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REGULAR ARTICLE

Reconfigurable Truncated E-Shape Electromagnetic Gap-Coupled Antenna with Air Gap and Switch Configurations for Wideband Wireless Applications

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This paper presents the design and analysis of a high-gain microstrip patch antenna optimized for wideband frequency applications in wireless communication. The proposed antenna employs advanced techniques, including direct coaxial probe feeding, a 5.9 mm air gap within the patch structure, and a truncated corner gap-coupled array with configurable switches S1, S4 ON. These design elements contribute to significant performance enhancements, achieving impedance bandwidths of 10.23 % and 47.44 % (VSWR ≤ 2) across the 2 GHz to 3.41 GHz frequency range. The antenna also demonstrates a peak gain of 12.42 dB at 2.67 GHz. A thorough parametric analysis compares the antenna's performance with and without the inclusion of switching mechanisms, revealing notable improvements in bandwidth and gain. The antenna design was validated through simulations using the method of moments-based IE3D software. The results highlight the antenna's potential for effective deployment in modern wireless communication systems, offering enhanced bandwidth, gain, and overall performance.

Keywords: Microstrip patch antenna, Wideband, Coaxial probe feed, Gap coupled array, Switch.

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1. INTRODUCTION

Microstrip antennas, widely utilized in aerospace and communication applications due to their compact form factor and cost-effectiveness, are inherently constrained by limited bandwidth and efficiency. This research systematically explores enhancement techniques such as gap coupling, the inclusion of air gaps, embedded slots, thicker substrates, and lower dielectric constant materials to address these limitations. Through a combination of theoretical analysis and experimental validation, the study evaluates the performance improvements associated with each method. Despite challenges such as spurious radiation from thicker substrates and practical limitations of low-dielectric materials, the research aims to optimize microstrip antenna performance to enhance the efficiency and reliability of communication systems [1]. Electromagnetic gap-coupled and air-gap microstrip patch antennas offer improved performance over conventional designs. These antennas can achieve broader bandwidth, dual-band operation, and compact size. An air-gap coupled antenna has been discussed in [2] for K/Ka band applications, achieving a gain of 9.34 dB and 76 % radiation efficiency.

Authors [3] demonstrated that varying the air gap in aperture-coupled antennas enables dual-band operation with a wide frequency range and improved impedance matching whereas a quarter-wavelength gap-coupled design [4] enhances bandwidth while reducing patch size by 50 %. These techniques offer significant advantages in terms of bandwidth, efficiency, and size reduction for various wireless applications. One of the potential methods for enhancing the bandwidth of microstrip antennas is gap coupling. Gap-coupled designs, such as, rectangular versions work better in ultra-wideband environments, while circular versions are best suited for wideband applications. This method has been identified as the most effective way to increase antenna bandwidth, outperforming thicker substrate options. [6] presents results from a study that used broadband microstrip elements to create a four-element linear array, achieving notable bandwidths of up to 15%, shows that how effective broad-band impedance matching is at boosting antenna bandwidth. When compared to single feed setups, the efficiency of dual feed line approaches greatly improves the bandwidth and axial ratio; for example, a square microstrip antenna can increase its bandwidth by 254.16 % [7]. The method also benefits array setups, with a 2 × 1 array achieving a 159.62 % bandwidth increase and 56.72 % better reflection coefficient at 8 GHz, showcasing its utility in radar systems [8]. Further, the advancements, single layer single patch microstrip antennas have not observed for their wideband capabilities. This modified configuration has the potential to achieve an antenna bandwidth approximately 2.8 times greater than that of

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a conventional rectangular patch antenna without slots [9] and with the introduction of a pair of right-angled slots and modified U-Shaped slot [10]. The effective integration of slotted resonances and a microstrip coupling gap with frontend circuits is demonstrated by [11]. For enhancing the gain of patch antennas across different frequency ranges and applications, cross-shaped designs received serious attentions, using superstrate structures [12], a dual-band cross-shaped patch antenna achieved gains of 6 dBi and 10 dBi at 2.4 GHz and 5 GHz, respectively for IEEE 802.11ax Wi-Fi applications [13], and a diamond-shaped microstrip antenna with cross-shaped parasitic elements has been proposed for microwave imaging applications [14] offering high gain and bandwidth in the 3.1-10.6 GHz range. A novice method for enhancing antenna bandwidth involves introducing an air gap in the stack-patch with a pentagonal antenna design [15] in the context of mobile satellite applications. The technique has been extended to circular and rectangular patch antennas by introducing an air gap between two substrates enables an increase in substrate thickness either by placing an air gap between the radiating element and the substrate or by inserting an air gap between the ground plane and the substrate, as discussed in [16]. Similarly, [17] achieved bandwidth enhancements of up to 117 MHz in a 4 × 1 proximity-coupled array with an air-gap. In addition to bandwidth enhancement, the air-gap method allows for tuning of resonant frequencies without requiring a new antenna design [18]. Slot-fed switched patch antennas incorporate switches offer a versatile solution for multi-frequency operation, i.e. enable frequency reconfigurability [19] allows operation across multiple frequency bands by adjusting the switch states. Similar designs have achieved dual-frequency operation with flexible frequency ratios and switching between specific frequencies like 1.6, 1.8, 2.0, and 2.4 GHz [20].

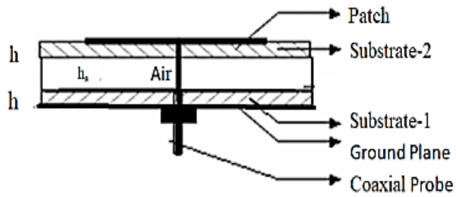
This paper investigates a novel antenna design for wideband applications, features a two-element truncated *E*-shape configuration with electromagnetic gap coupling. Performance is analyzed using two distinct broadbanding techniques: varying air gap spacing and incorporating switchable configurations. A comparative analysis explores the impact of these techniques on key antenna parameters, including gain, bandwidth, and efficiency. Simulations conducted using IE3D software validate the proposed design and demonstrate its potential for enhanced performance in various wireless communication scenarios.

2. ANTENNA CONFIGURATION AND DESIGN

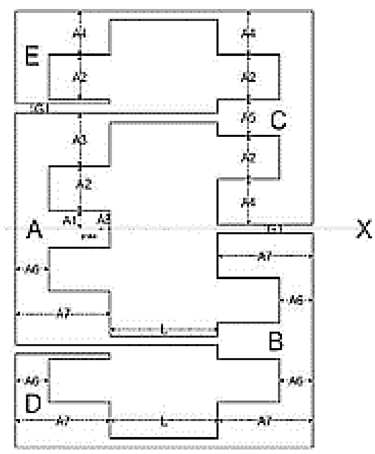
The configuration presented in [21] is modified for ultra-wideband application. The design incorporates two layers: a rectangular patch on the bottom and a corresponding patch on the top, both of which are reshaped into an *E*-shape to enhance performance characteristics. To further improve bandwidth and efficiency, an air gap is introduced between these two layers, leveraging the electromagnetic coupling benefits provided by this separation. In designing the *E*-shape microtstrip patch antenna the glass epoxy FR4 substrate of 1.6 mm thickness which is widely used by researchers for planar antenna design, easily available and cost effective also, dielectric constant 4.4 and loss tangent is 0.025. This optimized configuration not only addresses the limitations of traditional microstrip antennas but also extends their applicability to advanced UWB systems. The dimesnions are optimized as shown in Table 1.

Table 1 – Dimensions of proposed gap coupled *E*-shape microstrip patch antenna

Parameter's	Dimensions (mm)
Length of Patch	144
Width of Patch	196
Height of substrate	1.6
A1, A8	8
A2, A4	20
A3	24
A5, A6	16
A7	46
L	46
G1	52
G2	4
L	2



(a)



(b)

Fig. 1 – (a) Side view of proposed antenna. (b) Proposed antenna geometrical parameter

The depicted configuration, as illustrated in Fig. 1, utilizes a topology designed for enhanced bandwidth, employing *E*-shaped patches for all elements. Element A serves as a feed-split element, housing the primary feed, managing a portion of the radiation, and redistributing the remaining power to other elements. Elements B and C are identical and exclusively contribute to radiation. To capitalize on the space above and below element A, two additional radiating elements, D and E, are incorporated to augment broadside gain without increasing the overall footprint. Interconnecting these five patches are 4 mm wide microstrip lines. The entire structure maintains symmetry concerning the horizontal axis. This arrangement aims to optimize performance and achieve a wider operational bandwidth.

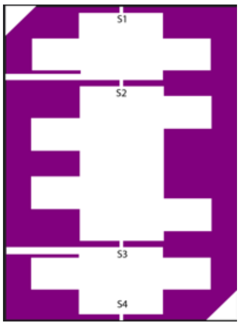


Fig. 2 – Two diagonal truncated gap coupled exotic shaped microstrip patch antenna with air gap 5.9 mm and switches S1, S2, S3 and S4

A Method of Moments (MoM)-based model is developed to calculate the induced current distribution by discretizing the integral into a solvable matrix equation. This involves dividing the antenna surface into small elements, enabling the extraction of S-parameters, radiation patterns, and other key metrics. MoM is chosen for its computational efficiency, and simulations are conducted using IE3D software. The prototype features two truncated diagonal corners (right triangles, 20 mm base and height) and four switches (S1, S2, S3, S4) for reconfigurability. Simulation results will be analyzed in a later section.

3. RESULTS AND DISCUSSION

The proposed antenna configuration has been analyzed using the IE3D simulator across a 2-4 GHz frequency range. Initially, a standard rectangular microstrip patch antenna exhibited low radiation efficiency, necessitating broadband enhancement techniques such as gap coupling and air gaps. The first design, a Two Diagonal Truncated Gap-Coupled Exotic Shaped Microstrip Patch Antenna with a 5.9 mm air gap, resonated at 2.09 GHz with a 6.1% bandwidth. Additionally, it demonstrated broadband behavior at 2.36 GHz, 2.69 GHz, and 3.08 GHz, achieving a total bandwidth of 38% (VSWR $\leq$ 2). The highest recorded gain was 12.30 dBi at 2.69 GHz, with a peak efficiency of 0.91. The second design tested the two diagonal truncated gap-coupled exotic shaped Microstrip Patch Antenna with various ON-OFF switch configurations with the air gap of 5.9 mm. Using the Coaxial Probe Feed Technique, when S1 and S4 are ON or S2 and S3 are OFF, the antenna demonstrated best result with a bandwidth of 10.38 % at 2.09 for the frequency range 2–4 GHz. By attaining a 47.44 % bandwidth (2.21 GHz–3.39 GHz) with VSWR < 2, additionally, it also exhibits broadband behavior at 2.35 GHz, 2.67 GHz, and 3.07 GHz. With a peak efficiency of 0.85, the maximum gain measured was 12.42 dBi at 2.65 GHz and 11.78 dBi at 2.35 GHz. These findings showed that the bandwidth increased from 38 % to 47.44 % when compared to the design without switches. At the optimal frequency of 2.65 GHz, the gain likewise increased to 12.42 dBi, however the efficiency decreased somewhat from 0.91 to 0.85. The performance of the proposed microstrip patch antenna has been enhanced significantly, i.e., bandwidth increased from 38 % to 47.44 % by deliberately turning on or off particular switches, indicating a more resilient broadband response. With a high gain of 12.42 dBi at 2.65 GHz, the addition of switches further increased gain in comparison to the switchless design. Antenna versatility for contemporary wireless applications is increased by the improved directivity, bandwidth, and gain, which also improve signal focus, increase communication range, and permit larger data transfer rates. Nevertheless, because to parasitic effects,

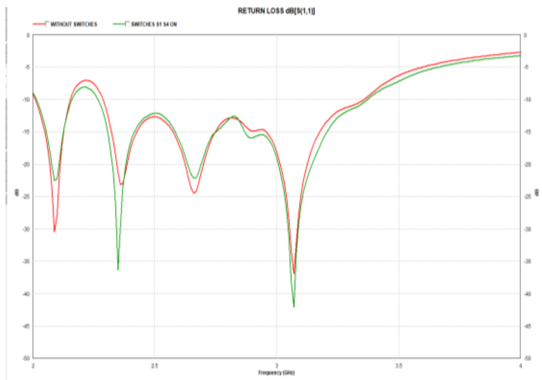


Fig. 3 – Return loss v/s Frequency

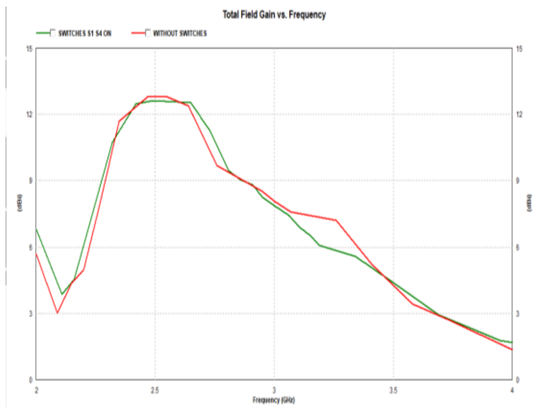


Fig. 4 – Variation of total field gain with frequency

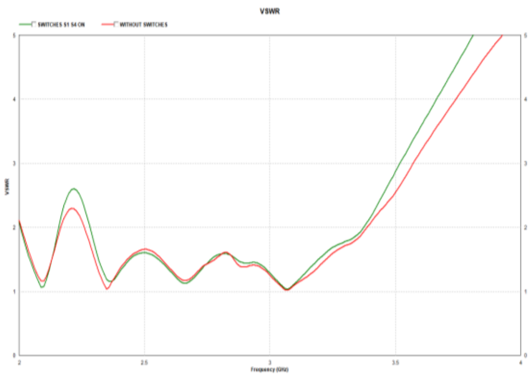


Fig. 5 – Variation of VSWR with frequency

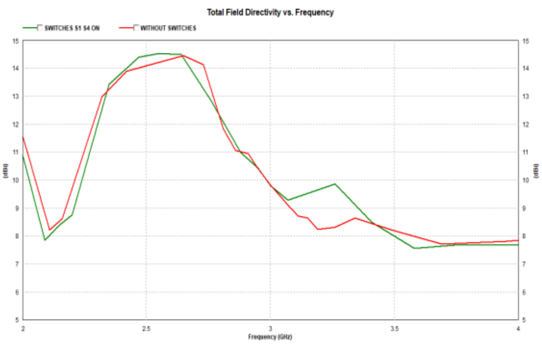


Fig. 6 – Variation of directivity with frequency

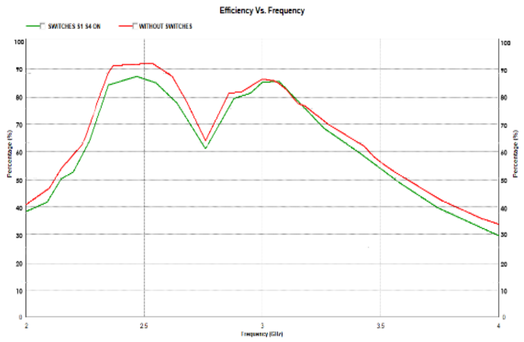


Fig. 7 – Variation of efficiency with frequency

impedance mismatches, and insertion losses, these advantages are somewhat less efficient. Notwithstanding this trade-off, efficiency losses may be minimized while enhancing total antenna performance by using low-loss switches and improving impedance matching.

3.1 Design 1: Air Gap

The first design employed a two-element truncated E-shape configuration with a 5.9 mm air gap. This reduces the effective dielectric constant (ε_{eff}), which lowers surface wave losses and increases impedance bandwidth. Additionally, a smaller ε_{eff} increases gain by strengthening fringing fields and enlarging the radiating aperture. Furthermore, air has a nearly insignificant loss tangent, which greatly lowers dielectric losses and raises radiation efficiency, which is crucial for high-performance wireless applications. This setup shows a major resonance at 2.09 GHz with a bandwidth of 6.1%. A total bandwidth of 38 % (VSWR $\leq$ 2) is obtained by observing broadband behavior at other resonant frequencies as well. The design maintained great efficiency while achieving a peak gain of 12.30 dBi at 2.69 GHz.

3.2 Design 2: Switchable Elements

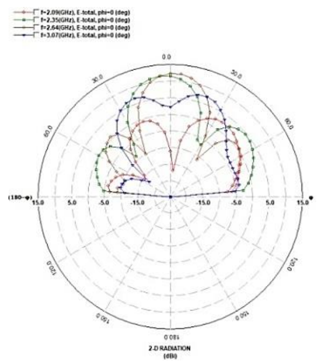
The second design integrated switchable components within the truncated E-shape antenna, maintaining the air gap of 5.9 mm, enables dynamic reconfigurability allowing control over resonant frequency, bandwidth, and gain. Switches contribute to frequency tuning, impedance matching, and radiation pattern optimization by modifying the current distribution, which improves overall performance. For applications like WLAN and WiMAX, this adaptability enhances versatility by supporting multi-band and wideband operation. While small insertion losses could happen, proper switch selection maximizes gain and directivity while minimizing efficiency loss. With these impressions, various switching configurations have been examined. The optimal configuration, with switches S2 and S3 deactivated (or S1 and S4 activated), demonstrated significant performance enhancements compared to the air gap-only design.

Table 2 – Comparative results of Design 1 and Design 2

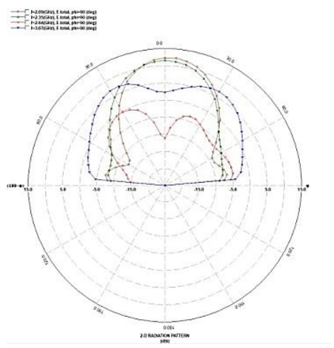
Parameter	Design 1	Design 2	Improvement
Bandwidth (%)	38 (at 2.69GHz)	47.61 (at 2.648 GHz)	+9.61
Gain (dBi)	12.30 (at 2.69 GHz)	12.42 (at 2.648 GHz)	+0.12
Efficiency	0.91 (at 2.69GHz)	0.85 (at 2.648GHz)	– 0.06

The findings highlight the advantages of including switchable components, as demonstrated by increased bandwidth and gain, which makes this design ideal for applications requiring dependable signal quality and high data rates. Although the proposed research work provides a good overview of the performance improvements, a more detailed investigation and quantification of efficiency and directivity are needed. Additionally, analyzing the radiation patterns would provide valuable insights into the antenna's overall performance capabilities.

3.3 2D Radiation Pattern



(a)



(b)

Fig. 8 – Antenna elevation gain pattern for 5.9 mm air gap as a function of frequencies and elevation angle (a) $\phi = 0$ and (b) $\phi = 90°$

Table 3 – Performance of proposed antenna with various enhancement techniques

Type of Patch Antenna	Resonate Frequency (GHz)	Bandwidth (%)	Gain (dBi)	Efficiency (%)
Single layered E-shape Patch	3.19	2.82	– 3.7	–
	3.588	3.068	2.45	0.26
Gap coupled E-shape patch with air gap 5.9mm	2.36	38.80	13.54	1.1
	3.04	38.80	9.90	1.19
Two truncated Gap coupled E-shape patch with air gap 5.9mm	2.1	6.10	3.74	0.38
	2.36	38	12.046	0.95
	2.688	38	12.30	0.90
	3.068	38	7.78	0.90
Two truncated Gap coupled E-shape patch with air gap 5.9mm and switch S2 & S3 off	2.098	10.23	3.31	0.42
	2.352	47.61	11.78	0.87
	2.648	47.61	12.42	0.85
	3.1	47.61	7.38	0.80

The radiation pattern of the antenna has been simulated at 2.09 GHz, 2.35 GHz, 2.67 GHz and 3.07 GHz with $\phi = 0$ and $\phi = 90$. The maximum gain of 12.42 dBi was found to be at 2.67 GHz. For all frequency at $\phi = 0$ radiation pattern was observed depicted in Fig. 8 (a) while at $\phi = 90$ radiation pattern was observed depicted in Fig. 8(b).

3.4 Comparative Analysis of Proposed Antenna with Others

To assess the proposed antenna's performance, we compare it with other reconfigurable microstrip patch antennas in terms of their key parameters The proposed antenna outperforms several existing designs in terms of bandwidth, achieving 47.44 %, which is significantly higher than other reconfigurable antennas in the S-band range, as shown in Table 4. Additionally, its peak gain of 12.42 dBi surpasses most of the compared designs, making it suitable for high-data-rate and long-range wireless applications. The use of switchable elements combined with a 5.9 mm air gap effectively enhances radiation efficiency while maintaining reconfigurability. Overall, the integration of switchable elements and an optimized air gap in the proposed antenna leads to superior performance, making it a strong candidate for modern wireless and communication systems requiring broadband operation, high gain, and adaptability.

Table 4 – Comparison of proposed antenna performance with others

Antenna Design	Frequency band	Band-width (%)	Gain (dBi)	Technique Used
Proposed antenna	S-band	**47.44**	12.42	Switchable elements + Air gap (5.9 mm)
Reconfigurable filtering patch antenna [21]	S-band, C-band	25	8	Embedded resonators + Switchable elements
Reconfigurable antenna for cognitive radio [22]	S-band	4.31	4.04	Defected ground structure + Switchable elements
Compact MPA with parasitically coupled feed [23]	S-band	15.4	14.8	Parasitic elements + Offset slot coupling
Reconfigurable dual-patch wideband antenna [24]	C-band	33.52	4.92	Dual-patch + Switchable elements

4. CONCLUSION

This study presents an analytical model for evaluating the resonant frequency of two diagonally truncated gap-coupled microstrip patch antennas with an air gap, comparing broadbanding techniques with and without switches. The results demonstrate that incorporating switchable configurations (e.g., all switches on, all switches off, two switches on, one switch on) leads to significant enhancements in bandwidth, gain, and directivity, thereby improving signal focus, extending communication range, and enabling higher data transmission rates. However, these improvements are accompanied by a marginal reduction in efficiency, attributed to insertion losses from switching components, impedance mismatches, and parasitic effects that contribute to power dissipation. Despite this trade-off, careful selection of low-loss switching elements and optimized impedance matching can mitigate efficiency losses while preserving the overall antenna performance. The findings suggest that the proposed diagonally truncated gap-coupled microstrip antennas, particularly with switchable configurations, exhibit strong potential for wideband applications such as WLAN and WiMAX. Additionally, integrating advanced techniques, such as reconfigurable elements or metamaterials, could further enhance the adaptability of the design, making it a promising candidate for modern and emerging wireless communication systems.

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Реконфігурована усічена Е-подібна електромагнітна антена з щілинним зв'язком, конфігураціями повітряного зазору та перемикача для широкосмугових бездротових застосувань

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У цій статті представлено дизайн та аналіз мікросмужкової патч-антени з високим коефіцієнтом посилення, оптимізованої для широкосмугових частотних застосувань у бездротовому зв'язку. Запропонована антена використовує передові технології, включаючи пряме коаксіальне живлення зонда, повітряний зазор 5,9 мм у структурі патча та усічену кутову решітчасту решітку з налаштовуваними перемикачами S1, S4 ON. Ці конструктивні елементи сприяють значному підвищенню продуктивності, досягаючи смуги пропускання імпедансу 10,23% та 47,44% (КСХН ≤ 2) у діапазоні частот від 2 ГГц до 3,41 ГГц. Антена також демонструє піковий коефіцієнт посилення 12,42 дБ на частоті 2,67 ГГц. Ретельний параметричний аналіз порівнює продуктивність антени з включенням та без включення механізмів перемикання, виявляючи помітні покращення смуги пропускання та коефіцієнта посилення. Конструкцію антени було перевірено за допомогою моделювання з використанням методу програмного забезпечення IE3D на основі моментів. Результати підкреслюють потенціал антени для ефективного розгортання в сучасних системах бездротового зв'язку, пропонуючи покращену смугу пропускання, коефіцієнт посилення та загальну продуктивність.

Ключові слова: Мікросмужкова патч-антена, Широкосмугова, Коаксіальне живлення зонда, Решітка з проміжним зв'язком, Комутатор.