Investigation on Substrate Integrated Waveguide Antenna Technology

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Substrate integrated waveguide is the most prominent technology to be used for mm-wave region operating components and circuits. SIW manufacturing is accomplished by connecting two parallel metal plates with two rows of conducting cylinders or slots inserted in a dielectric substrate. This provides a compact, reduced loss, flexible, and cost-effective result.This study introduces an overview of the modern research on SIW technology and advances made in modeling, numerical techniques, and designing SIW components and structures.

Keywords: Substrate integrated waveguide, Millimeter wave, Bandwidth, 5G applications, Antenna.

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1 Introduction

The growing traffic and increased interest in wireless components as well as a mobile communication system leads to the introduction of new applications of the millimeter waves. In the frequency range of 60-94 GHz, a variety of applications have been proposed, including wireless networks, vehicle radars, image sensors, and medicinal devices.[1]. In all the aforesaid bands,60GHz frequency rangeisthebest suitable oneasitoffersa largeamountofspectralspace which in turn is continuous and less restricted power limits[6].Implementing all the constituents (like antennas,power amplifiers and filters) requires a platform that provides superior performance, reduced cost, and consistent technologies. On lowerfrequencies, fabrication of these components is done using planar technology (microstripor elsecoplanar waveguide) however, at higher range of frequency i.e., above 35 GHz this technology leads to transmission and radiation losses [1].

We can therefore provide a platform for all these components which is a promising candidate i.e., technology based on SIW. Fabrication of a whole circuit in planar form by integrating all these components (transitions, rectangular waveguide, couplers, and antennas) using planar processing techniques (like a Printed circuit board and LTCC techniques) is possible using SIW technology.

SIW structure and components are easy to fabricate as they are light, compact, flexible, and are also cost-effective. Certain benefits of metallic waveguides (conventional) like low loss, extensiveshielding, improved and better-quality factor, and increased capability of power handling are preserved by SIW structures.

1.1 SIW Structures

The propagation physical characteristics of structures based on SIW are similarto that of conventional waveguides. SIW coincides with the guided mode i.e., TEn0 modes where n= 1,2……… of rectangular waveguide. TM modes due to the gap between the metal vias are not supported by SIW.

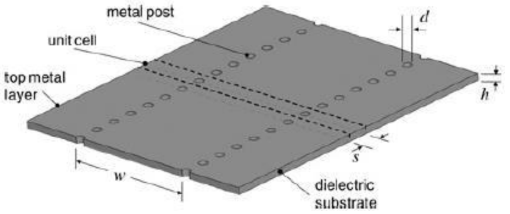

Fig.1. Geometry of SIW

Geometric dimensions of substrate integrated waveguide and rectangular waveguide's effective width together are related to each other in a way which has been determined considering same propagation characteristic and is given by equation as,

$$\mathrm{Weff} = \mathrm{W} - \frac{\mathrm{d}^2}{0.95\mathrm{s}}$$

d- metal vias diameter, W- spacing in transverse direction, and S-spacing.

In designing the SIW structure three major mechanisms of losses need to be considered like dielectric losses, conductor losses, and radiation losses [1].

However,calculation of insertion loss is made for structures based on SIW accounting for all such losses combined. By makingthe adjustments in surface roughness in the interior of the conductor's insertion loss can also be increased. It has been faced and reported that SIW structure provides comparable and lower losses when compared with the planar transmissionlines.

In SIW structure resonant frequency of fundamental mode is governed by its width. The bandwidth of operation is restricted to one octave [1]. Compactness of SIW structure can be improved for which various topologies have been proposed recently [5] (see Fig. 2.).

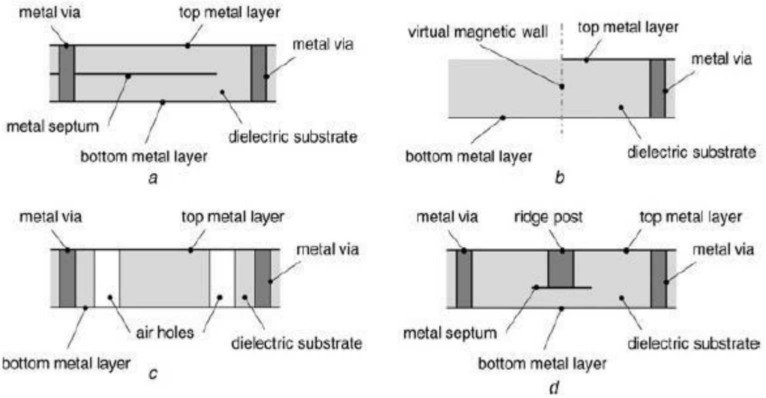

Fig. 2. SIW's topologies

- **a.** SIFW
- **b.** SIW with Half mode
- **c.** Substrate integrated waveguide based on slab
- **d.** Ridge SIW

2 SIW as a filter

Filters have gotten a lot of attention among the passive components. As previously indicated, a range of topologies for filters have been proposed [2]. (see Table 1).

Table. 1. Classes of SIW filters

S. No	SIW filters	Operating frequency
a	inductive post-based filters	28 GHz
b	irises windows-based filters	60 GHz
c	circular cavities-based filters	60 GHz
d	rectangular cavities-based filters	60 GHz

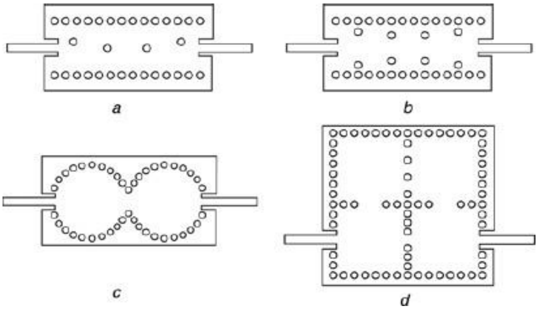

Fig. 3. Different classes of SIW filters

These topologies used in designing the filters provide advantages like flexible designs, higher selectivity, cross-coupling which helps in introducing transmission zeros. Many other design techniques were adopted like using a two-layer substrate which in turn helped in introducing an elliptic filter that can operate in a C band using four cavities. Introduction of wide frequency band pass filters was made in [3], an electromagnetic bandgap was used in the ground plane, with the operating range of frequency from 8.5-16.5 GHz.

Furthermore, several other passive components from filters, such as directional couplers, planar diplexers based on SIW were proposed with operating frequency of about 5 and 25 GHz. Two different structures of directional coupler were suggested. Initial configuration was applied in the designing of 3, 6 and 10-dB centered two adjoining SIW with common wall apertures and the second configuration was of circular form shape used to design 3-dB directionalcoupler.Various other structures like Magic-Tand circulators were implemented andverified experimentally.

3 SIW Active Circuits

The simulation and optimization in embedding of active devices in passive SIW circuits and interconnects of active circuits provide improvements such as reduced losses, higher isolation, and reduced size so as to accomplish good performance with fabrication techniques including lower losses. Latest advancement in mixers, oscillators, and amplifiers has been done as provided (see Table 2).

Table 2. SIW oscillators' type

SIW Oscillator types	Operating frequency	Output power	Phase noise	Designing technique
SIW oscillator with rectangular SIW resonator	12.02 GHz	0dBm	-105 dBc/Hz	Linear simulation technique
Reflection type oscillator with Gunn diode & rectangular SIW cavity	35.259 GHz	15.7 dBm	-91.2dBc/Hz	Linear simulation technique
Gunn oscillator by integrating it with a varactor diode inside rectangular SIW cavity	36.271 GHz	9.3 to 11.3 dBm	-102.1 dBc/Hz	Linear simulation technique

X-band feedback type oscillators using rectangular SIW cavity	12.64 GHz	4.5 dBm	--118 dBc/Hz	Harmonic balance simulation
X-band reflection type oscillators using rectangular SIW cavity	13.03 GHz	7.1 dBm	-118 dBc/Hz	Harmonic balance simulation

Like oscillators circuit development there are several areas like the design of mixers and amplifiers which can lead to improved performance like low insertion loss, improved isolation, increased efficiency. Proposed SIW structures has been used in designing of bias networks used for power amplifiers in the suppression of harmonic components i.e., second and thirdfrom flowing in the bias line along withthe supporting of large DC currents [1]. Several advancements need tobe made in the application of SIW technology including minimization of microstrip to SIW transitions, multi-device amplifiers, reconfigurable amplifiers with tunablebandwidth.

4 SIW Antennas

There has been a surge in interest in SIW-based antennas in recent years. The first SIW antenna was a four-by-four slotted SIW array that operated at 10 GHz and was made by etching longitudinal slits on the top metal surface of a SIW. This antenna's feed network is made up of microstrip power dividers that are built into the same substrate as the SIW antenna [3].

The suggested leaky wave SIW antenna, based on the TE20 mode of the SIW structure, outperformed the traditional leaky-wave antenna based on the basic mode of the SIW. SIW antennas with a cavity-backing have been created and tested. A slotted SIW cavity fed by a coplanar waveguide was presented as the simplest configuration. On a single dielectric substrate, the entire antenna may be readily integrated. A SIW cavity slotted by a meander line and fed by a microstrip line was offered as another alternative [1].

This solution improves the overall antenna's compactness in addition to integrating the entire antenna and feed system on a single substrate. SIW antennas with a cavity-backed back result in planar antennas with excellent efficiency (70 percent or more) and a favorable front-to-back ratio (up to 20dB). Finally, with SIW technology, an H-plane sectoral horn antenna was introduced. This antenna was also combined with a dielectric loading, incorporated in the same substrate, allowing high gain and narrow beamwidths in both the E-plane and the H-plane. At 27 GHz, this antenna topology was employed to create an array with better gain and a one-dimensional mono-pulse antenna array [1].

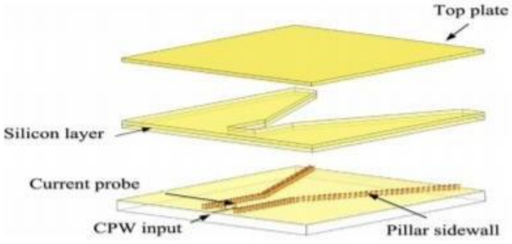

Fig. 4. Integrated SIW horn antenna

Scanned and multibeam antennas were developed recently with an aim of achieving wanted amplitude and phase coefficients. It is realized with the support of reflector antenna, parabolic in nature. Parabolic antenna has been designed based on the parabolic-reflector and implemented at 37.5 GHz [1]. Multi-beam antenna with SIW technique and centered around the Buttler matrix was introduced [2]. This solution was builton the basis ofa single layer printed circuit board process which is better than other processes like thick filmprocess.The active antenna, also known as a "circuit antenna module," refers to active integrated antennas, which have an active device built into the same substrate as the radiating antenna structure. It's utilized to change the antenna's attributes including beam direction, polarization, and bandwidth.

4.1SIW Antennas for 5G applications

According to the federal commission it has been identified and had opened a new-found microwave flexible usage of assistance in 29GHz(27–28GHz), 37GHz, 39GHz(38.6 GHz – 40 GHz), and band around 64-71 GHz i.e., unlicensed for 5G applications [4]. Bandsat millimeter-wave i.e., 30–100GHz are favorable for 5G applications as they provide wide bandwidth for improving channel capacity and high data transfer rate [1]. Many techniques like phased arrays, circularly polarized, multi beam are used to reduce the problems like multipath interference and also overcome polarization mismatch problems. It has been observed and experimentally verified that among all the favourable bands used for 5G applications, the band around 60 GHz is most favourable because of the huge spectral space available and provides less restriction and continuous power worldwide.

Near the 60 GHz band, the phenomenon of higher path loss and oxygen absorption of 10 to 15 dB per kilometre makes the 60 GHz connection small, allowing frequencies to be reused more frequently to boost network capacity [3]. This feature is very promising for the design of 5G wireless communication which further demands a high gain antenna. Antennas providing the advantages of high gain, efficiency, higher peak gain, and wider bandwidth are required in the designing of systems which helps in reducing the cost and improves theperformance.

The growth inefficiency and gain of antenna is affected as a result of the propagation loss which tends to be higher at the frequency with higher value and hence increases the level of the received signal. Millimeter-wave antenna technology solves this problem by providing high gain steerable beams. The list of spectrums assigned with maximum transmission power is shown (see table 3).

Table 3. list of allocated spectrums

Countries	**Spectrum (GHz)**	**Maximum transmission power (mW)**	**Maximum antenna gain (dBi)**
Japan	59-66	(10-250) mW	47
USA	57-64	500	-
Canada	57-64	500	-
Australia	59.4-62.9	10	-
Europe	57-66	20	37
China	59-64	10	34
Korea	57-64	10	-

In SIW antenna, feed plays an important role, and it has been observed that wave guide feed has more advantages over microstrip line, strip line and coplanar waveguide feed [7]. As waveguide feed provides reduced leakage, improved isolation, reduced propagation loss, and zero dielectric loss. SIW components available in the range of frequency from 60 to 350 GHz are useful for many applications in this era of wireless communication. These SIW components and interconnects are used in designing various scientific instruments, commercial circuits with lower cost,telecommunication sector, and many wideband filters, diplexers, and antennas required in the automotive radars operating with the frequency of 77 and 94 GHz. Many researchers have explored wideband antennas since bandwidth is restricted as per the antenna element design. The common choices till now were patch, slot, and cavity because of their advantage of having compact and planar structures. It has been recorded that antenna's efficiencycan be enhanced with implementation of wave propagation with suppressed surface and condensed coupling loss. Different mm-wave antennas have been intended and are mentioned in the table having different strategies toovercome design challenges and improve characteristic.

Table 4. Comparison of different types of SIW antenna

Ref. No	**SIW Antenna type**	**Max. Gain (dBi)**	**Radiation Efficiency**	**S11<-10dB Impedance Bandwidth**	**No of Elements**	**Size**
[7]	Multibeam array	14.6	-	(28-32) GHz	4x4	72x27.4x0.508 mm^3
[8]	Circularly polarized slotted cavity antenna	16	96%	4.6%	4x4	-
[9]	Aperture antenna using SIW corrugated structure	11.8	84%	6.1% (10.02-10.65) GHz	2 grooves	58x27.8x0.508 mm^3
[10]	Broadband ME dipole antenna	27.3	90%	16.9% (35.6-42.2) GHz 16.3% (35.4-41.7) GHz	8x8	66x85.4x6.6mm^3
[11]	Multibeam slot array	12.3	-	(28-31) GHz	4x4	23x49 mm^2
[12]	Aperture coupled patch antenna	12.2	77.5%	11.6% (57-64) GHz	2x2	-
[13]	Wideband linearly polarized antenna	26.7	80%	26.7% (57-71) GHz	4x4	14,4x14.4 mm^2
[14]	Endfire dual circularly polarized antenna	12.8	29.4%	29.7% (31.5-42.5) GHz	4x4	-
[15]	SIW fed spiral array	19.5 dBic	87.1%	14.1% (56.55-65.13) GHz	4x4	

[16]	SIW fed cavity backed patch array	26	68.5%	14.1% (58.2-67)GHz	8x8	6.33x7.08x 0.854 λo

For 60GHz limited design has been observed since their mechanism for excitation is complex of different feed. A summary of performance for reported linearly polarized element design at 60 GHz[12] (see Table 5)

Table 5. LP antenna for 60 GHz frequency

S. No	Antenna	Layers in no	Impedance Bandwidth	Gain (dB)
1	E-shaped Patch	1	22%	9.2
2	Cavity backed Patch	4	29.6%	8.2
3	Dielectric Resonator Antenna	18	24.9%	7.76
4	ME- dipole	1	33% (S_{11}<-15dB)	8
5	Cavity backed dipoles	2	38.7%	9.4
6	L-probe patch	10	50.4%	5.7

Therefore, SIW helps in solving a big problem arising at higher frequency i.e., surface waves arrival reduces the antenna's efficiency.

5 SIW Parameters

5.1 Substrate Materials

Low-loss materials are used to createintegrated circuits and system with high-performance because it is comparatively complicated to amplify over millimeter waves. Many factors like thermal effect, metallic surface roughness, and dielectric non-uniformity have been considered for better and accurate design. The substrate mostly preferred is Rogers RTduroid 5880 and another substrate along with it is Rogers RTduroid 6002 for standard PCB processing. All these materials are easy to fabricate as compared to those of ceramics and also provide better dimensional stability. An important role is played by thermal stabilityin the antenna's performance efficiency and ought to be considered during the designing of antenna. These substrate materials willimpact the performance as well as decide their capacity of power handling.

5.2 SIW Line Configuration

Varying by applications in terms of integrability, space allowed, task performed, and performance one of the SIW line configurations can be preferred [17] (see Fig. 5).

H to E-plane interconnection portrays a very significantpart in the design of multi-polarization feeding. When compared to other planar transmission lines, SIW structures form factor causes a problem in its integration with other components and circuit elements. The suggested structures feature transversely folded waveguides in a variety of configurations shapes such as C, T, and L-type [17].

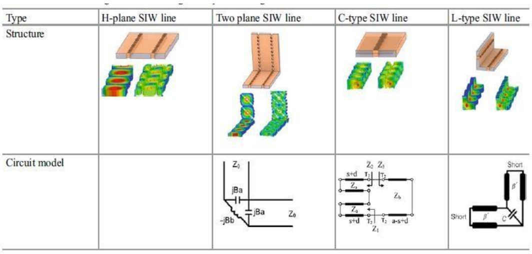

Fig. 5. SIW line configurations allow for spatial arrangement

Two types of folded waveguides are compared in Fig.6, when it comes to their dispersion coefficients with the original unfolded SIW design. It can be noticed as of the graph that resonant frequencies of the SIW linewith C and L-type are lesseras compared to that of the unfolded line configuration. This change is due to the addition of corners.

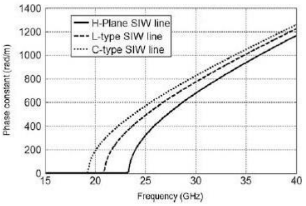

Fig. 6. Dispersion characteristics

5.3 Characteristic Impedance

When SIW is coupled to other planar and nonplanar structures, impedance is a critical factor. It can be defined for a transmission line supporting the TEM mode as given by the equation below

$$ZPV=VV^*/2Pt \qquad (1)$$

The voltage and current that are used are not always the same.

The three descriptions of impedance in a SIW is as follows [17]:

$$ZPV = 2h/aeq\ ZTE \qquad (2)$$

$$ZPI = \pi 2h^*/8aeqZTE \qquad (3)$$

$$ZVI = \pi h^*/2aeq\ ZTE \qquad (4)$$

where, the wave impedance of the TE mode is given by ZTE

5.4 Transitions for SIW

To connect high-Q waveguide components to active planar ones, transitions from SIW to microstrip or coplanar waveguide, or from SIW to air-filled rectangular waveguide, are required. It is essential to characterize transitions of the SIW components. Properties like low loss and minimum VSWR are important for transitions [17]. Broadband transitions require both impedance and field matching. The stimulation of higher-order modes complicates the transition between two different structures at the discontinuity. The majority of transitions are from waveguide to microstrip or CPW.

Table 6. Types of transition

S.no	Transition type	Remarks
1	Microstrip/CPW to SIW transition	Quarter wave transformer principle
2	Rectangularwaveguide toSIW transition	Two-step transformers are used

5.5 Electromagnetic Modelling

SIW technology acquires various numerical techniques for the designing and electromagnetic modeling of SIW structures among them full-wave numerical technique is adopted.The BI-RME approach is a very effective numerical technique for simulating arbitrarily shaped SIW components [1]. This method aids in identifying the frequency response's wideband expressionin one step for the SIW components so that one by one analysis of frequency can be evaded. The ability to directly determine equivalent circuit models of SIW discontinuities is another key advantage of the BI-RME technique.

Vital application of mentioned method is its ability to determine multi-modal equivalent circuit models that are parametric. Each parameter has its own effect on SIW performance (see Table 7).

Table 7. Parameters effect on SIW

S.No	Parameter	Losses in Conductors because of the Effects	Losses in Dielectric because of the Effects	Losses in Radiationsbecause of the Effects
1	The thickness of the dielectric substrate	Decreases	Not Affected	Not Affected
2	Diameter of the metal vias	Slightly decreases	Remains unchanged	Becomes significant
3	Longitudinal spacing	decreases	Remains unchanged	Reduces

6 Fabrication Techniques

With developments in mm-wave applications and SIW structures with frequencies ranging from 60 to 90 GHz, and even more technologies, Conventional PCB technique and LTCC technology are the two main kinds of fabrication technologies that are being widely used. Both these technologies have their merits and demerits in SIW implementation.

Low temperature co-fired ceramic (LTCC) process is more flexible in the implementation of random no of layers, open and embedded cavities whereas, in PCB technology manufacturing cost is higher as it involves the need of buried vias. In the higher frequency band, PCB technology is not preferred as it causes difficulties in fabrication and reduces the performance of the system as well as lowers the efficiency of the system [3].

LTCC technology helps in the availability of several layers and via holes reduced dimensions which makes it possible to implement very compact SIW components.

Photo imageable thick film materials with great dimensional tolerances and low dielectric loss were used to create SIW components operating at frequencies beyond 100 GHz[1].

6.1PCB Process

PCB process has its advantage of low-costdesign, but it also faces some challenges like fabrication forbearance and consistency of the procedure. In PCB fabrication technology it is easy to achieve multi-layer boards and it is easy to integrate components in the PCB technique

6.2 LTCC Process

LTCC is that technology which involves multilayers and is helps in integrated circuits packaging. This fabrication approach can be used for wireless communication applications to produce a single-chip transceiver at a cheaper cost and in large quantities.

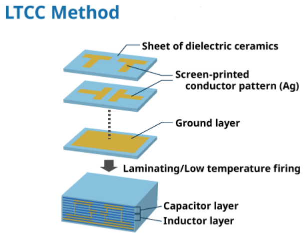

Fig. 7. LTCC fabrication process

7 Measurement of Antenna

There are many ways to test an antenna (called the AUT, or antenna under test), and lots of parameters that can be tested, antenna parameters can be tested both indoors i.e., anechoic chamber as well in outdoor. The measurements made are in more control in a chamber, but it has its own disadvantage like size restrictions and high cost. Antenna measurements were done outdoors, deal with more interference (physical and regulatory) are more affected by the weather, when compared to indoor measurements the outdoor is more suitable for real-world application.

Chambers are of two types

1. Anechoicchambers of rectangular type
2. Anechoicchambers of tapered type

Rectangular chambers are utilized for frequencies over 1 GHz, while tapered chambers are used for frequencies below 1 GHz. The antenna parameters can be measured using a variety of approaches, including radiation pattern directivity, gain, and polarization. Antenna measurement methods can be performed in the Near-Field of the Antenna under Test (AUT) or require the Far-Field criterion and homogeneous plane illumination.

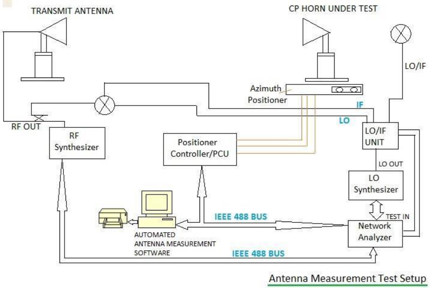

Fig. 8. Basic antenna measurement setup

A single-axis rotational pattern is used in the basic pattern-measurement technique. To construct a two-dimensional polar pattern, an AUT is placed on a rotational positioner and rotated around the azimuth [11].In both the E and H planes, this measurement is primarily utilized to estimate parameters such as antenna beamwidth.When the general polarization of the pattern is known, this technique is used to measure co-polar field components for simple horns or dipoles. It's crucial to be able to measure two orthonormal (i.e., perpendicular) field components when dealing with complicated radiators with unknown polarization or that change as a function of angle [11].

As the measuring antenna (MA), a dual-polarized horn, dipole antenna or log-periodic dipole arraywas used to get this result.Such a strategy necessitates the use of two receivers or the ability to rapidly flip the polarization of a single receiver, making the operation costly. This difficulty can be overcome by executingsame pattern test for every single MA polarization; however there are several drawbacks that could result in large time differences and alignment difficulties.

7.1Near-Field versus Far-Field Measurements

The observed parameters of the antenna do not appear to change as a function of separation distance or antenna position in the far-field free-space situation. The evaluated field levels may or may not change, but the recorded gain or pattern remains constant. It can also is explained that far-field free-space condition is the state in which all the conventional theoretical equations for estimating antenna attributes are valid [11].

The observed antenna parameters vary as a function of their environment in a near-field or non-free-space environment. Mutual coupling between the AUT and the measuring antenna, as well as mutual coupling between the antennas and other objects in the vicinity, as well as other near-field perturbations, make it impossible to determine the appropriate antenna attributes directly [11]. Even with a good free-space environment (i.e., a fully anechoic room), near-field testing has restrictions.Different regions for the measurement of the antenna (see Fig. 10.). The radiating near-field or Fresnel area is located inside the 2D2/ distance but outside the reactive near-field region, whereas the far-field or Fraunhofer region is located outside this distance. Normally, when it comes to antenna-pattern measurementswithin the reactive region of an antenna, less information is obtained.

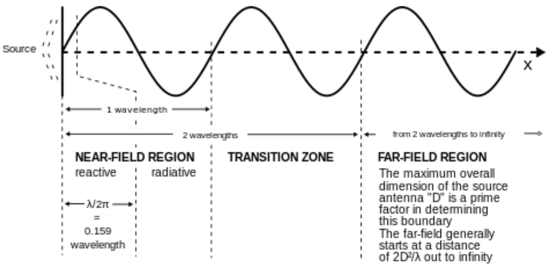

Fig. 9. Near and Far-field regions

SIW components are confined on both sides of the substrate by conducting surfaces, have extremely low (non-existent) radiation/leakage loss, and are insensitive to external interference.The measurement of SIW antennas is done with a vector network analyzer. SIW circuits are built on a thick substrate having low dielectric constant, which makes microstrip antennas impossible to build.

8 Future Trends

Applications of SIW technology in the upcoming time will be applied for designing the components to be used in the higher frequency range i.e., greater than 60 GHz. Investigation on new materials and fabrication technologies is required for integrating components based on approaches like systems on the substrate. Solution regarding various integrating techniques should be made which brings numerousbenefits in SIW technology asprofitable and allows to fabricate components with less losses and full shielding. Furthermore, all components are produced on the identical substrate, which helps to avoid transitions and linkages that cause losses and are parasitic.Research on the fabrication techniques has also been looked up for SIW components like HTCC (high temperature co-fired ceramic) which will help in the manufacture of three dimensional SIW components and will improve the parameters like flexibility and better performance. Many smart materials, nanomaterials, and electro-optical materials will be of significant use in the design and development of new SIW structures. SIW technology has recently seen entire circuits and frontends presented and experimentally proven.The system on substrate approach is the most advanced and has been used for the implementation of mm-wave circuits.

9 Conclusion

Substrate integrated waveguide technology is very beneficial for the incorporation of mm-wave circuits and uses in this frequency region. Various SIW components i.e., both active and passive along with SIW antennas, have been introduced by adopting various technologies and techniques in the different frequency region. Research and investigation on all these advances are done to find which one of these design exhibit parameters like low losses, good performance, and can even operate on a high-frequency range. SIW Technology will be a very promising and better candidate for 5G applications along with the mm-wave broadband wireless communication.

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