

Chapter 2

Analysis of Substrate Integrated Waveguide (SIW) Antennas and Systems

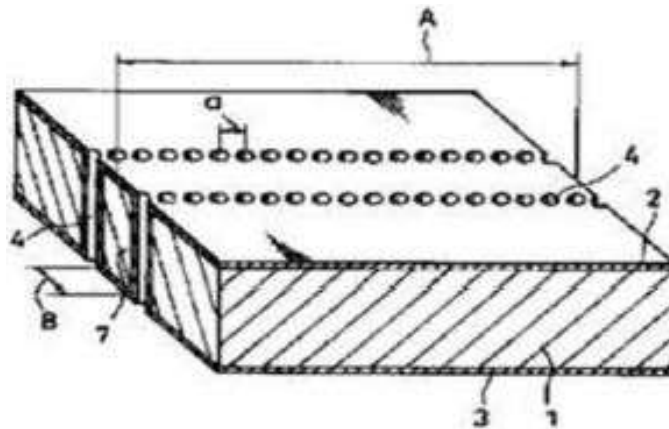
This chapter provides an introduction to Substrate Integrated Waveguide technology, as well as its working principles and design considerations. The SIW is a planar implementation of the conventional metallic waveguide structure. It inherits many characteristics of non planar waveguides. Planar antennas (such as slot or patch antennas) have a low profile, are lightweight, and are inexpensive. These antennas can be readily combined with other RF components on a printed circuit board (PCB), such as amplifiers, filters, and switches, to create a transceiver. Therefore, planar antennas are chosen in a variety of applications, including aeroplanes, spacecraft, satellites, and cellular phones, to mention a few. As a result, our dedication in this thesis was to designing compact SIW cavity-backed slot antennas. The literature includes discussions on SIW based cavity-backed wideband slot antennas, SIW based self-diplexing/self-triplexing antennas, and finally, SIW based MIMO antennas. All these different topics contribute to a better understanding of the research work described in this thesis.

2.1 Substrate Integrated Waveguide (SIW)

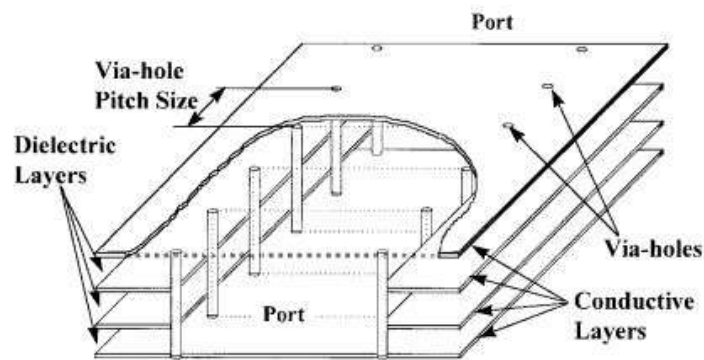
The substrate integrated waveguide (SIW) technology, which implements waveguide-based circuits in widely accessible planar substrates, has recently been proposed as a potential candidate for high frequency microwave and millimetre wave applications. The planar waveguide transmission line was earlier reported in a Japanese patent titled “Waveguide Line.” [20]. Later, Uchimura *et al.* published a comparable transmission line for millimeter-wave applications termed “Laminated Waveguide” [21]. Hirokawa *et al.* have presented important research on “Post Wall Waveguide,” which employs a planar structure with metallic holes to construct parallel plate waveguide-based circuits for millimetre wave wireless LAN (59–60 GHz) and vehicle collision avoidance radar (76.5–77.5 GHz) applications [22]. Fig.2.1 depicts the three primary structures.

The SIW idea was initially presented in [23], and has since spawned a wide variety of planar and non-planar circuits integrated into a single or many substrate layers. The most significant aspect of this technology is the ability to combine all components, including passive components (filters, couplers, etc.), active elements (oscillators, amplifiers, etc.), and antennas [24–27]. Moreover, [27] presents a comprehensive overview of the potential applications of this technology. Wu *et al.* [28] employed the use of periodic holes to create waveguide-based circuits in rectangular waveguide-based circuits on a planar substrate. Using this technique, known as substrate integrated circuits (SIC), the rectangular waveguide and comparable devices may be constructed directly on a planar substrate. Among these substrate integrated circuit families, the SIW is the most preferred choice for realising microwave and millimeter wave circuits in planar form.

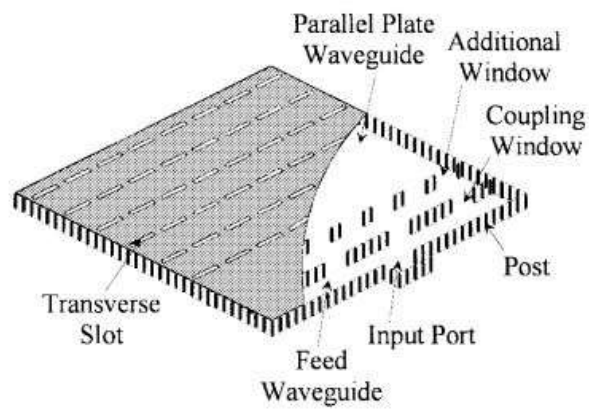
The top and bottom metallizations of the substrate serve as the top and bottom horizontal walls of the waveguide in SIW technology, while the vertical walls are created by drilling and metallizing vias through the substrate. Fig.2.2 shows a depiction of a SIW. A simple SIW antenna structure comprises of atleast one radiating element as a



(a) [20]



(b) [21]



(c) Postwall Waveguide [22]

Figure 2.1: (a) Waveguide Line (Japan Patent), (b) Laminated Waveguide , (c) Post-wall Waveguide.

first metal layer, a ground plane as a second metal layer, a dielectric substrate material positioned between these metallic layers and an electric wall arrangement. This electric wall arrangement consists of two (or more) rows of vias drilled inside the substrate and then filled with metal parallel to each other which resembles the waveguide arrangement. These waveguides can retain most of the well-known benefits of traditional rectangular metallic waveguides while also maintaining the benefits of microstrip lines, such as low profile, small volume, and light weight. As a result, by employing basic processing techniques such as PCB or Low-Temperature Co-fired Ceramic (LTCC), conventional waveguide devices may be built in a planar form at a low cost. The SIW technology also

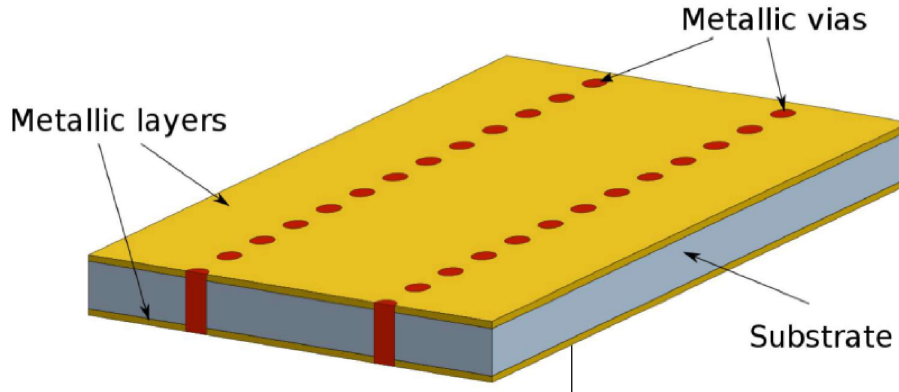


Figure 2.2: Physical structure of SIW.

provides the advantages of high quality factor(Q), good electromagnetic shielding, low loss, easy integration to planar circuits, easy fabrication process using PCB technology. However, to realise a low-loss, compact SIW transmission line, several factors need to be considered, e.g., SIW operation, cut off frequency, radiation loss, electromagnetic bandgap effect, over perforation, etc., which are described below in detail.

2.1.1 Operation Mechanism and modes in SIW

The SIW employs the same operating principle as the conventional rectangular waveguide; hence, all rectangular waveguide theory can be transferred to SIW technology

with a minimal variation. The shielded structure of the SIW helps to reduce radiation loss and surface wave loss, which makes it more advantageous than the microstrip technology for use in high-frequency microwave and millimeter-wave circuits. But switching from planar technology to SIW is easier than switching to nonplanar waveguide technology. This makes SIW a popular choice for implementing low-profile microwave circuits. SIW and conventional air-filled waveguides have equivalent properties since both tech-

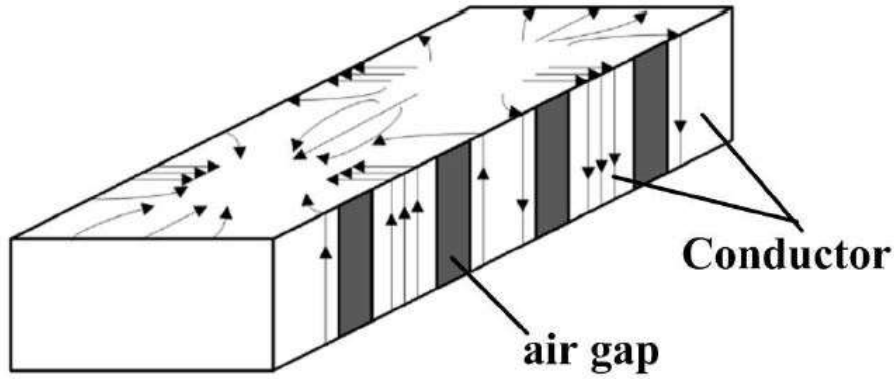
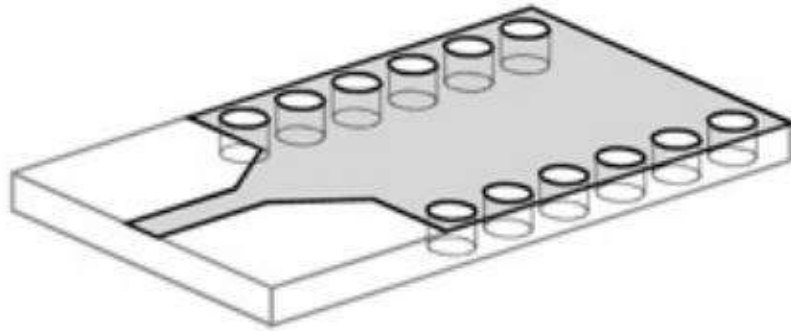


Figure 2.3: Surface current distribution of TE_{10} mode in equivalent rectangular waveguide model of SIW with slots in narrow wall.

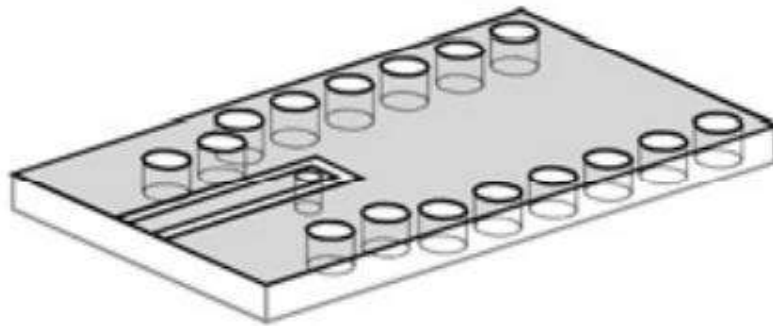
nologies support TE_{i0} modes, including the dominant TE_{10} mode, where the sub-index i refers to the direction parallel to the substrate plane. In contrast to conventional air-filled waveguides, which can support TM and TE_{ij} ($j \neq 0$) modes, the substrate-integrated waveguide cannot sustain these modes due to discontinuities in the side walls. As shown in the Fig.2.3, the surface current distribution of the dominant TE_{10} mode is parallel to the narrow slots in the sidewall, and hence the discontinuity in the sidewall does not disturb the propagation of the corresponding mode. As a result, [29] demonstrate that the SIW structure can support the TE_{10} mode. Using the same analogy, it was deduced that for any TE_{ij} ($j \neq 0$) or TE_{ij} mode, there exists a component of surface current in the direction perpendicular to the narrow slots. The presence of slots disturbs the current path, and as a result, a large amount of radiation may occur. Hence, these modes will not be supported in the SIW structure.

2.1.2 SIW Transition

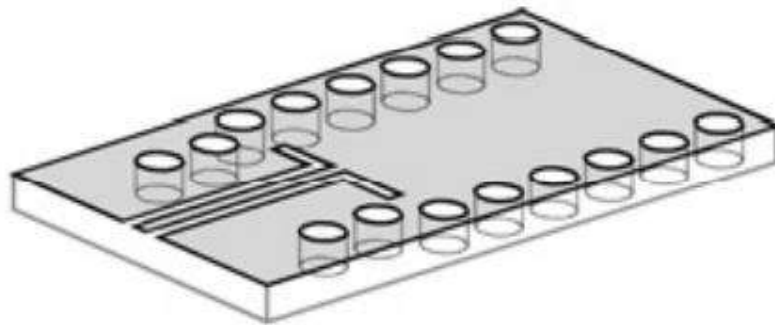
Because SIW components are always interconnected with other circuit components inside a system, it is essential to address device connections. An important part of SIW device design [27] is making the switch between planar transmission line technologies like microstrips and the SIW structure. Several articles have reported SIW components with various forms of input/output (i/o) connections. [30,31] described a microstrip to substrate-integrated waveguide transition built on a simple tapering. A 50W microstrip signal line is connected to a substrate-integrated waveguide through the tapered section. By converting the quasi-TEM mode of the microstrip technology to the TE_{10} mode of the SIW, the tapering is utilised. Coplanar waveguides (CPWs) have also played a significant part in this field of study. The conversion of a coplanar waveguide to a SIW using a ninety-degree bend is described in [31]. Another research study [32] described a type of conversion utilising a grounded CPW and SIW mounted on a current probe. The flow of current across the probe generates a magnetic field corresponding to the magnetic field within the SIW. Also proposed in [22,33] is a transition between the conventional rectangular waveguide structure and the SIW structure. Multiple-layered substrate microstrip-to-SIW conversions have been studied and reported [34]. [35] Nwajana *et.al.* presented a novel microstrip-CPW-SIW transition. The novel transition approach takes advantage of the step impedance on a 50W microstrip signal channel to the small impedance Grounded Coplanar Waveguide (GCPW), and then links to the SIW component through the short small impedance grounded coplanar waveguide signal path. The conversion approach is useful because it enables double flexibility in regulating i/o couplings; thus, the external quality factor may be modified by adjusting both the stepped impedance of the CPW and the size of the coplanar waveguide signal route. Fig.2.4 shows some of the most common ways that SIW components make use of transitions.



(a) Microstrip-to-SIW transition [27]



(b) CPW-to-SIW transition [27]



(c) CPW-to-SIW transition based on ninety-degree bend [27]

Figure 2.4: Some common SIW transitions

2.1.3 Loss Mechanism in SIW

The losses in SIW transmission line occurs due to three major reasons i.e. conductor loss, dielectric loss and radiation loss [36].

- (i) **Conductor Losses:** This includes the losses due to finite conductivity of the metallic parts such as vias, ground plane and radiating patch. The attenuation constant α_{ohmic} due to the conductor loss in the SIW can be given by [36]

As evident from equation (2.1), the conductor loss can be minimized by taking thick substrates with low permittivity, being $\alpha_{ohmic} \propto \frac{1}{h}$ and $\propto \epsilon_r$. But such substrates severely affect the impedance bandwidth of the antenna as it $B.W. \propto h$ and $B.W. \propto \frac{1}{\epsilon_r^2}$. So, there exists a tradeoff between the ohmic losses and impedance bandwidth of the antenna.

$$\alpha_{ohmic}(f) = \frac{1}{h} \sqrt{\frac{\pi f \epsilon_r \epsilon_o}{\sigma}} \frac{1 + 2(f_o/f)^2 h/W_{eff}}{\sqrt{1 - (f_o/f)^2}} \quad (2.1)$$

- (ii) **Dielectric Losses:** The dielectric loss is related to the loss tangent $\tan\delta$ which is derived from the rectangular waveguide can be expressed as [36]

$$\alpha_{diel}(f) = \frac{\pi f}{c} \cdot \sqrt{\frac{\epsilon_r}{1 - (f_o/f)^2}} \cdot \tan\delta \quad (2.2)$$

It is evident from equation (2.2) that α_{diel} is independent of substrate height h .

- (iii) **Radiation Losses:** The formulae for ohmic and dielectric losses can be derived from the rectangular waveguides by replacing its physical width with the effective width of the SIW cavity. Radiation losses occurs due to the leakage of energy through the vias. Since no such loss is present in rectangular waveguide, hence a new approach discussed in [37] has been developed for deriving the calculation of the radiation loss which is given by

$$\alpha_{rad} = \frac{\frac{1}{W_{SIW}} \left(\frac{d_{via}}{W_{SIW}} \right)^{2.84} \left(\frac{p_{via}}{d_{via}} - 1 \right)^{6.28}}{4.85 \sqrt{\left(\frac{2W_{SIW}}{\lambda} \right)^2 - 1}} \text{dB/m} \quad (2.3)$$

where λ is the operating wavelength in the substrate. All the above discussed losses in the SIW cavity are varied and their variation with frequency is shown in Fig.2.5.

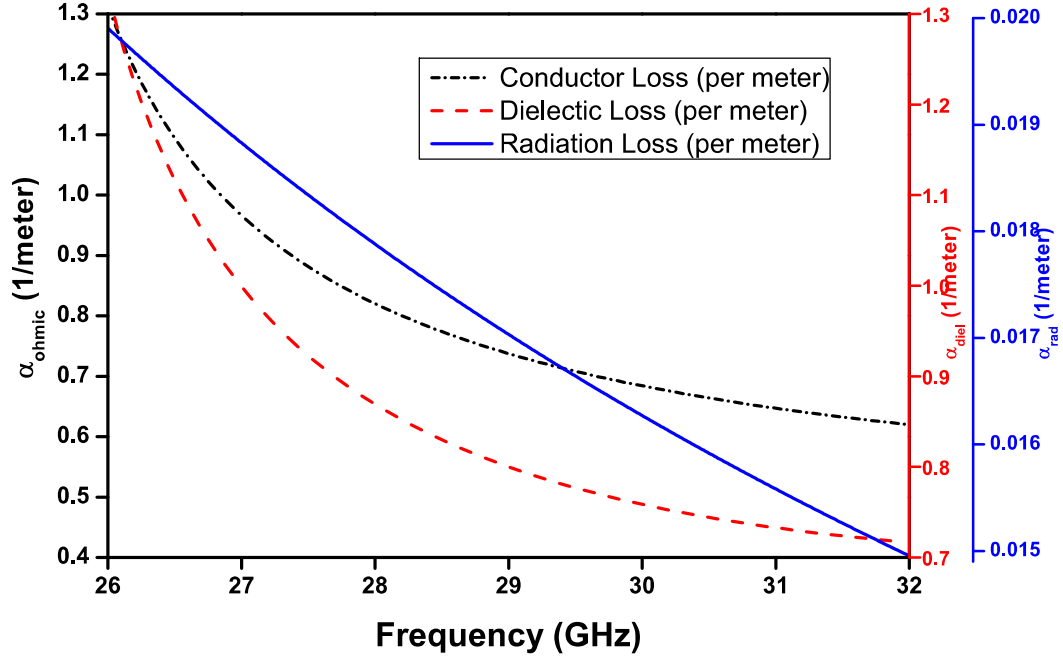


Figure 2.5: Variation in attenuation constant α_{ohmic} , α_{diel} and α_{rad} with frequency.

An useful relation to maintain minimum leakage loss is stated in [38] as below:

$$d < \frac{\lambda_g}{5}$$

$$s \leq 2d$$

2.1.4 Bandgap Effect

Periodic metallic vias in a SIW system provide electromagnetic bandgap or stopband phenomena [39]. It must be guaranteed that the stop band of the SIW occurs above

the frequency range of interest for SIW structures to operate well. For single mode operation of SIW with dominant mode TE_{10} , the stop band must be centred at the upper end of the working band, or above the cut-o frequency of TE_{20} mode ($k_0 = 2k_c$). Equation (2.4) states the requirement for bandgap phenomena.

$$\beta_z s = n\pi (n = 1, 2, ..) \quad (2.4)$$

where the first bandgap appears for $n = 1$.

Now, considering small leakage loss for TE_{20} mode,

$$\beta_z = \sqrt{k_0^2 - k_c^2} = \sqrt{4k_c^2 - k_c^2} = 2\pi\sqrt{3}/\lambda_c \quad (2.5)$$

Now, comparing equation (2.4) and (2.5), the maximum allowable pitch (s) to keep the bandstop effect above highest end of operating frequency range i. e. above $f_{cTE_{20}}$ is stated as

$$\frac{s}{\lambda_c} = \frac{1}{2\sqrt{3}} \quad (2.6)$$

However, as stated in [39], a more restrictive condition ($s/\lambda_c < 0.25$) is generally used to avoid any bandgap effect in the operating frequency range.

2.1.5 SIW design rules

As discussed in 2.1.1, Only TE_{m0} modes are supported in a SIW with via sidewalls due to the discontinuity in the sidewall of the SIW structure. [21] shows that connecting the metalized vias with a conductive material is necessary to keep the surface currents needed for TM and TE_{mn} , where $n \neq 0$, modes to spread. The TE_{10} mode is the dominating propagating mode in SIW structures, which is equivalent to the dominant mode in conventional rectangular waveguides (RWG). According to conventional waveguide theory, the cutoff frequency of a SIW structure is linked to its width in the same manner as it is for a conventional RWG. However, unlike the conventional waveguide structure,

the cut off frequency of SIW is also a function of diameter (d) and pitch (s) of the line.

In [40], the relationship between cutoff frequency and SIW dimensions is determined using least square curve fitting, as illustrated in equation (2.7).

$$f_{c(T E_{10})} = \frac{c}{2\sqrt{\epsilon_r}} \left(W - \frac{d^2}{0.95s} \right)^{-1} \quad (2.7)$$

where c is the speed of light in free space. However, the above approximate formula is valid for $s < \lambda_0\sqrt{\epsilon_r}/2$ and $s < 4d$. By comparing the aforementioned equation with traditional waveguide theory, an equivalent rectangular waveguide of SIW structure is derived in [40], where both SIW and the equivalent rectangular waveguide exhibit similar dispersion properties. The relation between SIW and equivalent waveguide dimension is as follows:

$$W_{eff} = W - \frac{d^2}{0.95s} \quad (2.8)$$

where W_{eff} is width of the equivalent rectangle waveguide. Equation (2.8) is refined by including $\frac{d}{W}$ ratio because this relation becomes invalid for larger value of diameter. However, a more accurate relation between SIW and equivalent waveguide is proposed in [29] as shown in equation (2.9). This relation is valid for $p/d < 3$ and $d/W < 0.5$.

$$W_{eff} = W - 1.08\frac{d^2}{s} + 0.1\frac{d^2}{W} \quad (2.9)$$

Therefore by using equations (2.8) or (2.9), the SIW structure can be directly converted to equivalent rectangular waveguide and hence all the conventional theory of the metallic waveguide can be directly implemented in SIW structure using the equivalent waveguide model. To reduce the amount of leakage and radiation losses, the following design

criteria need to be taken into consideration [39]:

$$s > d \quad (2.10a)$$

$$\frac{s}{\lambda_c} < 0.25 \quad (2.10b)$$

$$d < \frac{\lambda_g}{5} \quad \& \quad s \leq 2d \quad (2.10c)$$

$$\frac{s}{\lambda_c} > 0.05 \quad (2.10d)$$

$$\frac{l}{k_o} < 1 \times 10^{-4} \quad (2.10e)$$

where s is the gap between the two adjacent vias, d is the diameter of via, λ_c is the cutoff wavelength, l is the total loss and is the wave number in vacuum. The criterion in equation (2.10a) means that the diameter of the via (d) must be smaller than the distance between two consecutive vias (p) for the SIW structure to be realistically designable. The condition equation (2.10b) is followed to avoid any bandgap effect in the operating frequency band. Also to maintain minimum leakage loss, equation (2.10c) and equation (2.10e) should be followed. Finally, equation (2.10d) is defined to avoid over perforation which ensures that the number of holes does not exceed 20 per wavelength so that the mechanical rigidity of the substrate is not affected.

2.1.6 Design of SIW Rectangular Cavity

On a planar substrate, the SIW technique can also be used to create a metallic cavity resonator. The SIW cavity utilises four rows of metallic vias to create four sidewalls that

contribute to the cavity's metallic enclosure. However, similar to the SIW structure, the resonance frequency of the SIW cavity depends not only on the length and width of the cavity but also on the diameter and spacing of the metallic via rows of the SIW cavity. Equation (2.11). gives a design formula for the resonant frequency (f_{mn0}) of the TE_{mn0} mode.

$$f_{mn0} = \frac{c}{2\sqrt{\epsilon_r}} \sqrt{\left(\frac{m}{L_{eff}}\right)^2 + \left(\frac{n}{W_{eff}}\right)^2} \quad (2.11a)$$

$$L_{eff} = L - \frac{d^2}{0.95s} \quad (2.11b)$$

$$W_{eff} = W - \frac{d^2}{0.95s} \quad (2.11c)$$

where $m = 1, 2, \dots$ and $n = 1, 2, \dots$ are mode indices along the SIW cavity's length (L) and width (W). The effective length and width of the equivalent rectangular waveguide cavity corresponding to the SIW cavity are given by L_{eff} and W_{eff} . The SIW cavity has a relatively low height ($h \ll \lambda_g$). As a result, there is no change in the field along the height of the SIW cavity.

A brief overview of the design criteria of substrate integrated waveguide (SIW) is presented in this section. The effects of the SIW dimension on the performance of the design, such as cut off frequency, leakage loss, bandgap effect, etc., are discussed in detail. This section also includes the design equation for determining resonant frequencies of the SIW cavity modes for a given cavity dimensions. The goal of this research work is to study, design, implement, and analyse the wideband antennas, multiplexing antennas, and their MIMO counterparts capable of supporting modern wireless communication devices. In order to outline the scope of the thesis, we will now review some important literature on SIW antennas in the next section. Fig 2.6 presents the

overview of the literature survey, which is done on the basis of different techniques.

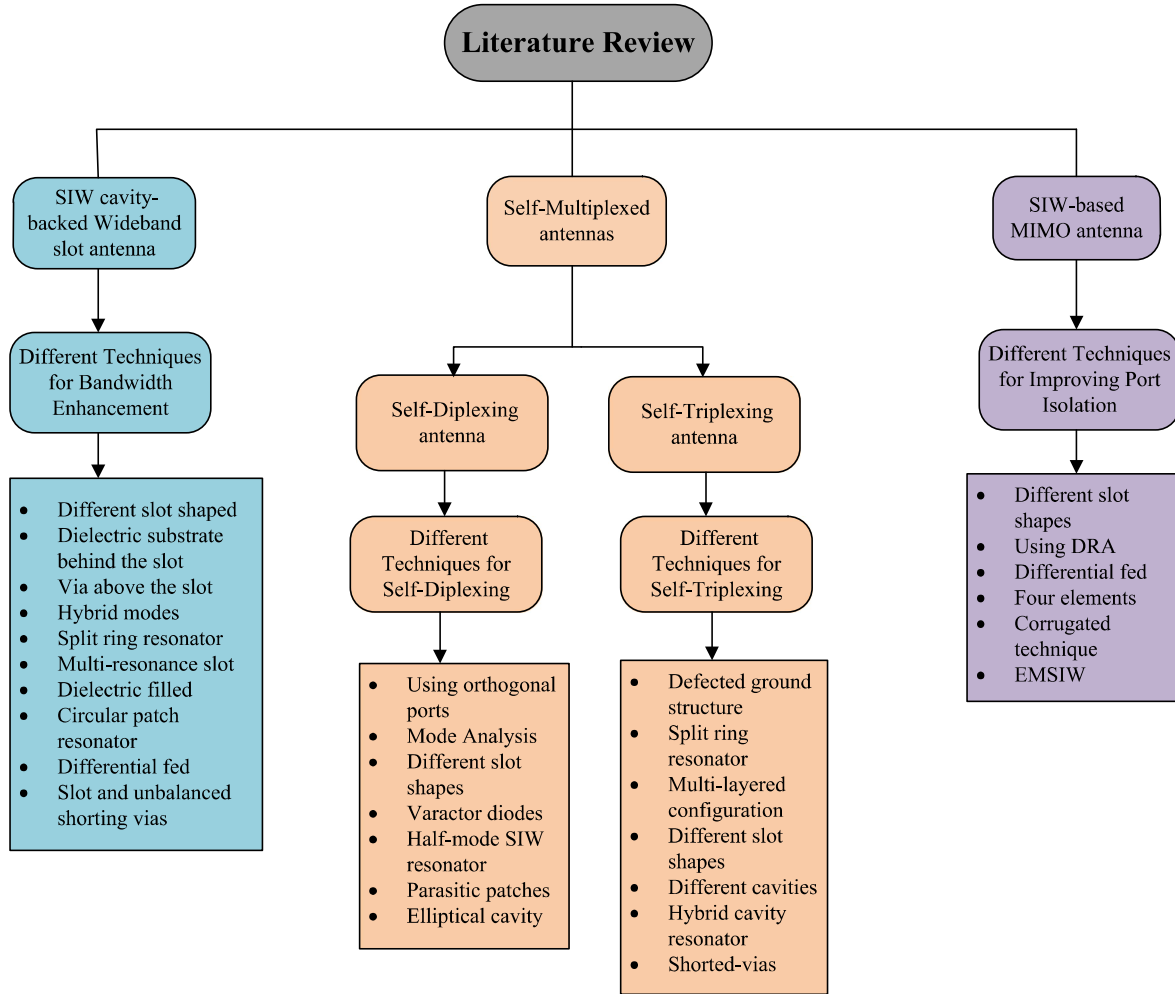


Figure 2.6: A tree diagram of literature.

2.2 Review of SIW Cavity-Backed Wideband Slot Antennas (SIW CBWSA)

The primary function of a cavity supporting a patch antenna is to efficiently restrict the propagation of parasitic surface waves, thus confining the energy beneath the patch. However, the use of SIW cavities instead of solid wall ones can cause some leakage and reduce the effectiveness of surface wave suppression. The SIW cavity-backed slot antenna is one of the most extensively used SIW technology antennas, in which a

planar slot antenna is supported by a SIW cavity to produce a unidirectional radiation pattern [41]. The design is a planar implementation of a nonplanar metallic cavity backed slot antenna. In a planar substrate, the slot antenna is placed in the middle of the SIW cavity. The cavity is fed by a $50\ \Omega$ microstrip line that excites the TE_{120} mode. The slot on the upper surface of the cavity disrupts the surface current distribution of the TE_{120} mode, causing it to radiate into free space. Several novel designs have been proposed in recent years to generate high gain radiation from SIW cavity-backed slot antennas. In [42], a meandered slot is used to get excited by the SIW cavity TE_{110} mode, which helps to reduce the overall size of the design while maintaining good performance. A design of a SIW cavity-backed crossed slot antenna for wideband dual polarization application is presented in [43]. However, the design used a complex feeding network to achieve a wideband response.

The Q of the SIW cavity is higher (~ 500). As a result, the high Q of the SIW cavity limits the bandwidth performance of SIW CBWSA ($\sim 2\%$). Hence a lot of research to enhance the bandwidth performance of the SIW CBWSA is carried out in recent years. In [44], a technique is presented by S. Nam *et.al.* where the dielectric substrate behind the slot is removed to modify the Q of the SIW cavity which helps to improve the bandwidth performance of the antenna. Another technique to improve the bandwidth of the SIW CBSA was reported in [45] where an additional via above the slot excites additional resonance in the design which helps to enhance the bandwidth performance. An efficient technique to enhance the bandwidth performance of the SIW CBWSA was reported in [46] where a pair of hybrid cavity modes are excited which creates two resonances of the antenna. The proposed antenna combine these two resonances to exhibit an improved bandwidth performance (6.4%) with high gain. There are numerous papers published within the time period of 1990s and 2000s to enhance the bandwidth of the SIW slot antennas. The (SIW) cavity-backed E-shaped patch antenna is reported in [47], to achieve a bandwidth of 10.9% with low profile and high gain. The other

E-shaped patch antenna is explored in [48] where a co-planar waveguide (CPW) is used to feed the proposed antenna with a metallized via for generating an additional resonant mode. The low profile configuration of proposed antenna makes it a promising candidate for meeting both the short- and long-rang communication requirements of the emerging Q-LINKPAN wireless system. A Triangular-Complimentary-Split-Ring-Slot (TCSRS) Antenna is presented in [49], which shows a impedance bandwidth of 16.67% and 22.2% at 28 GHz and 38 GHz, respectively. In [50], a modified triangular-ring-slot for broadband applications is proposed. The proposed antenna excites two hybrid-modes between TE_{110} and TE_{120} cavity modes. By proper tuning of these hybrid-modes in the desired frequency range, an improvement of impedance bandwidth was achieved. L.Wen *et.al.* [51] proposed a ring slot antenna, where the slot mode and the TE_{210} mode of the SIW cavity are excited by a TE_{20} mode SIW transmission line to realize IBW of 25.89%. The proposed structure makes it suitable for 5G applications. With the help of multi-resonance slots for **Ku**-band application is reported in [52]. An octa-star shaped slot, which displays a impedance bandwidth of 16.35% is presented in [53] for wireless transmission. A broadband cavity-backed slot antenna by combining the dumbbell-shaped slot and the high-order modes in the SIW cavity is presented in [54]. The high-order modes (TE_{102} , TE_{301} , and TE_{302}) are excited by the interaction of the slot and the feeding structure, and the broadband impedance bandwidth is produced by bringing the high-order modes close together. In 2021, again a dumbell shaped slot is introduced in [55] to obtain a wideband response by marging the slot mode and SIW cavity mode. A design of novel wideband planar SIW antenna is implemented in [56] where the modification of slot helps to introduce two hybrid modes which come close to each other. These hybrid modes serve to widen the fractional bandwidth upto 17.36%. The low profile configuration of the proposed antenna makes it suitable for **X**-band applications. In [57], a different technique from other cavity-backed patch antennas is investigated by T. Yang *et.al.*. To improve the bandwindth and radition efficiency, a

resonant dielectric-filled backed cavity is designed to resonate at its TE_{210} mode for millimeter wave (mmW) . A wideband antenna consist of shorting vias, are presented in [58, 59]. The lowest mode is moved upward and combined with two higher modes by loading the SIW cavity with shorting vias. As a result, the antenna has a wide bandwidth with triple resonances. A wideband patch antenna with filtering response using a circular patch resonator is proposed in [60], where the TM_{11} mode of the circular patch resonator and TE_{11} and TE_{21} modes of the SIW cavity are employed to achieve the widebandwidth.

A new design to enhance the bandwidth of the SIW antenna using substrate integrated coaxial line is studied in [61]. For wideband low-profile antenna, a novel bandwidth improvement method is described in [62] where the differential fed is incorporated to excite the proposed antenna structure. A practical method, to enhance the bandwidth is addressed in [63] by introducing a cross-shaped slot and a pair of unbalanced shorting vias into the SIW cavity. The resonant behaviour of the elliptical cavity is studied first. The SIW CBSA with penta-resonance is then designed by inserting a cross-shaped slot and a pair of unbalanced shorting vias into the cavity to excite two extra odd- and even-half degenerate quasi- TM_{110} modes, in addition to the previous three half quasi- TM_{010} and odd- and even- quasi- TM_{110} modes. Additionally, by adding another pair of unbalanced shorting vias, two additional higher-order modes, namely the odd- and even- quasi- TM_{210} modes, are successfully introduced to create a hepta-resonance antenna. Enhanced IBW was realized by combining a dual T-shaped slot and a shorting via in [64]. Moreover, the proposed antenna has low profile, planar, compact dimension with flat gain, and uniform radiation characteristics.

2.3 Review of SIW based Multiplexers

The rapid growth in wireless communication systems has increased the demand for multiband/multi-standard antennas for various operations [65]. Various wireless appli-

cations, such as mobile handheld devices [66] and RF front-end systems [67] require multiple transceivers to operate in different frequency bands. Hence, self-multiplexed antennas receive huge attention due to their simple and compact size with no requirement for a decoupling network [68], better isolation between the excitation ports and ease of integration with the RF front-end components [69, 70].

2.3.1 SIW based Self-diplexing Antennas (SDAs)

Recently, dual-band SIW cavity backed antennas have gained attention from antenna researchers as only a single antenna can be used instead of two different ones for supporting two different frequency bands. In the case of a dual-band antenna system, the separation of the received signals is accomplished by a diplexer. It has three ports and two filters that have different resonant frequencies. It also has a power divider that divides the power between the three ports. Designing a diplexer is not only a difficult task but also adds bulk to the RF front end. As a result, a dual-band antenna with good isolation between the ports at both operational frequency bands can avoid the need for higher-order diplexers, allowing for the design of a more compact, low-profile, and low-cost RF front-end system with fewer components. This type of antenna can be designated as a self-diplexing antenna. The circular polarization (CP) operation is also equally important as it eliminates the need for line-of-sight alignment of transmitter and receiver antenna systems. Also, it helps in combating multipath-fading, and polarization mismatch issues in a wireless scenario [71]. Dual-band antennas generally have poor isolation when connected to multiple transceivers, which can be improved by using a diplexer [72]. But the introduction of this extra circuitry will increase the overall size and complexity of the antenna system. Thus, the self-diplexing feature, i.e., where no additional circuitry is used for multiple frequency operation, was introduced due to several attractive features such as less complexity, low cost, compact size, and high isolation [73].

Several techniques are adopted to design self-diplexing antennas, as reported in the literature. The diplexers as discussed in [74–81] are linearly polarized (LP) with different ports. Two unique ports are used to excite two patches printed on different layers in [74, 75]. Using two orthogonal ports to excite the same radiating patches, the authors [76, 77] were able to create a self-diplexing antenna on a single substrate layer. In [78] and [79] use a single patch, although the designs necessitate the use of two substrate layers along with filtering mechanisms to achieve better isolation. An example of a self-diplexing antenna designed using mode analysis is presented in [80]. Using a single SIW square cavity with orthogonal feedlines, a compact, dual-mode, self-diplexing SIW antenna is described [81]. Intermodal coupling between two modes is a well-known technique in filter design for generating transmission zeros (TZ). The TZs are then used to significantly enhance the port's isolation. In contrast to traditional designs, the suggested method is better when two narrow communication channels are used. On the other hand, the antenna structures presented in [82–89] are CP. In [82], a dual-band CP antenna having two annular exponential slots having 3 dB axial-ratio bandwidth (ARBW) of 1.1% and 1.5% is presented. Another SIW based CP antenna, having a cavity similar to [82] (rather half-size) with a spoon-shaped slot is discussed in [83] shows the ARBW of up to 2.8%. Both antenna structures, as discussed in [82, 83] applies grounded coplanar waveguide (GCPW) operating in dominating TM_{010} mode. Another GCPW-fed antenna structure having an octagonal slot and a similar parasitic patch is proposed in [84] shows an ARBW of 0.9% due to with chamfered corners at both slot and parasitic patch. Another SIW based coaxial-fed antenna discussed in [85] where six elliptical slots of different dimensions are used to introduce the CP behavior. However, the ARBW of only 1.6% is reported. A novel idea of using an elliptical SIW cavity is explored in [86] where the slot antenna shows ARBW up to 0.44% with four different arc-shaped slots. To improve the ARBW and gain, [87] implement complex additional circuitry such as quadruple ridge waveguide polarizers for obtaining CP operation and

successfully achieved ARBW of 2.4%. Another coaxial probe-fed antenna with a high gain of 26.8 dBi is received in [88] whereas an ARBW of the only maximum up to 1.1% is reported when 8×16 array is implemented. In [89], SIW based CP diplexer with modified cross-slot is discussed. Here, an ARBW of 0.81% is obtained, and the structure was the first CP self-diplexing antenna with SIW technology. This examination of previously published works reveals that a substantial number of these designs employ a dual substrate layer. The use of many substrate layers complicates integration with other RF modules and also lacks ease of fabrication. However, their large size and lower tuning ranges make it difficult for them to be used in small and highly tunable RF front ends. Additionally, non-planar structures or the employment of a separate decoupling structure occupy larger spaces. Thus, it is a difficult problem to develop planar, simple, and compact self-diplexing antennas based on a single substrate layer that do not require any extra decoupling structure and still exhibit good performance.

2.3.2 SIW based Self-triplexing Antennas (STAs)

Different self-diplexing/triplexing antennas (SDA/STA) have already been designed in the existing literature using techniques such as defected ground structures (DGS) [90], metamaterial [91], multilayered configuration [92], split ring resonators (SRRs) [93] and spiral defected resonators [94]. However, the tuning of the resonant frequency in these multiplexers is hard to achieve. In addition, integrating them with planar circuits (particularly multilayered multiplexers) is a difficult and time-consuming task [95]. Also, when a single patch is excited using orthogonally placed feed lines, the isolation between the ports is hard to achieve (especially when $\frac{f_H}{f_L}$ approaches 2) [96]. One solution to these problems is implementation using the substrate integrated waveguide (SIW) technique, which exhibits attractive features such as low back-lobe radiation, improved isolation between/among the excitation ports, and easy integration with planar circuits [97–99].

Most recently, SIW based STAs with intrinsically isolated input ports and independently tuned frequency bands are discussed in [100]- [101]. In [100], a SIW-based STA having two bow-tie shaped slots etched on a SIW cavity is proposed. The position of the slots is varied to obtain the three distinct, independently tuned frequency bands centred around 7.89/9.44/9.87 GHz. Another SIW based STA designed for 4.18/5.2/5.8 GHz frequency bands is discussed in [102] where two different SIW cavities are formed, i.e., an outer cavity with two transverse slots for 4.18/5.2 GHz and an inner cavity with annular slot for 5.8 GHz frequency band. A similar concept with a modified outer cavity is presented in [103]. The outer and inner cavities of the proposed STA support 4.8/5.4 GHz and 3.5 GHz frequency bands, proving its suitability for 3.5/4.8/5.4 GHz WLAN, WiMAX and 5G wireless standards. The STA presented in [104] uses the innovative concept of a hybrid SIW cavity resonator (a combination of half-mode circular and rectangular SIW cavities) for the generation of 5.57/7.17/7.65 GHz frequency bands. The excitation ports are separated with the help of a T-shaped slots. Another STA supporting 5.6/6.64/6.95 GHz with T-shaped slot etched in the metallic ground plane is discussed in [105]. Here, three shorted-vias are introduced for good isolation of better than 25 dB among the excitation ports. Reference [106] also uses the idea of a half-mode rectangular SIW cavity for 4.95/5.3/5.9 GHz WLAN wireless application. The proposed STA consists of an inverted V-shaped slot etched on the SIW cavity which divides it into two sub-cavities, one eight-mode and the other one quarter-mode. Another STA with improved port isolation, i.e., more than 28.4 dB, is proposed in [107]. The proposed STA comprises a modified I-shape slot intently designed for the 4.14/6.1/8.32 GHz frequency bands. In [101], the reported work shows a dumbbell-shaped slot placed on the SIW cavity to radiate at 6.76/8.62/13.33 GHz, thus supporting C-, X- and K_u frequency bands simultaneously. Though the aforementioned STAs achieve good performance characteristics such as high isolation among the excitation ports and gain/efficiency levels, more compact and independently tuned STAs

with a lower number of tuning parameters need to be explored.

2.4 Review of SIW based MIMO ANTENNAS

Multiple-Input-Multiple Output (MIMO) antennas have become an important part of modern wireless communication systems due to its potential to provide increased channel capacity. MIMO technology has already been used in the long-term evolution standard (4G LTE). In the new 5G standard, MIMO antennas are going to play a significant role because high data speeds are going to be possible with the massive MIMO technology. In order to meet the demands for high data rates, millimeter wave (mmWave) radio frequency bands have been considered in the fifth-generation (5G) communication systems [108, 109]. At mmWave, a single antenna element can not overcome substantial path loss and air absorption [110, 111]. The (MIMO) approach will be employed, with multiple antenna components placed at both the transmitting and receiving ends of the wireless system [112]. High data rates are obtained by the use of multi-pathing, which increases range and dependability without the need for additional bandwidth. As a result, spectral efficiency improves and the data rate increases. A wide bandwidth, high gain necessity to compensate for atmospheric absorption in the mmWave band, and the relatively small size of the structure all provide design issues for developing MIMO antennas. Additionally, mutual coupling between antenna components is a performance-degrading factor that must be kept to a minimum [113]. In MIMO systems, a low envelope correlation coefficient (ECC) helps to build a high channel capacity, which is directly influenced by the impedance matching and isolation of the multi-element antennas [114, 115]. Both of these factors are important for the performance of MIMO systems. Poor isolation affects ECC, radiation efficiency, and channel capacity [116]. In addition, employing additional antenna components increases the system capacity in a $N \times N$ MIMO system [117]. However, because of the small size of the antenna array, the near proximity of the many antenna components results in

reduced isolation. As a result, one of the most important considerations for the design of MIMO systems is the isolation between antenna elements.

The field of MIMO antennas has been one of the most important and trending research topic nowadays. Several works have been reported on microstrip-based dual-band and dual-band dual-circularly polarized (DB-DCP) antenna in recent years. Owing to the rapid advancements in wireless systems, the dual-band dual-circularly polarized (DB-DCP) antenna have drawn much attention as they radiate electromagnetic waves in two orthogonal directions with almost the same strength [118]. Such antenna systems reduce the Faraday rotation effect of ionosphere [119], polarization misalignment issues between transmitting and receiving antennas [120], and facilitate the fading in multipath propagation due to the adverse weather, reflection from the ground surface, building, and walls [121]. Therefore, DB-DCP antennas become an integral part of many wireless applications, especially satellite communications, where the same antenna orientation is not available all the time and require double transmission channels for frequency reuse [122]. Wireless applications such as 5G cellular communications need large bandwidth and high data rates for streaming video content. For this, several multiple-input multiple-output (MIMO) configurations have already been proposed. These MIMO configurations supporting 28 GHz 5G application include capacitively loaded loop (CLL) based array [123], dielectric resonator antenna (DRA) [124], infinity shell-shaped monopole antenna [125] and hexagonal monopole antenna with rectangular slot [126].

Due to the structural limits of SIW technology, designing a MIMO antenna with this technology is very challenging. Furthermore, as compared to a microstrip antenna, a full-mode substrate integrated waveguide (SIW) cavity-based antenna requires a larger area since alternative size reduction techniques may be easily used in microstrip technology. Furthermore, the manufacture of sidewalls adds an additional level of complexity to the design. The number of published research on SIW MIMO antennas is therefore

limited, despite the fact that a large number of microstrip antenna-based MIMO antennas have been reported in recent decades. Because of these problems and drawbacks, there are many good reasons to use SIW technology when making a MIMO antenna for wireless communication. First, instead of employing the full mode, half-mode and other smaller modes may be used to significantly reduce the overall size of the antenna while maintaining or improving performance. Secondly, by making use of its cavity-based features, a well-thought-out design may be able to achieve better gain and power handling capacity than its microstrip counterpart.

A few designs of SIW-based MIMO antennas have been described in recent years. The first SIW cavity-based MIMO antenna was published in [127] in which four full-mode square cavity-backed slot antennas were positioned close together to create a MIMO antenna. A wall with a double-layer mushroom structure is symmetrically placed between the substrate-integrated cavity-backed slot (SICBS) antenna elements, blocking and absorbing the space-field/near-field from the antenna elements and thus improving interelement isolation by more than 42 dB between each antenna element pair. [128] describes a dual-frequency, SIW antenna with two ports. The antenna is able to operate at frequencies of 5.2 GHz and 24 GHz. It combines a lower-band slot antenna and an upper-band DRA. The former is comprised of a pair of differentially fed H-slots etched on the ground plane of a substrate, while the latter is made up of two concentric layers of holes and vias on the same substrate. To make the antenna smaller, the slot antenna has been filled with a square hollow patch. Using this technique, an isolation of up to 35 dB has been obtained. [129] presents a four-element SIW fed MIMO cylindrical dielectric resonator antenna (DRA). The proposed antenna works in the 27.7 GHz band and has port isolation greater than 27 dB. Over the operational band, the peak gain ranges from 5.07 to 5.70 dBi. In addition, polarization and spatial diversity are also presented. In [130] a technique is presented for increasing the isolation between two adjacent DRA components. By including a metal strip on

the upper surface of each dielectric resonator (DR), the strongest component of the coupling field is shifted away from the adjacent exciting slot of the DRA, resulting in a maximum isolation enhancement of 12 dB throughout the 27.5–28.35 GHz frequency range. The reflection coefficient of the proposed MIMO DRA with metal strips is less than -10 dB between 27.25 and 28.59 GHz, indicating that the addition of metal strips has no effect on the DRA's impedance matching. In addition, the ECC and the DG are discussed in detail. In [131] a SIW fed quad-elements DRA MIMO antenna for 5G wireless communication system is designed. The aim of this study is to examine a quad-element SIW-fed rectangular DRA MIMO antenna with dual-band characteristics. A SIW in TM_{10} mode was used to excite multiple modes in a rectangular DRA and achieve good isolation with less than 22 dB between orthogonal components and 17 dB between inline elements in the MIMO configuration. In addition to being good for 5G applications like IoT in smart cities, 5G routers, and repeaters, the new MIMO antenna is also good because it has a good radiation pattern, small size, high gain, high radiation efficiency, and good diversity performance.

Mingtuan *et al.* [132] reported a MIMO antenna based on the SIW corrugated technique. The proposed method makes MIMO antennas smaller so that they can be easily installed in wireless devices, which will help the next 5G technology. A novel four-element MIMO antenna system has been described in [133] for utilisation in 4G and 5G mobile services. When compared to a reference structure working at the same frequency, the design exhibits a size reduction of more than 46%. 8-mode SIW (EMSIW) technology is utilised to implement four radiating elements in a small region. Because of the extremely low envelope correlation value, the suggested antenna configuration exhibits extremely strong diversity performance. As a result, the MIMO antenna array is ideal for small, portable devices. The design of slot based MIMO SIW antenna is reported in [134, 135]. In [134], a SIW-fed tapered slot MIMO antenna covering the 24.25–27.5 GHz and 27.5–28.35 GHz 5G frequencies is presented. A peak gain of 8.2 dBi

to 9.6 dBi can be achieved over the frequencies from 24-32 GHz. A two rectangular slot based cavity-backed antenna has been proposed for MIMO applications [135]. For the first time, a semi-circular MIMO antenna with a compact size has been developed using two basic patch antennas symmetrically placed on an FR4 substrate. The SIW approach was employed in the proposed MIMO antenna design to improve the isolation between antenna ports. Metallic vias are positioned between the top and back sides of the substrate to increase the level of isolation between the two ports. This approach achieves a low mutual coupling in the working frequency band (less than 30 dB). A compact SIW fed annular slot dual-port MIMO antenna was developed by Muhammad *et.al* [136]. An SIW transmission line feeds the antenna on opposite sides of the substrate. In the band of interest, the measured isolation is more than 20 dB. Because of the high isolation between the ports, the suggested design can be used as a power combiner or as a transmitter and receiver antenna at the same time without the use of a T/R switch. At 28 GHz, this design provides the maximum gain possible from a single element with a compact area.

From the literature, it is concluded that a group of antenna parameters are optimized using the SIW technique, but limited efforts are made to optimize all the parameters in a single structure for the higher bands, particularly 5G. Multiplexed antennas achieve good performance characteristics such as high isolation among the excitation ports and high gain/efficiency levels. However, more compact and independently tuned self-diplexing antennas (SDA) and self-triplexing antennas (STA) with a reduced number of tuning parameters may need to be investigated. In the literature, earlier published SIW-based MIMO antennas occupy a larger area, which would make them incompatible with future-generation wireless devices. Moreover, very few of those reported antennas offer good isolation across all the operating bands. There is scope to make a miniaturised planar multiband SIW-based MIMO antenna that has high performance and strong isolation (at least 15 dB) at all communication frequency bands.

After the detailed study of the literature survey of SIW cavity-backed wideband slot antennas, it is observed that the use of high quality factor SIW cavity limits the bandwidth performance of the SIW cavity-backed slot antennas. To enhance the bandwidth of SIW antennas, a design of a substrate integrated waveguide cavity backed wideband antenna for 5G applications is presented in the next chapter.