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Substrate Integrated Transmission Lines: Review and Applications

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(Invited Paper)

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ABSTRACT This paper presents a general overview of substrate integrated transmission lines, from the perspective of historical background and progress of guided-wave structures and their impacts on the development of microwave circuits and integration solutions. This is highlighted through a technology roadmap involving the categorized five generations of microwave circuits. In particular, the substrate integration technologies are reviewed and discussed with focus on technical features, design highlights, component developments, structures evolution, and systems integration. A number of examples are presented to showcase some of the selected milestone research and development activities and accomplishments in connection with substrate integrated transmission line technologies, with particular focus on substrate integrated waveguide (SIW) techniques. Practical applications and industrial interests are also presented with key references and technical results, which show more and more product developments in the end-user sectors. It can be found that the popularity of SIW techniques is closely related to the achieved seamless integration of planar and non-planar structures into a unified design space, thereby allowing the possibility of combining major advantages of all the structures while alleviating their potential drawbacks. The future perspectives of the substrate integration technology are discussed through five major research directions, which suggest potential impacts in the development of future generations of circuits and systems such as system-on-substrate (SoS).

INDEX TERMS Guided-waves, microwave integrated circuits, millimeter-waves (mmWaves), substrate integrated waveguide (SIW), system-on-substrate (SoS), technology roadmap, terahertz, transmission lines.

I. INTRODUCTION

High-frequency transmission lines and guided-wave structures are no doubt the most fundamental building blocks of radio frequency (RF), microwave, millimeter-wave (mmWave) and terahertz circuits and systems that operate over the megahertz-through-terahertz frequency range. Such structures are engineered with specific geometry and materials in support of various active and passive analogue signal processing functions in either time domain or frequency domain. They are made in the form of metal-dominated non-planar and planar lines, such as rectangular waveguide, coaxial line, strip line, microstrip line and coplanar waveguide (CPW), for electronic components and circuits or dielectric-dominated lines, such as dielectric waveguide and optical fibre, for photonic components and circuits. Of course, guided-wave structures featuring hybrid metallic and dielectric geometries can be found in the frequency range where electronic and photonic efforts meet, specifically quasi-optical effects and terahertz domain. The wave propagation is universally governed by Maxwell's equations together with boundary conditions along transmission media.

A. HISTORICAL REVIEW

The long history of the development of guided-wave theory and techniques, intimately driven by the exploration of the fundamental electromagnetic theory since the original works of the earliest pioneers around the end of the 19^{th} century, namely Oliver Heaviside, J. J. Thomson, Oliver Lodge, and

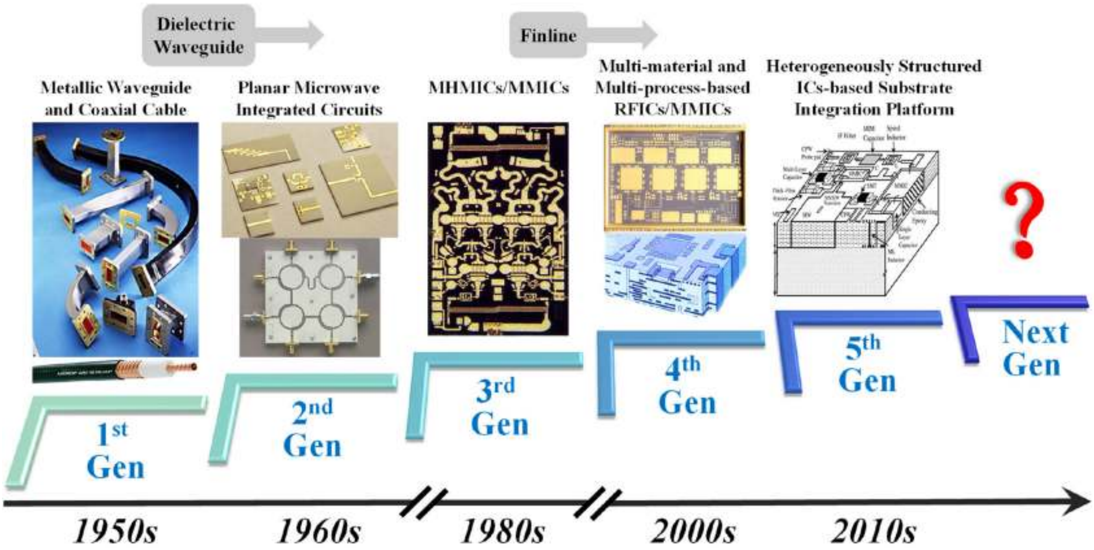


FIGURE 1. Generational evolution of microwave and mmWave circuits and related guided-wave technologies (some of the above illustrative images and figures may come from cyberspace without the possibility of identifying their exact sources).

Lord Rayleigh, has been extensively discussed and documented in a number of review papers [1]–[7], through two special issues of the IEEE Transactions on Microwave Theory and Techniques (September 1984 and March 2002), in addition to a series of invited papers published in other issues [8]. It is noticed that the development of coaxial lines, principally motivated by early low-frequency electronics, even dates back to the time before the development of hollow metallic tube waveguides [9]. The historical account of waveguide developments demonstrates how research interest in guided waves changed over the years from ground-breaking metallic wired lines to first bulky dielectric rods, surface wave guides, and subsequently planar integrated lines. Interestingly, all of those developments have been closely related to and mainly spurred by the progress of applied electromagnetics and wireless technologies at RF, microwave and mmWave frequencies.

As reviewed and discussed with details in the above-mentioned literature, the progress of microwave, mmWave and terahertz circuits and systems are obviously related to the exploitation of two-dimensional (2D) and three-dimensional (3D) guided-wave properties, which are generally characterized in the frequency domain such as waveguide modes, propagation losses, dispersion behaviors, field confinements, characteristic impedances, scattering parameters and equivalent models in connection with pre-defined functional design specifications. Fig. 1 presents a narrative description of the chronological and generational evolution of microwave circuits and related technologies for megahertz-through-terahertz applications. In this classification, mainly related to guided-wave structures, the non-planar rectangular waveguides and coaxial cables present the first generation of microwave circuits, which can be described by 3D non-planar geometries built mostly for one-dimensional (1D) circuit operations. Some of the most useful structures proposed and developed to date, namely the metallic rectangular waveguide and the coaxial cable line, including different variants such as ridge and partially dielectric-filled or air-filled structures, are still being used everywhere. Obviously, those 3D circuits are non-planar and non-integrable and they are bulky, heavy and costly. They are difficult to make at higher microwave frequencies because of tight mechanical tolerances, which generally requires post-fabrication tuning for meeting stringent design specifications. In spite of such drawbacks, the rectangular waveguide is still considered the best quality structure for its lowest transmission loss and unparalleled electrical performances, while the coaxial line offers the best transverse electromagnetic (TEM) mode structure for high-quality and dispersionless broadband microwave signal transmission. Both structures are the best candidates for designing high quality-factor (Q) components, and nearly packaging-free, high-power or noise-sensitive microwave circuits, which have been widely used in non-consumer sectors and conservative end-user equipment, such as space electromagnetic systems, wireless base-stations and defense electronics.

In parallel to the development of hollow waveguides and coaxial cables for high-frequency applications, dielectric waveguides were also studied extensively. However, this technology has not been well considered in practice because of some guided-wave drawbacks. First, dielectric waveguides like rectangular waveguides are generally bulky non-planar structures, which cannot be made for integration. Second, this type of waveguides is susceptible to parasitic radiation or leakage problems once they are made with discontinuities for circuit applications. This has been one of the most undesirable properties of general dielectric waveguides until the development of the non-radiative dielectric (NRD) waveguide [10] derived from the H-waveguide [11]. Third, there are complicated modal behaviours and dispersion properties caused by multiple air-dielectric or dielectric-dielectric interfaces along different directions. This turns out to be highly detrimental to the integration of active devices within the dielectric structures. This is why dielectric waveguides present a very limited popularity in industry, unlike other non-planar structures. Of course, this is different for photonics and optical circuits. Nevertheless, there is a renewed interest in this technology for mmWave and terahertz electronics, which will be discussed later.

Since the 1950s, the technology of microwave integrated circuits (MICs) [5] has become flourishing and omnipresent thanks to the development of microstrip line and its variants [12], which was further empowered by the invention and development of coplanar waveguide (CPW) and its variants [13]. This second generation of microwave circuits in Fig. 1 represents a truly revolutionary development for passive components in two-dimensions as it allows for the first time the possibility of structural integration and topological miniaturization with mass production, low profile and light weight at low cost. Compared to the above-mentioned non-planar waveguide techniques, one of the most striking advantages of the MIC technology is its natural integration with active devices and elements thanks to easily tailored TEM mode interfaces and flexibly arranged high-density circuits with adequate electrical and dimensional features, such as impedance matching, field matching and broadband design [14]. Furthermore, this development of MICs opened up a new horizon for involving continuously evolving materials and processes, which are made timelessly and universally. Eventually, the second generation lays the foundation for all the subsequent generational advancements, which will be discussed in the next paragraphs.

Without any surprise, the third generation of microwave circuits depicted in Fig. 1 was created by following up the same threads of MIC developments towards higher-density integration, which is enabled by advanced processing techniques, including ceramic-based miniaturized hybrid MICs (MHMICs) [15] and semiconductor-based monolithic MICs (MMICs) processing techniques [6]. This trendy progress was in line with the development of precision fabrication and semiconductor technologies. Again, this generation of microwave circuits still makes use of planar transmission lines as the previous generation. However, the use of different technologies results in a different circuit landscape. In particular, more components can be made altogether through the same process. Without reference to any carrier packaging roles, printed-circuit board (PCB) substrate integration and multi-chip module (MCM) aspects, MHMICs allow the integration of nearly all passive components within standard high-precision 2-to-3 layer processing techniques, whereas MMICs enable the integration of nearly all passive and active components within the same chip form through Si, GaAs or other III-V compound technologies. Again without speculation, the development of the fourth generation, as shown in Fig. 1, is nothing but an extension of generic 2D integrated circuits along the vertical direction to create stacked multilayered 3D integrated circuits of diversified forms that may involve multi-function and multi-technology processes.

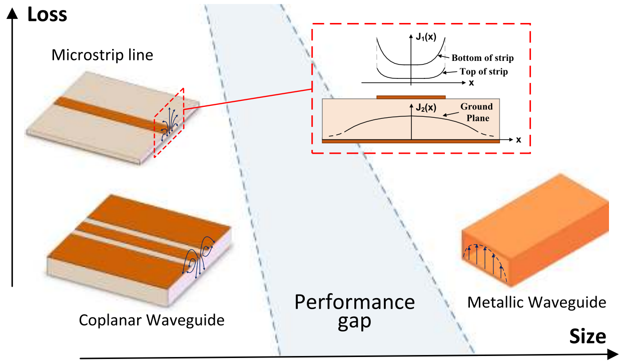


FIGURE 2. **Performance gap between planar transmission lines and metallic waveguides and its related physical explanation.**

However, all circuits still make use of planar transmission line techniques such as microstrip and CPW as well as their variants, which always consist of voltage- and current-based passive and active nodes together with distributed TEM mode structures and components. Indeed, such planar transmission lines allow an easy integration and direct compatibility with active electronic devices such as diodes and transistors that are universally defined by voltage and current.

In spite of the well-appreciated advantages as stated in the above discussion, planar transmission lines are known to exhibit high structure loss, low-Q effect, strong parasitic coupling, sensitive processing tolerance, and low power handling capability, which become more and more pronounced at higher frequencies such as mmWave and terahertz. Of course, this is the case mostly for planar TEM transmission lines. In fact, different modes present different electrical and mechanical properties along any given transmission line, which is a universal rule for guided-waves. A guided-wave structure has its own distinct features compared to its counterparts, which can well be reflected in modal behavior. As observed in Fig. 2, there is an obvious gap of performance between planar transmission lines and metallic waveguides. The fundamental limitation of the quasi-TEM modes along a microstrip line can be seen in the distribution of electrical currents induced on the signal line, which clearly show a pair of singular points of longitudinal current density along the two edges. These current singularities lead to numerous troubles, namely strong magnetic coupling with neighboring circuits and related packaging issues, sensitive line tolerance for characteristic impedance, and potential radiation loss with longitudinal line discontinuities. On the other hand, high conductive losses are induced by the high-density current flowing the signal line as well as the return path on the ground plane, which become more severe for thinner substrate and narrow line, needless to mention any underlying dielectric effects.

Naturally, combining the individual benefits of planar lines and rectangular waveguides would be a good way out of this impasse. In this case, desired and undesired guided-wave properties and technical features of the two groups of structures are nearly opposite in nature and truly complementary for deployment. Fig. 3 shows a number of commonly used

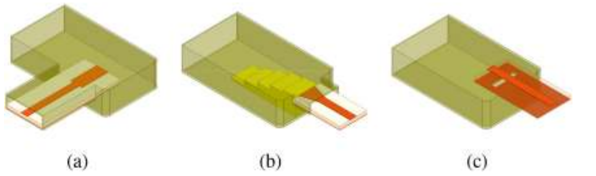


FIGURE 3. Selected three typical interfaces created for the electrical and structural assembling of planar circuits and waveguide components: (a) probe type, (b) ridge type and (c) slot type.

embedded "interfaces" rather than seamless "integration" schemes, which include three types of field matching and feed-through mechanisms (probe, ridge and slot). In this case, the planar circuits are generally the carrier platform in support of active circuit functions, while the waveguide components are used to comply with high-Q and/or high-power requirements. Generally, such interface techniques exhibit narrowband transmission behavior and costly mechanical manipulations are heavily involved for putting them together, which are not good for and generally not amenable to mass production. Since the waveguide is made of metallic enclosure while the planar circuit involves dielectric materials, thermal problems may occur because of material compatibility issues. In short, this type of interface may be susceptible to potential electrical, mechanical and thermal problems.

In the 1980s, there was a partially successful attempt to develop a hybrid integration approach called "fin line" technology in which planar circuits are accommodated in either the E- or H-plane of the waveguide (E-plane has been used in most cases) [16]. The original motivation of the fin line development was actually to use planar lines within a waveguide design environment. Unfortunately, the research and development activities of guided-wave techniques and integrated circuits during that period of time were marked with only a brief and ephemeral interlude devoted to the fin line technology. The terminology of hybrid integration was not really used until the start of a full-scale development of planar and non-planar structure integrations in the 1990s [17]–[19].

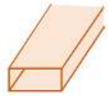
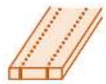
B. SUBSTRATE INTEGRATED WAVEGUIDE

In the early 2000s, the substrate integrated waveguide (SIW) was proposed and demonstrated in different manners [20]–[23], which merely presented a class of particular substrate integration scenarios of planar and non-planar structures. Actually, the development of substrate integration technology suggests that any non-planar structure can be synthesized in a planar form within a substrate design space so that it can be seamlessly integrated with other planar transmission lines if needed through the well-established processing technologies of planar integrated circuits. The planar synthesis of a non-planar structure may be made of either conducting through via hole arrays mimicking metallic walls to create a substrate integrated rectangular waveguide (SIRW earlier or SIW later) or air hole arrays locally reducing effective dielectric constants to create a dielectric contrast, leading to a dielectric guide (substrate integrated non-radiative dielectric or SINRD guide, for example). Of course, other artificial boundary conditions including nonlinear and magnetic effects are also possible in this synthesis, which are not necessarily limited to electric walls or effective dielectric constants. In essence, the synthesis of waveguides within planar substrate allows the creation of a panoramic vision for low-cost and unified fabrication and integration among any guided-wave structures, which effectively bridges the gap between TEM modes and non-TEM modes as well as between planar and non-planar structures with the same processing techniques. Typical planar and non-planar structures are compared in Table 1, which can be effectively combined on the basis of design considerations and practical needs. This points to the possibility of creating single-layer or stacked multilayer hybrid and monolithic substrate integration circuits and systems in which TEM and non-TEM modes can be wisely and readily deployed without obstacles, as shown in Fig. 1. This should be regarded as the disruptive fifth generation of microwave circuits, which breaks, for the first time, the iceberg of TEM mode transmission lines exclusively used for ICs developments.

There is a large number of flexible synthesis techniques available that make various scenarios of planarization possible, depending on the electrical, mechanical and economical requirements for specific applications. For example, metallized slot trenches can be used for rectangular waveguides instead of conducting via holes. In fact, prior to the development of SIW and its variants, there were attempts to create similar structures called waveguide line and post-wall waveguide [24]–[27], which were demonstrated on specific processing schemes but the prospective integration generalization of planar and non-planar structures was not thought of in those attempts. In fact, the use of fine vias before the 2000s was extremely difficult in practice. The breakthrough came in exactly 20 years ago with the first practical demonstration of a working transition between microstrip and SIW transmission lines [20], which has become the most cited paper of the IEEE Microwave and Wireless Components Letters to date.

In our opinion, the advent of SIW technologies including both metallic and dielectric types, has provided a fascinating development path for microwave circuits, which is particularly true for mmWave and terahertz integrated circuits and systems. This would trigger our imagination for the future developments in microwave circuits, for example, how the sixth generation of microwave circuits will look like. The concept and practice of substrate integration can be seen through some examples, illustrated in Fig. 4, which presents the three most popular non-TEM mode substrate integration schemes, including SIW [27], [28], SINRD [29] and Substrate Integrated Image Guide (SIIG) [30]. Clearly, all of them inherit the original waveguide techniques but are processed as planar transmission lines. To facilitate our following discussions without loss of generality, we will pay particular attention to the SIW for rectangular waveguide in planar form. Of course, the design and development of SIW are much involved because of the synthesized periodic guided-wave structures, which are subject to Bragg band gaps. In practice, this Bragg

TABLE 1 Popular Transmission Lines and Guided-Wave Structures for Megahertz-Through-Terahertz Design and Applications

Type	Coaxial Line	Dielectric Waveguide	Metallic Waveguide	Substrate Integrated Waveguide	Microstrip	Coplanar Waveguide	Strip Line
Illustration							
Fundamental mode	TEM	EH/HE	TE_{10}	Quasi-TE_{10}	Quasi-TEM	Quasi-TEM	TEM
Modal Dispersion	●●●●●	●	●●●	●●●	●●●●	●●●●	●●●●●
Monomode Bandwidth	●●●●●	●●	●●●	●●●●	●●●●	●●●	●●●●
Transmission Loss	●●●	●●●●	●●●●●	●●●	●	●●	●●
Power Handling	●●●●	●●●●	●●●●●	●●●	●●	●●	●●●
Physical Size	●●●	●●	●	●●●	●●●●●	●●●●	●●●
Ease of Manufacturing	●●	●●●	●	●●●●	●●●●●	●●●●●	●●●
Integration	●	●●	●	●●●●●	●●●●●	●●●●●	●●●●
Packaging and Shielding	●●●●●	●	●●●●●	●●●●	●●	●●	●●●

Scale: ● = very unfavorable; ●● = unfavorable; ●●● = average; ●●●● = favorable; ●●●●● = very favorable.

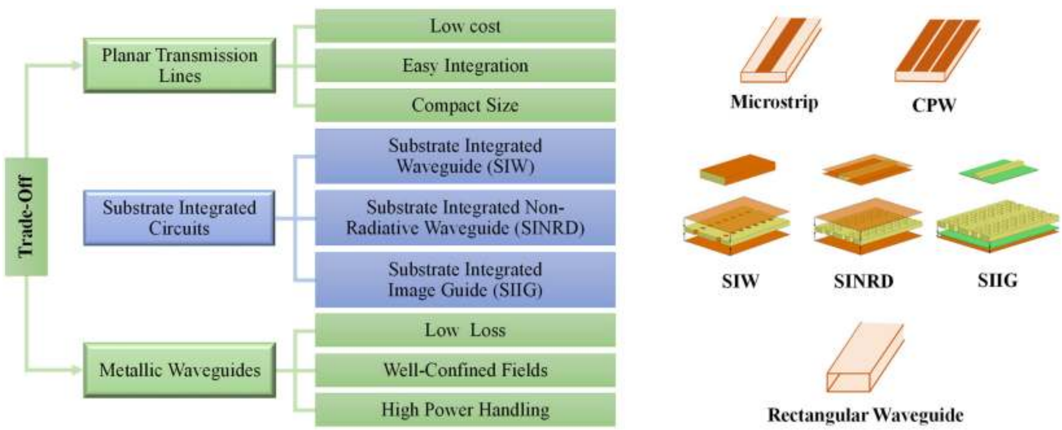


FIGURE 4. Three examples of substrate integrated guided-wave structures in planar form that exhibit non-TEM mode propagation and associated design and technology trade-offs with reference to microstrip line, CPW and rectangular waveguide in terms of technical features, design considerations, and performance indicators.

frequency is far away from the operating frequency points. The periodicity of the synthesized "fences" for SIW should be selected on the basis of the well-established Nyquist sampling theorem of fields corresponding to the shortest wavelength of an operating frequency band of interest for the quasi-TE_{10} mode. In other words, the choice of those "fences" in terms of spacing and geometrical dimensions would allow the guidance of a desired mode (quasi-TE_{10} mode, for example) through their resulting boundary conditions that however prohibit the leakage of energy along the bilateral direction to the outer regions. This is the underlying physics for the design of metallic "fences", which depends on a multitude of electrical and structural parameters and has been discussed in the literature [27], [28]. In this way, all design rules and theories of conventional waveguides and waveguide circuits can be recycled and reused in a straightforward manner through the equivalence of exact TE_{10} mode with the help of a corrected effective waveguide width, which should generate the same cutoff frequency as the original periodic waveguide does. The SIW structures can easily be integrated with other planar transmission lines such as microstrip lines and CPW. This is the reason why the SIW techniques have been widely studied and deployed at a very fast pace compared to other substrate integrated structures.

The popularity in both academia and industry can be witnessed by the publication of a very large number of technical papers [31] and the development of numerous consumer, industrial and defense products around the world. Fig. 5 presents the vividly evolving trends of publication records on SIW and its variants since the debut, suggesting a clearly linear increase of the number of IEEE technical papers from year to year over the last 15 years or so. The publication trend for all journals and conferences, including both IEEE and non-IEEE contributions, seems to be exponentially unfolding from year to year. Now, the SIW technique is even being used in publications without citing the early published papers, as if they were taken for granted. There are countless product developments and patent filing worldwide, which are

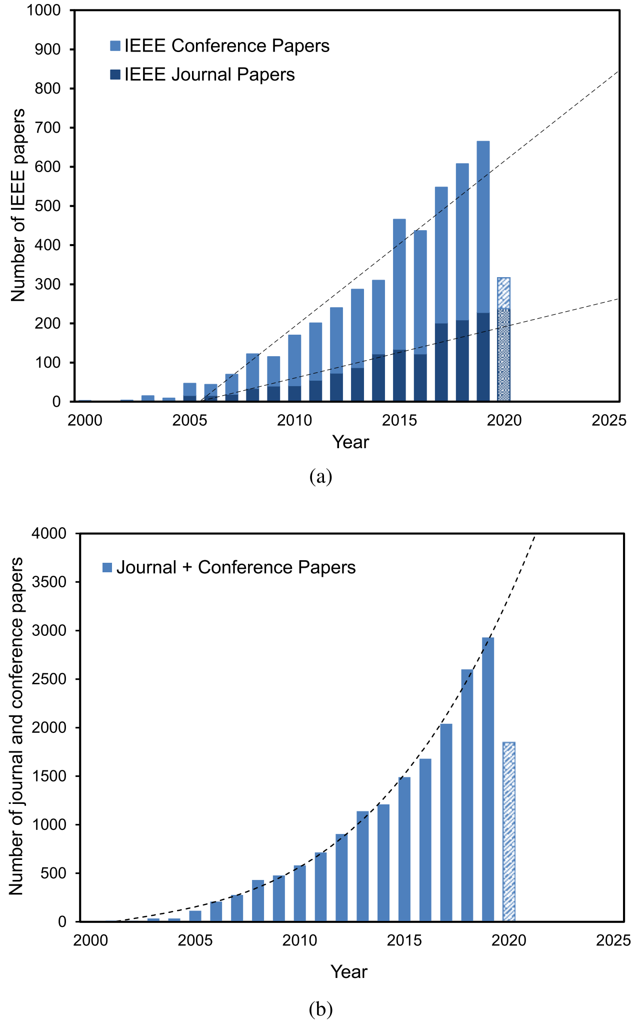


FIGURE 5. Chronological trends of SIW-related publication records in (a) the IEEE community (IEEE Xplore data) and (b) the global community (Google Scholar data), generated from SIW keywords.

generally embedded in microwave and mmWave front-end systems. In particular, the SIW technique has attracted much attention in the development of mmWave circuits, antennas and systems for 5G and beyond 5G (B5G) communications, automotive radars, satellite systems, emerging sensors, ultra-fast interconnects, and other advanced RF, mmWave and high-speed electronics techniques. Within the IEEE community, the SIW has influenced research topics in many societies, including the Microwave Theory and Techniques Society (MTT-S), the Antennas and Propagation Society (AP-S), the Electronics Packaging Society (EP-S), the IEEE Photonics Society (IPS), the Solid-State Circuits Society (SSCS), the Circuits and Systems Society (CAS) and the Aerospace and Electronic Systems Society (AESS) among many others. It is also worthwhile mentioning that the SIW technology was selected as the top-ranked technology among the 10 most promising and game-changing technologies that are the most likely to fundamentally change the future of

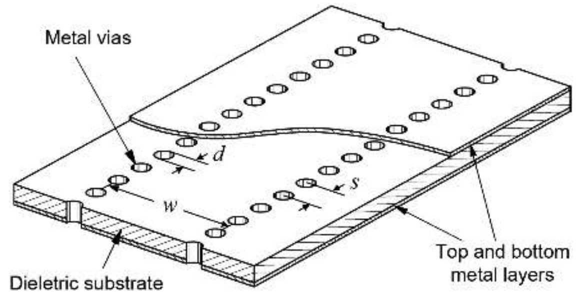


FIGURE 6. Geometry of the classical SIW structure, with the relevant geometrical dimensions.

passive and control components by the "Microwave Journal" [32], probably the most well-known industrial journal in the field of applied electromagnetic engineering.

In the following, the state-of-the-art of this emerging scheme is highlighted with emphasis on a global view of the development of SIW components, circuits, and systems, including system-on-substrate (SoS). Examples of current SIW-related realizations are discussed, covering a wide range of passive and active circuits as well as practical systems.

II. TECHNICAL REVIEW

Although the notation of the SIW technology can be referred to as the generalized planarization of any non-planar waveguide structures, the use of the terminology SIW by default is substrate integrated rectangular waveguide, unless otherwise specified. The SIW technology allows integrating rectangular waveguides, interconnects and circuits all in planar form, by adopting appropriate materials and manufacturing techniques that are typical of planar circuits (like microstrip lines and CPW). This following section describes various SIW structures developed in the past two decades, illustrates their operation principles and basic features, and highlights some fundamental design rules.

A. CLASSICAL SIW TRANSMISSION LINE

The classical SIW transmission line mimics the topology and the electromagnetic behavior of the classical rectangular waveguide [20], [31], [33]. The two ground planes represent the top and bottom metal walls of the rectangular waveguide and the rows of metal vias replace the sidewalls of the waveguide (Fig. 6). Metallized slot trenches can also be used instead of metal vias. The propagation of electromagnetic waves inside the SIW is similar to that of rectangular waveguides, and the fundamental mode is similar to the TE_{10} mode of the rectangular waveguide. Since the electric current density on the metal vias can only flow in the vertical direction, the SIW supports a set of modes similar to the TE_{n0} modes ($n = 1, 2, \ldots$) of the rectangular waveguide, where the electric current density in the side walls has only the vertical component. Conversely, the SIW does not support modes similar to TM modes and TE_{np} modes (with $p \neq 0$) of the rectangular waveguide, which require longitudinal electric current density on the sidewalls [28].

The similarity between the classical SIW and the rectangular waveguide is fully exploited by adopting the concept of the equivalent waveguide [34], as briefly mentioned earlier. In fact, the width of an ideal rectangular waveguide can be determined, in such a way that the SIW and the equivalent rectangular waveguide exhibit the same dispersion characteristics for the fundamental mode. Various formulas are available to calculate the width of the equivalent waveguide, based on the geometrical dimensions of the SIW (namely, the width w, the via diameter d, and the pitch s) [34]–[36]. Based on the concept of the equivalent waveguide, the dispersion characteristics of the SIW can be determined analytically (including the propagation constant and the characteristic impedance), and the design rules of the rectangular waveguide circuits can be adopted [34].

Losses in SIW structures are generally larger than in hollow rectangular waveguides, due to the presence of the dielectric substrate and to the small thickness. There are three major mechanisms of loss in the SIW [37]. The conductor loss is due to the finite conductivity of the top and bottom metal walls and of the vias, and it can be reduced by increasing the substrate thickness. The dielectric loss is due to the dissipation in the dielectric substrate material, and it can be reduced only by selecting low-loss materials, which exhibit low permittivity and low loss tangent. Finally, the radiation loss is due to the leakage through the gaps between vias [28]. If the metal vias are closely spaced ($s < 2d$, Fig. 6), the shielding effect on the electromagnetic field is practically perfect and the radiation loss is negligible [38]. When increasing the longitudinal spacing between the metal vias, the shielding effect is lost and the SIW radiates through the sidewalls, allowing the implementation of leaky-wave antennas, typically operating on the second mode of the SIW [39]. At high frequencies, the contribution to losses due to the effect of surface roughness is not negligible and it contributes to increase the overall attenuation [40].

SIW structures are realized by using the fabrication techniques usually adopted by the microstrip lines and CPW, like PCB [20], [33] and low temperature co-fired ceramic (LTCC) techniques [41]. In the terahertz region, the use of through-silicon via (TSV) technology allows the implementation of miniaturized SIW structures [42], [43]. Special fabrication techniques were adopted for the implementation of SIW on textile [44], on paper [45], and by 3D printing [46].

Due to their similarity with microstrip lines and CPW, SIW structures can easily be connected to other planar transmission lines, implemented on the same dielectric substrate, to obtain full systems integrated on one single dielectric substrate [47]. A variety of broadband transitions from microstrip to SIW and from CPW to SIW have been reported in the literature [48], [49]. The transitions are also needed for measurement purposes, to connect the SIW circuit to the ports of the vector network analyzer (VNA). In this case, sophisticated tools were developed to de-embed the effect of the transitions and obtain the electrical parameters of SIW circuits [50], [51].

B. COMPACT AND BROADBAND SIW STRUCTURES

Due to its similarity with the rectangular waveguide, the SIW shares the same limitations in terms of bandwidth and compactness. Since the SIW typically operates in the single-mode band, which ranges from the cutoff frequency of the fundamental (quasi-TE_{10}) mode to the cutoff frequency of the second (quasi-TE_{20}) mode, the useful bandwidth spans one octave. Therefore, the useful bandwidth is much narrower than in the case of the microstrip line or the CPW, where the fundamental mode has no cutoff and the single-mode band can extend for tens of gigahertz, up to the cutoff frequency of the first higher-order mode. In terms of dimensions, the width of the SIW is usually smaller than that of the hollow rectangular waveguide, due to the shrinking effect of the dielectric material. Nevertheless, the width is inversely proportional to the cutoff frequency of the fundamental mode, and it can be quite large for structures operating at the frequency of few gigahertz. In any case, the width of the SIW is usually broader than the width of a microstrip line. Consequently, several modified SIW structures have been proposed to overcome these limitations.

The substrate integrated folded waveguide (SIFW) [52], [53] consists of a standard SIW structure, folded around a metal septum, thus assuming a C shape (Fig. 7(a)). This topology leads to the reduction of the footprint by a factor of two, but a dual-layer technology is required. The mode pattern is practically unaffected by the folding, as well as the performance in terms of losses and dispersion characteristics. In particular, the electromagnetic shielding is fully preserved.

Another solution to reduce the size of the classical SIW is the half-mode SIW (HMSIW) [54], [55], where half of the structure is removed, by cutting along the vertical symmetry plane (Fig. 7(b)). This solution exploits the magnetic wall condition satisfied by the fundamental (quasi-TE_{10}) mode of the SIW along the vertical symmetry plane. When removing half of the structure, the low aspect ratio of the cross-section leads to a virtual magnetic wall condition along the open boundary, due to the large capacitance (vertical electric fields) between top and bottom metal planes. This phenomenon allows preserving the confinement of the electromagnetic field of the fundamental mode in the remaining half structure. As a result, the width of the half-mode SIW is reduced by a factor of two compared to the classical SIW, at the cost of a moderate radiation leakage along the open boundary (especially near the cutoff frequency, where the field is all in phase on the aperture). Moreover, the second (quasi-TE_{20}) mode of the SIW does not exhibit a magnetic wall condition along the vertical symmetry plane, and therefore, it is not supported by the half-mode SIW. The first higher-order mode is the quasi-TE_{30} mode, whose cutoff frequency is approximately three times larger than the cutoff frequency of the fundamental mode. Consequently, the single-mode bandwidth of the half-mode SIW is twice that of the classical SIW.

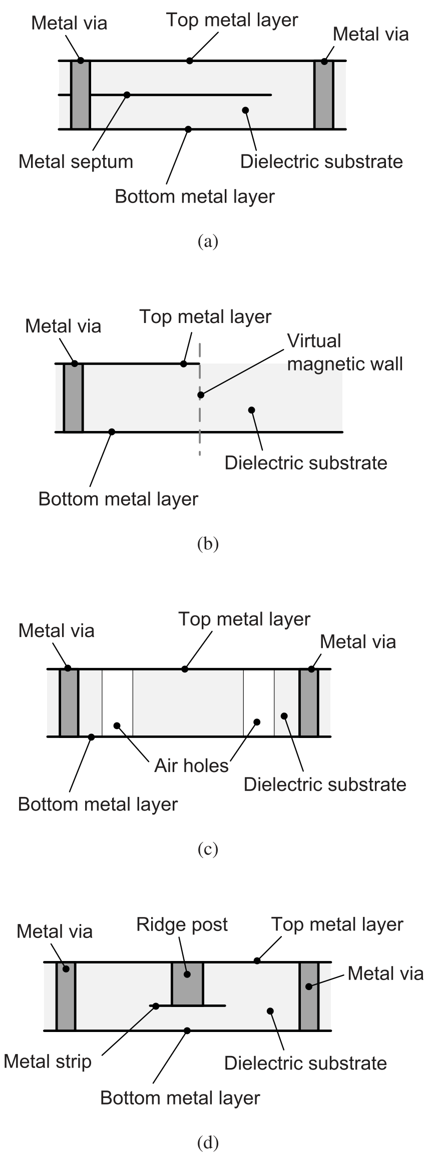


FIGURE 7. Cross section of compact and broadband SIW structures: (a) folded SIW, (b) half-mode SIW, (c) slab SIW and (d) ridge SIW.

The combination of the folded SIW and the half-mode SIW was also proposed [56], with the possibility of folding the structure multiple times to minimize the width.

The substrate integrated slab waveguide (SISW) [57] has been proposed to increase the single-mode bandwidth of the SIW. Based on the concept of the slab waveguide in classical rectangular waveguide technology, it consists of an SIW structure with air perforations of the dielectric substrate in the side portions of the SIW (Fig. 7(c)). These perforations locally modify the effective dielectric permittivity, which is lowered in the side portions. Consequently, the fundamental (quasi-TE_{10}) mode is unaffected, because its electric field is mainly concentrated in the middle of the SIW, whereas the cutoff frequency of the second (quasi-TE_{20}) mode is increased, as its electric field is mainly concentrated in the side portions and therefore, it is subject to a lower permittivity. This effect determines a larger separation of the cutoff frequency of the first and second SIW modes, which eventually results into a broader single-mode bandwidth. The fundamental mode is practically unaffected by the holes also in terms of losses and dispersion characteristics. An alternative fabrication procedure, based on additive manufacturing, allows fabricating the substrate integrated slab waveguide in one single step, by 3D printing the dielectric substrate with different infill [58].

The substrate integrated ridge waveguide [59], [60] is a dual-layer structure, which allows implementing a ridge in the broad wall of the SIW, by using a row of partial-height metal vias connected at the bottom by a metal strip (Fig. 7(d)). This metal strip avoids the appearance of a band-gap in the single-mode band of the structure, which would jeopardize its bandwidth performance [60]. Similarly to the ridge waveguide in classical waveguide technology, the presence of the ridge increases the capacitance per unit length, thus decreasing the cutoff frequency of the fundamental (quasi-TE_{10}) mode. The second (quasi-TE_{20}) mode, whose electric field has small amplitude in the middle of the structure, where the ridge is located, is practically unaffected by the presence of the ridge. Decreasing the cutoff frequency of the fundamental mode without changing that of the second mode leads to a broader single-mode bandwidth. In addition, for a given width, the ridge SIW exhibits a lower cutoff frequency of the fundamental mode than a classical SIW. In turns, for the same cutoff frequency, the width of the ridge SIW is smaller than the width of the classical SIW. This means that, besides the increased bandwidth, the ridge SIW also exhibits miniaturization properties. Due to the field concentration under the ridge, losses in the substrate integrated ridge waveguide are larger than in the classical SIW, and show some similarity with the losses in the microstrip line [60]. For the same reason, the fundamental mode of the substrate integrated ridge waveguide exhibits a smaller dispersion than the classical SIW.

The combination of the slab SIW and the ridge SIW [60] allows for a further increase of the single-mode bandwidth. In fact, compared to a classical SIW, the presence of the ridge decreases the cutoff frequency of the fundamental mode, and the presence of the air perforations in the side portions of the structure increases the cutoff frequency of the second mode. A similar effect can be achieved by adopting two different dielectric substrates, the one under the ridge with high dielectric permittivity and the other with low permittivity [61].

C. OTHER MODIFIED SIW STRUCTURES

A number of other modified versions of the classical SIW structure have been developed, to meet specific requirements (including lower losses and possibility of DC bias).

The substrate integrated coaxial line (SICL) [62] represents the integration of the coaxial cable in planar form. It is based on a metal strip sandwiched between two grounded dielectric layers, and it is side-limited by two rows of metal vias. Compared to the classical SIW, the SICL exhibits a number of advantages. The fundamental mode of the coaxial line is a TEM mode, which has no cutoff. Therefore, the single-mode band extends from DC to several tens of gigahertz, and it can be increased by miniaturizing the dimensions of the structure. Moreover, the propagation characteristics of the fundamental TEM mode are not dispersive, thus being particularly suitable for the implementation of broadband components. Finally, the presence of two conductors makes the SICL a good candidate for the integration of active components, as it allows to bias two-terminal active devices. On the other hand, losses are larger than in the classical SIW, due to the high current density at the edges of the metal strip.

The air-filled SIW (AFSIW) [63] was developed to reduce the losses in SIW structures. It is based on a three-layer topology: the top and bottom layers can be implemented by low-cost laminated substrates (like FR-4), and define the top and bottom ground planes. The middle layer is the dielectric substrate containing an air-filled region and the rows of metal vias. A small portion of dielectric is left in the region of the metal vias to permit the fabrication by a standard PCB process. This solution allows a lower dielectric loss than in the standard SIW, at the cost of a slightly larger size. Due to the increased size, also the conductor loss marginally decreases. Moreover, the top and bottom FR-4 layer can be used to implement baseband or digital circuits, thus leading to a compact and low-cost integration.

The corrugated SIW (CSIW) [64] is a modified SIW, which does not require metal vias for the lateral field confinement. The rows of metal vias are replaced by a periodic pattern of quarter-wavelength microstrip stubs located at the two sides of the top metal wall, which mimic the short circuit condition in a reasonably broad frequency band. Besides the purely 2D fabrication process, this structure facilitates the integration of active devices. In fact, it consists of two separate conductors, and therefore it allows the shunt connection of active devices that require DC bias.

A slow-wave SIW (SW-SIW) was proposed in [65] to reduce the phase velocity and, eventually, reduce the dimensions. It is based on a dual-layer structure, where the bottom layer includes an array of blind vias, connected to the bottom metal wall (bed of nails). In this case, the bed of nails has the effect to increase the effective permittivity, thus generating a slow-wave effect. This leads to a significant reduction of both the longitudinal and the transversal dimensions, with a substantial miniaturization of the components. An alternative solution to implement SW-SIW consists in SIW structures where the top metal wall is patterned with microstrip polylines [66]. In this case, the slow-wave effect is achieved by increasing the effective permeability.

III. APPLICATIONS

The very first microwave sub-systems reported in the literature using SIW technology were designed to operate in the lower range of the mmWave spectrum. These early designs were intended for use in wireless local area networks and collision-avoidance sensors. Besides few exceptions, the mmWave frequency range remains the prevalent usage of SIW technology, with extension to space, also including the ground segment, airborne, imaging and terrestrial communication applications. In fact, reported works cover all the gigahertz-through-terahertz frequency range, with particular interest in high-end microwave systems. This section reviews some of the key developments in these application domains, with no pretension of being exhaustive considering the amount of work based on SIW technology reported over the past two decades. It highlights the expected progression from stand-alone sub-systems, such as beamformers and filters, to more integrated microwave systems combining different transmission line technologies, including active antennas and radar RF modules.

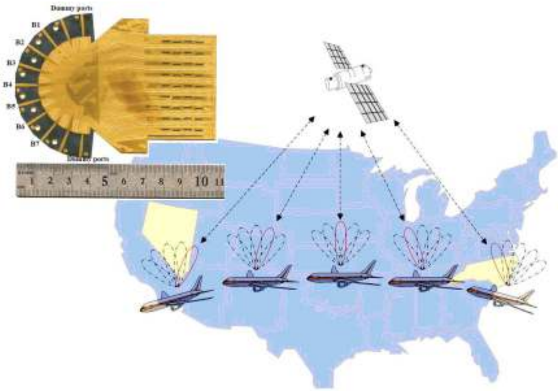


FIGURE 8. Multiple fixed-beam SIW Rotman lens array antenna for in-flight satellite connectivity at Ka-band [67].

A. SATELLITE GROUND AND SPACE SEGMENT

The turn of the 20th century brought a paradigm shift in the space sector. The need for more in-orbit capacity moved communication satellite payloads to higher frequencies, with the first Ka-band transponders being launched on board of the satellite Anik-F2 in 2004. Since then, the total in-orbit capacity has increased by several orders of magnitude, with currently developed satellites being capable of up to 1 Tbps of total capacity (e.g. ViaSat 3 due to launch by end of 2021). This is further amplified by on-going mega-constellation developments for global Internet access (e.g. OneWeb, Starlink). This has provided unprecedented opportunities for cost-effective user terminals with applications ranging from fixed professional satellite Internet access to consumer Satellite-On-The-Move (SOTM) connectivity at Ku and Ka bands. A fixed multiple beam array antenna based on an SIW Rotman lens beamformer is described in [67] for in-flight satellite connectivity (Fig. 8). SIW and strip line technologies were combined in a similar Rotman lens solution for Ku-band vehicular mobile satellite terminals [68]. More recently, passive array designs using SIW beamforming technology were proposed for Direct-To-Home (DTH) TV applications at Ku-band [69], [70].

Besides ground equipment, the emergence over the past decade of small-space platforms and CubeSats also calls for compact and lightweight solutions. The first reported design of a Nolen matrix in SIW [71], [72] was developed for

FIGURE 9. W-band mini-SAR with SIW antennas on a UAV [83].

Ku-band satellite payloads, as more conventional waveguide beamforming networks are bulky at those frequencies. Butler matrices were also developed at Ku-band for similar purposes [73], [74]. SIW technology has been considered at lower frequencies, including for instance X-band for data transmission systems [75], and even C-band for communication payload high-permittivity ceramic filters [76]. Inter-satellite link (ISL) is another field of application where some developments are reported using SIW technology, including for example passive array antennas at V-band [77] and integrated filters at Ka-band [78].

B. AIRBORNE AND HIGH ALTITUDE PLATFORMS

Besides in-flight satellite connectivity systems described in the previous section, SIW technology also finds applications in other airborne microwave systems, such as nose cone weather radars and rocket guidance systems. In particular, the use of SIW technology has been considered for the design of conformal frequency selective airborne radomes [79]. Radomes are indeed necessary to integrate antennas with poor aerodynamic properties (e.g. flat antennas) onto aircrafts' fuselage. Conformal antennas have been proposed as a possible alternative and conformal SIW slot arrays have already been reported [80].

For unmanned air vehicles (UAV), aerodynamics are generally less critical than size, weight and power (SWaP). SIW technology brings obvious benefits for such applications. An omnidirectional low-profile S-band antenna using SIW technology was proposed in [81] for the communication link between a UAV and the ground control stations. More advanced systems are also reported in the literature, including a 94 GHz radar system for high range target detection using an SIW transition to connect the waveguide ports of the radiating elements to the PCB [82] as well as a W-band synthetic aperture radar (SAR) system integrating two SIW antennas [83] (Fig. 9).

Another domain of application that may benefit from SIW technology in the near future is high altitude platforms (HAPs). While balloons were predominantly used for atmospheric sounding in the past (i.e. weather and environmental monitoring), there have been significant efforts over recent years to develop new HAPs, also referred to as atmospheric satellites, providing services offered by conventional satellites, like telecommunications and surveillance. This includes the developments of balloons, zeppelins and drones for such purposes. In particular, some Internet giants (e.g. Alphabet, Facebook) are developing HAPs to provide backhauling in remote areas difficult to connect with conventional terrestrial communications infrastructure. These solutions are also considered to provide "instant infrastructure" in emergency situations (e.g. natural disaster disrupting terrestrial communication services). A Ka-band phased array for such purposes was described in [84], integrating RF beamforming chips by Anokiwave with an array of open-ended SIW square horns, similar to the antenna element reported in [85].

C. AUTOMOTIVE RADARS

Automotive radars include short-range corner radars (e.g. blind spot detection systems), generally distributed around the car and mostly operating in the 24 GHz band reserved internationally for industrial, scientific and medical (ISM) purposes. They also include medium to long range front radars for collision warning or autonomous emergency braking systems, generally operating in the 77 GHz band to provide higher angular resolution and accuracy. Recent changes in spectrum regulations are moving all automotive radar systems to the 77 GHz band. Frequencies above 100 GHz are also being considered to address the more demanding needs of modern automotive applications, such as autonomous driving [86]. A detailed review of automotive radar systems is provided in the present issue of this journal [87].

Various microwave devices using SIW technology have been reported in the 24 GHz band for general purposes, with possible application to automotive radars. This includes for example the first multi-beam SIW pillbox antenna [88], a diplexing SIW antenna system [89] and a dual-layer Rotman lens [90]. Some specific technological developments for automotive radars at 77 GHz were also reported in the literature, including the first wideband Nolen matrix based on coupler delay compensation [91] and a two-layer Butler matrix without crossover [92]. Fully integrated systems were also described, including wafer level packaging with SIW resonators and bandpass filters [93], and an optimized SIW array antenna design combining long and medium range requirements in the same aperture with a flat-shoulder shaped radiation pattern [94] (Fig. 10).

D. TERRESTRIAL COMMUNICATIONS

The 5th generation (5G) mobile network, currently under deployment, is introducing a new air interface standard called New Radio (NR). It will extend the use of cellular networks beyond regular cellphones and mobile devices thanks to higher download speeds, comparable to Internet service providers. This is made possible by new frequency allocations. Frequency bands for 5G NR are separated into two frequency ranges, labelled Frequency Range 1 (FR1) and Frequency Range 2 (FR2). FR1 includes the bands used by previous standards as well as new bands in the sub-6 GHz

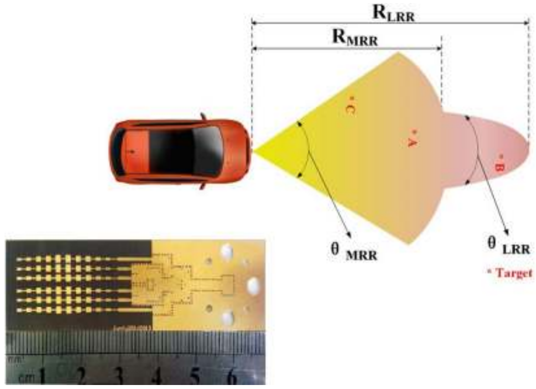


FIGURE 10. Array antenna for long- and medium-range 77 GHz automotive radar with an SIW corporate beamforming network [94].

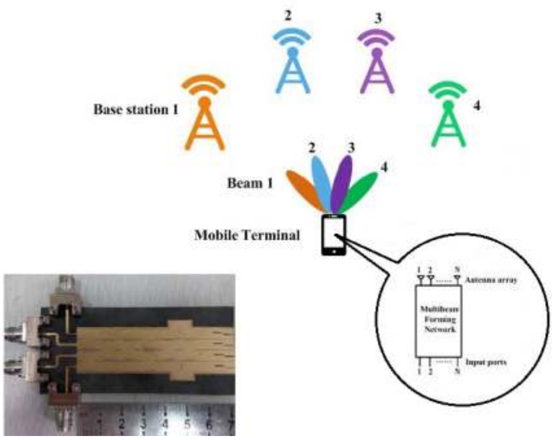


FIGURE 11. Butler matrix-fed multiple fixed-beam SIW array antenna for 5G mobile devices [96].

range. FR2 corresponds to the bands in the mmWave range, from 24 GHz up to 100 GHz. The new allocations provide significantly wider frequency bandwidth, enabling new applications such as Internet of Things (IoT) and Machine to Machine (M2M) communications.

In particular, FR2 includes some bands centered at 26 and 28 GHz, with allocations ranging between 24 and 29.5 GHz depending on the countries. These frequencies are very close to those discussed above for communication satellite ground equipment and automotive radars, and even overlap in some cases, making transfer of technology possible and SIW techniques a good candidate for 5G base stations and user equipment (UE) in the mmWave range. Some of the early works reported at 28 GHz proposed multiple beam antennas for mobile devices using corporate beamformers [95] and Butler matrices [96] (Fig. 11). Applying massive multiple-input multiple-output (MIMO) beamforming techniques in the mmWave range brings some integration challenges. In [97], a new type of SIW transition was proposed to feed an array of tapered slot antennas with a half-wavelength spacing while facilitating the integration with the electronics of the base station system. This solution provides 1D scanning, which is often a limitation of planar beamforming networks. A multilayer planar design combining H-plane Butler matrices was described in [98] to produce one of the first 2D multiple fixed-beam array antenna in SIW technology at 29 GHz. An alternative design combining E-plane and H-plane Butler matrices in a planar multi-layer form was reported more recently in [99].

There are also on-going discussions for allocations at higher frequencies, including bands centered at 38 or 39 GHz, typically within the range 37–40 GHz depending on the countries. There are already dual-band designs reported in the literature, such as a dual-band SIW filtering power divider operating at 28 and 38 GHz [100]. There are also some works at higher frequencies, including an interesting antenna design at 60 GHz based on substrate-integrated parallel plate waveguide in LTCC, characterized by a direction of propagation of the fundamental quasi-TEM mode parallel to the vias, using a 90° E-plane bend to transition from the conventional SIW transmission line to the proposed corporate array [101]. Some works were also reported in the sub-terahertz range, including an interesting bidirectional communication circuit working at 120 GHz and based on an SIW coupler for full-duplex operation [102].

E. SUB-TERAHERTZ IMAGING

Various applications ranging from industrial quality control to medical and security screening require to “see” beyond the visible range. At the boundaries between electronics and photonics, the terahertz region has emerged over the past decades as a promising solution for imaging applications and non-destructive testing (NDT) because terahertz radiation penetrates through a wide variety of materials.

A first experimental demonstration of passive mmWave (35 GHz) imaging system using SIW technology was reported in [103]. The SIIG has also been proposed to overcome some of the sub-terahertz system integration challenges [30] and the demonstration of a linear array based on that technology was reported at 94 GHz [104]. An LTCC SIW slot antenna array was demonstrated at 140 GHz in [105] and more recently, some elementary components have been reported at 300 GHz, including spline horns [106] and H-plane bends [107]. A complete sub-terahertz (239–281 GHz) receiver was demonstrated in [108] using a circularly polarized SIW antenna for imaging applications. While still limited at the moment, it is expected that research will intensify in this field as technology becomes more affordable.

IV. TOWARD COMMERCIAL PRODUCTS

With the technology maturing, substrate integrated transmission line solutions have been gradually transferred from academia and research institutes to industrial R&D departments and commercial vendors. While most of the developments reported in section III are research oriented, there are also a number of product developments in industry using SIW technology. This is apparent in patent filings, with a growing number of industrial applicants over the past decade (Fig. 12). This section reviews some of the developments reported by small companies and larger corporations.

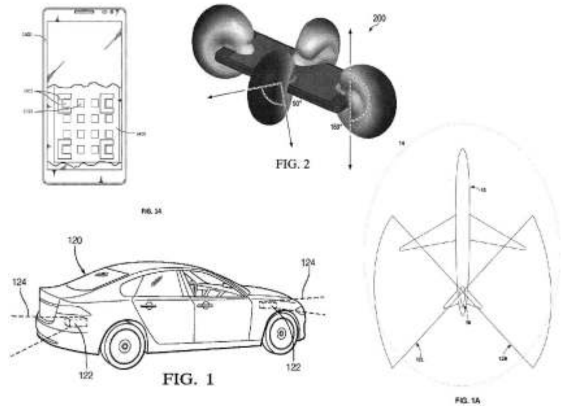


FIGURE 12. Examples of industrial patents using SIW technology: Huawei Technologies (top left [109]), Samsung Electronics (top right [113]), Aptiv Technologies (bottom left [121]) and Honeywell (bottom right [123]).

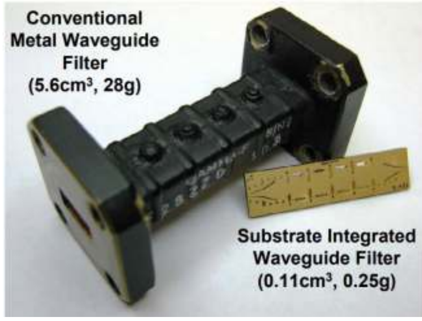


FIGURE 13. Custom SIW filters developed by MEMtronics for mmWave applications [125].

Several companies have reported developments using SIW technology for wireless communication devices, including mobile devices. This is clearly the most active field of application in industry, where the benefits of SIW technology, such as higher integration and lower cost, are expected to bring a significant impact due to the market size. The following list of industrial developments is obviously non-exhaustive and is mostly intended to highlight that key players in the field are working on the topic. Huawei Technologies (CN) has shown particular interest in the technology, with several patents filed, mostly on antennas and beam forming networks. This includes multi-mode beamforming networks for planar array antennas combining two types of transmission lines enabling dual-band operation [109]. Diplexers [110], switches [111] and layer transitions for surface mounted devices [112] were also reported for future wireless communication devices operating in the mmWave range. Samsung Electronics (KR) has filed a patent on open-end SIW antennas [113], suitable for integration at the edge of a substrate in a mobile device. Sony Mobile Communications (JP) has recently filed a patent describing a low gain antenna fed with a compact SIW transition for similar applications [114]. Ericsson (SE) is also investigating SIW technology for mmWave wireless communications, with patents filed on surface integrated antennas [115] and on waveguide-to-SIW transitions facilitating the integration of active components [116]. Sivers IMA (SE) has applied for a patent on a waveguide-to-microstrip transition using SIW technology to improve the integration of their chipsets at 60 GHz [117]. Infineon Technologies (DE) is developing RF modules for base stations using SIW filters [118].

Various industrial developments were also reported for automotive radars. Bosch (DE) has published some work on a new generation of medium-range radar antennas [119], demonstrating the benefit of an hybrid multi-layer approach combining SIW and other transmission lines. Aptiv Technologies (IE), formerly known as Delphi Automotive, has filed a few patents on antenna systems at 77 GHz using multi-layer PCB and including SIW technology [120], [121]. In fact, the SIW technology has been implemented in Aptiv's radar systems for many years, and millions of products have been shipped. LG Electronics (KR) has also filed a patent describing an antenna for automotive short-range corner radars using SIW technology [122].

In the aeronautical domain, Honeywell (US) has filed some patents based on SIW technology, including a collision avoidance system mounted in the vertical stabilizer of an aircraft [123] and an airborne weather radar aperture in PCB using slotted SIW antennas [124].

Some examples of generic products can also be found. This includes the Ka-band SIW filters in fused Silica developed by MEMtronics (US), which prove to be significantly smaller and lighter than their conventional waveguide equivalent [125] (Fig. 13). Apollo Microwaves (CA) has also developed an hybrid waveguide-SIW cross-coupler intended for monitoring purposes, allowing to detect potential malfunctions in a waveguide circuit [126].

V. CONCLUSIONS AND FUTURE PERSPECTIVES

Judging from the chronological roadmap of the technology development of microwave circuits as described in Fig. 1, we reiterate that there are three revolutionary progresses of fundamental structures used to construct microwave circuits, namely, the ground-breaking research of hollow waveguides (first generation) that underscored the birth of guided-wave structures, the invention of planar transmission lines pointing to the possibility of integration for the first time (second generation), and the development of substrate integration technologies allowing the heterogeneous and seamless integration of TEM and non-TEM mode structures (fifth generation). On the other hand, the development of the third and fourth generations of microwave circuits was fundamentally driven and enabled by the advancement of processing and material technologies, which does not change anything in terms of building structures. Although all the technologies can theoretically be considered for applications over the entire RF electromagnetic spectrum of megahertz-through-terahertz, each type of technology has its own advantages and disadvantages regarding the deployment of a specific frequency spectrum. In reality, the summarized technology roadmap talks about the story of integration evolving from non-planar to planar, and

FIGURE 14. SIW technology-driven developments and future research perspectives for integrated circuits and systems.

from low density to high-density. This always remains true for any future generation of microwave circuits, whether they are concerned with structural, functional and/or other aspects. Now, how about the future developments of microwave circuits and what the sixth generation will look like present some interesting questions and imaginative perspective.

Prior to discussing and answering the above-raised questions, let us look into the fifth generation of microwave circuits in Fig. 1. The SIW technique featuring the use of quasi-TE_{n0} modes, for example, seems to be more adequate for gigahertz-through-terahertz applications as its building blocks. This is because its cross-sectional dimension is closely related to the wavelength. TM modes are prohibited for guidance along the SIW structures, as discussed in Section II. In any case, the SIW geometry can co-exist with any other planar lines in both horizontal and vertical directions, which can be explored for various design and development needs. The coupling among circuit elements can be controlled and manipulated, which is an important aspect of packaging and interconnects as well as a design consideration for high-density integration. The hybridization of TEM and non-TEM modes presents a natural mechanism and potential in exploring metamaterial and metasurface circuit topologies [127] since the TEM case is a low-pass LC-model based right-handed structure, whereas the non-TEM case (TE mode in this example) is a high-pass CL-model based left-handed structure.

In our opinion, the future developments of microwave circuits based on SIW guided-wave structures can be reflected in Fig. 14 through five different and distinct directions, namely, miniaturization, tunability, nonlinearity, terahertz, and integration. All those directions are equally important. Obviously, they are closely dependent on the use of emerging and future processing techniques, advanced materials, and structural innovations. It should be noticed that the reduction of loss mechanisms is not listed as one of the future directions because this has been a constant effort for all loss-sensitive technologies. As we will see in subsequent discussion, some of those aspects are also coupled with one another. Therefore, it may be possibly anticipated that the sixth generation of microwave circuits could emerge in the same manner as we have observed for the third and fourth generations in which similar fundamental building blocks of hybrid TEM and non-TEM modes will remain in place. The following sub-sections will provide a narrative discussion and future implication on each of those five directions.

A. MINIATURIZATION

Besides the obvious use of high-dielectric materials in SIW circuits for low-profile applications, much efforts have been invested in the art of miniaturization of SIW structures since the early works in the 2000s [52], [54], [57], [128]–[130], which are studied and demonstrated through modal symmetry and multilayered topology. As discussed in Section II, the first successful attempts were the development of various half-mode and folded SIW techniques as well as ridge-loaded schemes [52], [54], [128]. Similar modal partition techniques have been used to reduce the size of resonant cavities such as quarter-mode for rectangular resonators or $1/n^{\text{th}}$ mode for circular resonators [129], which are generally seen in the design of filters and resonators. In addition, the use of metamaterials and metasurfaces may offer an additional degree of freedom in miniaturization through left-handed and right-handed combinations. Also, slow-wave effects can be explored for reducing the size of guided-wave structures [130]. Inevitably, the miniaturization leads to the increasing of transmission loss or the lowering of resonant Q-factor. To some extent, a compromised solution of miniaturization through the coherent conception of structure, material and mode altogether is desirable for most cases. The miniaturization is particularly critical for gigahertz circuits and terahertz chips design.

B. TUNABILITY

The parametric tuning and re-configurability present opportunities for developing frequency and/or structure-agile techniques [131], [132], which are generally of particular interest for multi-function, multi-band and multi-mode operations. This allows the development of software-defined smart and adaptable systems. SIW can easily accommodate tuning devices or materials through field-circuit interactions in the individual electric and magnetic tuning/switching, which present two popular fast schemes. In this case, tuning or switching elements may be in the form of diodes or transistors at the expense of losses incurred. Thermal, optical and mechanical actuations as well as fluidic controls may also be used for slow tuning or switching. In this case, the air-filled multilayered SIW techniques present an interesting solution as they can offer an adequate space for such actuations and controls. In the design of SIW-based tuning or reconfigurable circuits, it is worthwhile mentioning the distinct features of 2D simultaneous electric and magnetic tuning techniques, which offer a much wider tuning range, with a better controllable coherent coupling in the case of filter design, than other 1D techniques (electric or magnetic tuning) [132]. In particular, this design platform possibly allows a constant input impedance condition during the tuning or reconfigurable process, which cannot basically be done with the 1D solutions. Tuning or reconfigurable material-based techniques such as liquid crystal,

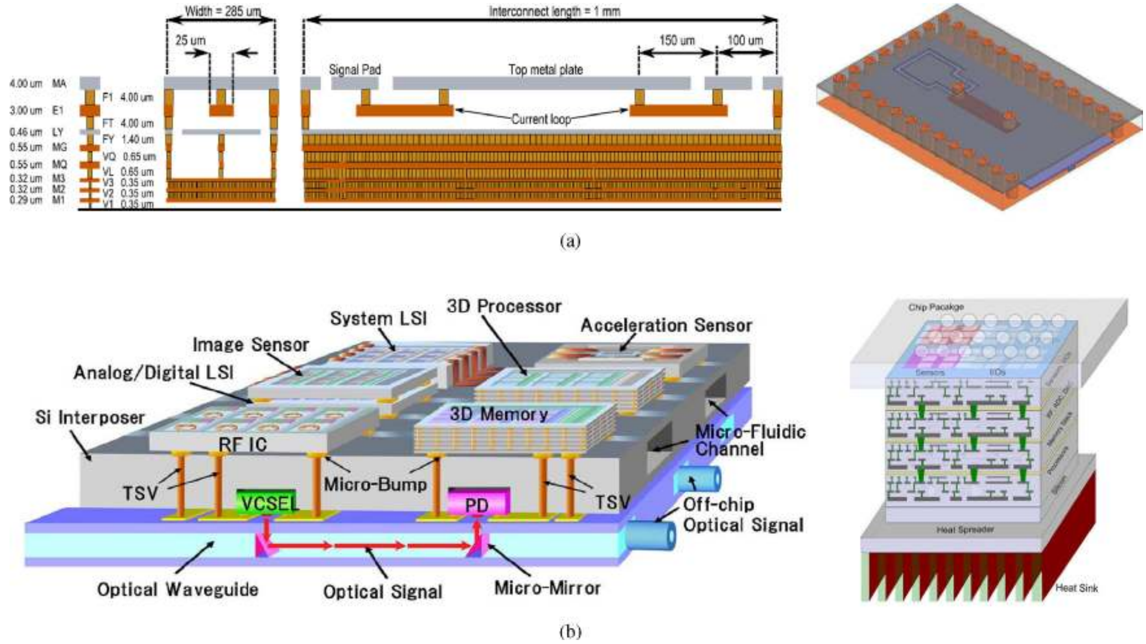


FIGURE 15. Potential hybrid and monolithic integrations of SIW and other non-TEM mode metallic and dielectric substrate integrated structures within diversified ICs: (a) T-FSIW using IBM 130-nm CMOS process [133] and (b) 3D heterogeneous integrated systems [134], [135].

ferroelectric, ferrite and phase changing materials present a series of emerging techniques for SIW integrated circuits.

C. NONLINEARITY

So far, nearly all of the SIW structures have been used as passive components and constituent parts of active circuits, for example, hybrid TEM and non-TEM mode techniques can be used in a straightforward manner. In the future, inherently nonlinear SIW techniques will be explored for various applications, which will investigate the nonlinearity of SIW structures rather than the intervention of external active devices into them. In this case, the nonlinear field effects of SIW substrate will be considered, subject to the external biasing conditions or not. This is extremely critical for the expansion of SIW techniques into non-conventional nonlinear circuits design and development without resorting to conventional TEM mode-based diodes and transistors, which are inherently not compatible with non-TEM mode guided-wave structures. In our opinion, there are three categories of non-TEM nonlinear transmission lines (NLTLs) based on materials, which will be studied, namely, electric nonlinear materials, magnetic nonlinear materials and dual electric/magnetic nonlinear materials. Of course, nonlinear resistivity materials can be regarded as part of those three categories. SIW-based NLTLs will provide means for high-pass pulse shaping and compression, parametric amplification, distributed mixing, and harmonic generations. Full pass techniques may also be considered through composite scheme of SIW and planar TEM lines [136], [137] for particular short pulse or broadband applications. In addition, nonlinearity within SIW techniques may also be observed for passive intermodulation (PIM) and other nonlinear issues for high-power developments.

D. TERAHERTZ

As terahertz technologies become more and more attractive, appropriate low-loss easy-to-integrate guided-wave structures become critical for the success of any terahertz circuits and systems developments and deployments. SIW techniques will likely call for the use of SIIG and SINRD guides, which will form a low-loss hybrid metallo-dielectric structure for terahertz applications. On the other hand, the SIW and its variants as well as SIIG and SINRD guides would all be considered in the design strategies of terahertz ICs such as complementary metal-oxide-semiconductor (CMOS) and III-V compound circuits and systems [133], as illustrated in Fig. 15, in which SIW is directly designed as part of CMOS multi-layered geometries. It can be anticipated that dielectric waveguides will be part of that CMOS or other low-loss substrates, which can create interesting distributed non-TEM mode-based passive and active functions. Of course, the current arrangement of CMOS with transistors presents some hurdle to the development of true active non-TEM dielectric and/or waveguide solutions. Nevertheless, this would open up an unprecedented possibility for the development of terahertz integrated circuits and antennas that benefit from both TEM and non-TEM mode propagations within ICs thanks to the development of substrate integration schemes. The hybrid metallic and dielectric waveguides can also naturally accommodate both electrical and optical properties in a flexible manner.

E. INTEGRATION

As suggested by the technology roadmap of microwave circuits in Fig. 1, the global development trend from generation to generation is fundamentally navigated and governed by the needs for higher integration. Judging from the demand of higher frequency design and cost-effective assembling, a scalable high-density integration is always the leading specification for productivity, efficiency, applicability, and reliability. To this end, SIW techniques offer self-packaging and ease-of-integration with any other planar structures. In particular, our recently proposed and proved unified and integrated circuit-antenna (UNICA) scheme [138], [139] would easily be incorporated in SIW design, in which the antenna can offer circuit functions and vice-versa. In this way, the active elements can be attached directly to antennas, which can offer the required impedance values without use of impedance matching networks. As such, the circuit-antenna integration can be made with extremely high signal power transfer efficiency and low loss. In addition, the above-mentioned ICs design strategies with all the substrate integration solutions can be deployed together with potential miniaturization techniques. The SoS concept [140] with a large scaled integration can effectively be used in connection with antenna-on-chip or antenna-in-substrate, depending on processing technologies and guided-wave methods. Within the integration platform, polarization diversity can also be deployed to create a joint operation of multiple polarizations within the guided-wave sections such as the devised and demonstrated polarization-selective coupling technique, integrated orthomode transducer and dual-polarization [141], [142]. The 3D SIW techniques can also be exploited for multi-polarization applications [143]. In the end, the SIW-driven integration will become an ultimate design choice of hybrid and monolithic system integration for putting circuits, antennas, and packaging altogether.

The above description of the five directions provides an intuitive view of future developments. As mentioned earlier, they are crossed-over and mutually related to one another. It can be found that SIW techniques and other non-TEM substrate integrated guided-wave structures definitely offer a fascinating perspective for future megahertz-through-terahertz science and engineering.

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