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REGULAR ARTICLE

Optimized Electromagnetic Gap Coupled Arrays of E-shaped Microstrip Patch Antenna with Air Gap for Wireless Communication

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This paper presents an optimized microstrip antenna design for wireless communication in the S-band. It includes a comparative examination of different air gap configurations to understand their influence on dielectric properties and antenna performance. The study shows that, within the specified frequency range, the antenna has the potential to be used in compact, high-performance applications. Based on the Method of Moments, the suggested design uses the IE3D program to generate a Gap Coupled Array of E-Shaped Patches with air gap on a glass epoxy FR-4 substrate. By contrasting the dielectric characteristics of various effective dielectric constants attained through altering air gaps, the study seeks to advance understanding. The antenna performs exceptionally well, with an astounding 39.57% (2.281 GHz – 3.378GHz) bandwidth and a peak gain of 12.91 dBi at 2.36 GHz. According to a study comparing several air gap configurations, the antenna has a lot of potential for high-performance, small-scale applications in the S-band frequency range. The results show how important it is to maximize the air gap to have the greatest wireless communication and radar system performance.

Keywords: Microstrip Antenna (MSA), Gap-Coupled, Air Gap, Bandwidth, S-band.

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1. INTRODUCTION

MSA are notable in the evolution of wireless communication because they are small, lightweight, effective, and simple to install. They do, however, have limitations on gain and bandwidth. To get around these issues, other strategies have been employed, including changing the patch's height, feeding in different ways, employing appropriate substrates, and incorporating innovative features including parasitic elements, slots, dual feeds, shorting pins, air gaps, and defective ground structures. These techniques aim to improve antenna performance without increasing the antenna's overall height [1-3]. A triple-band E-shaped microstrip antenna with broadside co-polar gains ranging from 1 to 5 dBi was developed by [4]. There is not much space between the triple frequencies. In a further investigation, [5] designed an H-shaped microstrip antenna with an air gap using HFSS software. The antenna is appropriate for applications like wireless communication because it features novel aperture coupling through a slot fed by a microstrip line. Three different approaches were used by [6] to optimise the radiation pattern of a printed compound air-fed array (PCAFA) antenna: a step-sized HIS base, a low-pass FSS cover, and a mushroom-type HIS. The antenna was confirmed to be suitable for a range of applications after passing testing and functioning as expected. [7] used a slot in the patch to construct a microstrip antenna with capacitive feed and examined the effects of design elements such feed point location, air gap, and gap width. The antenna showed an amazing 47 percent bandwidth. In a separate study, [8] examined the effects of air gap variations on stack-patch and pentagonal microstrip arrays. For mobile satellite communications, a circularly polarized stack-patch array operating at 2.5025 GHz produced an axial ratio beam width of < 3 dB (> 120°) and gain of > 5 dBi. At the resonant frequency of 2.4925 GHz, the circularly polarized pentagonal array yielded a 15.67 % band width, 8.74 dBi gain, and 0.06 dB axial ratio. A 33.5 % increase in bandwidth was proven by [9] through the use of IE3D to create a revised rectangular antenna without and with an air gap technique between substrate layers. For wideband and multiband applications, researchers have investigated a different gap-coupled microstrip antenna similar to this one [10]. Analytical methods like as FDTD,

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MoM, circuit approaches, and cavity models, which advocate for the use of gap-coupling to boost bandwidth, have been used to analyses the antenna performances for various applications. The study provides solutions and highlights how important mutual connections are.

A theoretical analysis of a dual resonance gap-coupled stacked E-shaped patch antenna has been described by [11]. It is appropriate for a variety of communication applications since it can operate at 40.43 % impedance bandwidth and 207 MHz broadband. Using proximity-fed gap-coupling as explained in [12], a broadband microstrip antenna can achieve bandwidth greater than 350 MHz. Half-E-shaped MSAs can provide a 7 dBi gain in bandwidth to 500 MHz by adding slots. Four half-E-shaped MSA configurations can be added to this to further improve it; the result is a bandwidth > 530 MHz and an approximate gain of 11 dBi. A redesigned TM01 mode increases cross-polarization in the bore-sight direction to mitigate signal loss in multipath scenarios. [13] illustrates a G-shaped slot MPA with a rectangular form, demonstrating its versatility in a variety of microwave applications. Three frequency bands are covered by this antenna design: 7.51 GHz, 8.01 GHz, and 10.68 GHz. It stands out for having an efficiency rating of 97.35 %, a bandwidth of approximately 15.47 %, and gain of 6.257 dB. According to [14], an ultra-wideband (UWB) antenna with a notch ranging from 3.2 GHz to 10.9 GHz has a compact reverse G-shaped structure. Furthermore, [15] and [16] suggest a three-band MSA with bandwidths of 1.3 GHz, 1.21 GHz, and 510 MHz. The MPA design has an inverted L slot, two uneven slits in the ground plane, and an O-shaped patch with a strip linked to the right side. A novel dual-band rectangular MSA designed for 5G millimeter-wave applications is shown in [17]. The gadget is perfect for integration into small-space devices due to its modest dimensions. According to simulation results, at frequencies of 23.8 GHz and 37.5 GHz, respectively, there are increases of 2.84 dB and 3.33 dB, with a return loss of roughly – 27.5 dB for bandwidths of 0.7 GHz and 1 GHz. A rectangular MSA with air as the substrate was designed for M2M RFID applications [18]. Using CST software for simulation shows a 7.27 dB gain. Because it is lightweight, moderately priced, and closely adheres to measured results, the design is appropriate for application in practical settings.

2. DESIGN APPROACH OF PATCH ANTENNA

In [19], a reconfigurable patch antenna served as the model for our purpose, where we have used FR4 substrate (thickness: 0.8 mm) to produce a simple 144 mm × 196 mm rectangular microstrip patch antenna. Fig. 1 shows the configuration that is being described. All of the components are E-shaped patches in order to provide a broader bandwidth. Element A is a feed-split element that stores the primary feed, regulates some radiation, and disperses the remaining power to other elements. Only radiation is added by the two identically constructed elements B and C. To take use of the regions above and below element A, two additional radiating components, D and E, are added to maximize broadside gain without increasing the overall area. Microstrip lines, each 4 mm wide, are used to connect these five patches in series. The horizontal axis is the center of symmetry throughout the entire structure. Patch A is connected to a 50 Ohm coaxial feed, which serves as the main excitation.

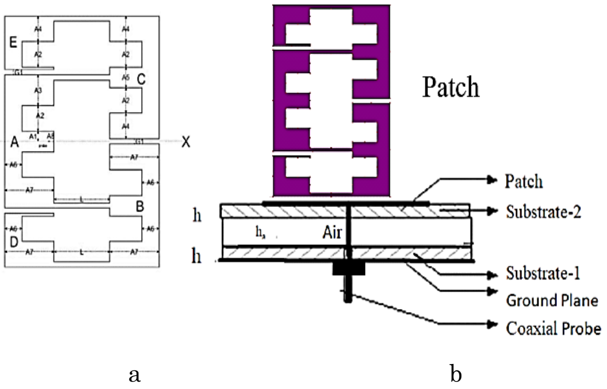


Fig. 1 – Gap Coupled E-shape MSA with air gap (a), Front View (b) Side View ($A_1 = 8$ mm, $A_2 = 20$ mm, $A_3 = 24$ mm, $A_4 = 20$ mm, $A_5 = 16$ mm, $A_6 = 16$ mm, $A_7 = 46$ mm, $A_8 = 8$ mm, $L = 52$ mm, $G_1 = 4$ mm, $G_2 = 2$ mm)

It is impossible for a single-layered construction with FR4 to offer a 10 % bandwidth. In the following section, the effect of using the air gap method to enhance the impedance bandwidth and gain in MSA is investigated. The research study compares antennas with and without air gaps to show how adding air gaps enhances overall antenna performance, which is determined by important factors such radiation pattern, bandwidth, gain, efficiency, and efficiency. Consequently, by employing different air gaps to separate the two FR4 substrates, the thickness is raised. We examine the impact of the air gap layer's thickness in this research.

3. RESULT AND DISCUSSION

The investigation employed IE3D simulator for a Rectangular MSA in the S-Band. At 3.96 GHz, S_{11} magnitude reached – 20.64 dB, yielding a gain of 1.9 dBi with a narrow bandwidth. At 3.19 GHz and 3.588 GHz, respectively, a single-layered gap-coupled E-shaped array MPA yields S_{11} magnitudes of – 27.01 dB and – 30.05 dB. At their operational frequencies, both topologies showed poor bandwidth; the corresponding gains were 3.7 dBi and 2.45 dBi. The simulations determined that a compromise between bandwidth, gain, and efficiency could be achieved with a thickness range of 5.5 to 6.2 mm. All radiation metrics taken together, however, indicated that an air gap of 5.9 mm was the best option for the prototype. This selection improved the performance range of the Gap Coupled E-shaped Array antenna over earlier designs, giving it a frequency range of 2.281 GHz – 3.378 GHz. The selected design demonstrated a notable increase in bandwidth from 3.068 % to 38.80 % when compared to a single-layered Gap

Coupled E-shaped Array patch antenna. The optimal resonance frequencies of the antenna were 2.36 GHz, 2.62 GHz, and 3.04 GHz. At 2.368 GHz, the default design's most efficient frequency, the observed gain was 12.18 dBi.

3.1 Results for Gap Coupled E-shape Array MPA

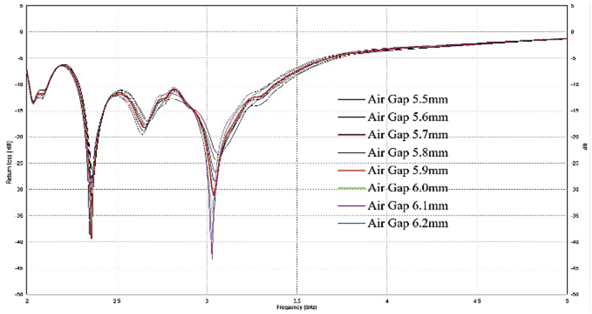


Fig. 2 – Return loss v/s Frequency

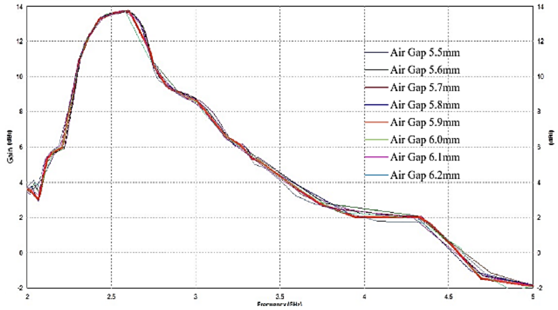


Fig. 3 – Gain v/s Frequency

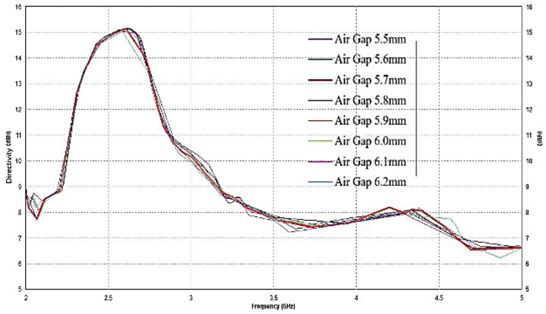


Fig. 4 – Directivity v/s Frequency

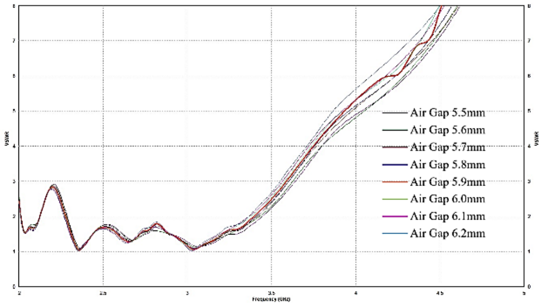
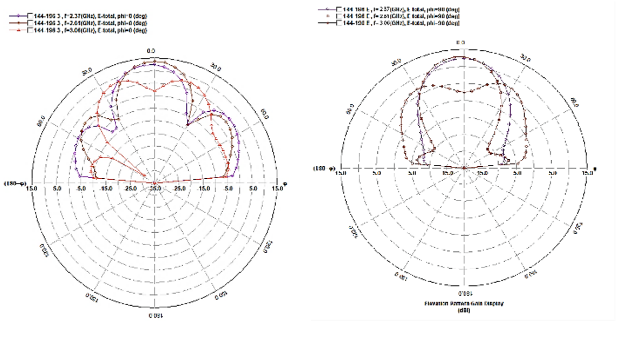


Fig. 5 – VSWR v/s Frequency



a b

Fig. 6 – Antenna elevation gain pattern for 5.9 mm air gap as a function of frequencies and elevation angle (a) $\varphi = 0°$ and (b) $\varphi = 90°$

Table 1 – Design Parameters using different air gaps

S. No.	Air Gap (mm)	Resonant Frequency (GHz)	Band Width %	Gain (dBi)	Efficiency %
1	0	2.96	1.01	8.16	62.96
		3.54	0.79	6.67	49.3
2	1	2.67	3.78	7.33	61.65
		2.89	1.72	8.79	70.94
		3.5	1.14	6.34	60.49
3	2	2.85	3.16	9.91	80.83
		3.39	2.94	7.15	68.95
4	3	2.81	4.98	10.4	82.75
5	4	2.77	29.4	10.8	81.03
6	5	2.38	7.12	12.8	90.22
		3.2	28	6.72	74.67
7	5.5	2.37	39.57	12.3	89.51
		2.67	39.57	12.9	86.87
		3.07	39.57	8.17	81.45
8	5.6	2.36	39.01	12.6	89.40
		3.06	39.01	8.19	82.81
9	5.7	2.36	39.11	12.14	89.46
		3.04	39.11	8.19	82.39
10	5.8	2.36	37.14	12.11	96.11
		2.67	37.14	12.08	93.07
		3.05	37.14	7.02	97.23
11	5.9	2.36	38.58	12.20	90.37
		2.62	38.58	12.77	87.59
		3.04	38.58	8.23	83.96
12	6	2.36	38.01	12.03	98.89
		3.03	38.01	8.168	91.77
13	6.1	2.35	37.9	12.06	92.27
		3.03	37.9	8.269	86.49
14	6.2	2.35	38.04	12.10	96.83
		3.03	38.04	8.213	92.69

3.2 Comparative Analysis

3.2.1 For Proposed Antenna with and without Air Gap

With significant increases in critical parameters, the air gap antenna clearly outperforms a single-layered gap-coupled E-shape patch antenna. The visual representation of return loss and gain responses in Figs. 7 and 8 emphasizes the advantages of the recommended antenna design with an air gap. Over a wide range of air gap sizes (5.5 mm to 6.2 mm), the antenna exhibits remarkable performance, especially at air gap of 5.5 mm, where the antenna shows a little superiority in terms of gain, bandwidth, and return loss.

Two resonant frequencies are detected, Fig. 2, for air gap dimensions of 5.6 mm, 5.7 mm, 6 mm, 6.1 mm, and 6.2 mm. Efficiency is greater at 5.8 mm, although bandwidth and gain are slightly reduced. When an air gap of 5.5 mm is added to an antenna, the return loss drops to – 39.8 dB, a significant improvement over the – 32 dB of the antenna without one. With a 5.5 mm air gap, the gap-coupled antenna reaches a maximum gain of 12.91 dBi with 86.87% efficiency and a broad bandwidth of 39.57% as illustrated in Figs. 3, 4, and 2, respectively.

It has been clearly shown that, maximum efficiency of 97.23% is achieved for thickness 5.8 mm, with a bandwidth of 37.14% and a gain of 12.11 dBi, which further improves in the bandwidth and gain for the thickness 5.9 mm are 38.58%, and 12.77 dBi respectively with the maximum efficiency of 90.37%. On the other hand, the identical antenna without air gap approach shows a mere 3% bandwidth, 2.41 dBi of gain, and 26% efficiency. Thus, the air gap techniques found noteworthy for wireless applications.

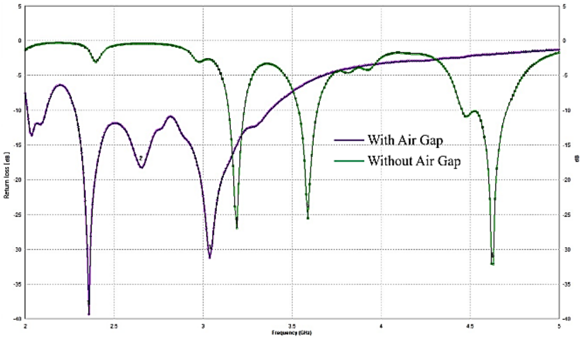


Fig. 7 – Return loss v/s Frequency

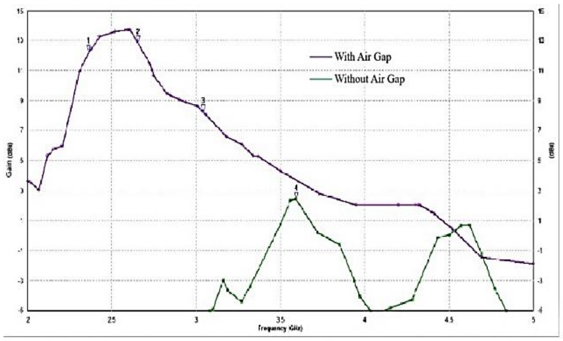


Fig. 8 – Gain v/s Frequency

Table 2 – Antenna parameter comparison with and without air gap

Antenna	Resonant Frequency (GHz)	B. W. (%)	Gain (dBi)	Efficiency
Without air gap	3.59	3.34	2.41	25.80
With 5.9mm air gap	2.36	38.58	12.20	90.37
	2.62	38.58	12.77	87.59
	3.04	**38.58**	**8.23**	**83.96**

3.2.2 Comparison between Proposed Antenna and Referred Antennas

The comparison in Table 3 demonstrates that the constructed antenna outperforms other antennas in numerous critical areas, including gain and bandwidth. With a gain of 12.77 dBi and an unusually wide bandwidth of 38.58 %, the suggested design outperforms its competitors, making it especially well-suited to the needs of Fifth Generation (5G) applications. Despite a minor drop in efficiency, the antenna's remarkable gain and bandwidth characteristics outweigh this disadvantage, demonstrating its appropriateness for high-performance wireless communication systems. It is crucial to remember that factors pertaining to the substrate, such as relative permittivity and thickness, greatly affect antenna performance. The behavior metrics and performance of the antenna are greatly influenced by these features. Therefore, much consideration must be given to selecting the substrate and refining the design.

Table 3 compares the developed antenna with other referred antennas. It appears that the suggested design performs best in terms of gain and bandwidth, exhibiting a gain of 12.77 dBi and a bandwidth of 38.58 % with a slight decrease in efficiency, albeit still satisfactory at 90 %. Additionally, the slightly higher dimension is more pertinent to Fifth Generation (5G) applications, which call for higher gain and a wider bandwidth. It was found that the substrate's thickness and effective relative permittivity had a significant impact on the antennas' performance.

Table 3 – Comparison of the proposed antenna design with referenced antenna

Ref	Patch Area (cm^2)	Resonant Frequency (GHz)	B. W. (%)	Gain (dBi)	Efficiency (%)
[18]	26,645	0.9	3.27	7.27	82
[20]	465.56	4.06	–	6.92	–
[21]	696	12.98	24	6.80	98
		16.94	15	3.72	97
[22]	9828	1.26	–	9.58	94.6
[23]	317.2	5.81	–	4.42	–
[24]	3635.8	2.38	–	9.18	–
[25]	1411.87	3.61	–	4.7	70.15
Designed Antenna	15.168	2.36	38.58	12.20	90.37
		2.62	38.58	12.77	87.59
		3.04	38.58	8.23	83.96

4. CONCLUSION

In this work, an E-shaped MSA with a gap-coupled array and variable air gaps for the S-band frequency range was designed and simulated using IE3D software. Using the gap-coupled array E-shaped antenna with the new air gap technology results a significant improvement in bandwidth, gain, and efficiency, according to the analysis. The introduction of the air gap approach led to notable improvements in the antenna parameters, which at first did not match the needs for the intended applications.

The antenna generated equivalent results with an air gap ranging from 5.5 to 6.2 mm. Return loss, bandwidth, and gain all performed somewhat better with three air gaps of 5.5 mm. The bandwidth and gain are decreased at 5.8 mm, but the efficiency increases. Further, at 5.9 mm, these become moderate. This is a huge improvement over the single-layered gap-coupled array E-shaped antenna's bandwidth of 3.068 %.

The overall bandwidth increased to an amazing 38.58 % from the previous 3.068 %. In addition, the gain increased significantly from 2.41 dBi to 12.91 dBi. Crucial performance metrics like efficiency and VSWR also showed appreciable gains in the performance of proposed antenna. Thus, the suggested antenna shows promise as a viable option for 5G applications, Wi-Fi, and Bluetooth, meeting the demands of voice communication, high-speed internet access, WLAN, and mobile data transmission.

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Оптимізовані електромагнітні решітки E-подібної мікросмужкової патч-антени з повітряним проміжком для бездротового зв'язку

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У даній статті представлено оптимізовану конструкцію мікросмужкової антени для бездротового зв'язку в S-діапазоні. Вона включає порівняльний аналіз різних конфігурацій повітряного зазору, щоб зрозуміти їхній вплив на діелектричні властивості та характеристики антени. Результати досліджень показують, що в межах зазначеного частотного діапазону антена має потенціал для використання в компактних, високопродуктивних додатках. Базуючись на методі моментів, запропонована конструкція використовує програму IE3D для створення масиву E-подібних патчів із пов'язаним розривом із повітряним зазором на скляній епоксидній підкладці FR-4. Проведене порівняння діелектричних характеристик різних ефективних діелектричних сталих, досягнутих шляхом зміни повітряних проміжків. Антена працює надзвичайно ефективно із смугою пропускання 39,57% (2,281 ГГц – 3,378 ГГц) і піковим посиленням 12,91 дБі на 2,36 ГГц. Відповідно до дослідження, у якому порівнювали кілька конфігурацій повітряного зазору, антена має великий потенціал для високопродуктивних невеликих застосувань у діапазоні частот S-діапазону. Результати показують, наскільки важливо максимізувати повітряний зазор, щоб отримати найкращу продуктивність бездротового зв'язку та радіолокаційної системи.

Ключові слова: Мікросмугова антена (MSA), Щілинна антена, Повітряний зазор, Пропускна здатність, S-діапазон.