Novel Classes of Bandpass Filters in Substrate Integrated Waveguide Technology

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I. INTRODUCTION: SIW technology

The evolution of 5G, wireless sensor networks (WSN) and Internet of Things (IoT) requires the development of novel classes of RF and microwave components. In particular, along with the stringent requirements in terms of performance, these new fields of application ask for low-cost, compact size, low weight components. In addition, in these applications the components can be widely spread, and this suggests that the use of green materials should be considered as a plus in the choice of the technology. Furthermore, the possibility to easily integrate an entire wireless system by adopting a cost-effective manufacturing process is another important feature. Considering all the available manufacturing and integration technologies for RF and microwave circuits, a good candidate, able to satisfy all the aforementioned requirements, is represented by the substrate integrated waveguide (SIW) technology. SIW technology integrates in planar form waveguide-like components: top and bottom ground planes cover a dielectric substrate and the side walls of the classical rectangular waveguide are substituted with rows of metal cylinders. Among all the possible microwave components that can be realized adopting this technology, filters are particularly suitable for the low losses (related to other planar technologies), high flexibility in realizing arbitrary geometries and multilayer structures (obtaining difficult couplings to obtain in other technologies).

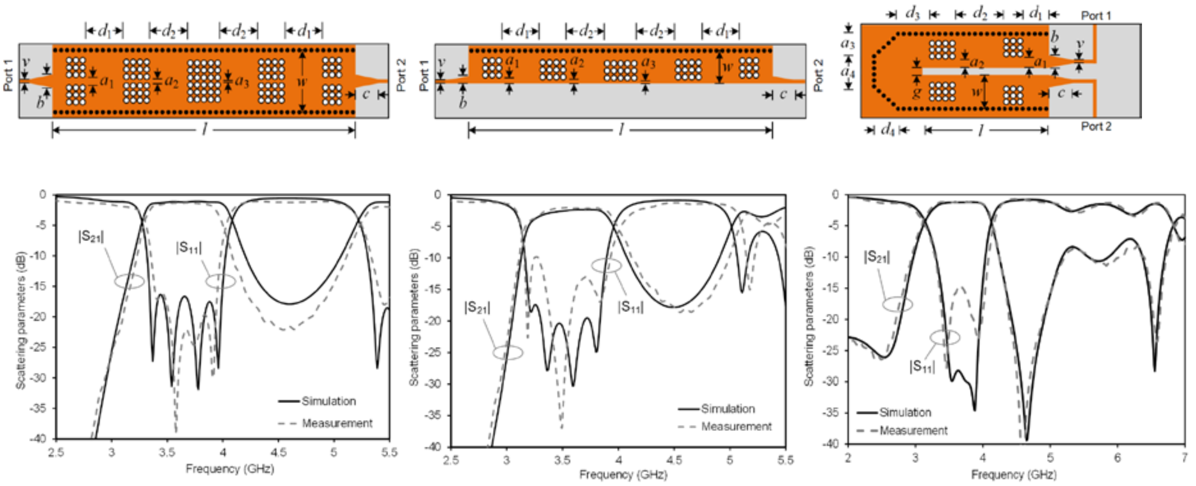
II. NOVEL CLASS OF SIW BANDPASS FILTERS BASED ON THE PERIODIC PERFORATION OF THE DIELECTRIC SUBSTRATE [1][2][3]

In the proposed class of filters the idea is to obtain a simple, low-cost design that can be realized by simply perforating the dielectric substrate with air holes. The primary effect of the air holes in the dielectric substrate is the local reduction of the effective dielectric permittivity. Consequently, these regions behave like iris windows, where the width of the waveguide is reduced to create a waveguide section below cutoff. The density and the position of the air holes allows controls the cutoff frequency (just like the width of the iris window) and the length of the perforated region determines the thickness of the iris.

The advantages of this proposed filter are related to a better out-of-band rejection and, most importantly, are related to its tolerance of fabrication inaccuracies.

The first proposed filter is a four poles full-mode bandpass SIW filter with a measured insertion loss (IL) equal to 1.31 dB at f_0 = 3.65 GHz and a bandwidth (BW) of 630 MHz defined at 10 dB input matching (Fig. 1(*a*)). The filter is realized on a commercial dielectric substrate Taconic CER-10 (thickness 0.64 mm, ε_r = 10.0, tan δ = 0.0035) with a mechanic LPKF E33 milling machine. The holes, constituting the side walls of the SIW structure are metalized with a LPKF ProConduct paste.

The main disadvantage is related to the increase of the overall dimensions, and for this reason a half mode filter can be implemented by simply removing half of the top metal plane from the previous structure. Due to the low aspect ratio of the open boundary defines an equivalent magnetic wall with reduced radiation losses. The previous full mode filter requires a small reoptimization with HFSS solver. In Fig. 1(*b*) the comparison of simulated and measured scattering parameters is presented. This demonstrates a measured insertion loss (IL) equal to 2.15 dB at f_0 = 3.65 GHz and a bandwidth (BW) of 760 MHz defined at 10 dB input matching. Simulations are slightly different with 2.4 dB IL and BW of 730 MHz.



(*a*) (*b*) (*c*)

Fig. 1. Realized filters: (*a*) full mode filter: model and |S| parameters comparison between simulation and measurements; (*b*) half mode filter: model and |S| parameters comparison between simulation and measurements; (*c*) folded half mode filter: model and |S| parameters comparison between simulation and measurements. [1][2][3]

In order to reduce the radiation losses of the previous structure a folded half mode topology has been implemented by folding the half mode structure on itself. The fringing fields at the open side cancel each other thus leading to reduced radiation losses with a result in line with the full mode filter but with reduced dimensions. The filter bandwidth, defined at 10 dB input matching, is 735 MHz in the simulation and 800 MHz in the measurement. The insertion loss at the central frequency f_0 = 3.65 GHz is 1.25 dB in the simulation and 1.20 dB in the measurement (Fig. 1(*c*)).

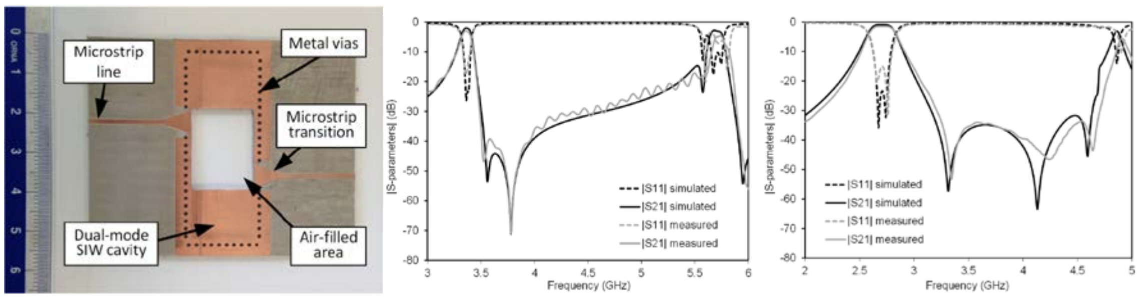
III. NOVEL CLASSES OF BANDPASS FILTERS BASED ON DUAL MODE AIR-FILLED SIW CAVITY: central excavation of the cavity [4][5]

This section describes a new class of bandpass filters based on the use of a dual-mode SIW cavity. The previous class of filters realizes low cost structure with the possibility to reduce the dimensions of the cavity with a poor out-of-band rejection. A dual-mode cavity exhibits the advantage of reduced the overall dimensions whilst improving the out-of-band rejection related to the use of non-resonating modes. The dual-mode cavity is realized by removing the dielectric substrate in the central portion of the cavity.

Considering the first (TM_{110}) and second mode (TM_{210}) modal fields of the dielectric filled cavity it is clear that, when removing the dielectric in the central portion of the cavity, the TM_{110} mode is more affected than the TM_{210} mode. Thus, the frequency separation between the two modes can be controlled, playing on the dimension of the air part. By changing the dimensions of the excavation and the cavity it is possible to obtain the control of the filter's characteristics such as spurious free bandwidth, relative resonant frequency separation and central frequency of operation.

Starting from the dual-mode air-filled structure, doublets - capable of two poles and two transmission zeros - have been analysed. In particular, the doublets have been fed by microstrip lines, placed anti-symmetrically respect to the center of the cavity in order to separately control the coupling between the input/output and the first and second mode. One of the transmission zeros is due to the asymmetric coupling whilst the other is due to the source to load coupling through higher order modes due to the proximity between the input and output.

Considering the previous considerations, the filters with 1.5% and 5% fractional pass-bandwidths and 20 dB input matching in the pass-band have been fabricated. The dielectric laminate is the Taconic CER-10 (with relative dielectric permittivity ε_{r1}=10.5, loss tangent tanδ=0.0035, and thickness 1.27 mm). The structures have been realized with the milling machine LPKF E33 and the metal vias have been metallized with the LPKF ProConduct paste. The photograph shows the prototype (1.5% FBW) before the metallization of the metal vias and the closing of the top/bottom air-filled area by copper sheets. The copper sheets at the top and bottom of the air-filled area have been applied and soldered as close as possible to the perforated region. Measurements have been performed using an Anritsu Universal Test Fixture (UTF) 3680 and an Anritsu 37347C vector network analyzer (VNA). No de-embedding was applied to the measured results, to remove the effects of connectors and transitions. The comparison between simulations and measurements are shown in Fig. 2 (*b*) and Fig. 2 (*c*). The measured insertion losses in the pass-band are slightly larger in the measured results than in the simulated. The overall agreement between simulation and results is very good, even in the out-of-bands.



(*a*) (*b*) (*c*)

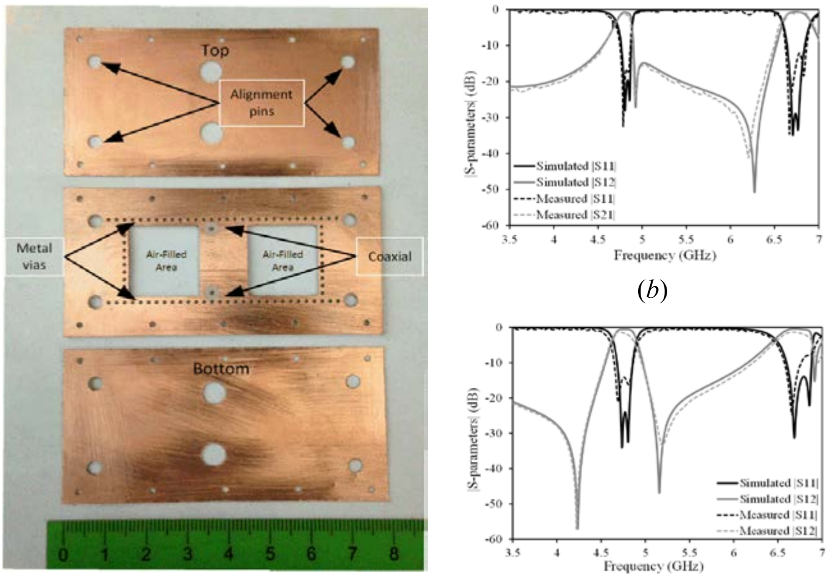
Fig. 2 Air-filled dual-mode SIW filter: (*a*) prototype; (*b*) |S| parameters comparison between simulation and measurements of the 1.5% FBW filter; (*c*) |S| parameters comparison between simulation and measurements of the 5% FBW filter. [4][5]

Doublets can be used as building blocks in order to create higher order filters still maintaining the position and the number of transmission zeros when cascaded throught a non resonating node.

IV. NOVEL CLASSES OF BANDPASS FILTERS BASED ON DUAL MODE AIR-FILLED SIW CAVITY: lateral excavation of the cavity [6]

Instead of removing the dielectric substrate from the center of the cavity it is possible to excavate the lateral sides. The first mode, previously altered by the dielectric removal in the central portion, is here untouched. Conversely, the second and third resonant modes are modified. The interesting result is related to the ability to change the lower resonance frequency mode between the quasi - TM_{120} and quasi - TM_{210} by simply changing the central dielectric portion. This possibility leads to the ability to control the position of the transmission zero related to the asymmetric coupling. The TZ can be placed now above or below the passband of the filter. The other transmission zero can be controlled with the source to load coupling. In particular, by using coaxial probes to feed the structure a new degree of freedom is achieved, related to the ability to place the probes along the long side of the cavity or transversally: in this case the transmission zero related to the source to load coupling can also be changed achieving all possible locations in respect to the passband. With this structure the transmission zeros can either be placed both above, one above one below or both above the filter passband. All the geometrical parameters of the dual-mode air-filled SIW cavity have been related to the control of specific filter characteristics such as central frequency of operation, spurious free bandwidth and relative frequency separation as for the previous structure.

The filters have been realized on Rogers 3010 substrate with $\varepsilon_r = 10.2$, tg$\delta = 0.0022$ and thickness 1.27mm and machined with the milling machine LPKF ProtoMat S103. The filters are composed by three different layers: top cover, dielectric substrate (dual-mode partially air-filled SIW cavity) and bottom cover. Top and bottom covers have been machined on the dielectric substrate Rogers 3003 (thickness 0.25mm) in order to realize all the layers in a single fabrication step. The metal lateral vias of the SIW cavity have been metallized with a LPKF ProConduct paste. Finally the coaxial probes have been soldered. All the prototypes have been measured with a Keysight VNA N5242A.



(*b*)

(*a*) (*c*)

Fig. 3 Complementary air-filled dual-mode SIW filter: (*a*) filter prototype before closing the top and bottom; (*b*) |S| parameters comparison between simulation and measurements with both TZs above the filter passband; (*c*)) |S| parameters comparison between simulation and measurements with TZs symmetrically placed respect to the filter passband. [6]

The first filter, with frequency response shown in Fig. 3(*b*) has been realized and measured. The first prototype shows a simulated insertion loss of 0.8dB while the measured one is slightly higher, being 1.4dB (1% *FBW*). The filter response with transmission zeros symmetrically placed respect with the passband, is presented in Fig. 3(*c*) with the comparison between simulated and measured results. In this case, the measured insertion loss is 1.2dB while the simulated one is 1.1dB (1.5% *FBW* at f_c = 4.8GHz). No de-embedding has been applied. In both cases simulations and measurements show a good agreement both in the entire passband and in the out-of-band.

V. CONCLUSIONS

This paper presents several solutions adopting the partial removal of the dielectric substrate for the implementation of bandpass SIW filters. The perforation of the substrate with air holes is investigated for its superior strength to the fabrication tolerances, compared to the iris-type filter (able to realize a similar filtering function). In addition, the half mode and the folded half mode have been studied in order to reduce the dimensions and compensate the radiation losses, respectively. A different approach, that can be used to increase the out of band rejection of the previous topologies whilst reducing the dimensions, is related to the use of dual-mode air filled SIW cavities. The removal of the dielectric in the center of the cavity realizes a doublet able to generate two poles and two transmission zeros. Two different examples are presented to show the control on the filter characteristics related to the geometrical parameters. Conversely, the excavation of the lateral portions of the cavity leads to the full control on the position of the transmission zeros. All the filters have been realized and measured confirming the theoretical studies.

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