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Research Article

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Posted Date: July 15th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1830533/v1

Design and Analysis of Compact Substrate-Integrated Waveguide (SIW) Cavity Resonator Based Microfluidic Biosensor for X-Band Applications

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Abstract

Biosensors are compact miniaturized devices to measure the biological samples based on the molecular structure and convert the same to electronic signals. The substrate Integrated Waveguide (SIW) cavity based resonators loaded with a circular cavity can be used as a biosensor in a non invasive manner to detect the biological tissues in the sample with better efficiency and miniaturized structure.The biosensing samples may vary from proteins to enzymes which has gained a huge response in the industries likes medical, agriculture, food processing industry and many more over the decades. The substrate material of antenna is designed with Rogers RT/Duroid 5870 which has the dielectric constant of 2.33. The Rectangular patch antenna is then loaded with the SIW vias for an enhanced performance of S parameter from -17.21 dB to -44.88dB operating at the X band (8 to 12 GHz) frequencies. The microwell made from the Polydimethylsiloxane (PDMS) material is inserted into the patch infrom of circular slot to achieve the biosensing application. The microwell based SIW cavity is then simulated for different diameters of PDMS to improve the S11 parameter and Voltage standing wave ratio. The fabricated antenna is tested to work in the TE110 mode at a resonant frequency of 12.12GHZ with a improved return loss characteristics of -42.45 dB

Keywords: Biosensors, microwell, substrate integrated waveguide (SIW), Polydimethylsiloxane (PDMS)

1 Introduction

BioMEMS or Biosensor are the measuring devices which detects specific molecules for informing the user about a certain disease and also to detect the chemical or biological materials in the environment. The measured molecules are named as biomarkers. The biosensor works based on the sample taken from the human body in case of invasive measurements few examples like a drop of blood or the tissues taken from the lungs of the human body like fibroblast cells [1] are analyzed. In case of non invasive measurements the biosensors are made to be worn by the individual for continuous monitoring of the physiological parameters. The biosensors can help the patients and the doctors with the information they need in order to optimize the treatment, reduces the continuous visit to the hospitals and also helps in continuous monitoring of health by enabling the self management of health and disease. In general a biosensor consists of four major components molecular recognition process from the samples collected from the human body, signal generator, disposable sensor device and a reader instrument with the display as shown in the Fig. 1. Molecule in the biosensors binds to the biomarkers where the recognition molecules maybe aptamers, enzymes or antibodies this leads to signals like optical, electronic or a magnetic signals which happens in a disposable sensor device where the molecules comes together. Finally the radio instrument measures the signal and transmits it into information which is meaningful for the user. Similarly many diseases and many biomarkers with different requirements are available which paves the way for many technological ways to design a biosensor. The biosensors can be classified into types based on its nature of sensing as Medical Telesensors, Micro-cantilever and Bioreporters[2].

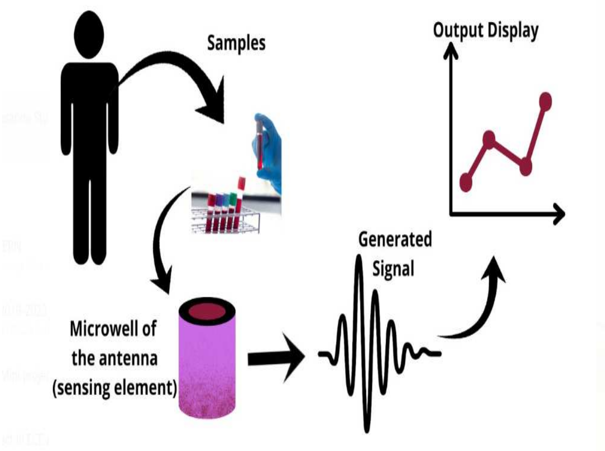

Fig. 1: Basic biosensing module

The material properties of biosensors can vary from biologically available tissues to the artificial polymers. The material classification can range from polymeric materials to biological materials [3].The technology is running behind the compact nature of biosensors as they provide higher sensitivity, reduction in volumes of test samples with good accuracy, manageability and trimness of the system. There are wide detection methodologies available in the biosensing application which predominantly falls under these categories like mechanical, electrical and optical [3] as shown in the Fig. 2. The Figure depicts the most important aspects of detection modalities.

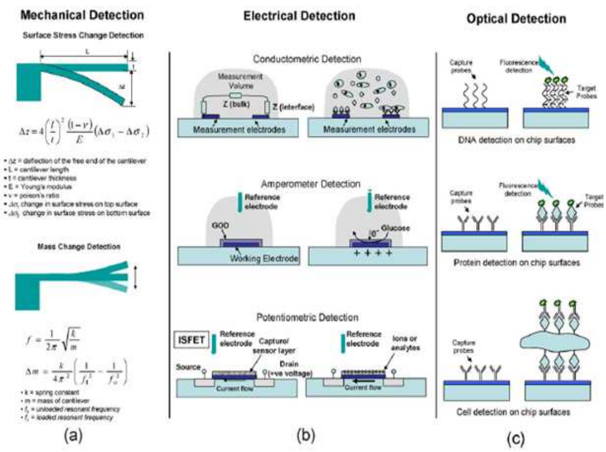

Fig. 2: key aspects of detection modalities in BioMEMS and biochip sensors[3].

The Substrate Integrated waveguides (SIW) [4] are more promising than the classical planar antennas by possessing the features like low cost, high density of integration, low losses, good power handling capabilities, complete shielding and packaging. In recent years the substrate integrated waveguide based antenna structures have gained interest in the areas like millimeter wave antennas and terahertz communication [5].The SIW antennas are also used in wide range of applications as discusses in the study given below. SIW based cavity backed slot antenna is used in wireless transceivers for communication in the vehicles[6]. The wearable technology is an area which is gaining a huge response from the recent decades. The SIW applications have its footprints in the wearable domain of Wireless Body area networks (WBAN) [7],[8]. SIW cavity based diplex antenna with hybrid half mode configuration is used in the on body transceiver [9] with a considerably low SAR value for wearable applications. The planar SIW antennas can also be configured for multiband applications by using cavity backed slot resonators [10].The process of polarization conversion [11] for high efficiency of transmission can also be achieved using the triple layer polarization converter using SIW technology. The SIW based cavity-backed slot antenna [12] which is fabricated and tested for a thin substrate is used for enhancing the bandwidth of the antenna in addition to the compactness in size and its uniform radiation properties. 3D SIW [13] structures consists of a H-plane transmission line model which is orthogonal in nature with the SIW cavity ascended on its surface are used for the millimeter wave application. SIW antennas can be designed and made to work as conformal sensors [14] for the frequency scanning application in the operating range of 28 – 40GHz. SIW metamaterial antenna [14] with the ballistic material is used for developing a helmet used in military applications. SIW antenna with the E band antenna [15] array gives a wider radiating band operating from 71-86 GHz frequency used for mm wave applications.

Antenna biosensors [16] have various advantages and versatile applications.For instance, without the requirement for labelling, chemical change, or physical intrusion, it offers real-time measurement of the electric or magnetic properties of materials at radio frequency. As a result, it has generated a lot of attention in the disciplines of biological research and material science. The goal of the sensing process with the proposed design is to identify changes in the return loss S11 level, relative permittivity (r), and loss tangent (tan) in the resonant band brought on by the samples. The simulation is carried out for the Substrate integrated waveguide with PDMS materials with different diameters resulting in optimal characteristics of Antenna at 2.5mm diameter resonating at 11.26 GHz.The same was compared with a measured result which has an empty circular slot for micro-well or it can act as a micro-container (can be loaded with the biomaterials in realtime) which can be focused to Bio-sensing application.It has good return loss characteristics at the resonant frequency thereby improving the overall efficiency of the antenna. The paper is organised as follows the section 2 describes about the design of a patch antenna and SIW concepts addressing from the design calculations to equivalent circuits and the comparative study of simulated parameters.The section 3 deals with the analysis of measured results followed by the conclusion in the final section.

2 SIW Antenna Design

2.1 Antenna Design

The design is constructed using the material Rogers RT/Duroid 5870 as the substrate. In order to obtain the best results, all possible methods to enhance the efficiency of the antenna are carried out. Initially, a base model with a rectangular patch was stimulated and its resonance was at a frequency of 12GHz with a return loss of -17.2128dB. Then the concept of Substrate Integrates Waveguide (SIW) is introduced alongside the edges of the rectangular patch and the results obtained after introducing the vias significantly improved the parameters like Return loss, VSWR and relative permittivity. The return loss of the antenna was further reduced to -44.886dB and the resonant frequency is at 11.48GHz. The model of the antenna design with and without Substrate Integrates Waveguide is depicted in the Fig. 3. The microwell is then added to the center of the patch for acquiring biomaterials as a small collection compartment.

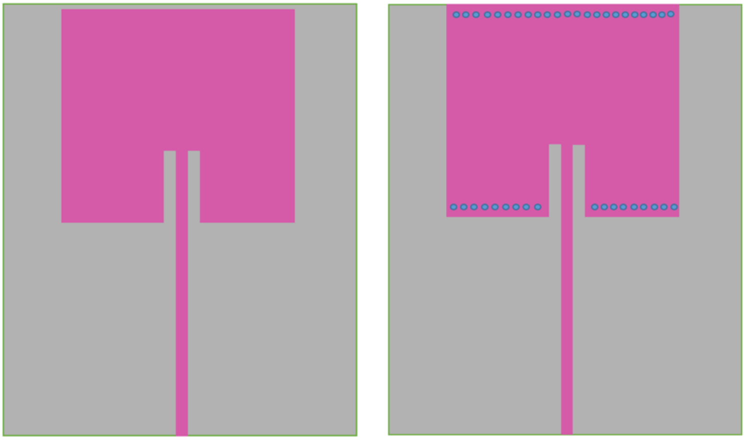

Fig. 3: Antenna design with and without SIW

The layout of a SIW cavity resonator is a rectangular patch in which the feeding mechanism is a blend of microstrip line feed and an inset feed. The vias are designed only alongside the edges of the rectangular patch of the antenna which in turn enhances its performance. The thickness of the designed substrate is hsub = 1.6 mm, dielectric constant = 2.33 and loss tangent tan(δ) = 0.0012. The resonant frequency (fmn) of the proposed SIW cavity resonator can be marked when the thickness of the SIW cavity (h) is significantly less than the width (W) and length (L).

$$fmn = \frac{1}{2\pi\sqrt{\mu\epsilon}}\sqrt{(\frac{m\pi}{Weff})^2 + (\frac{n\pi}{Leff})^2} \tag{1}$$

where ϵ is the permittivity of the dielectric material,μ is the permeability of the dielectric material, Weff is the effective width, and Leff is the effective length of the SIW structure. The integers m and n are the representation of indices, which indicates the modes of operation of the SIW structure.

At the base design the rectangular patch is constructed first, and then arrays of metallic vias are built at the top and bottom of the edges of the patch. The vias connect the metallic design on top which is the patch with the ground plane at the bottom. The electric field is contained within the rectangular patch by the magnetic sidewalls, and these fields are accountable for dielectric perturbation. The optimization of dielectric loss can be done by selecting a good dielectric material. The design factors that determines the performance metrics of Substrate integrated waveguides are the diameter of each via (D), the mid point-to-mid point spacing between two successive vias (pitch (p)), they are calculated using the formula given here below:

$$D < \frac{\lambda}{5} \tag{2}$$

$$P < 2D \tag{3}$$

where λg denotes the guided wavelength in the structure , D is the diameter of each via and p characterizes the center-to-center spacing between any of the two successive vias.

The distance between two vias becomes one of the main concern as it may have leakage losses.The Pitch (p) should be kept low to minimise leakage losses between adjacent vias and also the value of D may affect the return loss of the antenna. The values of p and D are selected, that these concerns are reduced considerably. The sidewall vias form a magnetic wall near the top and bottom edges of the rectangular patch. This aids in concentrating all electric field energy at the centre of the SIW cavity, where it can be used for sensing applications. The height of all vias (hsub) is same as the substrate thickness. After accounting for leakage and radiation losses, the values of D and p are set at 0.5 mm and 0.75 mm, respectively. The rectangular patch size (L x W) is chosen to excite the SIW structure (without the centre hole) in the TE110 as the dominant mode, and it resonates at 11.14 GHz with a return loss of -47.8614dB.

The power is given to the antenna through a microstrip line with an inset feed. The length and width of the microstrip line are selected for an ideal impedance matching with the SIW structure. The length and width of the microstrip line of the designed antenna are Lqt=27.5mm and Wqt=1.75mm respectively. The microstrip line is designed for a 50 Ω compatibility with a Sub Miniature version A (SMA) connector. The dimensions of the inset feed

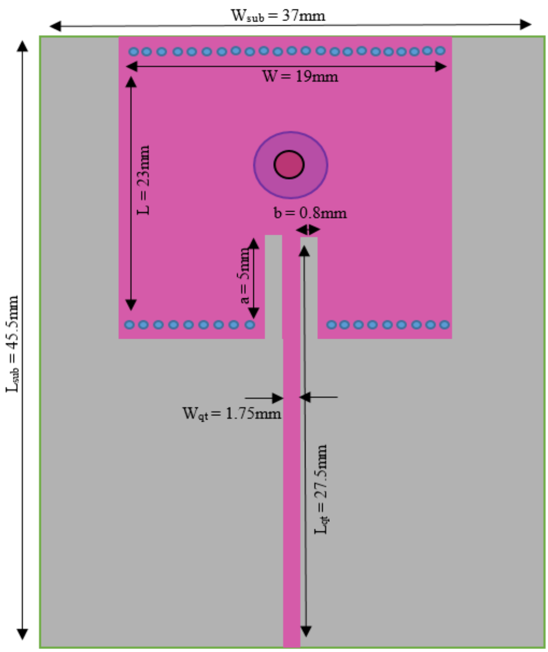

Fig. 4: Antenna specifications

(a x b) are 5mm and 0.8mm. The dimensions of the antenna is shown in the Fig. 4.

2.2 Microwell Design

The microwell is positioned at the center of the rectangular patch because the electric field is maximum at the center. The SIW cavity's maximal electric field is located in the centre. As a result, it is the ideal site for loading the microwell. The microwell is designed to keep the sensor's noncontact feature while taking into account the maximum frequency shift and fabrication constraint. A cylindrical/cup-shaped microcontainer may also be loaded in the SIW cavity's centre since it would allow the maximum amount of electric field lines to travel through the liquid-filled microcontainer, enhancing the interaction with the electric field lines. It would be more convenient to inject/remove the biomaterial from the microwell through a single hole. It also eliminates the requirement for a separate inlet and outlet, making our suggested microwell's design and fabrication simple.

Polydimethylsiloxane (PDMS)[17] based biosenors[16] have become increasingly popular in recent years. PDMS[18], a silicone polymer has attracted scientific attention due to its biocompatibility, transparency, and cost-effectiveness. When the lower end of the microwell[19] container meets the ground plane, a considerable frequency shift occurs. However, this would

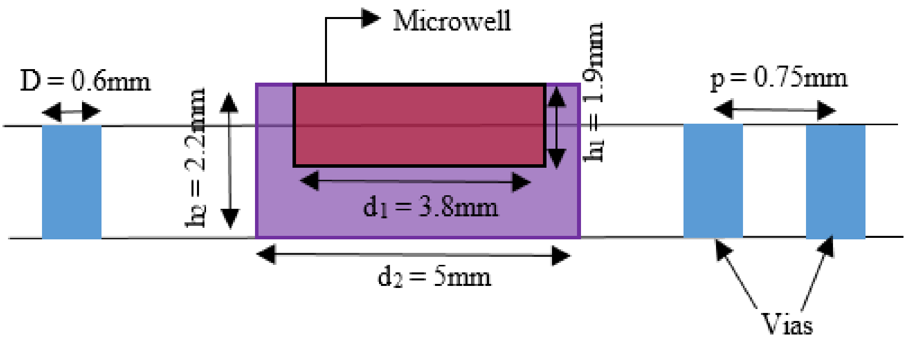

Fig. 5: Microwell specifications

Table 1: Design Specifications

Design parameter	Measurement Value(mm)
Length of the substrate(Lsub)	45.5
Width of the substrate(Wsub)	37
Height of the substrate(Hs)	1.6
Width of the Patch (W)	19
Length of the Patch (L)	23
Width of the microstrip (Wqt)	1.75
Length of the microstrip (Lqt)	27.5
Width of the feed (b)	0.8
Length of the feed (a)	5
Height of the biomaterial (h1)	1.9
Height of PDMS (h2)	2.2
Diameter of the biomaterial (d1)	3.8
Diameter of PDMS (d2)	5
Diameter of the via (D)	0.6
Distance between two vias (p)	0.75

either need the addition of an adhesive bonding layer to the bottom of the microwell, which would result in further losses, or the liquid would lose its non-contact property, in which case the liquid would directly contact the bottom ground. To tackle this issue, the resonance frequency shift is reduced significantly, and the bottom end of the microwell[19] is positioned slightly above the ground plane. The sensor stays noncontact and therefore safe as a result of this. The Fig. 5 shows the specifications of the microwell hole as well as the dimensions of the vias. The height of the microwell is 2.2mm and its radius is 2.5mm. Inside which the biomaterial to be tested is placed. The height and radius of the biomaterial is given as 1.9mm and 1.9mm respectively. Table 1 lists all of the design parameters for our proposed biosensor.

2.3 Equivalent Circuit of microstrip inset feed at the radiating edge

The microstrip inset feed overpowers the restrictions faced by the edge coupled and the gap coupled feed mechanisms. The edge coupled feed leads to impedance mismatch because the requirement of input impedance at the radiating edge of patch is very much higher than the 50 Ω impedance of the feed. The gap coupled feed requires a narrow gap width for handling the coupling power in an efficient manner. The narrow band gap leads to a limitation in the power handling capability and the open ends in the feed gives rise to spurious radiation. The inset feed position and the length of the inset l is selected in such a way that the impedance of the antenna is 50 Ω. The equivalent circuits of the inset feed microstrip patch antenna is shown in the Fig. 6. This feed should be modeled as the coplanar waveguide ground plane of finite size. A detailed study on the microstrip rectangular patch with the different feed lengths l is analyzed in the [20].

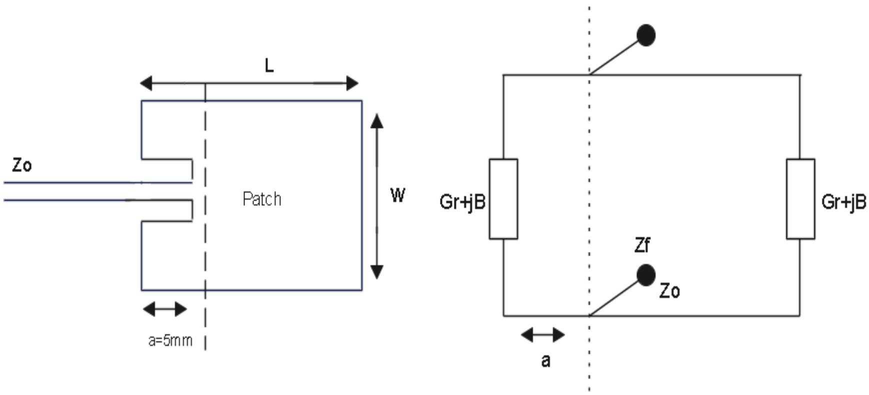

Fig. 6: Equivalent circuit of microstrip insert feed at the radiating edge

2.4 Equivalent circuit of circular slot

A circular slot can be used to model the microwell[19] designed in the patch for detecting biomaterial. The equivalent circuit of the same is depicted in the Fig. 7.The circular slot in the centre of the SIW functions as a cavity-based resonator, resulting in a TEmn mode with the resonance frequency of 12.12GHZ.The lumped elements R, L and C in the equivalent circuits is due to the circular shaped cavity. The Lc and Cc are the coupling capacitance and inductances respectively which is formed due to the SIW[21] cavity and planar transmission line.

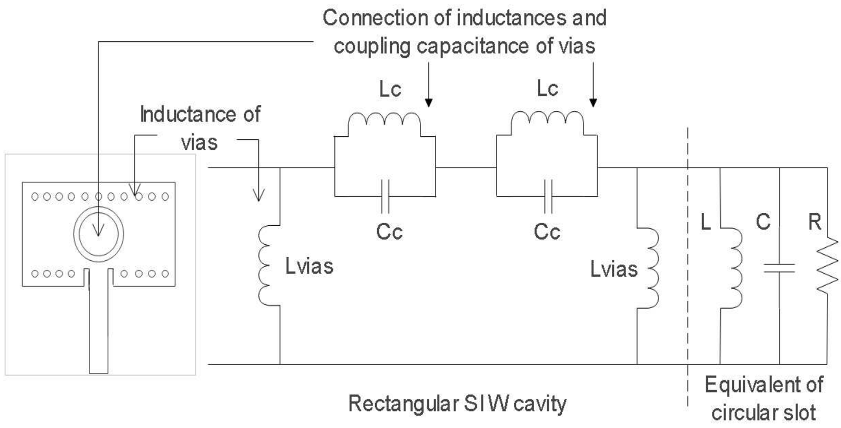

Fig. 7: Equivalent circuit of circular slot

2.5 Working mechanism

The EM waves at the boundaries of the cavity resonator is equivalent to the wave between the parallel plates of the perfect conductor. The square or a rectangular slots can also be modelled as a two element array model. Based on the above behavioural nature the proposed circular cavity based resonator with SIW has its field distribution in TE11 mode at the measured frequency of 12GHz.The measurement result also obeys the analytical modelling value of fc = 6.7GHz at TE11 mode by considering the parameters like relative permittivity as 2.33, relative permeability as 1 for Rogers RT/Duroid 5870 , the waveguide dimensions corresponds to 23mm x 19mm.

2.6 Simulation results

The stimulated results of the base design of the antenna with and without the insertion of SIW are compared. The Fig.8 shows the comparison of the return losses between the two designs. After the introduction of SIW the performance of the antenna has improved undoubtedly. Thus, based on the performance analysis it is proved that SIW has a better efficiency than the normal patch antenna.

The stimulated results of the antenna with the microwell are taken. For the stimulation purpose the antenna with an empty (or air) microwell hole is used. Since the addition of the microwell significantly changes the parameters of the antenna, a comparative study is made by varying the diameter of the PDMS material positioned at the center of the patch. Three values of d2 (diameter of PDMS), 2mm, 2.5mm, and 3mm are chosen and output plot for the return loss, and VSWR are presented.

Input impedance:The input impedance is defined at a given frequency as the relation of a small-signal input sinusoidal waveform voltage across the input

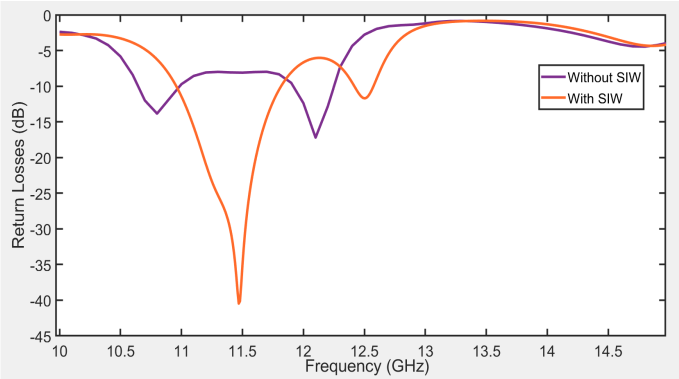

Fig. 8: Return loss(dB) plot of antenna with and without SIW

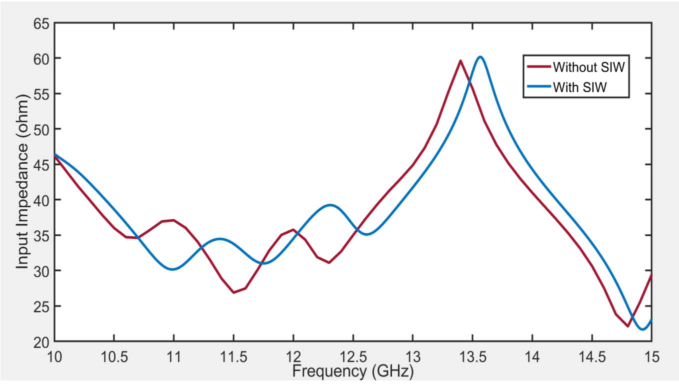

Fig. 9: Input Impedance plot of antenna with and without SIW

terminals to the current that flows into the input. Although it is commonly referred to as impedance, many amplifiers have it as a resistive component.Fig. 9 depicts the real part input impedance of the antennas before and after loading the SIW vias, which is dominant in TE11 mode.

Return Loss: The most significant parameter which determines the performance of the antenna is its return loss. The return loss of the antenna is measured in decibels (dB). In the Fig. 7, the return losses for different values of d2 (the diameter of PDMS material) is stimulated. From the results obtained, the optimal value of d2 is taken as 2.5mm. The stimulated return loss of the antenna is -32.43 dB resonating at a frequency of 11.26 GHz.

VSWR: The Voltage Standing Wave Ratio is another important specification of the antenna. It is the often termed as the other form of representing the return loss of the antenna. The value of VSWR is called ideal if it is lesser than two (>2). When simulated with an empty microwell hole, the value of

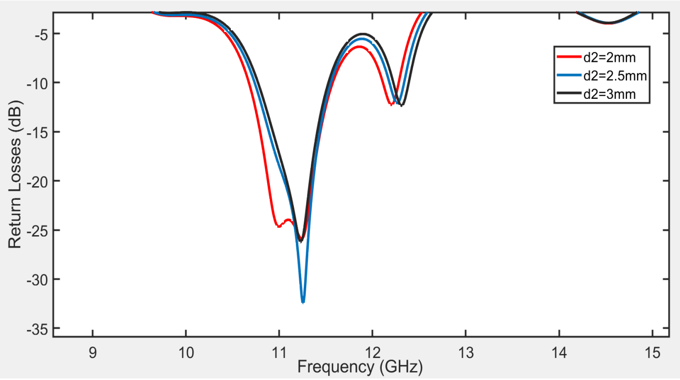

Fig. 10: Return loss(dB) plot of antenna for three different values of d2 (diameter of PDMS)

VSWR at the frequency of 11.26 GHz is lower than the others for the diameter value 2.5mm of the PDMS material. The stimulated result of the antenna at different diameters of PDMS (d2) is shown here in Fig 8.

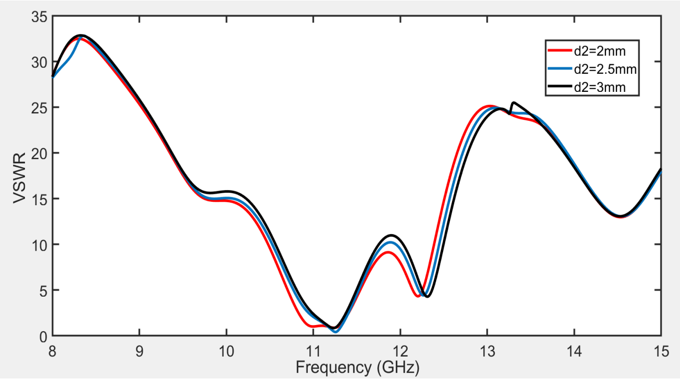

Fig. 11: VSWR of antenna with three different diameters of PDMS material

Relative Permittivity: The relative permittivity of any material is the ratio between the permittivity of that material and permittivity of air. The value of relative permittivity differs from material to material. The permittivity of a material describes how an electric field influences the antenna. When an antenna is placed in a material with a higher permittivity, the needed length reduces, resulting in a small sized antenna. Materials with different values of relative permittivity are compared and the performance of the antenna with the change in material is analysed.Based on an analysis of Er values ranging from 2 to 4, the best suitable substrate was preferred by modelling it with the closest dielectric constant value of 2.5 resonating at 11GHz and yielding a return loss of -35dB (Rogers RT/Duroid 5870).

$$k = \epsilon_r = \frac{\epsilon}{\epsilon o} \tag{4}$$

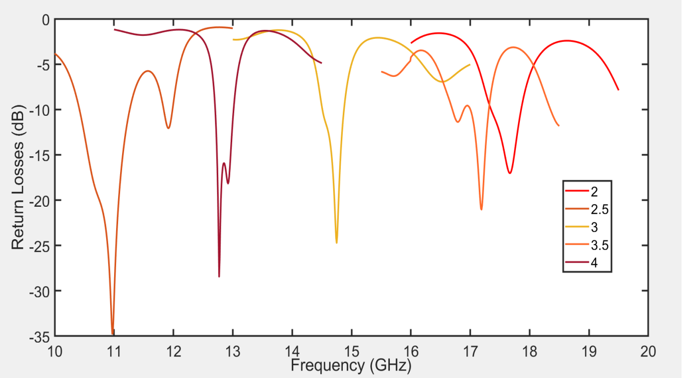

Fig. 12: Return loss for different values of Er

3 Measurement Results and Discussions

The fabricated antenna structure connected to the Vector Network Analyzer(VNA) is shown in the Figure.13. The experimental simulation results of the antenna measuring the S_{11} parameter is compared with the fabricated antenna with the help of E5063A Vector Network Analyzer . E5063A VNA is a product of keysight technologies which helps in testing of passive components like antennas and filters up to the frequency limit of 18 GHz. The measured return loss (S11) performances are then plotted with the simulated results as shown in the Figure 14.The stimulated return loss of the antenna is -32.43 dB resonating at a frequency of 11.26 GHz whereas the measured values shows a shift in resonance frequency of 12.12GHZ with a improved return loss characteristics of -42.45 dB. The disparities in the measured and simulated results such as shift in the frequency or a better return loss are mostly anticipated. The reason behind these dissimilarities are antenna excitation using the SMA connectors, Materials losses, near field scattering of objects and fabrication tolerances.

4 Conclusion

Biosensing device development trends are toward miniaturisation of circuits, non-invasive methods, and integration with microfluidic devices for sample handling. The above challenges should be addressed by an antenna-based

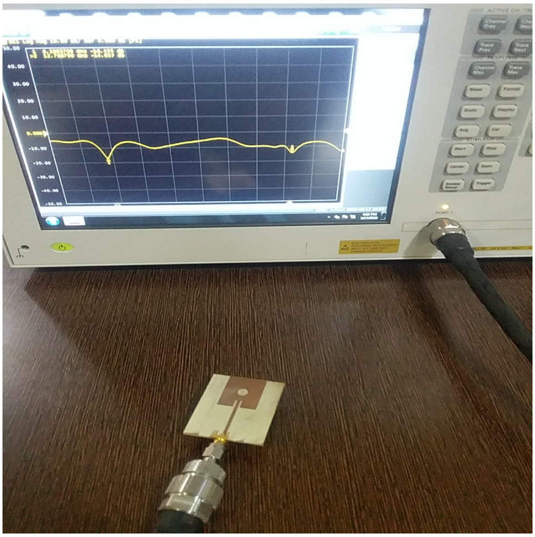

Fig. 13: Image of measuring the output

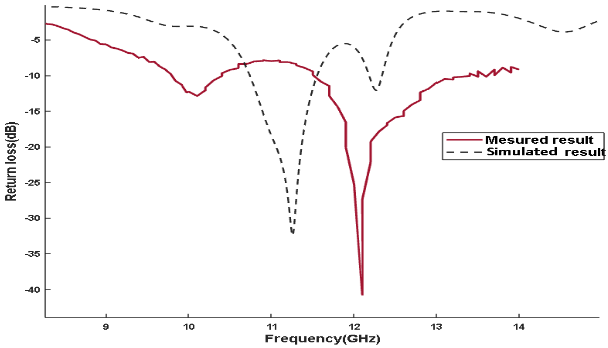

Fig. 14: Comparision

biosensor. The Circuits with SIW (Substrat Integrated Waveguide) are perfectly in line with the global trend and are currently the subject of numerous research topics with direct industrial applications. This paper describes the design of a new slotted antenna structure based on a SIW cavity for Biosensing applications while continuing to work toward a resonant frequency operating in X-band (8GHz-12GHz).The radiation characteristics of the fabricated antenna were tested. The simulated and tested results show a high degree of similarity.The SIW geometry and the parametric study of the innumerable components has resulted in efficient return loss of -42.45 dB at a resonant frequency of 12.12GHZ.

Declaration

The authors declare that they have no conflicts of interest.

Acknowledgments

Funding: There is no funding for this research article.

Availability of data and material

Data sharing not applicable to this article as no datasets were generated during the current study.

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