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A Critical Review of Substrate Integrated Waveguide for Microwave Applications

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***Abstract*—This paper shows critical review of substrate Integrated waveguide (SIW) technology. Dielectric filled waveguide is converted into SIW with periodic arrangement of metallized holes on both sides of the it. SIW exhibit high pass response of conventional waveguide and band stop characteristics of periodic design. So filters designed using SIW exhibit less loss, less cost , less weight, high quality factor and high power handling capability. Various SIW passive and active circuits has been studied. Numerical method for modeling and design of SIW components is shown. A SIW has been designed showing insertion loss less than 0.1 dB. Design solutions for loss reduction are also discussed. Future design scope mainly aiming at Systems-on- Substrate integration of SIW components at higher frequencies including Ultra Wide Band range are also discussed.**

Keywords-Millimeter-wave components; Dielectric filled waveguide(DFW); Substrate Integrated Waveguide (SIW; passive waveguide components; Systems-on-Substrate(SoS); Substrate Integrated Circuits (SICs).

I. INTRODUCTION

Transmission lines are capable of transmitting electromagnetic energy. These transmission lines exhibit various losses such as copper loss, dielectric loss, radiation loss and skin effect [1]. They are non planer so their integration with planer circuit and its components is difficult. As compared to traditional transmission lines metallic waveguide are better wave guiding option. Metallic waveguide are made of integration of active and passive components usually require transition from planar to non planar circuits. But, metallic waveguides are bulky and expensive to manufacture which make planar / non planar integration costly and voluminous [2]. An alternative option to metallic waveguides is synthesized called substrate integrated waveguide (SIW). SIW that was developed in 1998, was known as laminated waveguide. The SIW technology inherits the classical microwave components. SIW is designed with linear array of metalized cylindrical holes also known as posts are implanted inside the same substrate as shown in Fig. 1. [3]. SIW structure is a progression between microstrip and dielectric filled waveguide (DFW). DFW is novitiate to substrate integrated waveguide with the support of vias in the sidewalls of the waveguides structure [4]. SIW shows utmost of the advantages of metallic waveguides like low loss, high quality factor, shielding effect and more power handling capacity [5]. The SIW technology is used in various microwaves and millimeter wave devices such as active circuits and as well as antennas and a suitable for mass production of millimeter wave wireless system [6]. A non planar metallic waveguide can be modeled into a substrate integrated waveguide with easy fabrication process on the same substrate using SIW technology. SIW components are packed, small and elementary to put together on printed circuit technology offer a widespread solution for mm-waves commercial application such as wireless networks, automotive radar imaging sensor and biomedical devices [7]. This technology permits to tower more wafer chips on the same substrate. The concept of system on substrate is mimic in the design of RF designs. SOS technology presents effective easy fabrication and high performance mm-wave systems [8]. After the development of laminated waveguide a sincere efforts is done to the probing and progress of SIW technology. The paper covers a study on development of substrate integrated waveguide, its modeling and design. A band pass filter using a SIW technology has been proposed for K band applications and loss minimization design solutions are discussed. This technology based circuits like filters, antenna, tunable oscillators and circulators etc. has been studied. This study helps in carrying out research work on SIW technology as per future scope. The various SIW technology based components are discussed below.

II. SIW FILTERS

Filters are the backbone of wireless technology. In 2003 waveguide filters has been designed by K. Wu. based on single substrate integration technique. 3-pole Chebyshev filter of 28 GHz having inductive posts has been designed depicting

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the return loss superior than 17 dB and 1 dB insertion loss [9]. A substrate integrated waveguide filters with defected grounds has been designed and fabricated in 2005. This SIW cavity bandpass filter has been designed using finite-difference frequency domain method and measured at 5.8 GHz [10]. To expedient low insertion loss and sharp out of band performances for millimeter wave systems a super-wide bandpass SIW filter has been realized by combining periodic structures into the SIW at 8.5-16.5 GHz [11]. An unwavering and planar four-pole linear phase filter established on SIW is designed which exhibit plane group time delay in the pass band, packed size and less cost. The linear phase filter is designed around 10 GHz central frequency [12]. For more size reduction bandpass substrate integrated waveguide filter positioned on approbatory split ring resonators are cut at top metal of SIW structure. CSRRs technology provides feasibility in low temperature co-fired ceramic (LTCC). The filter is designed on standard printed circuit board (PCB) using CSRRs technology first time in 2007 by X.C. Zhang [13]. LTCC is technology is for designing highly integrated modules such as ridged waveguide electronic system. When SIW is loaded with CSRRs a forward passband in waveguide is achieved. In 2008 new type of bandpass filters at 8 GHz are designed by folding the substrate integrated waveguide cavity. Folding waveguide technology and capacitive post reduced the size of waveguide resonators [14]. To minimize the current size double folded SIW resonators are developed in 2009. In this waveguide resonator the size of footprint is only a quarter of conventional resonators. Double folded SIW resonators has been made by imbedding a metal plate with two quadrate slots into cavity using LTCC technology [15]. New types of filter are designed by changing orientation of CSRRs. These filters exhibit low insertion loss, ease of integration and high selectivity [16]. To improve quality factor half Mode Substrate Integrated Waveguide (HMSIW) is synthesized on a planar substrate in 2012. It exhibit low cost, high power ability and compact size also. Tunable elements are etched on the waveguide exterior of HMSIW. Half mode substrate integrated waveguide structure for bandpass filter and mechanical switchable bandpass filter application designed and studied [17]. Filters with defected ground structures are designed for microwave and millimeter wave applications. Defected ground structures are formed in bottom of PCB which generates resonance because of change in current distribution. It resulted in increase stopband suppression and reduced the size of circuit [18]. A progression from SIW to substrate integrated coaxial line is analysed by Qiang Liu in 2013. The transition exhibit ultra low loss lower than 0.25 dB with a fractional bandwidth over 10% [19]. Filter in ultra wideband range were also proposed [20].

II. SIW Antennas

In the last decade antenna based on SIW technology are growing fast. A variety of antenna configuration are proposed .The early SIW antenna was established on four by four designate SIW array driving at 10 GHZ was designed. Slotted SIW array antennas are fabricated by engraving length wise slots in surface metal of the SIW [21]. Another configuration was faulty wave antennas. Leaky wave antennas generates outflow loss when length wise layout proportion of metal vias in adequately comprehensive [22]. Double V type linearly lessen slot antenna was proposed alongside center frequency at 36 GHz [23].

III. Hybrid Circuits

Other than filters and antennas diverse different passive components are developed based on SIW technology. Super compact 3dB directional couplers were designed [24-25]. Planar SIW diplexers operating at 5 GHZ and 25 GHZ were sugessted [26]. Six port circuits [27] ,circulators [28], magic T [29], power dividers [30] were also designed and fabricated . A planar combination design of SIW and coplanar waveguide has been designed and implemented alongside good pass band and stop band performances in 2014. Hybrid structures with mixed electric and magnetic coupling is introduced [31] .Various prototypes with single and dual cavities are fabricated. The planar bandpass filters exhibit low insertion loss ,sharp roll off characteristics at transition band [32]. Electromagnetic band gap (EBG) structures and defected ground structures band pass filters are designed and tested which covered the frequency range of 8.5-16.5GHZ [33].

IV. MODELING OF SIW

EM software and specially refined numerical techniques are pre owned in SIW components modeling. EM codes established on integral equation, finite element or finite difference methods have been developed. Full wave analysis techniques are used for modeling and design of SIW structures [34].These include multilayered topologies, design of packed, broadband and low loss interconnects which leads to the reduction of losses. Due to metallic holes present in waveguide there is more leakage losses [35]. In the analysis of SIW guided wave complications a finite difference frequency domain algorithm is deployed match layer and floquet's theorem [36]. Efficient subroutines are used to transform into a standard matrix eigen value problem. Parameters of substrate integrated circuits can be extracted by an efficient hybrid algorithm called the domain decomposition finite difference time domain (DD-FDTD) method combined with numerical through line (TL) time and memory calibration technique save computation. The circuit parameters of planar SIW discontinuities can be extracted by calibration technique. The TL calibration technique helps in using the FDTD method to extract the parameters of SICs and to extract to obtain not known complex propagation constant of the SIW synchronously [37-38] . Domain decomposition is simply the proceeding of programming and simulation and increases simulation reliability. Boundary Integral Resonant Mode Expansion method is implemented for direct determination of equivalent circuit modes of SIW components. BI-RME method provide the admittance matrix of the design in the form of pole expansion in frequency domain. BI-RME method is used for the estimation of the frequency response of waveguide designs[39]. The admittance matrix relates modal currents and voltages at the terminal waveguide sections .For two port circuit with P modes defined on each port. The complarable admittance matrix is given in the form

$$Y(\omega) = \frac{1}{j\omega}A + j\omega B + j\omega^3 C(\Omega^4 - \omega^2\Omega^2)^{-1}C$$

Where Y, A and B are 2P*2P matrix, M is the number of resonant modes of the resonator which are obtained by short circuiting the ports, Ω is the diagonal matrix of the corresponding M resonance frequencies. In the view of N modes of the SIW and P modes of the metallic waveguide (with N<P), the two set of modal vectors are related as follows E'=TE

Where E' and E are column vectors with dimension 2N and 2P, respectively having the SIW and waveguide electric modal vectors on both parts and T is a 2N*2P transformation matrix . The generic element of matrix Y is given by

$$Y_{ij}(k_o) = \frac{A_{ij}}{j\eta_o k_o} + \frac{jk_o B_{ij}\epsilon_r}{\eta_o} + \frac{jk_o^3\epsilon_r^2}{\eta_o} + \sum_{p=1}^{P} \frac{C_{ip}C_{jp}}{k_p^2\,(k_p^2 - k_o^2\epsilon_r)}$$

Where k=w/c is the wave number at frequency of interest, c is the speed of light in vacuum, €r is the relative dielectric permittivity of the substrate. Aij and Bij are related to related to the low frequency behavior of admittance matrix, Kp is the resonance wave number of the p-th mode of the cavity, and Cip is related to the coupling between ith port mode and p-th cavity mode. The quantities Aij ,Bij,Cij and Kp are frequency independent [39].

Advantages of BI-RME modeling method

The SIW, microstrip & coplanar waveguide exhibit different types of losses.SIW structures show conductor losses due to the finite conductivity of metal walls [35]. Pattern of SIW design is done by using full wave numerical techniques. Electromagnetic modes based on integral-equation finite element or finite difference methods have been implemented. BI-RME technique is used for modeling of arbitrarily shaped SIW components. The SIW components in the lossless case are modeled by BI-RME method [39]. The frequency response of SIW components in wideband is obtained by BI-RME method in one shot which avoid repeated electromagnetic analysis frequency by frequency. Another advantage of the BI-RME method is the prospect to rightly find identical circuit models of SIW interuption [34]. The most important application of the proposed method is the determination of parameters multimodal equivalent circuit models, where the value of lumped elements depend on the geometrical dimensions of the components.

V. LOSS MINIMIZATION

The major design issue of SIW components is allied to reduction of losses, restricted to operate in the millimeter wave frequencies. The three types of losses in SIW structures.SIW designs have conductor losses because of certain conductivity of metal boundaries and dielectric losses based on loss tangent of dielectric substrate. The gaps along the side walls in SIW structures can estimate a radiation loss, due to a possible leakage through the gaps[39]. The various subdivision of losses in SIW can be reduced by altering few measurable parameters such as the substrate thickness h, the diameter d of metal vias and the spacing p (Fig.1.).

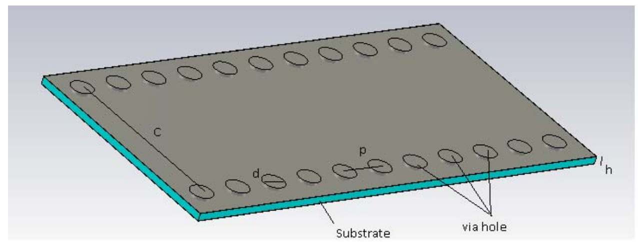

Figure 1. Substrate Integtated Waveguide

The conductor loss can be minimized by increasing h(while keeping the other dimensions unchanged) but has impact on dielectric loss. The radiation loss is not changed by the substrate thickness. SIW simulated results are shown in Fig. 2 depicting low insertion loss and return loss.

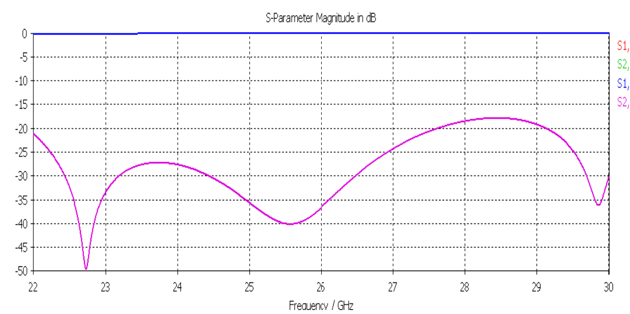

Figure 2. SIW simulated results depicting Insertion loss and Return loss

The diameter d of the metal vias is another important geometrical parameter. The conductor loss decreases when increasing the diameter d of the vias. The radiation leakage is small under condition p/d<2.5 [9]. The conductor losses are minimized by minimizing the value of s and dielectric losses remain unchanged. The dielectric and conductor losses show different dependence on frequency. So the dielectric losses are significance in mm wave frequency range. So a careful selection of dielectric material is extremely important.

VI. FUTURE SCOPE

The SIW technology based on system-on-substrate approach is used in fabrication and integration of complete systems devoted to the deployment of mm wave components in frequency band between 60 and 350 GHZ. The design of new innovative circuits and systems require size reduction, improvement in bandwidth, losses minimization and low cost fabrication.The multilayered SIW components can be used for wideband generations. Ultra wide band technology is used to support more users and to provide more information with higher data rates for wireless wideband communication. Data is transmitted at very high rates over short distance using ultra wideband wireless technology [20]. Another research trend is related to the use of new materials and different technologies like LTCC for fabrication of SIW components.This technology permits the fabrication of 3D SIW components which add more design flexibility with better performance. System on- substrate technology permits all the components to be mounted on the same board. The SIW technology seems very promising as it replaces microstrip or co-planar waveguides, DFW in mm-wave wireless systems . In this way the system-in-package approach will be overcome by system-on-substrate approach where all the components not included in the chip set are fabricated in SIW technology. The SIW technology has several advantages like low cost, low loss, compact size and complete shielding. System-on-substrate approach appears to be most promising for implementation of mm-wave circuits and systems for next decade.

VII. CONCLUSION

In this paper overview of substrate integrated waveguide technology is presented. SIW technology permits the integration of mm-wave circuits and systems for wireless communication systems. Several SIW components such as active and passive components as well as SIW antennas. The novel SIW structures are investigated, which exhibit low losses and better performance at millimeter wave frequencies. The future scope is the complete system integration in SIW technology according to the system-on-substrate approach. This approach could replace the current system-on-chip and become the promising candidate for mm-wave circuits and systems.

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