# A review on the Surface Integrated Waveguide (SIW): integrating a rectangular waveguide in a planar (M)MIC

# A review on the Surface Integrated Waveguide (SIW): integrating a rectangular waveguide in a planar (M)MIC

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***Abstract*—The paper provides a review on the Surface Integrated Waveguide approach to microwave and millimeter wave circuits. Although the history of SIWs is comparatively recent, this guiding structure has proven the capability to integrate within a (M)MIC approach a rectangular waveguide, allowing for the development of high Q and low-loss component that cannot be implemented in quasi-TEM transmissive media, like the stripline, the microstrip and coplanar waveguide. During the last few years SIW components and circuits have shown excellent capabilities in microwave and millimeter wave applications, providing low-cost, miniaturized implementations for a variety of passive components, such as filters, directional couplers, resonators, and antenna feeding systems. Micromachining has demonstrated the capabilities of the SIW approach within the framework of monolithic integrated passive components, while SIW implementations in flexible substrates will pave the way to low-cost, consumer electronic products that could not be realized in conventional quasi-TEM transmission lines.**

***Index Terms*—Surface Integrated Waveguides, (Monolithic) Microwave Integrated Circuits, microwave filters, couplers, transitions, resonators; micromachined circuits.**

## I. Introduction

Progress in the monolithic or hybrid integration of Microwave and Millimeter Wave circuits was fostered, starting from the fifties (see e.g. [1], Sec.16.2) by the introduction of planar TEM or quasi-TEM waveguiding structures, such as the stripline [2], the microstrip [3] and the coplanar waveguide [4]. Monolithic Microwave Integrated Circuits (MMICs) exploiting silicon (Si and SiGe), gallium arsenide (GaAs), gallium nitride (GaN) or indium phosphide (InP) substrates and the related transistor technologies (MOS, HEMT, HBT) are now widespread in a number of terrestrial, space and consumer applications thanks to their intrinsic advantages over metal waveguide circuits, such as low weight, low cost, small size and technological process well suited to mass production. Indeed, during the last 20 years MMICs have brought RF, microwave and millimeter wave electronics to the consumer market. Nevertheless, quasi-TEM waveguiding structures exploited in monolithic or hybrid MICs suffer from a number of limitations connected to their very propagation mechanisms, wherein the signal is led by a metal strip supported by a dielectric layer. Conductor (skin-effect) and dielectric (loss tangent) attenuations are well known to approximately scale as $f^{1/2}$ and as $f$, respectively, where $f$ is the operating frequency, thus leading to large losses, above all in the millimeter wave range; moreover, to avoid the onset of spurious higher-order modes the line cross section dimension has to be reduced when increasing the operating frequency, thus making the increase of losses vs. frequency even more remarkable. In conclusion, despite their flexibility, integrated quasi-TEM lines are hardly suitable to low-loss, high-Q components, not to mention their maximum power limitations when compared to conventional non-TEM closed metal waveguides.

The idea of integrating a non-TEM waveguide into a planar microwave circuit was proposed already in 1981 by Yoneyama and Nishida [5]; their millimeter-wave guiding structure (later denoted as the *non-radiative-dielectric waveguide*, NRD) was a dielectric waveguide sandwiched between two metal planes. Lateral confinement was achieved by the in-air separation between the planes being below cutoff, and the evanescent field region around the guide also allowed for the design of simple components such as directional couplers. As an example of the progress in NRD development, in 1997 Wu[1] and Han [6] proposed a technique to integrated the NRD into a planar circuit, presenting for instance a HEMT oscillator where the resonating element was a NRD section. Further work on the NRD approach from prof. Wu and coworkers was presented in the following years, see e.g. [7], [8], [9].

## II. From The Post-Wall Waveguide to the Integrated Surface Waveguide (SIW)

Introducing a dielectric element between two metal plates, as required by the NRD concept, implied of course a number of technological problems concerning the circuit layout and manufacturing, so that the NRD approach was hardly compatible with the conventional planar technology. These

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[1] Prof. Ke Wu of École Polytechnique de Montréal was to become one of the main investigators of the Surface Integrated Waveguide.

shortcomings could be overcome by replacing below-cutoff lateral field confinement by a process-compatible kind of conductor wall confinement, leading to a structure somewhat similar to a closed waveguide, albeit amenable to planar integration.

While introducing a full lateral metal wall within a planar process was hardly feasible, an intermediate solution based on laterally confining the field through a periodic array of metal posts emerged at the end of the 1990s under the name of "Post-wall waveguide" (Fig. 1), proposed in 1998 by Hirokawa et al. as an antenna feeding element, see [10]. The post-wall waveguide can be built in a circuit board by means of conventional via-hole techniques. Variations in the post-wall approach were then proposed in 1998 by Uchimura et al. [11] under the denomination of "laminated waveguide", see Fig. 2. Besides the presence of confining posts, this approach exploited additional lateral metal planes to improve the lateral field confinement.

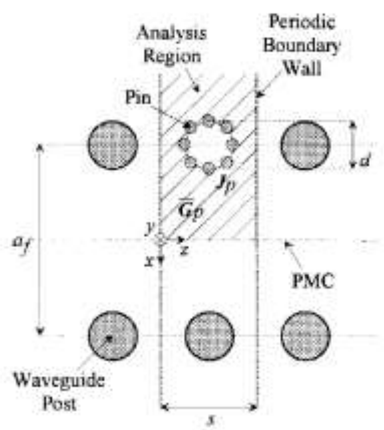



Fig. 1. Model for a Post Wall waveguide ([10], Fig.4).

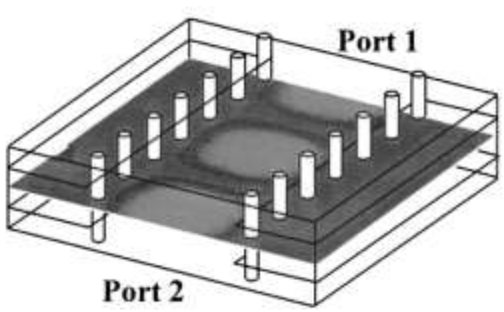



Fig. 2. Laminated waveguide and its H-plane electric field distribution (from [11], Fig. 3).

Prof. Wu's research group began to be involved in the development of the post-wall approach around 2000; in a paper from February 2001 [12] a microstrip to rectangular waveguide integrated transition is proposed where the on-substrate synthesized waveguide is implemented either through metallized via-hole arrays or through metallized grooves, see Fig. 3. The same group presented in [13] an integrated coplanar waveguide to post-wall waveguide transition. In the review paper presented at the 2001 APMC [14] prof. Wu again showed a comparison between different solutions for integrated waveguides, among which the NRD and the post-wall waveguide were discussed, without using, curiously enough, the "post-wall" keyword. While the "post-wall" name still survives in the Wikipedia article devoted to the Surface Integrated Waveguide (SIW), see [15], the latter name apparently surfaced in 2002 with a few papers by the Wu's research group in cooperation with the EM research group of the Università di Pavia, Italy, see [16], [17].

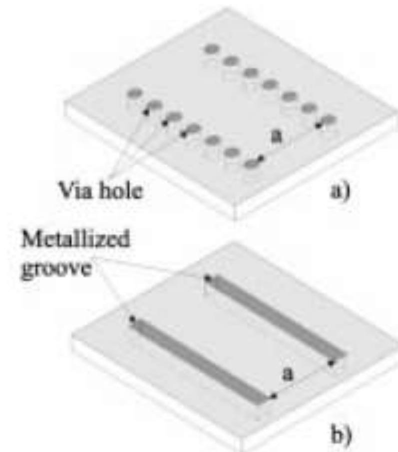



Fig. 3. On-substrate synthesized waveguide techniques: (a) metallized via-hole arrays and (b) metallized grooves (from [12], Fig. 3).

## III. SIW Propagation Characteristics and SIW Components

Papers 16] and [17] present a thorough investigation of the SIW propagation characteristics. Besides, complex SIW components can be analyzed today with comparative ease through electromagnetic modelling tools such as the Ansys HFSS. The SIW waveguide behaves like a rectangular waveguide supporting a $TE_{10}$ propagation mode, whose cutoff frequency is independent on the waveguide thickness *h* (see Fig. 4, a significant advantage, due to the small thickness of substrates). From [17] the fundamental mode cutoff frequency can be approximated as:

$$f_c = \frac{c_0}{2\sqrt{\varepsilon_r}}\left(W - \frac{D^2}{0.95b}\right)^{-1}$$

where $c_0$ is the velocity of light *in vacuo*, $\varepsilon_r$ the substrate relative permittivity, *W* the spacing between the posts centers, *D* the post diameter, and *b* the post spacing, see Fig. 4. The dielectric thickness only impacts on the waveguide characteristic impedance (that is typically low), and not on the propagation characteristics. An analysis of the loss mechanisms in the SIW can be found in [18], [19].

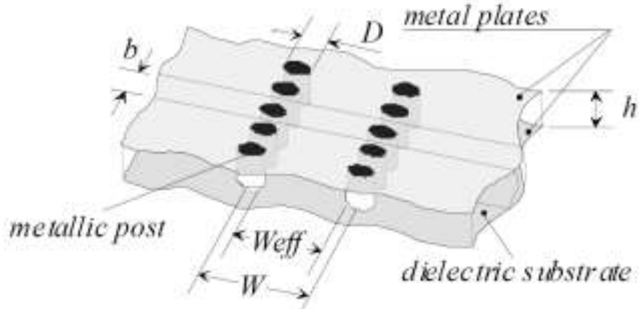



Fig. 4. SIW geometry (from [21], Fig. 2).

In general, metal, dielectric and leakage losses are present, leading however to a decreasing attenuation as a function of the operating frequency. Reviews of the early developments in SIW design and components can be found in [20], [21], [22].

Since the SIW introduction many SIW components were proposed, designed and realized: resonators [23], [24], directional couplers [25], power dividers [26], filters [27], [28]. An example of multi-branch power divider with microstrip input and output is shown in Fig. 5, clearly showing the PCB-like via-hole technique exploited to allocate the metallized posts. Notice also the design of SIW bends and tuning elements that can be nicely integrated in the circuit layout.

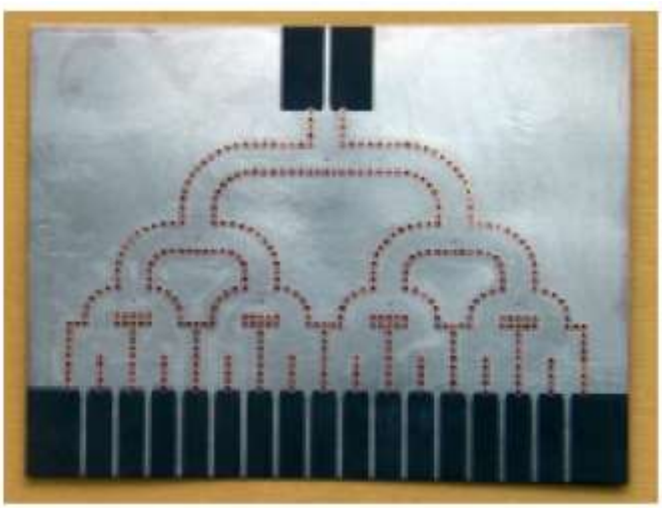


Fig. 5. SIW power divider with microstrip input and output (from [21], Fig. 4).

## IV. The SIW from Dielectric to Semiconductor Substrates and Beyond

The initial SIW development made use of a technology somewhat similar to the Printed Circuit Board (PCB) process, exploiting low-epsilon substrates. However, the potential of the technology in heavier and mechanically harder substrates was recognized already at an early stage, with the development of SIWs on light-temperature co-fired ceramic (LTCC), see [29]. A further step naturally led to the introduction of SIW components based on Si substrates, exploiting for their realization micromachining techniques. A few representative references on such developments are [30], [31], [32], [33]. Micromachining on Si substrates (see [33] for a detailed process flow example) allows for process repeatability, low cost, and reduced size, enabling the SIW technology to cover high-Q component needs from the Ka band till the mm-wave range. An example of micromachined filter, via-hole technology and filter response is shown in Fig. 6 [30].

More recently, the SIW design was extended to yet another application field by exploiting organic, flexible, textile and/or wearable, eco-friendly substrates, see [34], [35]. Finally, an air-filled SIW concept was recently proposed to overcome power limitations associated to the use of dielectrics at millimeter waves, see [36].

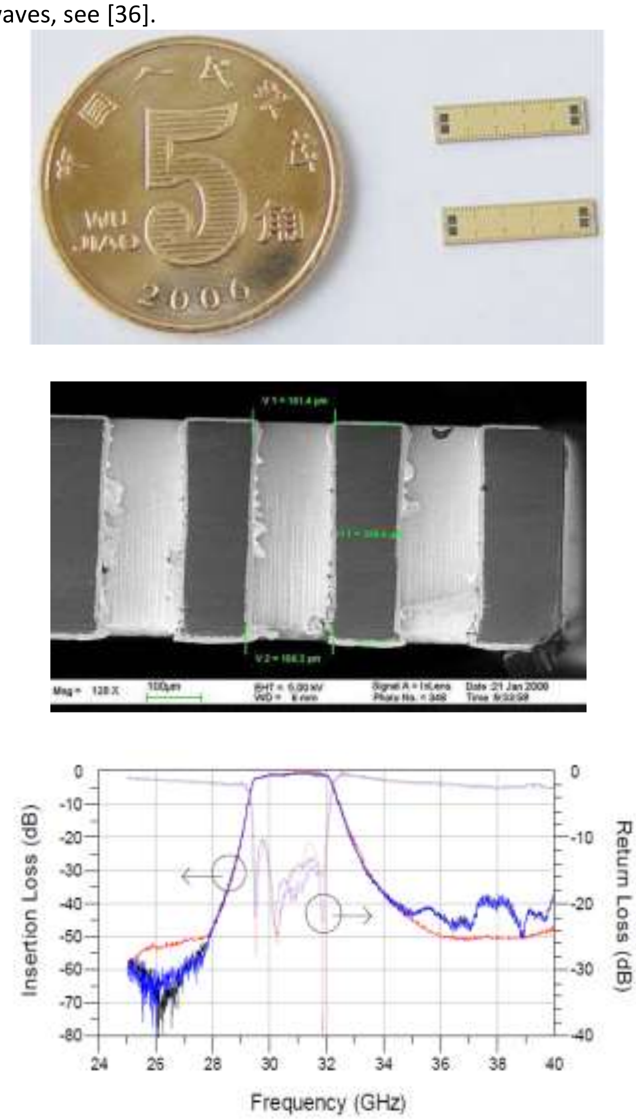



Fig. 6. Micromachined Si-based filter, via hole technology and measured filter response, from [30], Fig. 3-5.

## V. Development of Research on Surface Integrated Waveguides

Research on Surface Integrated Waveguides has already led to quite impressive results in terms of components, and some system implementations have already been proposed, see e.g.

[37] concerning the design of a 77-GHz automotive radar front-end exploiting SIW passive high-Q elements. Another interesting and innovative example concerns the possibility of integrating SIW components with electro-optic devices, as discussed in [38], see Fig. 7.

A search on the "Surface Integrated Waveguide" keyword in the IEEE-Explore database generates so far (April 7, 2015) 1517 hits distributed in years 2002-2015 (prior to 2002 the keyword was not clearly used as such, and therefore earlier versions of the keyword, such as the post-wall waveguide, are missing from the search). If we are inclined to carry out a somewhat futile exercise in bibliometry, the h-factor of this collective set is 34 and the most widely quoted paper (267 hits) is, not unexpectedly, [18]. Apart from these remarks, the number of papers in the SIW area has been increasing steadily during the last few years, with a quite impressive total citation count of about 600 citations per year, see Fig. 8 (the source is always IEEE Explore). As a final remark, a web site http://siwspace.com/ collects a number of data, references and design examples in Surface Integrated Waveguides.

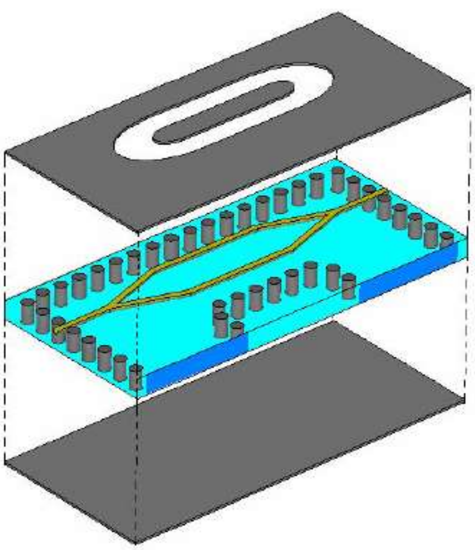
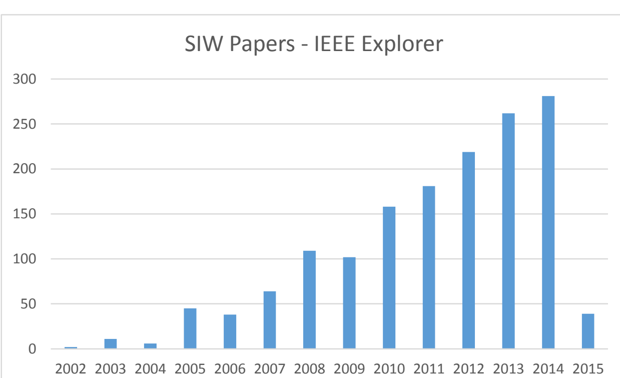


Fig. 7. SIW concept for an electro-optic Lithium Niobate Mach-Zehnder modulator, from [38], Fig. 8.



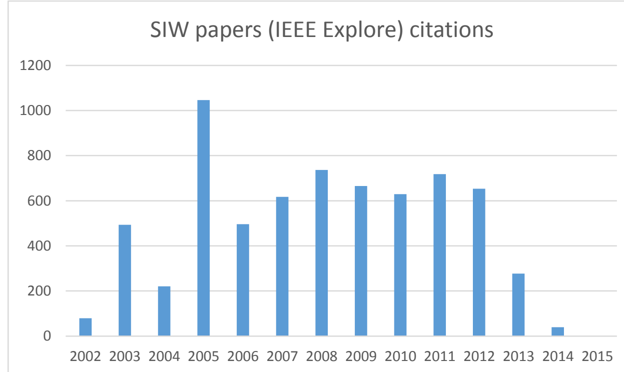




Fig. 8. Number of papers with the SIW keyword in the IEEE Explore database according to the publication year (above) and collective citation count for the set as a function of the year of citation (below). The source is the IEEE Explore web site as of April 7, 2015.

## VI. Conclusion

About 15 years after its introduction, the SIW has emerged as an interesting alternative technology able to integrated within a planar substrate high-Q components, well suited to bridge the gap between well established (M)MIC technologies and waveguide-compatible elements, like resonators, filters, and radiators or radiator arrays with their feeding networks. Recent developments in micromachining make this approach even more interesting, thanks to its promise in miniaturization and technology standardization.

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