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Improvement of microstrip patch antenna and bandwidth at 60ghz and x bands for wireless applications

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Improvement of Microstrip Patch Antenna Gain and Bandwidth at 60GHz and X Bands for Wireless Applications

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Abstract— A method has been proposed to simultaneously enhance the gain (14dB), bandwidth (BW) (12.84% of the operating central frequency) and efficiency (94%) of a microstrip patch antenna. The antennas have been designed based on the patch size improvement technique to improve the fabrication tolerance. The designed prototypes have been fabricated by conventional low cost Printed Circuit Board (PCB) etching method and tested at X-band (8-12GHz) and 60GHz band (57-66GHz) frequencies. Antennas' overall performance is maintained across their operating frequency range. The tested antennas for 60GHz band convince the requirements for multi-gigabits/s data rate Wireless Local Area Network (WLAN) and Wireless Personal Area Network (WPAN) applications recommended by IEEE 802.11ad and IEEE 802.15.3c standards. In all cases the simulation and the measured results are in good agreement.

Index Terms— High gain microstrip antenna, mm-wave antenna, 10GHz antenna, wide band patch antenna, 60GHz WLAN and WPAN antenna.

1.   Introduction

Microstrip antennas exhibit attractive features for high frequency wireless applications including compact size, low profile, low cost, and compatibility with on-chip and in package devices [1]. However, the conventional microstrip antennas inherently suffer as having insufficient gain (8-9dB), narrow bandwidth (<4%), and incredibly small dimensions when designed for mm-wave (30-300GHz) and higher frequencies [2]. As propagation at high frequencies incur severe free space losses, higher gain antennas are desirable to sustain a reliable wireless link. Moreover wideband antennas are essential to achieve exceptionally fast data rate throughput and fine resolution.

Among high microwave frequencies, X-band (8-12GHz) and 60GHz-band (57-66GHz) make a significant contribution to various applied and emerging wireless services [3]-[7]. X-band is mostly devoted to point to point wireless applications like on-road traffic control [3], air traffic control [4], imaging radar [3]-[5] and satellite communications [6] where low profile and highly directive antennas are appropriated as a reliable and economical solution for the transmission systems. On the other hand, 60GHz band is anticipated to be an essential host for multi-gigabits/sec WLAN/WPAN applications [7]-[10][11][13]. This frequency band can offer (i) license-free continuous spectral bandwidth (57-65GHz), (ii) higher user density due to frequency re-use opportunity because of extended atmospheric attenuation and (iii) compact components size [8]. Subsequently, it has been projected that 60GHz frequency band wireless technologies are most likely to open new horizons towards replacement of high data handling cable networks, HD video steaming, uncompressed data file transfer, and mobile data off loading [11]-[13]. In these paradigms, two standards, namely IEEE 802.11ad

[7] and IEEE 802.15.3c [9], have been recently published for 60GHz WLAN and WPAN applications, respectively, which determine the channel characterization and the system requirements for radio link configurations. . According to these standards, 60GHz band is further segregated into four 2.16GHz bandwidths sub-channels centered at 58.32, 60.48, 62.64 and 64.80GHz with the transmission being confined at least in one of these channels [10]. Based on the mentioned IEEE standards recommendations, a high gain, wide band, and highly efficient microstrip antenna is tremendously desirable in order to realise a trustworthy and cost effective radio link for 60GHz WLAN/WPAN applications [11],[14]-[15].

Traditionally, the gain of a microstrip antenna is improved by constituting an array of multiple patch elements [4]-[10],[16]-[17]. In doing so, theoretically, the number of patches should be doubled to enhance the antenna gain by about 3dB [1]. However, at high frequencies, this approach is limited by the declined antenna efficiency due to the substantial power losses commenced by the extended microstrip feeding network which is vital to deliver matched electrical signal to each radiating element [4]-[5], [8]-[11]. In [8], the performance of two microstrip arrays at 10GHz frequency have been studied; the first array consisted of four patches which yields 12.56dB gain, 75% efficiency and -14.84dB side lobe level, and in the second array, the number of patch elements were doubled which slightly improved the gain to 13.9dB but dropped the antenna efficiency down to 63.2% and increased the side lobe levels to -11.58dB. In [9], a ten-elements microstrip antenna array is designed for 60GHz WLAN/WPAN applications and only about 13dB gain is achieved with as low antenna efficiency as 63%. In [10], an array of four patch elements is designed for 60GHz wireless applications and a maximum optimized gain of 13dB is accomplished. Additionally, in both [9] and [10], the fine patterns of the feeding transmission lines degrade the fabrication tolerance when conventional PCB etching technique is applied [1]. An alternative method to simultaneously boost the microstrip antenna gain and bandwidth is to employ aperture coupling feeding scheme together with multi-layer technology [3], [16], [19]. However, this approach needs micro-machining and more sophisticated fabrication technologies which ultimately increases fabrication complexities and cost, especially at high frequency antenna designs. On the other hand, several procedures have been adopted solely to widen the impedance bandwidth of microstrip antenna, for instance, etching various slots in the patch [20]-[21], employing multi-layer technology [22], implementing thick dielectric material [23] and wide-band feeding network [24]-[25]. However, these approaches are inadequate for high frequency microstrip antenna design due to fabrication concerns and device efficiency degradation. Moreover, these techniques have been unable to address the peculiarity arisen in the gain fluctuation across the operating frequency band.

Many others microstrip antennas have been reported for WLAN/WPAN at 60GHz band based on Low Temperature Co-fired Ceramic (LTCC) and their performance is summarised in [26]. According to [26], in most cases the gain of LTCC based patch antennas were improved between 13 to 17dBi using 16 elements of patch antenna arrays. As compared with the other LTCC based antennas, the antenna proposed in [27] provides a better trade-off between the number of elements and gain where a gain of 13.6 dBi is achieved with eight patch elements. However, for the rest of LTCC based antenna arrays with smaller number of elements, the reported antenna's gain is much lower than 10dBi [26]. On the other hand, it has been reported in [28] that a patch antenna which is fabricated on a Duroid substrate has

better electrical performances as compared with that fabricated on a Liquid Crystal Polymer (LCP) substrate [28].

Despite of the fact that PCB/PTFE materials, like Duroid, have some advantages over both LTCC and LCP materials such as low dielectric constant, low loss tangent and low cost [28]-[29], the purpose of this paper is not to evaluate the advantage of Duroid over the other materials. Instead, the objective of this article is to show that by using the proposed method the gain and bandwidth of the microstrip antenna can be improved significantly and the antenna can be fabricated by using the conventional etching method which is cost effective.

In this paper, we have designed and tested microstrip antennas for X-band and 60GHz-band wireless applications with substantial improvement in gain, bandwidth and efficiency. The choice of 10GHz and 60GHz frequencies is made to verify the antennas' design approach at these frequencies which have high demand in the wireless applications. Each antenna is designed as a single patch element based on size improvement method [40] to mitigate the fabrication constraints imposed by the conventional etching process. The designed antennas are absolutely planar and have been fabricated by low cost PCB etching technology. Antennas gain is consistently maintained overall operating frequencies. The antennas tested at 60GHz band frequencies satisfy the requirements for multi-gigabits/sec data rate WLAN/WPAN applications by covering up to two sub-channels in 60GHz band. The rest of this article is organised as follows: Section II discusses the details of the antenna design procedure, section III presents the experimental results and discussions of various designed antennas and finally section IV concludes the work.

2.   Antenna Design Procedure

The microstrip antennas are designed for 10GHz and 60GHz frequency bands on a low loss PCB substrate 'RT/Duroid5880' with $\varepsilon_r = 2.2$ and loss tangent (tanδ)=0.0009. Fig. 1 shows the geometry and the dimensional parameters of the proposed antennas. It consists of two symmetrical rectangular slits which are carved on the patch sides, centred along the patch length 'L', and a metal cladding strip of length 'L/3' and width W_{T2} is reserved in the patch centre as demonstrated in Fig. 1. This patch antenna pattern is analogous to an array of two extra-wide microstrip patch elements fed in series.
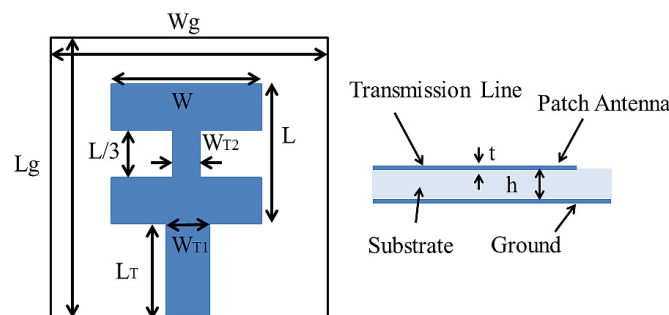

Fig. 1. The proposed patch antenna

For performance comparison, antennas have been constructed on two different substrate thicknesses (h) at each of the mentioned frequencies (i.e. 0.787mm and 1.57mm for 10GHz and 0.127mm and 0.254mm for 60GHz band). Initially, the patch antenna dimensions are

obtained by the size extension method in which the antenna is exited with one of its higher order TEM modes whose attributes are closely matched with the fundamental mode. The extended patch antenna width 'W' and length 'L' can be expressed as [40]:

$$W = \frac{(2N+1)}{\sqrt{\dfrac{\varepsilon_r + 1}{2}}} \times (\lambda/2) \qquad (1)$$

$$L = \frac{(2N+1)}{\sqrt{\varepsilon_{eff}}} \times (\lambda/2) - 2\Delta L \qquad (2)$$

where N is a non-negative integer (in this work we set $N = 1$), λ is the operating wavelength and ε_r is the relative dielectric constants. The patch length extension ΔL which is due to the fringing field effect and the effective dielectric constants ε_{eff} are given by the following expressions [2]

$$\Delta L = 0.412 h \frac{(\varepsilon_{eff} + 0.3)(0.264 + W/h)}{(\varepsilon_{eff} - 0.258)(0.8 + W/h)}$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \left(\frac{\varepsilon_r - 1}{2}\right)\left(1 + 12\frac{h}{W}\right)^{-1/2}$$

For the above antenna structure both the input impedance Z_{in} [1] and the microstrip transmission line length L_T [31], which is employed to feed the antenna and also to provide impedance transformation, can be expressed as:

$$Z_{in} = 29.9\frac{\lambda_0}{W} \qquad (3)$$

$$L_T = \frac{(2M+1)}{2} \times (\lambda/2) \qquad (4)$$

where λ_0 is the free space wavelength of the operating frequency and M is a non-negative integer (in this work we set M=1). The width 'W_{T1}' of the microstrip transmission line (TL) is computed using the procedure and expressions given in [32] where effects of both copper cladding (see Fig. 1) and frequency dispersion on the TL impedance have also been considered. At 10GHz frequency, two antennas have been designed on each of the aforementioned substrate thickness where in one design $W_{T2}=W_{T1}$ and in the other one $W_{T2}=W_{T1}/2$ in order to evaluate the trade off between the total antenna gain and the side lob levels in vertical plane $(\phi = 90^0)$ of the far-field radiation pattern. The ground length 'L_g' and width 'W_g' were initially set to be $L_g=L+6h$ and $W_g=W+6h$. The final designed antenna dimensions were optimized using CST Microwave Studio optimization tools to attain maximum antenna performance. In doing so 'L', 'W' and W_{T1} given in Fig. 1, were optimized to get the desired resonance frequency, highest possible gain, lowest side lobe level, and to have better impedance matching. The 10GHz and 60GHz bands antenna structures were designed based on the above mentioned procedure and were easily fabricated by conventional PCB etching technique.

3.   Results and Discussions

A. Microstrip antennas at 10GHz

Four 10GHz patch antennas are designed and fabricated on a low loss dielectric substrate 'RT/Duroid5880' as shown in Fig. 2 where they are fabricated on the substrates with thickness of 0.787mm ((a) and (b)) and 1.57mm ((c) and (d)). The power supplied to each of the radiating patch limb of antennas (a) and (c) is uniform as $W_{T2}=W_{T1}$ (see Fig. 1) whereas this is not the case for antennas (b) and (d) because $W_{T2}=W_{T1}/2$. Table I shows the optimized parametric values of the proposed antennas which are calculated through the procedure described in Section II.

TABLE I. Dimensions in mm of four 10GHz patch antennas

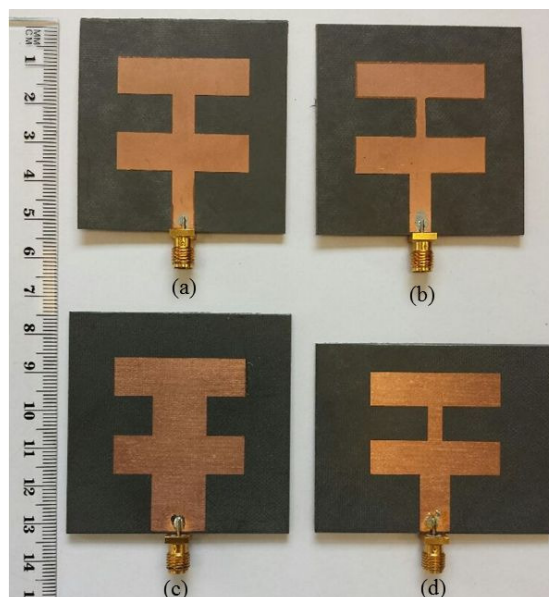| Antennas	L	W	L_T	W_T	h
(a)	29.52	34.35	25.94	6	0.787
(b)	29.33	34.35	25.94	5.8	0.787
(c)	30.85	34.45	25.64	14.39	1.57
(d)	27.07	34.45	25.64	8.1	1.57

Fig. 2. Fabricated antennas h=0.787mm for (a) and (b) but 1.57mm for (c) and (d)

Fig. 3 shows simulation and measured results of the return loss and far-field patterns in both E and H planes of the antenna shown in Fig. 2(a). For this antenna the measured minimum return loss, -10dB bandwidth, gain, side lobe level (SLL) and efficiency are, respectively, -15dB, 384MHz, 13.53dB, -9.92dB and 92%. Figs. 4 to 6 show simulation and measured results for the other antennas shown in Figs. 2(b), (c) and (d). The performance characteristics of these antennas are also listed in Table II. Let us consider antenna in Fig. 2(a) as a reference and compare the other antennas' performance characteristics. Based on this reference antenna, antenna 2(b) shows a small improvement in the bandwidth (i.e. 2.6%) but a small reduction in the gain (3.5%) whereas the gain of antenna 2(c) has increased by

0.8% at the cost of 24.5% reduction in the bandwidth. The best result has been achieved with antenna 2(d) where the bandwidth (12.84% of the central frequency) is about 3.2 times that of the antenna 2(a) and its gain has increased by 2.7%. Moreover, its side lobe level improved by about 2dB.
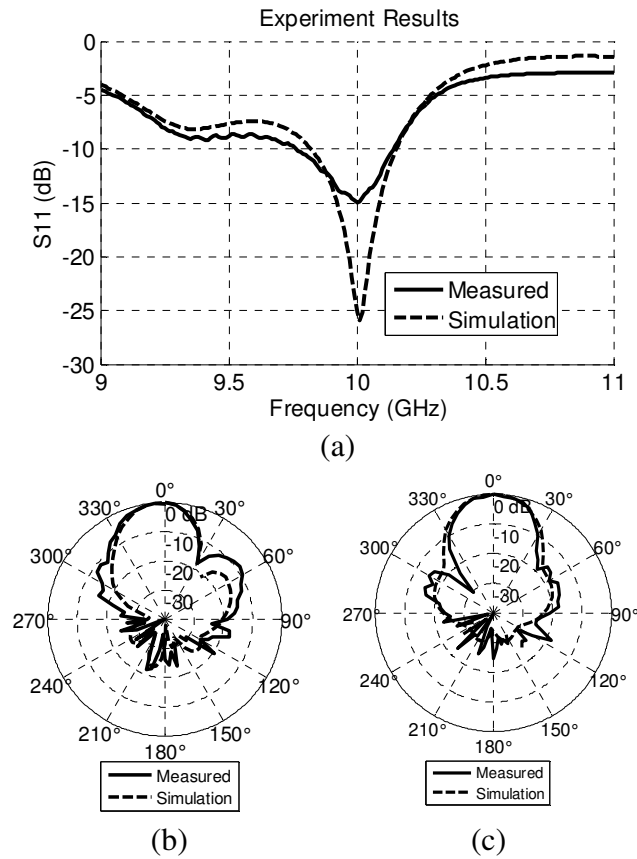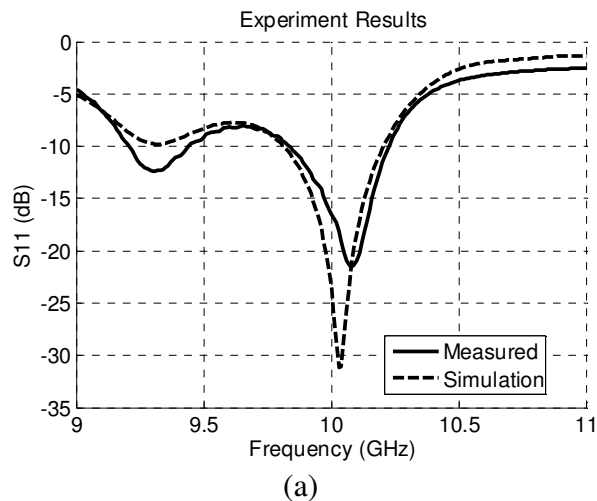

(a)

(b)   (c)

Fig. 3. Simulation and measured results of the antenna shown in Fig. 2(a); (a) return loss and far-field pattern at 10GHz in (b) E-plane and (c) H-plane

(a)

(b)   (c)

Fig. 4. Simulation and measured results of the antenna shown in Fig. 2(b); (a) return loss and
far-field pattern at 10GHz in (b) E-plane and (c) H-plane

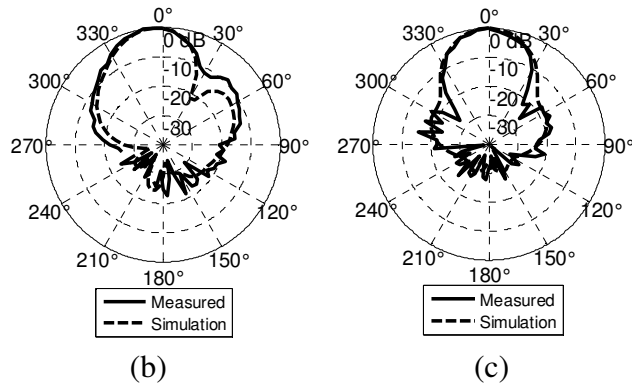(a)

(b)   (c)
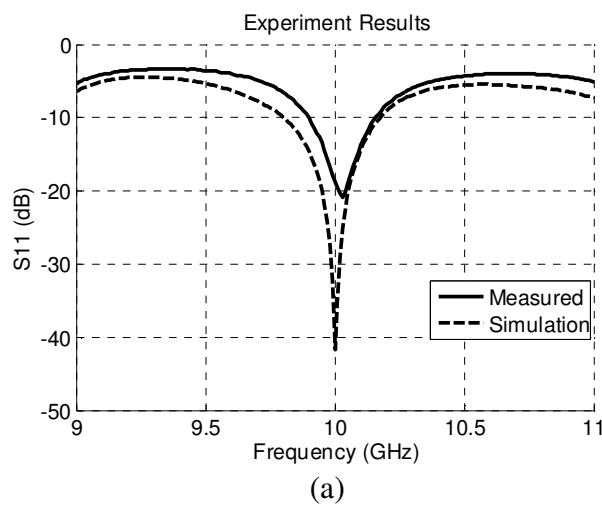
Fig. 5. Simulation and measured results of the antenna shown in Fig. 2(c); (a) return loss and
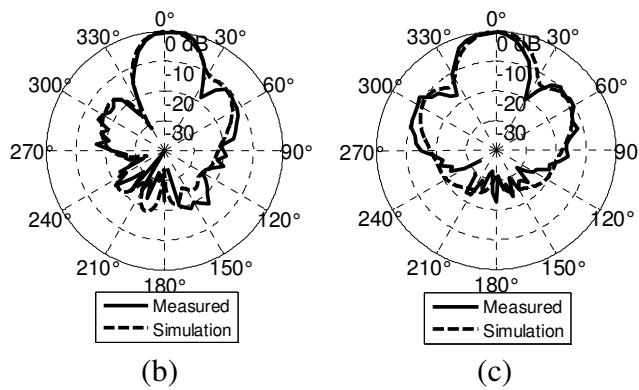far-field pattern at 10GHz in (b) E-plane and (c) H-plane
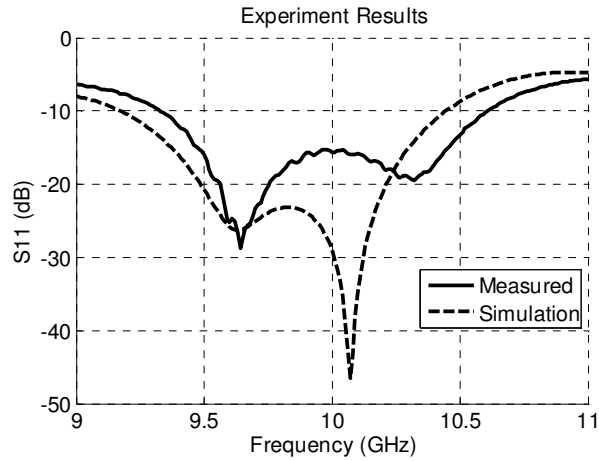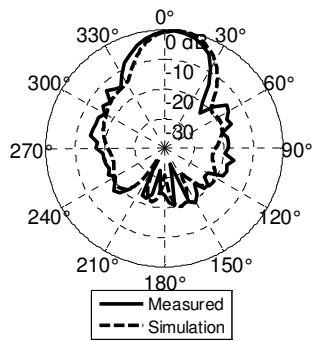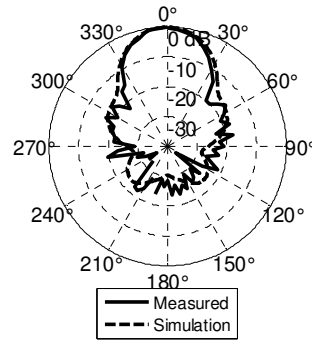
Fig. 6. Simulation and measured results of the antenna shown in Fig. 2(d); (a) return loss and far-field pattern at 10GHz in (b) E-plane and (c) H-plane

Figs. 7(a) and (b) show the measured gain and return loss frequency responses of antennas shown in Figs. 2(b) and (d), respectively. The results show that within each antenna's bandwidth the gain of the antenna shown in Fig. 2(b) fluctuates between 13dB and 15.4dB whereas that of the antenna shown in Fig. 2(d) remains almost constant at 14dB.
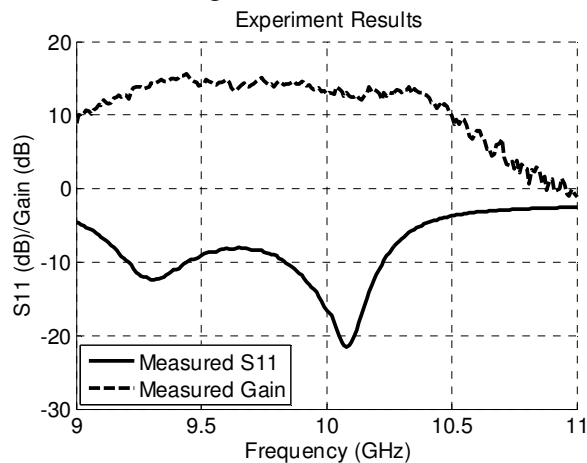
(a)
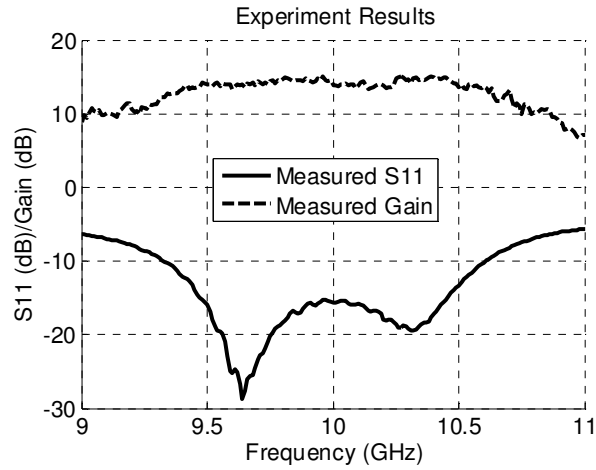
(b)
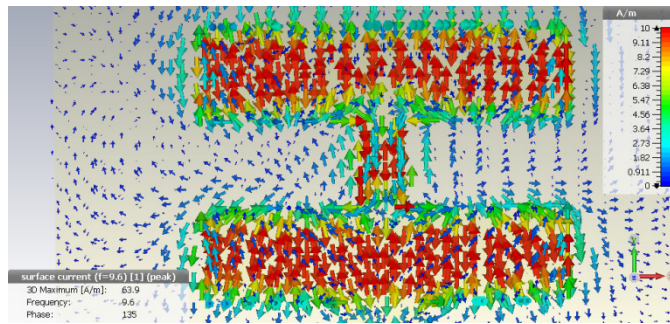
(c)
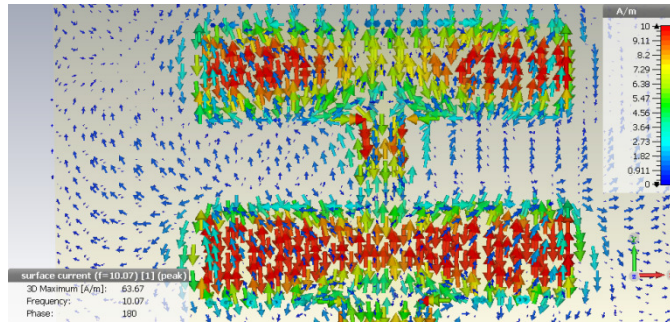
(d)

Fig. 7. Measured gain and returned loss (S_{11}) of Antennas shown in (a) Fig. 2(b) and (b) Fig. 2(d). Simulated maximum surface current distribution of Antenna shown in Fig. 2(d) is presented in (c) 9.6GHz and (d) 10.1GHz

Figures 7(c)-(d) illustrate the simulated surface current distribution on the patch wings of the antenna shown in Fig. 2(d) at both resonance peaks i.e. 9.6GHz and 10.1GHz with phase angles of 135^0 and 180^0, respectively. The surface current was maximum at the mentioned phase angles. From Figs. 7(c)-(d), it is clear that at the both resonance peaks the current remains in phase on the patch wings which explains the motive of gain enhancement across the operating frequency band by using the wide patches. The simulated axial ratio was 40dB at both mentioned frequencies which indicates that the antenna is linearly polarized in the operating frequency band.

In short, as Table II shows, in all four designed antennas the measured gain remains above 13dB and the total efficiency stays above 92%. The bandwidths of the antennas vary widely from 290MHz to 1.28GHz which gives an extensive flexibility to deploy one of the proposed designs in a specific X-band application depending on the bandwidth requirement.

TABLE II. The Designed Antennas' Performances

Antennas	BW (MHz)	Gain (dB)	S LL (dB)	Efficiency (%)
(a)	384	13.53	-9.92	92
(b)	394	13.05	-10	92
(c)	290	13.64	-10	94
(d)	1228	13.90	-12	94

B. Microstrip antenna at 60GHz

For 60GHz band applications, two antennas ((e) and (f) were designed and fabricated on substrate thickness 0.127mm and 0.254mm, respectively, to cover various frequency channels within 60GHz band as explained in section 1. The optimized dimensions of designed antennas are given in Table III. It is worth noticing that all of the dimensions shown in Table III are well above the minimum PCB fabrication limit of 152μm [1] imposed by the conventional PCB etching method. The fabricated antennas' photos and experimental setup are shown in Fig. 8(a).

TABLE III. Dimensions in mm of the 60 GHz Band Antennas

Antennas	L	W	LT	WT	h
(e)	4.44	5.54	2.51	0.595	0.127
(f)	4.3	5.57	2.49	1.79	0.254

Figs. 8(b)-(d) show the measured and simulated return loss responses and far-field patterns (in both E and H planes) at 62GHz for antenna (e). The measured -10dB bandwidth for this antenna is 4.92GHz (see Fig. 8(b)) which covers channels 2 and 3 of 60GHz WLAN/ WPAN standard as discussed in Section I. The results for antenna (f) at 60GHz are shown in Figs. 9(a)-(c). The measured bandwidth is 3.03GHz which is wide enough to be used for channel 2 of 60GHz band.
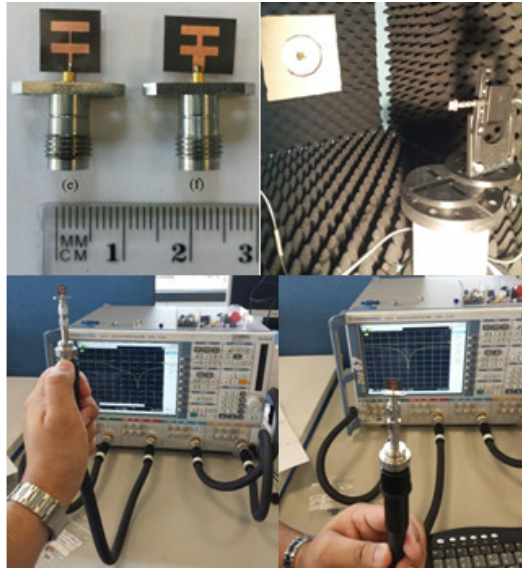
(a)
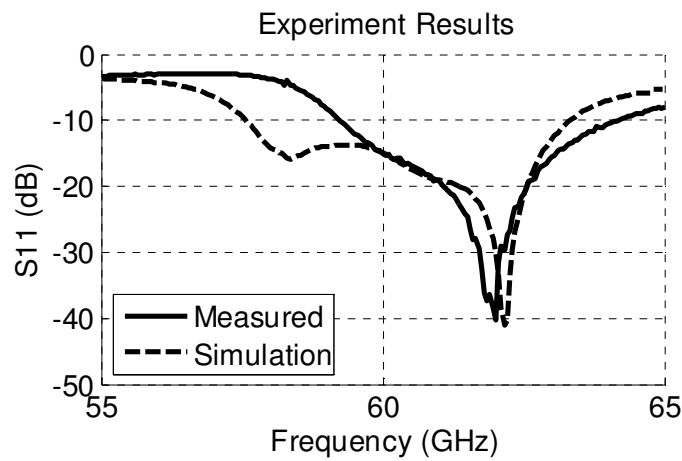
(b)
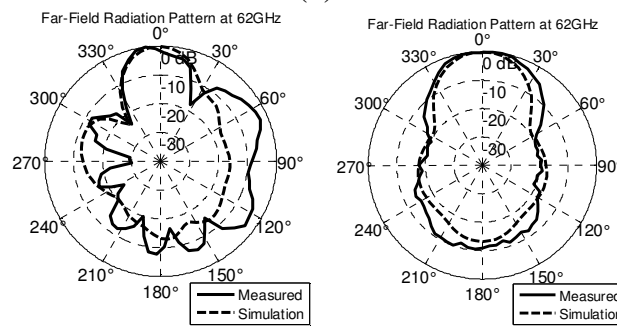
(c)   (d)

Fig. 8. Fabricated 60 GHz antennas and the experimental setup for far-field pattern and return loss measurements are in (a). The simulated and measured return loss of antenna 'e' is in (b) and the far-field patterns at 62GHz in both E and H planes are in (c) and (d), respectively.

Experiment Results

(a)

(b)   (c)
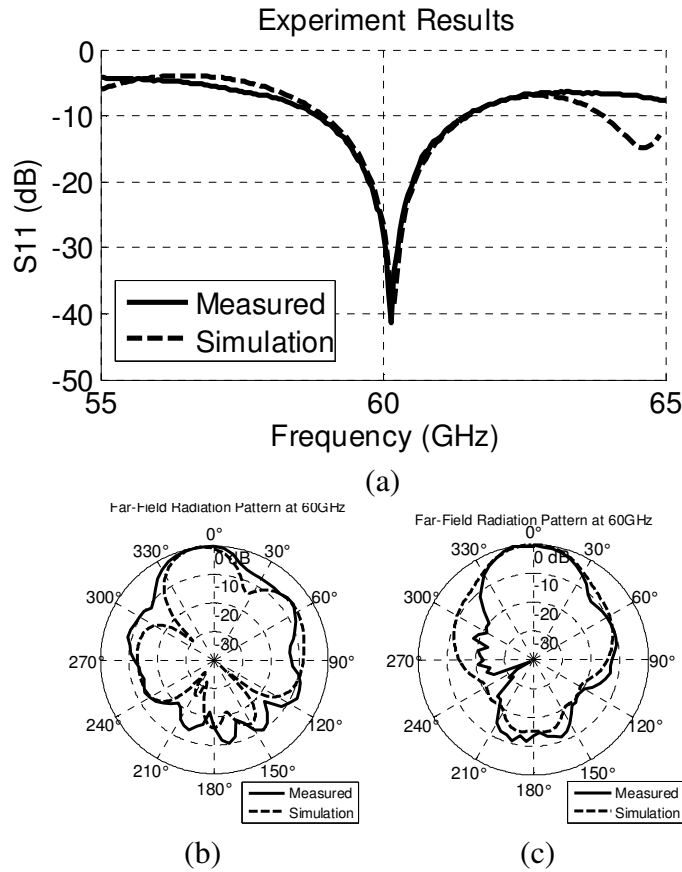
Fig. 9. Experiment results for antenna (f). The return loss is in (a) and the far-field patterns at 60GHz in both E and H planes are in (b) and (c), respectively.

The measured gains and directivities of antenna (e) are 10.1dB, 10.99dB, respectively, and those of antenna (f) are 9.1 and 10dB, respectively. Also, the measured half power beam widths (HPBW) of antennas (e) and (f) in E and H planes are (32^0, 55^0) and (42^0, 43^0), respectively.

Some distortions have been observed in the far-field patterns of these 60GHz antennas shown in Figs. 8 and 9 which are due to significant contribution of the multi-path reflection, obstruction from the surroundings and V-connector's body. The side lobe level of the proposed antennas can be further reduced in the absence of the V-connector transition when integrated with on-chip devices for 60GHz wireless applications [10], [11]-[13].

4.   Antennas Implementation for 60GHz WLAN/WPAN

As mentioned in section I, the employment of microstrip antenna at 60GHz in WLAN and WPAN applications is a matter of current interest and in recent years some valuable investigations have been reported in [9]-[13]. According to the analysis performed in [10], the 60GHz WLAN or WPAN coverage is required in a sector area of a medium size room (i.e. $\leq$ 10m$\times$10m) and in doing so, the 60GHz patch antenna needs to have 13.7dB gain and HPBW of 77.5^0 to fully cover the whole 10m$\times$10m room area when it is installed in the centre of the room's ceiling. In [10] two optimized 2×2 compact patch array antenna has been proposed for this application where the first and second array antennas are optimized to provide a high gain (13.2dBi) and a wide beam (76^0), respectively. Based on the antenna

requirement analysis reported in [9]-[10], the gain, bandwidth, and radiation pattern of the two patch antennas shown in 8(a) are suitable for point to point radio link as well as for a reasonable coverage in point to multi-point 60GHz WLAN/WPAN applications.

However, in point to multi-point links, the coverage area can be maximized up to 100% by installing two antennas in one of the room's corners with an inter-beam angular distance of 45^0 as shown in Fig. 10 where a square room of 10m diagonal length and 3.5m height is to be used for such application. The wireless service is required 1.5m below the ceiling in the xz-plane [10] as shown in Fig. 10(b) (i.e. shaded sector). The room is further divided into two sub-sectors across the diagonal line. The two antennas are installed in the access point located in the corner at 1.5m from the ceiling in such a way that one antenna covers one sub-sector of 45^0 angular width and the other antenna covers the other half part.
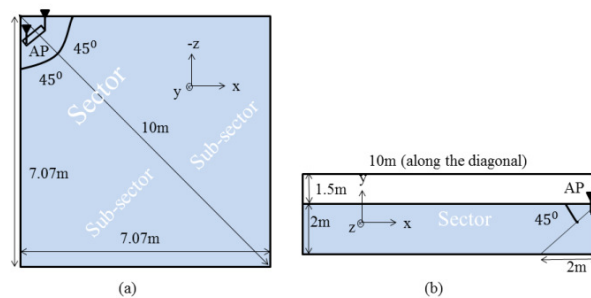

Fig. 10. Proposed antenna implementation for 100% WLAN/WPAN coverage; (a) Top view and (b) side view of the room

5. Conclusion

A novel procedure has been introduced to simultaneously enhance the bandwidth, gain and efficiency of the planner microstrip antenna.

In contrast to some miniaturized half-wavelength low frequency and low gain H-shaped antennas reported in the literatures [33]-[39], the proposed antenna shape is analogy to an array of two extra-wide patches fed in series which results in improvement of the gain and bandwidth as well as easy to fabricate it at mm-wave frequencies using conventional etching technique. Six antennas have been designed and tested, four for X-band and two for 60GHz WLAN/WPAN applications. The X-band antennas (10GHz) showed maximum bandwidth of 1.2GHz and gain of 13.9dB. The antenna's bandwidth, gain and efficiency (94%) fully satisfy the famous Chu's limits which specify the maximum achievable fractional bandwidth (FBW) and maximum gain (Gm) for a specific antenna size, as given in [40]:

$$Q > \left[\frac{1}{(ka)^3} + \frac{1}{ka} \right] \times \eta \qquad (5)$$

$$FBW = 1/Q \qquad (6)$$

$$Gm < \left[(ka)^2 + 2(ka) \right] \qquad (7)$$

Where Q is the quality factor, $k = 2\pi / \lambda$, 'a' is radius of a sphere containing the antenna and its associated current distribution and η is antenna efficiency. For our microstrip patch antenna $a = (W/2 + 2h)$ where $2h$ is the approximated width extension due to the fringing field [1], and $\eta = 94\%$. Hence, for the proposed antenna's dimensions using Eqs. (5) to (7)

we obtain values of 13.14% and 17dBi, respectively for FBW and Gm considering double resonances in the operating band (i.e. Fig. 7(b)). The measured maximum values for both FBW and Gm are 12.84% and 15.4dB which are within the limits.

The performance of the proposed 60GHz antennas satisfied the requirements of IEEE 802.11ad and IEEE 802.15.3c standards for multi-gigabits/s 60GHz WLAN and WLAN applications. The proposed designing approach can be particularly useful, in terms of manufacturing and performance, to design wide band and high gain microstrip antenna at terahertz (THz) frequency bands (0.1-3THz). Moreover, since each of the presented single element antenna has a reasonably high gain they can be used to construct array antenna with small feeding network to further increase the gain which is desirable for various mm-wave and THz applications [41]-[42].

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