Scientific Journal of Impact Factor(SJIF): 3.134
e-ISSN(O): 2348-4470
p-ISSN(P): 2348-6406

International Journal of Advance Engineering and Research Development

Volume 2,Issue 3, March -2015

# Design of Tunable Substrate Integrated Waveguide Cavity Resonator in Ku Band

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**Abstract** — *Substrate integrated waveguide (SIW) technology, an emerging and very promising in the field of electromagnetics for design and development of microwave and millimetre wave circuits and components, permits implementation of classic rectangular waveguide components in planar form. The paper presents a design of single layer cavity resonator in Ku band based on SIW technology. The proposed model is a planar SIW reflective cavity resonator designed using circular metallic vias in Naltec substrate with dielectric constant of 3.2 and thickness measuring 0.762mm. Design simulation resulted in the circuit resonating at 12.276 GHz with a return loss of 13 dB. Tuning achieved using a surface mounted varactor coupled to SIW resonant cavity has been simulated with CST microwave studio . In this case, the resonant frequency of SIW cavity resonator is tuned by introducing different capacitances through varactor coupled to the cavity. Simulated results show that tuning range of resonator is about 125 MHz .Fabricated SIW resonator can be further used in low phase noise Voltage Controlled Oscillator (VCO) suitable for low cost microwave and millimeter wave applications.*

***Keywords***-*Substrate integrated waveguide (SIW), cavity resonator, tunable resonator, varactor, voltage-controlled oscillator (VCO).*

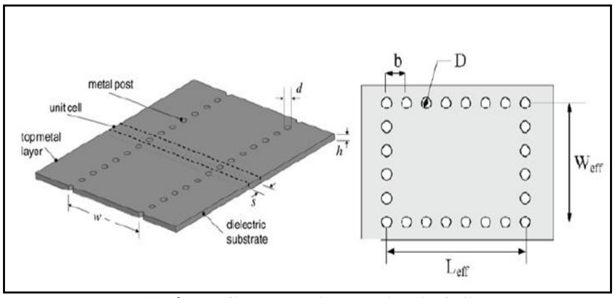
## I. INTRODUCTION

Many research's have been carried out in order to develop high performance microwave and millimeter - wave waveguides components that are fabricated using low-cost technologies. The classical waveguide technology is still the mainstream for designing high-performance millimeter - wave systems. However, the waveguide components are not suitable for low-cost mass- production. Tedious and expensive post-fabrication tuning and assembling becomes a real problem for manufacturers. In addition, the waveguide technique cannot be used to reduce the weight and volume. On the other hand, challenging problems are often encountered in the design of low-loss ICs, e.g., high-Q band pass filter and diplexers, to which the planar technique is fundamentally limited in performance. As such, non-planar structures such as the classical metallic waveguide are usually needed, thus hybrid schemes of planar and non-planar structures become attractive. In fact, an easy-to-handle low-cost hybrid design strategy is of critical importance for the development of high-volume millimeter wave ICs and systems. A number of design techniques of planar circuits integrated with rectangular waveguide have been reported that may not be so attractive for widespread applications. This is because dielectric waveguide has received little attention for microwave and millimeter - wave circuit designs even though it has been studied since many years. This is because it has two fundamental problems, namely, radiation loss due to discontinuity and difficult modal transition to planar circuits. Subsequently, the concept of a new generation of high-frequency integrated circuits called "Substrate Integrated Waveguide circuits (SIW)" [1] has been developed. This new concept has unified the hybrid and monolithic integrations of various planar and non-planar circuits that are made in single substrate and /or multilayer platforms [2]. The SIW technology can greatly facilitate interconnects and integrations between planar and non-planar circuits, which can be made within a patch fabrication process. At the same time, this scheme can be used to design low-cost high-performance (high-Q) passive circuits such as resonators, filters, couplers, power dividers, circulators and antennas [6]. The components such as power divider, resonator cavities and filters that have been developed using micro strip, strip line and milled-waveguide technologies are now redesigned using SIW platform.

SIW-based components like waveguide cavities have also been integrated directly into a PCB platform, allowing significant cost reduction in development and mass production of resonator based microwave oscillator and filters. The high quality factor of waveguide cavities provides excellent frequency selectivity for cavity coupled filters and resonators. SIW structures are generally fabricated by using two rows of conducting cylinders or slots embedded in a dielectric substrate that connects two parallel metal plates, and permit the implementation of classical rectangular waveguide components in planar form, along with printed circuitry, active devices and antennas. SIW structures exhibit propagation characteristics similar to those of rectangular metallic waveguides, provided that the metallic vias are closely spaced and radiation leakage can be neglected. More specifically, SIW modes practically coincide with a subset of the guided modes of the rectangular waveguide [5] [3], namely with the $TE_{n0}$ modes, with n=1, 2, etc. The TM modes are not supported by SIW, due to the gaps between metal vias. In fact, transverse magnetic fields determine longitudinal surface currents, which are subject to strong radiation due to the presence of the gaps. In particular, the fundamental mode is similar to the TE10 mode of a rectangular waveguide [4], with vertical electric current density on the side walls. Owing to this similarity between SIW and rectangular waveguide, empirical relations have been obtained between the geometrical dimensions of the SIW and the effective width of the rectangular waveguide with the same propagation .Most radar and communication applications need a voltage-controlled oscillator (VCO) as the local oscillator (LO) source. Thus far, VCOs based on the SIW resonator have not been reported because it is difficult to design tunable SIW resonators. Although one tunable SIW resonator was developed in [7], it cannot be tuned continuously. The proposed model provides a continuously electrically tunable SIW reflective cavity resonator that can be used to design tunable devices such as VCOs and tunable filters. This resonator makes use of a typical SIW cavity resonator that is combined with a surface mounted varactor to realise the desired tuning function at Ku band. Described in Section II are the design and analysis of the proposed tunable SIW resonator with its simulated and results. The shift in resonant frequency is achieved by applying reverse dc voltage over the varactor. All the structures in this paper are simulated by means of the simulation tools CST 2010.

## II. DESIGN

A typical SIW cavity resonator is shown in the figure. The walls of the cavity are realized by using the metallic vias as shown in the figure. Thus the SIW cavity acts like a rectangular waveguide cavity provided the calculations of these vias have been done as per equations mentioned later in the section.




***"Fig 1.SIW Design Principle"***

The propagation properties of the TE10-like mode in the SIW are very similar to the TE10 mode of a rectangular waveguide [3]. As a result, a SIW cavity can be designed by using the following equations:-

$$Fr(TEmoq) = \frac{c}{2\sqrt{\epsilon r}}\sqrt{\left(\frac{m}{Weff}\right)^2 + \left(\frac{q}{Leff}\right)^2} \qquad (Eq.1)$$

$$Leff = L - \frac{D^2}{0.95b} \qquad (Eq.2)$$

$$Weff = W - \frac{D^2}{0.95b} \qquad (Eq.3)$$

$$b < \lambda\sqrt{\epsilon r}/2$$

$$b < 4D$$

Here Fr represents the resonant frequency of the cavity and L eff and W eff are the effective dimensions of the SIW cavity. This is valid for b < λ (εr) ^1/2 and b < 4D where D is the diameter of the metallic holes and b is the pitch. Usually we use (Eq.1), (Eq.2) and (Eq.3) to determine the resonant frequency of the cavity when the metallic holes are used. To eliminate the error caused by the approximation for the dimensions W and L of the cavity, the metallic holes are replaced by metallic slots, where Ws and Ls are the width and length of such slots. The other two conditions as mentioned above needs to be satisfied while designing the resonant cavity.

### *A. Design Implementation*

Considering TE101 mode as dominant mode in the cavity, dimensions are obtained for effective length (Leff) and width (Weff) of the resonator corresponding to a resonant frequency of 12.1 GHz as per the above mentioned equations using Naltec substrate ( εr=3.2, 30 mils).On obtaining Leff and Weff ,diameter (D) of via and spacing between adjacent vias (b) for circular metallic vias ,based on the following equations are observed as 0.48mm and 1 mm respectively.

### *B. Loss Considerations*

One of the major issues in design of SIW components is related to minimization of losses. There are three mechanisms of loss in the SIW structure due to their similarity to rectangular waveguides. SIW structures exhibit conductor loss due to finite conductivity of metallic walls and dielectric loss due to loss tangent of dielectric substrate. Moreover, the presence of gaps in SIW structures along the side walls will cause a radiation loss due to possible leakage of field through the gaps. The different kinds of losses in substrate integrated waveguide interconnects could be minimised by modifying some geometrical parameters, namely substrate thickness 'h', diameter 'D' of the metal vias, and their longitudinal spacing 'b'. The thickness 'h' of dielectric substrate plays an important role. Increasing 'h' (while keeping other dimensions unchanged) determines a significant reduction in conductor loss but has no effect on the dielectric loss. In general, radiation loss is not affected by the substrate thickness (as long as 'h' is smaller than a half wavelength).Another important geometrical parameter is diameter'd' of the metal via. The variation of conductor and dielectric losses versus d is limited. In particular, the conductor loss slightly decreases when increasing the diameter d of the vias. Finally, the radiation leakage becomes significant when the condition b/D < 2.5 is not met. A similar behaviour is observed while varying the longitudinal spacing 'b'. On decreasing the value of 'b', conductor loss decreases (due to increased metallic surface) and dielectric loss remains unchanged. With regards to radiation loss, it remains stable under the condition b/d <2.5. b/D ratio for SIW resonator incorporating circular metallic via is as given in table 1.

| Via type | b (pitch) | d(diameter) | b/D ratio |
|---|---|---|---|
| Circular | 1mm | 0.48mm | 2.08 |

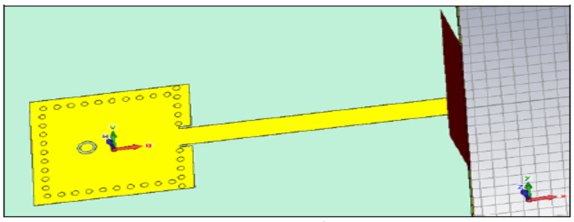
***"Table 1. b/D ratio for resonator with circular vias"***

*C. Design And Analysis Of SIW Tunable Resonator*

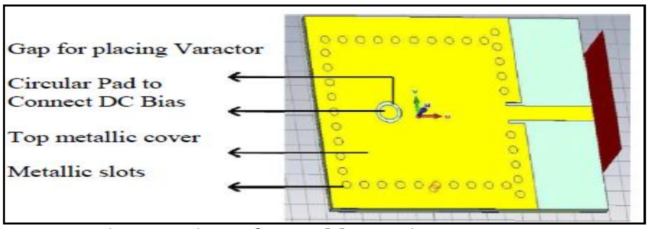
Physical configuration of the electrically tunable SIW reflective cavity resonator is depicted in Fig. 1.The white and yellow (in online version) areas stand for the substrate and metal covers of substrate, respectively. Separate circular metal cover is used for providing a dc bias to the varactor. Explanation to mount the varactor and set dc bias line follows subsequently. External coupling to cavity using microstrip line is firstly developed, and then cavity coupling to the varactor is designed.

*D. Coupling Varactor to SIW Resonant Cavity*

Subsequent to resonator's design, challenge now was to make it tunable. Tuning was achieved through a varactor coupled to the cavity. In the SIW structure, the metallic slots connect the top metallic cover to bottom metallic cover, so the top metallic cover cannot be used for DC bias line or connected with DC bias line of active devices. Therefore, it is necessary to use a separated metallic cover/pad to connect DC bias to the varactor. The circular pad is created which is not connected to grounded SIW cavity as shown in Fig.2



"***Fig 2.Design Prototype of cavity resonator***"




"***Fig 3.Design of Tunable cavity resonator***"

In the SIW structure, the metallic slots connect the top metallic cover to the bottom metallic cover, and thus the top metallic cover cannot be used for the dc-bias line or connected with the dc-bias line of active devices. Therefore, it is necessary to use a separate metallic cover to connect dc bias for active devices. In our circuit, the circular metallic cover with a diameter of $R$ is used for dc bias, where $W_G$ is the width of the gap and $L_d$ is the distance from the center of the separated circle to the center of the cavity. The bias line outside the cavity can be connected to circle metallic cover through a bonding wire. The circle metallic cover provides dc bias for the varactor, its cathode is connected on the circle metallic cover, and its anode is connected on the other top metallic cover (ground). Electric field in the cavity can be coupled to the separated metallic cover through the gap so the varactor will mainly be excited by a magnetic coupling. On investigation, if distance $L_d$(distance of circular pad from centre of patch) changes from 0.6 to 3 mm, the simulated resonant frequency shifts downward. The increment in tuning range indicates increase in coupling strength between the cavity and capacitor. Tuning of the designed SIW cavity was to be implemented using the varactor coupled to the cavity. For simulating the tuning conditions in the CST Microwave Studio, fixed capacitance was connected between the centre circular pad and grounded SIW cavity. Tuning was observed for capacitance variation from .1pF to 30pF. A tuning range of 125 MHz was obtained for these capacitance values and is shown in Figure 3 to Figure 7 below. The tuning range for the SIW cavity for these capacitance values is shown in Table below.

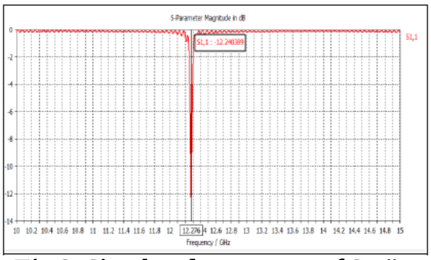
 

| Capacitance (F) | Resonant Frequency (GHz) |
|---|---|
| 30 X $10^{-12}$ | 12.185 |
| 15X $10^{-12}$ | 12.19 |
| 5X $10^{-12}$ | 12.23 |
| .1 X $10^{-12}$ | 12.31 |

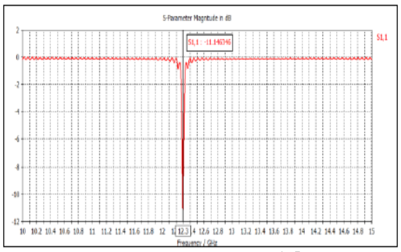
***"Table.2.Tuning range for different capacitance values"***

## III. RESULT

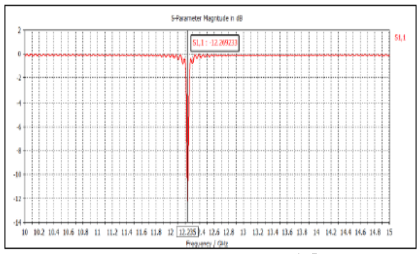
The prototype of cavity resonator at 12.1 GHz depicted in Fig 1. , consisting of circular metallic vias on NELTEC substrate with a dielectric constant of 3.2 and thickness 0.762 mm was designed with an objective to obtain low levels for S11.Fig 1.indicates low transmission from port 1 to 2 at resonant frequency is indicative of high Q factor.



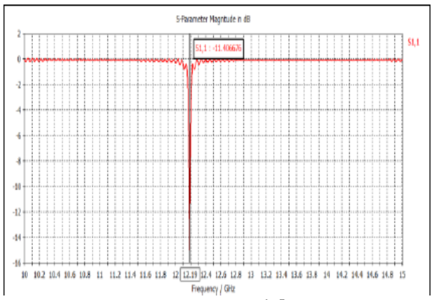
***"Fig 3. Simulated parameter of $S_{11}$"***



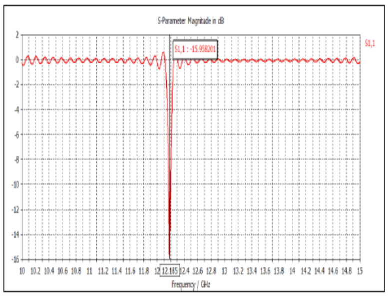
***"Fig 4. $S_{11}$ parameter with.1pF"***



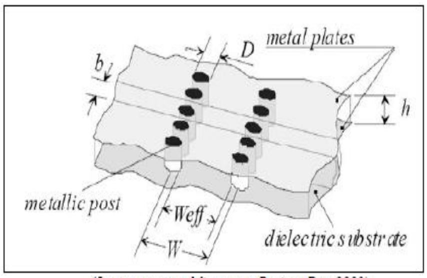
***"Fig 5. $S_{11}$ parameter with 5pF"***



***"Fig 6. $S_{11}$ parameter with 15pF"***



***"Fig 7. $S_{11}$ parameter with 30pF"***




(Image courtesy-Microwave Review, Dec-2003)

***"Fig 8. Dimension of SIW cavity in case of circular vias"***

## IV. DISCUSSIONS

The shift in resonant frequency from the calculated 12.1GHz (using the equations mentioned in section II) to 12.276 GHz can be depicted with the Fig 8. mentioned below ,wherein the effective length and width (Leff & Weff ) calculated is not exact as per design equation and differ by radius of the via, due to geometry of circular vias. The varactor proposed to be used is MA-COM **MA46H120** series GaAs Constant Gamma Flip-Chip Varactor Diode.

## V. CONCLUSION

The cavity resonator based on SIW technology with circular metallic vias has been designed with successful simulations and measured results at 12.276 GHz. The prototype, presents favourable resonating characteristics around the operation frequency. Further design of a novel tunable SIW cavity resonator has been developed and analysed. The proposed tunable resonator not only realizes a tuning function of 125 MHz around the resonant frequency by adjusting the DC biasing voltage of the varactor, but also retains the inherent high characteristics of the SIW cavity resonator.

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