Comparison of Planar Fractal Filters on Defected Ground Substrate

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Abstract: *The paper discusses approaches to the reduction of dimensions of planar filters (microstrip ones and coplanar ones). Filter dimensions are reduced by applying the fractal theory to the geometry of a filter, and by the defecting of the ground plane of a filter. An optimum combination of both approaches enables us to reach smaller dimensions of planar filters and protect other parameters.*

In order to demonstrate advantages of the fractal defected ground approach, we review the designs of existing low-pass filters with defected ground structures (DGS). Results produced by simulations of these filters are compared with results of simulations of a novel fractal DGS filter. The investigated filters are manufactured and measured.

Keywords

Planar filters, fractals, defected ground structure.

1. Introduction

Usually, we try to design microwave circuits, which require minimum dimensions of a substrate. This is the case of planar filters also. The decrease of dimensions of a designed planar filter can be achieved by several ways.

First, minimum dimensions of a filter can be achieved by increasing permittivity of a substrate. Unfortunately, substrates with a higher permittivity support the excitation of surface waves. In order to suppress surface waves, the filter has to be completed by an electromagnetic band gap structure [4], [5].

Second, we can design a planar filter above a defected ground. The defected ground structure (DGS) is created by slots etched into the ground plane.

As a fundamental work in the area of planar low-pass filters with a defected ground, a paper authored by D. Ahn et al. [11] can be considered. In this paper, the authors etched two square slots connected by a narrow slotline to the metallic ground plane of a microstrip transmission line. That way, authors created a resonant circuit providing low-pass filtering. Composing a filter from several square couples of different dimensions, the bandwidth of the filter could be synthesized [12]. Replacing the microstrip trans-

mission line by a planar filter, high-order filters could be built on small-dimension substrates [13].

In our approach, the square slot is understood as the zero iteration of the Minkowski loop. In our design, we increase the order of iteration of the Minkowski loop so that the dimensions of the filtering structure can be reduced.

The reduction of dimensions of planar filters by applying principles of the fractal theory was described in [6] and [7]. Thanks to the fractal geometry, we can create longer current lines on a smaller area. Longer current lines can increase values of reactive elements in the equivalent resonant circuit of the DGS (see Fig. 1). That way, the cutoff frequency of the DGS structure is decreased, and dimensions of DGS units can be reduced [14].
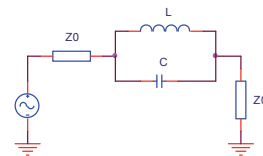

Fig. 1. Equivalent resonant circuit of the DGS.

In this paper, we discuss an optimum combination of a DGS approach, which was introduced in [11] to [13], and a fractal approach, which was described in [6] and [7]. This development is aimed to reach even smaller dimensions of planar filters.

Section 2 is devoted to the design of a low-pass filter with a fractal DGS. An optimum combination of defects in the ground plane [11], [12] with the fractal prolongation of current lines [6], [7] on the bottom side of the substrate, and exploitation of conventional planar filters on the top side of a substrate [14] enables us to reach even smaller dimensions of a filtering structure when preserving other parameters of filters. The described technique is the original contribution of the paper.

In order to demonstrate the advantages of the proposed technique with the relation to the existing ones, we review:
- A fractal microstrip DGS filter [1] in Section 3;
- A fractal coplanar DGS filter [2], [3] in Section 4.

Filters from Sections 3 and 4 are recalculated so that all the filters to be compared cover the same pass band.

Filters are primarily modeled in CST Microwave Studio, which performs the electromagnetic analysis using the time-domain finite integration technique.

Section 5 concludes the paper. In conclusions, we compare properties of the novel compact low-pass filter and properties of existing solutions, reviewed in the paper. Results of simulations are verified experimentally.

2. Novel Compact Low-Pass Filter

The low-pass filter with a fractal DGS was designed on the substrate Arlon 25N with the relative permittivity $\varepsilon_r = 3.38$ and the thickness $h = 0.76$ mm. The filter consisted of two parts:

- A conventional low-pass filter on the top side of the substrate;

- A six-element fractal DGS on the bottom side of the substrate.

First, we designed a conventional low-pass filter with stubs separated by transmission lines. The layout of the filter is depicted in Fig. 2. The design procedure was adopted from [9]. The conventional filter was of the 11th order. The 3dB bandwidth of the designed filter was 4.60 GHz.
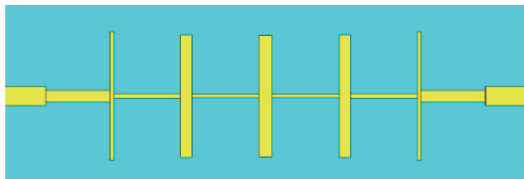

Fig. 2. Layout of the low-pass filter with stubs separated by transmission lines.

Dimensions of the designed filter are given in Tab. 1. Here, w_i is the width of lines and l_i is the length of lines. The layout of the designed filter is symmetric with respect both to the horizontal axis and to the vertical one.

Parameter	Dimension (mm)	Parameter	Dimension (mm)
w	1.79	l	3.93
w_1	1.12	l_1	6.18
w_2	0.35	l_2	12.33
w_3	0.44	l_3	6.38
w_4	1.09	l_4	11.70
w_5	0.30	l_5	6.44
w_6	1.26	l_6	11.61

Tab. 1. Dimensions of the conventional low-pass filter above the solid ground plane. Substrate: ARLON 25N, $\varepsilon_r = 3.38$, $h = 0.76$ mm.

The frequency response of the return loss S_{11} and the insertion loss S_{21} of the conventional low-pass filter 11th order over the solid ground plane are shown in Fig. 5 (blue lines).

Second, we designed a filter, which consisted of a 50 Ω microstrip transmission line on the top side of the substrate, and a six-element fractal DGS on the bottom side

of the substrate. The filter is depicted in Fig. 3. The designed filter exhibited the bandwidth 4.60 GHz.
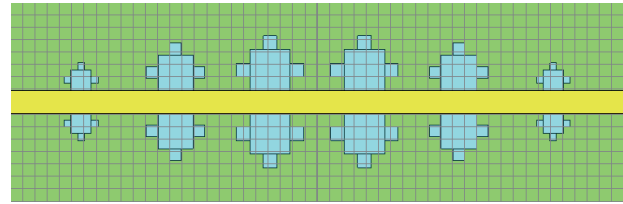

Fig. 3. Layout of the 50 Ω microstrip transmission line completed by the six-element fractal DGS.

Two square holes with the side a connected by a narrow slot line with the length w and the width g were a basic shape of the DGS as explained in [11]. We call the connected couple of squares the Minkowski couple of the zero iteration. The period of Minkowski couples is $d = 2a$.

The first iteration of the Minkowski couple is created as follows:

- The sides of the squares are divided into three identical segments;

- The central segments are moved for $a/3$ from the squares center (see Fig. 4).

The reduction of dimensions of the Minkowski couples in the fractal DGS follows the values of the normalized Chebyshev coefficients (see Tab. 2) [10].

Number of elements	Chebyshev coefficients
5	0.308; 0.808; 1.000; 0.808; 0.308
6	0.501; 0.866; 1.000; 1.000; 0.866; 0.501
7	0.222; 0.624; 0.901; 1.000; 0.901; 0.624; 0.222

Tab. 2. Normalized Chebyshev coefficients.

The frequency response of the return loss S_{11} and the insertion loss S_{21} of the 50 Ω microstrip transmission line above the six-element fractal DGS are shown in Fig. 5 (red lines).
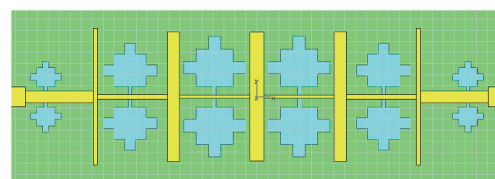

Fig. 4. Layout of a novel compact low-pass filter consisting of a filter with stubs separated by transmission lines and a fractal DGS.

A novel compact low-pass filter was formed by associating the conventional low-pass filter with stubs separated by transmission lines of the 11th order (the top side of the substrate) and the six-element fractal DGS (the bottom side of the substrate). When associating these two filters, the 3 dB bandwidth was decreased from the original value 4.60 GHz to 3.43 GHz. Hence, we can reach much lower frequencies with a structure of the same dimensions.

The frequency response of the return loss S_{11} and the insertion loss S_{21} of the novel compact filter is shown in Fig. 5 (green lines).
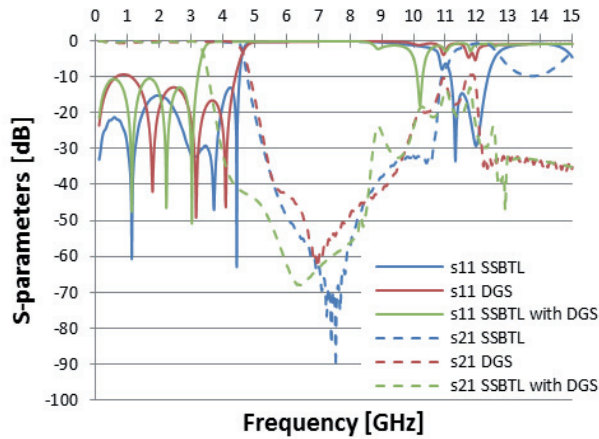
Fig. 5. Frequency response of return loss S_{11} (solid) and insertion loss S_{21} (dashed) of a low-pass filter with stubs separated by transmission lines above a solid ground plane (blue), 50 Ω transmission lined above the fractal DGS (red), low-pass filter with stubs separated by transmission lines above the fractal DGS (green).

In order to demonstrate the influence of fractal motifs to the properties of studied filters, we compared frequency responses of scattering parameters of a 50 Ω microstrip transmission line on the top side of the substrate and six Minkowski couples on the bottom side of the substrate. The Minkowski couples were:

- Of the zero iteration (squares) and the identical dimensions (blue lines in Fig. 6);

- Of the zero iteration and the reduction of dimensions of the Minkowski couples in the fractal DGS follows the values of the normalized Chebyshev coefficients (see Tab. 2);

- Of the first iteration and the reduction of dimensions of the Minkowski couples in the fractal DGS follows the values of the normalized Chebyshev coefficients (see Tab. 2).

Frequency responses of scattering parameters of the designed structures are depicted in Fig. 6. Obviously, the fractal Minkowski couples with the exponentially decreasing dimensions exhibited the lowest cutoff frequency (4.60 GHz), the highest attenuation in the stop band, and a significantly low return loss in the passband.

The novel compact low-pass filter was manufactured (Fig. 8) and measured (Fig. 7). Fig. 7 shows that the low-pass filter has a 3 dB pass band of 3.20 GHz with a ripple level of 0.44 dB. The maximum reflection loss equals to −15.06 dB. The measured reflection loss is for 4.41 dB better compared to the simulation. The low-pass filter exhibits a stop band with a maximum attenuation of 67.330 dB at a frequency of 6.53 GHz, the 6.56 GHz bandwidth with a transmission under −20 dB and the 4.89 GHz bandwidth with a transmission under −40 dB. The selectivity of the measured filter is 43.21 dB/GHz.
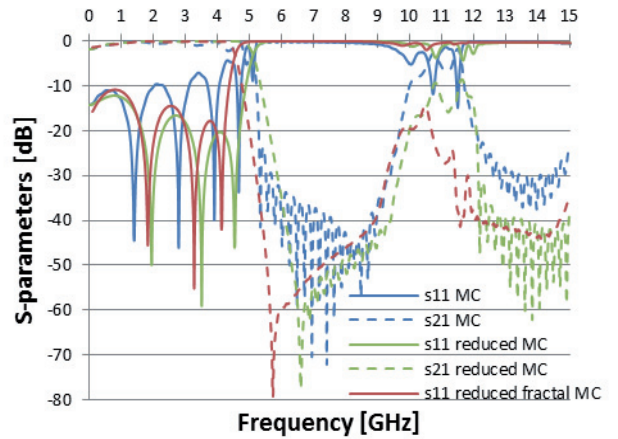

Fig. 6. Frequency response of return loss S_{11} (solid) and insertion loss S_{21} (dashed) of a filter with DGS created by Minkowski couples (blue lines), DGS created by reduced Minkowski couples (green lines), DGS created by reduced fractal Minkowski couples (red lines).

The designed filter was fabricated and measured. The measured results are in good agreement with simulated results.
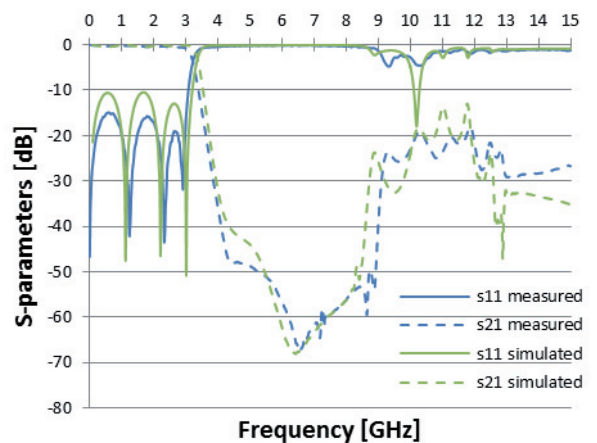

Fig. 7. Frequency response of the return loss (solid) and the insertion loss (dashed) of the simulated compact low-pass filter (green) and the measured one (blue).

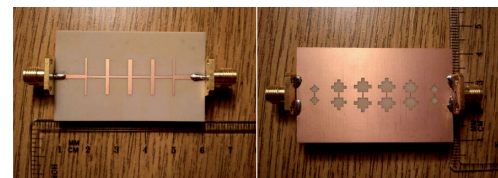The novel compact low-pass filter was 50 mm long and 30 mm wide.

Fig. 8. Photograph of the manufactured compact low-pass filter: the top layer (left), the bottom layer (right).

In the following sections, we will redesign DGS fractal filters, which were published in an open literature. In the redesign, we consider the same substrate and the same cutoff frequency as in case of the novel compact low-pass filter. Then, we can compare properties of existing solutions.

3.　Fractal Microstrip DGS Filter

The fractal microstrip low-pass filter with DGS of the 11th order was described in [1]. The filter was created by seven transmission lines and six squares on the top side of the substrate, and five squares etched in the ground plane on the bottom side of the substrate (see Fig. 9). The period d of squares on the top side and etched squares in the ground plane was half of the wavelength (Bragg´s condition). The dimension of the fractal factor was d, and the size of the main squares was half of the period (the fractal factor) d. The layout of the filter is symmetric to the vertical axis).

The filter was designed with a 3 dB bandwidth 3.80 GHz. The dimensions of the fractal microstrip DGS filter are shown in Tab. 3, where w_i is the width of the line, e_i is the width of squares on the top side of the substrate, a_i is the width of etched squares in the ground plane on the bottom side of the substrate and d is the period.
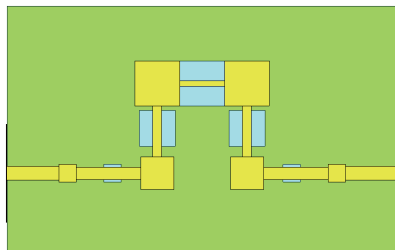

Fig. 9.　Layout of the fractal microstrip DGS filter.

The fractal microstrip DGS filter was recalculated for the substrate Arlon 25N and the cutoff frequency 3.43 GHz.

The fractal microstrip DGS filter was manufactured (Fig. 10) and measured (Fig. 11).

Fig. 11 shows the frequency response of the return loss S_{11} and the insertion loss S_{21} of the manufactured filter. Obviously, the 3 dB pass band of the filter is 3.34 GHz, a ripple level is 0.29 dB, and a maximum reflection loss is –20.86 dB.

Parameter	Dimension (mm)	Parameter	Dimension (mm)
a	5.57	e_2	4.07
a_1	5.57	e_3	2.17
a_2	4.46	w	1.72
a_3	2.17	w_3	1.53
d	11.14	w_4	1.08
e_5	5.57	w_5	0.64

Tab. 3.　Dimensions of the fractal microstrip DGS filter. Substrate: ARLON 25N, $\varepsilon_r = 3.38$, $h = 0.76$ mm.

The fractal microstrip DGS filter has a stop band with a maximum attenuation of 55.45 dB at a frequency 6.15 GHz, the 7.50 GHz bandwidth with a transmission under –20 dB and the 1.17 GHz bandwidth with a transmission under –40 dB. The selectivity of the measured filter is 17.84 dB/GHz.

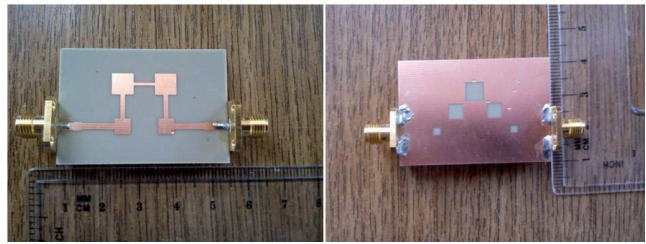The measured results are in good agreement with the simulation results.

Fig. 10.　Photo of the manufactured fractal microstrip DGS filter: the top layer (left), the bottom layer (right).
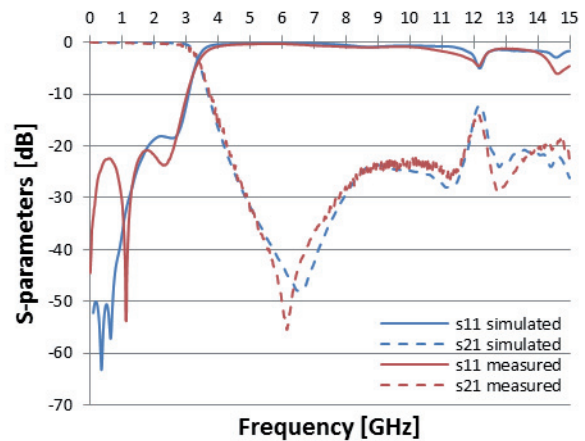

Fig. 11.　Frequency responses of the return loss (solid) and the insertion loss (dashed) of the simulated filter (blue) and the measured one (red). The fractal microstrip DGS filter.

The fractal microstrip DGS filter was 44 mm long and 30 mm wide.

4.　Fractal Coplanar DGS Filter

The fractal coplanar DGS filter of the 8th order was described in [2], [3]. The coplanar filter was created by eight Minkowski loops with a period d, which corresponds to half of the wavelength. The fractal factor of the Minkowski loop is one third of the size of the main square a. The dimensions of the new square (the first iteration) are the width $a_1 = a/3$ and the height $a_2 = 0.83\,a_1$. The layout of the fractal coplanar DGS filter is shown in Fig. 12.
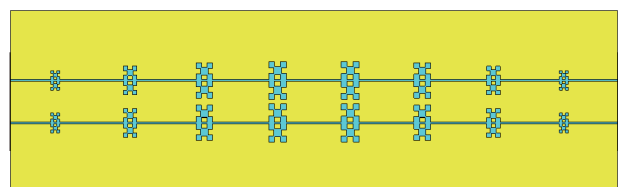

Fig. 12.　Layout of the fractal coplanar DGS filter.

This filter was designed with a 3 dB bandwidth 12.40 GHz. The filter was recalculated for the substrate Arlon 25N and the cutoff frequency 3.43 GHz. The dimensions of the fractal coplanar DGS filter are shown in Tab. 4, where d is the period between the neighboring squares with Minkowski loops, and x_i is the width of the basic squares.

Parameter	Dimension (mm)	Parameter	Dimension (mm)
d	16.70	x_3	2.00
x_0	4.00	w	9.00
x_1	3.72	w_1	0.32
x_2	3.00		

Tab. 4. Dimensions of the fractal coplanar DGS filter. Substrate: ARLON 25N, $\varepsilon_r = 3.38$, $h = 0.76$ mm.

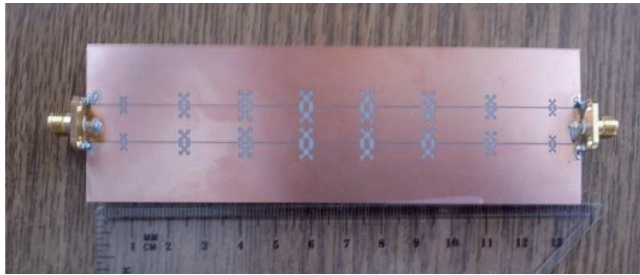The fractal coplanar DGS filter was manufactured (Fig. 13) and measured (Fig.14).

Fig. 13. Photograph of the fractal coplanar DGS filter.

Fig. 14 shows the frequency response of the return loss S_{11} and the insertion loss S_{21} of the manufactured filter. Fig. 14 shows that the manufactured filter has a 3 dB pass band of 3.59 GHz with a ripple level of 0.460 dB and a maximum reflection loss of −11.44 dB.

The fractal coplanar DGS filter has a stop band with a maximum attenuation of 45.01 dB at a frequency 5.64 GHz, the 3.70 GHz bandwidth with a transmission under −20 dB and the 2.30 GHz bandwidth with a transmission under −40 dB. The selectivity of the measured filter is 19.99 dB/GHz.

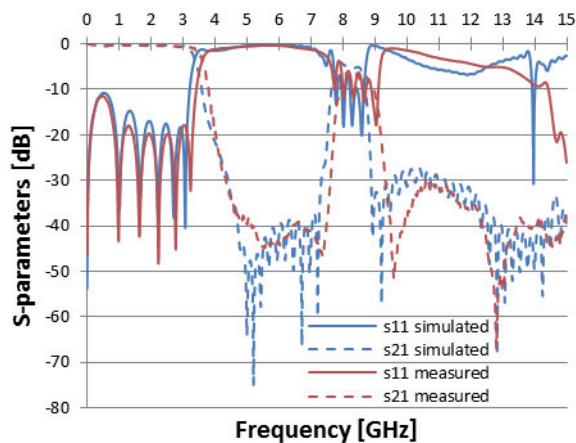The measured results are in good agreement with the simulation results.

Fig. 2. Frequency response of the return loss (solid) and the insertion loss (dashed) of the simulated filter (blue) and the measured one (red). The fractal coplanar DGS filter.

5. Summary

In the paper, we presented a novel low-pass filter with stubs separated by transmission lines above the ground plane with a fractal DGS. We compared this novel compact filter with the fractal microstrip DGS filter and the fractal coplanar DGS filter.

Fig. 15 and Tab. 5 show that all filters exhibit a frequency shift of cutoff frequency:

- The novel compact filter was shifted from the value 3.43 GHz to the value 3.20 GHz;

- The fractal microstrip DGS filter was shifted from the value 3.43 GHz to the value 3.34 GHz;

- The fractal coplanar DGS filter was shifted from the value 3.43 GHz to the value 3.59 GHz.

The best parameters were achieved by the novel compact filter of the 11th order. This filter exhibits the strongest attenuation in the stop band (67.33 dB) and the selectivity 43.21 dB/GHz. Moreover, the layout of this filter occupies the second smallest area of the substrate (50 × 30 mm).

The fractal microstrip DGS filter of the 11th order exhibits the worst attenuation in the stop band (about 12 dB worse value than the novel compact) and the worst selectivity (about 26 dB/GHz). On the other hand, the fractal microstrip DGS filter occupies the smallest area of the substrate (44 × 30 mm).

The fractal coplanar DGS filter of the 8th order requires the largest substrate (135 × 40 mm). This filter exhibits a worse maximum attenuation in the stop band (45.01 dB) and a worse selectivity (19.99 dB/GHz) than the novel compact filter.

	Novel compact filter	Fractal microstrip DGS filter	Fractal coplanar DGS filter
Return loss [dB]	-15.06	*-20.86*	-11.44
Insertion loss [dB]	0.44	*0.29*	0.46
3 dB passband [Ghz]	3.20	*3.34*	3.59
Selectivity [dB/GHz]	43.21	*17.84*	19.99
Transmission under -20 dB [GHz]	6.56	*7.50*	3.70
Transmission under -40 dB [GHz]	4.89	*1.17*	2.30
Maximum attenuation [dB]	67.33	*55.45*	45.01
Frequency of max. attenuation [GHz]	6.53	*6.15*	5.64
Dimensions of filter [mm]	50 x 30	*44 x 30*	135 x 40

Tab. 5. Comparison of the measured values of filters.

The compared filters were fabricated and measured. The measured results are in good agreement with simulated ones (as shown in Fig. 15).
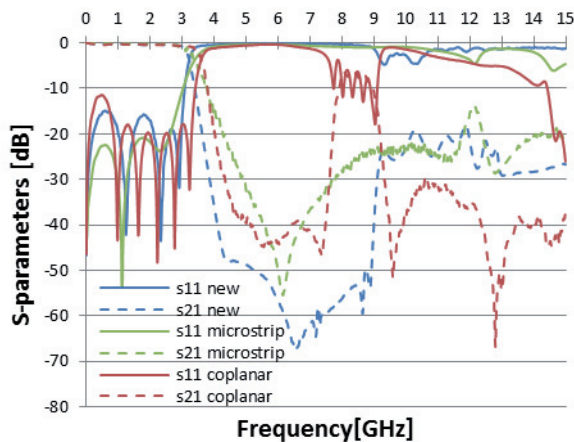

Fig. 15. Comparison of the measured filters.

Acknowledgements

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Zbyněk RAIDA has graduated at the Brno University of Technology (BUT), Faculty of Electrical Engineering and Communication (FEEC). Since 1993, he has been with the Dept. of Radio Electronics FEEC BUT. In 1996 and 1997, he was with the Laboratoire de Hyperfrequences, Universite Catholique de Louvain, Belgium, working on variational methods of numerical analysis of electromagnetic structures. Since 2006, he has been the head of the Dept. of Radio Electronics. Zbynek Raida has been working together with his students and colleagues on numerical modeling and optimization of electromagnetic structures, exploitation of artificial neural networks for solving electromagnetic compatibility issues, and the design of special antennas. Zbynek Raida is a member of IEEE Microwave Theory and Techniques Society.