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LOW COST 60 GHz NEW THIN PYRALUX MEMBRANE ANTENNAS FED BY SUBSTRATE INTEGRATED WAVEGUIDE

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Abstract—A low cost technology based on FR4 and thin flexible Pyralux substrate to develop membrane antennas/array with high efficiency and wide bandwidth for high speed V-band communication systems is proposed in this paper. A new low cost thin Pyralux substrate with a thickness of 75 µm, relative permittivity of $\varepsilon_r = 2.4$ and $\tan\delta = 0.002$ is used. First we developed the known classical aperture coupled antennas based on FR4 and pyralux substrate to validate this technology. The simulated and measured antenna radiation parameters for a single patch and 1×4 array of patches using aperture coupled technology give good results in terms of S_{11} bandwidth, gain and radiation pattern. But the back radiation is found to be high due to some radiation from the slot and the feeding microstrip line. Measurements of the antennas show approximately 9.7% and 10.8% impedance bandwidth ($S_{11} = -10$ dB) with a maximum gain of 7.6 dBi and 12.4 dBi around 60 GHz, respectively. In order to reduce the back radiation, we developed slot coupled antennas with substrate integrated waveguide (SIW) technology. Measurements show 10% and 7.5% impedance bandwidths with maximum antenna gains of 7.9 dBi and 12.7 dBi around 60 GHz for SIW single patch and 1×4 array antenna, respectively. The efficiency in this case is found to be very good due to very low back radiation. The measured results are in good agreement with the numerical simulations. The

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new thin substrate used for making the antenna helps easy integration with millimeter wave components and circuits.

1. INTRODUCTION

MODERN multimedia applications demand higher data rates, and the trend towards wireless is evident, not only in telephony but also in home, office networking and customer electronics. This has been proven by the accelerating sales of IEEE 802.11 family WLAN hardware recently. Current WLANs are, however, capable of delivering only 30–100 Mb/s connection speeds, which is insufficient for future applications such as wireless high-quality video conferencing, multiple simultaneous wireless IEEE 1394 (Firewire) connections or wireless LAN bridges across network segments. For these and many other purposes more capacity — wirelessly — is needed. The service provided by IEEE 802.11 WLANs only fulfills the needs of normal internet users and office workers. But, bandwidth demands are still rising. In such a context, 60 GHz millimeter wave (MMW) systems constitute a very attractive solution, due to the fact that there is a several GHz unlicensed frequency range available around 60 GHz, almost worldwide. In Europe the frequency ranges 62–63 GHz and 65–66 GHz are reserved for wideband mobile networks (MBS, Mobile Broadband System), whereas 59–62 GHz range is reserved for wideband wireless local area networks (WLAN). In USA and South Korea, the frequency range 57–64 GHz is generally an unlicensed range. In Japan, 59–66 GHz is reserved for wireless communications [1–5]. This massive spectral space enables densely situated, non-interfering wireless networks to be used in the most bandwidth-starving applications of the future, in all kinds of short-range (< 1 km) wireless communication. Also in this band, the oxygen absorption reaches its maximum value (10–15 dB/km), which gives an additional benefits of reduced co-channel interference. Hence it is a promising candidate to fulfill the future needs of very high bandwidth wireless connections. It enables up to gigabit-scale connection speeds to be used in indoor WLAN networks or fixed wireless connections in metropolitan areas. The IEEE standards in this band are IEEE 802.11.ad for high speed WLAN and IEEE 802.15.3c for HDTV application.

Requirements generally specified for antennas used in mm-wave systems concern gain, radiation efficiency, operating bandwidth, technological reliability, cost and compatibility with other RF modules. Significant efforts have been made during the past few years for designing and implementing efficient miniaturized antennas for mobiles or radio communications equipments. This results in a quasigeneralization of microstrip antennas, with some original features about feeders, shapes and supporting material. This has also contributed to a better understanding of operating properties and constraints of such radiating elements, with respect to materials, design methodology, electromagnetic compatibility. With the rapid development of advanced millimeter wave systems and applications, highly efficient antennas and RF circuits are required. Millimeter wave antennas with silicon technology have been developed and explained in [6–9]. But in all these cases the problem of antenna integration is not easy to have a good gain. Hence membrane antenna technology is a good solution, because an air cavity can be made in silicon to improve antenna performances. This membrane can be made with thin silicon or BCB material as explained in [10], for 60 GHz beam forming application. Another 60 GHz antenna for beam forming using silicon/BCB membrane technology is given in [11]. Membrane supported Yagi Uda antenna at 45 GHz is presented for wideband at millimeter wave applications [12]. This antenna used micromachining process. Another membrane supported double folded coplanar wave guide feed MEMs antenna operating at 77 GHz and 94 GHz was presented in [13]. Here micromachining process is also used which is expensive as well as not easy to develop.

Rectangular waveguides are widely used in microwave engineering, particularly at millimeter wave frequencies, due to their advantages of low losses, high power handling, and high isolation. However, the manufacturing of these waveguides needs to be accomplished with sufficient accuracy so as to allow for operation at millimeter wave frequencies. Micromachining has been successfully used to fabricate hollow waveguides at very high frequencies [14, 15]. But, applications of waveguides at millimeter wave frequencies are still limited by high manufacturing cost, relatively large volumes, and difficulties of integration with other components. Recently, the substrate integrated waveguide (SIW) technique has been proposed [16] which maintains the advantages of rectangular waveguides as well as additional merits (e.g., ease of integration, low cost, and reduced size). Many novel SIW-based circuits and devices for millimeter wave applications can be developed using different manufacturing processes on various substrate materials. Conventional printed circuit board (PCB) processes can be used to realize SIW-based structures and reduce manufacturing cost. Antennas based on SIWs with operation frequency range up to Ka-band have been realized using standard PCB processes [17, 18]. SIW-based antennas operating at higher frequencies are possible. For example, a 60 GHz post-wall waveguide aperture antenna with directors made by multilayer PCB process is explained in [19], for mobile terminal wireless file transfer applications. Here the antenna radiation is in end fire radiation. Another W-band single slot antenna has been demonstrated in [20]. In this case, relatively costly materials and manufacturing processes were used. A 79 GHz slot antennas based on SIW on a flexiable printed circuit is explained in [21]. In this case, the prototypes are fabricated on a polyimide flex foil using printed circuit board (PCB) fabrication processes. Micromachining process is used to make the walls on SIW, which is expensive and not an easy process. The losses are very high and hence the efficiency of all the prototypes explained on that paper is very low.

In this paper, the authors are proposing a very low cost membrane antenna technology based on FR4 and pyralux substrate. A single patch and 1×4 array of microstrip patch antennas (MPA) fed by microstripline and substrate integrated wave technology are designed and developed. In the first part of this paper, the authors verified the technology using classical aperture coupled patch antenna. The membrane supported antenna using SIW technology is designed, developed and explained in the second part of this paper.

2. DESCRIPTION OF TECHNOLOGY

The authors are proposing a very low cost technology based on FR4 substrate with a drilled air cavity inside, and a thin flexible pyralux substrate to do the membrane. Fig. 1(a) shows the detailed layers used in this technology. It consists of a new low cost pyralux TK 187518R [22] flexible substrate with thickness of 75 μm, relative permittivity $\varepsilon_r = 2.4$ and loss tangent $\tan\delta = 0.002$. The substrate has a top and bottom metal layer of 18 μm. A microstrip line is etched on the bottom layer. Just above the pyralux substrate a thin sheet of 3M glue of approximately 40 μm is placed to glue with the 200 μm non metalized FR4 substrate. We used the FR4 substrate because it is very cheap and compatible with mass production PCB technology electronics. On the top of FR4 substrate, again another sheet of 3M glue and then the pyralux substrate is present. The patch is etched on the bottom part of the top pyralux substrate. An air gap is created by drilling the FR4 substrate, the lower and the upper 3M glue sheet which will avoid the chance of covering the glue in the antenna slot area during the binding process. All the layers are then binded at low temperature to avoid the membrane bending. Due to lightness, flexibility and low cost in manufacturing technique, it is a good substrate material for millimeter wave antenna front ends.

3. VALIDATION OF THE TECHNOLOGY USING CLASSICAL APERTURE COUPLED ANTENNA

3.1. Slot Coupled Classical Single Patch Antenna Design

The side view of a classical microstrip fed slot coupled membrane supported patch antenna is shown in Fig. 1(b) and the detailed view of patch and slot shown in Fig. 1(c). The microstrip patch antenna

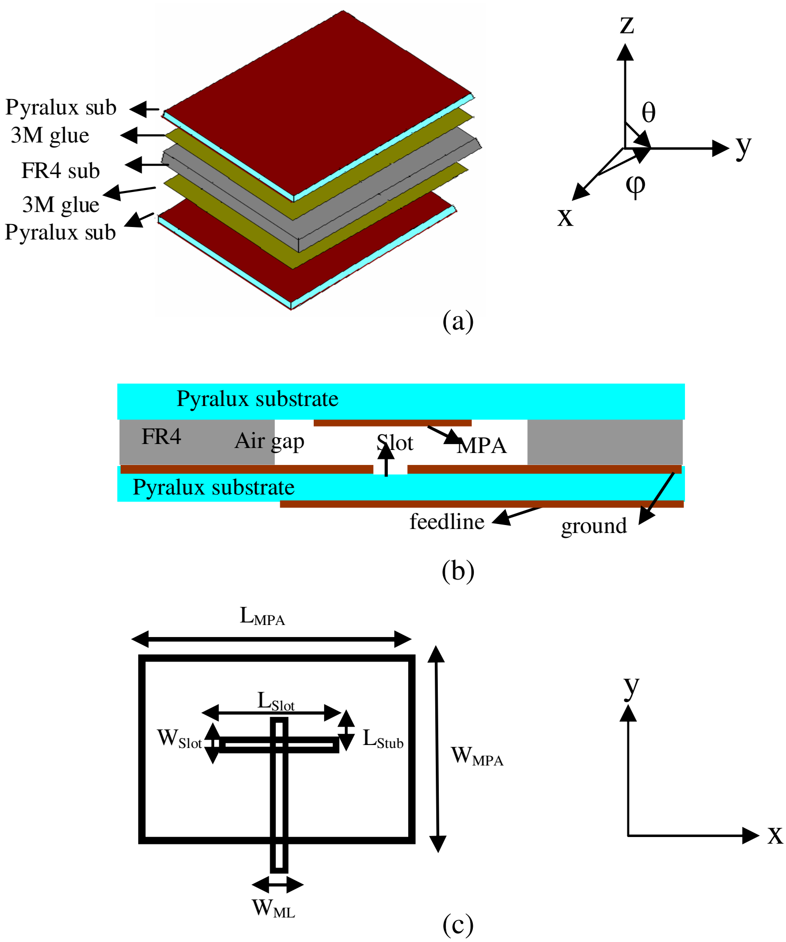


Figure 1. (a) 3D view of the multilayer technology. (b) Side view of membrane supported slot coupled single patch antenna. (c) Detailed view of patch, stub and slot. $L_{\text{MPA}} = 1.4\,\text{mm}$, $W_{\text{MPA}} = 1.64\,\text{mm}$, $L_{\text{slot}} = 1\,\text{mm}$, $W_{\text{slot}} = 0.145\,\text{mm}$, $W_{\text{ML}} = 0.22\,\text{mm}$, $L_{\text{stub}} = 0.3\,\text{mm}$.

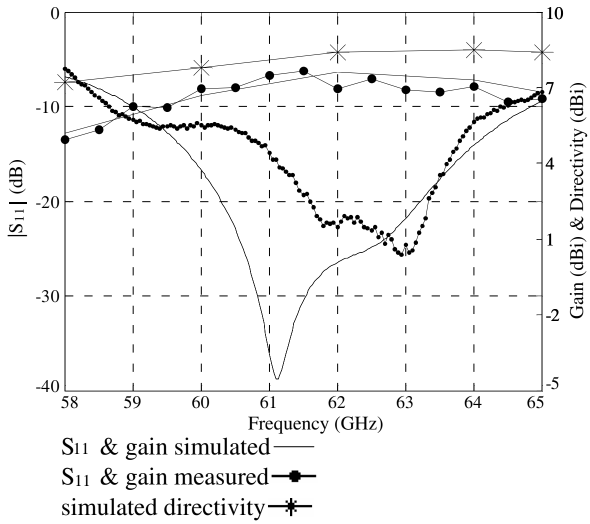


Figure 2. Comparison of simulated and measured results of S_{11} and gain, simulated directivity.

(MPA), $1.4 \times 1.64\,\text{mm}^2$, is etched on the top of PYRALUX substrate. Then we cut the FR4 substrate and also the glue sheet so as to make an air gap of $2.5 \times 2.5\,\text{mm}^2$ under the MPA, which creates an air cavity as shown in Fig. 1(b). The total height of the air cavity thus is 280 µm (i.e., $200\,\mu\text{m} + 40\,\mu\text{m} \times 2$). The patch is excited through a rectangular slot, which is optimized to be $1 \times 0.145\,\text{mm}^2$. A $50\,\Omega$ microstrip line is etched on the lower side of the lower Pyralux substrate, with a width of 0.22 mm, and a stub length of 0.3 mm. The total size of the antenna is taken as $30 \times 30\,\text{mm}^2$ for connecting the V-coaxial connector for doing the measurement. This antenna is manufactured in collaboration with the company named LITHOS, France.

The comparison of simulated and measured S_{11} bandwidths, gains and simulated directivity are shown in Fig. 2. It is clear from the figure that there is a good agreement between the simulation and measurement results. Simulations are done using CST Microwave Studio®. It is found that the measured 2 : 1 VSWR bandwidth is from 58.7 GHz to 64.5 GHz (9.7%). The maximum measured gain is 7.6 dBi at 61 GHz. The maximum directivity is 8.5 dBi. The estimated efficiency is 81%. The gain is found to be flat (ripple ~ 0.5 dB) over a frequency range of 60 GHz–64 GHz.

3.2. Slot Coupled Classical 1 × 4 Array Antenna Design

Figure 3(a) shows the side view of the classical microstrip fed 1 × 4 aperture coupled membrane supported antenna array. Here the antenna array is aligned on horizontal plane (Fig. 3(b)) All the substrates and the parameters of the antenna are the same as used for single patch antenna. The distance between the element is taken as 2.9 mm (0.58 λ_0 at 60 GHz). Here the dimension of the air cavity under the patches is 2.5 × 11.2 mm^2. Total size of the prototype is 30 × 30 mm^2.

The comparison of the simulated and measured S_{11}, gains and the simulated directivity are shown in Fig. 4. The measured 2 : 1 VSWR is found to be 58.7 GHz to 65 GHz. The maximum measured gain is 12.4 dBi. The maximum simulated directivity is 13.7 dBi. The estimated efficiency is found to be 74%.

Since the antenna array is placed on H-plane, the E-plane (E_θ at $\varphi = 90°$) radiation pattern is the same as that of a single patch. The simulated and measured H plane (E_φ at $\varphi = 0°$) radiation pattern at 62 GHz is shown in Fig. 5 and is found to be stable in all the frequencies in the band. The simulated and measured patterns are in acceptable agreement. The measured 3 dB beam width at 62 GHz is 22°. Due to the radiation from the slots and the microstrip feed line, the back radiation in this case can be high. In order to reduce this effect we are going for Substrate Integrated Wave Guide Technology.

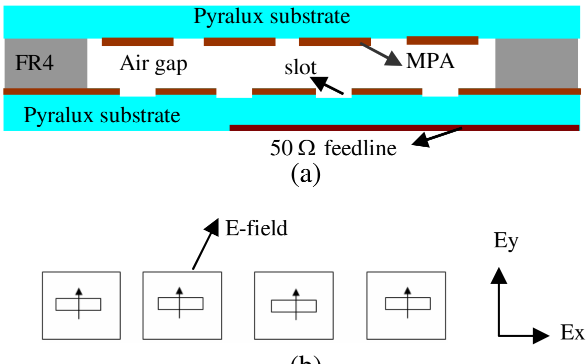


Figure 3. (a) Side view of membrane supported slot coupled 1 × 4 patch antenna array. (b) Orientation of patches (H-plane).

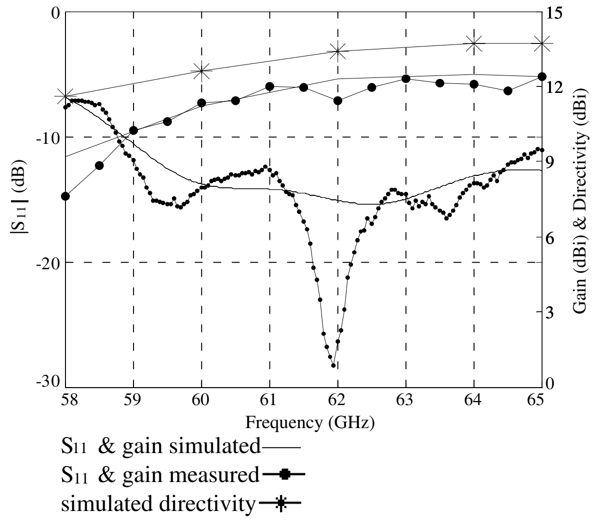


Figure 4. Comparison of simulated and measured results of S_{11} and gain, simulated directivity of 1×4 antenna array.

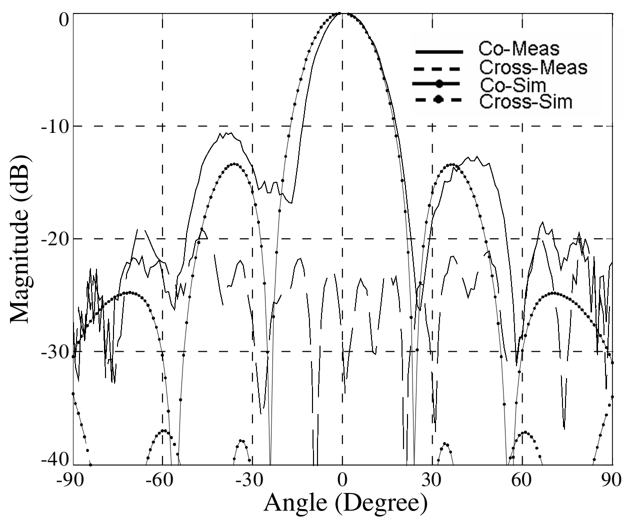
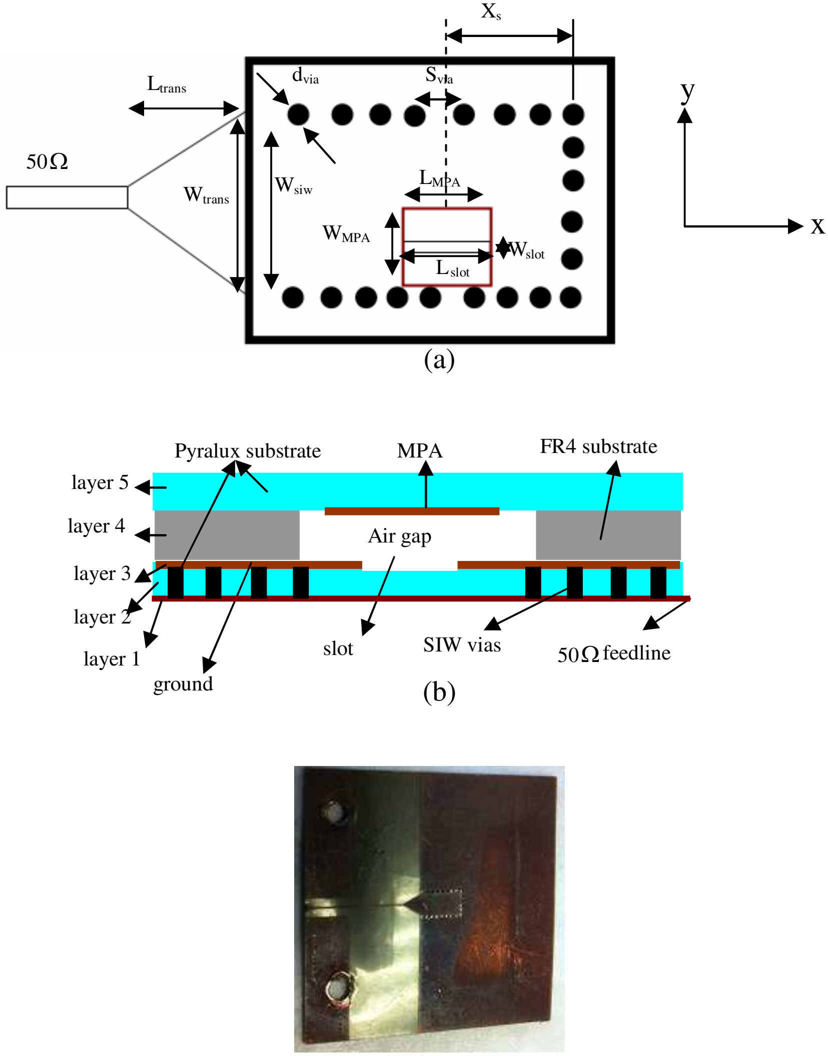


Figure 5. The simulated and measured H-plane radiation pattern of 1×4 array at 62 GHz. Co-pol E_φ at $\varphi = 0°$, θ variable. Cross-pol E_θ at $\varphi = 0°$, θ variable.



(c)

Figure 6. (a) 2D view of SIW antenna. $W_{\text{siw}} = 2.5\,\text{mm}$, $d_{\text{via}} = 0.4\,\text{mm}$, $S_{\text{via}} = 0.6\,\text{mm}$, $L_{\text{MPA}} = 1.7\,\text{mm}$, $W_{MPA} = 1.5\,\text{mm}$, $L_{\text{slot}} = 1.8\,\text{mm}$, $W_{\text{slot}} = 0.35\,\text{mm}$, $X_s = 2.9\,\text{mm}$, $W_{\text{trans}} = 2.48\,\text{mm}$, $L_{\text{trans}} = 2\,\text{mm}$. (b) Side view of SIW antenna. (c) Back view of SIW antenna prototype, showing microstrip to waveguide transition and specific terminology.

4. SUBSTRATE INTEGRATED WAVEGUIDE (SIW) TECHNOLOGY

4.1. SIW Single Patch Antenna Design

The 2-D view of the aperture-coupled MPA fed by SIW is shown in Fig. 6(a) with a slot in a longitudinal arrangement. We used a very thin pyralux substrate (75 microns) for the SIW, and it is not classical compared to other works where thick substrate was used to avoid loss in waveguide [23]. We want to design SIW on thin substrate to add easily active components even if we know that the loss will increase. The proposed MPA and its feeding structure are implemented on two dielectric layers, MPA-SUB, and SIW-SUB, made of the same new low-loss/cost material, where the SIW is formed by buried metal via holes. The SIW *(Layer 1, Layer 2, Layer 3)* as shown in Fig. 6(b), which is integrated on SIW-SUB, is formed with metallic holes, and closely aligned metallic holes via arrays that serve as two sidewalls separated by width W_{siw} (so the cut off frequency for the TE_{10} mode is $\sim 38.7\,\mathrm{GHz}$) and are electrically connected to the top and bottom metallic layers. The vias diameter (d_{via}), and all the antenna parameters are given in Fig. 6(a). The SIW parameters are designed using the guidelines presented in [24] which use the SIW equivalent rectangular waveguide model.

As explained in Section 3, for the aperture coupled antenna design, here the total antenna consists of five layers as shown in Fig. 6(b). The radiating element, MPA (on the bottom of *Layer 5, shown in Fig. 6(b)*), of dimension $1.7 \times 1.5\,\mathrm{mm}^2$ is realized on the bottom surface of MPA-SUB. It is supported by FR4 substrate of thickness $200\,\mu\mathrm{m}$ by providing an air gap of $2.5 \times 2.5\,\mathrm{mm}^2$ under the MPA. The MPA-SUB and SIW-SUB and FR4 substrate is glued as explained in Section 2. Since the thickness of the 3Mglue sheet is $40\,\mu\mathrm{m}$, the total height of the air column is $280\,\mu\mathrm{m}$ (i.e., $200\,\mu\mathrm{m} + 40\,\mu\mathrm{m} \times 2$). It is excited by longitudinal slot (Fig. 6(a)) located on the top ground plane of SIW structure (on *Layer 3*) at a distance from the SIW short-circuited, as shown in Fig. 6(a). Usually the distance (X_s) between the center of the slot and the shorted end of the waveguide is a quarter of the guided wavelength. However, this distance is chosen to be three quarter of the guided wavelength in all the presented antennas due to limitations in the present manufacturing processes (i.e., if we took $\lambda g/4$, then the distance between the SIW short end and the centre of slot is very small which is less than the minimum manufacturing distance). Hence the coupling distance has to be chosen in the vicinity of $\sim 3\lambda g/4$ (Fig. 6(a)) (λg is the guided wavelength). A microstrip to waveguide transition is used to excite the waveguide as shown in Fig. 6(a). Fig. 6(c) shows the back view of the prototype. The electromagnetic (EM) solver CST Microwave Studio is used to design the antenna parameters shown in Fig. 6(a) to enhance the coupled power to MPA. Extensive simulation work has been done using CST to find the optimum patch and the slot dimensions to combine their resonance frequencies for wide bandwidth operation.

Figure 7 shows the comparison between simulated and measured antenna reflection coefficients S_{11} (dB). The measured S_{11} is between 58.5 GHz and 64.5 GHz (10%). The maximum measured gain is 7.9 dBi, where the simulated maximum directivity is 8.2 dBi. The estimated efficiency is 93%.

The simulated and measured radiation patterns of the proposed antenna are shown in Figs. 8(a) and 8(b) in both E- (Horizontal plane — E_θ at $\varphi = 90°$) and H- (Elevational plane — E_φ at $\varphi = 0°$) planes, respectively, at 62 GHz. There is a small ripple in elevational plane radiation pattern which is due to the diffraction of the limited ground plane. There is a good cross polar ratio of less than -18 dB for all the frequencies in the band.

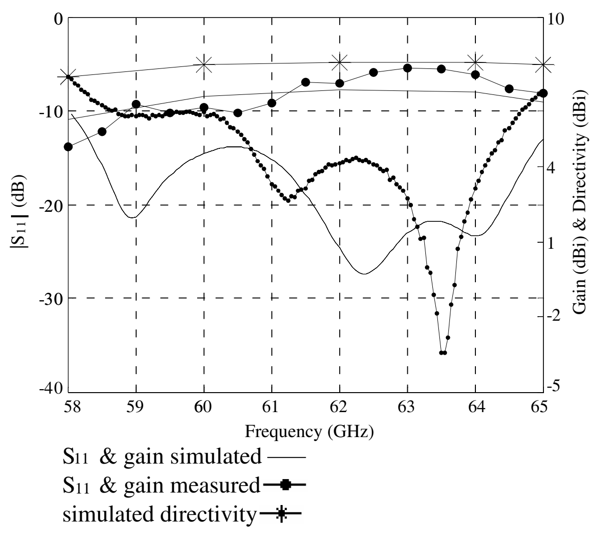


Figure 7. Comparison between simulated and measured results of S_{11} and gain, simulated directivity.

4.2. Integrated Waveguide 1×4 Patch Antenna Array Including Microstrip Feedline Network

A photograph of the back view of the 1×4 SIW antenna array is shown in Fig. 9(a). Here the antenna array is placed on E-plane (E_θ at $\varphi = 90^\circ$ — Fig. 9(c)) and hence the H-plane (E_φ at $\varphi = 0^\circ$) pattern is same as that of a single element. The distance between the elements in the array (array factor) is 2.9 mm, i.e., $0.58\lambda_0$ at 60 GHz (inner distance of SIW is 2.5 mm + via diameter 0.4 mm). All the antenna parameters such as slot length, patch size, etc., are same as that of single patch. In order to achieve maximum directivity, the linear arrays are uniformly excited through a feed network. The feed network consists of three identical 3 dB power splitters (Fig. 9(b)). As shown in Fig. 9(b), each power splitter consists of a T-junction, in which the 50 Ω microstrip line is connected to two identical branch lines. The total size of the antenna is taken as 30×30 for the measurement purpose.

The simulated and measured S_{11} bandwidths are given in Fig. 10. The measured S_{11} is matched from 60.5 GHz to 65 GHz (7.5%). There is a frequency shift in the band which may be due to the effect of V-connector. The maximum measured gain is 12.6 dBi with a maximum directivity of 13.3 dBi. The estimated efficiency of this array is 85%.

The measured and simulated E plane radiation patterns at 62 GHz are shown in Fig. 11. It is found that the simulated and measured results are in good agreement. The cross polar level is lower than -15 dB. This level may be due the tolerance in the manufacturing of

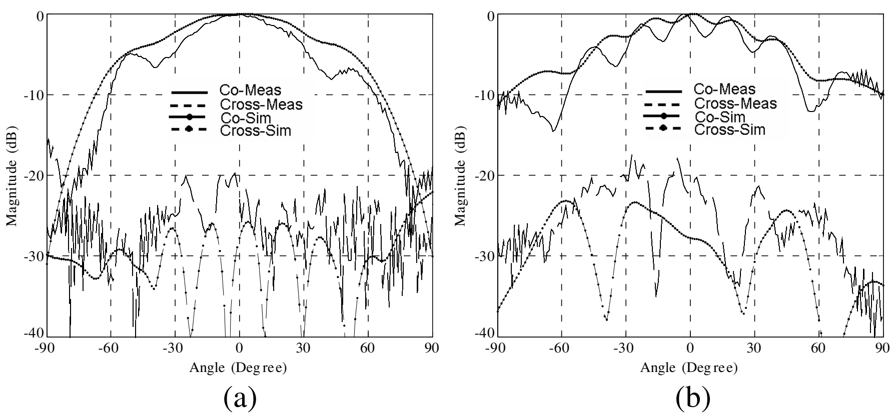


Figure 8. The simulated and measured (a) E-plane radiation pattern (Co-pol E_θ at $\varphi = 90^\circ$, Cros-pol E_φ at $\varphi = 90^\circ$). (b) H-plane radiation pattern (Co-pol E_φ at $\varphi = 0^\circ$, Cros-pol E_θ at $\varphi = 0^\circ$) of a single element.

the SIW and which results the leakage on the walls of the SIW, and the diffraction from the V-connector. The 3 dB beam width at 62 GHz is 24°.

In order to study the back radiation of SIW antenna array compared to the conventional slot coupled array, we did the measurements of 1 × 4 array of SIW and classical slot coupled prototypes. Fig. 12 shows the comparison of back side to front side pattern ratio of aperture coupled classical 1 × 4 array and SIW slot coupled 1 × 4 array at 62 GHz. It is found that back radiation is very low for SIW antenna in all frequencies in the band and is higher for classical slot coupled antenna because of the radiation from the slot.

To summarize, Table 1 gives complete results of all the prototypes explained in this paper. It is found that the membrane supported SIW antenna technology with single patch and 1 × 4 array of patches with microstrip feed network is good for high speed V-band communication.

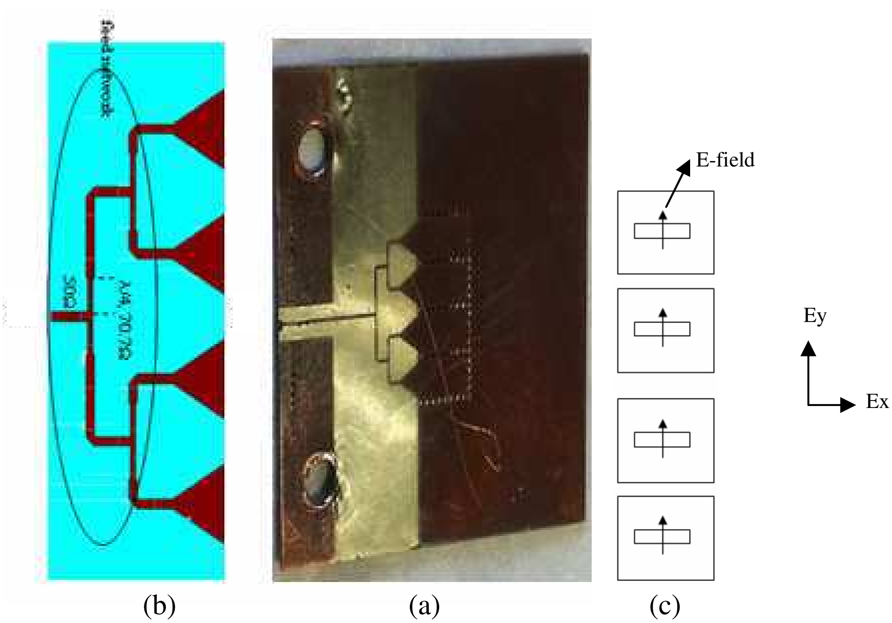


Figure 9. (a) Back view of the SIW-based 1 × 4 slot array antenna. Dimensions of each longitudinal slot array are identical to those shown in Fig. 7. The distance between each two neighboring rows is D_{array} is 2.9 mm. (b) Feed network. (c) Orientation of patches (E-plane).

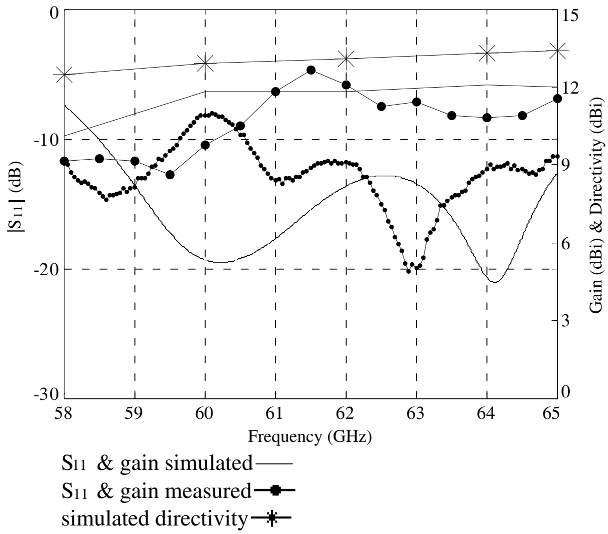


Figure 10. Comparison of simulated and measured results of S_{11} and gain, simulated directivity.

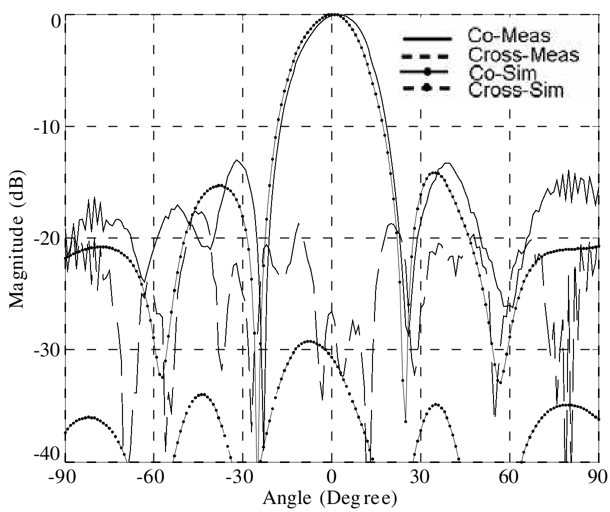


Figure 11. The simulated and measured E-plane radiation pattern (Co-pol E_θ at $\varphi = 90°$, Cros-pol E_φ at $\varphi = 90°$).

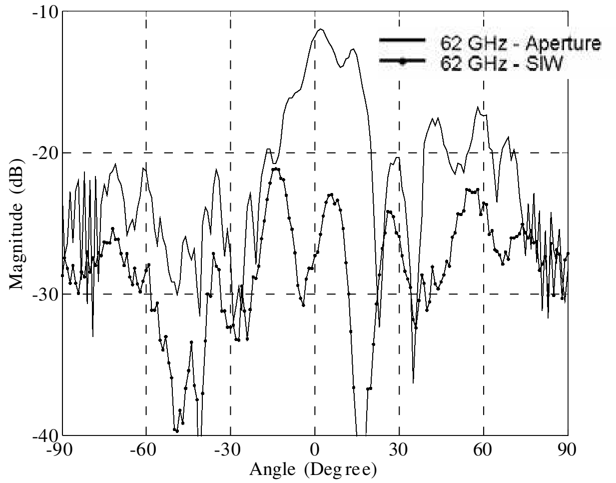


Figure 12. Comparison of back radiation of microstrip fed aperture coupled 1×4 array and SIW fed aperture coupled 1×4 array.

Table 1. Comparison of S_{11}, gain and efficiency of all the prototypes.

Antenna	Return loss bandwidth (simulated)	Return loss bandwidth (measured)	Maximum Directivity of the prototype (simulated)	Maximum Gain (measured)	Efficiency Estimated η
Classical Single patch	59–64.82 GHz (9.7%)	58.7–64.5 GHz (9.7%)	8.5 dBi	7.6 dBi	81%
Classical 1×4 array	58.9–66.9 GHz (13.3%)	58.7–65.2 GHz 10.8%)	13.7 dBi	12.4 dBi	74%
SIW single patch	58–66 GHz (13.3%)	58.5–64.5 GHz(10%)	8.2 dBi	7.9 dBi	93%
SIW 1×4 array with microstrip feed network	58.5–66 GHz (12.5%)	60.5–65 GHz (7.5%)	13.3 dBi	12.6 dBi	85%

5. CONCLUSION

Membrane supported slot coupled MPA/array fed by a substrate waveguide technology is designed and manufactured on a very low cost thin PYRALUX substrate. The validity of this technology is first verified on the classical aperture coupled antenna technology. From the measured results, it is clear that SIW antenna technology is very good in terms of bandwidth, gain, very low back radiation and high efficiency. Hence it is highly suitable for 60 GHz applications.

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