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Compact Multilayer Bandpass Filter with Modified Hairpin Resonators

*Dejan Tošić and Milka Potrebić**

School of Electrical Engineering, University of Belgrade, Bulevar kralja Aleksandra 73, PO Box 35-54, 11120 Belgrade, Serbia.

Abstract: Compact selective bandpass filter, based on the Rhodes approximation, is proposed using the novel modified hairpin resonators realized on a double-sided microstrip. The equivalence is presented between the hairpin resonator realized on a single-sided microstrip and the modified hairpin resonator realized on a double-sided microstrip. The footprint area of the filter is reduced by 50% with the multilayer realization. The proposed design methodology is exemplified by a fourth-order multilayer bandpass filter, which is fabricated and measured. The simulated and measured results are in agreement.

Key words: Bandpass filter, modified hairpin resonator, multilayer realization, Rhodes approximation

Kompaktni večslojni pasovni prepusti filter z modificiranimi resonatorji v obliki lasnic

Povzetek: Predlagan je kompaktni selektivni prepustni pasovni filter na osnovi Rhodesove aproksimacije in uporabe novih modificiranih resonatorjev v obliki lasnic. Filter je realiziran na dvostranskem mikrotraku. Predstavljena je primerjava med lasničnimi resonatorji na enostranskem in dvostranskem mikrotraku. Površina odtisa filtra je pri uporabi večslojne realizacije zmanjšana za 50 %. Predlagana metodologija dizajna je predstavljena na, izdelanem in izmerjenem, večslojnem propustnem pasovnem filtru četrtega reda. Rezultati simulacij se dobro ujemajo z meritvami

Ključne besede: prepustni pasovni filter, modificiran lasnični resonator, večslojna izvedba, Rhodesova aproksimacija

** Corresponding Author's e-mail: milka_potrebic@etf.rs*

1. Introduction

With the development of modern wireless communications, designing compact and high-performance microwave filters in communication systems is largely required, which exhibit frequency and time-domain requirements.

Among the bandpass filter types, the parallel-coupled half-wavelength resonator filter (PC λ/2) has been widely used for filter structures in wireless systems up to now because of its simple design and easy to control the bandwidth by changing the coupling strength between resonators [1]. However, this filter realization is too large to be used for wireless handset communication systems, where engineers are always looking for smaller microwave components [2]. Several microstrip single-layer structures have been proposed in order to minimize the filter size: the U-turn hairpin [3] resonator, the open-loop resonator [4], the slow-wave resonator [5], and the spiral resonator [6] reduce the size of the parallel-coupled line resonator by folding the resonators to get a more compact configuration.

Another method to reduce the size of filter realizations consists on using multilayer structures. In [7, 8], multilayer bandpass filters, based on resonators with different geometries (square-loop, hairpin, etc.), have been proposed. This multilayer topology consists of two layers of microstrip hairpin resonators. Each resonator itself is printed on a single layer. To ensure couplings between the resonators in the upper layer and those in the lower one, two rectangular slots are etched in a common ground plane placed between the two layers. Using this configuration, the size of the proposed filter can be reduced to half that of conventional microstrip filters.

In this paper, a new method for filter size reduction has been proposed. A novel double-sided microstrip realization of a narrow bandpass filter is presented that uses modified hairpin resonators (MHR). Arms of each resonator are printed in different layers – the upper and the lower dielectric layer separated by a common ground plane, which can be referred to as a double-sided microstrip. There is no coupling between the arms of the proposed resonator. The arms are connected by a via which passes through the structure without electrical connection to the common ground plane. The undesirable couplings between resonators are minimized as follows: (a) the arm on the lower layer (of each resonator) is shifted with respect to the arm on the upper layer, (b) the structure is housed in a metallic box, and (c) the distance between the top/bottom cover and dielectric is about substrate thickness.

We compare the characteristics (frequency response and footprint) of the hairpin microstrip realization and the proposed multilayer realization. We explain the design methodology and show the results generated by electromagnetic (EM) simulation and the measurement results made on the fabricated structure. Hence, conclusions are drawn about the performance of the analyzed structure.

2. Design of Modified Hairpin Resonators for Multilayer Bandpass Filter

As is known, the open-line resonator (Figure 1a), implemented on a single layer, is folded to form the hairpin resonator (Figure 1b) in order to reduce the size of the parallel-coupled half-wavelength resonator filter (Figure 2a). In the hairpin filter (Figure 2b) the separation between arms (d_0) should be large enough to minimize undesirable coupling between the arms, so that the equivalence of Figure 1 holds.

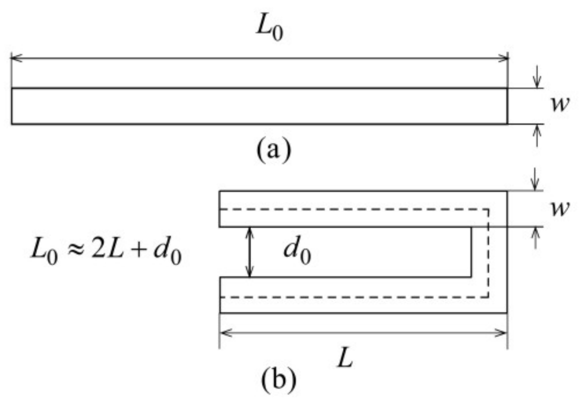

Figure 1: Standard realization of (a) the open-line and (b) the hairpin microstrip resonators.

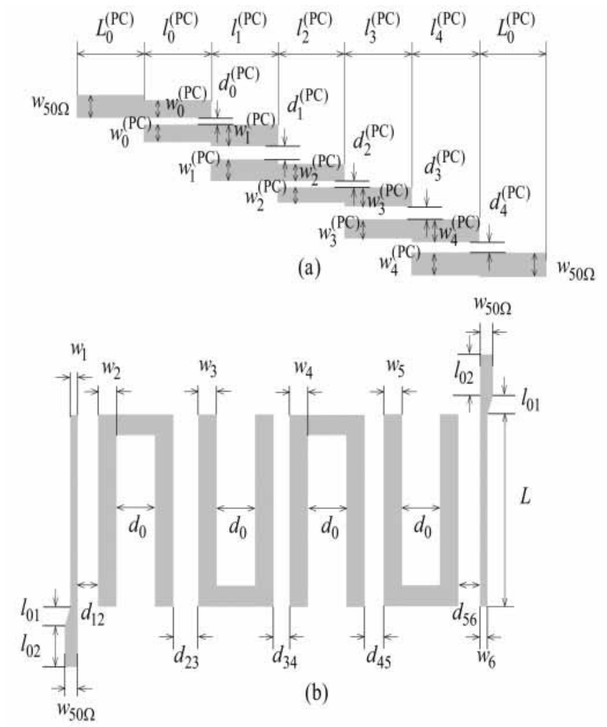

Figure 2: (a) The parallel-coupled half-wavelength resonator filter, (b) the hairpin filter.

To measure the undesirable coupling between the arms of a hairpin resonator we analyzed a symmetrical pair of coupled microstrip lines, and computed (1) the ratio between elements of the characteristics impedance matrix $r_c=|Z_{c12}/Z_{c11}|$ and (2) the ratio between transmission scattering parameters $r_1=|S_{21}/S_{31}|$, $r_2=|S_{41}/S_{31}|$.

In this study, we use the Rogers RO4003C substrate: ε_r=3.55±0.5 [9], tanδ=0.0021, thickness of copper foil t = 0.03 mm, and thickness of substrate h = 0.508 mm. The resonant frequency is 2GHz, which corresponds to L0 = 45.3 mm and w = 1 mm. The distance between the hairpin resonator arms is taken from the range $3h \le d_0 \le 20h$ and L = 23 mm.

The ratios r_c, r_1, and r_2 have been computed for various d0. It was estimated that, from the filter design viewpoint, each ratio should be less than 0.01 in order to keep the undesirable coupling sufficiently low, Figure 3. Consequently, for the substrate considered the separation between the arms should be about 10h which increases the footprint of the hairpin filter.

A technique to reduce the undesirable coupling between the arms, and to keep d_0 as small as possible, is to house the filter in a metallic box. The distance, designated by h_u, between the top cover and dielectric is found to be within the range $h \le h_u \le 2h$.

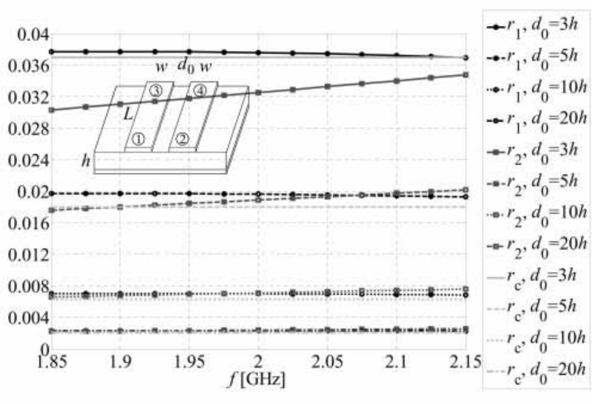

Figure 3: Measure of undesirable coupling between the arms of the hairpin resonator from Figure 1b.

In this paper, we present a new method of further reducing the size of the resonators that constitute the filter by printing the arms in two layers. This multilayer topology consists of two dielectric layers separated by a metallic foil (common ground plane). One arm of a hairpin resonator is printed on the top layer and the other arm is printed on the bottom layer as shown in Figure 4. Since the dielectric layers are separated by a common ground plane, there is no coupling between the arms. The arms of a resonator are connected by a via that passes through the structure without electrical contact with the common ground plane. The length of the via is $H = 2h + h_0 \approx 2h$, where $h_0 = 2t$.

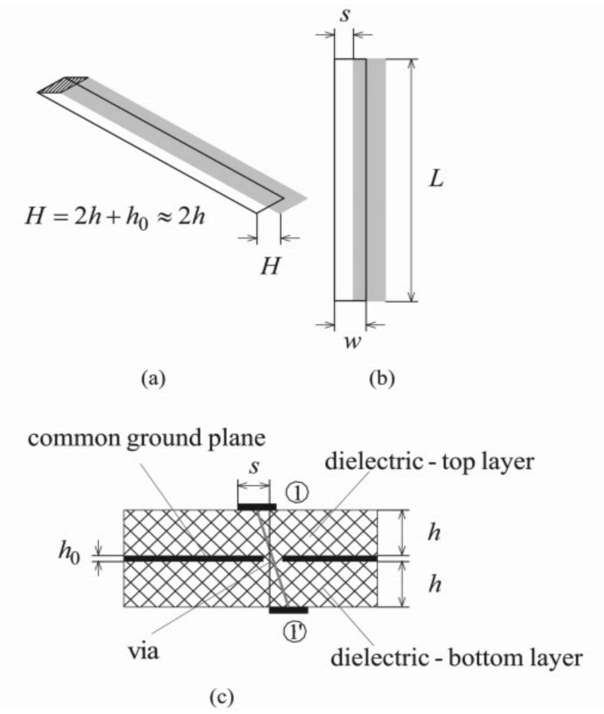

Figure 4: Modified hairpin resonator: (a) 3D view (without the dielectric and common ground plane), (b) top view, and (c) cross section.

The proposed resonators are edge-coupled with quarter-wavelength sections. In order to realize this coupling with only quarter-wavelength sections, the arm on the lower layer (of each resonator) is shifted (for *s*) with respect to the arm on the upper layer (Figure 4b-c). This arrangement of resonator arms minimizes the undesirable couplings between resonators.

Two edge-coupled modified hairpin resonators are shown in Figure 5. The distance between the coupled quarter-wavelength sections is *d*. The shift between the arms of each resonator is designated by s_i, $i = 1,2$. Sometimes, the distance between the arms of adjacent resonators (D_0) is not sufficient to minimize the undesirable coupling between adjacent sections (on the same side) which should not be coupled. In this case, housing a structure in a metallic box is used to reduce undesirable couplings with the distance between the top/bottom cover and dielectric of $h \leq h_u \leq 2h$.

The main idea of the method is to reduce the size of a hairpin filter by transforming its resonators into a multilayer structure, but without deteriorating the filter performance. With this approach, the size reduction is about 50%.

This method can be summarized as follows:
Step 1. Design the optimal single layer hairpin filter housed in a metallic box.
Step 2. Modify the hairpin filter by printing each resonator in two layers. Preserve the resonator width, the distance (gap) between the edge-coupled quarter-wavelength sections, and the length of the arms. A short microstrip line which connects the arms in a single layer design is replaced by a thru via in a multilayer design. To achieve the equivalence between the single layer hairpin resonator and the multilayer modified hairpin resonator, the length of the via and the via pad should correspond to the line that connects the arms. House the multilayer filter in a metallic box and preserve the distance between the top/bottom cover and dielectric as designed in Step 1.
Step 3. Find the minimal distance D_0 between two adjacent arms, printed on the same layer, that belong to adjacent resonators, but which should not be coupled.

3. Design Example and Experimental Results

In this paper, we consider the fourth-order bandpass filter centered at $f_0 = 2$GHz, with a relative bandwidth $B = 0.05$, and nominal impedances (at both ports) $Z_0 = 50\Omega$. The maximal insertion loss at the center frequency is $A_0 = 3.5$ dB and the return loss in the passband is

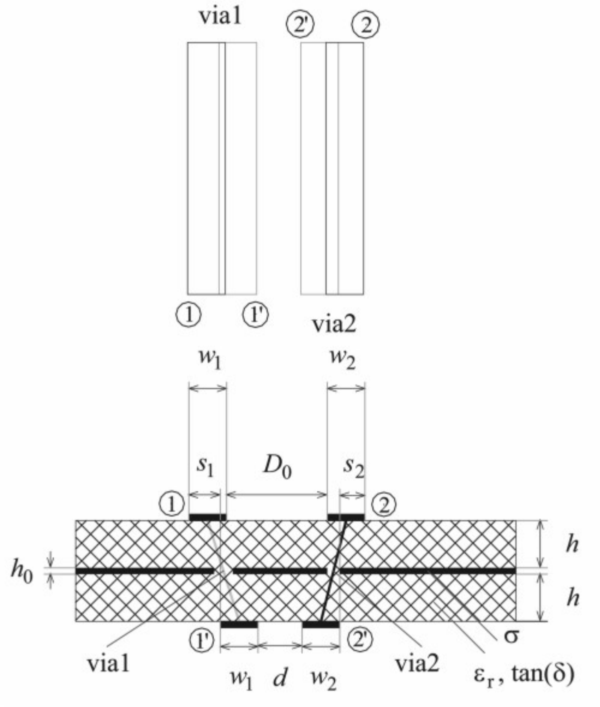

Figure 5: Two adjacent MHRs that are edge-coupled with quarter-wavelength sections.

better than 12 dB. The filter is based on the Rhodes prototype [10], [11]. The filter is housed in a metallic box and the distance between the cover and the dielectric layer is $h_u = 1.5h$.

Coupling coefficients and external quality factors of the hairpin resonators are computed as described in [12]: $M_{12} = 0.032$, $M_{23} = 0.049$, $M_{34} = 0.091$, $Q_{ex1} = 29.94$, $Q_{ex4} = 9.77$.

To estimate the range of possible widths and gaps between the hairpin resonators, first we designed the corresponding parallel-coupled half-wavelength resonator filter with the metallic cover. The dimensions of coupled lines are determined to correspond to the even- and odd-mode impedances $(Z_{0e})_{j,\,j+1}$ and $(Z_{0o})_{j,\,j+1}$ [13], Table 1. It was found that the relevant ranges are: $0.5(w^{(PC)})_{min}<w<1.5(w^{(PC)})_{max}$ (0.3mm<w<1.3mm) and 0.1mm<d<0.8mm [14].

Table 1: Dimensions of the PC λ/2 filter ($L_0^{(PC)}$=5mm, $w_{50\Omega}$=0.87mm).

			all dimensions are in mm			
i	$Z_{0e}[\Omega]$	$Z_{0o}[\Omega]$	$w_i^{(PC)}$	$d_i^{(PC)}$	$l_i^{(PC)}$	$w_{i,cor}^{(PC)}$
0	64.075	41.171	0.752	0.172	24.445	0.88
1	52.638	47.614	0.863	0.651	24.225	0.88
2	54.193	46.412	0.853	0.496	24.249	0.88
3	58.119	43.902	0.819	0.3	24.323	0.88
4	78.073	37.992	0.59	0.1	24.658	0.59

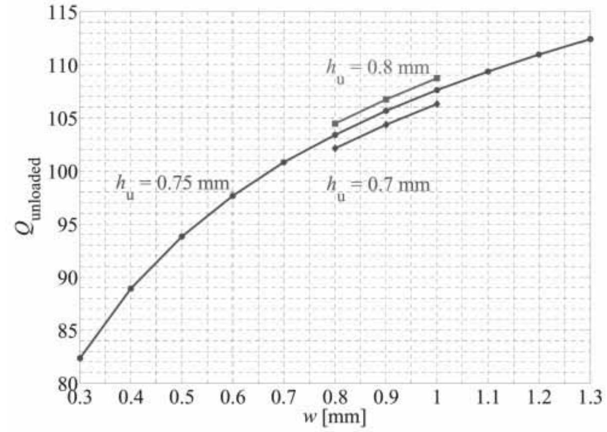

Figure 6: Design curve of unloaded Q-factor of half-wavelength resonator as a function of the line width.

The unloaded Q-factor for the resonators is estimated by using the expected midband filter loss A_0:

$Q_u = \frac{4.343}{B A_0}\sum_{i=1}^{N} g_i$ [dB]=105.28, where g_i, i=1,...N, are the lowpass prototype parameters and N is a filter order. The unloaded Q-factor of a half-wavelength resonator is shown in Figure 6, as a function of the line width. Q-factor of the actual fabricated resonator can be sensitive to the manufacturing processes and depends on the distance between the metallic top cover and dielectric. Therefore two additional curves are presented in Figure 6, for h_u=0.7mm and h_u=0.8mm. For expected midband filter loss A_0, we have found that the initial width of the half-wavelength resonator is $w_0^{(PC)}$=0.88mm.

3.1. Covered hairpin filter

To find the optimal dimensions of hairpin resonators we proceed as follows: (1) if the line width $w^{(PC)}$ differs more than 25% from the initial value $w_0^{(PC)}$, we do not change this value; (2) for all other cases we set the line width to the initial value (see Table 1).

The initial length of the hairpin arm is L=22.9mm and the distance between the arms is d_0=5h=2.54mm. From the desired external quality factors, according to the design curves shown in Figure 7, we find the initial width of the feed line and coupling gap (separation) between the feed line and the corresponding resonator, Table 2.

The coupling gaps between resonators are found according to the design curves shown in Figure 8, as follows: d_{23}=0.63mm, d_{34}=0.45mm, and d_{45}=0.3mm, which correspond to the coupling coefficients M_{12}, M_{23}, M_{34} respectively.

The initial dimensions are refined by optimization and the corrected dimensions are presented in Table 3.

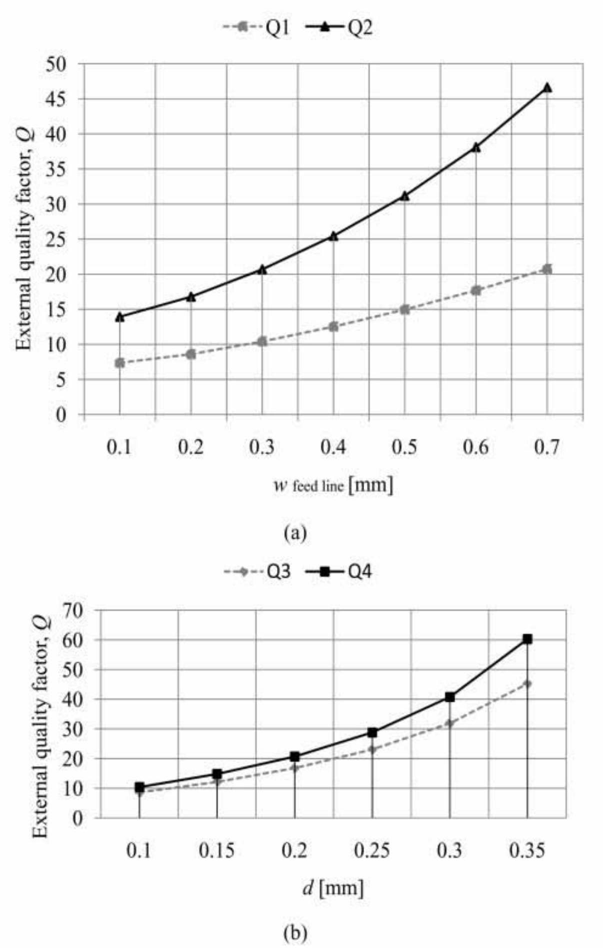

Figure 7: External quality factor for the hairpin bandpass filter when *w*=0.88mm: (a) Q1 for coupling gap (separation) *d*=0.1mm and Q2 for *d*=0.2mm, (b) Q3 for $w_{feedline}$=0.2mm and Q4 for $w_{feedline}$=0.3mm.

Table2: Dimensions of the feed lines and coupling gaps of the single layer hairpin filter.

	w_1	w_2	w_3	w_4	w_5	w_6	$w_{50\Omega}$	L
Initial	0.3	0.88	0.88	0.88	0.59	0.2	0.87	22.9
Optimized	0.3	0.9	0.96	0.89	0.61	0.23	0.87	22.86

	d_0	d_{12}	d_{23}	d_{34}	d_{45}	d_{56}	l_{01}	l_{02}
Initial	2.54	0.25	0.63	0.45	0.3	0.125	4.5	0.5
Optimized	2.54	0.2	0.63	0.45	0.27	0.13	4.5	0.5

Table 3: Dimensions of the single layer hairpin filter (all dimensions are in mm).

No. of port	First	Second
Width (feed line)	0.3 mm	0.2 mm
Coupling gap (feed line & resonator)	0.25 mm	0.125 mm
External Q-factor	30	9.8

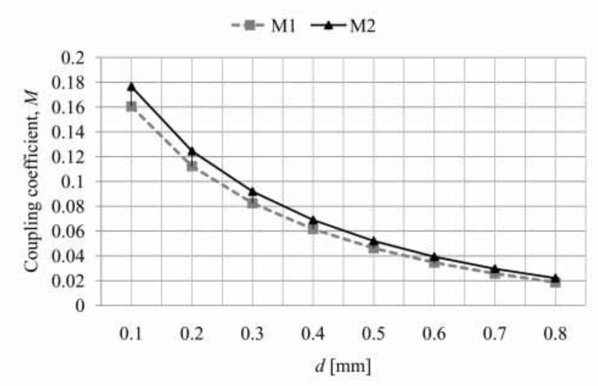

Figure 8: Coupling coefficient for the single layer hairpin filter: M1 for the identical hairpin resonators (w_1=w_2=0.88mm), M2for the resonators with different width (w_1=0.88mm, w_2=0.59mm).

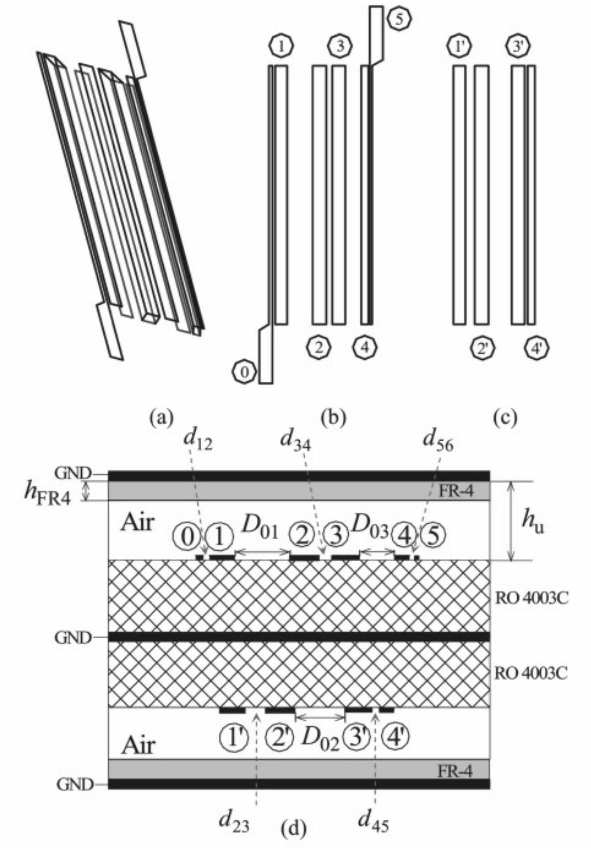

Figure 9: Configuration of the proposed multilayer filter: (a) 3D model (without common ground plane and dielectric layers), (b) top view – top conductor lines, (c) bottom view – bottom conductor lines, (d) cross section of multilayer filter with common ground plane (vias are not shown). The arms of resonators are numbered from 1 to 4 and the feed lines with 0 and 5.

3.2. Covered multilayer filter with modified hairpin resonators

The multilayer filter is obtained from the optimized single layer hairpin filter. The hairpin resonator and the modified hairpin resonator are electrically equivalent: the line width and the length of the arms are the same. In the multilayer filter, the modified hairpin resonator is realized with a via that connects the arms. The length of the via and the via pad should correspond to the line that connects the arms of a hairpin resonator in the single layer structure. The coupling gaps between the arms of adjacent modified hairpin resonators are the same as in the single layer realization.

In the multilayer filter, there are arms, on the same side of multilayer structure, which should not be coupled. The distance between these arms (D_0 in Figure 5) should provide a negligible coupling, but is limited by the via design and requirements for miniaturization. The optimal values of D_0 are D_{01}=1.9mm, D_{02}=1.72mm, and D_{03}=1.3mm . The configuration of the proposed multilayer bandpass filter is shown in Figure 9.

Frequency response of the covered hairpin filter and covered multilayer filter is shown in Figure 10. The curves are generated by circuit simulation [15] and verify the equivalence between the two filter realizations.

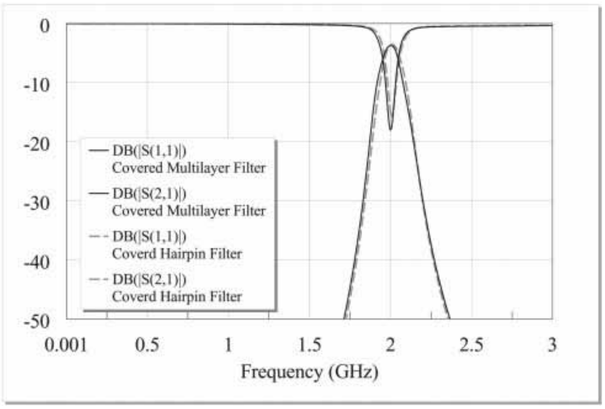

Figure 10: Scattering parameters of the equivalent circuit model of the single layer and the multilayer filter housed in a metallic box.

3.3. Experimental results

The fabricated multilayer filter has a footprint of $0.257\lambda_g$ x $0.072\lambda_g$, 24.86mm x 7.01mm (not including the feed lines and guard zone), where λ_g is the guided wavelength of a 50Ω line on the substrate at the center frequency. Thus, we can conclude that the proposed design achieves a size reduction of 50%, as compared to the conventional covered hairpin filters implemented on a single layer at the same band.

The structure is housed in a metallic box and the distance between both metallic covers (top and bottom) and dielectric is h_u=0.85mm, Figure 9d. The covers are realized with FR-4 laminate of 0.85mm thickness with t=18μm copper cladding on one side. With milling process [16] we removed almost all FR-4 substrate without digging into the copper foil. After milling, we have found that a thin dielectric layer of thickness h_{FR4}=0.4mm remained. This imperfection has been added in the final 3D EM model of the multilayer filter [17].

The filter dimensions are checked after fabrication in order to find the deviation from the designed values. It is found that the maximum deviation is 5μm.

The photograph of the fabricated filter is shown in Figure 11. The filter is measured using an Agilent E5062A network analyzer. The filter enclosure minimizes "leakage" of the energy from the electromagnetic field and hence reduces conducted emissions.

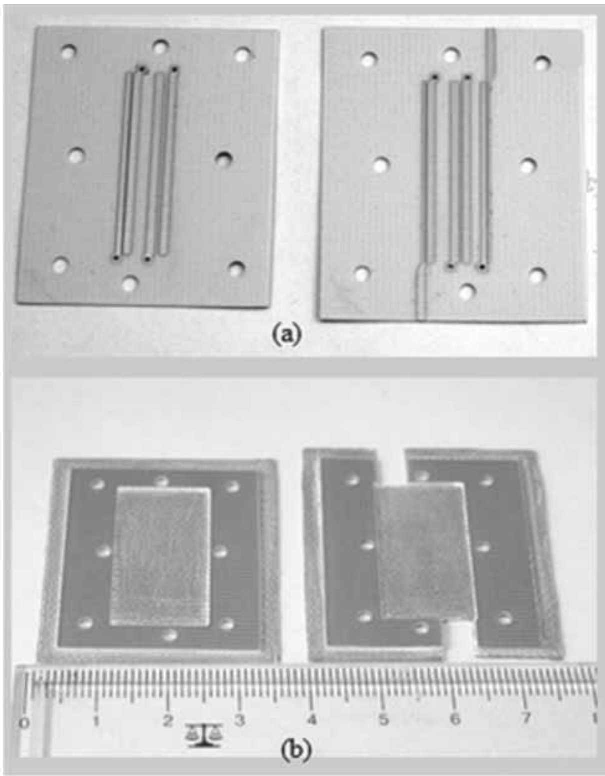

Figure 11: Photograph of the filter: (a) conductor lines – top/bottom view, (b) metallic top/bottom cover.

The simulated and measured response of the proposed filter is shown in Figure 12. Measured results have validated the theoretical analysis well. The filter has an insertion loss of 3.26dB at the central frequency (1.89GHz) due to the conductor and dielectric losses. The conductor losses dominate. The center frequency is shifted by 110MHz for several reasons: (1) the tolerance of ε_r of RO4003C substrate [9], (2) parasitic dielectric layer on the covers, and (3) the fabrication tolerances.

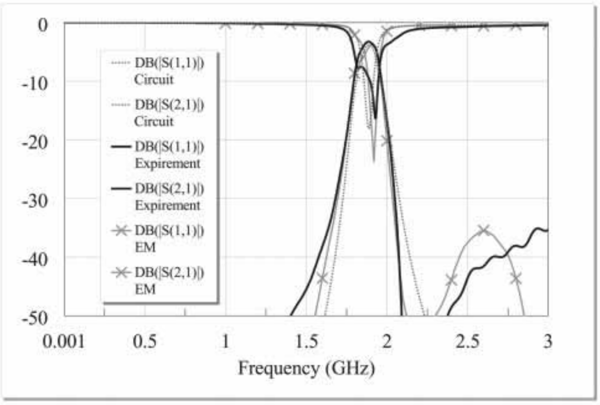

Figure 12: Scattering parameters of the covered multilayer filter with modified hairpin resonators: circuit simulation, EM simulation, and experiment.

4. Conclusion

We have studied realizations of a compact multilayer bandpass filter that has been deduced from the corresponding covered hairpin filter. A novel realization of the multilayer bandpass filter has been presented and it is based on the modified hairpin resonator realized on a double-sided microstrip structure. The benefit of the proposed multilayer filter is a reduction of the footprint by 50% without changing the performance of the original hairpin filter.

In this paper, we have presented the new method to reduce the size of a hairpin filter without deteriorating the filter performance. First, we have designed the optimal single layer hairpin filter with a top metallic cover. Secondly, the hairpin resonators have been replaced by equivalent modified hairpin resonators which were printed in two layers.

Design methodology has been presented and validated by EM simulation. The multilayer filter has been fabricated, measured, and the experimental results are in good agreement with the theoretical and simulation results.

Acknowledgements

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