Substrate Integrated Waveguide Cavity Filters: Miniaturization and New Materials for IoT Applications

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Abstract. *This paper presents an overview of the current research trends in the field of substrate integrated waveguide (SIW) technology, with particular emphasis on the issues related to the emerging applications in the framework of the Internet of Things (IoT) and the fifth generation of mobile communication (5G). More specifically, different techniques adopted to miniaturize SIW cavities are described, with the aim of reducing the footprint of SIW components and filters. Moreover, the use of innovative materials, like paper, textile and 3D printed dielectric substrates, is presented and discussed, and the implementation of ecofriendly, wearable, and fully 3D structures is illustrated.*

Keywords

Substrate integrated waveguide (SIW), filters, paper-based electronics, wearable microwave components, additive manufacturing

1. Introduction

The rapid evolution of new applications in the framework of the Internet of Things (IoT) [1], [3] and the fifth generation of mobile communication (5G) [4], [5] poses a set of requirements for the developers of microwave wireless systems. Besides the low cost, the fast design process, and the simple fabrication technology, the future generation of microwave systems needs to exhibit easy integration, compact size, as well as the possibility to be implemented on unconventional materials (like paper, textile, and 3D printed materials).

The future generation of microwave systems needs to integrate in a single device the microwave circuitry, sensing capability, and wireless transmission of data and (possibly) power. In order to keep the design and fabrication costs as low as required by the market, the use of a single, suitable technology is mandatory.

Moreover, specific applications require the use of innovative materials that are not commonly used in the fabri-

cation of microwave circuits: wearable components and antennas, for instance, can be conveniently integrated on garments, by adopting the textile as the substrate material. Ecofriendly applications, in the field of agriculture and environmental monitoring, can benefit from the use of paper (instead of plastic) for the dielectric substrate.

In this scenario, the substrate integrated waveguide (SIW) technology [6], [7] represents a particularly suitable candidate, due to its capability to implement passive components, active devices, and antennas by using a single technology and manufacturing process. High performance components in terms of losses are usually realized by using waveguide technology. A lot of effort has been devoted to mass and weight reduction for this technology [8]–[11], even in combination with high dielectric materials [12], [13]. The main problems remain their integrability. SIW is the integrated version of this technology and is very competitive from the point of view of losses. In fact, the SIW technology allows to implement interconnects and cavities by using a standard printed-circuit board (PCB) process, based on a laminated dielectric substrate and metal vias that provide the lateral confinement. SIW technology presents several advantages over other planar technologies (e.g., microstrip line and coplanar waveguide), such as complete shielding, and low loss, while preserving a low fabrication cost and a well-established manufacturing process.

One of the major limitations of SIW structures, however, is related to the dimensions, which depend on the operation frequency and the dielectric material. While using dielectric substrates with high permittivity allows reducing interconnect and cavity size, it has typically a detrimental effect on losses, and consequently it leads to poor quality factors. For this reason, several solutions have been proposed to reduce the size of SIW structures, including the substrate integrated folded waveguide [8] and the half-mode substrate integrated waveguide [15].

This paper presents an overview of recent achievements in the implementation of novel SIW cavity filters for IoT applications, with particular emphasis on the miniaturization and the use of new materials. The use of folded, half-mode and quarter-mode SIW cavities will be discussed
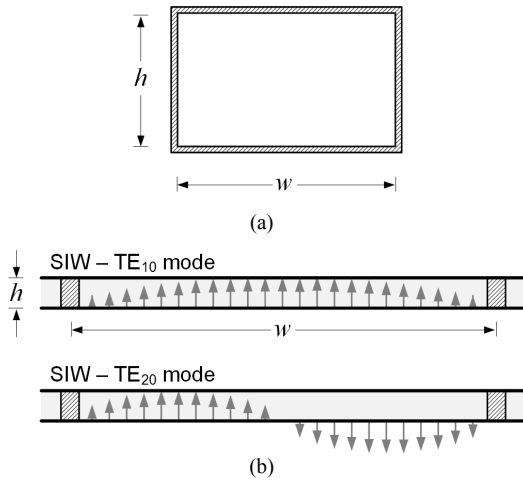
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Fig. 1. Geometry comparison of a standard and an integrated waveguide: (a) Cross section of a standard rectangular waveguide; (b) Cross section of a substrate integrated waveguides, and electric field of the first two modes.

and several filters based on these structures will be presented. Moreover, the implementation of SIW filters on paper (for eco-friendly applications), on textile (for wearable systems), and by 3D printing (to exploit the maximum versatility and to tailor the material properties) will be presented and discussed through several examples.

2.   Miniaturized SIW Cavities

The substrate integrated waveguide represents an integrated version of the classical rectangular waveguide [6], [7]. As shown in Fig. 1, the main difference in terms of dimensions resides in the height: in the standard rectangular waveguide the height h is usually about a half of the width w, while in SIW the dimension h is much smaller than w and it corresponds to the thickness of the dielectric substrate, used in the PBC fabrication.

2.1 Folded SIW Cavity

The basic idea of folded SIW is to reduce the footprint by folding the structure around a metal septum [8]. This solution allows reducing the footprint of the structure by a factor two.

A folded SIW can be obtained by using a two-layer topology (Fig. 2). The metal septum between the two layers is connected to the side posts on one side, whereas it leaves a gap on the opposite side. This leads to a U-shaped waveguide. The electric field of the fundamental mode of the folded SIW is depicted in Fig. 2 (above) and in practice corresponds to the fundamental TE_{10} mode of the standard rectangular waveguide, once the waveguide is folded around the metal septum. Conversely, the electric field of the second mode of the folded SIW is illustrated in Fig. 2 (below): this mode corresponds to the TE_{20} mode of the standard rectangular waveguide, after folding the structure around the metal septum.
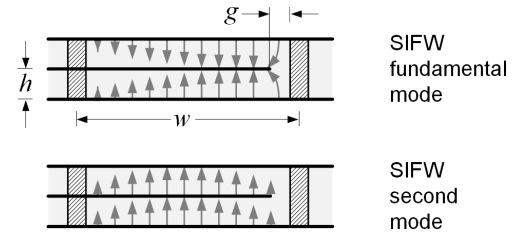

Fig. 2. Geometry of a folded SIW and representation of the electric field of the first two modes.

Note that the fundamental mode exhibits an odd symmetry with respect to the middle plane between the two dielectric layers, while the second mode shows an even symmetry.

Because of its topology, this structure can be easily fed by stripline and, thanks to the modal symmetry, the stripline excites the fundamental mode but not the second (TE_{20}) mode, thus resulting in a wider spurious free behavior.

The gap g between the metal septum and the side posts (Fig. 2) affects the resonance of the folded waveguide by changing the electrical length of the structure. In particular, the narrower the metal septum, the higher is the waveguide cutoff frequency. This effect can be exploited for obtaining filtering structures as that sketched in Fig. 3 [16]. In this case, the waveguide sections with a large septum alternate to waveguide sections with a narrow septum (which defines the insets). Large-septum waveguide sections behave as resonators, narrow-septum waveguide sections behave instead as impedance inverters. This leads to the classical equivalent circuit shown in Fig. 4, consisting in transmission lines and admittance inverters.
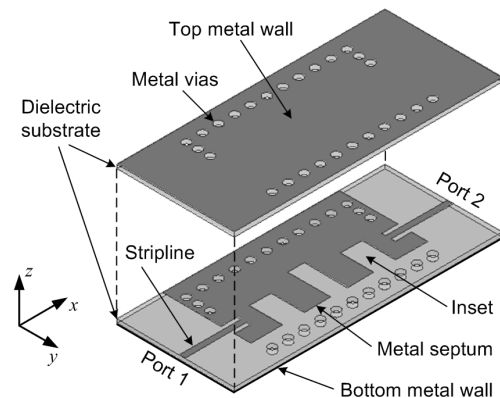

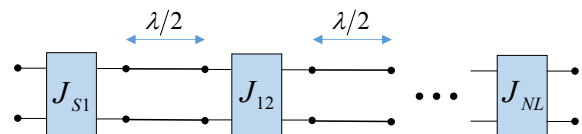**Fig. 3.** Geometry of a filter based on the folded SIW cavity (from [16]).

Fig. 4. Equivalent circuit of folded SIW filter.

By using the proposed topology, a two-pole filter centered at 4.5 GHz with 1.4 GHz bandwidth has been designed and manufactured [16]. The filter design can be performed in two different ways: the classical way is based on the properly dimensioning of resonator lengths and insets, to realize the filtering response of the equivalent circuit in Fig. 4. The second technique, described in [16], is based on the tuning of the resonant modes of the cavity, by modifying the size of the insets.

The filter has been manufactured by milling technique, by adopting two layers of Taconic TLX-9 laminate, with dielectric permittivity $\varepsilon_r = 2.5$, loss tangent $\tan \delta = 0.0019$, and thickness $h = 0.76$ mm. The photograph of the prototype is shown in Fig. 5a. The comparison between measured and simulated scattering parameters is reported in Fig. 5b.
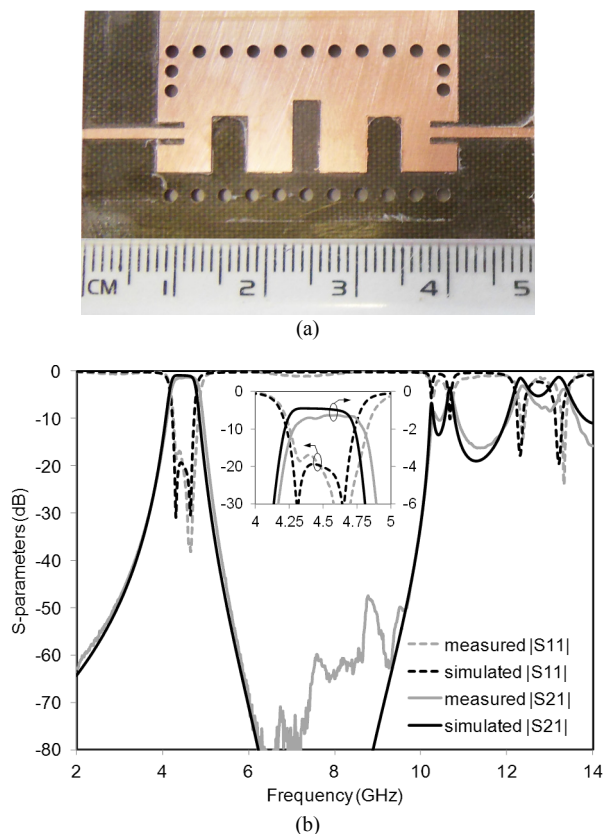

(a)

(b)

Fig. 5. Second order filter based on a dual-mode folded SIW cavity (from [16]): (a) Photograph of the bottom layer; (b) Comparison between simulated and measured scattering parameters of the filter.
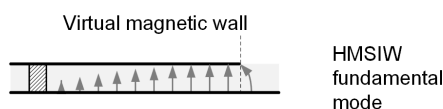

Fig. 6. Geometry of a half-mode SIW and representation of the electric field of the fundamental mode.

2.2 Half-Mode SIW Cavity

As shown in Fig. 1b, the fundamental mode of the SIW structures exhibits a magnetic wall in the vertical symmetry plane. This suggests that it is possible to use just a half of the SIW if the cut is closed with a magnetic wall.

Unfortunately, on the contrary of the electric wall that can be created simply by a metallic material, the magnetic wall is more difficult to realize. The behavior of the magnetic wall can be approximated by exploiting a high impedance load. According to Fig. 6, an abrupt interruption of the upper SIW wall results in a high impedance discontinuity. This effect can be considered a sort of virtual magnetic wall, and this allows to obtain the half-mode substrate integrated waveguide (HMSIW) [15].

The same concept can be exploited in the design of cavity resonators, to be adopted in the implementation of filters. Of course, the fact that the impedance is high but not infinite leads to an electromagnetic field that is not completely confined inside the SIW. Therefore, a small leakage due to radiation is present. This effect decreases the Q-factor. In any case, lower SIW height h or higher dielectric constant allow the implementation of a better virtual magnetic wall (with a higher Q-factor).

By using the HMSIW technology, it is possible to realize a filter with a geometry very similar to that used for folded waveguide, as firstly proposed in [17]. In fact, the fundamental mode of the HMSIW can be excited by a microstrip line, same as the fundamental mode of the folded SIW can be excited by a stripline. According to Fig. 7, wide HMSIW sections can be exploited as resonators, while narrower sections can be used to implement admittance inverters. This leads to the implementation of the circuit of Fig. 4, where narrower HMSIW sections correspond to lower values of impedance inverters.

By adopting the proposed geometry, a four-pole filter with central frequency at 4.5 GHZ and 1.4 GHz bandwidth has been designed and manufactured in [17]. In this case, the fabrication required the processing of one single layer of Taconic TLX-9 laminate, with a complexity reduction compared to the folded SIW filter proposed in the previous section. The photograph of the prototype is shown in Fig. 8a, and the comparison between measured and simulated scattering parameters is reported in Fig. 8b.
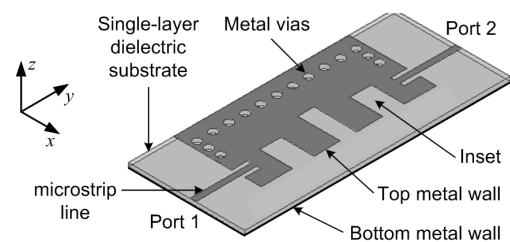

Fig. 7. Geometry of a filter based on the half-mode SIW cavity (from [17]).

(a)

(b)

Fig. 8. Four-pole filter based on a half-mode SIW cavity (from [17]): (a) Photograph of the prototype; (b) Comparison between simulated and measured scattering parameters of the filter.

2.3 Quarter-Mode SIW Cavity

The concept of HMSIW cavity can be further extended to obtain a quarter mode SIW cavity (QMSIW). As shown in Fig. 9, a quarter mode-SIW cavity can be obtained by cutting a rectangular SIW cavity into four parts along the symmetry planes [18]. This is obtained by removing the top metal wall and metal vias of three quarters of the cavity, thus reducing the footprint of the cavity by 75%.

Fig. 9. Geometry of a quarter-mode SIW cavity and representation of the electric field of the fundamental mode (from [18]).

(a)

(b)

Fig. 10. Coupling mechanisms in a two-pole filter based on quarter-mode SIW cavity (from [18]): (a) Coupling is obtained by removing the common posts; (b) Coupling is controlled by shifting the two cavities.

(a)

(b)

Fig. 11. Four-pole filter based on a quarter-mode SIW cavity (from [18]): (a) Photograph of the prototype; (b) Comparison between simulated and measured scattering parameters of the filter.

The equivalent circuit of Fig. 4 can be implemented also by using QMSIW cavities. According to Fig. 10a, the coupling between two adjacent QMSIW cavities is obtained by removing the row of common posts. The control

of the coupling is obtained by side shifting the two cavities, as shown in Fig. 10b. The smaller the shift x, the lower is the admittance inverter value. The coupling to input and output transmission lines is instead controlled by the value of z: the larger the shift z, the lower is the admittance inverter value. In fact, small values of z mean that the microstrip line is connected to the point where the electric modal field is large (see Fig. 9), thus determining a large external coupling.

A four-pole filter centered at 4 GHz and with an FBW of 16% has been designed and manufactured in [18]. A dielectric substrate Taconic RF-35, with $\varepsilon_r = 3.5$, $\tan \delta = 0.0018$, and thickness $t = 0.508$ mm, was adopted for the fabrication. A photograph of the manufactured prototype is shown in Fig. 11a. Measured results are plotted in Fig. 11b, where also the simulated results and the response of the equivalent circuit are reported.

3. SIW Based on New Materials

The use of new materials and fabrication technologies is expected to be a key point of the next generation of wireless systems. The spread of wearable systems will lead to the use of fabric-based components, where the microwave structures are embedded in the garments. Examples of SIW components and antennas in textile have been reported in [19] and [20]. The need to implements eco-sustainable wireless systems is expected to be a strong requirement for some applications, for instance in the field of agriculture and environmental sensing. SIW circuits based on paper substrates and implemented by different techniques have been described in [21]–[23]. Finally, the additive manufacturing represents an emerging area of research, where the microwave components are fabricated by 3D printing, in a single-pass, low-cost manufacturing process. The fused-deposition modeling has been adopted for the implementation of SIW components and antennas [24], [25], by exploiting the possibility to synthetize the required dielectric material by properly adjusting the infill percentage during the printing.

3.1 Paper-based SIW Filters

The use of paper for the implementation of microwave components is particularly interesting, as paper is a cheap material, it is flexible and therefore potentially suitable to the implementation of conformal circuits and antennas, and it is eco-friendly, for those applications (agriculture, environmental monitoring, …) where reducing the ecological impact is critical.

SIW technology is particularly suitable to the implementation on paper, and two different techniques can be adopted. The use of inkjet printing was proposed in [22]: an inkjet printer, that uses a special ink with silver particles, realizes the top and bottom metal layers of the SIW, and the vias consist of brass rivets. Another approach was

adopted in [23]: aluminum foils are pasted at the top and bottom sides of a thick paper sheet by using epoxy glue, to define the top and bottom metallization of the SIW structure; subsequently, a classical milling technique is adopted, and the metal vias are realized by conductive paste. The latter solution avoids the sintering process of the conductive ink and reduces the fabrication to a well establish PCB process.

The filters presented in the previous section and based on classical plastic substrates can be implemented on paper. The filters presented in this section have been fabricated by using the technology described in [23], based on the standard milling processing of a paper layer with aluminum foils. The paper substrate exhibits a thickness of 500 μm, relative dielectric permittivity $\varepsilon_r = 2.2$, and loss tangent $\tan \delta = 0.04$.

Two-pole filter on paper, based on a half-mode SIW cavity and operating at the central frequency of 4.5 GHz, was proposed in [20]. The photograph of the prototype is shown in Fig. 12a: the filter is quite compact, with a length less than 40 mm, including the input/output microstrip transitions. The simulated and measured frequency response is reported in Fig. 12b, showing a measured insertion loss is 5.0 dB at the frequency of 4.5 GHz.
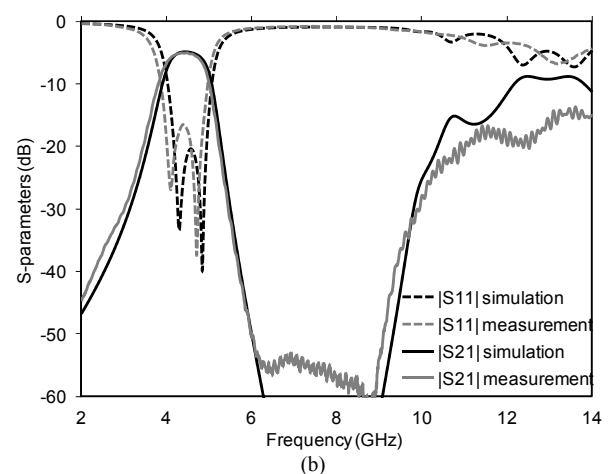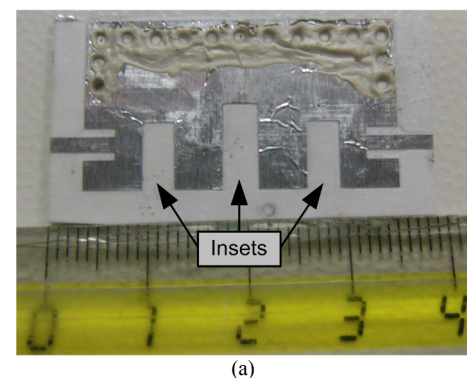

(a)

(b)

Fig. 12. Two-pole filter on paper, based on a half-mode SIW cavity (from [26]): (a) Photograph of the prototype; (b) Comparison between simulated and measured scattering parameters of the filter.
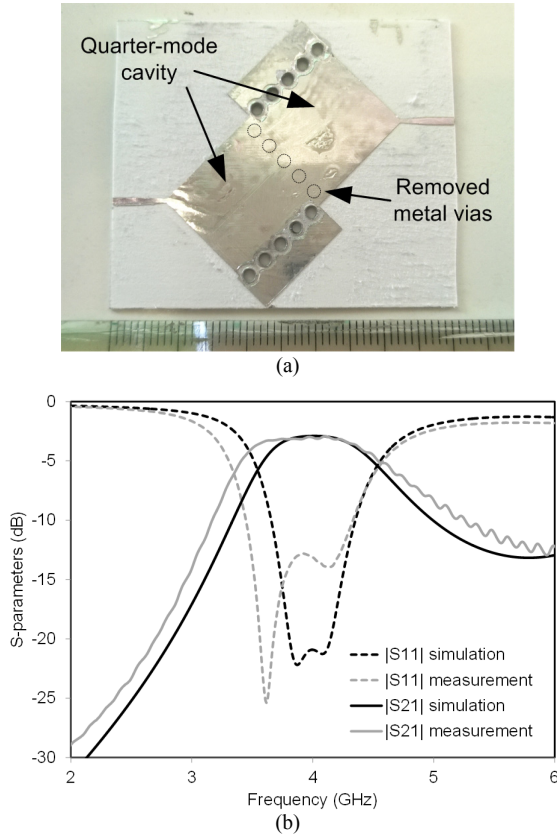
(a)

(b)

Fig. 13. Quarter-mode SIW filter on paper, fabricated by milling technique (from [23]): (a) Photograph of the prototype; (b) Comparison between simulated and measured scattering parameters of the filter.

A quarter-mode SIW filter on paper, operating at the frequency of 4 GHz, was firstly presented in [23]: it consists of two side-coupled quarter-mode SIW cavities, fed in the corners by microstrip lines with tapered transitions. Fig. 13 shows the photograph of the prototype and the simulated and measured frequency response of the filter.

3.2 SIW Filters on Textile

The deployment of wearable electronic devices is gaining increasing popularity, with applications in a variety of different fields, ranging from healthcare to rescue of workers in harsh environments [28]. Among the different solutions for the implementation of wearable devices, the direct use of textile as the substrate for the microwave components and antennas represents a particularly interesting solution, with the results of a perfect integration of the electronics in the garments.

SIW structures have been implemented on textile [19], [20], by using a layer of expanded cell rubber as the dielectric substrate, a conductive fabric (specifically, electro textile) for the metal layers, and brass rivets for the metal vias. Multilayer topologies are possible, by stacking different dielectric layers, with conductive fabric glued in between. The dielectric textile material adopted in this work exhibits a dielectric permittivity $\varepsilon_r = 1.575$ and a loss tangent $\tan \delta = 0.0238$, and the single-layer textile with
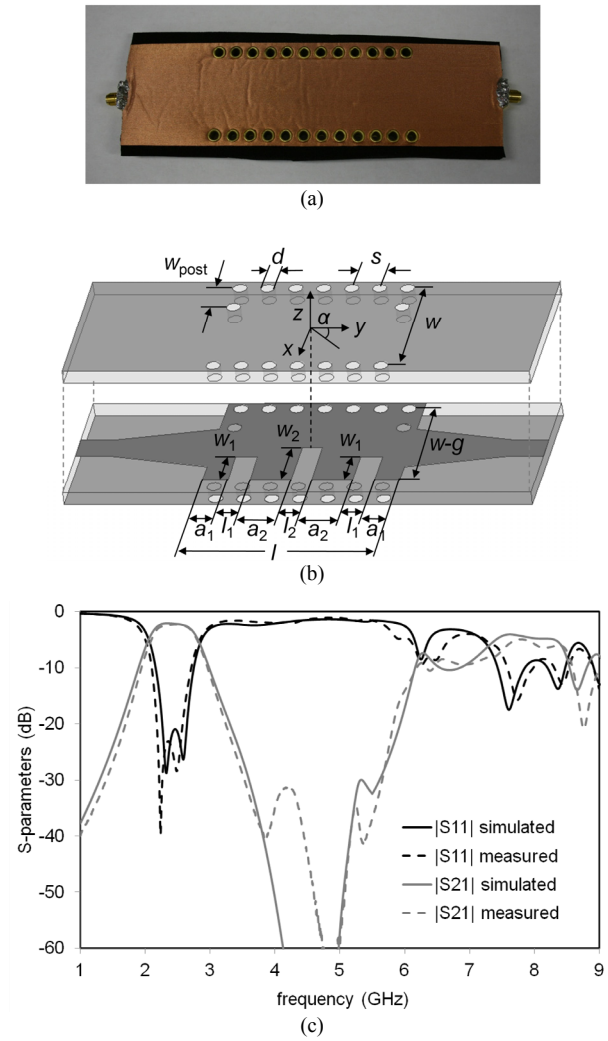

(a)

(b)

(c)

Fig. 14. Folded SIW filter on textile (from [20]): (a) Photograph of a folded SIW waveguide on textile; (b) Geometry of the filter; (c) Comparison between simulated and measured scattering parameters.

a thickness of $h = 3.94$ mm. The photograph of a folded SIW structure is shown in Fig. 14a.

A two-pole SIW filter on textile, based on a folded SIW cavity with insets in the middle metal septum, was proposed in [20]. It was designed to operate at the frequency of 2.45 GHz, in the industrial, scientific and medical (ISM) band. The geometry of the filter is shown in Fig. 14b, and its simulated and measured frequency response is reported in Fig. 14c. The 3 dB bandwidth of the filter is 725 MHz and the insertion loss is 2.3 dB at 2.45 GHz.

3.3 SIW Filters by 3D Printing

Additive manufacturing techniques are becoming very popular in the microwave community, because they allow a great versatility in terms of shapes, materials, and fabrication process.

SIW structures based on 3D printing has been proposed in last few years, starting from the first 3D wave-

guide [24] to microfluidic sensors based on a 3D printed SIW cavity [29], and broadband slab SIW structures [25].

Among the variety of 3D printing techniques, the fused deposition modeling (FDM) is particularly interesting, as it allows to print structures with different material density (infill) from 100% to roughly 10% [30]. This feature permits to control the dielectric permittivity and loss tangent. In fact, in FDM process, the material is heated and extruded through a nozzle, and deposited to form a two-dimensional pattern. Stacked 2D layers results into the final 3D printed structure. One unique feature of the 3D printing is the capability of changing the density of the printed object, by varying the spacing during the filament deposition.

The flexibility of FDM technique can be conveniently exploited in the design of SIW cavity filters. In [27], ABS filament with dielectric permittivity $\varepsilon_r = 2.7$ and loss tangent $\tan \delta = 0.02$ was adopted. By using 40% infill factor, the dielectric permittivity is reduced to $\varepsilon_r = 1.6$ and the loss tangent is simultaneously reduced to $\tan \delta = 0.008$. The effects are a larger size of the circuit dimensions, as well as an increase in the quality factor of the resonant cavities. Based on this concept, two examples of three-pole
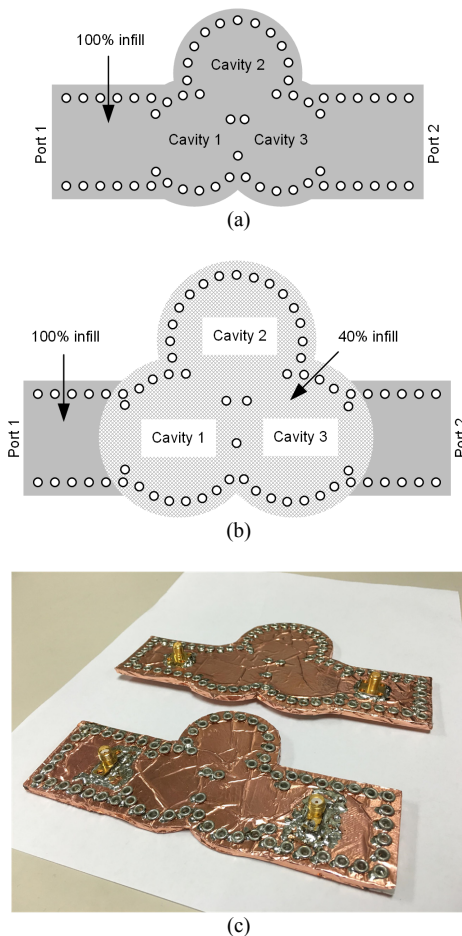

Fig. 15. 3D printed SIW filter with different infill (from [27]):
(a) Geometry of the filter with 100% infill;
(b) Geometry of the filter with 40% infill;
(c) Photograph of the two prototypes.

filters were designed in [27]: the former with 100% infill (Fig. 15a) and the latter with 40% infill (Fig. 15b). While the smaller infill leads to increased component dimensions (Fig. 15c), it also guarantees an increased Q-factor and lower insertion loss, as demonstrated in [27].

Acknowledgments

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