A Comprehensive review of substrate integrated waveguide (SIW) technology in the development of 5G microwave components

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Abstract:

This research aims to study and analyze the theoretical and technical foundations related to the design and development of microwave components used in fifth generation (5G) systems. This research focuses on Substrate Integrated Waveguide (SIW) technology, one of the most promising technologies in the field of modern communications. The importance of this research is highlighted in light of the growing need to improve the performance and efficiency of components used in wireless communication networks, especially with the development of high frequency requirements and the global transition to a fifth-generation network infrastructure.

The research addresses the problem of the limited performance of some traditional components (such as microstrip lines and rectangular waveguides) at high frequencies, in terms of signal loss, narrow bandwidth, and the difficulty of integration into printed circuit board (PCB) systems.

The research methodology relies on analyzing theoretical studies and comparing models presented in the scientific literature, without resorting to field experiments, with the aim of extracting the fundamental performance differences between conventional components and components built using SIW technology.

The research concludes with recommendations for combining SIW with modern technologies such as massive MIMO and beamforming to overcome traditional performance limitations and achieve the highest possible efficiency in future 5G networks. It also demonstrates the scientific and technical value of using SIW technology in 5G environments.

Keywords: 5G Microwave Components, Substrate Integrated Waveguide, Technology.

1. Introduction:

In recent years, the world has witnessed a tremendous boom in wireless communication technologies, particularly with the spread of fifth generation (5G) networks, which require advanced infrastructure capable of providing high speeds, low latency, and high spectral efficiency. Among the most prominent technical challenges in this field is the need to develop highly efficient microwave components, especially in high-frequency bands such as millimeter waves. Substrate Integrated Waveguide (SIW) technology is one of the most prominent innovations that has contributed to improving the performance of antennas, filters, and routers by combining the advantages of traditional hollow waves with modern manufacturing techniques on dielectric substrates.

With the rapid expansion of 5G networks, there is a need for waveguide technologies that support high frequencies and deliver high performance. Substrate-integrated waveguide (SIW) technology is a promising solution in this field, combining the advantages of traditional routers and embedded technologies, enabling the design of compact and efficient microwave components. Studies show that SIW delivers excellent performance in the millimeter-waveband, making it suitable for advanced 5G applications.

SIW technology is characterized by a decrease in signal loss compared to traditional transport lines such as microscope, especially at high frequencies. SIW also provides easy integration with printed circuits, which reduces the size of the total system and increases its efficiency. In addition, SIW allows the design of high-quality components (High-Q) and a high energy bearing capacity, making it ideal for modern communication applications.

Despite the advantages of SIW, the design of its components faces technical challenges, such as determining the optimum dimensions of metal holes (VIAS) and the distances between them to ensure reduce signal loss and prevent radiological leakage. The transition between SIW and other transport lines requires the design of effective transformers to reduce reflections and improve compatibility. Research shows that improving these aspects can lead to a better performance of the components designed with SIW.

SIW technology is used in the design of a variety of micro -components used in 5G networks, such as filters, dividers, and couplers. Studies show that these components provide excellent performance in terms of frequency, efficiency, and small size. The use of SIW also contributes to reducing electromagnetic overlap and improving the reliability of the total system.

This analytical study aims to explore the potential of SIW technology in the design and development of microwave components for 5G networks, focusing on technical challenges and possible solutions. Through an analysis of current literature and practical experiences, the study seeks to provide useful insights for researchers and engineers in the field of microwave communications. It also hopes to shed light on future trends in the development of this technology and its applications in next-generation networks.

1.1. Study Problem:

5G networks face increasing technical challenges at the infrastructure level, particularly in designing high-performance, small-sized, and low-cost microwave components. Although several conventional technologies are available (such as microstrip transmission lines and waveguides), many of them suffer from high losses, large size, or frequency limitations.

Hence, the main question of this study is:

How efficient is substrate-integrated waveguide (SIW) technology for designing and developing microwave components supporting 5G networks compared to other conventional technologies?

The following sub-questions out from the main research question:

- What are the engineering and technical characteristics of SIW technology?
- What are the basic components that can be designed using SIW (such as antennas, filters, and routers)?
- How does SIW technology compare in performance and efficiency to traditional microwave technologies?
- How compatible is SIW with 5G frequency requirements?
- What are the most notable recent studies that support the use of SIW in 5G applications?

1.2. Study Objectives:

- Introduction to SIW technology and its fundamentals, and analysis of its characteristics and applications in microwaves.

- Analysis of the design of this technology's components, starting with filters, power dividers, and SIW-fed antennas.

- Determine the extent to which SIW technology contributes to improving properties such as return loss, expanding the operating bandwidth, and supporting frequencies beyond 28 GHz used in the millimeter wave bands of 5G.

- Providing a critical analytical view of the true capabilities of SIW technology and identifying the technical limitations facing its use in commercial applications.

- Providing recommendations for integrating SIW technology with modern technologies such as Massive MIMO and Beamforming.

- Clarifying the scientific, technical, and industrial value of using SIW technology in a 5G environment.

- Compiling and analyzing previous studies in this field.

- Providing recommendations for improving future designs of microwave components using SIW.

1.3. Study significance:

This study is of theoretical and applied importance. From a theoretical perspective, it contributes to enriching the literature on SIW technologies, while from a practical perspective, it provides an engineering reference that helps researchers and designers develop effective components for 5G networks, using technologies with small size, high efficiency, and low manufacturing costs.

1.4. Study Terms:

SIW – Substrate Integrated Waveguide: A technology for guiding electromagnetic waves through dielectric substrates using embedded metal holes.

5G: The fifth generation of wireless communications networks, characterized by very high data transmission speeds and operating frequencies in the millimeter wave range.

Microwave: A frequency range between 1 GHz and 300 GHz, used in communications and radar.

Resonance: A physical phenomenon in which the response of a system is amplified at a specific frequency.

1.5. Study structure and topics:

The study consists of the following sections and headings:

Section One: Literature Review and Previous Studies:

- Presentation of fifteen Major Studies
- Analysis and Summary of Results

Section Two: Theoretical Background and SIW Technology

- Defining SIW technology and its operating principles.

- Analyzing the design of SIW technology components.
- The efficiency of substrate-integrated wave (SIW) technology for designing and developing microwave components supporting 5G networks.
- The scientific, technical, and industrial value of using SIW technology in a 5G environment.

Section Three: Study Results, Conclusion and Recommendations

2. Methodology:

This study falls within the scope of descriptive analytical research, relying on an analysis of recent scientific literature for last ten years, comparative studies, and engineering models published in reliable scientific databases such as IEEE and ScienceDirect. A number of graphs and design tables from previous studies and technical sources will also be analyzed to evaluate the efficiency of SIW compared to other technologies.

3. Literature Review:

In a study conducted by Sharma, & Singh. (2019) for Design and Analysis of Substrate Integrated Waveguide (SIW) for High Frequency Applications, high frequencies suffer from a number of factors that cause the signal to weaken or attenuate during transmission. The most prominent of these factors is atmospheric absorption, particularly due to water vapor and oxygen gas, as these gases absorb a portion of the electromagnetic energy. The researcher adopted the waveguide integrated with the substrate as an improved method for the waveguide. The SIW is a transition between a microstrip antenna and a dielectric-filled waveguide antenna. SIWs feature planar structures, allowing them to be fabricated on printed circuit boards (PCBs) and easily integrated with additional transmission lines. The design of the SIW structure was modeled and simulated on a computational machine having 2.60 GHz. 3.2 GB was the virtual memory used while computing. The study concluded that there are numerous pros for SIW over the micro-strip and DFW, SIW is low loss waveguide for the transmission of higher frequency ranges.

Vivek & Tanuj (2022) developed A circular slotted SIW guide and analytically evaluated to study its various output quality factors. After the theoretical study, various calculations of the SIW were performed with the help of MATLAB, and the design was simulated using ANSYS HFSS. The study explained the relationship between S parameters and frequency and demonstrated the range of return losses or input reflection coefficient (S11) from 10.44 GHz to 20.24 GHz and return loss drops around -51dB at 14.81 GHz. This shows that proposed SIW design is capable of beam scanning in the range of 10.44 GHz to 20.24 GHz efficiently.

A review of substrate integrated waveguide (SIW) technology, a design example and a discussion of key characteristics at 11 and 20 GHz conducted by Soundarya & Gunavathi (2020) found that SIW characteristics such as impedance is inversely proportional to dielectric constant and effective width of equivalent waveguide, whereas the phase constant is directly proportional to the dielectric constant and independent of effective width of equivalent waveguide. SIW characteristics make it a suitable candidate for miniaturized, low loss, high power handling planar components.

Nwajana et al, (2016) conducted a study titled Low Cost SIW Chebyshev Bandpass Filter with New Input/Output Connection. Using low-cost, commercially available printed circuit board (PCB) technology, A filter was designed with a center frequency f_0 of 1.684 GHz; a partial bandwidth FBW of 4%; and a passband return loss RL of 20 dB. A standard low-pass filter circuit model was constructed from the standard low-pass filter. The parameters of the standard Chebyshev low-pass filter g were determined at a passband ripple of 0.04321 dB. J-inverters were used to transform the standard low-pass filter into a shunt-only network. Each shunt capacitor was designed to be equal to g1. The simulation and measurement results show that an insertion loss of 1.3 dB was achieved across the band. The simulated and measured return losses of 15 dB and 16 dB respectively were achieved. The simulated and measured results show good agreement with the passband centered at 1.684 GHz as expected.

Hadi et al. (2020) performed a design and evaluation model of a dual-band circular aperture integrated waveguide antenna for K-band applications using an EM simulator in CST Microwave Studio. The researchers found that the SIW technology make the antenna performance enhanced in the term of matching, and this led to enhanced in the directivity and gain to make antenna suitable for K-band applications requirements.

Lalit Kumar et al. (2023). investigated and designed a spliced patch antenna (SPA) for the 5G frequencies N257 (28 GHz) and N258 (26 GHz), supported by a substrate-integrated waveguide (SIW) cavity. The researchers found that the proposed antenna has high gain, a small size, and broad spectral coverage all of which make it ideal for 5G applications.

N. Al-Fadhali et al. (2019) propose a compact, wide-bandwidth, millimeter-wave (MW) cavity-hole antenna design for 5G communications applications. The proposed antenna has an average gain of 8.574 dBi, with a compact dimension of 20×20 mm². The antenna operates efficiently at 28 GHz and covers a wide frequency range from 22 to 30 GHz, making it suitable for various 5G applications within this band. Simulation results show that the reflection coefficients (S11) remain below -10 dB across the entire band, indicating good radiation performance. At 28 GHz in particular, the antenna achieves high efficiency and excellent gain.

Bharti et al. (2025) designed and simulated two Gysel SIW-based power dividers operating at 15 GHz. The measured results showed isolation above 22 dB at 15 GHz, return loss better than 10 dB at each port, and an insertion loss of 2.44 dB, all of which closely match the simulated data. This demonstrates the effectiveness of the proposed design approach.

Singh and Mishra (2021) designed a compact leaky wave antenna based on a substrate-integrated waveguide (SIW) using a slot-section technique operating at millimeter-wave (mm-wave) frequency bands at 38 GHz. It was analyzed using a Finite Integration Technique (FIT)-based full-wave electromagnetic simulation tool. The radiating patch was printed on a Rogers's RT 5880 (lossy) substrate measuring $7.5 \times 27 \times 0.254$ mm^3, with a relative permittivity of 2.2 and a loss tangent of 0.0009. The antenna exhibits an impedance bandwidth of 230 MHz (38 GHz–38.23 GHz). The radiation efficiency is 82.7% with a directivity gain of 6.68 dB at 38 GHz.

Pei-Ling Chi et al. (2020) proposed a balanced filtered SIW power divider operating at two frequencies (28 and 39 GHz) for millimeter wave (5G) applications. The researchers used three SIW cavities to tune the differential and common modes and achieve dual-band pass-through with high co-pass suppression. The methodology involved designing resonant cavities, introducing isolation resistors, and achieving phase and intensity balance between the outputs. Experimental results demonstrated good performance in both bands in terms of input and output loss, isolation, and co-pass suppression (>30 dB). The study recommends the use of this design in differential air-feed networks for high-frequency systems due to its simplicity, efficiency, and small size.

Honari et al. (2017) proposed a high-gain open-loop antenna design using substrate-integrated waveguide (SIW) technology with corrugated cavities, aiming to support 5G applications in the 10 GHz band. The researchers used three layers of dielectric materials to form the antenna in a compact and lightweight manner without the need for traditional metal components. Two versions of the antenna (with two and four cavities) were tested, and the results showed that increasing the number of cavities leads to a significant gain improvement (up to 12.8 dBi), with a narrower beamwidth and improved radiation steering. The study recommends the application of this design in miniaturized 5G antennas integrated with integrated circuits.

Bhat et al. (2023) conducted a comprehensive review of substrate-integrated waveguide (SIW) technology, its pivotal role in 5G filter design, and the challenges associated with its miniaturization. The paper highlighted the advantages of SIW technology in terms of low cost, small size, high efficiency, and easy integration with other components on printed circuit boards. It also reviewed the most prominent modern filter miniaturization techniques, such as half-mode SIW (HMSIW) and full mode SIW (FSIW) and demonstrated that these technologies enable high performance in the millimeter-wave frequency bands required for 5G networks. In terms of future direction, the study anticipated that research would focus on integrating SIW components into integrated systems-on-a-substrate (SoS) and developing low-cost, precision manufacturing processes that support mm-wave and THz applications. It also highlighted the importance of integrating this technology with CMOS and MMIC technologies to achieve higher levels of functional integration, making SIW a promising candidate for meeting the requirements of future communications networks, the Internet of Things, and smart systems.

Zhu et al. (2017) conducted a design and implementation of a broadband linear polarization antenna using substrate-integrated waveguide (SIW) technology to cover the unlicensed band from 57 to 71 GHz, a key band in 5G applications. The radiating element design is based on a complementary source combining an electric dipole and a magnetic notch surrounded by a square cavity to improve the radiation efficiency and extend the bandwidth. The core element demonstrated a bandwidth of 38.7% with an average gain of 8.7 dBi. 2×2, 4×4, and 8×8 arrays were formed using multi-layer SIW-based feed splitters to ensure uniform power distribution and minimize cross-polarization. The 8×8 array achieved an experimental bandwidth of 22.9% with a maximum gain of 26.7 dBi and a radiation efficiency exceeding 80%. The results showed that using an SIW structure with integrated radiation sources provides a low-cost, high-performance, and integrable solution within future millimeter-wave communication systems, which reinforces the trend toward adopting this technology in high-capacity 5G systems.

Kumar et al. (2023) noted that maintaining a small footprint is one of the most important features of SIW antennas, as antennas with a small footprint, higher gain, and higher efficiency across a wider frequency range are more beneficial and effective. The authors designed a slotted patch antenna (SPA) for the 5G n257 (28 GHz) and n258 (26 GHz) frequency bands, supported by a substrate-integrated waveguide (SIW) cavity using RT/Duroid 5880 dielectric substrate material, with $\varepsilon r = 2.2$ and a thickness of 0.787 mm. The antenna is excited by a 50 Ω microstrip transmission line to a transition-modulated SIW-taper to achieve optimal electrical performance. By understanding the antenna performance using the reflection coefficient (S11), radiation patterns, and electric field distribution, the proposed antenna features high gain, small size, and broad spectral coverage, making it ideal for 5G applications.

SIW technology is complex in terms of micromanufacturing and expensive, as it requires drilling tiny metal holes. Passia & Yioultsis (2025) present a theoretical and experimental analysis of a new metamaterial-inspired planar waveguide known as the Uniplanar Single-CSRR (SIW). This structure aims to simplify the manufacturing process of high-frequency waveguides used in mmWave and 5G applications by replacing rows of metal holes with rows of grounded CSRRs, resulting in what is known as the uniplanar CSRR-SIW. Coupled mode theory (CMT) was used to accurately design and analyze the response of this structure. Results from finite element (FEM) simulations and the fabrication of an actual prototype antenna indicate that the new design offers performance comparable to conventional waveguides with simpler manufacturing and greater design flexibility, such as the ability to vary the number of CSRR rows or use heterogeneous patterns to achieve advanced functions such as dual-band or in-band blocking filters.

4. Theoretical Framework:

4.1. Defining SIW technology and its operating principles

Substrate Integrated Waveguide (SIW) technology is a recent innovation in microwave and millimeter-wave communications, representing a compromise between the advantages of traditional metal waveguides and planar transmission lines such as microstrips. The SIW structure consists of an insulating substrate covered with two metal layers on top and bottom, with two parallel rows of metal holes (vias) that mimic the side walls of a conventional waveguide. This structure enables routing characteristics similar to rectangular waveguides, with the possibility of manufacturing using printed circuit board (PCB) or low-temperature ceramic (LTCC) technologies, which reduces cost and facilitates integration with other components (Bozzi, et al; 2011).

The SIW technology operating principles:

- Basic Structure:

The SIW consists of a dielectric substrate between two metal layers (top and bottom), just like a printed circuit board.

Along the substrate, two parallel rows of metal via holes are installed. These are connected to the top and bottom metal layers, forming virtual walls that mimic the walls of a metal guide.

- Wave Transmission:

Electromagnetic waves travel within the "channel" defined by the top and bottom metal layers, with lateral boundaries formed by the two parallel rows of vias.

This structure forces the wave to propagate in a pattern similar to that of a conventional metal guide (typically a TE_{10} pattern), but on a printed, integrated substrate.

- Interfacing with Other Circuits:

The SIW can be easily connected to microstrips or other printed transmission lines, making it ideal for integration into microsystems or high-frequency integrated circuits.

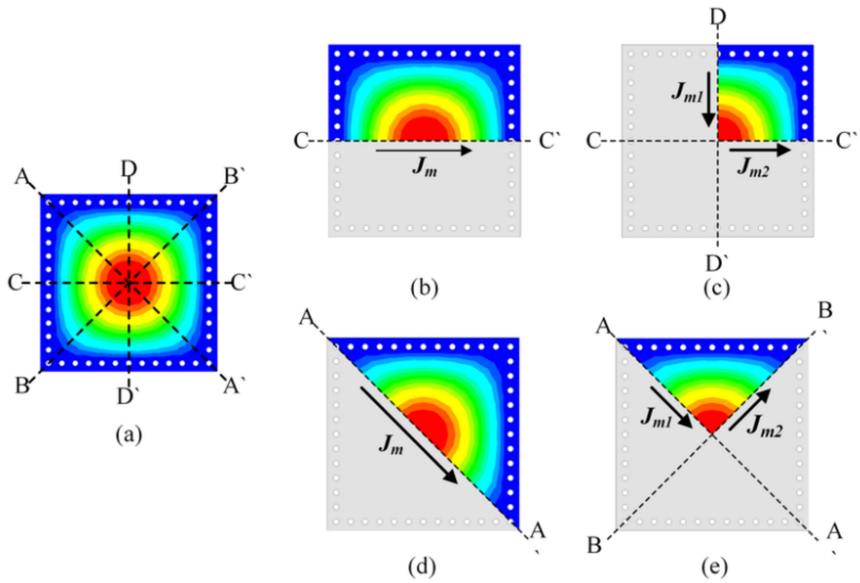

Fig 1. The E-field distribution diagram in the SIW cavity

The electrical distribution in this diagram in Fig.1 shows how waves travel within the SIW in a manner similar to a conventional metal guide, while maintaining the advantages of integration with printed circuits.

4.2. Analyzing the design of SIW technology components

SIW is synthesized by embedding two rows of metallic vias on a dielectric substrate with top and bottom metal claddings (see Fig. 2). The 7 Via holes short both the top and bottom copper claddings so that a vertical current path exists. The propagation characteristics of SIW are almost the same as traditional waveguide.

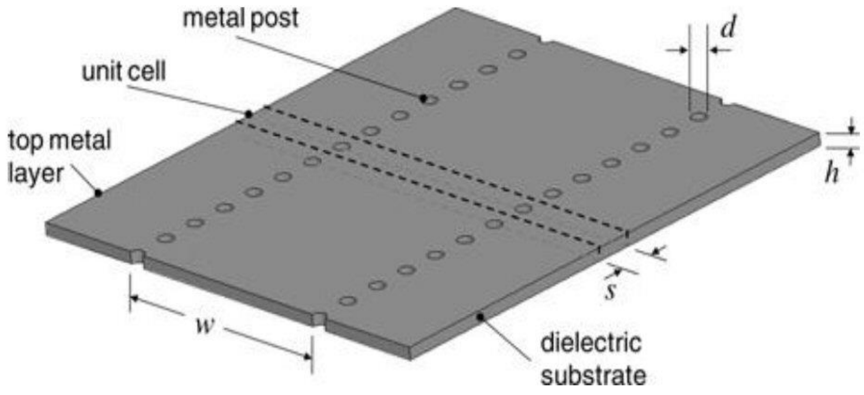

Fig 2. Substrate integrated waveguide (G. Soundarya and N. Gunavathi, 2020)

Where W is Substrate width, L: Substrate length, h: Substrate height, d: Via diameter, s Spacing (pitch), w: SIW width, w_{eff}: Effective width.

4.2.1. Bandpass and lowpass filters:

A bandpass filter in SIW technology is a component used to pass a specific range of frequencies and block frequencies outside that range. The design is shown in Fig. 3. This type of filter is designed using resonant cavities within the Substrate Integrated Waveguide, where the pass and rejection characteristics are controlled by the dimensions and distribution of the cavities. These filters feature high efficiency and low losses, making them suitable for high-frequency communications applications such as fifth generation (5G) networks.

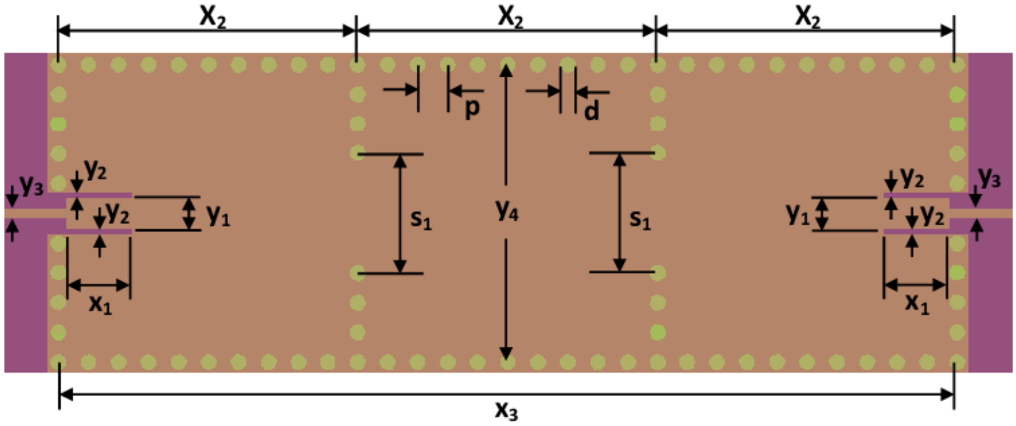

Fig 3. Substrate integrated waveguide bandpass filter layout with physical dimensions in mm (d = 2.0, p = 3.725, s1 = 13.05, x1 = 8.125, x2 = 37.25, x3 = 111.75, y1 = 3.9, y2 = 0.7, y3 = 1.1, y4 = 37.25). (Nwajana et al, 2016)

4.2.2. S-parameters and the S_{21} transfer coefficient:

Dispersion coefficients (S-parameters) are used to describe the behavior of linear electrical networks when exposed to stable electrical signals. These parameters are essential in the analysis and design of high-frequency components in substrate-integrated waveguide (SIW) technology.

Dispersion coefficients are elements of a matrix that describes the relationship between the electrical waves entering and exiting an electrical network. In a two-port network, the matrix expresses the following relationship:

In the context of substrate-integrated (SIW) routers, the S_{21} coefficient represents the ratio of the waveform coming out of port 2 to the waveform entering port 1, assuming port 2 matches the reference impedance. This is expressed mathematically as:

$$S_{21}=b_2/a_1$$

Where a_1 is the wave entering Port 1.and b_2 the wave coming out of Port 2. This represents the portion of the signal that was successfully transmitted through the component to the other end. The closer S_{21} is to 1 (or 0 dB), the better the signal transfer.

This parameter indicates how efficiently the signal travels through the component. In filters or routers designed using SIW, S21 is used to evaluate insertion loss and bandwidth.

The S21 factor is of great importance in SIW design, in terms of determining the efficiency of the component in transmitting the signal between ports, adjusting the dimensions of the SIW to achieve the required performance, and integration into systems by ensuring that the component is compatible with the rest of the system in terms of impedance and frequency.

The S_{11} is a measure of the amount of signal that is reflected at a specific point in the structure, usually due to a difference in the imbalance (Impedance Mismatch) or an incompatibility with the transition between the components (such as an antenna and a SIW or between two different sections of SIW). If $S_{11} = 0 \Rightarrow$ There is no reflection (all the signal passes). And if $S_{11} = 1 \Rightarrow$ Each sign is reflected (no energy passes). A good design goal is to have a less than -10 DB ⇒, meaning that only 10% of the energy is reflected. Any repercussions that distort signal, and a loss of efficiency.

4.2.3. Power dividers:

Power dividers are essential components in microwave systems, used to distribute electrical signals into multiple paths while maintaining power balance and transmission efficiency. In substrate-integrated waveguide (SIW) technology, power dividers offer a compact and efficient alternative to conventional designs, due to their ability to reduce radiation losses and offer good compatibility with printed circuit boards. SIWs feature a compact structure and are suitable for integration with antenna systems and frequency filters in modern applications such as 5G communications and radars.

SIW power dividers are essential components in SIW antenna arrays. SIW technology replaces microstrip structures, eliminating the drawback of excessive radiation leakage at high frequencies. However, the design process for SIW power dividers is more complex than that of conventional microstrip power dividers. Farah et al. (2023) analyzed various types of T- and Y-type SIW power dividers based on their configurations, functions, and operating principles, providing guidelines including insertion loss, isolation, common phase bandwidth, return loss bandwidth, and phase balance. The researchers classified power dividers into several main types: corporate power dividers, which are further divided into single-layered and multi-layered types; series power dividers, which include HMSIWs; MMIs, which include Wilkinson power dividers; Gysel power dividers; and finally, cavity-based SIWs, which include QMSIWs and EMSIWs.

4.2.4. Power distribution range:

The power distribution range (PDR) of substrate-integrated waveguide (SIW) technology is a key element that significantly impacts the signal transmission efficiency and power distribution in modern systems. SIW designs achieve even power distribution across multiple channels, contributing to improved overall performance of micro-components such as power dividers and antennas. This is achieved by designing SIWs that can precisely manage high frequency bands. SIWs also offer advantages such as reduced signal losses and reduced radiation losses compared to conventional designs.

4.2.5. Impedance matching:

Impedance matching is a vital factor for ensuring optimal performance in SIW systems, as it helps reduce reflection losses and improves power transfer between different components such as antennas and power dividers. When designing SIW components, it is essential that the microwave and microwave equations are matched at every point along the structure to ensure efficient signal transmission. In SIW technology, metal vias and design techniques such as narrowband expansion or slot line adjustment are used to modify the impedance and ensure that electrical components such as inputs and outputs are impedance matched.

4.2.6. SIW antennas:

SIW antennas are one of the advanced ingredients in the technology of the compact wave guide in the substrate, as it combines the advantages of traditional wave guide with integrated circuits techniques. These antennas use the compact pillars that include the rows of metal lights (VIAS) to form wave walls with characteristics similar to those in traditional microscopic waves. These antennas provide advantages such as high efficiency, simple integration with compact circles, and small size, which makes them ideal for high frequency applications such as V -5G connections (5G) and high -frequency microbial systems.

4.3. Efficiency of substrate-integrated wave (SIW) technology for designing and developing microwave components supporting 5G networks.

SIW technology is a cornerstone in the development of highly efficient microwave components that meet the requirements of 5G networks in terms of wide bandwidth, low losses, and seamless integration with miniaturized communications systems. Unlike traditional lines such as microstrips, the SIW structure offers properties similar to rectangular waveguides, enabling high signal transmission quality over frequency ranges up to tens of gigahertz, which is compatible with the mmWave bands used in 5G. Electromagnetic waves travel within a specific channel in the dielectric substrate, between two metal layers, surrounded by walls of metal holes (vias) that prevent signal leakage and maintain the wave directional pattern.

One of the most notable advantages of SIW is its high integration with printed circuit board (PCB) systems, making it ideal for designing components such as filters, power dividers, antennas, and resonators within a single environment and in miniaturized sizes. This integration reduces insertion loss and minimizes the connection problems that arise when using separate components. The SIW design also enables a relatively high Q-factor, which is essential for ensuring spectral efficiency and reducing channel interference, especially in high-spectral-density applications such as 5G networks.

Furthermore, SIW facilitates the creation of smart phased arrays at a lower cost, as they can be easily integrated with advanced feeds to support the beamforming systems used in 5G. They also offer multi-layer design capabilities, which enhances vertical space utilization and facilitates the design of integrated transceiver modules (TRx modules). With the ability to be manufactured using conventional PCB manufacturing techniques, SIWs enable low-cost, high-performance solutions, making them an ideal choice for next-generation mobile communications systems.

4.3.1. 5G Microwave Components that Use Substrate Integrated Waveguide (SIW) Technology:

Substrate Integrated Waveguide (SIW) technology is widely used in the design of microwave components for 5G technologies, as it combines the efficiency of waveguide technology with PCB integration. The most important microwave components used in 5G and implemented using SIW technology include:

- Filters, which are used to separate or pass a specific frequency band, such as bandpass filters, low-pass filters, and high-pass filters. SIW makes filter designs compact, low-loss, and easy to manufacture. - Power Dividers/Combiners: These are used to split or combine signals across multiple channels, such as the SIW Wilkinson Power Divider and the SIW T-junction Divider.

- Resonators: These are used to tune specific frequencies or to manufacture filters such as bandpass filters and sensors.

- Directional Couplers: These are used to separate a portion of the passing signal for monitoring or measurement. They provide good isolation between ports. SIW couplers provide high performance at the millimeter frequencies used in 5G.

- Antennas: SIWs integrate the antenna with the rest of the circuit, especially slot or leaky wave antennas using SIWs, SIW Slot Antennas, SIW Leaky Wave Antennas, and SIW Cavity-backed Antennas. The following Fig. 3 shows the SIW technology used in 5G Microwave Components:

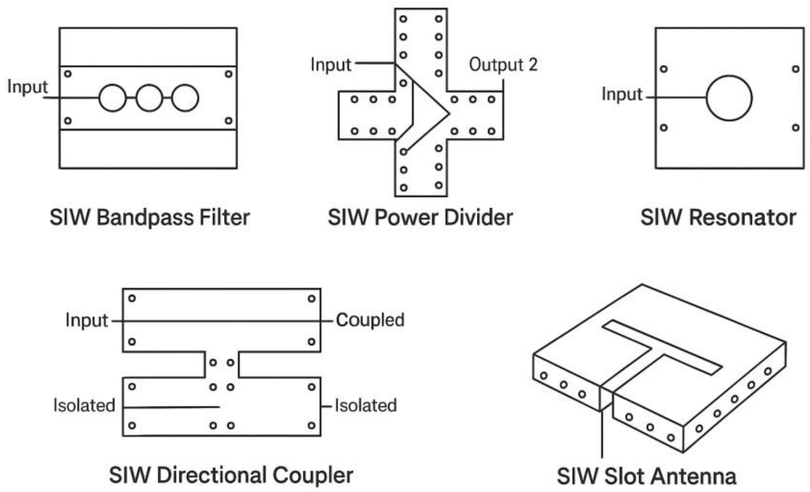

Fig 3. Substrate Integrated Waveguide (SIW) technology That used in 5G Microwave Components. (Prepared by the Author)

The 5G components that the SIW (Substrate Integrated Waveguide) is involved in, as well as the functionality that the SIW performs within each component, can be summarized in the (Table 1). From table 1, We find that; the Substrate Integrated Waveguide (SIW) is involved in many components of the 5G Microwave and offers reduced signal loss compared to traditional lines such as microstrip, easy integration with components on the same substrate, good support for mmWave frequencies (24–100+ GHz range), and improved thermal and electromagnetic performance.

4.4. The scientific, technical, and industrial value of using SIW technology in a 5G environment

4.4.1. The Scientific and Technical Value of SIW Technology in the 5G Environment

Advanced Electromagnetic Integration: SIW provides an ideal environment for transmitting electromagnetic waves at high frequencies (especially mmWave) without the need for traditional metal routers, while maintaining the desired propagation patterns (such as TE_{10}), thus enhancing signal accuracy and speed.

Table 1. Substrate Integrated Waveguide within 5G Components and its functions.

No	Component	SIW role within the component (function)
1	Power Dividers	Distributes the signal evenly or in a specified ratio among multiple outputs while minimizing loss.
2	Filters	Passes a specific frequency range and blocks unwanted frequencies with high accuracy and stability.
3	Waveguides	Directs the electromagnetic signal within the system with high efficiency and low loss.
4	Phase Shifters	Modifying the signal phase within the beamforming systems in antenna matrices.
5	Resonators	Generates a resonance at a specific frequency used in filters and vibrations.
6	Combiners	Merging multiple signals into one path without significant loss or unwanted overlap.
7	Directional Couplers	Isolation and division of signals to monitor them or for control and guidance uses.

8	Frequency Multipliers	Efficient generation of frequencies efficiently within the wave tracks.
9	Switches	Directing signal to different paths in the system, especially in multi -ports.
10	Amplifier Feed Lines	Modifying the signals efficiently using a low -loss path and engineering fit.
11	Integrated Antennas	Feeding the antenna with a directed signal with good radiation efficiency and reducing interference.

Efficiently Supports High Frequencies: SIW has lower losses than microstrip lines at high frequencies, making it an ideal choice for designing 5G systems based on the 24 GHz, 28 GHz, 39 GHz, and other millimeter wave bands.

Miniaturization and PCB Integration: SIW components can be implemented on printed circuit boards, allowing them to be integrated directly with other active and passive circuits, reducing the need for interconnection via cables or separate components.

Improving the performance of smart systems: SIWs effectively support beamforming and smart antenna array technologies, enhancing network coverage efficiency and reducing interference in 5G networks.

Reliability and thermal stability: Thanks to their relatively closed structure, SIWs exhibit high resistance to external interference and noise, and possess good thermal stability, which is required for 5G applications operating in harsh environments.

4.4.2. Industrial value of SIW technology

Ease of manufacturing using standard PCB technologies:

SIWs enable the manufacture of high-frequency components using relatively low-cost, conventional manufacturing processes, enhancing the potential for large-scale production.

Reducing system costs:

By integrating components onto a single chip, SIWs reduce the need for external components, contributing to a lower overall system cost.

Enhancing flexibility in industrial design:

The SIW design can be easily customized to meet the requirements of diverse devices such as transceivers, 5G access points, and Internet of Things (IoT) devices.

4.4.3. The Practical Industrial Applications of SIW Technology

Bandpass/Stopband Filters: SIWs are used to design precise filters that separate frequency channels in 5G wireless communication systems, with low insertion losses and high-specificity performance.

Integrated Antennas: SIWs are used to design slot antennas or integrated slot antennas on PCBs for high-frequency applications, such as transmitting and receiving stations in towers or smart cars.

Power Dividers and Couplers: They are used to distribute signals evenly across multiple paths within data transmission or reception units in base stations.

High-Q Resonators: They are used in the design of precision sensors, or as components in filters or oscillators in mmWave systems.

Integrated Transceiver Modules (TRx Modules): In small cells and mobile devices, SIWs are used to combine antennas, signal dividers, and frequency amplifiers into a single structure.

5. Conclusion:

Substrate Integrated Waveguide (SIW) technology is a superior choice for microwave component design in 5G systems, especially in high-frequency bands such as mmWave, as it offers high transmission efficiency, low loss, and good integration with printed circuit boards. Compared to technologies such as microstrip, coplanar waveguide (CPW), and traditional hollow waveguides, SIWs offer superior performance at higher frequencies, reduced unwanted radiation, and ease of integration into miniaturized systems. However, each technology has its own advantages depending on the application: microstrip and CPW are better suited for lower frequencies and lower cost, while hollow waveguides offer higher efficiency but require complex size and manufacturing. Depending on the nature of each component in a 5G system, the most suitable technology varies depending on the requirements in terms of frequency, efficiency, size, and cost.

5.1. Summary of Results:

- SIW technology is used as a transmission medium in high-speed circuits, antennas, comparators, and dividers.

- SIW technology is small, inexpensive, non-dimensional, and can be easily integrated with flat transmission lines, and easy to manufacture, minimal loss and maximum power handling capacity.

- SIW technology achieves high efficiency at high frequencies (mmWave) with low radiation loss.

- SIW technology enables excellent integration with printed circuit boards (PCBs) thanks to its in-substrate construction.

- SIW technology offers performance similar to traditional hollow guides, but with a smaller size and easier manufacturing.

- SIW technology features good impedance and effective isolation between components, enhancing routing and control accuracy.

- SIW technology is ideally suited for 5G applications such as filters, antennas, dividers, and directional couplers, and it is scalable and repeatable, facilitating industrial production in large quantities.

5.2. Recommendations:

SIW technologies are recommended for use in advanced and complex 5G systems, particularly in base stations, radar systems, and beamforming antennas. Precise simulation tools (such as HFSS or CST) are recommended to fine-tune the design and reduce development time for SIW technology.

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