A Semi-Hexagonal Array (1×2) Antenna Using Half Mode Substrate Integrated Waveguide for Short Range Communication Devices

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***Abstract*—In this paper, the authors propose a single element semi-hexagonal half mode substrate integrated waveguide (HMSIW) antenna split across the line joining the opposite edge center of a hexagonal cavity, such that the line of separation includes the radiating edge, while the other edges are lined with metallic vias. The antenna was designed and fabricated on Arlon AD270 and the substrate has a gain of 5.8 dB at 5.9 GHz. The proposed array element is then used to design a linear array (1×2) resonating at 5.95 GHz. Antennas are useful applications in vehicular communication systems, serving as internal pa[illegible] of dedicated short range communication devices with frequ[illegible] operation laying in the IEEE 802.11p band.**

Keywords—semi-hexagonal array; short range; vehicul[illegible] communication

I. Introduction

Dedicated short range communicat[illegible] (DS[illegible] popularized worldwide as the wireless com[illegible]atio[illegible]rotocol for vehicles following Wi-Fi architecture [1] a[illegible] initially focused on low overhead operations f[illegible]ving IE[illegible]2.11a standards. However, with the adv[illegible] of years a[illegible] in compliance with development and [illegible] needs to support high-speed moving vehicles and[illegible] simplify the communication mechanisms, IEE[illegible] working [illegible] amended IEEE 802.11 standards to in[illegible]porate Wireless [illegible]ccess in Vehicular Environments (WA[illegible]). WAVE formed the core of DSRC in supporting intellig[illegible] trans[illegible]tation systems' (ITS) applications for short range [illegible]mmu[illegible]tion. W[illegible]VE, following IEEE 802.11p standards, p[illegible]des [illegible]-time t[illegible]ic information, improves transportation safe[illegible]imize[illegible]affic congestion and helps maintaining transpo[illegible]ability. It helps establishing commu[illegible] between[illegible]ehicles (V2V) or between vehicles a[illegible]roa[illegible]e information (V2I) in the 5.9 GHz band (5.85–[illegible]25 GH[illegible]th the involvement of several compa[illegible] ca[illegible]ufacturers and universities worldwide pursu[illegible]sive research to develop IEEE 802.11p standard com[illegible] products. Researchers extended their contribution in develop[illegible]rinted antennas and arrays to be used in conjunction with other devices for short range communication to support ITS applications [6-9].

Though hexago[illegible]aped substrate integrated waveguide (S[illegible]) based components are widely popular [10-14], yet little [illegible]en reported about the unexplored domain of hexagonal [illegible]W based [illegible]ennas and arrays. As a result, in this paper, [illegible]uthors prop[illegible] a novel semi-hexagonal HMSIW antenna [illegible]erating at [illegible]EE 802.11p frequency of 5.9 GHz and [illegible]quentl[illegible]eveloped linear and planar arrays using the fo[illegible]ay elements. The 1×2 semi-hexagonal HMSIW array operates at a resonating frequency of 5.9 GHz with a gain [illegible]f 8.2 dB. The antennas are designed and fabricated using [illegible]270 substrate and the necessary full wave simulation [illegible] all carried out in ANSYS HFSS v15.0. The simulation [illegible]btained results are compared with experimentally obtained results.

II. Antenna Design

The concept of hexagonal waveguide is further extended to a substrate integrated waveguide concept wherein the metallic walls lying along the direction of the propagation are replaced by metallic conducting vias and the whole waveguide is integrated into a dielectric filled PCB. Due to the resemblance of the hexagonal waveguide with the circular/cylindrical one, the former has been modeled in terms of its circular counterpart. The first twenty one normal modes and corresponding cut-off frequencies are all obtained for the E-modes of waveguides with regular hexagonal cross-section. The cut-off frequency of the first mode for a hexagonal waveguide is given as the designing of antenna is achieved level by level in a appropriate way. The basic shape is shown in Figure 1[14-18].

$$fc_{mn} = \frac{c}{2\pi\sqrt{\varepsilon_r}}\frac{k_{cmn}}{s} \qquad (1)$$

where c is the speed of light in vacuum (≈3×10^{10}cm×s^{-1}), k_{cmn}, is the cut-off wave number and s is the side length of the regular hexagon. The fundamental TM01 mode is chosen as the mode of operation as it provides maximum directional radiation from the antenna. The cut-off wave number of the TM01 mode obtained after putting m=0, n=1 and k_{c01}=2.69 is

$$f c_{01} = \frac{2.68c}{2\pi s\sqrt{\varepsilon_r}} \quad (2)$$

However a direct approximation from a circular waveguide leads to the value shown in [15]. The fact that numerical methods have been used for approximating the cutoff wave number of the hexagonal waveguide, and also, the application of such a structure modeled as a substrate integrated cavity, leads to the acceptance of the modified value as applicable in the designed prototypes. Thus the formula for the cut off frequency of a full mode hexagonal SIW cavity, operating in the TM01 mode is given by

$$f c_{01} = \frac{2.75c}{2\pi s\sqrt{\varepsilon_r}} \quad (3)$$

Initially a full-mode SIW (FMSIW) regular hexagonal cavity with side length s=15mm was designed at the center frequency of 5.9GHz exciting the fundamental TM01 mode. With the array incorporation along its periphery the actual side length reduced to 13.5mm. Substituting s=13.5mm in (3), the theoretical cut off frequency of a full mode hexagonal SIW cavity for TM01 mode obtained is 5.9GHz which is equal to the resonating frequency obtained through simulation. The fabricated prototype and the fundamental TM01 mode at 5.9GHz are shown in Figure 1 (b) and (c) respectively, their other dimensions are shown in Table I.

A. Substrate Selectivity

Substrate selectivity is the first step when designing a patch antenna. Due to its high performance and high reliability characteristics Arlon AD270 is chosen as substrate f[illegible] proposed design [16].

B. Patch Width

With the help of the following equation, the width of th[illegible] patch is calculated [17].

$$W = \frac{c}{2f0\sqrt{\frac{\varepsilon r+1}{2}}} \quad (4)$$

Here εr is the relative constant wi[illegible]ctioning frequency and C is the rapidity of light in [illegible]cuum.

C. Patch Length

With the help of the following [illegible] the length of the patch is calculated [17-18].

$$L = L(eff) - 2\Delta L \quad (5)$$

where $L(eff) = \frac{c}{2f0\sqrt{\varepsilon_{(r}}}$ [illegible] (6)

and

$$\varepsilon_{(reff)} = \frac{\varepsilon r+1}{2} + \frac{\varepsilon r-1}{4}\left(1 + \frac{12h}{W}\right) \quad (7)$$

The hexagonal [illegible]vity [illegible] symmetrical about two axes. Hence, preservin[illegible]e TM[illegible] the parent hexagonal resonator, we ca[illegible]tain t[illegible]ypes of half mode SIW antennas by bisecting the ca[illegible]wo ways: Type-1, in which the line of bisection lies alon[illegible]plane joining the opposite edge centers and Type-2, in whic[illegible]ine of bisection lies along the diagonal of the hexagon, as depicted in Figures 2(a) and 2(b) respectively. We chose the Type-1 HMSIW structure. The HMSIW based semi-hexagonal antenna lined with metallic vias along the walls of the hexagon with the radiating surface, vias devoid, lying along the line of bisection of the full mode hexagonal cavity and excited with inset feed is depicted in Figure 3. The antenna is deve[illegible] on Arlon AD270 substrate (tm) with 0.79 mm thick[illegible]c constant εr=2.7 and loss tangent tanδ=0.00[illegible] with its [illegible]all size being 60 mm(L)×60 mm(W). T[illegible]ength of eac[illegible]de of the antenna, considering the correct[illegible] length, is [illegible]13.5 mm. The vias' diameter is 1 mm while t[illegible]eparation (center-to-center) is 1.5 mm. [illegible] excite the [illegible]ental TM01 mode, the inset feed of wi[illegible] L7=0.58 mm is inserted at an optimized distance of L5=[illegible]2 mm [illegible]om the base of the semi-hexagonal structure to m[illegible]h wi[illegible] the 10[illegible] impedance in order to suppress refle[illegible]ucing [illegible]urious beams. The other necessary d[illegible] a[illegible]na are enlisted in Table II.

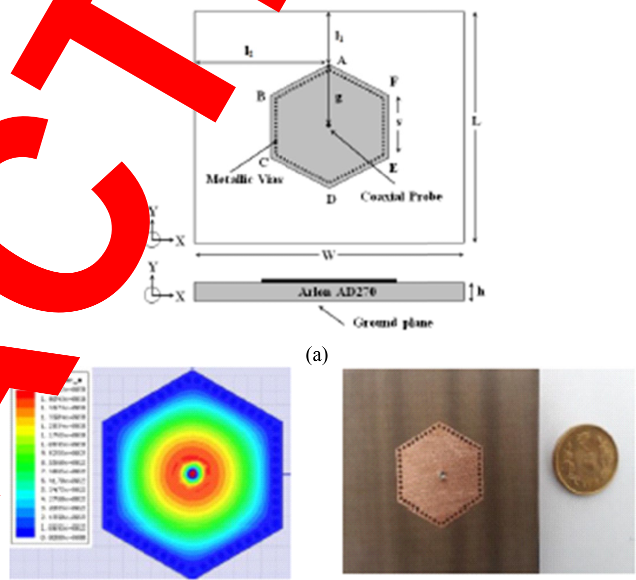


Fig. 1. (a) Geometry of the FMSIW hexagonal cavity. (b) Electric field distribution for the principal TM01 mode at 5.9GHz. (c) Fabricated prototype of the cavity.

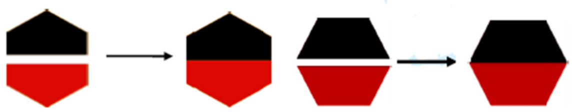


Fig. 2. Design of (a) Type-1 and (b) Type-2 HMSIW semi-hexagonal antenna

TABLE I. DIMENSIONS OF THE FMSIW HEXAGONAL CAVITY (mm)

L	W	s	h	l_1	l_2	g
60	60	15	0.78	15	15	15

TABLE I. DIMENSIONS OF THE FMSIW HEXAGONAL CAVITY (mm)

L	W	h	l_1	l_2	l_3	l_4	l_5	l_6	l_7
60	60	0.78	15	30	17	30	8.21	1.72	0.56

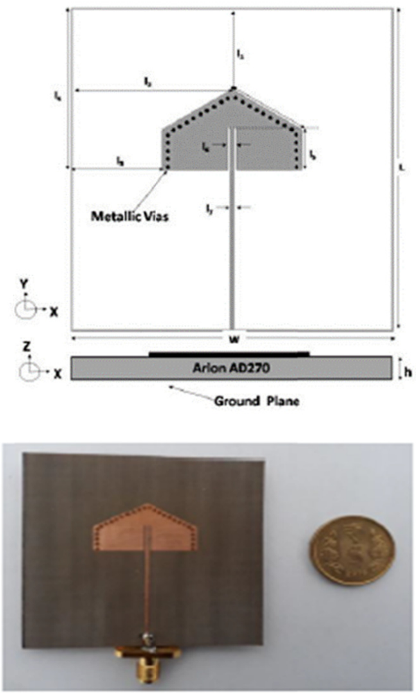


Fig. 3. (a) Geometry of the HMSIW semi-hexagonal antenna. (b) Fabricated prototype of the cavity.

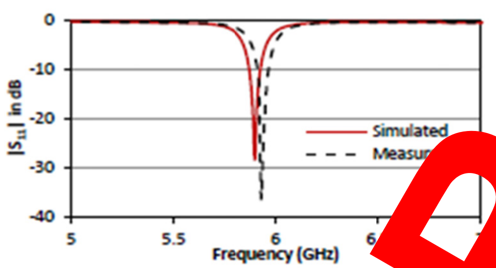


Fig. 4. Simulated and measured return loss value of the HMSIW semi-hexagonal antenna for TM01 mode.

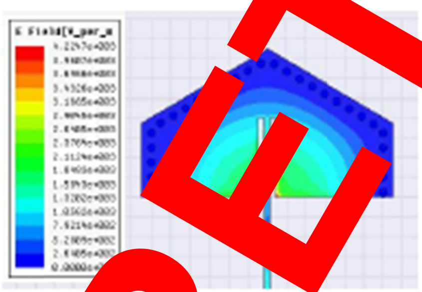


Fig. 5. Electric Field Distribution of the array element at 5.9 GHz for TM01 mode.

The simulated fundamental resonating frequency for the TM01 mode of the single array element is 5.9 GHz with an optimized return loss value (S11 parameter) of -28.4 dB with a narrow impedance bandwidth of 80 MHz (5.93-5.85 GHz) i.e. 1.36% fractional bandwidth. The same S11 parameter measured through Anritsu VNA is -36.1 dB at 5.93 GHz thereby reflecting very close agreement between simulated and measured values. Figure 4 depicts the simulated and measured return loss (S11 value) for TM01 mode for the parent HMSIW semi-hexagonal antenna and Figure 5 reflects its electric field distribution for the same mode. The E-plane and H-plane radiation pattern of the single array element is depicted in Figure 6. The radiation pattern of the antenna is measured with the help of Hittite HMC-T2[illegible] microwave signal generator (10 MHz–20 GHz) and [illegible] Krytar [illegible] power meter. From the figure it is evident that the simulated E-plane co-polarized gain is 5.8 dBi while the measured value is 5.6 dBi while the simulated and measured value co[illegible] values for the H-plane are 4.8 dBi and 4.[illegible] respectively. The cross-polarized values for both E- and H-plane are found to be well below 20-30 dBi and the antenna is observed to [illegible] 89.5% radiation efficiency.

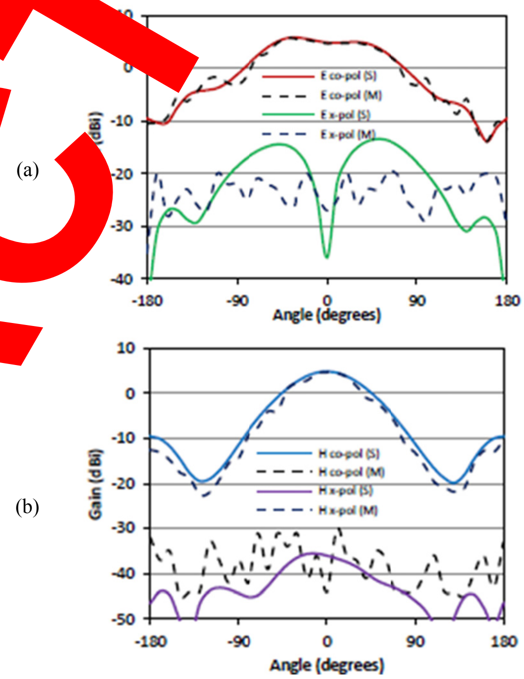


Fig. 6. (a) E-plane and (b) H-plane radiation pattern of the single element antenna array element at 5.9GHz. S: Simulated Results. M: Measured Results.

III. Mutual Coupling Between Two Similar Array Elements

Table IIII depicts the mutual coupling study between two similar HMSIW semi-hexagonal antenna array elements with variations in inter-element spacing (center-to-center distance) d. The results obtained are depicted in Figure 7 which illustrates a variation plot of S11 and S21 parameters with frequency f for different values of d. The coupling values of S21=-24.26,-25.51 and -25.79 dB are observed for values of separation distance d=37.42, 35.59 and 33.18 mm respectively. From the Figure, it is observed that with change in inter-element spacing, a small shift in the resonating frequency occurs as reflected in Table III. Owing to the typical design of our antenna array element, the lateral sides of the adjacent array elements have non radiating PEC walls which causes appreciable low values of mutual coupling between them thereby significantly reducing the total size of the antenna array constituted with such elements as they can be brought close together to an appreciable extent. Here, for designing antenna arrays, the values of d=35.59 mm≡0.7λ_0 with corresponding values of S21=-25.51 dB and S11=-28.66 dB have been chosen.

IV. ANTENNA DESIGNING AND RESULTS OF 1×2 LINEAR ARRAY

Two linear HMSIW semi-hexagonal array antennas, viz Antenna-1 (1×2) elements have been designed and fabricated using Arlon AD270 substrate using the parent HMSIW semi-hexagonal antenna structure as shown in Figure 8 with their dimensions listed in Table IV and V. The arrays are designed with a view to not only increase the gain but also to improve the scanning capabilities of the antenna. The realization of the antenna array is done with the help of power distribution network and for the most optimized performance the distribution network is designed in order to feed equal power into each array element spaced at a distance of 0.7λ_0 from each other. In this consideration, we designed a corporate feed network for power splitting and realized it using quarter-wavelength (λ/4) impedance transformers to match the 50 Ω feed to the 100 Ω inset feed line.

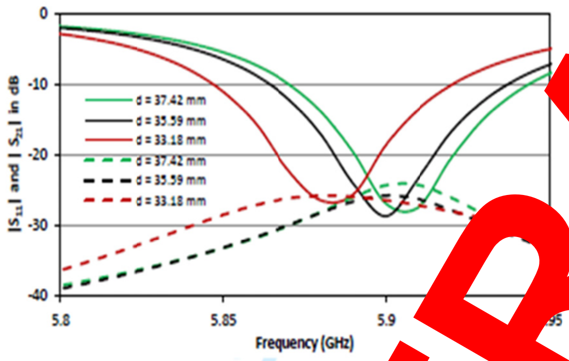


Fig. 7. Variation of S11 and S21 for two [illegible]enna array eleme[illegible]ith different inter element spacing d. d=37.42 m[illegible]1: Green solid line, S21: Green dashed line), d=35.59 mm (S11: Bla[illegible] S21: Black dashed line), d=33.18 mm (S11: Red solid line, S2[illegible]ed dash[illegible]

TABLE II. MUTUAL COUPLI[illegible]TUDY BETWEEN TWO [illegible]MSIW SEMI-HEXAGONAL ANTENNA ELE[illegible]TS

d (mm)	f (GHz[illegible]	S11 ([illegible]	S21 (dB)
37.42	5.91	-27[illegible]	-[illegible]6
35.59	5.[illegible]	-[illegible]6	[illegible]51
33.18	5.88	[illegible]41	[illegible]5.79

TABLE III. DIM[illegible] ANTENNA[illegible]2 ELEMENTS) (mm)

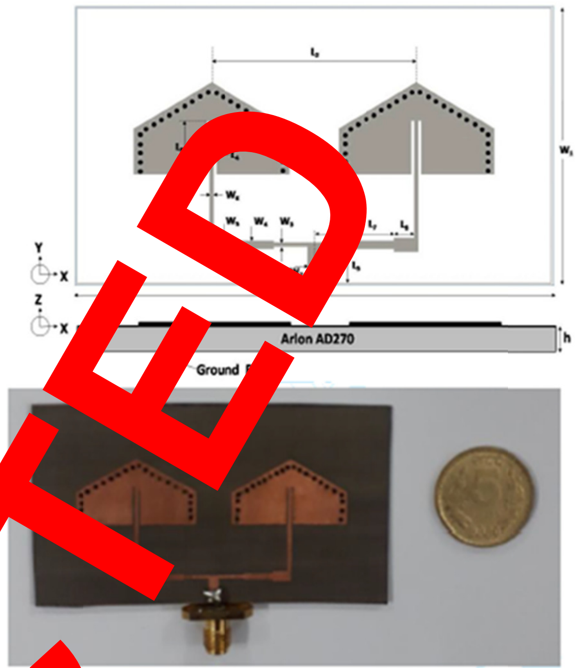
L_1	L_2	[illegible]	[illegible]	[illegible]	L_6	L_7	L_8
80	34	[illegible].84	[illegible]	[illegible]	6.82	4	44

TABLE I. DI[illegible] OF ANTENNA-1 (1×2 ELEMENTS) (mm)

W_1	W_2	[illegible]	W_4	W_5	W_6
45	2.1	0.59	1.3	2.2	0.59

(a)

(b)



[illegible]ig. 8. Anten[illegible] (1×2 array elements) (a) Geometry of linear array [illegible]enna. (b) Fabr[illegible]ed prototype

[illegible]TENNA DESIGNING AND RESULTS OF 1×2 LINEAR ARRAY

[illegible]he simulated results, the linear arrays (1×2) are found [illegible]perate at 5.91GHz. The obtained simulated return loss is -[illegible].6dB while the corresponding measure value using Anritsu [illegible]NA is -26.6dB at 5.86GHz. In Figure 11 we see that for [illegible]ntenna (1×2), the simulated E-plane co-polarized gain is [illegible]2dBi with the corresponding measured value being 8.1dB. [illegible]or the same antenna, the simulated and measured H-plane co-polarized gains are 8.1dBi and 7.9dBi respectively. Thus a gain improvement of 2.4dBi is achieved with the 1×2 array in comparison to the single element antenna.

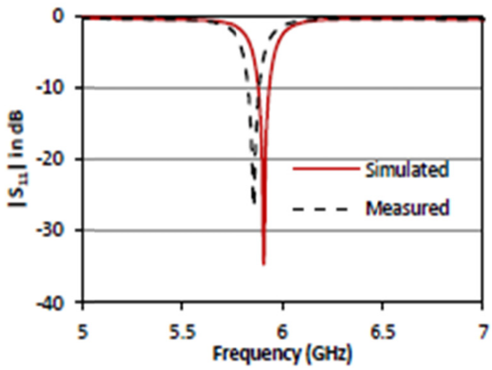


Fig. 9. Return loss (S11) parameters of Antenna (1×2) array

VI. CONCLUSION

An HMSIW based semi-hexagonal antenna is proposed and designed at IEEE 802.11p frequency of 5.9 GHz producing a gain of 5.8 dB. This parent antenna is used as an array element in designing and fabricating linear and planar antenna arrays at 5.9 GHz and their various parameters are studied extensively. It is observed that the presence of PEC walls on the two sides of the array elements reduces the mutual coupling between them to a greater extent thereby facilitating the design of compact arrays with reduced sizes. The primary objective of gain enhancement has been successfully achieved. For the linear 1×2 the corresponding gain is 8.2 dB indicating gain enhancement by 2.4 and 5.4 dB over the parent antenna.

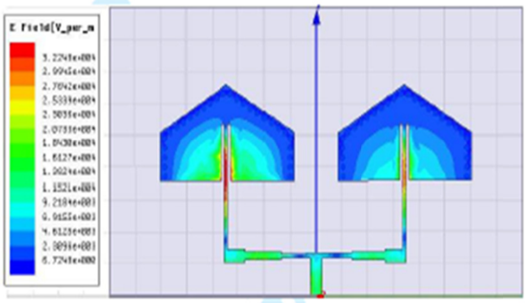


Fig. 10. Electric field distribution of Antenna-1 (1×2 elements) for TM01 mode

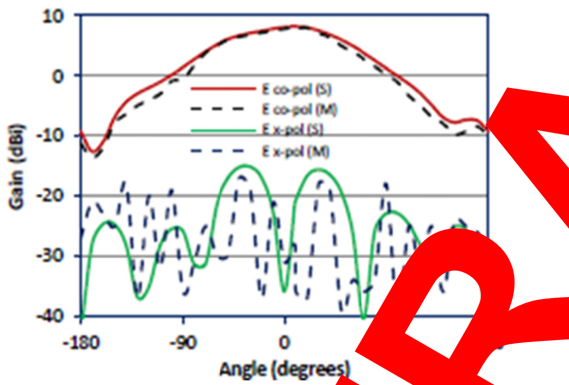


Fig. 11. E-plane pattern of antenna (1×2 an[illegible]a array) at [illegible] S: Simulated results. M: Measured results.

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