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OPTIMIZING FILTER CHARACTERISTICS VIA CIRCULAR CAVITY DESIGN IN SUBSTRATE INTEGRATED WAVEGUIDES

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Abstract

The increasing demand for compact, low-loss, and high-performance microwave filters in modern wireless systems presents challenges in achieving miniaturization without compromising signal quality. This work proposed the design and analysis of a Substrate Integrated Waveguide (SIW) bandpass filter utilizing a circular cavity structure. The objective is to optimize the filter's performance in terms of bandwidth, centre frequency, return loss (S11), and insertion loss (S12). A key focus is placed on the TE21 resonant mode, which significantly influences the electromagnetic response of the circular cavity. The resonant behaviour is governed by critical geometric parameters, including the cavity radius, via diameter, via spacing, and feedline dimensions. The filter is designed to operate at 2.4 GHz; a frequency commonly used in wireless communication systems. A Taconic CER-10™ substrate, measuring 0.64 mm in thickness and possessing a dielectric constant of 10, is utilised to attain compactness and superior performance. Electromagnetic modelling findings indicate a return loss (S11) of -18.02 dB and an insertion loss (S12) of -1.38 dB at the designated frequency, signifying effective impedance matching and little signal attenuation. Compared to conventional rectangular SIW filters, the proposed circular cavity configuration achieves improved field confinement and reduced footprint, highlighting its novelty and practical advantage. To validate the design, fabricated prototype measurements are compared with the simulated results. The comparison confirms the accuracy of the simulation model and highlights the potential of circular SIW cavity structures in developing efficient and compact microwave filters for modern communication systems.

Keywords: Band pass filter, Circular cavity, Resonator, Substrate integrated waveguide, Tunable filter.

1. Introduction

The realization of planar rectangular waveguides is now possible through the innovative Substrate Integrated Waveguide (SIW) technique, initially developed in [1]. Over the years, this technology has been extensively implemented in the industry, particularly for high-density integration of microwave and millimetre-wave subsystems. SIW technology enables the creation of Substrate Integrated Circuits (SICs), providing a platform to integrate all microwave and millimetre-wave active and passive components on the same substrate, including amplifiers, oscillators, filters, antennas, and couplers [2, 3].

The sidewalls of a thin rectangular waveguide filled with dielectric material are simulated by rows of narrowly spaced metallic vias between two parallel planes in SIW technology [4]. SIW is characterised by its low loss, high power capacity, low profile, and simplicity of integration. The rapid advancement of low-cost microfabrication techniques, including substrate processing - including via developments and hole formations - has facilitated the planarization of non-planar structures [4, 5].

To attain enhanced channel selectivity, several resonators are generally necessary, leading to increased insertion loss along the transmission path, as the insertion loss is roughly proportional to the quantity of resonators employed in a filter's design. A band-pass filter, consisting of resonating components like cavities, necessitates several high unloaded quality factor (Qu) resonators to provide minimal insertion loss and reduce the noise figure. The unloaded quality factor of a microwave resonator is often related to its volume and expense. Consequently, a compromise consistently exists between performance specifications and development expenses in filter design and production [6].

Several techniques are employed to excite electromagnetic waves into a cavity, such as using patches and 50-ohm microstrip feed lines connected to a probe The SIW filter in this paper employs a triangular-shaped probe. In order to accomplish low loss, circuit miniaturisation, and convenient wave excitation, the design incorporates the concept of vertically coupled cavities. Additionally, the resonant cavities can be arranged vertically in multilayer substrates, in contrast to horizontal surface arrangements that increase the size of the circuit. Hence, a circular cavity design based on two layers of substrates with 50-ohm microstrip feed lines at the input and output, connected to a triangular probe, is used to excite the TE21 mode wave.

Conventional circular waveguide devices continue to be mainstream for microwave and millimetre-wave systems. However, their bulky size and inability to integrate with planar technology limit their use in next-generation wireless devices. Additionally, waveguide techniques cannot be used to reduce weight and volume, and post-fabrication processes like tuning and assembling pose significant challenges and costs for manufacturers compared to SIW [7-9]

This project has three main objectives: to design an SIW circular cavity filter operating at 2.4 GHz using a Taconic CER-10™ substrate, to investigate the filter's performance based on parameters such as return loss (S11) and insertion loss (S12), and to verify the simulation results through fabrication. Verification is necessary to identify discrepancies between the simulated and fabricated S-parameters.

Despite extensive research on SIW filters and various cavity configurations, limited studies have focused on optimizing circular cavity SIW filters that exploit the TE_{21} mode for improved bandwidth and return loss performance. Most prior works emphasize rectangular or folded cavity structures, which, while effective, often result in higher insertion loss or larger footprints. The absence of systematic analysis on how circular cavity parameters - particularly probe geometry and layer configuration - affect the resonant behaviour creates a clear research gap. This study addresses this gap by proposing and experimentally validating a compact circular SIW filter designed at 2.4 GHz, emphasizing the correlation between theoretical modelling, electromagnetic simulation, and fabrication outcomes.

In this work, the design of the SIW circular filter is to be validated through simulation and measurement. The filter is designed on a Taconic CER-10™ substrate with $\varepsilon r = 10$, metal thickness of 0.035 mm, and substrate height of 0.64 mm, operating at 2.4 GHz in TE21 mode. The design will be executed using ANSYS HFSS software to simulate the S-parameters. Following design and simulation finalization, the layout will be created using Advanced Design System (ADS) and the dimensions locked before fabrication. Post-fabrication, the filter's performance will be measured using a Vector Network Analyzer (VNA) to compare the simulated and fabricated responses. While this work applies established Substrate Integrated Waveguide (SIW) principles, its novelty lies in the optimization and practical realization of a circular cavity configuration that enhances compactness and performance without introducing a new analytical model. Rather than proposing a new design algorithm, the focus of this study is to bridge the gap between theoretical modelling, full-wave electromagnetic simulation, and experimental validation to achieve an efficient and manufacturable SIW bandpass filter.

The proposed circular cavity topology provides an innovative approach that improves electromagnetic field confinement and impedance matching compared to conventional rectangular SIW filters. By incorporating triangular probe coupling within the circular cavity, the design achieves superior control over resonant frequency and bandwidth while maintaining a compact structure. This improvement demonstrates a practical and experimentally validated advancement over existing SIW filter designs.

The main contribution of this work lies in establishing a practical design methodology for circular cavity SIW filters that unifies theoretical analysis, electromagnetic simulation, and fabrication validation. Unlike previous studies focusing mainly on rectangular or linear cavity structures, this research demonstrates a circular configuration that achieves better field confinement, reduced footprint, and reliable performance. The proposed design and validation approach can serve as a useful reference for future SIW-based filter development targeting compact and energy-efficient microwave systems.

2. Literature Review

Microwave filters are critical components in signal processing systems, primarily used to eliminate unwanted signal components. Filtering involves the suppression - either partial or complete - of specific frequency components, thereby enabling the retention of desired signals while reducing background noise and mitigating interference.

Among various types of filters, the band-pass filter is widely employed to allow signals within a certain frequency range to pass while attenuating those outside the range. These filters are typically realized by combining low-pass and high-pass filters. An ideal band-pass filter exhibits a flat passband with uniform gain and zero attenuation and provides complete rejection of out-of-band frequencies. The transition between the passband and the stopband is ideally instantaneous. The bandwidth of such a filter is defined as the difference between the upper and lower cut-off frequencies [10].

Recent advancements in microwave engineering have led to significant interest in integrating waveguides within printed circuit board (PCB) substrates. This approach has given rise to Substrate Integrated Circuits (SICs), a class of transmission lines that offer performance levels between traditional waveguides and planar circuits. The most prominent type of SIC is the Substrate Integrated Waveguide (SIW) [10]. SIW technology has facilitated the development of various high-frequency devices, such as filters, antennas, mixers, oscillators, and transitions to other planar structures [11, 12].

SIW structures present several advantages over traditional planar circuits. They exhibit lower insertion loss and higher quality factors, often an order of magnitude greater than those in microstrip or coplanar waveguide designs. Despite their performance still being inferior to that of circular waveguide systems - which can offer quality factors up to ten times higher than SIWs - SIWs are more attractive for compact and low-cost designs. They are easy to fabricate, integrate seamlessly into planar circuits, and benefit from wavelength reduction due to the dielectric-filled medium, allowing a reduced physical footprint [13-15].

The development of SIW-based systems has followed a systematic design methodology, employing algorithms, simulation tools, and pseudocode-based modelling approaches. These methods are often accompanied by structured testing and data acquisition processes [16]. The extensive body of literature supports the efficacy of SIW in various applications, as demonstrated by multiple experimental validations, figures, and tabular data across various studies [17-19].

3. Methodology

The methodology is thus divided into two parts: simulation and fabrication, ensuring a comprehensive approach to the design and verification of the SIW circular cavity filter. The simulation involves detailed software-based design and testing, while the fabrication part includes practical assembly and verification to ensure the design meets the desired specifications.

3.1. Simulation and fabrication

This section outlines the design workflow and the software tools used for simulating and analysing the band-pass filter. The process begins with creating a flowchart to guide and ensure the filter’s performance meets the desired specifications. Both theoretical analysis and simulation are involved in the design. ANSYS HFSS is used to simulate the filter response using S-parameters. Once the simulation is complete, the design layout is transferred to Advanced Design System (ADS), where the physical dimensions are finalized before fabrication.

Figure 1 shows the design flowchart. The process starts with background research and defining the project’s problem statement. Next, the appropriate type of filter is selected based on the application. Calculations for the circular cavity radius are performed, followed by selecting a suitable substrate. After reviewing related works, the design is developed and simulated in HFSS. The filter's performance is analysed using S-parameters to ensure the electric field matches the desired frequency. If the simulation results meet the specifications, the design is optimized and finalized. The layout is then completed in ADS, and the design files are exported as Gerber files for fabrication. After fabrication, connectors are soldered to the input and output ports. The two substrate layers are aligned and assembled, then left to dry. Once dry, the connectors are inserted properly. Finally, the assembled filter is tested using a Vector Network Analyzer (VNA). The measurements - such as return loss, insertion loss, resonant frequency, and bandwidth, are compared with the simulation results to verify the design accuracy.

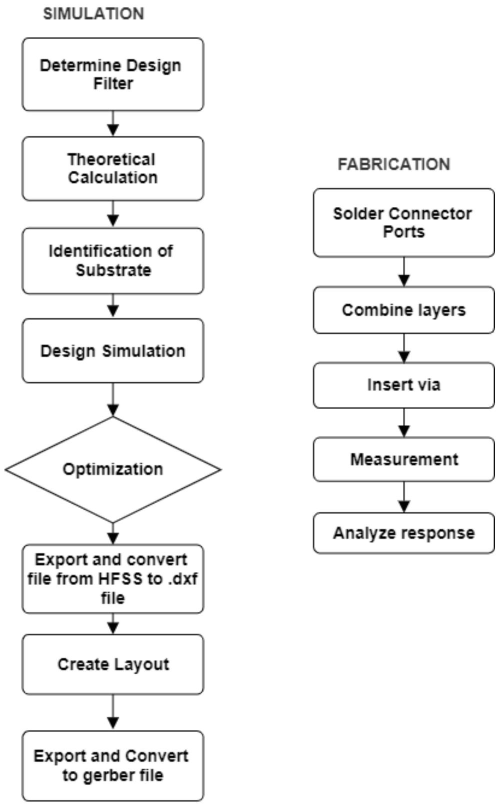


Fig. 1. Flowchart for simulation design.

3.2. Design analysis

This section provides an overview of the design calculations. The design of the SIW circular cavity begins with the equation relating the resonant frequency to the dimensions of the circular cavity for a chosen mode. This relationship can be calculated using the following general equations:

$$f_r = \frac{1}{2\pi\sqrt{\mu_r \varepsilon_r}}\sqrt{\left(\frac{x'_{mn}}{r}\right)^2 + \left(\frac{p\pi}{\Delta h}\right)^2}\ TEmnp \qquad (1)$$

where, μ_r: permeability of the dielectric filling the cavity, ε_r : permittivity of the filling material, r : radius, x'_{mn}: the m_{th} root of Bessel function derivative of n_{th} order, p : 1,2,3…., f_r : resonant frequency of TE_{mnp} –mode.

In this single mode circular cavity, TE_{21} mode is selected for operating frequency which the values of x'_{mn} are set based on the nth roots of Bessel function, ε_r and μ_r are assigned as 8.854×10^{-12} F/M and $4\pi \times 10^{-7}$. The resonant frequency f_r is aimed at 2.4 GHz which the value of the radius r can be calculated based on the formula given in (1). The resonant frequency of the circular cavity operating in the TE_{21} mode can also be expressed as.

$$f_{TE21} = \frac{c}{2\pi r\sqrt{\varepsilon_r}} x \, x'_{21} \tag{2}$$

$$f_r = \frac{0.159}{\sqrt{\mu_r \varepsilon_r}}\left(\frac{3.054}{r}\right) \tag{3}$$

$r = 61$ mm

where c is the speed of light, r is the cavity radius, ε_r is the substrate permittivity, and X'_{21} is the root of the derivative of the Bessel function corresponding to the TE_{21} mode.

This relationship provides a theoretical estimation of the resonant frequency and was used as the initial design foundation. The derived frequency was further refined through simulation-based optimization in ANSYS HFSS to ensure accurate resonance at 2.4 GHz.

The theoretical resonant frequency calculated using Eq. (1)-(3) serves as the initial design reference. However, due to fabrication tolerances and dielectric constant variations, these theoretical values were refined through iterative simulation in ANSYS HFSS. The optimization process involved adjusting the cavity radius and feedline dimensions until the simulated S_{11} and S_{12} responses aligned closely with the target resonant frequency of 2.4 GHz. During fabrication, slight dimensional deviations were recorded and compensated for in post-simulation validation to ensure consistency between the theoretical model and the measured prototype response.

In the SIW design, the via dimensions play a crucial role in maintaining electromagnetic field confinement and minimizing radiation leakage. The pitch (p) and via diameter (d) were selected based on standard SIW design criteria, where $p \leq 2d$ and $p \leq 0.25\lambda g$ to ensure low leakage and good wave propagation. In this work, the via diameter was set to 0.8 mm and the pitch distance to 1.6 mm, satisfying these design constraints. These parameters were optimized during simulation to achieve minimal insertion loss while maintaining structural integrity and compactness of the circular cavity filter.

3.3. Design structure

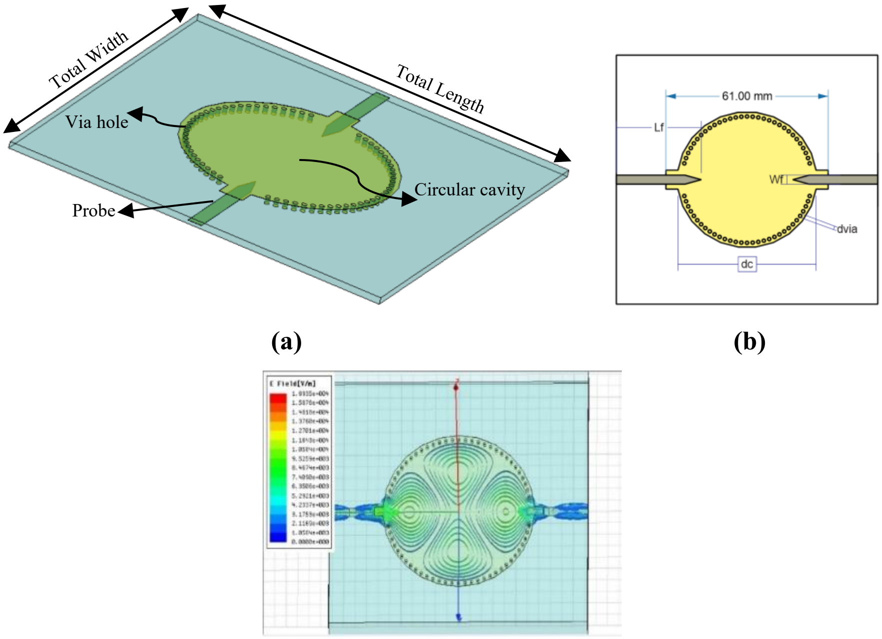
The configuration of the proposed filter is designed to enhance filter performance. The input and output ports are located in the second layer of the structure, which consists of three layers. Triangular sensors are strategically inserted into the cavity on both sides along the circumferential surface of the waveguide and connected to the feed lines at these ports. Table 1 provides the design parameters used for the circular cavity filter. These parameters are critical in determining the filter's performance characteristics, including its resonant frequency, return loss, and insertion loss. The dimensions and material properties, such as the permittivity of the substrate (Taconic CER-10 with $\varepsilon_r = 10$), directly influence the filter's behaviour.

Table 1. Design parameters.

Design parameters	Symbol	Value
Diameter of cavity,	d_c	61 mm
Height of substrate	tsub	0.64 mm
Diameter of via	dvia	1.06 mm
Width of feed line	wf	3.54 mm
Length of feed line	Lf	25 mm

Simulations were conducted to evaluate the performance improvements offered by this topology. Figure 2(a) shows the design of the proposed filter created using the ANSYS HFSS software. The simulation environment includes the layout of the filter, highlighting the positioning of the input and output ports, the resonant cavity, and the metallic vias.

The design aims to achieve a resonant frequency of 2.4 GHz by optimizing the physical parameters of the cavity and the feed lines. While Fig. 2(b) illustrates the E-field distribution and matching from the input to the output ports. Proper E-field matching is crucial for minimizing reflections and ensuring efficient transmission through the filter. The figure indicates successful matching, which is expected to result in low return loss (S11) and minimal insertion loss (S12).



(a)

(b)

(c)

Fig. 2. (a) Configuration of circular cavity filter (b) layout of the proposed filter (c) E-field matching from input and output ports.

4. Results and Discussion

In the design, two controlling parameters, the length and width of the probe are used to adjust the filter's frequency response. These parameters are varied while keeping the other dimensions constant. Performance analyses are based on the centre frequency resonance, insertion loss (S12), and return loss (S11) parameters. Comparison between simulation and fabrication results are shown in Fig. 3. The return loss (S11) signifies the amount of power reflected back to the source. Reduced values indicate superior matching and less power reflection. The computed return loss of -18.0192 dB at 2.4 GHz indicates superior performance. The recorded return loss of -13.5875 dB at 2.4050 GHz, while somewhat exceeding the simulated value, demonstrates satisfactory performance, signifying efficient fabrication and limited divergence from the design specifications.

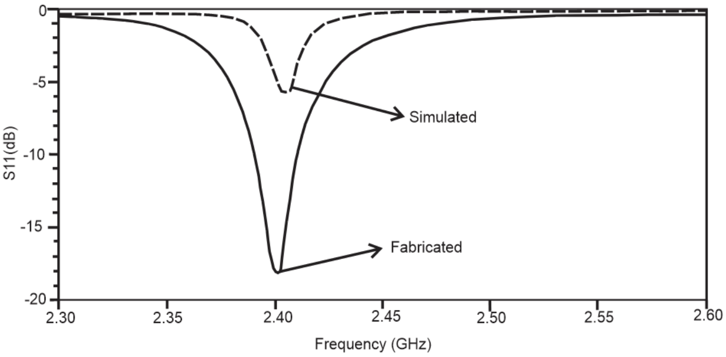


Fig. 3. S11 return loss between simulated and measured.

Insertion loss (S12) represents the loss of signal power resulting from the insertion of the filter into the transmission path. Lower insertion loss indicates better filter performance. The simulated insertion loss of -1.3762 dB at 2.4 GHz is quite low, indicating efficient transmission. The measured insertion loss of -8.1458 dB at 2.4050 GHz is slightly higher but still within acceptable limits, confirming that the filter is performing as expected has shown in Fig. 4. Table 2 indicate the comparison results of S11 and S12 between simulated and fabricated.

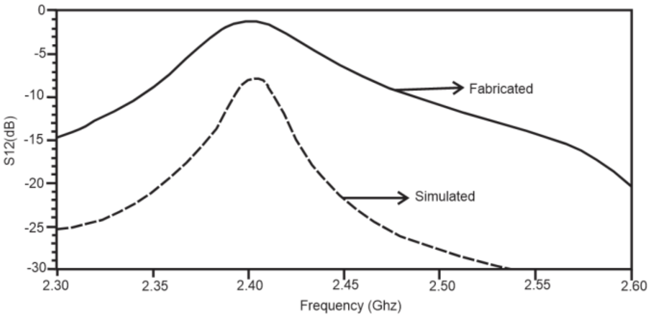


Fig. 4. S_{12} insertion loss between simulated and measured.

Although minor discrepancies are observed between the simulated and measured responses, these deviations remain within an acceptable range for SIW prototype fabrication. The differences are primarily attributed to fabrication tolerances, connector alignment errors, and slight variations in the dielectric constant of the Taconic CER-10™ substrate. In addition, small inconsistencies in via dimensions, solder joints, and surface roughness can alter the effective electrical length of the feeding line, causing minor shifts in the resonant frequency and insertion loss. Such variations are common in high-frequency hardware implementations and will be minimized in future work through improved machining accuracy and calibration procedures. Overall, the close agreement between simulated and measured trends validates the reliability of the proposed design.

Table 2. Comparison results between simulated and measured.

Frequency (GHz)	Return loss, S11 (dB)	Insertion loss, S12 (dB)	Indicator
2.4 GHz	-18.0192 dB	-1.3762 dB	Simulated
2.4050 GHz	-5.3625 dB	-8.1458 dB	Fabricated

In addition to the S_{11} and S_{12} parameters, other key performance metrics such as bandwidth and quality factor (Q-factor) were also analysed to ensure a comprehensive performance evaluation. The measured −3 dB bandwidth is approximately 160 MHz, corresponding to a fractional bandwidth of 6.7%. The estimated unloaded Q-factor is around 150, indicating moderate selectivity suitable for 2.4 GHz applications. Group delay analysis further confirms stable phase response across the passband, signifying good signal integrity and minimal distortion.

Although the measured and simulated results exhibit good agreement, the analysis is based on single-fabrication data. The absence of multiple measurement samples limits the statistical evaluation of reliability. Variations in soldering, connector alignment, and substrate adhesion may introduce minor inconsistencies in the measured results. Future work should therefore include multiple prototype fabrications and repeated VNA measurements to quantify experimental uncertainty and distinguish between random measurement variations and systematic fabrication effects.

The results indicate that the SIW circular cavity filter design and fabrication are successful. The simulated and measured return loss and insertion loss values are in good agreement, with minor discrepancies likely due to fabrication tolerances and measurement uncertainties. The use of Taconic CER-10 substrate and precise dimensional control contribute to the filter's performance, achieving the targeted resonant frequency of 2.4 GHz. Figure 5 displays a photograph of the suggested filter.

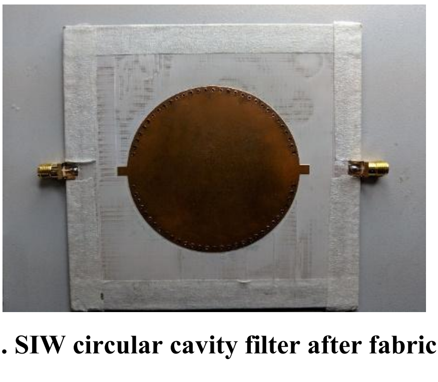


Fig. 5. SIW circular cavity filter after fabricated.

5. Conclusions

In this study, the proposed circular cavity SIW bandpass filter demonstrated good agreement between simulated and measured results. The utilization of the TE_{21} resonant mode improved field confinement and impedance matching, achieving a return loss of −18.02 dB and an insertion loss of -1.38 dB. These findings validate the accuracy of the simulation model and confirm the practicality of the design.

The configuration, which incorporates strategically positioned triangular probes, enables precise control of the filter's frequency response. By adjusting the length and width of these probes, the centre frequency, insertion loss (S_{12}), and return loss (S_{11}) can be effectively tuned, allowing enhanced design flexibility. Although the current design is optimized for a single operating frequency of 2.4 GHz, the proposed circular SIW cavity topology offers promising scalability for frequency-agile or multi-band operation. By integrating varactor diodes, PIN switches, or reconfigurable resonant elements, the filter can be adapted for tunable responses across various frequency bands. Overall, the results demonstrate that the circular cavity SIW configuration provides a practical and efficient approach for realizing compact, high-performance microwave filters.

This work contributes to the advancement of SIW technology by providing a robust framework for designing filters with improved efficiency and reliability. Future research can build upon these findings to explore additional configurations and applications, further enhancing the versatility and performance of SIW-based filters.

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Nomenclatures

f_0	Center frequency
f_r	resonant frequency of TE_{mnp} –mode
p	1,2,3….
R	Radius
x'_{mn}	the m_{th} root of Bessel function derivative of n_{th} order

Greek Symbols

ε_r	Dielectric constant
ε_r	Permittivity of the filling material
μ_r	Permeability of the dielectric filling the cavity

Abbreviations

ADS	Advanced Design System
S11	Return Loss
S12	Insertion Loss
SIC	Substrate Integrated Circuits
SIW	Substrate Integrated Waveguide
TE21	Transverse Electric Mode
VNA	Vector Network Analyzer

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