Multi-Dimensional Substrate Integrated Waveguide for High Density Integration

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Abstract—This paper analyses the main configuration of the substrate integrated waveguide (SIW) allowing spatial arrangement and miniaturization. With the increasing performance demand on wireless systems, high-density millimeter-wave system integration techniques have been under intense development. The performance of the guided-wave structure is crucial for the design of millimeter and sub-millimeter systems. Following the appearance of SIW, many researchers worked to develop an improvement of the standard version. The main known configurations of SIW: half mode SIW, folded C-type SIW, ridge SIW, E-plane SIW and folded L-type SIW are summarized in this paper. The losses and propagation constant are compared. The proposed configurations don’t allow only spatial arrangement and miniaturization but also the control of other characteristics like bandwidth, loss and impedance. To illustrate the advantages and flexibility of these lines, four structures feed by this type of lines are presented.

Index Terms—Multi-dimension, substrate integrated waveguide (SIW), LEGO-style design.

I. INTRODUCTION

With the increasing of performances requirement on wireless systems for GHz and THz applications, high-density system integration techniques have been under intensive development. The characteristics of the guided-wave line are crucial for the design of these systems. Rectangular metallic waveguides are commonly used in low-loss mmW circuit designs. It has the benefits of high Q-factor and high power handling capability. However, it is a heavy guided wave structure compared to conventional Microstrip, slotlines and CPW. Substrate integrated waveguide (SIW) also known as laminated waveguide or post-wall waveguide has an operation mode quite similar to rectangular waveguide.

SIW structure has received particular consideration over the past two decades. It provides a compact, lightweight, low cost and planar substitute to conventional waveguide. Recently, a new innovative three-dimensional (3-D) disposition of SIW has been used for the development of innovative filters, couplers and antennas [1]. This new disposition is used to innovate all passive components. The developments of new SIW structures can be summarized into two different categories namely stacked multilayer and non-stacked 3-D expandable LEGO-style. A LEGO approach was successfully demonstrated. These new dispositions permit the use of the SIW lines to ensure the propagation in any direction without using connectors, coaxial cables, etc. This has a direct impact in reducing losses and other undesirable parasitic effects.

Fig. 1. Substrate integrated waveguide configurations and the magnitude distribution (the field showed are the electric (left) and magnetic (right) fields distribution at 35GHz simulated using HFSS): a) classic SIW (1990), b) half mode SIW, c) folded C-type SIW (2005), d) ridge SIW (2008), e) E-plane SIW (2012) and f) L-type SIW (2012).

This article presents a review of the most attractive SIW configurations allowing a special arrangement and miniaturization. Cut-off wavelength and characteristic impedance which represent the most important parameters was compared.

II. SPACIAL ARRANGEMENT OF SUBSTRATE INTEGRATED WAVEGUIDE

The half mode SIW, folded C-type SIW, ridge SIW, E-plane SIW and folded L-type SIW are presented in Fig. 1. All these structures are implemented in a dielectric substrate with thin metal layers and two lateral rows of metal posts. The electric and magnetic fields for corresponding first mode at 35 GHz simulated using ANSYS-HFSS electromagnetic solver are also shown in Fig. 1. These guided wave structures have a different performances. For designers the cut-off wavelength, characteristics impedance and the losses are the most important parameters. The size, the weight, the flexibility of the configurations and integrability are also crucial.
keys. A brief description of the main SIW configurations is given below.

a) Half mode SIW (HMSIW)

HMSIW can be considered nearly the half of SIW[2] as shown in Fig.1 and is not a closed structure as it has an open side. The equivalent circuit model is in Tab.1. The dominant mode in such a structure is just like one half of the dominant mode TE$_{01}$ in a complete SIW. In the area close to the aperture, the field is out diffused a little bit to satisfy its boundary conditions.

b) Folded C-type SIW

Folded C-type SIW is a transversely folded waveguide which is suitable for SIW miniaturization as its width is much larger than its height [3]. The one shown in Fig.1c uses 2 stacked layers which also can be folded and extended to three or more layers using the same principle.

c) Ridge SIW

The ridge SIW is implemented by conductive posts in multilayer substrate as shown in Fig.1. This structure was proposed for bandwidth enhancement of the classic SIW. The ridge SIW can significantly reduce the cut-off frequency of the fundamental mode with limited effect on the cut-off frequency of the second mode. For example the ridge SIW presented in[4] has a bandwidth enhancement of 100%

d) L-type SIW

This transmission line is formed by folding an SIW along its longitudinal center line as illustrated in Fig.1. One advantage is that it reduces the PCB footprint by a factor of almost two compared to the SIW line and presents the same width as C-type folded SIW[5]-[8].

e) E-plane SIW

Two SIW are used to construct the E-Plane bend [1]. To realise the plane transformation the two lines are coupled through a slot. The vertical, the horizontal and the slot has the same width. Tab.1 shows the schematic view of equivalent circuit models. All these configurations can be used separately or combined to reduce size. For example HMSIW can be combined with folded C-type SIW, resulting in a folded half-mode SIW (FHMSIW) which can permit a size reduction of nearly 75%.

By comparing the variation of phase and attenuation constants over the frequency bandwidth, performance parameters can be extracted like monomode bandwidth and losses. To develop a coherent study the different guides are simulated in the same band and using the same substrate. The substrate used is Rogers RT/Duriod 6002 with thickness $t=0.762$ mm. The dielectric, conductor and radiation losses are considered. The cooper in the top and the bottom of the substrate has a thickness of 0.014 mm. in this simulation the same width is considered

Attenuation due to the dielectric losses is related to $\tan\delta$ of the dielectric substrate:

$$\alpha_d = \frac{k^2 \tan\delta}{2\beta} \quad (1)$$

Attenuation due to conductive loss:

$$\alpha_c = \frac{R_s}{a^4 \mu_0 k \eta} \left(2b \pi^2 + a_{sw}^3 k^2 \right) \text{ with } R_s = \frac{\omega \mu_0}{2\sigma} \quad (2)$$

The radiation leakage is due to the gaps between the metal vias or slots. Fig. 2 shows the propagation constant of the different guides. The SIW line presents a larger monomode bandwidth compared to C- and L-type. The ridge version allows the enhancement of this band. At 30GHz for example, the $\beta_{C,\text{type}}$ is the higher one, followed by the $\beta_{L,\text{type}}$ and the $\beta_{SW}$. This factor affects the dielectric loss for each structure according to eq (1) and (2). The Metallic loss is more affected by the width of the guide. That explains the results shown in Fig. 3. The total losses of three structure show the standard SIW have 50% more losses compared to the C-type

$$\alpha_R = \frac{1}{a_{sw}} \left( \frac{a_{SW}}{a_{SW}} \right)^{2.84} \left( \frac{b}{a} - 1 \right)^{6.28} \left[ \frac{dB}{m} \right]$$

$$4.85 \sqrt{ \left( \frac{2a_{SW}}{a_y} \right)^2 - 1 }$$

$$\quad (3)$$

III. 3D SIW COMPONENTS

To construct high-density integrated systems, innovative components made on SIW structures are proposed. The developed structures are based on the use of third dimension (the vertical dimension) of planar structures to overcome the bottleneck problem of size and footprint within the planar structures. In Fig. 4 a set of components working at Ka-band using the E-plane as additional degree of freedom are shown: E-plane junction, 20 dB Schwinger coupler, cavities filter, and twist with four integrated antennas. Results are tabulated in Table II to highlight interesting features, low loss and broadband attractive performances of those new components for millimeter-wave
applications. The coupler and filter have 30% smaller footprint compared to the planar counterpart.

These prototypes are fabricated using PCB process involving several steps in the Poly-Grames research center. First, slots are cut from double-sided copper-clad substrate with a laser micromachining. Then, slots are metalized by using a vacuum metallization process. The top and bottom copper layers are chemically etched to achieve the desired traces. The PCBs are arranged using a LEGO-like interconnect. The vertical PCBs are manually inserted in the horizontal part through alignment posts. Then, the pieces are soldered together on both sides of the vertical PCB while applying a sufficient force to avoid potential air-gap at the interconnection.

The proposed structures, the E-plane junction, Coupler and the Twist, are useful to implement compact six-port, front-end and 3-D feeding networks.

![Comparison of the attenuation constant of the different configurations](image)

**TABLE II**

<table>
<thead>
<tr>
<th>Component</th>
<th>Band(GHz)</th>
<th>TL(dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-junction</td>
<td>30-40</td>
<td>16</td>
</tr>
<tr>
<td>Filter</td>
<td>34-35</td>
<td>12</td>
</tr>
<tr>
<td>Coupler</td>
<td>30-38</td>
<td>25</td>
</tr>
<tr>
<td>Twist</td>
<td>26.5-40</td>
<td>18</td>
</tr>
</tbody>
</table>

![3D SIW components](image)

**IV. CONCLUSION**

Substrate integrated waveguide has drawn much attention at millimeter-wave and THz frequencies due to their attractive advantages, such as low loss, low cost, high Q-factor and easy integration with other planar circuits. In order to improve the performance of the classic SIW, several modified structures such as half mode SIW, folded C-type SIW, ridge SIW, E-plane SIW and folded L-type SIW have been developed.

This article shows a comparison between the six most known and used configurations. The Ridge SIW presents the highest mono-mode bandwidth, the half mode SIW is the smallest in size. C-type shows the lowest loss performance and L-type allows special arrangement and feeding of antenna. Therefore, SIW present a great flexibility and freedom in the choice and integration of different transmission line platforms. Those different planarized waveguides offer various guided-wave properties. Depending on the application in term of allowed space, the integrability, the task and the performance one of them can be used.

**REFERENCES**


