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A Novel Application of Waffle Iron Filters in Microwave and mm-Wave Systems: Resolving Conductive Junctions Challenges

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Abstract – **In this paper we demonstrate a novel idea and solution introduced to resolve challenges related to achievement of high conductive contacts and junctions. Such challenges are related to various technological issues that are particularly pronounced at higher microwave and millimeter wave frequencies. The concept presented here combines two filter technologies in a single composite filter - these are dielectric resonator filter technology and asymmetrical waffle iron filter technology. With dielectric resonator filter technology is realized the main bandpass filter response at millimeter wave frequencies while asymmetrical waffle iron filter technology is used to confine electromagnetic waves within filter cavities but without any conductive (i.e. "low ohmic") and mechanical contacts between functional filter parts which is commonly required in classical solutions. Performances of a novel concept are also demonstrated.**

Keywords – **Dielectric resonator filter, Waffle iron filter, Asymmetrical waffle iron filter, Microwave filter, Millimeter wave filter.**

I. INTRODUCTION

Performances and functionality of many devices in higher microwave and millimeter wave regions rely on precise, tight, stable and reliable electrically conductive mechanical contacts. Such kind of junctions and contacts are essential to realize specified functions and achieve required levels of reliability. Each application imposes its own set of requirements for junction's materials and the material choice usually depends on applications and environmental requirements [1]. Clearly, high quality electrically conductive and tight mechanical junctions and contacts are of high importance for applications in aforementioned frequency ranges.

While at lower frequencies it is not usually much pronounced, as it is well known in microwave and millimeter wave frequency ranges poor quality of conductive junctions and connections directly reflects to the poor quality of achieved electrical function of devices and systems. In the worst situations poor conductive junctions lead to a complete malfunctioning of a device as its function is not realized or its performances are unacceptably degraded. This is because major performance parameters of devices like insertion loss (*IL*), reflection loss (*RL*), isolation (*ISO*), rejection levels (*REJ*) for circuits, and gain (*G*) and efficiency (η) in the case of antennas, are directly dependent on the quality of manufacturing and quality of conductive junctions. It is also often the case in practice that poor electrically conductive junctions lead to appearance of unwanted spurious and resonance responses and similar effects that degrade electrical function and cause malfunctioning of a device.

With current state of the art, in microwave and millimeter wave regions, solutions for tight and conductive electrical contacts include usage of [1]:

- high precision CNC (Computer Numerical Control) machining and alignment of connecting interfaces
- soldering of functional parts (that usually requires plating interstage operation and technology)
- welding, usually used for special applications (e.g. laser welding. which requires special technology as well)
- high conductive compounds and glues (e.g. silver epoxies), mostly used for commercial applications.

In applications most commonly used option is high precision CNC machining of conductive interfaces with appropriate interfacing materials. At lower frequencies high quality manufacturing now days is usually easy to achieve, however at higher frequencies it is not the case and achieving high quality manufacturing is directly related to considerable increase of manufacturing time and costs.

In summary, currently used solutions require precise operations, special materials or use of additional materials and technology operations together and generally this is not a preferable for industrial environment.

Having in mind aforementioned challenges in achieving high quality conductive junctions in microwave and millimeter wave regions - motivation for work presented in this paper is to investigate and demonstrate an interesting idea and performances of a novel solution that aims to resolve mentioned challenges. The approach presented here uses waffle iron filters at the areas where high conductive junctions are needed. Though at DC the core waffle iron geometry represents an open circuit, in working microwave and millimeter wave frequency ranges the waffle iron structure, with proper design, could represent an "virtual short circuit",

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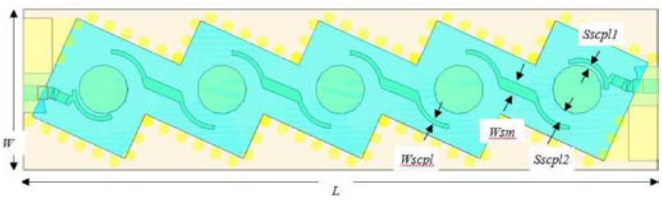
for dominant mode as well as for higher order waveguide modes. With appropriate implementation of that special feature of waffle iron filters, it is possible to replace high conducive junctions ("ohmic junctions") with "virtual junctions" that are essentially open circuits for DC.

To demonstrate the concept here is presented a solution that combines two filter technologies in a single composite filter - these are dielectric resonator filter technology (Fig. 1) [2-5] and asymmetrical (Fig. 2 a)) [6], or symmetrical (Fig. 2 b)) [7-9] waffle iron filter technology. Dielectric resonator filter technology is used to realize the main bandpass filter response at millimeter wave frequencies while waffle iron technology is used to confine electromagnetic waves within cavities.

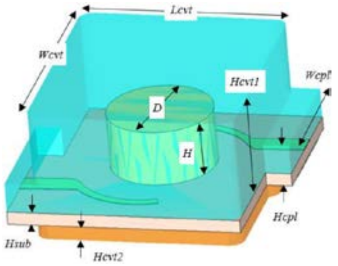
Unlike to the classical solutions that require tight mechanical and electrical junctions between functional parts of the filter (to create closed filter cavities), here advantages of waffle iron filters are used to achieve tight electromagnetic "virtual" connections without any physical contacts between functional parts (so it is a contact-less solution).

II. Description of the Concept

In [2] is described a design of millimeter wave bandpass dielectric resonator filter (BPDRF) and internal structure of the filter (without metal housing elements) is shown in Fig. 1. In presented solution dielectric substrate (i.e. PCB) with dielectric resonators and other elements is sandwiched between the top and the bottom functional metal blocks that form the filter cavities. Connection between the top and the bottom part is achieved by PCB vias (or tight direct metal contacts between the parts where application allows it). This connection creates the filter cavities and is essential to achieve good filter response, low insertion loss, high rejection and preserve spurious modes response in the band pass or rejection region.



(a)

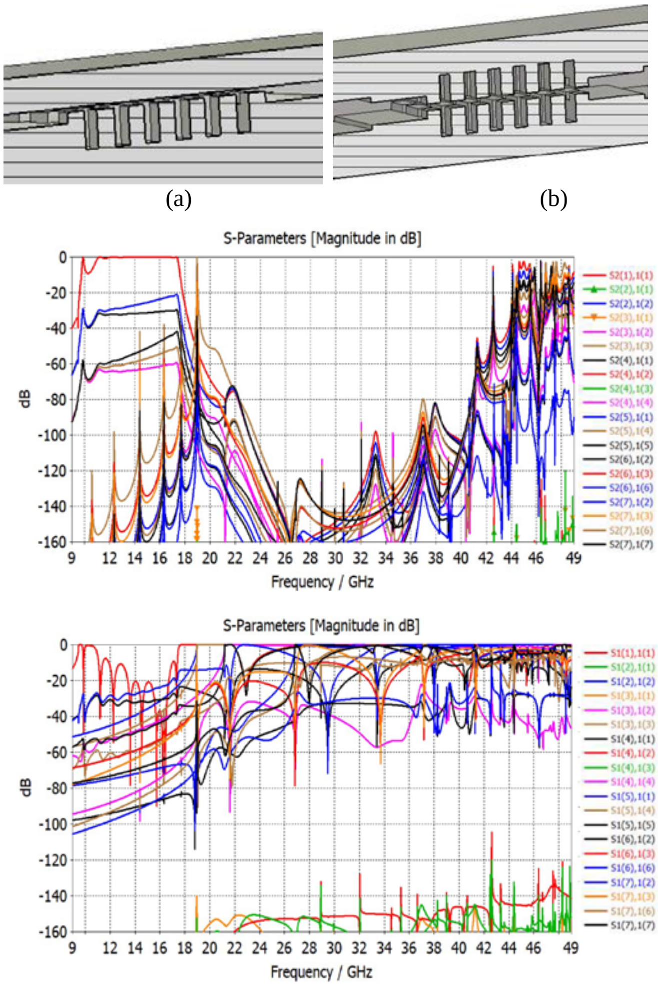


Lcvt	4.047
Wcvt	4.547
Hcvt1	2.013
Hcvt2	0.452
D	2.067
H	1.093
Wcpl	2.48
Hcpl	0.843
Hsub	0.254

L	26.76
W	6.77
Wscpl	0.172
Wsm	0.444
Sscpl1	0.168
Sscpl2	0.69

(b)

Fig. 1. Dielectric resonator filter structure (housing is not shown) [2]: (a) Filter layout and dimensions, (b) Filter cavity and dimensions



(c)

Fig. 2. Waffle iron filters types: (a) Asymmetrical waffle iron filter [6], (b) Symmetrical waffle iron filter [7-9], (c) Illustration of a typical multimodal response [6]

To demonstrate importance of good connection between functional parts in Fig. 3 are shown responses of the BPDRF where the top and the bottom functional parts are:
a) connected by Copper or vias ("Cu")
separated/disconnected by air slot with:
b) Air slot width s = 0.100mm ("Air 1")
c) Air slot width s = 0.254mm ("Air 2").

As it could be seen in Fig. 3 lack of good conductive contact leads to:

- unacceptable degradation of insertion loss (increased to 3.5-6dB levels)
- completely degraded band pass response
- considerable degradation of the rejection regions and rejection levels (bellow and above the pass band).

This is because the flat surfaces on the interface between metal parts do not offer any selectivity, and essentially they are equivalent to segments of parallel plate transmission line.

In addition to the abovementioned issues related to the connection quality - in practice additional and more serious effects could be observed like unwanted resonances in the band pass or rejection region or spurious responses that are difficult to control and get rid of and also difficult to capture and analyse in simulation as well.

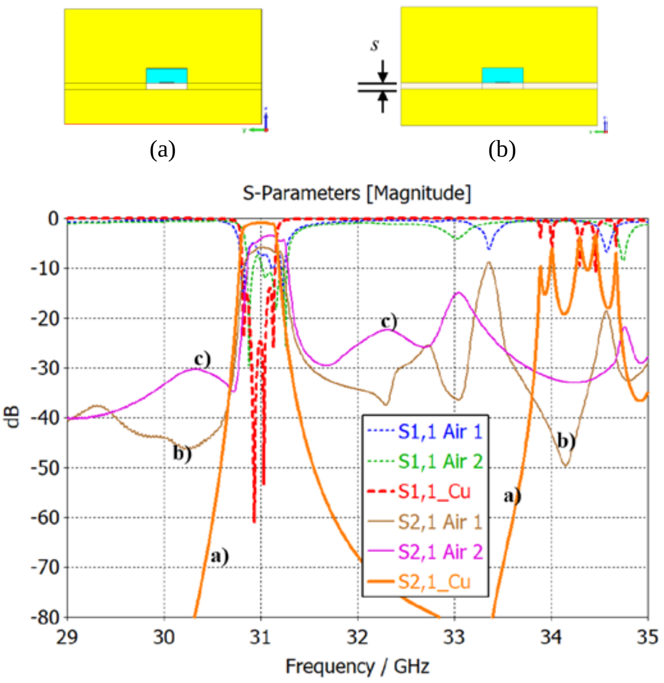


Fig. 3. Side view of BPDRF with different filling of the slots between the filter blocks: (a) Copper connection, (b) Air Slot, (c) Comparison of the filter response when functional filter blocks are: a) connected by Copper ("Cu") separated by air slot (i.e. disconnected) with: b) Air slot width s=0.100mm ("Air 1") c) Air slot width s=0.254mm ("Air 2")

In Fig. 4 a), b) are shown details and appearance of the realized reference BPDRF where good conductive contacts between the filter functional blocks are used. Performances of the filter are shown in Fig. 4 c). The figures show good agreement between performances of the simulation model and the realized filter. Also, realized BPDRF has quite good and clean rejection responses bellow and above filter pass band region.

From Fig. 3 and Fig. 4 it is clear that, with classical approach, high quality conductive junctions and contacts between functional parts of BPDRF are necessary to avoid serious degradation of the filter performances. As it could be seen from Fig. 3 and Fig. 4 classical solutions could also offer good performances in that case. However, as mentioned, the classical solutions require additional/high performance technologies and have also challenges that becomes even more pronounced and difficult to deal with at higher microwave and millimeter wave regions.

To help to resolve such challenges - in this paper a new idea is presented where waffle iron filters are used along the edge contours of the BPDRF cavities to achieve "virtual connections" on each side of the main signal path and to prevent filter degradation but at the same time to avoid need of high-quality conductive contacts between the functional parts. Thanks to the special features of waffle iron filters, with such approach, the signal becomes confined along the main signal path and cavities for dominant mode as well as for higher order modes.

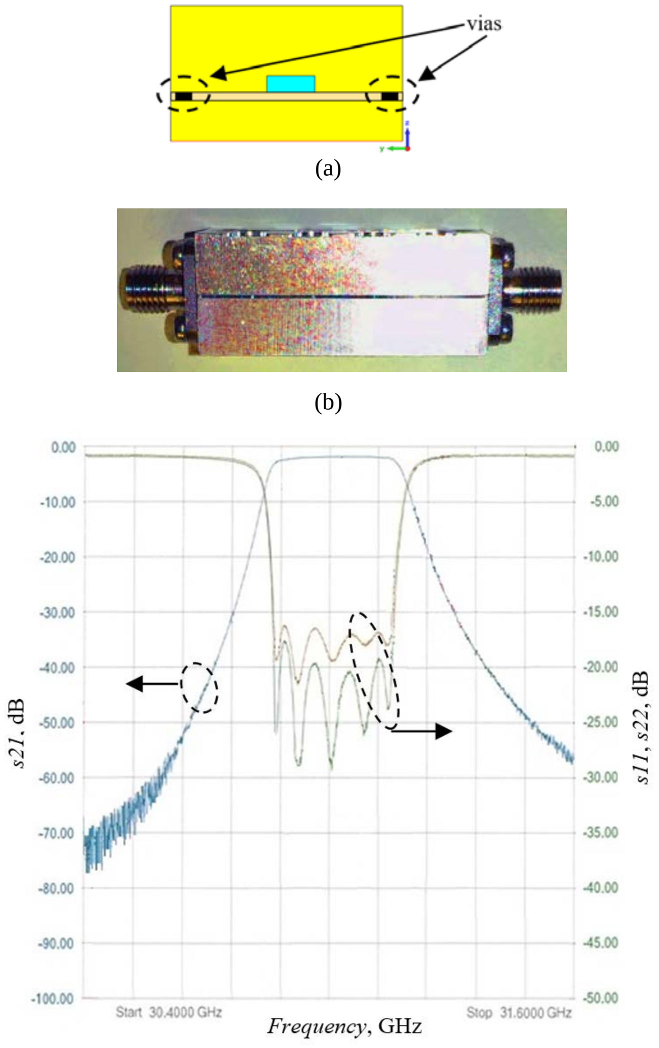


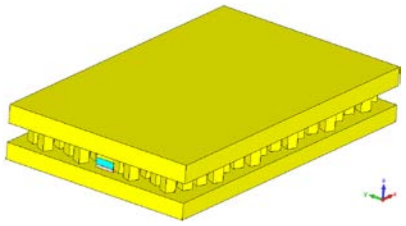
Fig. 4. BPDRF with conductive contacts between the filter functional blocks: (a) Conductive connection (with vias), side view of BPDRF, (b) View of realized BPDRF, (c) Performances of realized BPDRF

Consequently, side waffle iron filters in such solution effectively represent a virtual connection between the filter blocks along the main filter path. This is achieved even though filter building blocks are not mechanically connected at all, which represents a more desirable construction for many applications. The solution with details is shown in Fig. 5.

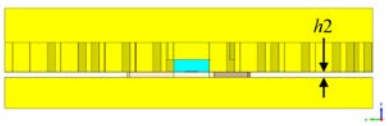
As shown in Fig. 5 on each side of the main dielectric resonator filter one specially shaped asymmetrical waffle iron filter is fitted to help to confine the signal along the main path and in the cavities.

To demonstrate performances of the proposed solution - in Fig. 6 simulated results for the composite filter with two different spacings are shown: for designed spacing h_2= 0.100 mm and for test spacing h_2= 0.254 mm.

Spacing h_2= 0.254 mm is just increased spacing from the designed one to check performances without any re-optimization. For reference in Fig. 6 is also shown the response of the original filter with high conductive connections between the filter functional blocks.



(a)



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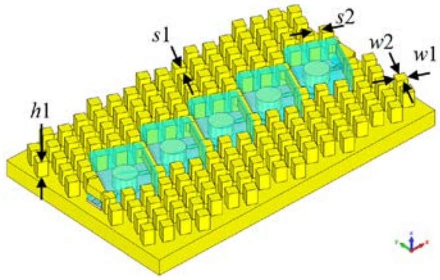

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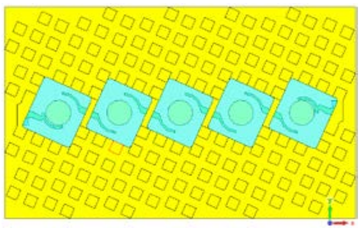
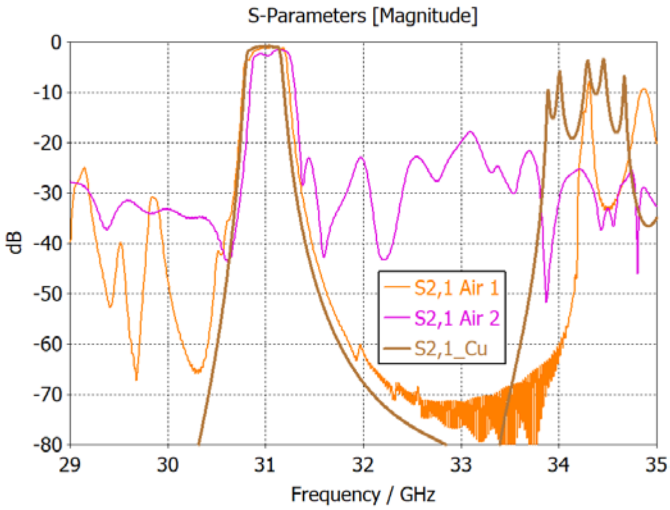


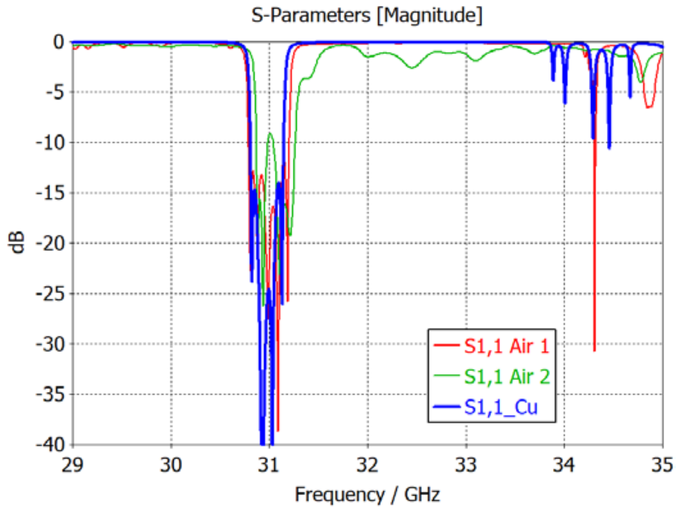
w1	0.90
w2	0.90
s1	0.70
s2	~0.65
h1	1.40
h2	

(d)

Fig. 5. Composite dielectric resonator and waffle iron filter assembly details: (a) 3D view, (b) Side view, (c) Internal structure, 3D view (top metal block above the pegs is hidden), (d) Internal structure, top view (top metal block above the pegs is hidden)



(a)



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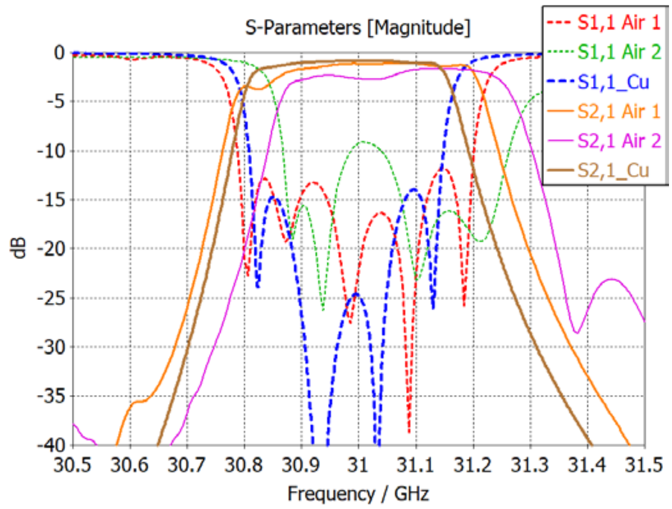

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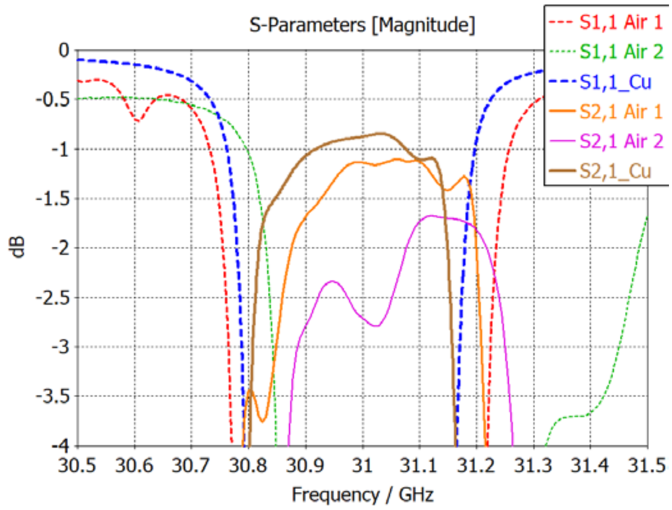

Fig. 6. Performances of the composite dielectric resonator and waffle iron filter assembly, when functional filter blocks are: i) connected by Copper (Cu) – original filter Separated by air slot (i.e. disconnected) with: ii) Air slot width *s*=0.100mm (Air 1) – per design iii) Air slot width *s*=0.254mm (Air 2) – test: (a) *S*21 parameters of the composite filter, wideband, (b) *S*11 parameters of the composite filter, wideband, (c) Pass band performances of the composite filter, (d) Insertion loss details in band pass region for the composite filter

As it could be seen in Fig. 6 the proposed configuration (with spacing h2 per design) provides tight electromagnetic virtual connection between important building elements of the filter and mostly maintains performances of the original dielectric resonator filter and confirms the proposed concept.

In presented solution (Fig. 5) an asymmetrical waffle iron filters are used [6] though in some applications symmetrical double-sided waffle iron filters (Fig. 1 b)) [7-9] could be more preferable solution. Asymmetrical waffle iron filters require fewer machining operations and have different content of higher order modes [6] comparing to standard symmetrical double sided waffle iron filters. However, in some cases like for higher power applications - symmetrical waffle iron filters could be a more preferable solution.

In proposed solution the BPDRF is designed using common circuit and 3D simulation tools [10, 11], while asymmetrical waffle iron filter is designed (as illustrated on Fig. 2) by 3D simulation tool which is necessary to perform multimodal analysis and optimisation [11]. The filter structure proposed in Fig. 5 is suitable for classical CNC manufacturing, however modern 3D printing or laser micromachining are also interesting options for realization [12].

The simulation model for the composite filter (Fig. 5) is based on the model developed for BPDRF which has been realized, tested and verified (Fig. 1 and Fig. 4).

Additionally, the results from the measurements of such realized filter were fed back into the simulation model for further improvement, which is of high importance in production environment.

III. Analysis of Results

As Fig. 3 shows without high quality conductive connection the whole filter response is considerably degraded.

Rejection is reduced but more serious effect is increase of the *IL* in the band pass region which for better rejection levels goes up to ~6dB and which is unacceptable high *IL* figure. These degradations are result of signal leakage out of the main filter path through the slots between functional filter blocks.

On the other side application of the proposed idea with asymmetrical waffle iron filters on each side of the signal path effectively ensures good quality electromagnetic virtual connection between functional filter blocks and performances of the original filter (with high conductive connections) are mostly preserved.

From Fig. 6 a), b), where filter wideband performances are shown, it could be seen that bellow pass band degradation in rejection starts bellow ~30GHz, while above pass band - high levels of rejection of the original filter is practically preserved and minor degradation that could be seen is not relevant for most practical applications.

Fig. 6 c) shows bandwidth response of the composite filter. As it could be seen insertion loss and return loss of the original filter are mostly preserved with minor degradation (*IL* degradation ~0.25dB, *RL* degradation 4-5dB in average).

Fig. 6 d) shows more details about insertion loss performances of the composite filter inside bandwidth region for all tree cases analysed (“Cu”, “Air1”, “Air2”). As it could be noticed, considerable increasing of spacing *h*2, without additional optimization degrades *IL* performances (in level and shape), but they are still in the acceptable region.

Based on results it could be concluded that quite good performances are achieved with the proposed solution.

Additional experiments implicate that better performances could be achieved by further optimization of the composite filter.

IV. Conclusion

In this paper we demonstrated a novel idea and concept where asymmetrical waffle iron filters are used to confine electromagnetic waves within the main signal path and in the filter cavities of the dielectric resonator filter. In this novel concept there is no any classical tight (“ohmic”) mechanical and conductive electrical contacts between related functional filter blocks. The proposed concept uses “virtual contacts/junctions” to achieve required functional junctions and that is achieved thanks to the special properties of waffle iron filters. In such solution the asymmetrical waffle iron filters prevent signal dispersion out of the filter cavities and the main path for fundamental mode as well as for all higher order modes in the waveguide space. As a result, proposed application of waffle iron filter technology offers tight and good quality virtual electromagnetic connection between filter building blocks without any physical contact between them. The solution mostly preserves filter performances to remain close to the original filter that has classical tight conductive electrical junctions along the filter cavity contours, and that confirms feasibility of the proposed idea. Further work is ongoing in which various aspects of the proposed solution will be analyzed in more details and further optimized. Also, additional work will involve checking of some aspects of the proposed solution in wider frequency region through building and testing of an additional prototype.

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