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RESEARCH PAPER

# Membrane antenna array based on substrate integrated waveguide technology for 94 GHz communication systems

HAMSAKUTTY VETTIKALLADI, MUHAMMAD KAMRAN SALEEM AND MAJEED A.S. ALKANHAL

*The design and the results of a single slot coupled substrate integrated waveguide (SIW)-fed membrane antenna and a 1 × 4 array is presented for 94 GHz communication system. The membrane antenna is designed using Ansys high frequency structure simulator and consists of six layers. The microstrip patch antenna placed on the top pyralux substrate layer is excited by means of a longitudinal rectangular slot placed over the SIW structure in the bottom pyralux substrate. The simulated antenna impedance bandwidth is found to be 5 GHz (91.5–96.5 GHz) for both single element and 1 × 4 array. Furthermore, the gain is found to be 7 and 13 dBi for the single element and the 1 × 4 array elements, respectively. The results are verified using Computer Simulation Technology (CST) Microwave Studio and are found to be in good agreement.*

**Keywords:** Antenna design, Modeling and measurements, Antennas and propagation for wireless systems

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## I. INTRODUCTION

Since last decade significant advances in millimeter-wave (mmW) technologies have been made to cope with the increasing interest. The mmW technology has gained a lot of attention in recent years. The W-band (75–110 GHz) window centered at 94 GHz is in focus due to its unique property of high transmission through atmospheric barriers such as smoke, thin dielectrics and clouds [1] as well as for the development of high-resolution imaging applications, and ultra-broadband wireless communications [2]. Furthermore, the shorter wavelength at mmW permits the production of compact systems for various advance communication systems, such as remote sensing, radio astronomy, cloud radar, automotive collision warning, and multi GBPS point to point communications.

The general requirements for mmW antennas concerns wide/ultra-wide impedance bandwidth, high-radiation efficiency, high-antenna gains, and compatibility with other communications modules. One of the suitable technologies for mmW antennas is substrate integrated circuits (SICs) [3–5]. In principle the SICs are used to synthesize and convert nonplanar structures and three-dimensional (3D) geometries into planar form which makes SICs very attractive for mmW applications [6]. Any nonplanar structure can be converted to its equivalent planar structure utilizing SICs technologies such as [2]

- Substrate integrated waveguide (SIW)
- Substrate integrated slab waveguide (SISW)
- Substrate integrated non-radiating dielectric guide (SINRD)
- Substrate integrated image dielectric guide (SIIDG)
- Substrate integrated inset dielectric guide (SIINDG)
- Substrate integrated insular guide (SIIG)

The SIW [3–5] is the most matured and popular structure in family of SICs. Several advantages of a rectangular waveguide such as high power handling, high *Q*-factor, and electrical shielding are attained in SIW technology. Furthermore, the radiation leakage can be ignored in the SIW structures having metallic vias placed in close proximity, resulting in propagation characteristics similar to metallic rectangular waveguides [7]. The SIW-based structures can be implemented by various manufacturing processes such as conventional printed circuit board process (PCB) [8, 9], multilayer PCB process [10], photoimageable thick film technology [11], and low-temperature cofired ceramic (LTCC) technique.

In this paper, we present the design and the results of a single multilayer membrane antenna and a 1 × 4 array based on SIW technology operating at 94 GHz. The available low cost, low loss DuPont™ Pyralux TK185018R, and FR4 substrates are utilized in the proposed antenna structure. The Ansys high frequency structure simulator (HFSS) is utilized for modeling and the optimization of proposed antenna, whereas CST Microwave studio is used for validation of the results.

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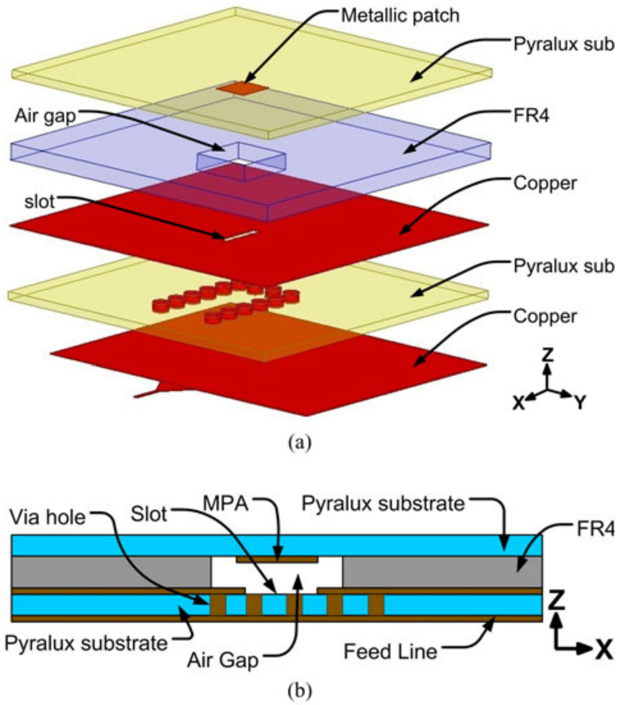


**Fig. 1.** Proposed membrane antenna geometry. (a) 3D layered model. (b) 2D side view.

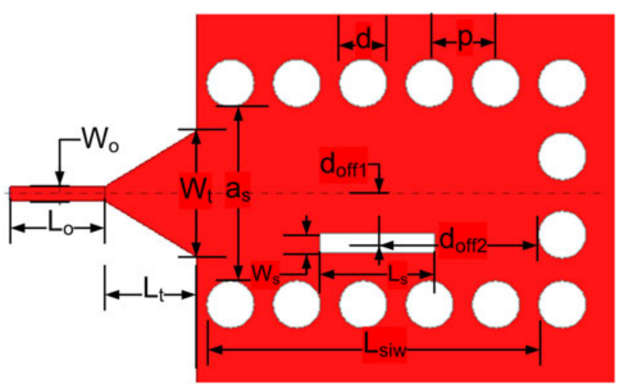


**Fig. 2.** Top view of SIW antenna along with rectangular slot.

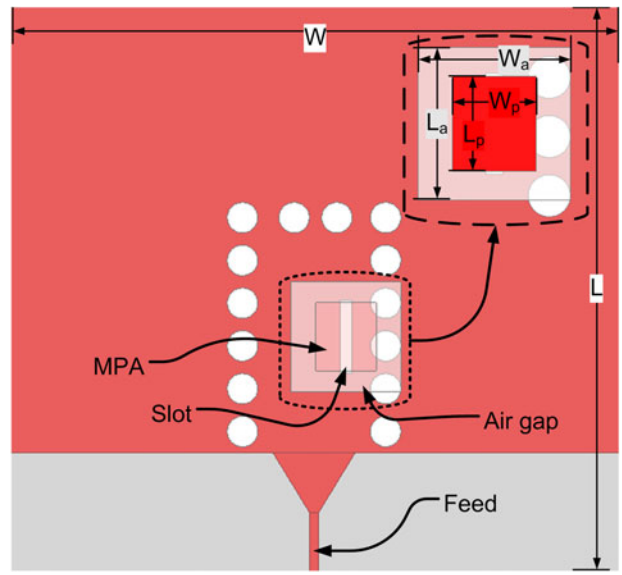


**Fig. 3.** Top view of proposed membrane antenna geometry.

## II. SINGLE ELEMENT SIW-FED MEMBRANE ANTENNA

### A) Design and configuration

The single element SIW-based structure of the proposed membrane antenna with six layers is shown in Fig. 1. The two substrates are utilized in design, i.e. pyralux substrate with $\varepsilon_r = 2.4$ and loss tangent $(\tan\delta) = 0.002$ and FR4 substrates with $\varepsilon_r = 4.4$ and loss tangent $(\tan\delta) = 0.02$. The losses are incorporated in simulation. As shown in Fig. 1(a) the top layer consists of a microstrip patch antenna (MPA) etched below the pyralux substrate. The second layer consists of the FR-4 substrate with an air cavity to support the top substrate layer. An air gap is drilled on the second layer to enhance the bandwidth of the antenna. We used the FR4 substrate because it is very cheap, low loss, and compatible with mass production PCB technology electronics. The bottom three layers makes up a SIW slot antenna, where rectangular slot [12] in the top metallic layer of SIW is utilized to excite

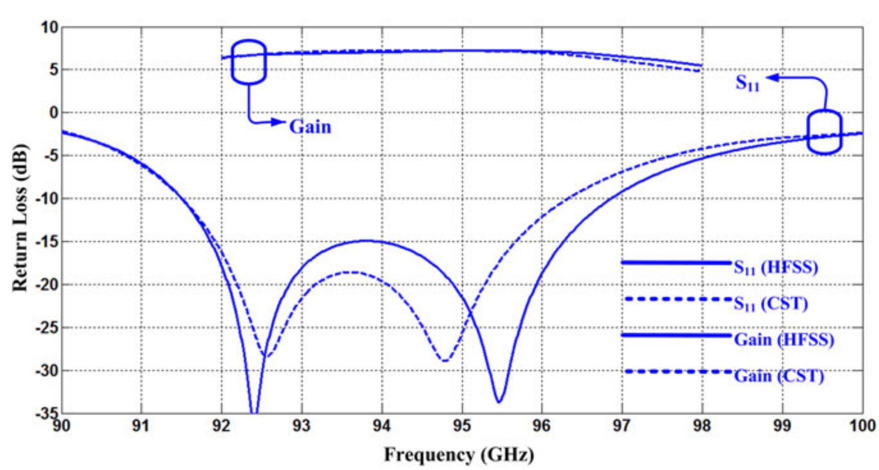


**Fig. 4.** Simulated return loss $S_{11}$ and realized gain.

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the MPA through the air gap made within the FR4 layer. The metallic via holes are made with in the bottom layer of pyralux substrate to form the SIW structure. The proposed membrane antenna structure in XZ plane is shown in Fig. 1(b) for a better understanding of various layers. All copper layers used in proposed antenna structure have thickness of 18 $\mu$m, while the thickness of pyralux and FR-4 are taken to be 50 and 100 µm, respectively.

The distance between two rows of metallic via holes along with the dielectric between them determines the cut off frequency. The SIW design generally works in $TE_{no}$ mode and does not support propagation of TM modes. For the dielectric filled waveguide (DFW) with same cut off frequency, the broad side dimension of waveguide, i.e. $a_d$ is found by [13],

$$a_d = \frac{a}{\sqrt{\varepsilon_r}}, \quad (1)$$

Where, $\varepsilon_r$ is the dielectric constant of substrate and dimensions of "$a$" are taken from the standard WR-10 waveguide (i.e. 2.54 mm). Once the dimension $a_d$ for DFW is known, we can use the following equation is find the separation distance, i.e. $a_s$ between the via rows of SIW [14],

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

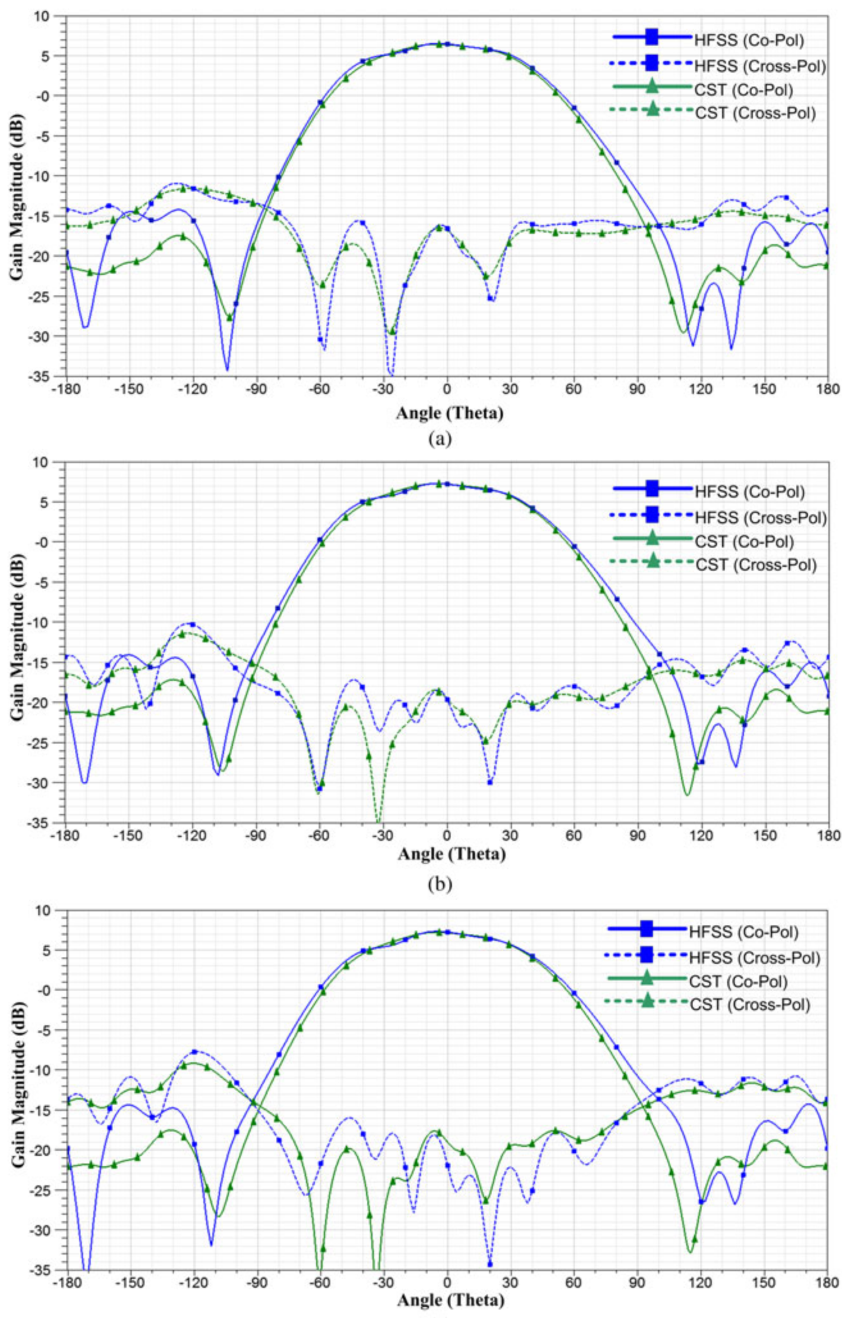


**Fig. 5.** 2D radiation pattern in *H*-plane with co- and cross-polarization. (a) 92 GHz. (b) 94 GHz. (c) 96 GHz.

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Where, $d$ is the diameter of metallic via holes connecting the upper and lower metallic layers of the bottom pyralux substrate. The via diameter ($d$) is taken by $d = \lambda_g/5$ and pitch, i.e. center to center distance between the via holes is taken by $p < 2d$ [15].

In Fig. 2 the top view of proposed membrane antenna along with longitudinal slot placed on the top ground plane of SIW structure is shown. Usually the distance from the short circuited end of SIW to the center of slot, i.e. $d_{off2}$ is a quarter or multiple of quarter of the guided wavelength. Initially, this distance is chosen to be three quarter of the guided. Furthermore, the slot offset i.e. $d_{off1}$ is optimized for proper excitation of longitudinal slot as well as the metallic patch antenna on the top layer. The initial dimension for longitudinal slot length is taken by [13],

$$L_s = \frac{\lambda_o}{\sqrt{2(\varepsilon_r + 1)}}, \tag{3}$$

The pyralux substrate with patch on top layer is supported by a layer of FR4 substrate having an optimized air gap of 1.8 × 1.8 mm under the MPA. The optimized dimensions for MPA are found to be 1.12 × 0.99 mm. The total size of antenna is found to be 10 × 10 mm. A conventional 50

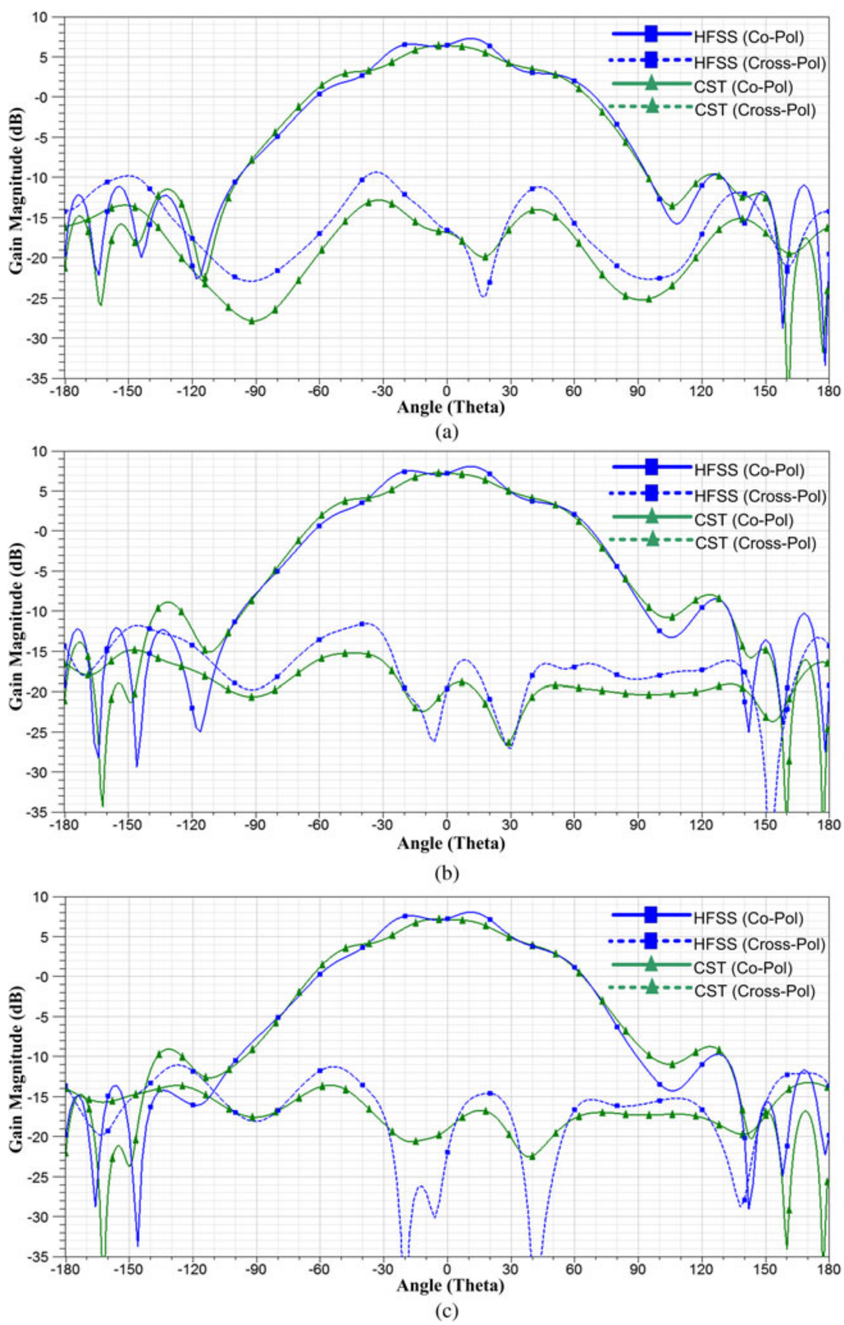


**Fig. 6.** 2D radiation pattern in $E$-plane with co- and cross-polarization. (a) 92 GHz. (b) 94 GHz. (c) 96 GHz.

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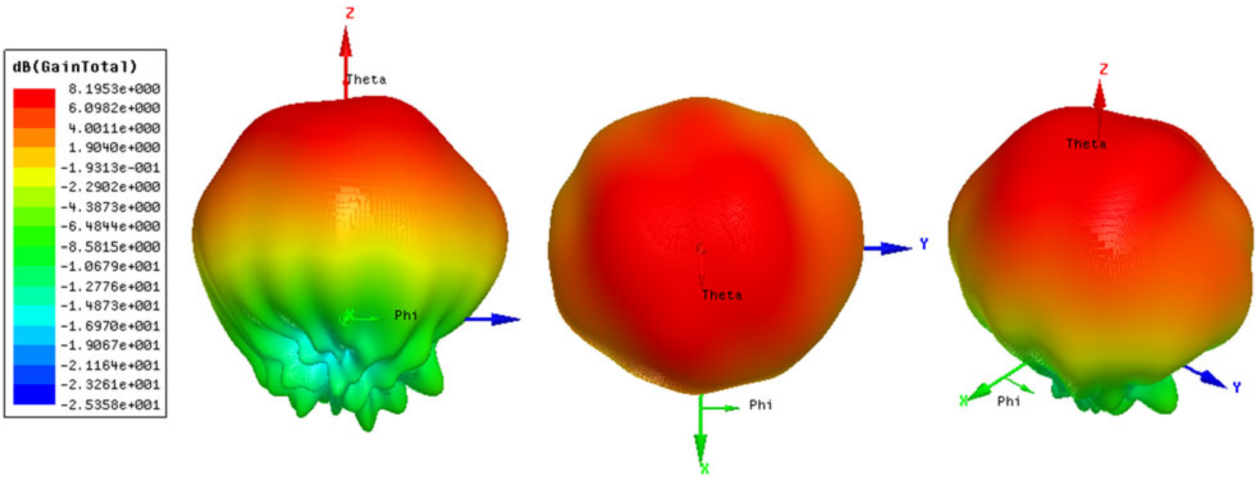


**Fig. 7.** 3D radiation pattern of the proposed single antenna.

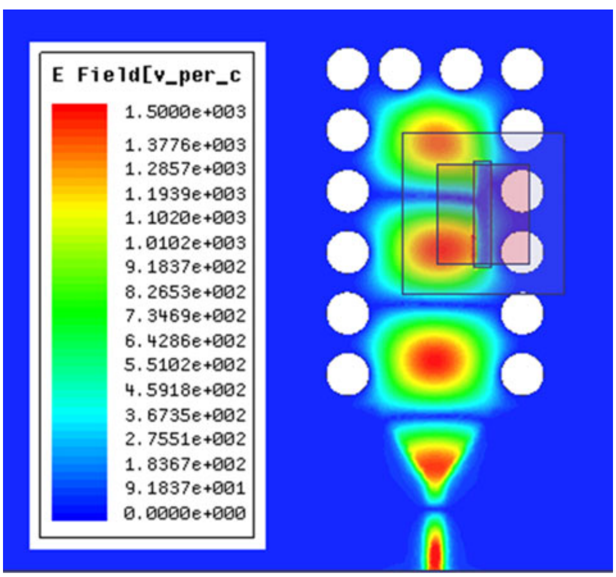


**Fig. 8.** Electric field distribution of the proposed single antenna.

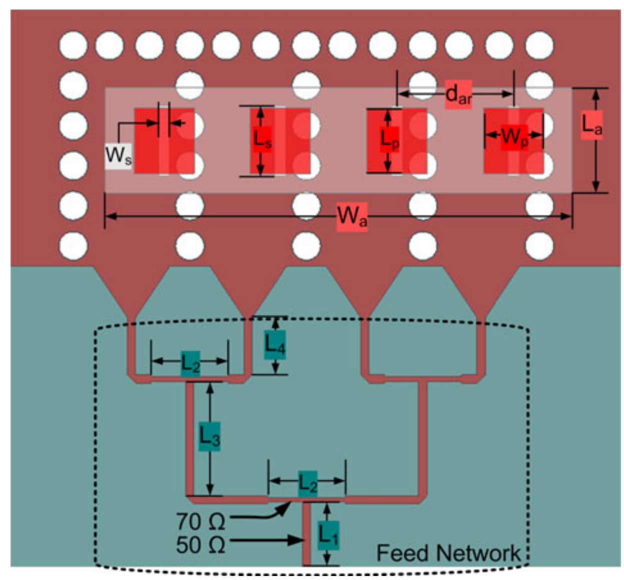


**Fig. 9.** Top view of proposed 1 × 4 element array with, $d_{ar} = 2.03$ mm, $L_a = 1.85$ mm, $W_a = 8.14$ mm, $L_1 = 2$ mm, $L_2 = 1.345$ mm, $L_3 = 2$ mm, and $L_4 = 1$ mm.

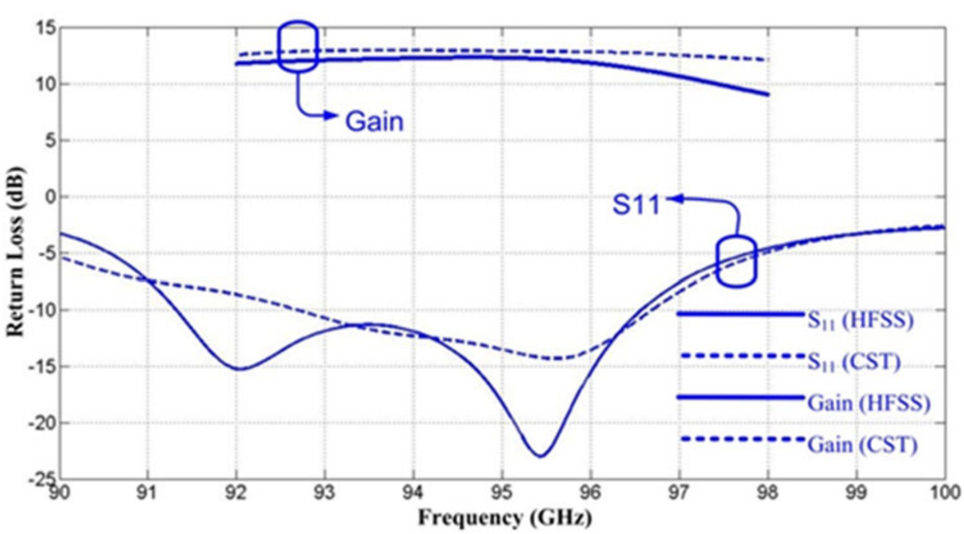


**Fig. 10.** Simulated return loss $S_{11}$ and realized gain for 1 × 4 array.

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Ω microstrip line is utilized as a feed element in the proposed antenna. The microstrip to SIW transition consisting of a tapered microstrip is also optimized for proper impedance matching. The detailed view of proposed single membrane antenna along with various important design parameters for MPA and air gap in FR-4 substrate are well explained in [16] and in Fig. 3.

The optimum dimension for the proposed membrane antenna structure are $W_o = 0.145$ mm, $W_t = 1.34$ mm, $L_o = 1$ mm, $L_t = 0.9$ mm, $d = 0.5$ mm, $p = 0.7$ mm, $a_s = 1.5$ mm, $W_s = 0.2$ mm, $L_s = 1.225$ mm, $L = 3.5$ mm, $d_{off1} = 0.55$ mm, $d_{off2} = 1.4125$ mm, $L_a = 1.85$ mm, $W_a = 1.85$ mm, $L_p = 1.15$ mm, $W_p = 1.05$ mm, $L = 10$ mm, and $W = 10$ mm.

## III. RESULTS AND DISCUSSION

The proposed antenna structure is simulated and optimized using Ansys HFSS©. The results are further verified by simulating the proposed antenna structure in CST Microwave Studio.

A comparison between the simulation results of $S_{11}$ and gain obtained from HFSS and CST are given in Fig. 4. The two resonances at 92.4 and 95.5 GHz are due to presence of slot and patch in antenna geometry respectively, which are kept in close proximity to achieve wide impedance bandwidth. The FR-4 support with air gap plays an important role in merging the two resonances to achieve a wide impedance bandwidth. The antenna impedance bandwidth is found to

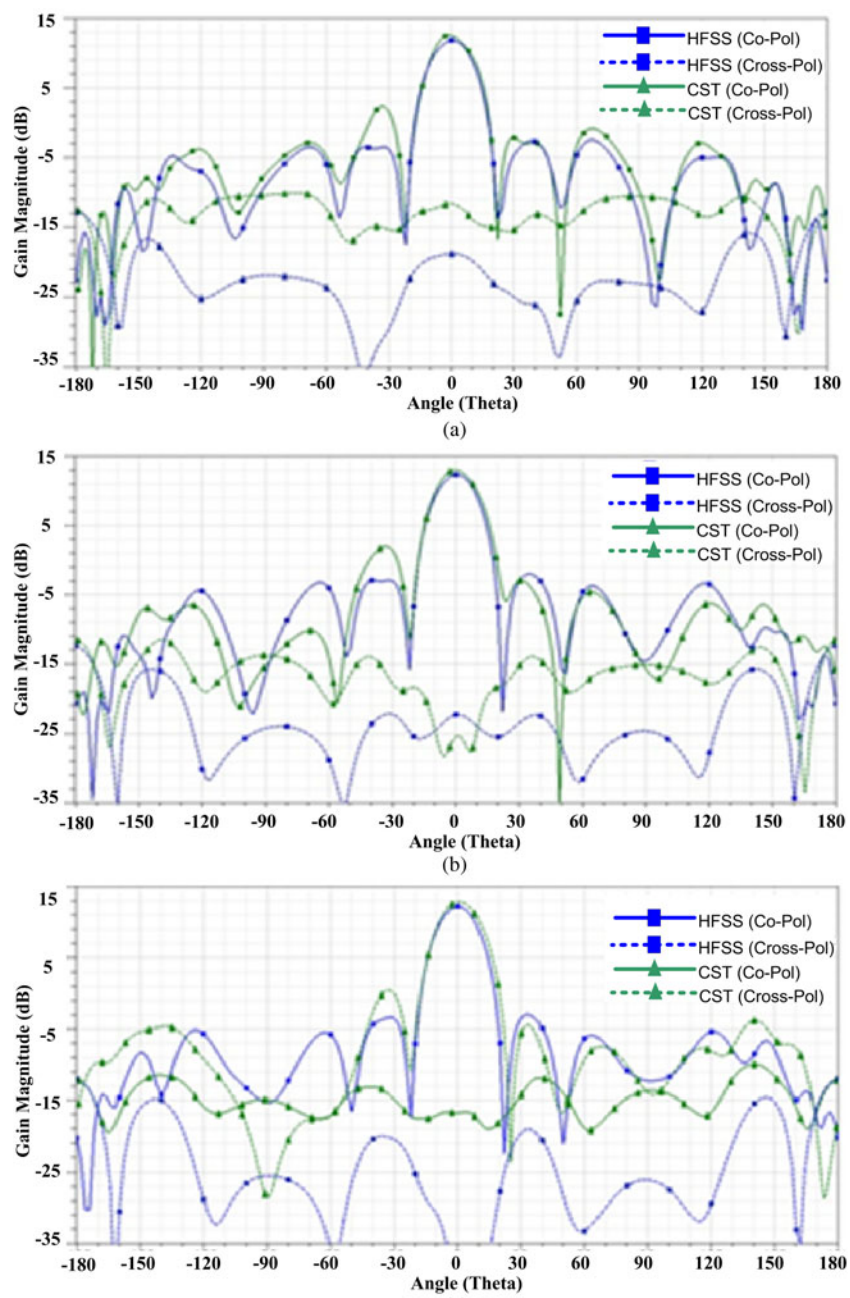


**Fig. 11.** 2D radiation pattern in *E*-plane with co- and cross-polarization. (a) 92 GHz. (b) 94 GHz. (c) 96 GHz.

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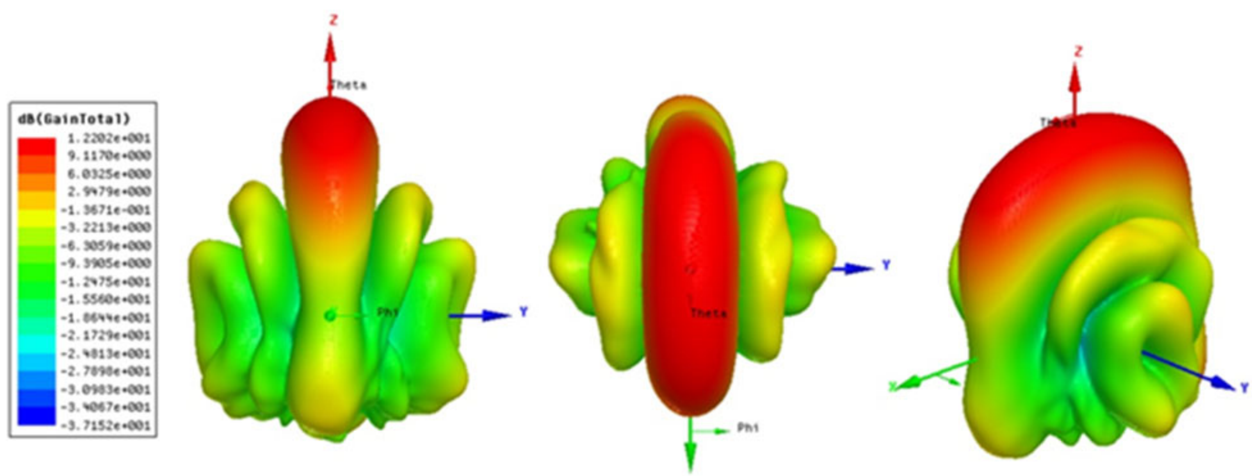


**Fig. 12.** 3D radiation pattern of proposed 1 × 4 array.

be 5.4 GHz (91.5–96.9 GHz) from HFSS while from CST the impedance bandwidth is found to be approximately 4.9 GHz (91.5–96.4 GHz). The gain is found to be 7 dBi at the center frequency of 94 GHz. The peak gain of 7.5 dB is found at 95.5 GHz. Furthermore, the antenna gain remains above 6.7 dB in whole frequency band of operation.

The antenna radiation pattern in both *E*-plane (horizontal plane) and *H*-plane (vertical plane) remains similar throughout the whole frequency band of operation. The comparison of two-dimensional (2D) radiation patterns obtained from HFSS and CST at 92, 94, and 96 GHz in both vertical plane ($\varphi = 90^\circ$) and horizontal plane ($\varphi = 0^\circ$) plane are shown in Figs 5 and 6 respectively. By increasing the ground plane size the small ripples in *E*-plane radiation pattern can be reduced, which are mainly due to diffraction of the limited ground plane. The cross-polarization ratio of less than −20 dB is achieved in *E*- and *H*-plane radiation patterns, respectively. The antenna 3 dB beam width is found to be 50° and 45° in *E*-and *H*-planes, respectively. For a better understanding the 3D radiation pattern for single element membrane antenna is shown in Fig. 7, whereas the wave propagating inside the SIW structure is illustrated by the electric field distribution plot as shown in Fig. 8.

## IV. 1×4 ANTENNA ARRAY DESIGN

Figure 9 shows the top view of the proposed SIW-fed slot coupled 1 × 4 membrane antenna array. The four antennas are placed in horizontal plane (*E*-plane) improve the gain. The distance between the longitudinal slot is kept at $d_{ar} =$ 2.03 mm, i.e. $0.64\lambda_0$ where $\lambda_0$ is the free space wavelength at 94 GHz. The array parameters such as slot length, slot width, patch length, patch width etc. are same as given in single element design in the previous section. The array is uniformly excited by a feed network to achieve maximum gain. The feed network consists of three identical 3 dB power splitters, each having a 50 Ω microstrip line connecting to two identical 70.7 Ω line for equal power transmission. The dimensions of microstrip lines for feed network are $L_1 = L_3 = 2$ mm, $L_2 = 1.345$ mm, $L_4 = L_1/2$. The total array size is 16 × 11 mm. The top view of array along with some important parameter values is shown in Fig. 9.

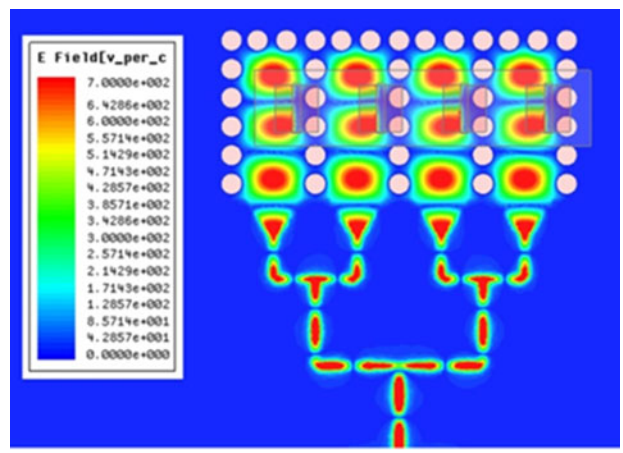


**Fig. 13.** The electric field distribution of the proposed 1 × 4 array.

The return loss obtained from both HFSS and CST along with the gain is shown in Fig. 10. The array impedance bandwidth is found to be 5.2 GHz (91.3–96.5 GHz) from HFSS while from CST the impedance bandwidth is found to be approximately 4.2 GHz (92.5–96.7 GHz). The maximum gain is found to be 12.7 dB at 95.5 GHz whereas the overall gain of array is above 10.5 dB for the whole frequency band of operation. The estimated efficiency of the array is 76%.

The simulated *E*-plane radiation patterns from HFSS and CST at 92, 94 and 96 GHz are compared in Fig. 11. The array beam width in *E*-plane is found to be 20°. The cross-polar level is lower than −16 dB. The radiation pattern in *H*–Plane remains similar to as shown for the single element case. The 3D polar radiation pattern is shown in Fig. 12 for a better visualization of antenna array radiation pattern. Finally, the electric field distribution in antenna array is shown in Fig. 13.

## V. CONCLUSION

The design and the results of a six layer membrane antenna/array based on SIW technology are presented. A MPA/array along with a longitudinal slot is utilized to achieve a wide impedance bandwidth of 5 GHz at center frequency of 94 GHz. The gain of the antenna for the single element is found to be above 6.5 dB in whole frequency band of operation and for the $1 \times 4$ array, it is found to be above 10.5 dB for whole frequency band of operation. Furthermore, similar antenna radiation patterns are achieved in whole frequency band of operation for single element, whereas for the $1 \times 4$ array the antenna beam width is reduced to $20^\circ$ in *E*-plane while *H*-plane radiation patterns remains similar to that of a single element case. The proposed antenna finds applications in 94 GHz communication systems.

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