Effect of Various Slot Parameters in Single Layer Substrate Integrated Waveguide (SIW) Slot Array Antenna for Ku-Band Applications

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Abstract ─ Extended study on SIW slot array antenna based on substrate integrated waveguide (SIW) has been proposed in this paper. Unlike recent publications, the effect of offset gap, gap between the slots and the gap between the last slot with the edge of the SIW antenna are extensively studied and effective formulation for proper positioning of the slots has been done. The structure consists of an array of slot antenna designed to operate in Microwave Ku Frequency bands. The basic structure is designed over a dielectric substrate with dielectric constant of 3.2 and with a thickness of 0.782 mm. The design consists of a SIW antenna fed with a microstrip to SIW transition. Multiple slot array effects are also being studied and analyzed using CST full wave EM Simulator. The designs are fabricated and supported with variation of return loss and radiation pattern characteristics due to appropriate slot offset. The analysis is being carried out to support integration to system-on-substrate (SoS) which promises more compact layouts.

Index Terms ─ Substrate Integrated Waveguide (SIW), slot array, slot offset, System-on-Substrate (SoS), Ku-band, Di-electric Filled Waveguide (DFW).

I. INTRODUCTION

Substrate integrated waveguide (SIW) has emerged as a new concept for millimeter-wave (mm-wave) integrated circuits and systems for the next decade due to their manifold advantages. SIW yields high performance from very compact planar circuits.

Recent past witnessed several substrate integrated waveguide (SIW) slot array antennas have been analyzed for their wide application in millimeter-wave communication systems due to advantages like high gain, efficiency and low-profile [1]. They are found to have manifold applications collision avoidance automotive radar, monopulse radar and synthesis aperture radar (SAR). Slotted SIW antennas also have special characteristics like accurate beam forming as well as low side lobe levels [2]. These antennas also find application in high-speed wireless communication and direct broadcast satellite systems which require specific linear or circular polarization.

The concept of waveguide slot antenna has been implemented on SIW slot antenna arrays in this study and several aspects are elaborately studied and presented with required details.

II. SIW ANTENNNA DESIGN

SIW are integrated waveguide-like structures fabricated by using two rows of conducting cylinders and slots embedded in a dielectric substrate that connect two parallel metal plates.

This concept was proposed by Bozzi, Xu, Deslandes and Wu in several papers. The non-planar rectangular waveguide can thus be made in planar form compatible with existing planar processing techniques [1]-[2], as in Fig. 1.

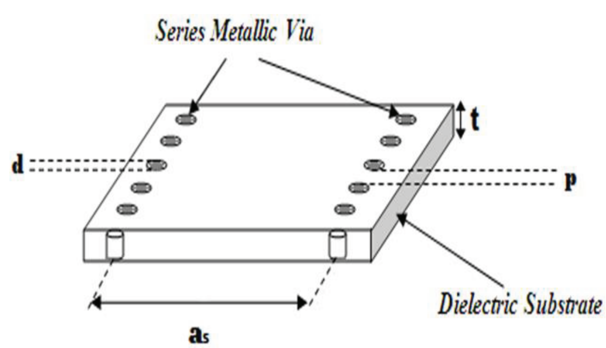

Fig. 1. Basic SIW structure realized on a dielectric substrate.

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SIWs exhibit propagation characteristics similar to the ones of classical rectangular waveguides. The modes of the SIW practically coincide with a subset of the modes of the rectangular waveguide, namely with the TE_{n0} modes, with n=1, 2, … In particular, the fundamental mode is similar to the TE_{10} mode of a rectangular waveguide, with vertical electric current density on the side walls. TM modes cannot exist in the SIW, due to the gaps between metal vias; in fact, transverse magnetic fields determine longitudinal surface current. Due to the presence of the gaps, longitudinal surface current is subject to a strong radiation, preventing the propagation of TM modes. Moreover, SIW structures preserve most of the advantages of conventional metallic waveguides, namely, high quality-factor and high power handling capability [3].

Stern, et. al., has presented the theory of longitudinal slots over waveguide section in [2], where method of moments type solution yield the design parameter of the longitudinal slots as well as the offset. Henry, et. al., applied the concept for development of millimeter wave slot antennas over multi-layer substrates at 70 GHz bands in [4].

This concept was further developed with study on 79 GHz antennas by Cheng, et. al., in [5]. However, Ku-band slot array antennas have been presented by Navarro, et. al., in [7] with ten element linear resonant longitudinal SIW slot arrays. In all these articles, the designers obtained good results with the efficient use of inter slot spacings and slot offsets as needed for their designs.

This has been the major area of concern in this paper and it is found that the slot spacing and slot offset has direct effect on the performance of the design. This aspect, which was to some extent undescribed till date, and our study presents full details of these effects with accurate formulations which will prove to be the basic building blocks starting with SIW slot antenna array designs. Zeng, et. al., successfully studied the SIW slot array effects producing dual band structures in [8]. Several other related designs and studies are obtained in [9]-[11].

The proposed structure is fed using conventional microstrip line. The section of the microstrip line connecting the radiating surface has been tapered for proper impedance matching. The dimension of the taper is properly optimized with CST Microwave Studio to ensure maximum power transfer to the proposed SIW slot array antenna. The structure used is commonly known to us as ‘Microstrip-to-SIW Transition,’ as in Fig. 2. Several other transition techniques can be consulted in [2].

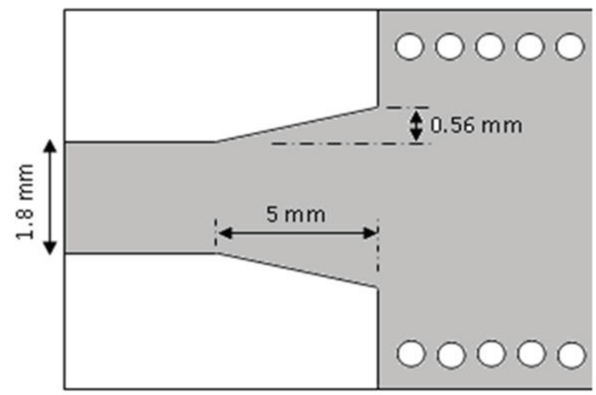

Fig. 2. Microstrip-to-SIW Transition.

The design equations for SIW, which may be given as:

$$a_s = a_d - \frac{d^2}{0.95p}, \quad (1)$$

where, a_s is the separation between via rows (centre to centre), a_d is the width of di-electric filled waveguide (DFW), d is the diameter, p is the pitch as shown in Fig. 1.

The cut-off frequency of the SIW can be obtained using the above design equations:

$$f_c = \frac{C}{2W_{eff} \times \sqrt{\varepsilon_r}}. \quad (2)$$

In this paper, the antenna has been designed to resonate at frequency of 17.4 GHz. The dimensions of the slots are important for the antenna to behave as a slot antenna. The dimensions of the slots can be obtained in [6] with the help of the following relations:

$$b = \frac{\lambda_0}{\sqrt{2(\in_r + 1)}}. \quad (3)$$

Dimension of c as in Fig. 3, doesn’t matter much but should be less than half of b. The gap between centre to centre of slots g' is considered as $\lambda_g/2$ in several articles [3]-[5], whereas the gap between the last slot and the closing face (edge) g has been extensively analysed for obtaining a maximum return loss at the impedance bandwidth. The offset slot gap is denoted by d. To implement accurate analysis of these gaps (g and g') for exact positioning of the slots, all necessary plots are provided in this paper as obtained using CST Microwave Studio.

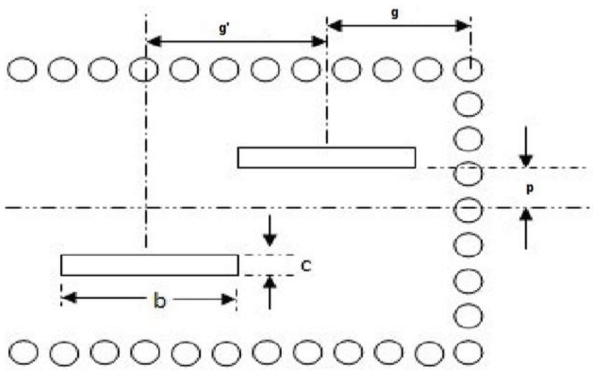

Fig. 3. Slot dimensions and gap between slots.

The proposed structure as obtained after a microstrip to SIW transition with 2 slots is depicted in Fig. 4. The top and bottom view of the fabricated prototypes are shown in Fig. 5. Comparison of the return loss of the 2 slot structure as obtained using EM CAD tool and after measurement is provided in Fig. 6. The antenna has been found to resonate at 17.5 GHz with a return loss of 23 dB for a slot offset of 0.25 mm.

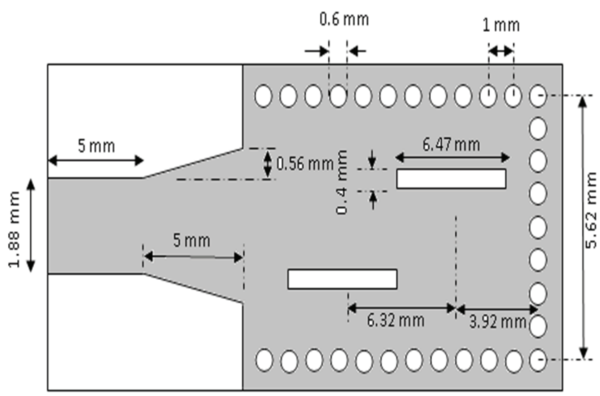

Fig. 4. Dimension for 2 slot SIW array antenna.

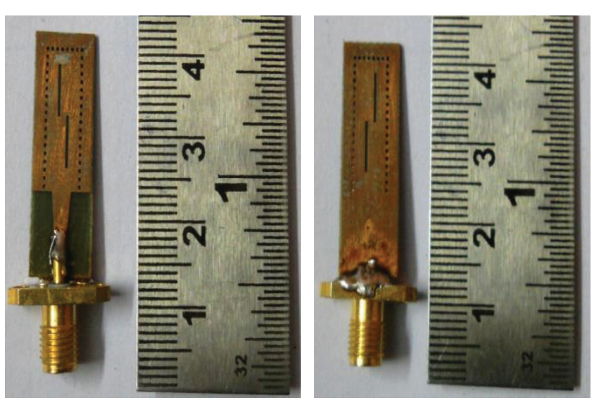

Fig. 5. Fabricated prototype of SIW slot antenna with 0.25 mm offset; top (left) and bottom (right).

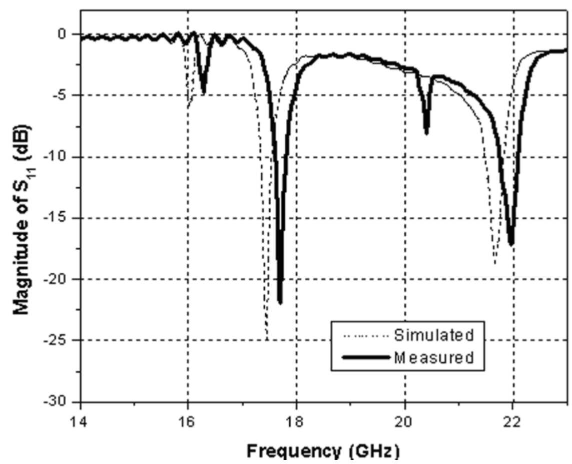

Fig. 6. Simulated and measured return loss for 2 slot SIW array antenna.

The antenna as noticed from the S-parameter tends to resonate at another frequency at about 21.5 GHz (image frequency/secondary resonance), which happens to be a function of the distance between the edges of the antenna to the last radiating slot. In this paper, primary focus is to study the effect of offset gap variation over the return loss and the gain of the SIW antenna. After obtaining proper offset gap, the effects of *g* & *g′* are studied further.

III. PARAMETRIC ANALYSIS

The variation of several antenna parameters are analyzed with variation of offset gap. Figure 7 depicts the variation of return loss as well as frequency obtained by varying the slot offset gap. The analysis clearly shows that for smaller offset gap, the return loss increases while antenna resonating frequency shifts to the lower side of the band.

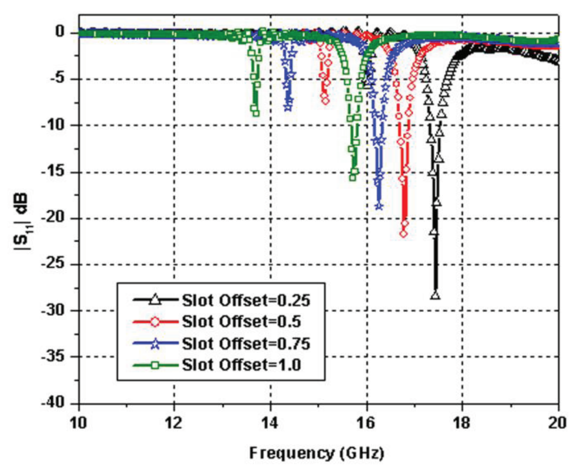

Fig. 7. Parametric analysis of several slot offset gap (p).

The fabricated SIW slot antennas with different slot offsets are shown in Fig. 8. Positioning of the slots, i.e., the slot offset has its effects over the resonating frequency, return loss and the gain of the radiating systems. The resonating frequency of the antenna is found to vary inversely with the increase of the offset. This can be related to the increased obstructions caused by the slots to the surface current of conventional rectangular waveguides, and hence, the slight shift in the return loss and gain of the system has been observed.

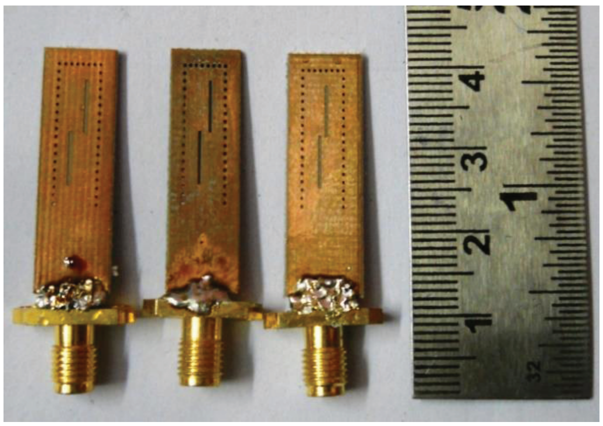

Fig. 8. Fabricated SIW slot antenna prototypes with different slot offsets.

The experimental set-up for measurement of the fabricated prototypes is shown in Fig. 9.

Fig. 9. Experimental set-up for radiation pattern measurement.

Also for lower offset, an improved return loss characteristics have been observed which is found to degrade with increase of offset values. The system shows better gain with lower offset values. The results of extensive studies as mentioned above have been shown in Fig. 10, Fig. 11 and Fig. 12.

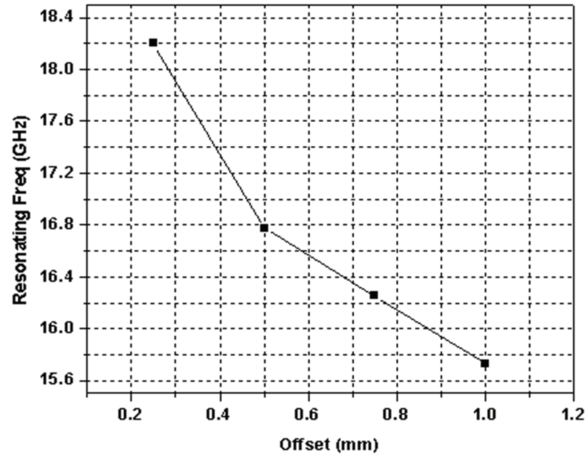

Fig. 10. Variation of resonating frequency (GHz) for variation of slot offset gap (p) (measured).

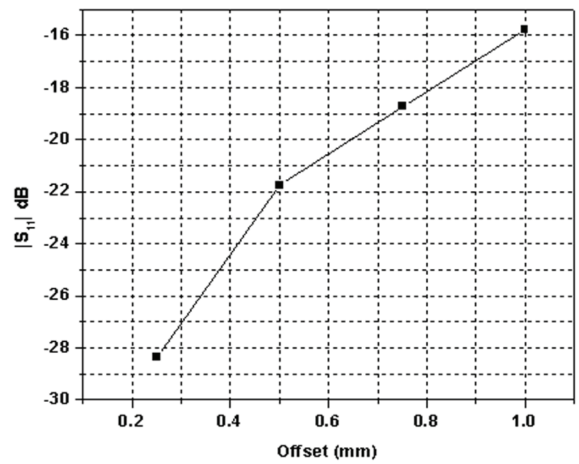

Fig. 11. Variation of return loss for different slot offset gap (p) (measured).

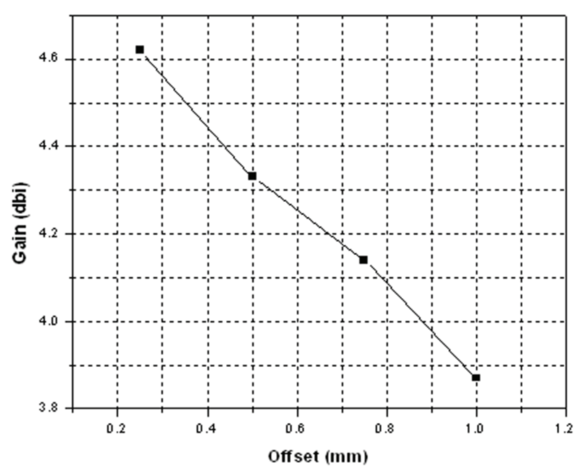

Fig. 12. Variation of antenna gain for different slot offset gap (p) (measured).

Detailed analysis on the effect of the gap between slots *g'* is also studied and presented with appropriate outcome. The results re-established that for a gap of $\lambda g/2$, maximum return loss will be achieved. The study further provides possible effects arise for gap length other than $\lambda_g/2$. The effect of the secondary resonance of the antenna has been found to vary with various slot gap *g'* and position of the slot from the end wall *g*. The return loss of the secondary resonance varies with spacing between the slots. For a gap of about 6 mm between the slots, both the return loss of the resonating frequency and the return loss of the secondary resonance have been found with acceptable results. The effects of s and *g'* over the various SIW slot antenna paramters are shown in Figs. 13-16. The results provide direct solution for several slot effects and enhance the possibility to design more compact layouts.

Fig. 13. Effect of various slot gap *g'* for on return loss of resonating frequency and image frequency (measured).

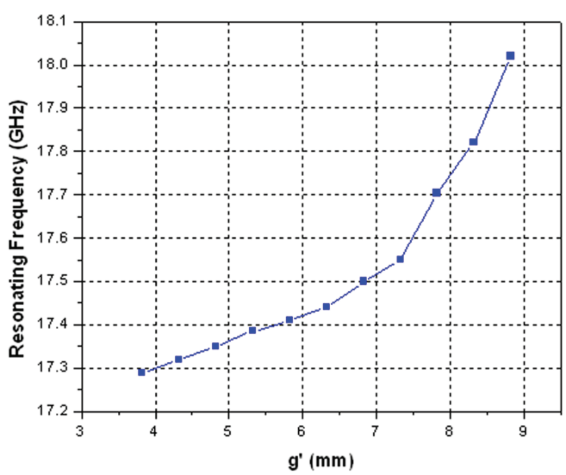

Fig. 14. Effect of various slot gap *g'* for on resonating frequency (measured).

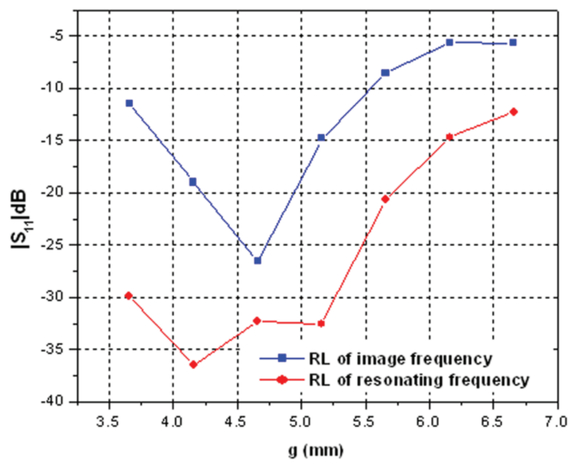

Fig. 15. Effect of slot position from end wall *g* on return loss of resonating frequency and image frequency (measured).

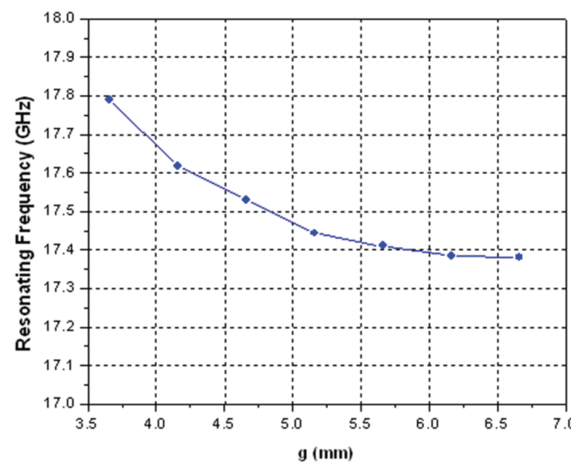

Fig. 16. Effect of slot position from end wall *g* on resonating frequency (measured).

IV. CONCLUSION

The effect of various slot offset, gap between slots and position of last slot from the end wall has been presented in details in this paper. The design comes with a microstrip to SIW transition feeding technique. Positioning of the slots has been found to have an impact over the gain as well as the return loss of the structure. The designs are fabricated and validated with the measured results. The results prove to be a direct solution to the SIW antenna design engineers for effective and accurate designs as required for different applications with consultation of the results presented in this paper, and thus, reducing time as well as human effort.

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