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RESEARCH ARTICLE

Novel High-Q Partially Air-Filled Pedestal Resonator and Filter Integrated in a Printed Circuit Board (PCB)

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ABSTRACT In this paper, a resonator and second order filter are fabricated using a novel technological process based on micromachining and thermo-diffusion. The use of this innovative process opens the way to the design of RF components relying on partially air-filled Substrate Integrated Waveguides (SIW). These topologies and particularly the proposed partially air-filled pedestal SIW resonator is suitable to design high-Q, yet compact SIW resonators. In this paper, a study of partially air-filled pedestal SIW resonator is proposed to offer an optimized trade-off between Q-factor and compactness. Then, based on this study, a partially air-filled pedestal resonator working at 5 GHz is designed and manufactured. The measured prototype exhibits a Q-factor of 285, which represents a 53 % increase in Q-factor compared to a fully dielectrically-filled-in pedestal SIW resonator, while the size is kept constant. Finally, a second order filter based on this resonator topology is also designed, measured and discussed.

INDEX TERMS SIW, AFSIW, ESIW, micromachining, PCB process, thermo-diffusion, resonator, filter.

I. INTRODUCTION

Planar and waveguide technologies are the most commonly-used to design microwave filters and resonators. Planar topologies include microstrip line, stripline and coplanar waveguide, which exhibit low cost, light weight and compact sizes. They are easily manufactured and straightforward to integrate into systems. However, these planar topologies show more losses and lower quality (Q) factors than classical waveguide structures. Indeed, waveguide resonators and filters have much higher Q-factors and better power handling capabilities, however, they are usually large, heavy and difficult to integrate into systems.

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In 2001, a technique called Substrate Integrated Waveguide (SIW) was first introduced [1] with the purpose to bridge the gap between planar and waveguide topologies by reaching electrical performances close to those of waveguide structures while using planar fabrication processes. SIW consists in designing structures based on waveguide modes, the structure being filled-in with dielectric and delimitated by two metal layers that are connected with via hole arrays to form the side walls. As they can be manufactured thanks to classical planar technological processes, it results in cheap and light structures that can be easily integrated into systems [2].

Additionally, as the resulting waveguide is filled in with dielectric substrate, it leads to rather compact devices [3]. Nevertheless, although achieved Q-factors with SIW are higher than those reached with standard planar topologies, the use of dielectric materials with non-null loss tangents limits the Q-factors that can be reached with SIW. Indeed, in most cases, the main contributor to the losses in SIW structures is the substrate material.

To reduce the losses and increase the Q-factors of SIW structures, air -filled SIW (AFSIW) were proposed in [4]. In these structures, air is the main propagating medium, lowering the losses associated to the dielectric substrate, while keeping a planar-like fabrication process. Using air as the propagation medium implicates larger structures compared to the classical dielectrically-filled in SIW. Nonetheless, the resulting trade-off is interesting and devices such as phase shifters [5], [6], and a leaky-wave antenna [7] have also benefited from the AFSIW topology.

Recently, empty SIW (ESIW) [8] filters have been presented, although the principle is similar to that of the AFSIW [9], [10], the novelty mainly relies on the transitions from microstrip to waveguide modes, leading to more compact structures. Q-factors of around 350 have been reported for filters operating in the C and X frequency bands [11], while Q-factors of around 740 have been reported for filters operating in the K band [9]. Indeed, ESIW or AFSIW techniques are useful when high Q-factors are seeked and for relatively high frequencies. For lower frequencies, the size, and, as a matter of fact, the larger size of these structures than that of their conventional SIW counterpart is a major drawback.

To overcome this flaw, and to reach new trade-offs in the Q-factor vs size ratio, one solution is to design partially air-filled SIW. The aim is to introduce novel trade-off between electrical performances and occupied area, which means greater Q-factors than dielectrically-filled-in SIW and smaller sizes than ESIW, which is evidently relevant only when size of ESIW is prohibitive, that is to say for relatively low frequencies.

Therefore, the present work aims to develop novel partially air-filled resonator and second order filter working at 5 GHz and based on a pedestal SIW topology [12], which is a capacitively-loaded SIW cavity based upon a ridge waveguide principle.

Previous works on pedestal SIW resonators presented in [12], [13], and [14], also called mushroom resonator in [15] have demonstrated the possibility to decrease the size of a SIW resonant structure by loading the guide with an intermediate metal plate. In the present work, we propose to combine the advantages of the ESIW (Q-factors) and pedestal topology (compacity) to take benefit of their respective advantages.

To achieve the realization of these structures, an innovative fabrication process based on micromachining and thermo-diffusion assembling was used.

The next section details the interest of the proposed topology and the key-aspects of its design while section III describes the manufacturing steps and presents the achievement of both a resonator and a second-order partially air-filled pedestal filter. Finally, section IV presents the measurement results and discussion.

II. PEDESTAL TOPOLOGY

The pedestal resonator consists of a classical SIW cavity loaded with a metal plate suspended at an intermediate height and short-circuited on one of its sides by one or several metal posts [10], [11]. The cross-sectional view of a pedestal SIW resonator is shown in Fig. 1(a). Height between the bottom ground plane and the pedestal plate is denoted h1 while the height between the pedestal plate and the top ground plane is denoted h2. For practical reasons, the intermediate plate is built upon a dielectric support, which is itself crossed by a via-hole to enable a conductive connection between the pedestal plate and the bottom ground plane. With such a configuration, E-field maximum is located between the top metal layer of the cavity and the metal plate of the pedestal as shown in Fig. 1(b). As mentioned in the introduction, one of the main advantages of pedestal resonators is that they allow for size reduction compared to ESIW or AFSIW cavities. To illustrate the size of the resulting resonator, Fig. 2 shows the top view of a cross- sectional cut of the partially air-filled cavity made in the pedestal plate plane. As denoted in Fig. 2, L is the outside length of the square SIW cavity while W is the width of the pedestal plate.

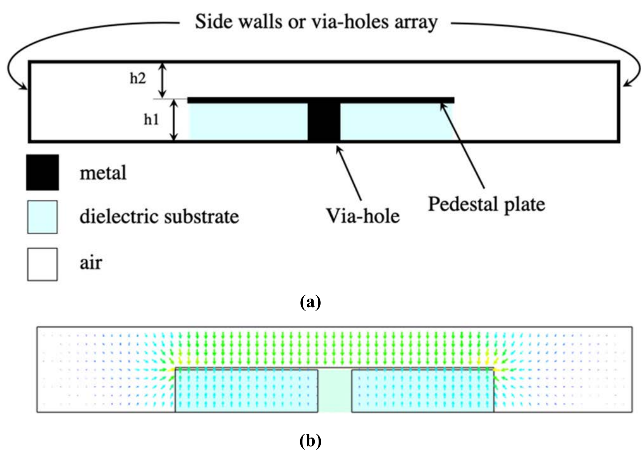


FIGURE 1. (a) Side view of partially air-filled pedestal resonator and (b) Field distribution inside the resonator.

To evidence the interest of the proposed partially-air filled resonator, several eigenmode simulations were performed with different values for the outer area (L × L), Q factor being extracted for each case (Fig.3 (a)). To allow for fair comparisons, the resonant frequency was kept constant and set to 5 GHz. To maintain a constant resonant frequency with various outer area (L × L) values, the pedestal width W had to be tuned accordingly. Fig. 3 (b) shows, for each value of the area (L × L), the corresponding values of the W/L ratio necessary to maintain a constant resonant frequency of 5 GHz. The simulations were performed with CST Studio Suite with the relative dielectric permittivity of the substrate (ε_r) is 3.55, its loss tangent (tan δ) being 0.0027 and conductivity of the metal (σ) being set to 5.96×10^7 S/m. As a first approach, heights h1 and h2 were both set equal to 0.5 mm.

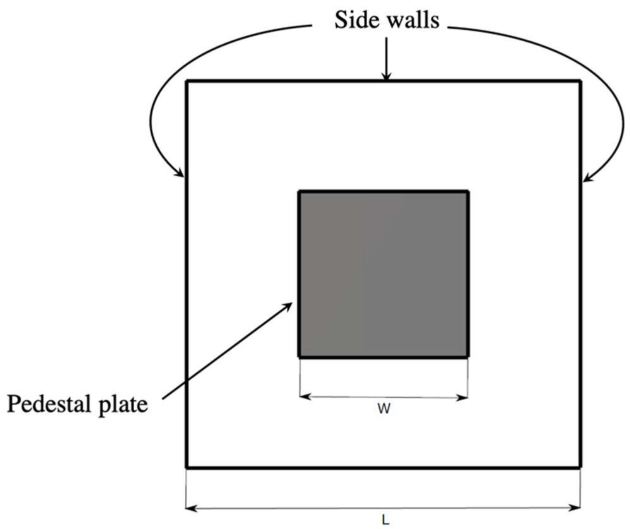


FIGURE 2. Top view of the partially air-filled pedestal resonator.

For each resulting design, the Q-factor of the resonator was extracted and plotted in Fig. 3(a) as a function of the outer area of the SIW cavity (L × L). Values of the W/L ratio to maintain a constant resonant frequency of 5 GHz are plotted in Fig. 3(b).

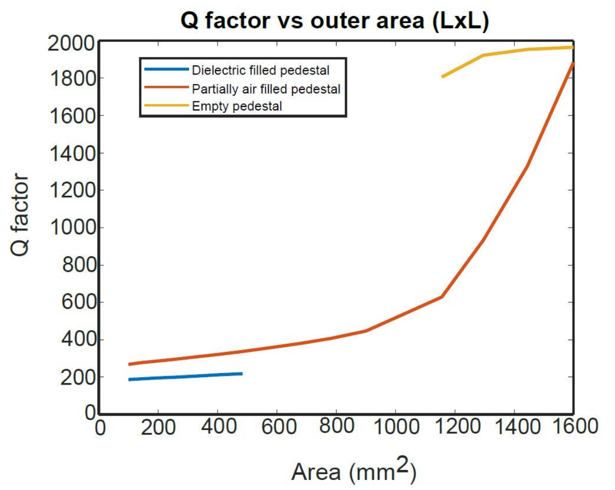
In Fig. 3, in addition to partially air-filled pedestal topology, results for empty pedestal resonator (i.e. totally air-filled) and fully dielectric-filled pedestal configurations were also plotted when possible. Indeed, for the empty pedestal configuration, it is not possible to achieve structures smaller than 1 100 mm^2 while it is impossible for fully dielectrically-filled configuration to obtain sizes greater than 500 mm^2.

As an example, with the same materials characteristics, the reachable Q-factor of a partially air-filled pedestal SIW resonator (orange lines) is around 300 for a given area of 200 mm^2 (Fig. 3(a)). This Q-factor is computed at a resonating frequency of 5 GHz, which is achieved by designing a pedestal with a W/L ratio of 0.55 (Fig. 3 (b)). For the fully dielectrically-filled counterpart (blue lines), and by considering both the same area and the same frequency, which is achieved with a W/L ratio of 0.3 (Fig. 3 (b)), reachable Q-factor is around 200 (Fig. 3(a)).

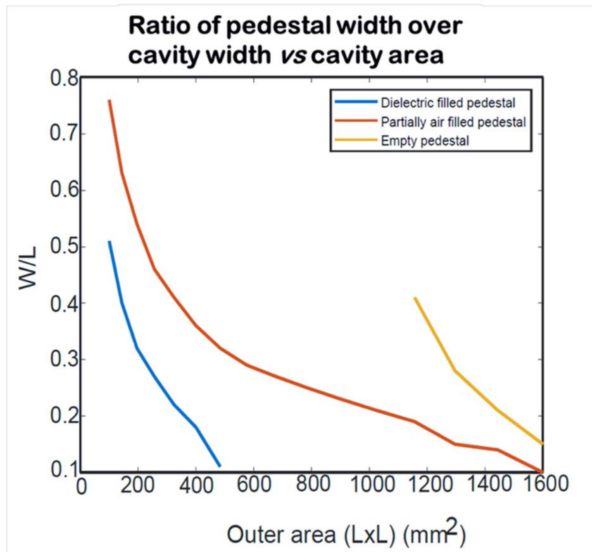
Those two figures evidence the trade-off between size and Q-factors a designer has to cope with. Furthermore, the results also highlight the interest of the proposed configuration as it enables to reach Q-factors greater than those of fully dielectrically-filled resonators (approximatively 200) while maintaining the outer area smaller than those of empty pedestal configuration (1 100 mm^2).

Additionally, Fig. 3 shows that partially air-filled pedestal topology also permits to reach higher Q-factors than the fully dielectrically-filled pedestal configuration for the same outer area, thanks to the compensation on the pedestal dimensions.

As expected, the empty pedestal resonator achieves the highest Q-factors, however, it is of key-importance to



(a)



(b)

FIGURE 3. (a) Q-factor of the partially air-filled pedestal resonator as a function of the cavity outer area (*L* × *L*) and (b) Width of the pedestal plate to cavity length ratio (*W*/*L*) plotted as a function of outer area (*L* × *L*) to maintain a resonant frequency of 5 GHz.

underline that the empty pedestal resonator cannot be manufactured, at least not with classical PCB processes. Indeed, the intermediate conductive plate needs to be supported, although this configuration is unrealizable, it was included in the study for comparison sake.

Finally, the partially air-filled pedestal resonator is able to achieve a wide range of sizes and interesting Q-factors (always higher than the dielectrically filled-in structure).

From these considerations, and because of its large range of design options and its versatility, it appears clearly that the partially air-filled pedestal topology stands as a competitive candidate when optimal Q-factor/size trade-offs are seeked. As a counterpart, it necessitates specific features in the manufacturing process, which are detailed in the next section.

III. DESIGN AND MANUFACTURING

To validate assertion of performances of the partially air-filled topology detailed in the previous section, experimental measurements need to be performed. Prior to the electrical measurements, the design of the input/output feedings of the structure together with the manufacturing steps will be detailed.

The input/output structures are based on a topology alike the one detailed in [16]. It consists of a 50 Ω grounded coplanar line connected at the end to a via hole from the top to the bottom metal layers. The existence of a magnetic loop around this short-circuit-terminated via-hole ensures the excitation of the resonating mode. Input/Output coupling via-holes are located in the vicinity of the center of the intermediate metal plate of the pedestal resonator to allow for sufficient coupling levels. One should note that the distance between the center of the pedestal and the Input/Output coupling via-holes determines the coupling strength and can thus be used to tune it as desired. Furthermore, to enable a structural support during the manufacturing process, the coplanar line is etched on the top layer of a dielectric slab, which is made through a tapered substrate connected to the pedestal dielectric support.

Top view of the inner layers and exploded 3D view of the resulting structure is shown in Fig. 4.

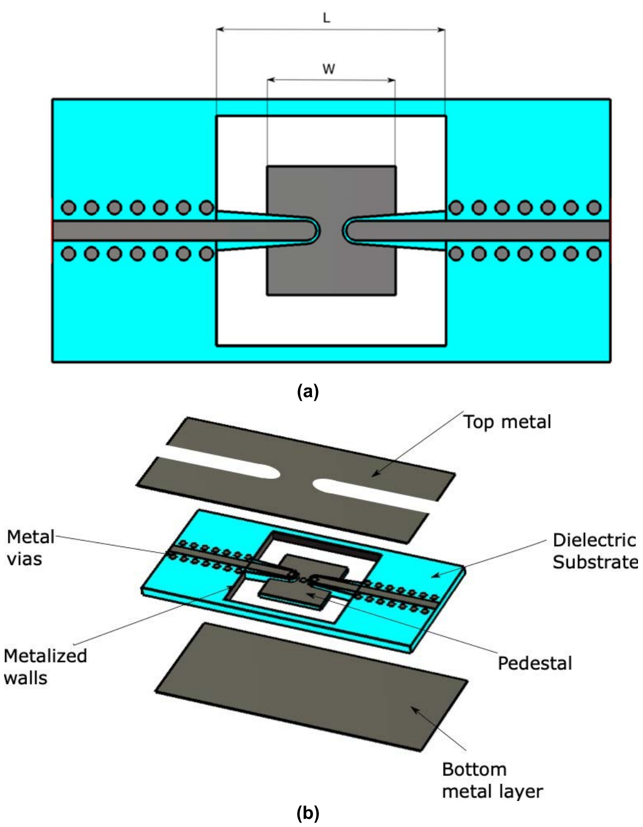


FIGURE 4. (a) Top view of the inner layer and (b) Exploded 3D view of a partially air-filled pedestal resonator.

Dimensions of the design are h1 = h2 = 0.5 mm, W = 7.84 mm, L = 14 mm (pedestal and cavity are square-shaped, which means a surface of 196 mm^2). The chosen substrate, Rogers RO4003C^{TM}, has a relative dielectric permittivity (ε_r) of 3.55 and a loss tangent (tan δ) of 0.0027.

Now that the principle and the design of a partially air-filled pedestal resonator have been introduced, the structure has to be realized.

The conventional way of manufacturing Air-Filled- or Empty- Substrate Integrated Waveguides on Printed Circuit Boards (PCB) processes is to mill a double-sided board that is then mechanically-assembled with copper foils, generally through the means of bolts.

Although this results in a cheap process, problems for alignment, reliability, and conductive continuity arise, thus it is not suitable for industrial deployment. For this reason, we choose to fabricate this resonator with a process constituted of three stages: micromachining of the cavity, metallization and thermo-diffusion stacking.

Firstly, from a classical copper-cladded double-side dielectric board (Fig. 5 (a)), a depth-controlled micro-machining or laser-based process selectively removes the substrate and metal to create the pedestal shape, as shown in Fig. 5 (b). In this figure, the left part presents the top view of the resonator while the right-hand side of the figure shows cross- sectional cuts along the AA' and BB' lines. Dielectric substrate is depicted with blue shades, air is white-colored whereas metallization is represented in black.

Secondly, via-holes are drilled (Fig. 5 (c)) and the all the surfaces are the metallized, including via-holes, cavity sidewalls and pedestal edges, as presented in Fig. 5 (d). De-metallization of specific areas, such as pedestal or accesses edges is then made by using a precise milling machine or a laser (Fig 5 (e)). Then, a 35-micrometer-high copper foil is bonded, by means of thermo-diffusion, onto the top of the structure to create an enclosed quasi-empty SIW cavity, as shown in Fig. 5 (f). To realize this thermo-diffusion-bonded closure of the cavity, a specific metal layer has been deposited on the copper metallization, which creates a strong conductive adhesion with the top copper foil under precise temperature and pressure conditions. Finally, slots are etched on the top copper foil to allow for the realization of planar lines accesses (Fig. 5 (g)).

A picture of the realized device is shown in Fig. 6. The next step is to proceed with its electrical measurement, which was achieved with an Anritsu® 3680-20 cell connected to a properly-calibrated Rhode & Schwarz® ZVA 67 Vectorial Network Analyzer.

IV. RESULTS

The simulated and measured results can be seen in Fig. 7. A very good agreement, both in the general shapes and in the magnitude levels between simulated and measured results can be noticed. One specific feature of the presented electrical responses is the occurrence of a transmission zero located around 6 GHz related to a direct input-to-output cross-coupling. Unloaded Q-factor was extracted from measurements and the obtained values, Q = 285, which is very close

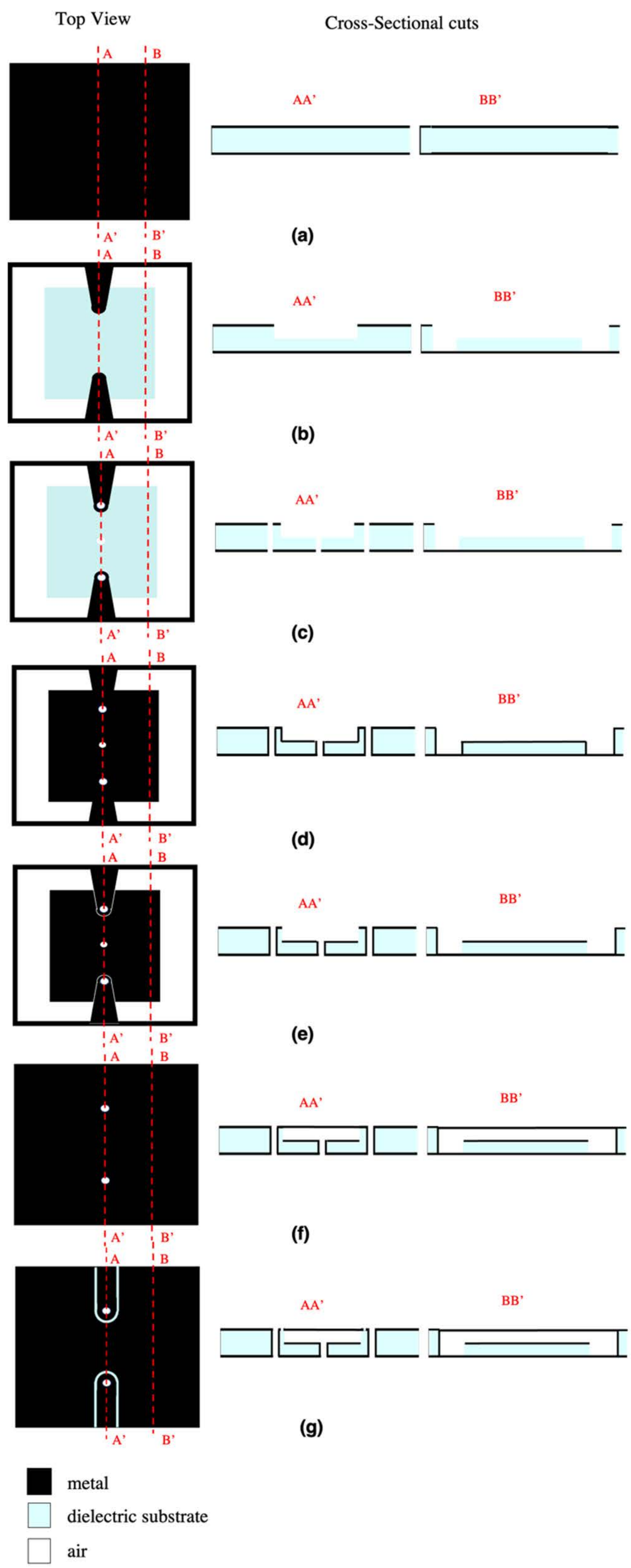


FIGURE 5. Steps of the technological process. (a) initial double-side copper-claded substrate, (b) micro-machining, (c) via-hole drilling, (d) metallizing, (e) selective de-metallizing, (f) cavity closing, (g) feeding lines etching.

to the simulated one, has to be compared to that of an equivalently sized (14 $\times$ 14 mm^2) fully dielectrically-filled-in

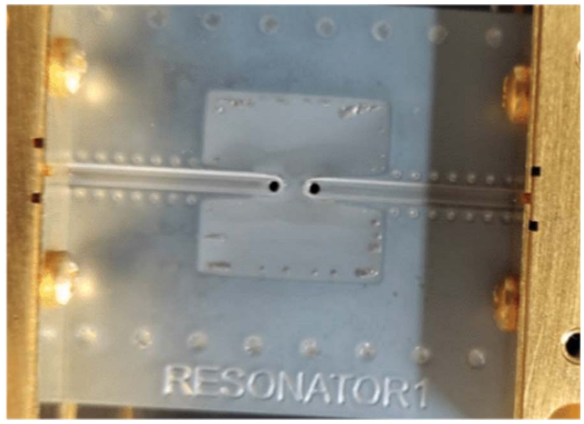


FIGURE 6. Photography of the realized resonator.

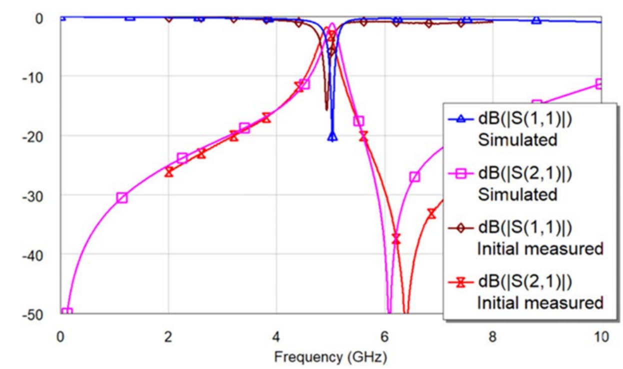


FIGURE 7. Simulated and measured results of a partially air-filled pedestal resonator.

pedestal resonator. For this latter, simulations performed with CST Studio Suite resulted in an unloaded Q-factor of 186.

This evidences an unloaded Q-factor increase of 53% for the partially air-filled pedestal topology with respect to the dielectrically-filled counterpart. It is paramount to note that this Q-factor increase was made at no cost regarding the overall volume (14 $\times$ 14 $\times$ 1 mm^3) occupied by the resonator, evidencing the interest of the proposed concept and technology.

Further to the manufacturing of a resonator, and to pinpoint the relevance of this topology, a second order filter was designed. An overview of the second-order partially air-filled filter can be seen in Fig. 8.

The first step was to characterize the coupling between the two pedestal resonators in order to achieve the desired passband. The inter-resonator coupling is tuned through the variation of D, distance between the central via-holes of the pedestal resonators. The coupling level as a function of the distance D was computed thanks to full-wave simulations performed with CST Studio Suite and the corresponding plot is proposed in Fig. 9. Using this abacus, a second-order filter based on partially-air filled pedestal resonators is designed. The targeted relative bandwidth is 2% and the filter is centered at 5 GHz. All the dimensional parameters related to the

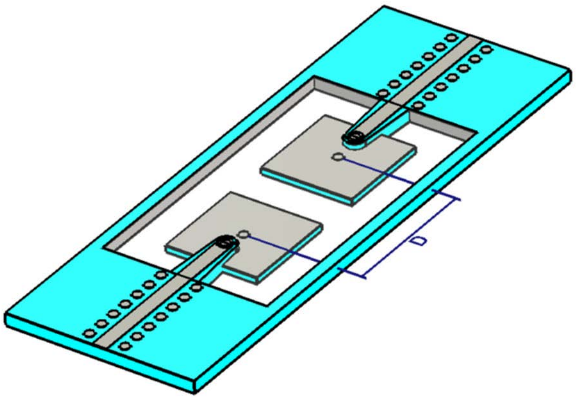


FIGURE 8. Overview of the second-order partially air-filled pedestal filter (top and bottom copper claddings are not shown here).

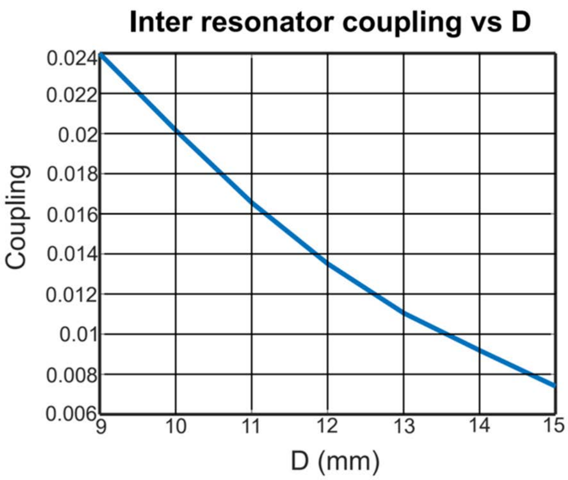


FIGURE 9. Inter-resonator coupling as a function of distance D.

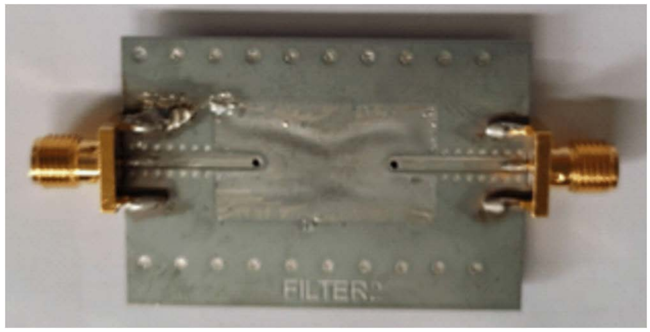


FIGURE 10. Photography of the second-order filter.

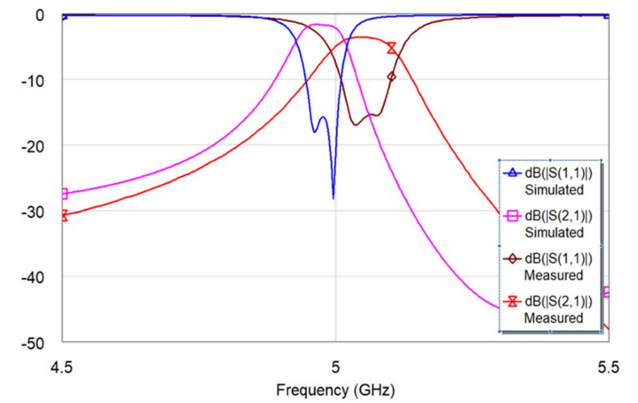


FIGURE 11. Simulated and measured results of the second-order partially air-filled pedestal filter.

TABLE 1. Performances comparison.

Ref.	order	Fc (GHz)	FBW (%)	IL (dB)	Q	Size (λ^2_{air})	FoM (Q/Size)
[8]	4	11	2.72	0.9	710	0.57	1246
[17]	3	5.2	38	0.74	46	0.086	534
[18]	3	7.8	22	1.5	39	0.115	342
[18]	5	8.79	40	1.2	45	0.138	327
[19]	3	30.05	6.02	0.99	219	1.135	193
This work	2	5.05	2.67	3.53	92	0.054	1692

resonators are similar to those detailed in section III, and the inter-resonator distance D is set to 11.4 mm.

A photography of the realized filter is shown in Fig. 10. The filter is then measured with the same measurement set-up as the one detailed in section III. Measured electrical response of the filter is shown in Fig. 11 together with the full-wave simulated results. From the simulation, expected insertion loss is 2.39 dB. Simulation and measurements show a good agreement in their shape, which validates the interest of this technological process associated to the pedestal topology. However, measurement exhibits higher losses (3.53 dB), increased bandwidth (2.67%) and a frequency shift toward higher frequencies (5.05 GHz) compared to the simulation. After a careful inspection of the realized prototype, it appears that the top copper foil is slightly distorted (as it can be seen in Fig. 10), which could explain the increase of the bandwidth and the frequency shift. Some other geometrical inaccuracies, such as changes in pedestal dimensions or height could also explain these effects. Additional losses could be explained by a conductivity lower than the expected one.

A full-wave simulation with a 2% decrease on the pedestal width (W) and a lowering of the metal conductivity from 5.96×10^7 S/m to 2×10^7 S/m ha lowering of the metal conductivity from 5.96×10^7 S/m to 2×10^7 S/m s been performed. Simulation results and measured electrical response are presented in Fig. 12. Characteristics of the realized filter together with data from recently-published, size-reduced SIW bandpass filters (including Air-Filled and Empty SIW) in terms of center frequency (fc), order (n), fractional bandwidth (FBW), insertion losses (IL), and surface of the circuit expressed in square wavelengths (computed in the air) are given in Table 1.

Additionally, Q-factor extracted from the measurements of the filters responses (from FBW, n and IL using [20]) is also presented. Finally, a Figure of Merit (FoM) computed as the

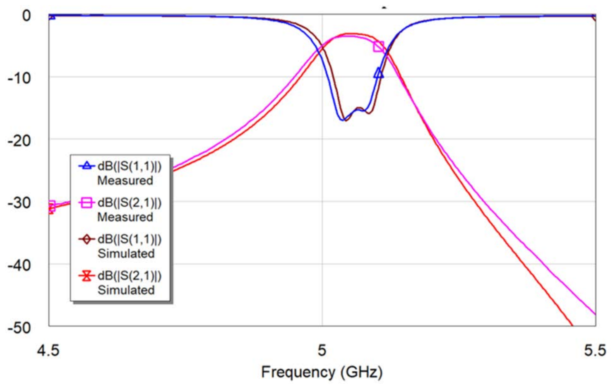


FIGURE 12. Measured results and simulation with a 2% decrease on pedestal width and conductivity of 2×10^7 S/m.

ratio between Q-factor and circuit surface (expressed with respect to the square air wavelength) is computed to evidence the trade-off between size and electrical performances. The high value of the FoM reached by the proposed Partially-Air-Filled SIW second-order filter clearly shows that the proposed topology enables the achievement of a novel trade-off in the Q-factor *vs* size ratio.

V. CONCLUSION

In this paper, partially air-filled pedestal Substrate Integrated Waveguide topology has been investigated. It has been proven to feature interesting possibilities regarding the trade-off between size and Q-factor. To evidence the relevance of this topology, a prototype has been manufactured. Micro-milling and thermo-diffusion associated with conventional PCB operations have been used to achieve the manufacturing of both a resonator and a second-order filter. Measurements have enabled the extraction of the unloaded Q-factor, which reaches 285, an increase of 53% with respect to a dielectrically-filled pedestal SIW topologies. Finally, a 2%-bandwidth, second-order filter based on the same topology has also been presented.

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