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Uros Jankovic[#1], Nandun Mohottige[*], Ananjan Basu[%] and Djuradj Budimir[#2,&]

[#]Wireless Communications Research Group, University of Westminster, UK

[*]Global Invacom Ltd, UK

[%]Indian Institute of Technology, Delhi, India

[&]School of Electrical Engineering, University of Belgrade, Belgrade, Serbia

[1]uros.jankovic@my.westminster.ac.uk, [2]d.budimir@wmin.ac.uk

***Abstract* — In this paper, a new type of simple and inexpensive waveguide filter manufacturing that minimizes material consumption and has capabilities of high performance and rapid prototyping is presented. Filter inserts are fabricated by a combination of additive dielectric manufacturing and subtractive metal manufacturing, whereas standard waveguides are used as housings, utilizing best properties of each technology. Along with it, a suitable filter design using metal rectangular rings has been developed. Since the rings that act as positive reactance discontinuities in the passband are resonant at frequencies below it, it is possible to bring lower stopband transmission zeros near the passband to create sharp skirt. A resonator of such a filter and a third order bandpass filter sample have been designed at 11.13 GHz and 11.36 GHz centre frequencies respectively. In addition, smaller size rectangular rings in waveguide can realize upper stopband transmission zeros while acting as negative reactance discontinuities in the passband. This was utilized in fourth order bandpass filter at 11.36 GHz centre frequency with finite transmission zeros in both stopbands. All the filtering structures have been fabricated with 3D printer to extrude polylactic acid and circuit board plotter to mill copper sheet, and tested. Excellent measurement results that have been obtained validate the proposed design. Practical sides of achieving quality 3D printouts are analysed.**

***Keywords* — 3D printed, additive manufacturing (AM), direct-coupled-resonator filter, frequency-variant couplings, waveguide filter.**

I. INTRODUCTION

Waveguide filters are an essential part of numerous microwave radar and communication system infrastructures. One of the areas of their improvement is fabrication technology. We are witnessing the years of great expansion of additive manufacturing during so called Fourth Industrial Revolution, and so far filters implemented as both conventional waveguide structures [1,2] as well as SIW structures [3] have been made by 3D printing of polymers and their subsequent metallization. Nevertheless, they suffer from problems with the plastic-metal interface, no matter if the plastic is located on the outer or inner side of the metal walls. Main issues are with large scale surface roughness of the polymer caused by its layered fabrication and the metallization process itself, either using electrochemical deposition or covering with metal tape. Here, 3D printing is chiefly utilized to create holders for complex object positioning and subtractive technologies are still used to fabricate critical metal parts to maintain high performance.

Classical direct coupled waveguide filters have shunt inductive discontinuities realised as diaphragms, posts or circular irises [4]. E plane waveguide filters [5] were later introduce as alternative for cost effective mass production. Downsides of using E plane inductive strips are worse upper stopband and increased filter length, which is particularly pronounced for narrower bandwidths.

The aim of the proposed hybrid manufactured filters is to add fabrication benefits of E plane discontinuities to transverse discontinuities, which have size and performance advantages. They are very suitable for prototyping, as it takes less than 2 hours for an entire 3rd order filter insert to be fabricated using currently affordable desktop machines and materials. Furthermore, no demanding process such as metal plating is necessary, hence mostly automated procedure can be repeated as many times as needed to obtain good experimental results. Unlike conventional realisations, the one being described here can be used with monolithic waveguide sections, not only simplifying production, but also being able to completely eliminate signal leakage.

II. RECTANGULAR RING DISCONTINUITIES

Standard inductive diaphragms (FIG. 8.06-1,2 in [4]) rely on electrical connection between the conductors of the diaphragm and the housing. The response is very sensitive to the gaps that can appear next to the top and bottom H-plane side walls, introducing series capacitances in the shunt discontinuity networks inversely proportional to the gap height. During our initial experimental attempts, good metal contact with the housing could not be achieved when using independent filter insert composed solely from 3D printed polymer and cut copper diaphragms, repeatedly obtaining responses without a distinctive resonance.

In order to stabilize the response, two side of symmetrical diaphragm are first connected by top and bottom sections to form a rectangular iris. Now, when the rectangular iris is detached from the waveguide side walls, it emerges as a connected rectangular ring discontinuity (Fig. 1) with significantly larger gap capacitances due to longer outer

H-plane ring edges. In the frequency range of interest, the newly formed rectangular ring can be approximated by a series inductor. This inductance is mainly increased by enlarging the ring hole area and reducing ring metal surface to produce higher magnetic flux.

Thus, around the passband, the rectangular ring can be represented by a series LC network, whose antiresonant frequency in the lower stopband can be pushed up to increase roll off either by decreasing gap capacitance or ring inductance. At the same time, this shunt network needs to have selected negative susceptance in the passband to control the couplings of waveguide resonators.

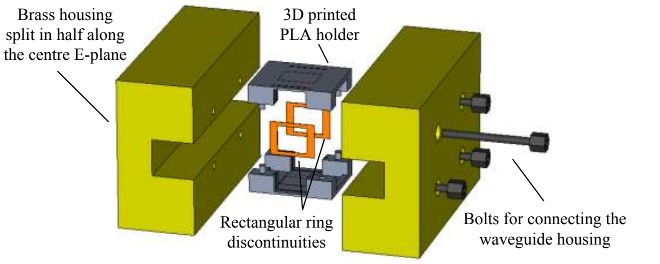

Fig. 1. Proposed waveguide resonator: metal rings milled from a copper sheet are enclosed within a 3D printed thermoplastic holder to form an insert that can be put inside a brass waveguide housing.

III. Proposed Resonator

A cavity resonator is formed by positioning two rectangular rings in transverse waveguide planes so that the dominant quasi TE_{10} mode sees 180° phase difference between them at the transmission pole (TP) frequency. The resonator which exploded view drawing is given in Fig. 1 is inside WR 90 waveguide housing with inner ring dimensions of 6 mm x 6 mm, horizontal ring thickness of 2.4 mm, vertical ring thickness of 1.4 mm, and the distance between the two rectangular rings of 14.7 mm.

Insert holders have the main task to keep the distance between the rings, at the same time tightly positioning them within their cross sections. Holders have been fabricated by fused deposition modelling (FDM) method with Ultimaker 2+ Extended 3D printer and 0.4 mm nozzle for extruding heated polylactic acid (PLA, a biodegradable bioplastic derived from renewable resources) filament. It was chosen that the melted PLA is deposited in 0.05 mm thick H-plane layers (vertical resolution). In addition, the shell thickness was set to 0.4 mm and the top and bottom layer thicknesses to 0.2 mm, whereas the enclosed volume was selected to be 40% filled with PLA. Lower fill densities experimentally proved to have less spurious effects. Since PLA material properties are not optimized for EM applications, the holder was shaped to be inclined towards low passband dielectric losses in the tradeoff with the size. Thus, it provides support along all the principal waveguide axes, but is hollow in the central parts of ring and cavity resonators, where the strongest EM field is localized. Before an insert is ready for use, it is often needed to remove PLA residues in several locations, the hardest ones being spots in inner corners.

The rings have been cut out of 0.1 mm thick copper foil with the ProtoMat C60 milling unit. Influence of ring bending can be reduced by using thicker copper sheet as well as by taking care of 3D printing imperfections. For that reason, slits holding rectangular rings were set for printing slightly wider than the copper thickness with the aim to prevent the hot PLA bonding over them.

In Fig. 2 are shown simulated and measured resonator S-parameters. The dominant resonant mode TP is at $f_0 = 11.13$ GHz, with the bandwidth $\Delta f_{3dB} = 157$ MHz. The transmission zeros (TZs) are essentially at the same frequency of around 8.7 GHz as the two synchronously tuned rectangular rings are mutually loosely coupled, having the coupling coefficient $k_R = 0.0021$. The full wave EM analysis was performed using CST Studio Suite. Dielectric modelling was simplified and simulation time reduces by using effective medium approximation [3] for PLA characteristics instead of applying exact inner geometry specified to the 3D printer in the G-code file, which is by itself prone to fabrication irregularities.

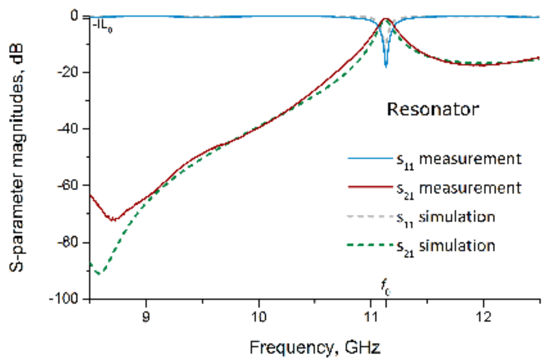

Fig. 2. X band resonator simulated and measured frequency responses.

Unloaded quality factor of the resonator obtained from the transmission S-parameter measurement of symmetrical network is

$$Q_u = \frac{f_0}{\Delta f_{3dB}} / (1 - 10^{-IL_0/20}) = 624.$$

IV. Higher Order Filters

In order to test the proposed filter structure, a 3rd order unit has been designed. Its fabricated insert, now containing 4 rings, is displayed in Fig. 3 together with assembled filter after testing with the Agilent Technologies E8361A PNA Network Analyzer.

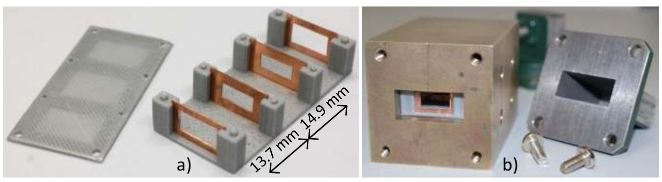

Fig. 3. Photographs of a) 3rd order filter insert with asymmetrical holder and b) complete filter with removed waveguide to coaxial adapters. Grained texture of the bottom part of this sample is due to low infill percentage.

In the resonator case, the thermoplastic holder was built from two equal parts (Fig 1.) that can interlock with each other along the centre H-plane through pins and holes, similar to Lego bricks. This is very useful in terms of need to design just one half of the holder, while the interlocking also deals with the issue of misalignment. Nevertheless, another interlocking H-plane near waveguide sidewall was gradually adopted for higher order filters (Fig. 3*a*) to allow for easier connecting of the two PLA parts together that does not require additional care about ring alignments.

The dimensions of the fabricated filter are presented in Table I and the corresponding layouts are in Fig. 4, where inner waveguide dimensions are $a = 22.86$ mm and $b = 10.16$ mm. The top and bottom dielectric layer thicknesses are $T_B = 1$ mm. Fill density of 15% was used in this case.

Table 1. Designed 3rd order filter dimensions in millimetres.

Filter element	Dimension				
	a_r	b_r	W_{ar}	W_{br}	W_P
Inner ring	8.6	3.8	3.6	2.8	4.1
Outer ring	10.0	5.4	2.2	2.0	4.8

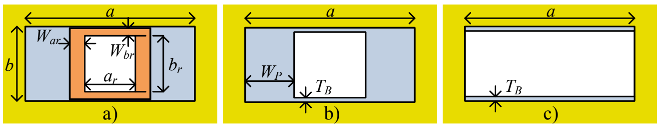

Fig. 4. Filter transversal cross sections: a) ring plane, b) plane of dielectric that holds the ring in place along the longitudinal direction, and c) waveguide sections containing top and bottom dielectric slabs as parts of the insert.

In Fig. 5 are given the results of this measurement, compared to the simulation responses. A very good overlapping of the two has been achieved when small undercutting of 0.1 mm on each edge of the rings made by the circuit board plotter had been taken into account.

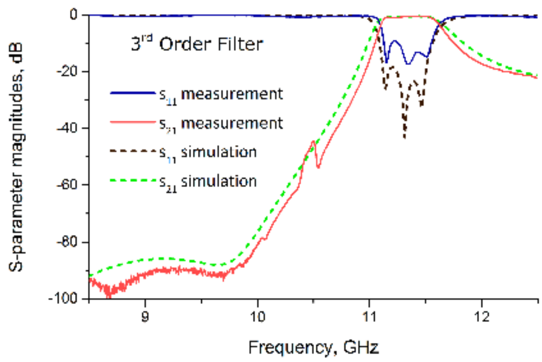

Fig. 5. Simulated and measured S-parameters of the designed and fabricated 3rd order bandpass filter with 3D printed insert dielectric.

The filter has 4.6% 3 dB fractional bandwidth. Measured insertion loss at the centre passband frequency of $f_0 = 11.36$ GHz is about 0.6 dB. and it is not higher than 1 dB between 11.15 and 11.55 GHz. The first upper spurious TP is at 1.39 x f_0, which is 20% larger difference than in the case of a corresponding E-plane filter. The locations of the two pairs of finite TZs are 8.65 GHz, produced by outer rings, and 9.7 GHz, produced by inner rings.

Hybrid manufactured waveguide bandpass filters with rectangular rings can, in fact, feature both inductive and capacitive couplings. In Fig. 6 is shown such a filter together with its frequency responses. It produces 3 TZs in the lower stopband and 2 TZs in the upper stopband. Rectangular rings that produce capacitive couplings are of smaller sizes than those which produce inductive couplings.

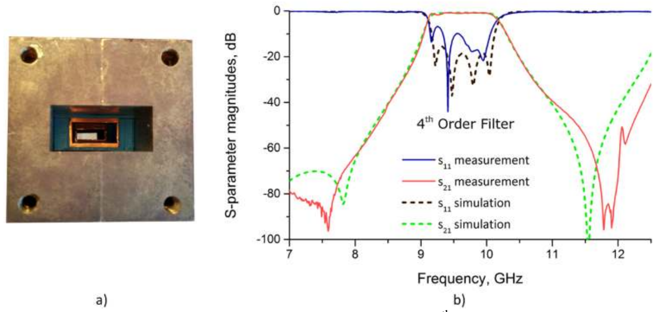

Fig. 6. a) One-point perspective along fabricated 4th order bandpass filter with 3D printed insert dielectric inside its waveguide housing, and b) simulated and measured S-parameters of this structure.

V. Conclusion

A novel type of waveguide bandpass filters optimized for low-cost hybrid additive/subtractive manufacturing has been presented in this paper. The flexibility of 3D printing is suitable for realization of contactless discontinuity geometries like the rectangular ring ones. A resonator of 11.13 GHz centre frequency fabricated with 40 % fill density was experimentally evaluated to have Q factor > 620. In addition, a third order filter with two pairs of transmission zeros in the lower stopband has been designed, being 34.3% shorter than its E-plane counterpart. Its minimum measured insertion loss in the passband when printed with 15 % infill was 0.6 dB. A fourth order filter with three transmission zeros in the lower stopband and two in the upper one has been designed as well to demonstrate possibility of good roll-off on both sides of the passband. Very good matchings of simulation and measurement results have been obtained.

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