# A Review: Substrate Integrated Waveguide Antennas and Arrays

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***Abstract*—This study aims to provide an overview and deployment of Substrate-Integrated Waveguide (SIW) based antenna and arrays, with different configurations, feeding mechanisms, and performances. Their performance improvement methods, including bandwidth enhancement, size reduction, and gain improvement are also discussed based on available literature. SIW technology, which acts as a bridge between planar and non-planar technology, is a very favorable candidate for the development of components operating at microwave and millimeter wave band. Due to this, SIW antennas and array take the advantages of both classical metallic waveguide, which includes high gain, high power capacity, low cross polarization, and high selectivity, and that of planar antennas which comprises low profile, light weight, low fabrication cost, conformability to planar or bent surfaces, and easy integration with planar circuits.**

***Index Terms*—SIW; Vias; Antenna and Arrays; CRLH; CBA; LWA; Horn Antenna.**

## I. Introduction

The classical rectangular waveguide devices still serve as the mainstream for microwave and millimeter wave systems. However, the bulky size and inability of these devices to integrate with planar technology, i.e. PCB, prevent them to be used in the new generation wireless devices. In addition, the waveguide technique cannot be used to reduce the weight and volume. Hence, it is not appropriate for low-cost and bulk-production. Further, its post fabrication processing, like tuning and assembling becomes a real problem for manufacturers.

The realization of the planar rectangular waveguide is now possible by a newly promising technology called Substrate Integrated Waveguide technique (SIW), developed by K. Wu [1]. This technology has earned much attention over the recent years, in the area of high density integration of microwave and millimeter wave subsystems. The SIW allows us to create Substrate Integrated Circuits (SICs), as it provides the platform to integrate all microwave and millimeter wave active and passive components on the same substrate, such as the oscillators, amplifiers, filters, couplers, antennas and many more [2,3]. In this technique, rows of narrowly spaced metallic vias between two planes emulate the adjacent walls of a thin rectangular-type waveguide filled with dielectric [4]. The properties of SIW include low loss, low profile, high power capacity, easy integration and fabrication with planar technology, and mass production. Therefore, by implementing SIW, any non-planar guided-wave structure can be converted into its planar equivalent and facilitate the merits of planar and non-planar guided structures [5-7].

Owing to the design of antennas and arrays, conventional metallic rectangular waveguide feedings for achieving satisfactory radiation performances have been extensively reported in the literature. They also have the capability to handle high power, high Q-factor and are prone to radiation losses. Nevertheless, because of their bulky volume and high manufacturing cost, it makes them unfit for many practical applications [8]. Although printed antennas can overcome the above said disadvantages, they still suffer from power handling capability, making them unsuitable for designing antenna arrays. In addition, their feeding networks suffer from high ohmic losses, dielectric losses and spurious radiation, lead to the reduction of the gain and radiation efficiency of the antenna that degrade their performances.

In recent years, SIW techniques have been adopted to design microwave and millimeter wave antennas and arrays as well as feeding networks. This article presents a review and discussion related to SIW-based antennas and arrays, such as slot array antennas, cavity backed antenna travelling wave antennas, horn antennas, monopulse antennas, beam forming antennas, and many others with different configurations, different feeding structures. Additionally, their performance improvement methods, the critical issues related to design mechanism of SIW-born antennas and arrays and the technological solution proposed in published papers are also reviewed and discussed.

## II. Design Rule For SIW Metallic Posts

The SIW is composed of densely arranged metallic posts that realize the bilateral edge walls [4] as shown in Figure 1. The basic parameters of the SIW are the distance between the two parallel metallic vias i.e. the width of the waveguide '$a$', diameter of metallic vias '$d$' distance between two consecutive vias '$s$'. The width '$w$' of the SIW can be determined by formula [8] in Equation 1.

$$w = a - \frac{d^2}{0.95s} \tag{1}$$

The equation mentioned above does not include the diameter to width ratio $d/a$. When the diameter increases, it gives an error, so the more correct formula for the width calculation is given by [9],

$$w = a - 1.08\,\frac{d^2}{s} + 0.1 \times \frac{d^2}{a} \qquad (2)$$

Similar kind of relation was suggested in [10],

$$a = \frac{2w}{\pi}\cot^{-1}\left(\frac{\pi s}{4w} + \ln\frac{s}{2d}\right) \qquad (3)$$

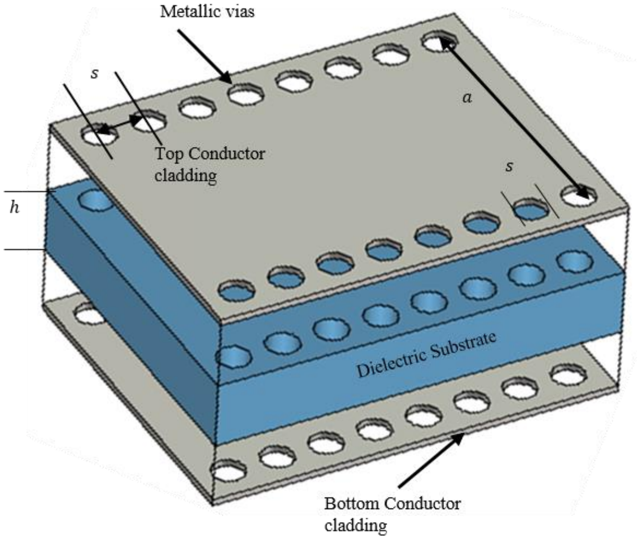

Figure 1: Configuration of SIW

Generally, due to the presence of the dielectric substrate, the width of SIW is narrower than that of the conventional waveguide. Owing to the limited thickness of the dielectric substrate, the electromagnetic field, along the height of SIW remains constant. Hence, the propagation and non-propagation of modes get excited inside its cavity [8]. These are $TE_{m0}$-like-modes, which drifts parallel to the side walls formed by contiguously located metallic posts, that are similar to that of the conventional waveguide. Additionally, the $TM$-mode is not possible due to non-continuous lateral walls as the gap between the posts does not allow the flow of current along them. These gaps also are responsible for the leakage of the field and it may cause the bandgap in the desired frequency band. Hence, in order to avoid this bandgap, $s/\lambda_o$ must be less than 0.25[6]. Nonetheless, decreasing the distance between consecutive drilled vias will affect the mechanical stability adversely. Thus, optimally, the number of these vias should not exceed 20 per wavelength.

## III. SIW-SLOT ARRAY ANTENNAS

Overview of the newly adopted SIW technology for the improvement of low profile slot array antennas is introduced in this section. It includes SIW-inspired transverse/longitudinal slot antenna arrays, SIW-CRLH/metamaterial slot array, and HMSIW slot array, SIW conformal slot array etc. Further, some focus on the size miniaturization techniques in SIW are highlighted.

In the background of modern digital wireless systems, slot array antennas have been extensively studied and employed. It constitutes slots that are transverse/longitudinal on the broad side or narrow wall of the guiding structure which lead to discontinuities, hence power radiation. Firstly, SIW used in antenna design was introduced in [11], wherein the SIW-slot array antennas were designed similar to the classical longitudinal slotted waveguide antennas. Slots are etched on the top metal cladding of their substrates so that the waveguide and slots are possible to mount on the same plane. Even though the SIW-inspired slot antennas are developed similar to that of the conventionally fed slot antennas, they do not demonstrate the drawbacks of the conventional structures.

For high gain and high radiation efficiency, longitudinal slot array antennas are preferred and can be achieved by Elliott's design procedure [12]. Using this method, SIW-based longitudinal slot array antenna was developed in [13,14]. Subsequently, a planar choke structure was proposed to improve Front-to-Back Lobe Radiation (FTBR) and Side Lobe Level (SLL) of the SIW slot array antenna [15]. It has a combination of short ended stubs and microstrip line which creates a very high impedance surface at the ground plane of the antenna, and ultimately eliminates the undesired surface current at the edge of the ground plane.

In order to have a radiating slot on the wall of the waveguide, it is required to have it at a specific distance from the center axis of SIW walls, but at the cost of cross polarization, which will eventually degrade the antenna performance. Following that, an eight element collinear shunt longitudinal slotted array antenna was presented [16] based on Elliot's procedure with two ridges placed close to the narrow wall of the SIW. This method caused the slot located on the center axis to radiate, hence improved the cross polarization level. In order to suppress the mutual coupling neighboring elements, SIW corrugations between subarray elements is recommended [17].

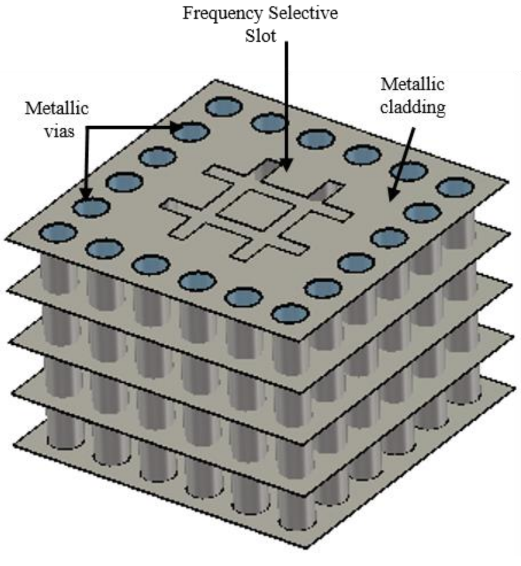

Figure 2: FSS using cascading SIW cavities [18]

The high-$Q$ property of SIW cavities significantly is improved with the use of Frequency Selective Surfaces (FSS) on its cavity as illustrated in Figure 2. The SIW-FSS takes the advantages of low insertion loss, hence high $Q$-factor is due to the closed cavity nature, as in the conventional FSS [18,19]. When the SIW cavities cascaded with FSS, the selective performance becomes more perfect; however, insertion loss and bandwidth are insensitive to number of cavities, incident angle and polarization states. The first dual-band FSS-SIW antenna was introduced in [20], where two orthogonal slots are etched on the broad side SIW, in which they are responsible for dual-band dual-polarization. Initially, a highly efficient microstrip array antenna was proposed, pertaining to Circular Polarization (CP) at $Ku$-band. Small microstrip subarrays are combined by SIW-like structure, and the author named it as 'Printed Circuit Board Waveguide' [3]. It also exploits the benefits of planar technology without any compensation of radiation efficiency. A sequence of SIW-based linearly polarized (LP) resonant series slot array antennas for $Ka$-band was proposed in [21-23]. The radiating slot for these antennas are slanted at an angle of 45$^{o}$, and separated by an approximately half of wavelength, in which it is able to generate alternating reactance slot pairs. Due to these alternating patterns of slots, the antenna achieved good impedance matching, uniform field excitation, and suppression of grating lobes simultaneously. A circularly polarized wave will be generated if two such slot arrays are symmetrically excited with 90$^{o}$ phase difference [24]. Also, SIW has the capability to solve the difficulty of integration between the array element and feed network [25]. In order to diminish the radiation loss over long distance communication, sequential-feeding network via-SIW for antenna array was suggested in [26]. The sequential-feed will minimize the radiation losses; hence, it shows a significant improvement in bandwidth in terms of CP gain and axial ratio (AR). Moreover, the SIW technology has the interesting feature of conformability. A SIW-slot array was investigated in [27] with low SSL. In this slot array, all components are conformal, including a one to eight divider, a phase compensated network and an 8×8 slot array.

### *Size miniaturization of SIW slot array antenna*

Although SIW antennas incorporates the features of both the rectangular waveguides and planar structures, its size is too large for many practical applications. Thus, different techniques have been suggested to achieve size reduction. A super compact Folded SIW (FSIW) antenna was developed and employed as feeding networks [28], but the FSIW or folded structure have multiple layers and complicated structure. Half mode SIW (HMSIW) transverse slot array antenna, which operates on the fundamental quasi-$TE_{0.5,0}$was designed in [29]; hence, the HMSIW array antenna is more compact since its size is reduced by half. Size miniaturization can also be achieved by coupling the higher modes and resonant modes in the cavity [30-32]. The mode cavity feeds all of the slot elements simultaneously, hence, it generates a broadside radiation beam resulting in increased radiation efficiency. Further, due to higher order modes, the amount of metallic posts used for the formation of the cavity is reduced, leading to a reduction in size as well realization cost. Many other techniques have been employed for the size reduction of SIW, such as HMSIW/QMSIW/eighth-mode SIW (EMSIW) [33], meandering the slot, composite right/left-handed (CRLH) SIW [34,35], and implementation of metamaterial structure [36]. The electric field of the different modes of SIW is illustrated in Figure 3.

In spite of the SIW miniaturization, the radiation performance is fairly good in the above examples, but the limited height of the substrate may cause distinct features such as low $Q$-factor of resonance generated by periodic elements due to the open structure.

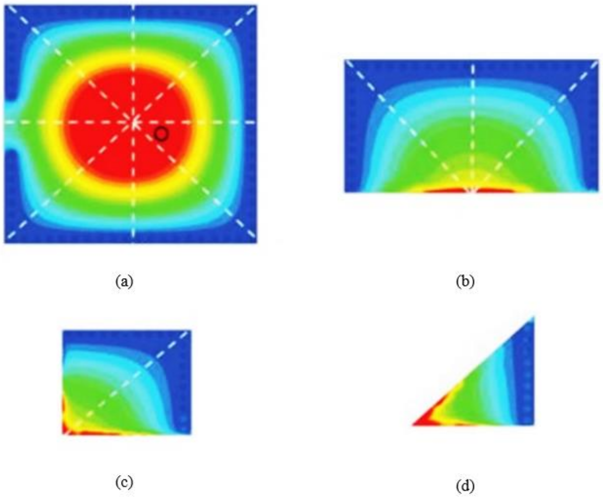

Figure 3: Electric field distribution of (a) full-mode SIW, (b) HMSIW, (c) QMSIW, (d) EMSIW [33]

## IV. SIW-Leaky Wave Antennas

Leaky Wave Antennas (LWA) uses travelling wave on the transmission line as a main radiating mechanism. Often, these antennas have waveguide like structures, which allow the leakage of energy to radiate. Unfortunately, SIW causes leakage losses because it can have an open structure and has non-continuous lateral walls, which is positively used in the designing of LWAs [37]. These are non-resonant type of antennas frequently used for wideband applications. In this section, SIW-based LWA is introduced. Based on the radiation leakage mechanism, they can be either uniform-type or periodic-type LWA.

### *A. SIW-Uniform LWA*

These kind of antennas radiate along the length of the guided structure uniformly and continuously [38]. Even though, the uniform and periodic antennas are similar, they possess different performances in terms of scan range, for example, uniform-type antenna can scan in forward quadrant only. Generally, uniform design of any slot array antenna suffers from high SLL and low gain, whereas asymmetry in structures will worsen cross polarization level. Hence, several strategies using SIW have been developed to overcome these problems, for example a uniform type long slot LWA was implemented with SIW in [39]. In order to optimize SLL, lateral walls of the SIW was meandered along the long straight slot while maintaining the distance between the walls constant; however, at the same its cross polarization level is affected. A new technique, ridged-SIW (RSIW) is suggested to alleviate the problem of cross polarization, which arises due to the offset slot from centerline of guiding structure [40]. It has longitudinal continuous asymmetric ridges beside the SIW lateral walls, which perturbs field distribution asymmetrically around the centered slot on the top cladding of the SIW structure. To improve SLL and cross polarization level, a longitudinally non-uniform, transversely uniform-like configuration consisting of sequence of wings like slotted SIW antennas has been designed [41,42].

### B. SIW-Periodic LWA

As SIW is consisted of densely arranged metallic posts, it has a very low radiation loss. However, leakage loss of SIW structures can be increased with the variation of the distance between metallic posts [37]. Radiation leakage can also be generated through periodic perturbation on top cladding of SIW, which will interrupt the current flow and may excite three kinds of modes simultaneously, which are (i) leaky wave mode, during which antenna will not radiate close to end fire, (ii) proper waveguide mode ($TE_{10}$) and (iii) surface wave like mode, where the antenna will radiate near the end fire [43]. SIW-feed is alternately adopted in the LWA to provide a wide broadside scan range [42].

Lately, a periodic-type CRLH-inspired dual band SIW-based LWA was proposed in [44]. It can be realized by periodically loading the series interdigital capacitors on the waveguide claddings. It has the capability to scan the radiated beam from the forward direction to the backward direction. In other examples, CRLH was loaded on guided structure to radiate orthogonal 45o LP waves [45], and CP [46]. In these designs, interdigital slots on the SIW are rotated by +45° /−45° with respect to the wave propagation direction with the phase difference of 90° to generate CP. The implementation of CRLH is also helpful for size reduction and performance improvement in terms of radiation gain and SSL [47].

For better cross polarization level, a periodic-slotted ridged SIW antenna array was suggested in [48,49]. This geometry is more dense and costly in comparison to similar conventional counterpart, but it possesses a relatively low cross polarization level due to symmetric slots with the centerline of the top plane. Additionally, compact size HMSIW-slot antennas which are capable of leaking a certain portion of power through the open aperture, were developed by many researchers [50-52]; thus, offering comparable performances to many SIW-based CRLH LWA [46,47].

## V. SIW-CAVITY BACKED ANTENNAS

SIW technology is widely adopted in modern Cavity Backed Antenna (CBA) designs. SIW-based CBA takes the benefits of classical metallic CBAs, such as high $Q$-factor due to closed structure and high power capability. In this session, SIW-CBA with different configuration, feeding mechanism, and techniques for enhancing bandwidth and gain, and size miniaturization are described.

All Microstrip antennas suffer from an inherent property of limited bandwidth; hence, they are not suitable for wideband applications. In such situation, conventional metallic CBAs are excellent candidates to address the limited bandwidth, although hand fabrication is a tedious process, as the configuration need assemblage of metallic cavities along backside. Consequently, SIW-CBA emerged as an alternate to conventional metallic cavity backed antenna for microwave and millimeter wave subsystems, was first presented in [53]. The backed- cavity can be realized by using arrays of metallic posts, embedded in a single layer or multilayer substrate. Generally, the conventional metallic CBAs have depth approximately equals to one quarter of the wavelength. In order to make SIW-CBA, there is a need to follow a condition, i.e. $d/s \geq 0.5$ and $d/\lambda_o \leq 0.1$, where $d$ is the diameter of metallic vias, $s$ is the space between the two neighboring vias and $\lambda_o$ is the free space wavelength [54].

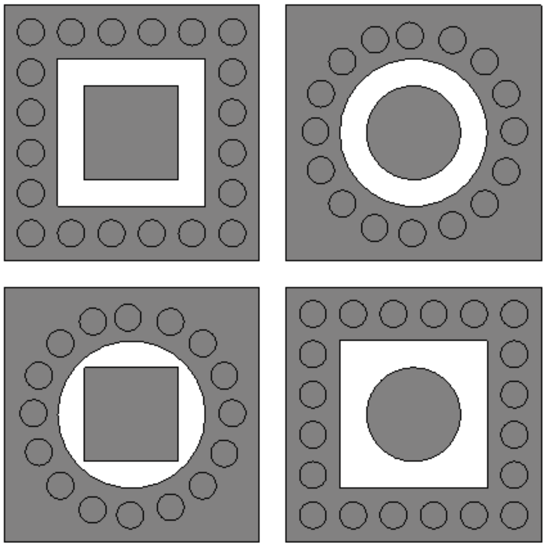

Figure 4: SIW cavity-backed microstrip antennas [55]

SIW CBAs were demonstrated on a single layer substrate in [56,57], where Grounded-CPW (GCPW) is used as feeding line to the cavity. It excites $TE_{120}$ and $TE_{210}$ mode, which generates dual polarization, linear and circular. Its radiation performance is similar to that of the conventional CBA. Further, a multilayered cavity backed array for CP and wideband characteristics was investigated in [58]. In this study, SIW cavities were rotated into elliptical shape, fed by a slot on the broad sidewall, in which it works as a radiating element of the CP antenna array.

### A. Bandwidth and Gain Improvement Techniques for SIW-CBA

CBAs exhibit narrow bandwidth as its size reduces. Many bandwidth enhancement methods have been suggested in the literature. In [62], a GCPW feeding was used for bandwidth enhancement. This feed excites two hybrid modes ($TE_{110}$ and $TE_{120}$ resonances) simultaneously and merges them within the required frequency range in the cavity. A broadband characteristics of SIW-CBA is also achieved by a bow-tie-shaped slot [63] and a dumbbell shaped slot [64] instead of using a conventional slot. Both antennas are excited by a

GCPW feeding technique that induces strong loading effect in the cavity and generates two hybrid modes leading to an enhanced bandwidth. Additionally, stacked SIW-CBA was suggested for high radiation and aperture efficiency [65,66].

Enhancement in bandwidth is achieved by dual-resonance in many examples. In [67], a via-hole near slot was employed to produce the other resonance, while in [68], SIW was used as a reflector and radiator for dual resonance. Multi-feeding networks like series and parallel feeds were preferred with suitable power divider for high gain and large bandwidth [59]. Lately, a linearly and circularly polarized antennas were designed which were coupled with HMSIW cavity. The proximity coupling causes improvement in the bandwidth and gain effectively [69]. Some other techniques for bandwidth enhancement, such as removal of the substrate underneath the radiating slot to decrease the capacitance of the slot [70] and coupling of two adjacent resonant frequencies [71] were also suggested.

### B. *Size Miniaturization of SIW CBA*

Standard techniques for size miniaturization, such as reducing the size of SIW-cavity and radiating slot have been investigated by many researchers. The backed cavity was miniaturized by folding the cavity using stacks of substrate [72] and twisting the opening from the end of the cavity to the radiating slot [34]. The meandered slot can act as a left-handed (LH) capacitor and vias constructing SIW act as LH inductors. For the first time, a wideband HMSIW cavity-backed slot antenna was designed with a cork substrate [73] in which compactness of nearly 50% was realized by the HM-SIW operation of a multi-moded cavity with non-resonant slot without deteriorating its performance. Later, a QMSIW-CBA was reported in [74]. It is a quadrant sector of a square SIW cavity, the physical parameters of the proposed antenna was reduced by 75% of that of counterpart SIW. Another type of SIW-CBA dual-band triangular-ring slot antennas was reported in [75] for the size reduction in which the lowest mode $TE_{110}$ was used to excite the triangular slot.

Thus, due to SIW, it is possible to realize the whole cavity-backed structures in planar form, which leads to substantial fabrication cost reduction. In addition, it prevents the propagation of surface wave, and decreases the power losses, hence improves the antenna efficiency.

## VI. SIW HORN ANTENNA

In this section, the planar version of the rectangular horn antennas developed by using SIW technology is introduced, including issues related to the matching of the horn flare with air.

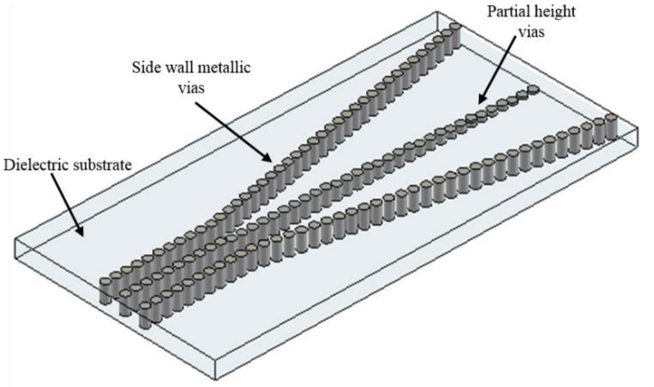

Figure 5: Typical RSIW-horn antenna

Horn antenna is a very popular endfire antenna for wide bandwidth. With increasing demand for compact wireless communication devices, integration of antenna along with the Microwave Integrated Circuits (MICs) becomes a challenging task. Concerning this, SIW-horn antenna was developed in [76], in which, an air filled horn is formed by using metallic vias/posts, which is fed by a CPW, which consequently leading to the integration of the horn antenna on a low cost PCB. Later, a SIW-based $H$-plane horn antenna was presented in [77]. In this antenna, two air slots on the portion of flare have been cut for better matching between the feedline and horn. As the design procedure of a SIW-horn antenna is similar to that of the conventional horn antenna, the performance also can be improved by a similar technique like placing a lens on the horn aperture, which can be either metallic or dielectric [7]. In the case of [78], a lens-like air-via perforated dielectric slab was loaded by extending dielectric substrate, which leads to bandwidth enhancement. In order to avoid the polarizing effect and diffraction, dielectric lenses are preferred than metallic lenses. Dielectric lens ridged-like geometries have also been generally implemented to increase the bandwidth of SIW $H$-plane horn antennas as well as improve antenna performances [79,80].

### A. *Matching Techniques for SIW-horn to Free Space*

A critical issue pertaining to the design of SIW-horn is mismatching of radiating edge with the air, which eventually affects the operational bandwidth. This problem occurs due to the abrupt transition from the waveguide horn to free space around ($377\Omega$).

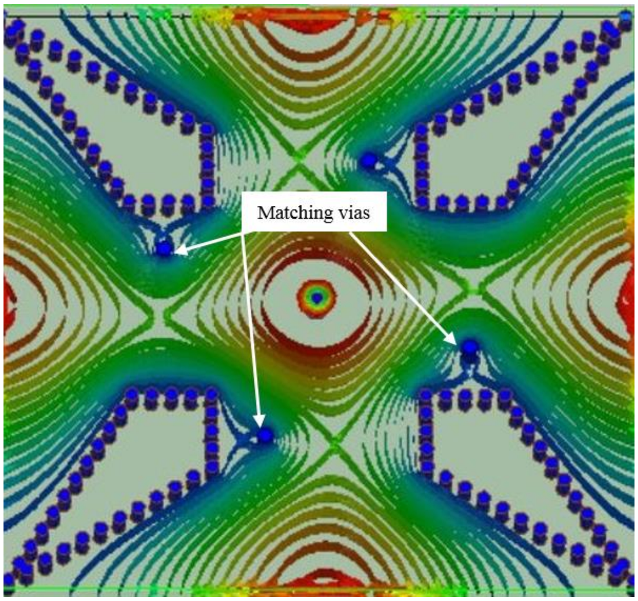

Figure 6: Field distributions in multi-horn antenna with matching vias [84]

To address this issue, the dielectric constant of the loaded dielectric slab is decreased by loading air-vias perforated dielectric wedge in the SIW horn aperture. This provides a gradual transition from the impedance of waveguide to that of free space. It acts like a progressive matching transformer [81,82]. It also enhances front to back ratio (FTBR) as well as reduces the phase error. However, the performance of this method is limited by the thickness of the dielectric substrate forming horn. Generally, SIW-antenna performances degrades considerably when the substrate thickness is much smaller than the free space wavelength $\lambda_0$ and mismatch occurs when dielectric thickness is less than one sixth of $\lambda_0$ [83]. The solution could be thick substrates, but it will be difficult to make it conformal. Also, for $h \geq 2.5$ mm, the fabrication of SIW becomes more challenging [84].

Many other approaches have been developed, such as placing metallized vias in front of the aperture, which in turn causes shunt reactance [85], metal-vias implanted inside the SIW-horn aperture, which can perform as a phase shifter to improve the aperture efficiency and impedance matching by adjustment of the positions of the metal-vias [86]. The antenna presented in [87] used three impedance matching methods, including the dielectric slab, air holes and ridge structure. Furthermore, for better matching and high efficiency, an empty SIW $H$-plane sectorial horn antenna filled with air was first investigated in [88]. It is composed of a partially empty or hollow space in between the multi layered substrate.

Table 1
Comparative results of Different SIW-born antennas

| Ref. | Operating Freq.(GHz) | No. of Elements | Polarization | X-Pol. (dB) | Peak Gain (dBi) | Substrate/ Dielectric Constant | Effi. (%) |
|---|---|---|---|---|---|---|---|
| [3] | 11.5-13.5 | 2×16 | LP/CP | - | 23.0 | FR4 | 63 |
| [13] | 9.65–10.11 | 8×8 | LP | >25 | 20.30 | 2.2 | - |
| [17] | 56.5-66 | 2×2 | LP | - | -- | Rogers 5880 | 83 |
| [21] | 34.07-35.1 | Single | LP | 15.66 | 15.64 | Rogers RO3035 | 72.4 |
| [24] | 10.8-11.8 | 8×16 | CP | - | 17.13 | Rogers 5880 | 80 |
| [26] | 8-8.5 | 2×4 | CP | 15 | 14.6 | RT/Duroid 5880 | -- |
| [27] | 34.2-35.8 | 8×8 | LP | >41 | 13.0 | Rogers 5880 | 60 |
| [46] | 4.2 -4.85 | Single | CP | 15 | - | RT/Duroid 6010 | - |
| [50] | 8.4- 11.6 | Single | LP | - | 10.0 | Rogers RO3210 | 77 |
| [58] | 22-24 | 4×4 | CP | > 30 | 17.9 | 2.2 | - |
| [61] | 20.2-21.6 | 4×4 | LP | - | 17.8 | Rogers 5880 | - |
| [63] | 14.7-10.52 | Single | LP | >20 | 4.0 | Rogers 5880 | 95 |
| [65] | 9.45–10.54 | 2×2 | LP | 20 | 13.2 | Rogers 5880 | 67 |
| [66] | 12.6-13.6 | 2×2 | LP | >20 | 13.5 | Rogers 5880 | 70 |
| [68] | 57–64 | 2×4 | LP | >25 | 12.0 | RO3006 | -- |
| [69] | 7.49-8.36 | single | LP/CP | >22 | 7.50 | TLY031 | 90 |
| [71] | 12.8-12.8 | 8×8 | LP | >23 | 24.0 | Rogers 5880 | 50 |
| [75] | 15.55-16.50 | 1×8 | LP/CP | >17 | 6.15 | Rogers 5880 | - |
| [80] | 22-40 | Single | LP | - | 10.0 | 2.2 | 97 |
| [83] | 26.80-27.25 | Single | LP | 20 | 9.1 | 4.8 | - |
| [90] | 9.35-10.05 | 1×4 | LP | - | 13.0 | 2.2 | - |
| [93] | 9.76–10 | Single | CP | - | 12.3 | Rogers4003 | 69 |
| [96] | 27-30 | 7×9 | LP | - | 18.5 | Rogers5880 | 19.8, 54 |
| [97] | 25.5-27.5 | 2×2 | LP | >17 | 8.6 | Rohacell31, ULTRALAM | 70 |
| [100] | 27.06–36 | Single | LP | >20 | 16.87 | Rogers Duroid 3003 | 96.80 |

## VII. SIW-BASED MONOPULSE ANTENNA

Monopulse antenna is a well-established technique, for precision angle estimation, and it is usually employed in rapid direction finding systems, such as radars [89]. The conventional antenna systems, such as cassegrain and parabolic or lens antenna are commonly applied in the monopulse, although they are complicated and heavy, which make them difficult to handle. Compact size and good antenna performances are desirable for monopulse networks; thus, planar microstrip monopulse antennas are alternatively adopted. However, they are not suitable because the feeding mechanism causes radiation losses, especially at millimeter wave frequency band and when high power transmission is desired. To eliminate these drawbacks, the SIW technique is implemented for the development of monopulse antennas in the recent years. The first SIW monopulse Yagi antenna was demonstrated in [90]. It owns high gain, wide bandwidth, light weight and compact structure. Later, single layered, complete SIW-based monopulse slot antenna arrays without any microstrip-like structures were demonstrated for $Ka$-band tracking system [91] and $W$-band [92] applications. These antennas are considerably larger than the radiating aperture due to their simplified SIW feed. Here, the corresponding aperture efficiency is smaller compared to the conventional waveguide-based structure.

Subsequently, SIW circular polarization dual-mode monopulse CBAs were proposed in [93]. These antennas consist of two CP cavity-backed SIW array, a dual-mode section, and two input ports. $TE_{10}$ and $TE_{20}$ modes were excited in the dual-mode hybrid to yield the sum and difference patterns. The pairs of sum or difference beam were generated due to even or odd mode excitation by a dual-mode coupler. Such antennas are more efficient at the cost of using two layers of substrate. In [94], SIW technology was implemented in a millimeter-wave filtering monopulse antenna array. This consists of vertically stacked SIW cavities that are an assembly of a filter, a monopulse comparator, a feed network, and four antennas. Such antenna arrays are suitable for practical integrated design of millimeter-wave subsystems.

## VIII. SIW BEAM FORMING ANTENNAS

SIW technology are used significantly in the realization of Beam Forming Network (BFN) antennas. Usually, the BFNs need compact size antennas; thus, there is a trade-off in obtaining compact size and good aperture efficiency. Recent progress of emerging SIW technology in the applications of BFNs antennas have been introduced, including the modified R-KR, Rotman lens, and $2D$-steering antenna.

SIW multibeam antennas based on the mechanism of R-KR lens [95] and Rotman lens [96] were studied and arrays of SIW-BFN based on the principle of lens were developed with multi-input ports. They present very promising characteristics that can be realized without complicating the conventional feeding structures. They are capable to generate a number of beams for large scanning angle. Further, the concept of SIW technology is highly efficient to $2D$ steering antenna systems, including high integration profile and cost-effective designs [97]. A miniaturized CPW center-fed SIW slot-array antenna was recommended in [98] for relatively smaller lower SLLs. Later, a high gain SIW based antenna array was proposed in [99], exhibiting CP for BFNs. By introducing a couple of radiating slots and shorting metallic via-brick into the SIW cavity, two orthogonal modes having almost the same cutoff frequency ( $TE_{120}$-like and $TE_{210}$-like modes) are excited by a single GCPW line to produce a CP radiation. In [100], SIW array antenna was designed with continuous transverse stubs (CTS). These CTS are periodically arranged on top of the SIW and are perpendicular to the wave propagation direction to generate radiation efficiently. The size of the stub and the distance between them are the controlling parameters for impedance matching, high radiation power, and beam steering capability.

As SIW does not demonstrate surface wave loss, it avoids the undesired beam squinting with frequency. Still, conductor and dielectric losses will cause significant power loss inside SIW-BFNs.

## IX. OTHER SIW-BORN ANTENNAS

Many other types of SIW-born antennas have been reported with improved performance, such as an active type reconfigurable antenna, antenna oscillator, tunable antennas, wearable textile antennas and SIW with DRA etc.

A reconfigurable SIW antenna was reported in [101]. The antenna is based on the multimode characteristic of SIW cavity which operates in dual band and radiates in LP/CP depending on the tuning of crossed slot by means of variation in the bias magnetic field due to ferrite slab loading. SIW based Dielectric Resonator Antennas (DRA) have been implemented for efficient radiation at high frequency in [102]. Since the SIW is a high-quality structure and the dielectric resonator antenna is a low loss radiator, they exhibit less conductor loss, high radiation efficiency, and larger bandwidth than microstrip patch antennas. A novel and low cost wearable SIW antenna fabricated entirely from textile materials was proposed in [103]. This exhibits robustness against flexibility, low influence of the human body and high FTBR. SIW based 340 GHz and 140 GHz on-chip antenna demonstrating high gain and high aperture efficiency were investigated in [105] and [105]. It was concluded that the SIW cavity is helpful to defend the surface waves and separate the radiation aperture from the low-resistivity substrate.

## X. CONCLUSION AND FUTURE SCOPE

Recent advances of antennas and array structures based on Substrate Integrated Waveguide (SIW) technology presented in published papers have been reviewed and described. Issues related to the design and modelling, and the different scientific explanations proposed for the application of SIW in modern antennas and arrays have been addressed. From the available literature, it is observed that most of the conventional rectangular waveguide fed antenna and array structure can be developed by SIW technology. Yet, most of them operate at higher frequency. The implementation of SIW in arrays and antenna structure in the lower range of frequency comes across a lot of technological difficulties like miniaturized dimensions, losses, precise manufacturing of SIW structures, fabrication limitations and selection of proper substrate, etc. It seems that SIW-based antennas and arrays in the modern wireless system open new possibilities for the development of highly compact and integrated systems.

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