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Survey on Substrate Integrated Waveguide for Communication Systems

Salma Zaidani[1*], *Hamid* Bouyghf[2], *Abdelmounaim* Kchairi Belbachir[3], and *Souad* Akkader[4]

[1]Hassan II University, Faculty of sciences and Techniques, Laboratory of Engineering Sciences and Biosciences, Mohammedia, Morocco
[2]Hassan II University, Faculty of sciences and Techniques, Laboratory of Engineering Sciences and Biosciences, Mohammedia, Morocco
[3]Hassan II University, Faculty of sciences and Techniques, Laboratory of Engineering Sciences and Biosciences, Mohammedia, Morocco
[4]Hassan II University, Faculty of sciences and Techniques, Laboratory of Engineering Sciences and Biosciences, Mohammedia, Morocco

Abstract. Because of its many benefits, including small size, low losses, and inexpensive fabrication, substrate integrated waveguide structure is a promising option for components used in communication systems, especially for mm waves. This work presents the key elements that influence substrate-integrated waveguide (SIW) design and manufacturing, such as losses, size, and bandwidth, which provides a reflection on new geometrical structures and materials to suit new applications and demands. Especially, the growing demand for flexible wireless systems made of environmentally friendly materials and manufacturing processes.

1 Introduction

Advancements in planar waveguide technologies, such as Substrate Integrated Waveguide (SIW), have led to miniaturization ([1], [3]), enhanced performance, and cost-effectiveness in microwave and millimeter-wave circuits. The ability of Substrate Integrated Waveguides (SIWs) to combine the benefits of conventional waveguide which offers less loss but cannot integrate others components and planar circuit, and microstrips which frequently experience radiation losses but represent a low-cost fabrication and a compact size [2], made them an appealing option for contemporary communication systems. To increase performance and expand application areas, there is a rising interest in investigating innovative materials, such as flexible substrate ([14],[15],[17]) textile ([18],[19]), and 3D-printed substrates [14] also sophisticated manufacturing procedures. However, current studies typically concentrate only on certain applications or structural aspects, creating a fragmented picture of the relationships between them. In order to fill this gap, this paper offers a comprehensive survey that covers not only the structure of SIW, loss mechanisms, miniaturization and bandwidth enhancement but also the integration of novel materials. By doing so, it offers a global vision of current trends and identifies future research opportunities.

* Corresponding author: salmazaidani.sz@gmail.com

2 SIW structure

2.1 Geometrical structure of the SIW

A SIW structure can be described as a waveguide embedded within a dielectric layer covered by two parallel metallic surfaces that run from top to bottom and are connected by two parallel arrays of conductive cylinders or vias as indicated by (Fig. 1) [1]. It is an enhanced version of the conventional rectangular waveguide.

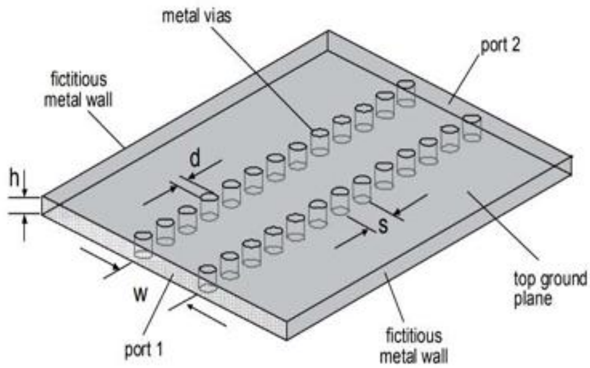

Fig. 1. Basic SIW structure

Miniaturization, various types of loss, and material selection are some of the challenging issues that must be addressed to employ this structure as a platform for connection and integration of multiple components.

2.2 SIW technology's benefits

The SIW propagation characteristics closely resemble those of conventional rectangular waveguides, as both structures present similar field configurations and dispersion responses. SIW structures preserve most of the advantages of rectangular waveguide including self-consistent electrical confinement, high quality factor, and high-power handling capabilities. SIW technology's major advantage is its ability to combine all of the components, including active devices, passive circuits, and antennas, onto a single substrate.

3 SIW field distribution

SIW only supports the transverse-electric (TE) mode, whereas a classical wave-guide can handle both TE and TM modes. Due to the spacing between the metallic vias on the side walls, the TM mode cannot be supported, the electromagnetic wave in the SIW is unable to produce a steady current at the sides of the vias, making it ineffective for transmitting. (Fig. 2) [4] displays the electric field pattern of the fundamental propagation mode (TE_{10}) in the SIW structure. It can be noticed that the fundamental mode distribution in the classical waveguide is similar to that of the SIW structure.

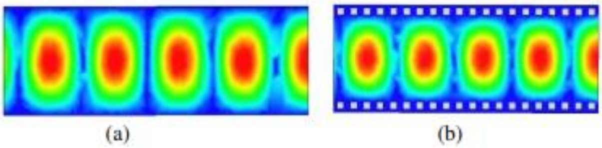

Fig. 2. Comparison of the TE10 mode between the equivalent rectangular waveguide (a) and the SIW structure (b)

Relation between the equivalent rectangular waveguide effective width w_{eff} and the SIW geometrical dimensions was derived in [5]:

$$w_{eff} = w - \frac{d^2}{0.95s} \quad (1)$$

The diameter of the metal vias is presented by d, w is the width of SIW which is the transverse spacing between the two rows of metal vias, and finally s is their longitudinal spacing.

For a larger value of d, (1) is no longer valid so that the ratio d/w is added [3]:

$$w_{eff} = w - 1.08\frac{d^2}{s} + 0.1\frac{d^2}{w} \quad (2)$$

4 SIW loss mechanism

Loss minimization is a crucial consideration in SIW structure design, and it becomes even more important when using mm-wave frequencies. When designing SIW structures, three main mechanisms of loss must be taken into account: dielectric losses caused by the lossy dielectric substance, conductor losses caused by the metallic walls limited conductivity, while the radiation losses caused by the energy leakage through the gaps [6]. Substrate-integrated wave-guide components experience similar conductor and dielectric losses as rectangular waveguide components. Conversely, the periodic gaps separating the two via walls integrated into the dielectric substrate are the cause of the radiation loss, which represent a specific limitation of the SIW [2].

The dielectric loss depends only on the loss tangent of the substrate material, rather than the substrate-integrated waveguide physical dimensions. Especially, the substrate thickness (h) has no effect on this type of loss [7]. Which means making prudent choices when choosing the appropriate substrate material is crucial.

SIW conductor loss can be reduced by increasing the substrate depth while keeping the same other dimensions. Same behaviour is observed while decreasing the value of s, due to the improvement of the metallic coat [8].

According to [9], in order to get low radiation loss performance, the ratio between the via spacing and the via diamater (s/d) should not exceed 2.5. An optimal SIW when the via spacing satisfies (s = 2d).

Losses in SIW are strongly influenced by its geometric characteristics, including the substrate thickness (h), the diameter of the metallized vias (d), and longitudinal distance between adjacent vias (s). Lastly, dielectric losses depend on frequency range, and are generally more pronounced at millimeter-wave frequencies [7].

5 Size and operational bandwidth

It is essential to take into consideration SIW structure dimension and operation bandwidth when designing SIW.
Recently, many waveguide configurations have been developed, aimed at reducing the size of SIW structures. SIFW, Substrate integrated-folded waveguides was suggested in [10], by incorporating a metallic septum that allows the waveguide to fold as illustrated in (Fig. 3) [2], reducing its size by more than a half, however, leads to a slight increase in losses.

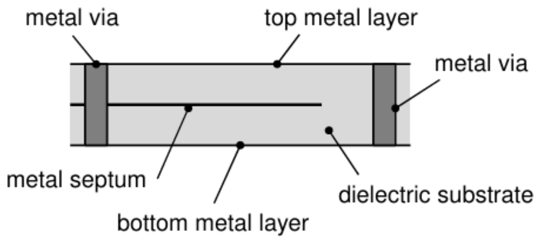

Fig. 3. Substrate-Integrated Folded Waveguide (SIFW)

The disadvantage of the folded version of SIW is the dual-layer manufacturing procedure which is complicated than a single-layer fabrication.

The Half-Mode Substrate-Integrated Waveguide (HMSIW) was introduced in [11], it offers a size reduction of about 50% based on the waveguide's vertical cut being approximated as a virtual magnetic wall (Fig. 4) [2].

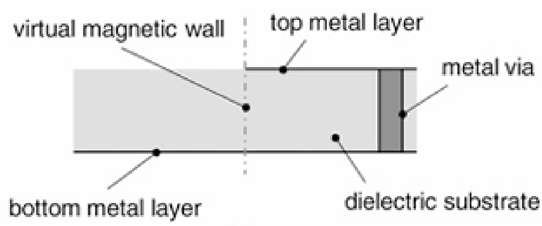

Fig. 4. Half-mode SIW

It was also suggested to combine the two techniques, which produced the Folded Half-Mode Substrate-Integrated Waveguide (FHMSIW), allowing an additional size reduction [12].

It is possible to convert the HMSIW cavity to the quarter-mode SIW (QMSIW). By successively dividing the cavity, the Quarter-Mode SIW (QMSIW) can be transformed into the Eighth-Mode SIW (EMSIW), followed by the Sixteenth-Mode SIW (SMSIW) and Thirty-Two-Mode SIW (TMSIW).

There are various waveguide configurations that have been designed to overcome bandwidth limitations. The Substrate-Integrated Slab Waveguide (SISW), was initially introduced in [13] (Fig. 4), is a structure made up of a SIW with air-filled holes periodically perforating the dielectric medium in the wave-guide's lateral section. With a 40% bandwidth improvement, this method made it possible to create a waveguide operating in a single-mode regime operating in the frequency range of 7.5-18 GHz.

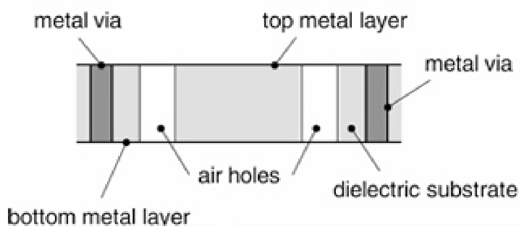

Fig. 5. Substrate-integrated slab waveguide

A ridge-based SIW structure was proposed in [2], where a series of thin metallic with partial height posts along the center of the longer side of the waveguide. This configuration extended bandwidth by 73% enabling single-mode operation from 4.9 to 13.39 GHz.

A modified ridge based on SIW technology was presented in [14] (Fig. 6), where a series of reduced height metallic posts along the broad wall of the SIW and interconnected by a metallic strip at the substrate bottom. This design modification led to a substantial improvement, achieving a 168% enhancement of the bandwidth and covering the 6.8–25 GHz frequency range.

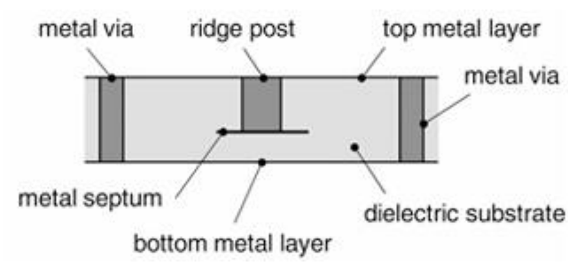

Fig. 6. Ridge SIW topology

An additional enhancement has been achieved with the addition of air-filled holes to the ridge SISW. A ridge SISW with a 232% bandwidth increase was planned and built in this instance, covering the whole frequency range of 7.1–30.7 GHz.

The following table summarizes the different SIW topologies and highlights the main advantages of each configuration.

Table 1. Different typologies of SIW to increase bandwidth

SIW topologies	Bandwidth increase (%)	Frequency range
SISW	40%	7.5 to 18 GHz
Ridge SIW	73%	4.9 to 13.39 GHz
Ridge SIW + metal strip	168%	6.8–25 GHz
Ridge SIW + metal strip + air-filled holes	232%	7.1–30.7 GHz

6 Material manufacturing of SIW

6.1 3D printing Slab SIW

Materials with various dielectric permittivities have been created and tested in [15] by taking advantage of FDM's characteristics. They have been employed to implement a SISW, which is 50% larger than a typical SIW and covers a single-mode band. The proposed waveguide offers a simplified fabrication approach, as it can be produced in a single operation using only one type of thermoplastic filament, in addition to its wider operating bandwidth. Even though 3-D-printed structures still have significant losses today, several materials are being developed to meet the requirement of emerging 3-D printing applications that should show much reduced losses soon. In (Fig. 7) both standard 3D printed SIW and 3D printed SSIW :

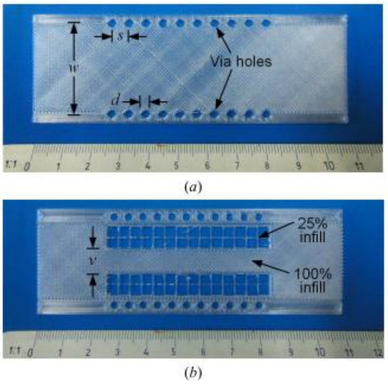

Fig. 7. Photographs of the 3-D-printed prototypes: (a) conventional 3D-printed SIW (b) 3D-printed slab SIW

6.2 Paper-based SIW components

Two methods are available for producing paper-based SIW structures. The first relies inkjet printing [17], while the second consists of a multilayer paper enclosed between aluminum aluminum, followed by milling process [18]. The SIW component made using the milling approach [18] is a quarter-mode SIW filter on a single paper layer. Its thickness is 500 Pm, and it has a dielectric permittivity of $\varepsilon_r = 2.2$ and a loss tangent of $\tan\delta = 0.04$ (Fig. 8) [16]. The selected topology allows for the minimization of the filter size.

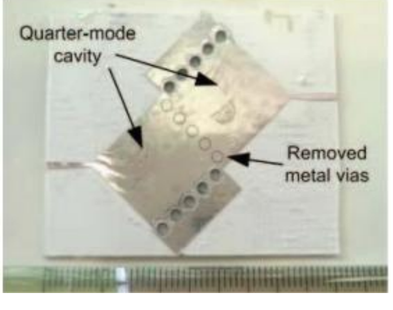

Fig. 8. A quarter-mode SIW filter designed on paper and made using milling technique

6.3 SIW textile components and antennas

The idea of using textile fabrics to implement SIW components and antennas was first suggested in [19], [20]. Copper-plated nylon fabric (Taffeta) was used for the conductive layers, while the dielectric substrate was made of a closed cell expanded rubber with a thickness of 3.94 mm, a dielectric permittivity (ε_r) of 1.45, and a loss tangent (tan δ) of 0.017. Lastly, brass eyelets were used to implement the metal vias. The flexibility of the structure is maintained while a satisfactory ohmic contact between the two ground planes is achieved without requiring silver epoxy thanks to the little compression of the eyelets. (Fig. 8) shows a textile antenna built on a folded cavity-backed SIW configuration [19].

Fig. 9. Textile-based folded cavity-backed SIW antenna

The suggested antenna consists of a folded SIWcavity that acts as the radiating patch, with a square ring slot introduced in the top metal layer. The proposed folded SIW cavity was obtained by assembling two textile layers around a metallic patch. A metallic via with a rivet was introduced at the center of the cavity to connect the lower metal patch to the bottom ground plane [16]. A coaxial probe feeds the antenna from the backside.

7 CONCLUSION

Over the past few decades, there has been a growing need for components with compact size and best performance due to the rapid growth of modern wireless communication systems. This work aims to present the aspects that should be taken into account when designing and manufacturing SIW components. Changing the SIW architecture can ensure miniaturization, examples include the Folded SIW (FSIW) and from the Half Mode SIW (HMSIW) to the Thirty-Two-Mode SIW (TMSIW). SIW components can be integrated into materials like paper, textile, or 3D printing which is a revolution for wireless communications, particularly in the Internet of Things. Despite the significant progress, some technical and practical limitations remain to be addressed in future research. Specifically, production scalability, fabrication costs, and material limitations such as substrate flexibility and thermal stability.

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