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REGULAR ARTICLE

Design and Simulation of Microstrip Patch Antenna for Inter-Aircraft Communication in UHF, *L*-band and *S*-band

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This paper focuses on the design and development of a novel microstrip patch antenna (MPA) in ultra-high frequency (UHF) (0-1GHz) and *L*-band (1-2 GHz) for Traffic/Aircraft Collision Avoidance System (TCAS/ACAS) applications, with an extension to *S*-band (2-4 GHz) for weather radar, surface ship radar, and some communications satellites. The antenna is created in MATLAB software to fulfil the present demands of the aircraft collision avoidance system while also overcoming any constraints associated with previous approaches. It utilized FR4 substrate having dielectric constant 4.4, thickness 4 mm, and loss tangent 0.002. The simulation findings provided insight into antenna performance and other aspects. The average return loss (S11) is – 11 dB, with a voltage standing wave ratio (VSWR) near to one. The antenna attained a gain of 4.03 dBi. This antenna is ideal for TCAS/ACAS applications because to its excellent reflection coefficient, VSWR, 50 Ω impedance matching, directional radiation pattern, and high gain at operational frequencies. The suggested antenna is intended to fulfil the advanced avionics criteria for design simplicity, lightweight, and high performance.

Keywords: TCAS/ACAS, Reflection coefficient, VSWR, Gain, Directivity, Patch antenna.

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1. INTRODUCTION

Telecommunication technology allows for everyday human communication as well as transcontinental communication over large oceans via radio waves broadcast by land-based antennas or geostationary satellites circling Earth. An antenna is an essential component of the communication system. It acts as a transducer, transforming electrical energy into radio waves and radio signals back into electrical energy. Aircraft antennas are critical to enabling flawless communication, navigation, and safety in the aviation sector [1-4]. Aircraft antennas send and receive communications between the aircraft, ground control stations, and other aircraft. They are critical to maintaining real-time communication and guaranteeing aeroplane safety. Without proper communication between an aircraft and air traffic control, flying would be extremely dangerous.

The traffic collision avoidance system (TCAS) was created to lessen the likelihood of mid-air accidents between aircraft [5]. In 1991, K.S. Sampath, R.G. Rojas, and W.D. Burnside of Ohio State University's ElectroScience Laboratory explored various implementations of the TCAS Antenna [6]. Currently, TCAS/ACAS use a directional antenna installed on top of the aircraft. An omnidirectional transmitting and receiving antenna is fitted at the aircraft's bottom to give TCAS with range and altitude data from traffic below it. In addition to the two TCAS antennas, the Mode *S* transponder requires two antennas as well. These antennas enable the mode *S* transponder to receive interrogations at 1.03 GHz and respond to them at 1.09 GHz [7].

Millimeter waves flow smoothly through the target and are reflected, allowing the imaging system to concentrate on the target and expose its information. This makes it valuable in a defensive system. Such an application necessitates enhanced capacity, speed, dependability, and low latency, all of which are typical of millimeter waves. Antenna size, purpose, and placement aboard an aircraft are typically defined by their directional characteristics and the electromagnetic frequencies at which they operate. Antennas are used in aircraft for communications as well as various navigation systems, spanning from 30 MHz to 4 GHz and beyond, and are classified as ultra-high frequency (UHF) (0-1GHz), *L*-band (1-2 GHz), and *S*-band (2-4 GHz). These navigation systems provide a variety of functions for aircraft operation [8-11], including direction finding (DF), distance measuring equipment (DME), global positioning system (GPS), microwave landing system (MLS), radar altimeter (RadAlt), very high frequency communication (VHF Comms) system, traffic collision avoidance system (TCAS), and air traffic controller (ATC) system, among others. The RF antenna is the most important subsystem in every aircraft system design. They are required for wireless communications to function. The design and size of aircraft antennas can vary greatly depending on the manufacturer. The size and design of antennas can impact the

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airflow surrounding the aircraft, affecting its performance and fuel economy.

Antennas' performance is also heavily influenced by their directional characteristics and coverage area. Different antennas may perform better in certain scenarios.

This study describes the design, investigation, and presentation of innovative microstrip patch slotted antenna with coaxial feeds, copper radiating patch, FR4 as substrate material, and copper ground of equivalent size of substrate. The primary goal of this work is to apply a new antenna technology in TCAS applications with improved performance. Microstrip patch antennas are widely used in commercial and communication systems. A microstrip antenna allows for frequency adjustment, radiation beam shaping, tuning, and scanning. These antennas are exceedingly mechanically robust, which is a huge benefit in this application.

In this work it is intended to design and develop a novel microstrip patch antenna (MPA) in ultra-high frequency (UHF) (0-1 GHz) and L-band (1-2 GHz) for Traffic/Aircraft Collision Avoidance System (TCAS/ACAS) applications. Further, designed antennas extension to *S*-band (2-4 GHz) for weather radar, surface ship radar, and some communications satellites, will also be explored. For different purpose of communication and navigation, different antennas are used in the frequency range 30 MHz to 4 GHz, like DF, DME, GPS, MLS, RadAl, VHF Comms system, TCA and ATC. An effort to develop one antenna, using microstrip elements for all work is described in this paper. This is uniqueness of the work. This suggested antenna is made up of patches and slots. The antenna construction is built in such a way that its radiation may cover the most area of the azimuth plane. The proposed antenna has compact design, high gain, wide impedance bandwidth, adequate return loss, and enhanced efficiency. It is also highly lightweight and cost effective. The planned antenna may be incorporated in the aircraft's body, with no restriction to airflow. Aside from the design issues, it saves on maintenance because it is not immediately exposed in the path of the airflow. The designed antenna has matching specifications for TCAS/ACAS applications, but comes with a new design.

1.1 Placement of Antenna on Aeroplane

There are multiple types of antennas used aboard aeroplane to support various communication and navigation systems. VHF antennas, which operate at 108 MHz-118 MHz for navigation and 118 MHz - 137 MHz for communication, are in charge of communicating between aircraft and air traffic control, as well as between aircraft. VHF antennas are used for voice communications and can be installed on the top or bottom of the aircraft. Global positioning system (GPS) antennas, which are positioned on top of the aircraft or on the underbelly for better reception when flying, receive signals from satellites and transmit accurate location data to the aircraft, assisting in navigation. Transponder antennas, blade-style antennas, and integrated VHF/GPS antennas improve air traffic safety by sending identification and altitude information. Loran antennas, which may be mounted on the top or bottom of an aircraft, typically have an amplifier integrated into their base to improve signal quality or a smaller amplifier installed just beneath the skin. Aircraft loop antennas, located on either the top or bottom of the aircraft, are made up of two or three distinct coils that resemble a flattened bagel, with each signal received at varying intensities between the coils. Marker beacon antennas are designed to pick up signals from ground-based marker beacons. These beacons give critical positioning information to pilots during approaches and landings. Navigation The antenna, which is always located on the vertical tail, is a critical component of an aircraft's navigation system. Radio altimeters use radio waves to determine the distance between an aircraft and the ground. Radio altimeter antennas, which are normally situated on the aircraft's bottom, are particularly built to emit and receive these radio waves, allowing pilots to accurately monitor their altitude.

Microstrip antennas have gained popularity among communication engineers and academics, particularly in recent years, due to their ease of installation. Furthermore, they offer several advantages, including low cost, light weight, and ease of use. Furthermore, when they use slotted structures of various types, they may increase bandwidth to the point that many bands can be covered at the same time. Furthermore, radiation loss in these antennas has been observed to be significantly decreased [12-14]. A multiband slot antenna can be more effectively manufactured when a slot with the proper size is carved into the microstrip patch [15-17]. Because of its thin planar shape, MPA may be readily merged/unified with the surfaces of equipment such as aeroplane without creating significant drag. All of the qualities listed above make it a unique and high priority choice for aeroplane.

Bazan conducted a thorough investigation into the design of a circularly polarized patch antenna for satellite communications in L-band for use in communication-navigation services. The designs were created using the simulation programme Advance Design System (ADS). The antennas are engraved upon an RT/Duroid with a dielectric substrate of 3.38 [18]. In the Airbus A321, a microstrip patch antenna system has been built as an access point for the 5 GHz band, in accordance with the IEEE 802.11 ac/ax standard. 5 GHz WiFi internet service is provided at the 5300 MHz (CH 60) center frequency using four FR-4 dielectric antennas. [19]. A novel wireless heterogeneous architecture is presented, with the goal of integrating several existing communication technologies and allowing the passenger control unit to be set autonomously without the need for external intervention [20]. A microstrip patch antenna operating in the ultra-high frequency band was constructed, and its properties such as gain, directivity, return loss, voltage standing wave ratio (VSWR), and radiation pattern were analyzed and simulated using the Ansys high frequency structure stimulator (HFSS) [21]. An array of 1x4 microstrip antenna elements was developed with the shortest feed line width and analyzed in terms of electrical metrics such as return loss, gain, directivity, and radiation efficiency at a resonance frequency of 16 GHz [22]. A dual feed and dual patch microstrip antenna developed in CST studio suite achieved satisfactory return loss and VSWR with 50 Ω impedance matching, making it appropriate for TCAS applications [23]. The electric field integral equation, the electric/magnetic current combined-field integral equation, and the multilevel rapid multipole algorithm were used to design a low profile conformal vertical polarization antenna that may be used in the *X*/*K*-band spectrum [24].

Paper organization is as follows. Section 2 describes antenna design, wherein the antenna design equations and the optimized parameters are reported. Simulation results and discussions on the results are given in section 3. Finally, conclusion is presented in section 4.

2. ANTENNA DESIGN AND CONFIGURATION

The proposed microstrip patch slotted antenna has been shown in Figure 1. The antenna comprises of a ground plane, a radiating patch, and a substrate in between the two. Copper sheet used for radiating element and ground plane has a thickness of 0.035 mm. It employs substrate material FR4 having dielectric constant 4.4, thickness 4 mm, and loss tangent 0.002. FR4 material is utilised as a substrate due to its electrical properties, moisture resistance, superior electrical insulation, high strength-to-weight ratio, accessibility, low cost and ease of availability. A finite ground plane of equivalent size of the substrate and thickness of 0.035 mm is used. a uniform 50-ohm coaxial probe is used to excite the patch and the resultant electric fields are generated. Co-axial feed is a contact technique of radio frequency (RF) power feed for antennas. Co-axial feed has the advantage of avoiding spurious radiation and attaining high bandwidth. Photo-etching is used to install the radiating element and feed lines on the dielectric material. Volumetric dimension of the antenna being 152.4 × 101.6 × 1.6 mm^3. Copper patch is designed and used as radiators. Patch is of circular shape (radius 34 mm) with two rectangular arms (100 mm × 20 mm) extending and protruding along one of its diameters along X-axis. Two identical circular slots (radius 4 mm) are cut out from the patch just at the boundary of the main patch and its rectangular arms. That is, two narrow slots are identical but opposite in position to each other. After this, two L-shaped slots with horizontal arm of dimension 20 mm × 30 mm and vertical dimension 30 mm × 10 mm, are made at the diagonally opposite sides of the main circular patch close to the two narrow slits. The L-slots are positioned in inverted order.

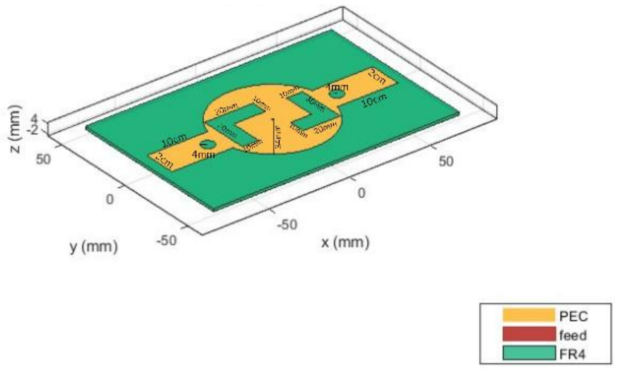

Fig. 1 – Design of the proposed microstrip patch slotted antenna

When building a circular microstrip antenna, numerous factors must be considered, including the radius of the circular patch, the thickness of both the patch and the ground, and the substrate's dimensions in terms of width, ground length, substrate length, and circular patch radius. To calculate the size of the patch antenna, apply the basic standard antenna formulae (1-9) [25].

$$width\ of\ patch(w) = \frac{c}{2f_0\sqrt{\frac{\varepsilon_r+1}{2}}} \tag{1}$$

$$L = \frac{c}{2f_0\sqrt{\varepsilon_{eff}}} - 0.824h\left(\frac{(\varepsilon_{eff}+0.3)\left(\frac{w}{h}+0.264\right)}{(\varepsilon_{eff}+0.258)\left(\frac{w}{h}+0.8\right)}\right) \tag{2}$$

$$f_0 = \frac{c}{2L_e\sqrt{\varepsilon_r}} \tag{3}$$

$$effective\ length\ (L_e) = \frac{c}{2f_0\sqrt{\varepsilon_{eff}}} \tag{4}$$

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[\frac{1}{\sqrt{1+12\left(\frac{h}{w}\right)}}\right] \tag{5}$$

where,
$c = velocity\ of\ light,$
$f_0 = resonant\ frequency,$
$\varepsilon_r = substrate\ dielectric\ constant,$
h = substrate height,
$L_e = effective\ length,$
$\varepsilon_{eff} = Effective\ constant$
$L = Length\ of\ Patch$

If the size of the ground plane exceeds the patch's dimensions by nearly six times the substrate thickness all around, then the ground plane follows the measurements:

$$Lg = 6h + L \tag{6}$$

$$Wg = 6h + W \tag{7}$$

Radius of the circular patch is calculated using the following equation [26].

$$r = \frac{F}{\sqrt[2]{1+\frac{2h}{\pi F \epsilon_r}\left(In\left\{\frac{\pi F}{2h}\right\}+1.773\right)}} \tag{8}$$

$$\text{where } F = \frac{8.791\times10^9}{f_0\sqrt[2]{\epsilon_r}} \tag{9}$$

The dimensions of the antenna elements and the corresponding optimized values are given in Table 1.

Stepwise design of antenna is shown in Figure 2. Once the initial antenna size is identified, the 3D electromagnetic simulations and further refinement of the design is done using Matlab. Matlab creates 3D model using digital, RF, and antenna elements to explore and optimize system behaviour for mm wave wireless communication. Firstly, the circular patch is configured. This is followed by providing two rectangular arms extending and protruding outwards along the X-axis. Up to these steps, antenna resonates at 2.2 GHz and has return loss of – 9 dB, implying no impedance matching at all. In the third step, two narrow slots are created at the just boundary of the circular patch and the rectangular extended patches. These resulted in improvement of the return loss values over the theoretically allowed value of – 10 dB. This also resulted in one additional resonance at 0.7 GHz.

Table 1 – Dimensions of the patch antenna design

Quantity	Symbol	Dimension (mm)	Optimized dimension (mm)
Length of substrate/ground	L	152.4	152.35
Width of substrate/ground	W	101.6	101.61
Thickness of substrate	h	1.6	1.6
Diameter of Feedline	D_f	1	1.01
Length of Patch	L_p	152.4	152.35
Width of Patch	W_p	101.6	101.61
Thickness of Patch/ground	h_p	0.5	0.51
Radius of Circular slot	R_n	34	34
Radius of narrow slots	r_n	4	4
Length of *L*-shaped slots (horizontal arm)	L_h	20	20
Width of *L*-shaped slots (horizontal arm)	W_h	10	10
Length of *L*-shaped slots (vertical arm)	L_v	30	30
Width of *L*-shaped slots (vertical arm)	W_v	10	10

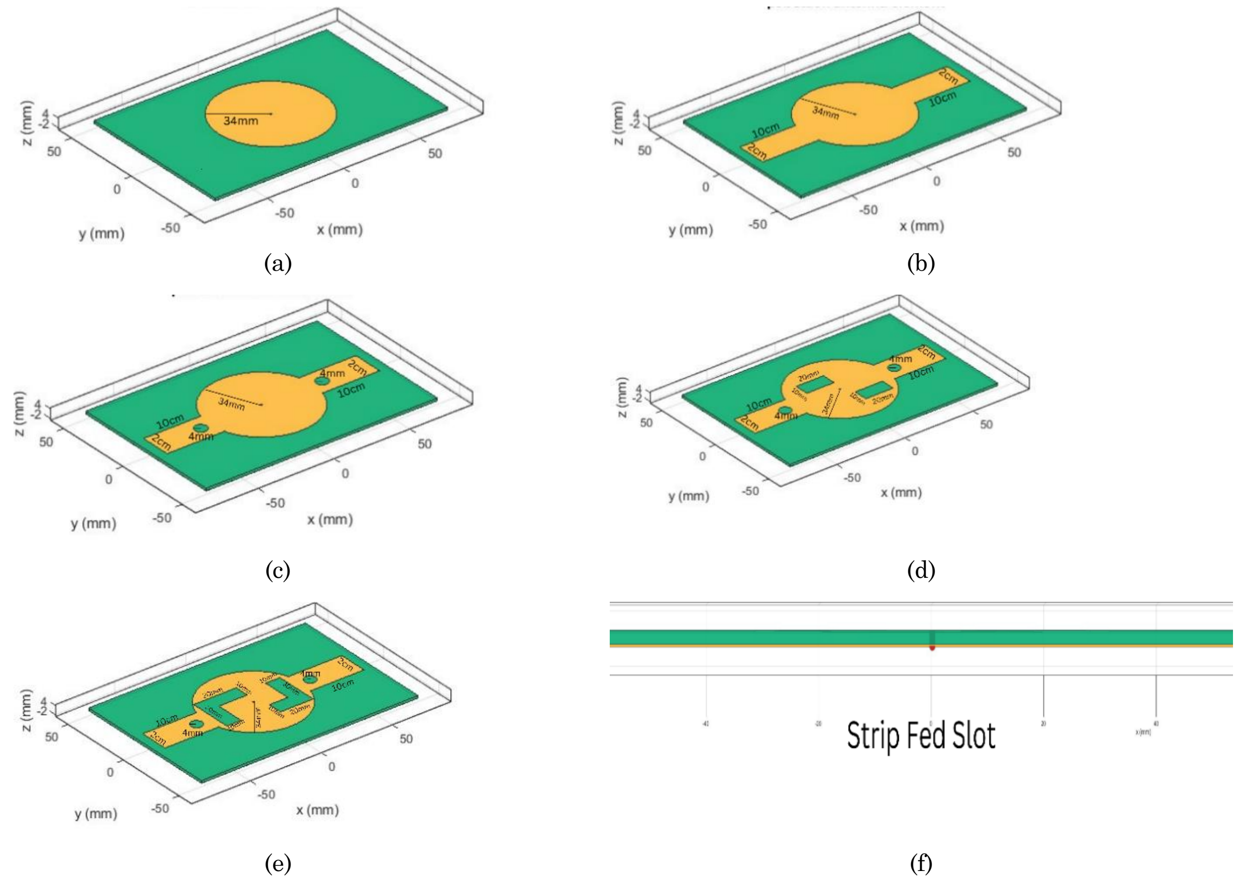

Fig. 2 – Stepwise design of proposed antenna and fed slot

The final step of the design had been the provision of two inverted *L*-shaped slots on the main circular patch, symmetrically located on either side of it close to the two narrow slots. *L*-shaped slots enabled the creation of both horizontal and vertical polarised signals. Furthermore, because the rectangular patch is the best match, it is easier to alter the resonator's length. The choice of *L*-shaped resonator was based on the fact that adjusting the distance between the arms of *L*-shape allows for a more varied distribution of resonant frequencies than quarter- or half-wavelength resonators. Then fine tuning of the resonance frequency and return loss was done with rectangular slots gradually until the targeted values are closely realized. Fine tuning was accomplished by conducting experiments on conventional antenna equations and analysing the response pattern. At this stage, the design process is complete and the multiband resonance frequency is obtained 0.7 GHz, 2.1 GHz, 3.9 GHz and 4.4 GHz, with maximum return loss value of – 16 dB.

3. SIMULATION RESULT AND DISCUSSION

The simulation results for the proposed antenna include return loss, VSWR, gain, impedance, 2D radiation pattern, 3D radiation plot, and surface current distribution. The antenna insertion loss is given by S11. The antenna input power is inversely proportional to the insertion loss. In general, antennas radiate successfully within a specific frequency range. At these frequencies, the input power would almost precisely equal the radiated energy, resulting in extremely little reflected power. Obtaining a return loss greater than – 10 dB is critical for producing an effective radiation mode. From the simulated results, it is observed that the suggested antenna has a return loss of – 11 dB at frequency 0.7 GHz and – 11.5 dB at frequency 2.1 GHz. Return loss at other two resonant frequencies of 3.9 GHz and 4.4 GHz are found to be – 11.2 dB and – 16 dB respectively (Fig. 3). The terms 'S11', 'return loss' and 'reflection coefficient' have been used interchangeably to describe the same antenna characteristics.

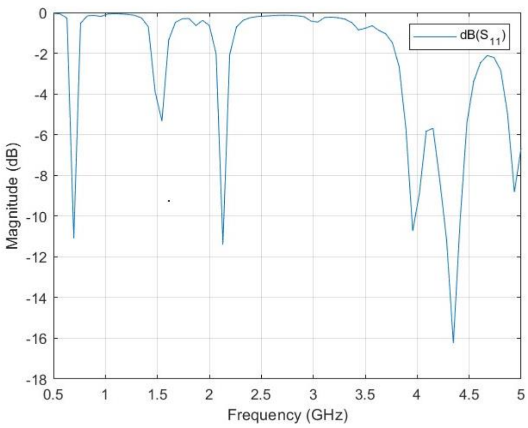

Fig. 3 – Return loss (S11) vs. operational frequency range

The antenna better complements the transmission line, receiving more power with a lower voltage standing wave ratio (VSWR). VSWR over the operating band indicates a satisfactory match between the radiating patch and the feed line. The optimal VSWR value examined is one. This number is optimal because at this VSWR, the antenna does not reflect any electricity. The VSWR value in our study is 1, as seen in Fig. 4. The finest feature is that the VSWR value is kept around 1 for all resonant frequencies, resulting in a very excellent match with the load and nearly no power loss due to reflection.

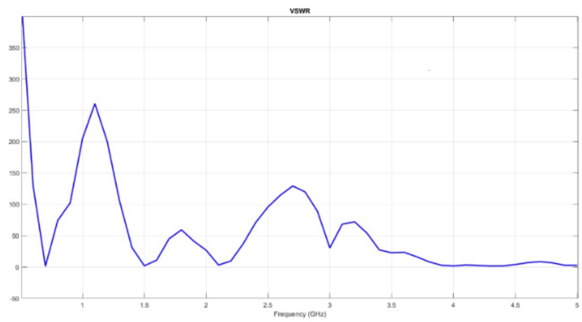

Fig. 4 – Voltage standing wave ratio (VSWR) vs. operational frequency range

Figure 5 shows the simulated antenna impedance characteristics in which resistance and the reactance parts are shown independently. At the resonance frequencies 0.7 GHz, 2.1 GHz, 3.9 GHz and 4.4 GHz, the proposed antenna offered resistance of 22 Ω, 30 Ω, 50 Ω and 55 Ω respectively. Simulation results for the proposed antenna design is shown in Table 2.

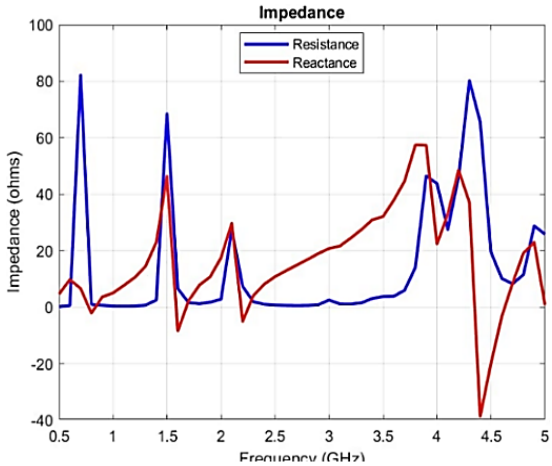

Fig. 5 – Impedance vs. operational frequency range

Table 2 – Simulation results of the antenna

Freq. (GHz)	S11 (dB)	VSWR	Resistance (Ω)	Gain (dBi)
0.7	– 11.0	1.0	22.0	3.41
2.1	– 11.5	1.0	30.0	3.40
3.9	– 11.2	1.0	30.0	3.92
4.4	– 16.0	1.0	55.0	4.03

Figure 6 depicts the two-dimensional radiation pattern for the planned antenna in the E plane at $\varphi = 0°$. The 2D radiation patterns showed better antenna directionality, with maximal radiation on the emitting patch's bore side. Good antenna matching and the use of low-loss substrate materials lead to good radiation and overall efficiency.

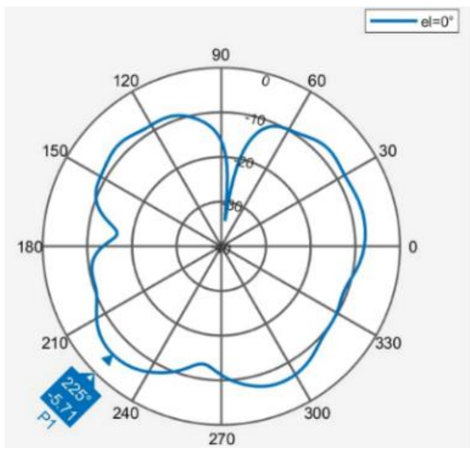

Fig. 6 – 2D Plot

Figure 7 shows the predicted 3D radiation pattern of the proposed antenna at both frequencies. At the four observed resonant frequencies, the antenna radiates in the end-fire direction along the azimuth plane. The greatest average gain observed in the azimuth – 180° to + 180° and elevation – 90° to + 90° is 3.41 dBi.

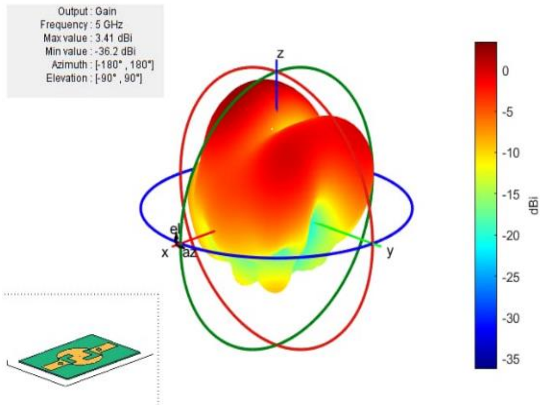

Fig. 7 – 3D Radiation Plot

Figure 8 depicts the dispersion of surface current. The current is focused along the microstrip feed line and at the gap's margins. Around the microstrip's outside margins, the current density is around 3 A/m. It can also be observed that the current density at the patch's centre and slit edges is around 8 A/m. Generally, along the patch, the minimum and maximum current distribution variation vary from 0.5 A/m to 150 A/m.

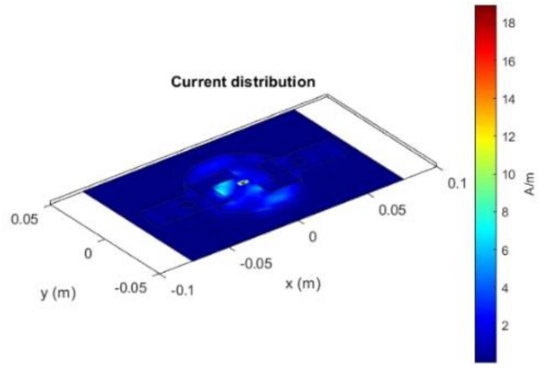

Fig. 8 – Current distribution

Table 3 compares current work data to the results of prior publications. The findings were compared to prior notable studies on aircraft communication antennas mostly employing substrate with dielectric constant (ϵ_r) 4.4, with the exception of one with dielectric constant 1.0. The comparison took into account return loss, bandwidth, resonating frequency, antenna gain and substrate dielectric constant. The suggested antenna clearly has a number of advantages, including multiband function, multipolarization capabilities, a compact size, adaptability, ease of fabrication, and a reasonable gain. The uniqueness of the proposed antenna in this work is its multiband operational capacity in and around the same central frequency as compared to other works reporting comparable results.

Table 3 – Simulation results of the antenna

Ref.	S11 (dB)	BW (GHz)	Freq (GHz)	Gain (dBi)	ϵ_r
[19]	– 18.7	0.2	5.3	2.92	4.4
[21]	– 22.0	0.1	1.1	7.55	4.4
[23]	– 28.8, – 26.4	0.1	1.1, 1.1	8.55, 8.25	4.4
[25]	– 19.0	0.1	2.0	-	1.0
This work	– 11.0, – 11.5, – 11.2, – 16.0	0.1	0.7, 2.1, 3.9, 4.4	3.41, 3.40, 3.92, 4.03	4.4

4. CONCLUSION

This study describes a design approach for a microstrip patch antenna with ultra-high frequency (UHF) (0-1GHz), *L*-band (1-2 GHz), and *S*-band (2-4 GHz) frequencies that may be utilised as an aeroplane tracking antenna for TCAS/ACAS applications. The suggested antenna can also be utilised for weather radar, surface ship radar, and some communications satellites. The suggested microstrip antenna array outperforms the present monopole TCAS/ACAS antenna in terms of high gain, strong directivity, wide impedance bandwidth, and small beamwidth. With suitable port excitation, the entire antenna array structure may cover a 360° surveillance radius surrounding the aircraft. This suggested antenna is also highly lightweight and cost effective. It has been constructed with the dielectric most suited to the specified frequency of operation. The patch's length and breadth have been determined to fit the available space bracket on the aircraft. The above-mentioned antenna has comparable specifications to the original antenna, but with a new design. As a result, with these suggested system implementations, this TCAS antenna is predicted to fulfil advanced avionics criteria for design simplicity, lightweight, and high performance.

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Проектування та моделювання мікросмужкової патч-антени для міжповітряного зв'язку в УВЧ, *L*-діапазоні та *S*-діапазоні

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Ця стаття присвячена дизайну та розробці нової мікросмужкової патч-антени (MPA) у надвисокій частоті (UHF) (0-1 ГГц) і *L*-діапазоні (1-2 ГГц) для системи запобігання зіткненням літаків (TCAS/ACAS) з розширенням до *S*-діапазону (2-4 ГГц) для метеорологічних радарів, радарів надводних кораблів і деяких супутників зв'язку. Антена створена в програмному забезпеченні Matlab, щоб задовольнити поточні вимоги системи запобігання зіткненням літака, а також подолати будь-які обмеження, пов'язані з попередніми підходами. Він використовував підкладку FR4 з діелектричною проникністю 4,4, товщиною 4 мм і тангенсом втрат 0,002. Результати моделювання дозволили зрозуміти характеристики антени та інші аспекти. Середні зворотні втрати (S11) становлять – 11 дБ, з коефіцієнтом стоячої хвилі напруги (КСВН) близько одиниці. Антена досягла посилення 4,03 дБі. Ця антена ідеально підходить для додатків TCAS/ACAS завдяки чудовому коефіцієнту відбиття, КСВ, узгодженню імпедансу 50 Ом, спрямованій діаграмі спрямованості та високому посиленню на робочих частотах. Запропонована антена призначена для виконання передових критеріїв авіоніки щодо простоти конструкції, легкої ваги та високої продуктивності.

Ключові слова: TCAS/ACAS, Коефіцієнт відбиття, КСВ, Посилення, Спрямованість, Патч-антена.