 2 and 3 and thus to relax fabrication tolerances.

V. CONCLUSIONS

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.

These results were used in the design of a BPF with a ground slot. The needed couplings were obtained using an in-house developed program.

The filter's layout was designed after a study of the coupling coefficients versus gaps, based on EM-field simulation.

EM-simulation of the designed defected ground filter structure showed the possibility of using larger gaps between resonators, when tight couplings are needed. This design technique can be applied to many other types of band-pass filters, allowing a relaxation of the fabrication tolerances.

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