Design and Characterization of Compact Aspen Shape Multi-Element Antenna with Isolation Improvement for SWB Applications

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Abstract

Compact four - element Multiple – Input Multiple Output (MIMO) antenna is suggested to cover Ultra wide band (UWB: 3.1 – 10.6GHz), X-band (8 – 12GHz), Ku – band (12 - 18GHz) and K – band (18 – 26.5GHz) for future use in industrial, scientific and medical (ISM) systems as well satellite applications. Suggested design consists of four Aspen shape radiators with partial ground planes printed on Rogers RT / Duroid 5880™ substrate material having dielectric constant of 2.2, loss tangent 0.0009, thickness 0.787mm and its compact size is 43mm x 43mm. This design has been simulated using Ansys High Frequency Structure Simulator (HFSS) tool. The proposed antenna produces operating bandwidth at -10dB reflection coefficient is 23.66GHz (4.12 – 27.78GHz), having fractional impedance bandwidth (FBW) of 148.33%. Proposed antenna offers improvement in the isolation greater than -20dB in the operating super wideband (SWB) and voltage standing wave ratio (VSWR) is less than threshold value 2 in the obtained SWB range. Proposed antenna achieves peak gains within the operating band at selected frequencies 4.8GHz, 8GHz, 14.1GHz, 16.2GHz and 23.6GHz are 3.16dBi, 5.19dBi, 5.82dBi, 5.13dBi and 6.98dBi respectively. Furthermore, MIMO antenna parameters such as envelope correlation coefficient (ECC < 0.015), diversity gain (DG ≈ 10dB), total active reflection coefficient (TARC < 0.45), channel capacity loss (CCL < 0.30bits/sec/Hz) and mean effective gain (-4.5dB ≤ MEG ≤ -7dB) are investigated within the acceptable limits.

Keywords - Aspen shape, MIMO antenna, Irregular Isolating element, SWB, HFSS, Envelope Correlation Coefficient (ECC)

1. Introduction

With the advanced developments in the technology there is an enormous increase in the communication systems. Antenna plays a key role in the communications for the purpose of transmitting and receiving of the information. For designing an antenna [1], it should satisfy some of the requirements as high bandwidth, faster data rate, high efficiency, good resolution, high capacity. For designers it is a challenging activity to design a high-speed multimedia connectivity for wireless communication and also it requires covering wide bandwidth [2]. As, the signals gets weaker when it gets wider and also, it's harder to detect and send the wideband signals are the drawbacks. Due to this drawback ultra-wideband antennas [3] came into existence as it has the ability to provide the high data rate wireless communication systems. Its transmitting power is low, in multipath channels high performance; in adverse condition it delivers high signal strength. As it has some of the drawbacks like its adoption rate is slow, signal acquisition times is long, FCC has the limited emission, issues of co-existence and interference with other radio technologies, high cost. Due to its drawbacks, it has been recent trend to employ super wideband antenna [4] as it can offer high bandwidth by covering both long- and short-range communication. SWB has a bandwidth ratio greater than or equal to 10:1 and has a large BDR, high data rate, and electrical dimensions less, at faster rate data and video, increased channel capacity, greater time accuracy. It's now employed in monitoring systems, military and civil applications. To cover such large frequencies Multiple Input Multiple Output antenna is suitable as it is primarily utilized for the systems as multiple antennas employed for both source and destination in this case a single MIMO [5] antenna can be able to handle. With the help of the Spatial Multiplexing and multiple antennas high data rate achieved. MIMO based systems reduce fading effects, the systems with MIMO offers high Quality of Service and helps in achieving Bit Error Rate.

With the increase of technology there is a huge demand for the wideband communication. For the purpose of ultra – wide band applications MIMO antenna [6] designed with the size of 58.6 x 46mm^2 and it ranges entire UWB of 3.1-10.6GHz and has low correlational coefficient of < 0.02. In this article [7], with novel stub structure UWB-MIMO antenna is designed on FR4 substrate with the size of 40 x 68mm^2 and its frequency ranges from 3.2-10.6GHz and its IBW is 7.4GHz isolation less than -15dB and its gain is less than 2.5dB. In this paper [8], for the dual band MIMO system in the 5G smartphone an eight-antenna proposed. The overall dimensions of the antenna are about 145 x 75mm^2 on FR4 substrate and its frequency ranges from 3.3-3.6GHz and 4.8-5GHz and its ECC is less than 0.15. For the purpose of ultra-wideband systems an antenna which is uni-planar polarisation diversity is designed [9] with the size of 50 x 50mm^2 on Rogers RT/Duroid 6035HTC with the frequency ranges from 2.76-1075GHz. For the purpose of 5G smartphone application [10], MIMO antenna which is dual band is designed and the size of the antenna is 130 x 74mm^2 on FR4 substrate as its frequency ranges from 3.3-3.6GHz, 4.8-5.0GHz. With WLAN band rejection a compact 4 x 4 UWB-MIMO antenna designed [11] with the size of 60 x 60mm^2 and its frequency ranges from 2.73-10.68GHz and its IBW is 7.95GHz. In this article [12], using carbon black film in UWB MIMO antenna system isolation improvement proposed and the overall size is of 50x40mm^2 and the frequency ranges from 2.5-11GHz and the gain of 2.11dBi and the efficiency of 69.2%. In this paper [13], with dual polarization UWB-MIMO antenna which is compact coradiator proposed on FR4 epoxy with the size of 48 x 48mm^2 which frequency ranges from 3-11GHz. MIMO antenna system [14], UWB Bi-planar Yagi-like which is miniaturized is proposed with the size of 50 x 80mm^2 and the frequency ranges from 4.183 – 6.584GHz and the efficiency of 80%. In this article [15], with 5.5GHz band-notched characteristics UWB diversity slot antenna which is compact printed on FR4 substrate which is 48 x 48mm^2 in which frequency ranges from 2.5-12GHz. In UWB-MIMO antenna using F-shaped stubs [16], mutual coupling reduction proposed and the size of the antenna is about 50 x 30mm^2 and has low mutual coupling of less than -20dB and ECC < 0.04, DG > 7.4dB. In this article [17], with WLAN band-rejection UWB MIMO antenna which is Koch fractal is proposed and the size of the antenna is about 45 x 45mm^2 and S_{11} < -10dB from 2-10.6GHz. For mobile platform based on the theory of characteristic modes planar UWB MIMO [18] antenna with the pattern diversity and isolation improvement designed. The overall size is about 85 x 50mm^2 and the bandwidth ranges from 2-9.5GHz and the gain is above 1.5dBi. High gain monopole antenna [19] which is triple band and fractal based is proposed and the overall size of the antenna is about 90 x 59mm^2 and the gain of the antenna is about 5dBi. In this article [20], coplanar strips rectangular spiral antenna which UWB coplanar waveguide in which its size about 50 x 40mm^2 on Rogers RO4003C substrate and its frequency ranges from 3.5-10.6GHz and gain about 4.7dBi. In this paper [21], for the purpose of Bluetooth/WLAN applications integrated wideband antenna which is multiband designed and the size of the antenna is about 60 x 50mm^2. For super wideband applications [22], circular monopole antenna which is elliptical slot loaded partially segmented proposed on Rogers RT/Duroid 5880 substrate.

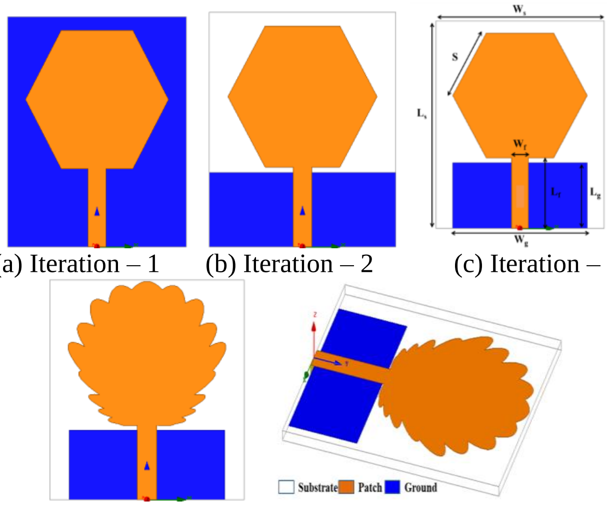
In this paper, four – element Aspen shape multiple - input multiple - output (MIMO) antenna using irregular polygon shaped isolating element is used for developing SWB applications, which is printed on Rogers RT / Duroid 5880 ™ dielectric material having thickness of 0.787mm. Section 2 organizes as Aspen shape monopole antenna with partial ground plane and its characteristics. Furthermore, in order to improve the high data transmission rate and coverage area four – element MIMO antenna is implemented with and without isolating element. Simulation characteristics are analysed in the section 3. MIMO antenna parameters (ECC, DG, TARC, CCL and MEG) are investigated in the section 4. Section 5 shows the advantages of the proposed antenna with comparison of existed models [6 – 21] reported in literature. Finally this work is concluded with applications in section 6.

2. Aspen shape Monopole antenna design configuration and its performance characteristics

Conventional hexagonal microstrip patch antenna is designed using standard mathematical expressions [23-24]. Designed antenna is a three layer structure, Rogers RT / Duroid 5880 substrate material is sandwiched between the two perfect electric conductors (PEC) named as patch and ground layers. It has compact size of 20mmx 23mm. 50Ohm transmission line feeding is used for impedance matching with the characteristic impedance in free space. Proposed structure is designed and simulated using Ansys HFSS software.

2.1. Implementation of proposed Aspen geometry with partial ground

The proposed Aspen shape monopole antenna with partial ground and its development from conventional structure are shown in figure 1. Rogers RT/ Duroid 5880™ substrate is used to implement this proposed design due to it exhibits unique electrical properties, chemical resistance and low moisture absorption. Because of these properties, Rogers material is highly desirable for SWB applications. The proposed antenna is derived from conventional hexagon structure with radius (S) of 8mm as shown in figure 1(a). There are four derivation stages for the proposed Aspen structure: Iteration – 1, 2, 3 & 4. In the first stage, Iteration – 1 is 50ohm transmission line fed hexagon microstrip patch antenna is designed. Iteration – 2 is partial ground plane with the full hexagon radiator. Iteration – 3 is partial ground plane width is reduced with hexagonal radiator. Finally, iteration – 4 is Aspen structure derived from the hexagon geometry with width reduced partial ground plane. The optimized dimensions of the proposed design are L_s = 23mm, W_s = 20mm, L_f = 7.75mm, W_f = 2mm, L_g = 7.25mm, W_g = 16mm, S = 8mm. Three dimensional view of the proposed design is shown in figure 1(e).



(a) Iteration – 1 (b) Iteration – 2 (c) Iteration – 3

(d) Iteration – 4 (e) 3D view

Figure 1. Evaluation of the proposed Aspen shape monopole antenna from conventional structure

2.2. Simulation results

The performance characteristics of the various iterations are evaluated from 3 – 30GHz interms of reflection coefficient (S_{11}) and voltage standing wave ratio (VSWR) as shown in figure 2 & 3. It is noticed that from figure 2, iteration – 1 is clearly resonates at the 19.30GHz with an impedance bandwidth (IBW) of 0.60GHz or 600MHz operating from 18.99GHz to 19.59GHz. By reducing the length of the ground plane, bandwidth can be improved to 16.99GHz from 0.60GHz for the 2nd iterative structure. Partial ground plane has been reduced to miniaturize the structure as shown in iteration – 3 and observed that there is an improvement in the IBW as well FBW. Iteration – 3 produces IBW of 21.67GHz at -10dB reflection coefficient and covers spectrum from 4.77 to 26.44GHz. Bandwidth ratio (BR) and fractional bandwidth (FBW) of iteration – 3 are 5.54 and 138.86%. Finally, regular hexagon structure is reshaped into Aspen shape structure with partial ground plane in case of iteration – 4. Impedance bandwidth, bandwidth ratio and FBW at -10dB are 24.03GHz, 6.25 and 144.88% respectively. VSWR signifies the designed antennas impedance matching condition with the characteristic impedance in free space. Ideal value of VSWR is 1 to infinity. Corresponding minimum VSWR values of the designed iterations 1 to 4 are 1.35, 1.01, 1.04 and 1.05 respectively as shown in figure 3. Table 1 reports the simulation characteristic parameters of the designed iterations.

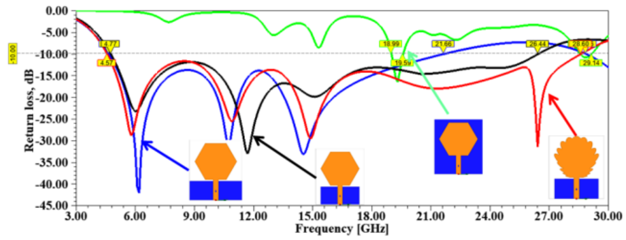


Figure 2. Reflection coefficient performance of designed antenna evaluations

Table 1. Simulated characteristic parameters of suggested Aspen monopole antenna

S.No	Parameter	I - 1	I – 2	I – 3	I - 4
1.	f_L, GHz	18.99	4.67	4.77	4.57
2.	f_H, GHz	19.59	21.66	26.44	28.60
3.	IBW, GHz	0.60	16.99	21.67	24.03
4.	S_{11}, dB	-16.2	-42	-34	-30
5.	BR	1.03	4.63	5.54	6.25
6.	FBW, %	3.11	129.05	138.86	144.88
7.	VSWR	1.35	1.01	1.04	1.05

(I – Iteration, f_L – Lowest operating frequency, f_H – highest operating frequency)

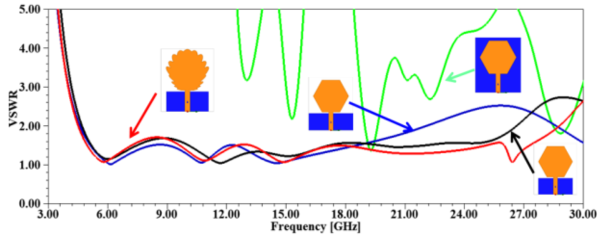


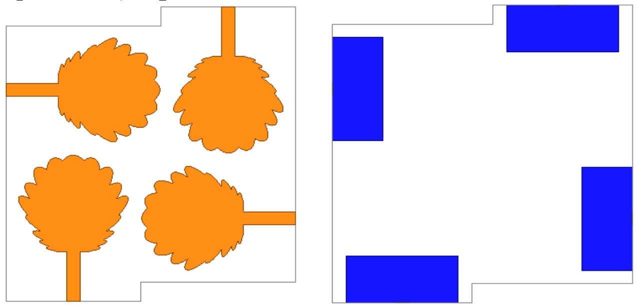
Figure 3. VSWR characteristics of the designed evaluations represented in figure 1(a – d)

3. Proposed MIMO antenna design and its characteristics

In order to improve the high date transmission rate and increasing the efficiency of the designed monopole antenna, multi - port antenna has been designed for provide efficient characteristics. Figure 4 shows the suggested four – element MIMO antenna configuration. Furthermore, to improve the isolation and reducing the mutual coupling between the two elements and to meet essential characteristics, the parameters are optimized and added isolating element in the ground plane as shown in figure 5. Three dimensional view of the proposed four element MIMO antenna with partial ground plane are configured in figure 6. The geometrical dimensions of the designed MIMO antenna are L_1 = 23mm, L_2 = 20mm, W_1 = 3mm, W_2 = 40mm.

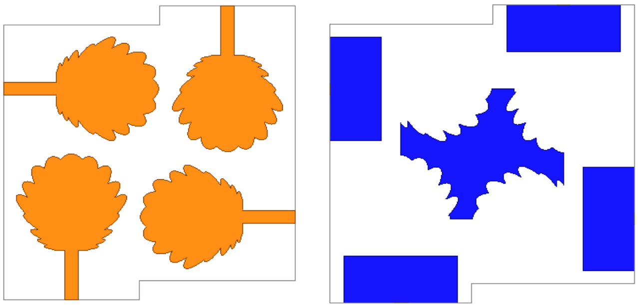
3.1. MIMO antenna geometrical configuration

To address the high channel capacity, low latency and high data transmission rate, four – element MIMO antennas are considered as standard to obtain these characteristics. Figure 4 shows the geometrical configuration of the 4 – element MIMO antenna. Similar elements are placed orthogonally next to each element for its diversity characteristics. The reason behind this configuration is to reduce the mutual coupling between elements. Furthermore isolation between radiating elements is improved with adding the irregular polygon structure acts as decoupling structure as shown in figure 5. Three dimensional view of the proposed four – port MIMO antenna with isolating element is shown in figure 6. The geometrical dimensions of the designed MIMO antenna are L_1 = 23mm, L_2 = 20mm, W_1 = 40mm, W_2 = 3mm.



(a) Top view (b) Bottom view

Figure 4: Four element MIMO antenna without isolating element



(a) Top view (b) Bottom view

Figure 5: Four element MIMO antenna with isolating element

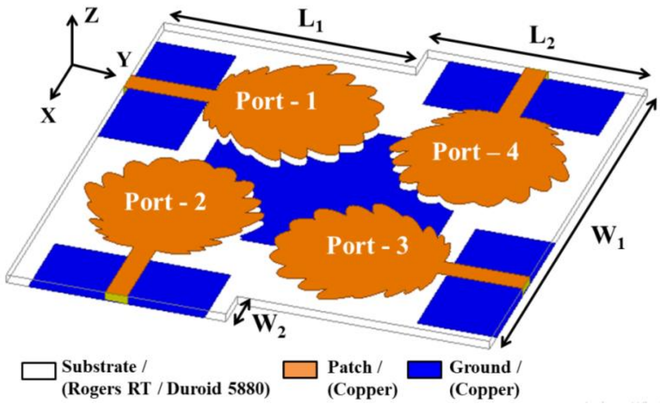


Figure 6: Three dimensional view of the proposed MIMO antenna

3.2. Simulated characteristics of the proposed design

Scattering parameters (S_{11} - reflection coefficient and S_{12} - insertion loss) of the designed four – element MIMO antenna with and without isolating elements are given in figure 7 and 8. From figure 7, MIMO antenna without isolating element operating from 4.38GHz to 26.72GHz at -10dB reflection coefficient with an IBW of 22.34GHz and its peak reflection coefficient is -29.98dB. Bandwidth ratio ($BR = {f_H}/{f_L}$) and fractional bandwidth ($FBW = \frac{2*(f_H - f_L)}{(f_H + f_L)}*100$) are 6.10 and 143.66%. Isolation between the MIMO elements is less than -15dB as shown in figure 8. According to the simulations of the proposed antenna (with isolating element), the proposed MIMO antenna operates frequency spectrum from 4.12GHz to 27.78GHz with S_{11} < -10dB. Due to the similarity of the antennas and its symmetrical arrangement, reflection coefficient characteristics of the suggested antenna are same. The corresponding BR and FBW are 6.74 and 148.33%. Figure 8 shows the insertion loss characteristics of the proposed MIMO antenna with isolating element. It can be noticed that by adding isolating / decoupling structure of the MIMO antenna, isolation factor has been increased by an average of 5dB. Proposed MIMO design has an isolation less than -20dB. The simulated VSWR Characteristics of the designed MIMO antenna with and without isolating elements are given in figure 9. The VSWR values of the designed MIMO antennas are 1.7:1 and 1.5:1 throughout the operating band respectively. The proposed antenna has very low VSWR value of 1.02 at 16.90GHz. Low value of VSWR indicates that very less impedance mismatch loss throughout the operating spectrum, which indicates the low power reflected and good impedance matching. Table 2 represents the simulated parameters such as lowest operating frequency, higher operating frequency, impedance bandwidth, reflection coefficient, bandwidth ratio, fractional bandwidth, VSWR and isolation value over the operating band for the designed MIMO antennas with and without isolating elements.

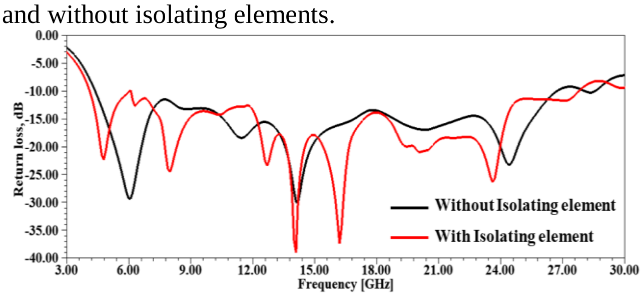


Figure 7. Reflection coefficient characteristics of the MIMO antenna design with and without decoupling structure

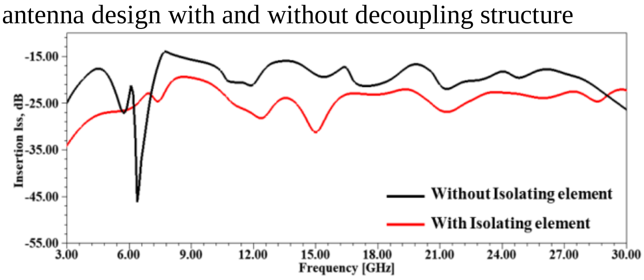


Figure 8. Insertion loss characteristics of the MIMO antenna design with and without isolating element

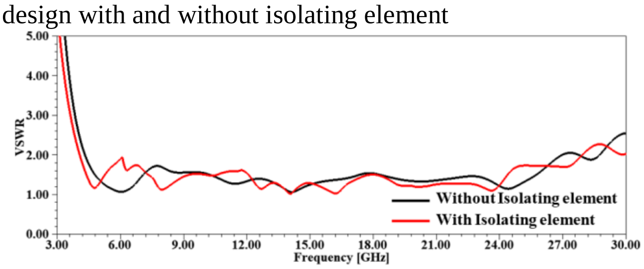
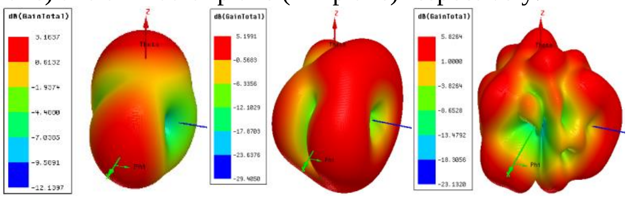


Figure 9. VSWR characteristics of the MIMO antenna design with and without isolating structure

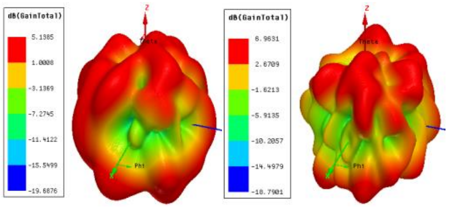
Table 2. Simulated electrical parameters of the designed MIMO antennas

S. No	Parameter	MIMO without isolating element	MIMO with isolating element
1.	f_L, GHz	4.38GHz	4.12GHz
2.	f_H, GHz	26.72GHz	27.78GHz
3.	IBW, GHz	22.34GHz	23.66GHz
4.	S_{11}, dB	-29.98dB	-39.00dB
5.	BR	6.10	6.74
6.	FBW, %	143.66%	148.33%
7.	VSWR	1.06	1.02
8.	S_{12}, dB	< -15dB	< -20dB

Figure 10 shows the simulated gain characteristics of the proposed MIMO antenna designed on Rogers RT / Duroid 5880™ substrate material in 3D polar plots. Peak gains achieved at the selected resonant frequencies 4.80GHz, 8GHz, 14.1GHz, 16.2GHz and 23.6GHz are 3.16dBi, 5.19dBi, 5.82dBi, 5.13dBi and 6.98dBi respectively. Figure 11 represents two dimensional radiation patterns of the proposed MIMO antenna interms of elevation plane (E - plane) and azimuthal plane (H - plane) respectively.

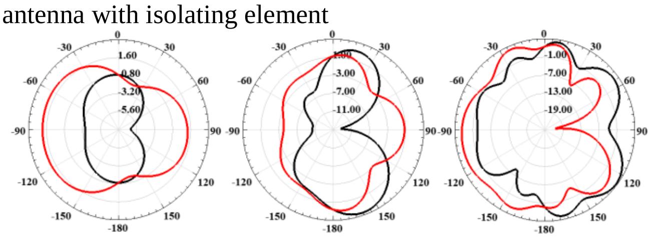


(a) 4.80GHz (b) 8.00GHz (c) 14.1GHz

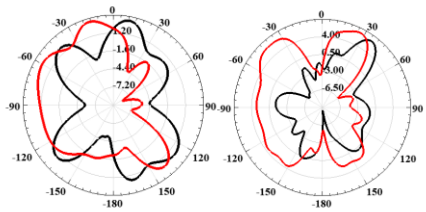


(d) 16.2GHz (e) 23.6GHz

Figure 10: 3D gain plots of proposed closely spaced MIMO antenna with isolating element



(a) 4.80GHz (b) 8.00GHz (c) 14.1GHz



(d) 16.2GHz (e) 23.6GHz

Figure 11: 2D radiation characteristics of MIMO antenna (Red – Elevation, black - Azimuthal)

4. MIMO antenna parameters

Another important parameter to measure the mutual coupling between antenna elements is envelope correlation coefficient (ECC). ECC value is less than 0.015 (practically less than 0.5) over the operating band 4.12 – 27.78GHz, which indicates the low mutual coupling between antenna elements. ECC value is evaluated using S – parameters, given in [25-26]. Figure 12 shows the ECC between the individual antenna elements – 1&2, 1&3 and 1&4 respectively. Other parameter to measure the amount of power transmission without loss is diversity gain (DG). Diversity gain is evaluated from ECC, given in [25-26]. Lowest value of ECC indicates the high value of diversity gain. This value is closure to 10dB which is approximately equals to ideal value across the operating band. Figure 13 shows the diversity gain characteristics of the proposed MIMO antenna design. Total active reflection coefficient (TARC) measures the complete description of the proposed MIMO antenna potentiality. Ideal value of TARC is less than 0dB. From figure 14, it is observed that TARC is less than -8dB for the obtained bandwidth within the acceptable limits. Figure 15 shows the channel capacity loss (CCL) plot of the proposed MIMO antenna with isolating element. CCL measures the loss in channel capacity due to correlation between the MIMO antennas. Ideal value of CCL is less than 0.4bits/sec/Hz. From figure 15, it is observed that CCL is lower than 0.3bits/sec/Hz, which is within the limits. Mean effective gain (MEG) of individual elements in the proposed MIMO antenna characteristics are represented in figure 16. It is observed that practically proposed MIMO antenna achieves MEG within -4.5 to -7dB within the ideal acceptable range -3dB to -12dB.

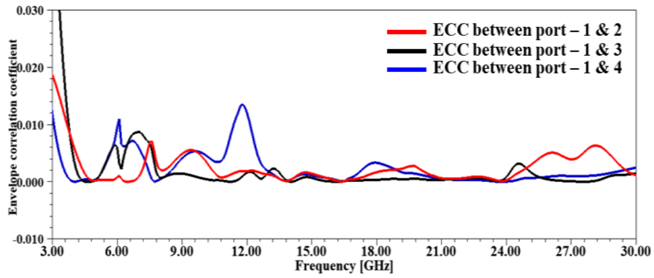


Figure 12. ECC vs frequency

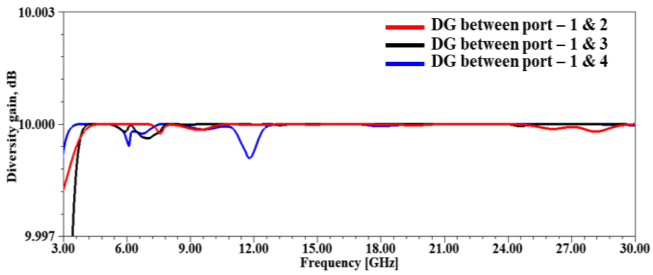


Figure 13. Diversity gain vs frequency

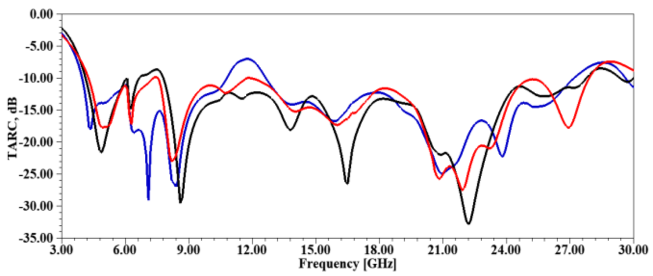


Figure 14. TARC vs frequency

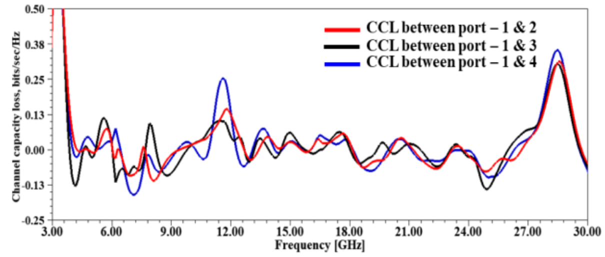


Figure 15. CCL vs frequency

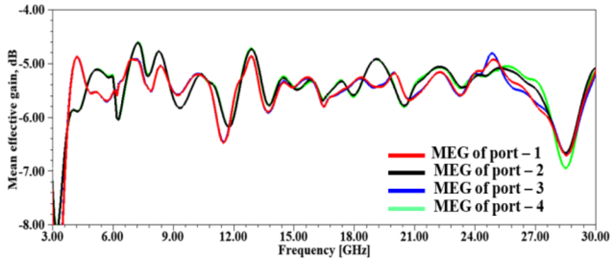


Figure 16. MEG vs frequency

5. Comparison of the proposed antenna

Simulation characteristics of the proposed MIMO antenna with some existed antennas [6-21] is shown in table 3. In this table proposed antenna has several advantages compared to the existing models. **i) Miniaturization** – smaller in size, 43mm x 43mm **ii) Better impedance** – Covers frequency band from 4.12 to 27.78GHz at S_{11} < -10dB **iii) Fractional bandwidth** – Proposed design obtains 148.33% **iv) Good isolation** – Proposed antenna has isolation between elements is less than -20dB **v) Peak gain** – It obtains peak gain of 6.89dBi with directional characteristics **vi) High radiation efficiency** – Suggested MIMO antenna with isolating element has higher efficiency 96%, which signifies that proposed design has efficient transmission / receiving capability **vii) ECC** – Mutual coupling between antenna elements is improved and its isolation is less than 0.015.

Table 3. Performance comparison of proposed MIMO antenna with other existed antennas

Ref.	Size, mm^2	f_L - f_H, GHz	IBW, GHz	FBW, %	Isolation, dB	Gain, dB	η, %	ECC
[6]	58.6 x 46	3.1 – 10.6	7.5	109.48	< -13	2.1-5.4	NR	< 0.02
[7]	40 x 68	3.2 – 10.6	7.4	107.24	< -15	< 2.5	70 - 85	NR
[8]	75 x 145	3.3 – 3.6 & 4.8 – 5.0	0. 3 & 0.2	8.69 & 4.08	< -10	NR	60-85	< 0.15
[9]	50 x 50	2.76 – 10.75	7.99	118.28	< -15	5.5	68	< 0.025
[10]	130 x 74	3.3 – 3.6 & 4.8 – 5.0	0.3 & 0.2	8.69 & 4.08	< -12	NR	> 50	< 0.1
[11]	60 x 60	2.73 – 10.68	7.95	118.56	< -15	7	NR	NR
[12]	50 x 40	2.5– 11	8.5	125.92	< -15	2.11	69.2	< 0.02
[13]	48 x 48	3 – 11	8	114.28	< -15	4	80-90	NR
[14]	50 x 80	4.183 – 6.584	2.501	46.02	< -17	6	80	< 0.056
[15]	48 x 48	2.5 – 12	9.5	131.03	< -15	< 3	NR	< 0.005
[16]	50 x 30	2.5 – 14.5	12	141.17	< -20	4.1	NR	< 0.04
[17]	45 x 45	2 – 10.6	8.6	136.5	< -17	3	NR	< 0.1
[18]	85 x 50	2 – 9.5	7.5	130.43	< -20	1.5	70	< 0.03
[19]	90 x59	3.34-14.96	11.62	126.99	NR	5	66	NR
[20]	50 x 48	3.5-10.6	7.1	100.70	NR	4.7	73	NR
[21]	60 x 50	2.05-10.86	8.81	136.48	NR	5.03	NR	NR
Proposed	43 x 43	4.12 – 27.78	23.66	148.33	< -20	6.89	96	< 0.015

6. Conclusion

Using HFSS simulation program, a new design of super wide band (SWB) planar monopole antenna loaded with Aspen shape and partial ground plane has been designed for serving SWB wireless communication systems. The antenna operates over the frequency range from 4.57GHz to 28.60GHz and its size is 20mm x 23mm x 0.787mm. A compact 4-port MIMO antenna with SWB is proposed to cover industrial – scientific – medical (ISM), satellite, radar, military and microwave applications. The proposed MIMO antenna covers impedance bandwidth (IBW) of 23.66GHz at -10dB reflection coefficient from 4.12 – 27.78GHz. The proposed antenna has bandwidth ratio (BR) of 6.74 and fractional impedance bandwidth (FBW) of 148.33%. Within this operating band, the mutual coupling / insertion loss / isolation between these antennas is purely greater than -20dB. All other parameters like mutual coupling, ECC, DG, TARC and CCL are depicted in results and discussed. During this entire band, the radiation pattern maintains stable characteristics and it has good diversity performance. Its planar footprint and SWB features make it a good candidate for wireless devices.

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