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Low-profile Compact Printed Monopole Antenna for Satellite-based AIS Application

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ABSTRACT

In this paper, a simple, low profile compact printed monopole antenna has been proposed for satellite based automatic identification system (SB-AIS). The design consists of a printed monopole, which has been meandered to achieve optimum size reduction. The detailed investigation in terms of bending of the arms of monopole, width of the patch and dimensions of the ground plane on the resonance frequency and input impedance is presented. The antenna is matched to a typical 50 Ω coaxial line without any requirement of external matching structures. The prototype of the antenna is fabricated and tested at an operating frequency of 161 MHz for SB-AIS, with compact size of 44.5 × 17 cm^2. The measured results show that the antenna has a bandwidth of 15 MHz (9.3 per cent), gain of 1.87 dBi and beam-width of 82° in the elevation and omnidirectional in azimuthal plane. The size reduction is 53.8 per cent as compared to a linear printed monopole antenna.

Keywords: Satellite based-automatic identification system; Printed monopole antenna; Meandered monopole antenna; VHF antenna; Compact monopole antenna

1. INTRODUCTION

A traditional line of site based automatic identification system (AIS) has limited communication range, to extend the range of the communication (>80 km), it has to be undertaken through a satellite, which also makes the data worldwide[1]. Satellite based-automatic identification system (SB-AIS) is a maritime surveillance system working on VHF band of 161 MHz over the channel 1 and channel 2[2,3]. It finds its application in Navy, Coast guard and Maritime patrol police to secure the coastal and maritime environment. The SB-AIS, being in VHF range, the antennas of these satellites becomes large in comparison with the size of satellite itself. Thus, it becomes difficult for satellites to accommodate these large VHF antennas. The mass and the volume of the satellite are the two fundamental driving factors for the choice of an antenna arrangement. Several approaches have been proposed for the choice of an antenna for SB-AIS such as, deployable wire monopole antenna[4] and helical antenna[5]. The conventional deployable monopole and helical antenna have linear dimension of a quarter wavelength and 4m, respectively, and weighs up to several kilograms. The deployable nature of this heavy antenna also required high core strength and good spring stiffness. The special mechanism is needed for maintaining the stability of satellite during deployment of these large antennas, which also adds mass to the satellite. Owing to such bulky structure and the other mechanisms, planar/printed antennas would become the natural choice for on-board applications. With the advent of technology and miniaturisation of satellite payloads, there has been a need to develop compact and easily integrable on-board antennas. This led to popularisation of printed/patch/planar antennas[6]. Printed antennas, have a variety of beneficial properties including mechanical durability, conformability, compactness and cost-effective manufacturability. As such, they have a range of applications in both the military and the commercial sectors, and are often mounted on the exterior of the aircraft and spacecraft as well as incorporated into mobile radio communication devices. Recently, a compact array of patch antenna was developed[7] for space based AIS with overall dimension of 50 × 50 cm^2 and mass of approximately 3.9 kg. In order to reduce the profile, patch array antenna based on an artificial magnetic material (AMM) was presented[8]. However, for manufacturing of these elements, aluminum slabs were machined using high precision CNC and laser cutting technology, which were very cumbersome and expensive. In another method, a printed folded line fed by a short probe monopole, using a concept of capacitive coupling, was presented[9], which suffered from very poor gain of -11.6 dBi. In the last decade, wide range of monopole structures have been studied such as T-shape[10], rectangular-shape[11], elliptical-shape[12], metamaterial inspired monopole[13]. All these structures, when considered for AIS applications, are not suitable as they are bulky and do not meet its required specifications[2]. A quarter-wave linear printed monopole antenna (LPMA) has been considered for SB-AIS.

In this paper, investigations have been carried out to reduce the size of a LPMA. It is proposed to achieve the size-reduction by meandering the monopole antenna, which is an effective way to reduce the length for the given resonance frequency. The parametric study leading to an optimum design of a compact meander line printed monopole antenna (MLPMA) has been presented. A compact MLPMA of overall size of 44.5 × 17 × 0.159 cm^3 has been realised on a low-cost Glass

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Epoxy substrate (FR4). The overall dimension of the designed MLPMA has been reduced to 53.8 per cent as compared to a LPMA. A commercially available electromagnetic modelling software CST microwave studio is used for the design and analysis of this antennas[14]. To verify the simulated results, the proposed antenna is fabricated on FR4 glossy epoxy substrate and measurements have been carried out for validation. This antenna is designed for SB-AIS, which is used in Navy, Coast guard and Maritime patrol police to secure the coastal and maritime environment.

2. LPMA DESIGN

First, the LPMA was designed at 161 MHz, the initial length of which is calculated theoretically from Eqn (1)[15,16]. These relations were derived by equating the area of the patch with that of an equivalent quarter wave cylindrical monopole antenna with same length. The resonance frequency is given as,

$$f_L = \frac{c}{\lambda} = \frac{7.2}{(L + r + p) \times k} \tag{1}$$

where L is the length of the patch line (in cm), r is the radius of the equivalent cylindrical monopole antenna $\left(r = \frac{W}{4\pi} \right)$ (in cm), W is the width of the patch line (in cm), p denotes the small length of the centre conductor of the coaxial connector above ground plane at the bottom of the antenna (feed point). The value of p is equal to zero in the present configuration, k is a correction factor of 1.15 for the FR4 dielectric and f_L is in GHz.

With this calculated L and W, the final dimension of the LPMA has been optimised through simulations by considering the effect of the ground plane, as it influences the resonance frequency[17]. The LPMA oriented along the x-axis is shown in Fig. 1, which is printed on a FR4 substrate with $\varepsilon_r = 4.4$, copper thickness 0.0035 cm, substrate height (h) of 0.159 cm and loss tangent of 0.02. Slightly higher value of the loss tangent does not affect the radiation efficiency of the antenna as there is no backing ground plane behind the radiator and also the design frequency is relatively lower. The antenna is fed with 50 Ω microstrip line of width W_f = 0.31 cm over the ground plane at its bottom end. The width of the patch W is optimised as 0.35 cm to match with the 50 Ω microstrip feed line. The ground plane of length (L_g) and width (W_g) are 4.5cm and 27 cm, respectively, which is printed in the backside of the feed microstrip line. The straight length of the monopole antenna, L = 58 cm is obtained through simulations. The length L_s is chosen as 60 cm, so that there is sufficient dielectric substrate beyond the open end of the LPMA, which also leads to better input matching and better radiation efficiency. The final dimensions of the LPMA are listed in Table 1. Simulation results of LPMA are shown in Figs. 2(a) and 2(b). Here the antenna is placed along the x-axis in xy-plane. The monopole antenna resonates at the designed frequency of 161 MHz with reflection coefficient better than -30 dB. The radiation patterns in E and H planes are 'Figure of 8' and omnidirectional, respectively. There were negligibly small cross pol components in both the planes. The radiation patterns are exactly same as that of a conventional dipole antenna with gain of 1.9 dBi.

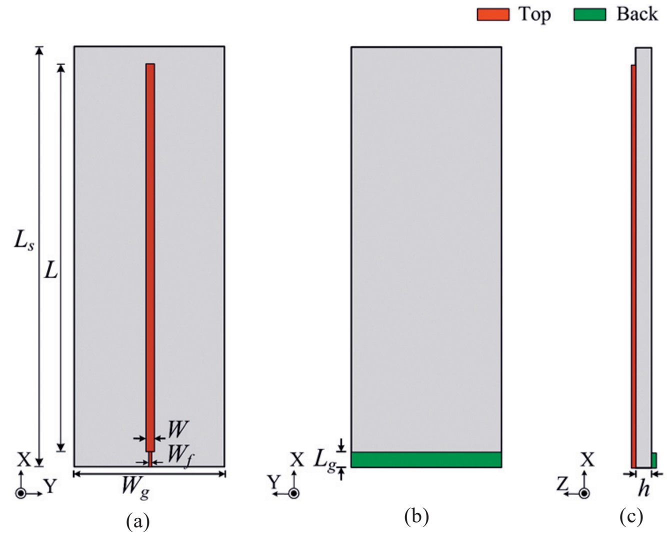


Figure 1. A geometry of the LPMA (a) top view, (b) back view and (c) prospective view.

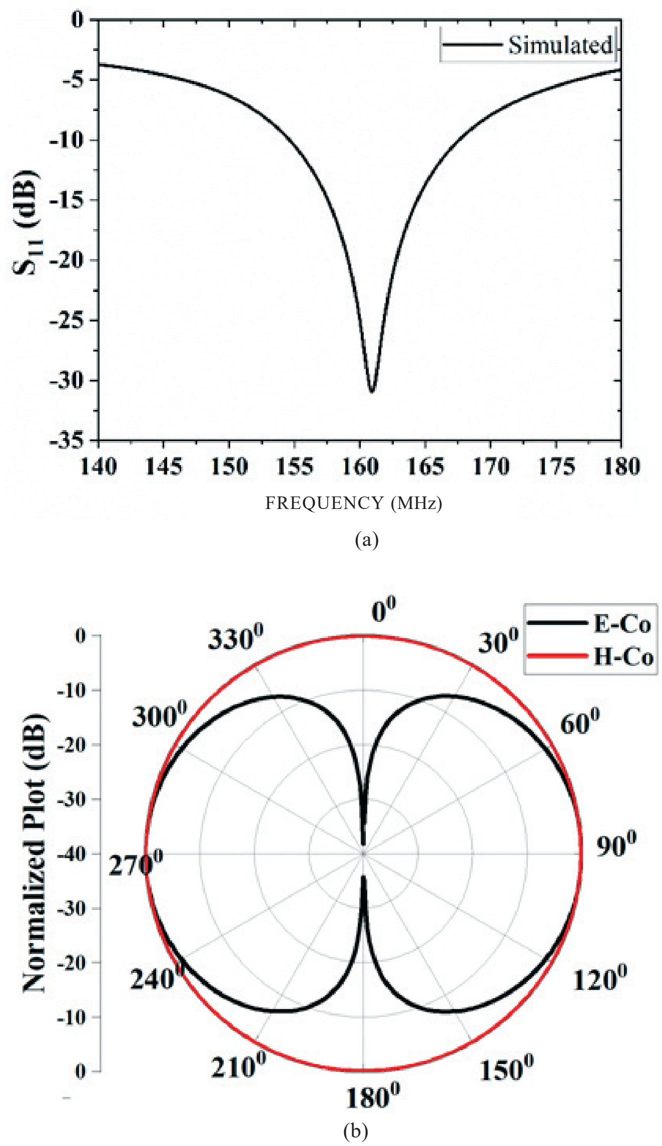


Figure 2. Simulation results for LPMA (a) reflection coefficient S_{11} (dB) and (b) radiation pattern plots in E and H planes.

Table 1. Dimensions of the LPMA

Parameter	Value (cm)
Width of microstrip feed line, W_f	0.31
Ground plane width, W_g	27.0
Ground Plane length, L_g	4.5
Total Length of line, L	58.0
Width of the patch, W	0.35
Total Length of the substrate, L_s	60

3. DESIGN AND ANALYSIS OF THE MEANDERING OF THE LPMA

The miniaturisation of the printed monopole antenna based on meander line is presented in this section. The proposed compact antenna is designed at 161 MHz by meandering the conductors symmetrically along the x-axis on the FR4 substrate, as shown in Fig. 3(a). The meandering of monopole is achieved by folding the conductor back and forth, in the form of 'U' shaped segment symmetrically along the feed line axis. The conductor of LPMA designed is meandered, so that physical straight length of the antenna becomes shorter keeping the electrical length a quarter wavelength at 161 MHz.

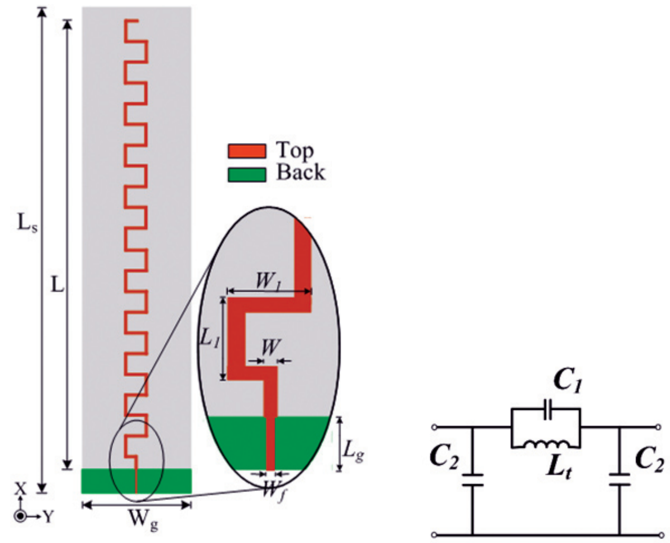
The equivalent circuit representation of the meandered sections is represented by L and C model, as shown in Fig. 3(b)[18,19]. The capacitive effect between the bent lines and the inductive effect of the conductor segments decides the electrical length, the physical length and consequently the resonance frequency of the MLPMA.

The resonance frequency is calculated by simple formula,

$$f_r = \frac{1}{2\pi\sqrt{L_t C_t}} \tag{2}$$

where L_t is total inductance of a U-shaped arm and C_t is total capacitance between U-shaped arm.

Increasing the total metal line length of the MLPMA by number of segments, reduces the resonance frequency making it compact. Here a U-shaped meandering with equal arm length and width on one side of the symmetrical feed axis is considered as one segment ($N = 1$). Based on the parametric study presented in the following section, the final optimised dimensions are as given in Table 2. The overall size of the antenna obtained is $44.5 \times 17 \times 0.159$ cm^3. The insight on the functioning of the MLPMA is visualised from the simulated surface current distribution of the antenna at 161 MHz, which is as shown in Fig. 4. The surface current has variation of quarter wave length with maximum magnitude at the feed end and minimum at the open circuited end. It is noted that by meandering the conductor, the current path increases facilitating to achieve quarter wavelength variation in reduced physical length.



(a) (b)

Figure 3. A configuration of the MLPMA (a) geometry and (b) equivalent circuit model.

Table 2. Dimensions of the MLPMA

Parameter	Value (cm)
Width of microstrip feed line, W_f	0.31
Ground plane width, W_g	17.0
Ground plane length, L_g	4.5
Width of the patch, W	0.35
Length of meander line, L_1	2.0
Width of meander line, W_1	3.3
Total length of the substrate, L	44.5
Total length of line, L	42.0

4. PARAMETRIC ANALYSIS

The objective of the analysis is to have a compact antenna structure for almost the same performance as compared to that of the LPMA with metal patch line length L, with overall substrate length of L_s and width W_g. In this section, the effect of the variation in dimensions of parameters as listed in

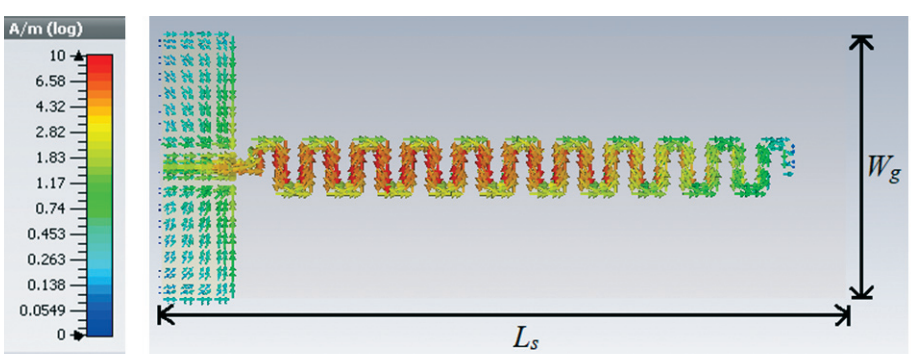


Figure 4. Simulated surface current distribution on MLPMA at 161 MHz.

Table 2 are analysed to observe the antenna performance. For the simulation, one parameter is varied at a time, keeping other dimensions fixed as listed in Table 2.

4.1 Effect of Variation in Meander Section Length

As the meander section length L_1 is increased from 1.8 to 2 cm, the effective resonant length of the antenna increases, decreasing its resonance frequency from 172.7 MHz to 150.8 MHz as shown in Fig. 5(a). The corresponding decrease in reflection coefficient from -14.52 dB to -25.7 dB is due to the improvement in impedance matching, which is clearly seen from the impedance plots, as shown in Fig. 5(b). Also, from the impedance loci plots it is noted that the increase in length between the arms of the U-shaped patch increases corresponding total inductance L_t, which resulted in slight inductive shift and reduction in capacitive effect. L_1 = 2 cm is chosen for reasonably good impedance matching at desired resonance frequency of 161 MHz.

4.2 Effect of Variation in Meander Sections Width

As the meander sections width W_1 is increased from 3.1 to 3.5 cm, the resonance frequency of the antenna decreased slightly as depicted in Fig. 6(a). It is noticed that, this variation of W_1 has not made much effect in reduction of antenna length. This is well justified from the impedance loci plots, as shown in Fig. 6(b). The increase in W_1, increases the length of the U-shaped armswhich results in increase of total capacitance C_t. At the same time, as the patch length increases, the inductive effect is also increased slightly, which leads to compensation of the capacitive effect. W_1= 3.3 cm has been chosen for the desired resonance frequency.

4.3 Effect of Variation in Meander line Width

The variation in line width W is analysed here. The segment of the line width W is a transition between the monopole and a 50 Ω feed width, which directly affects the matching and also the resonance frequency. Fig. 7(a) shows reflection coefficient plots for the variation in W from 0.3cm

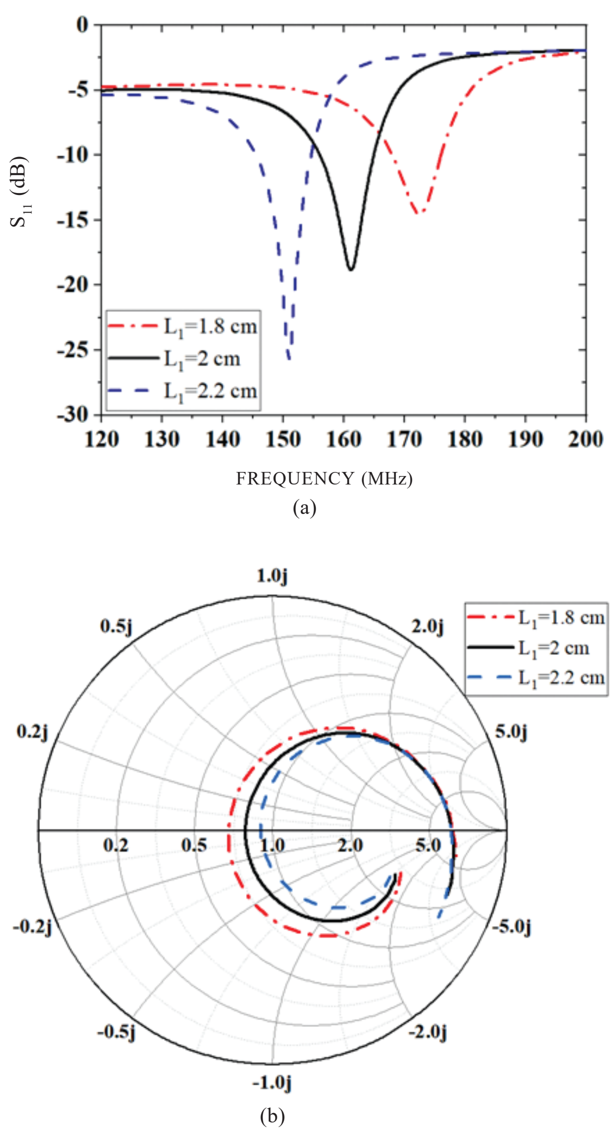


Figure 5. Effect of the variation of driven meander section length W_1 on (a) reflection coefficient S_{11} (dB) and (b) input impedance loci plots.

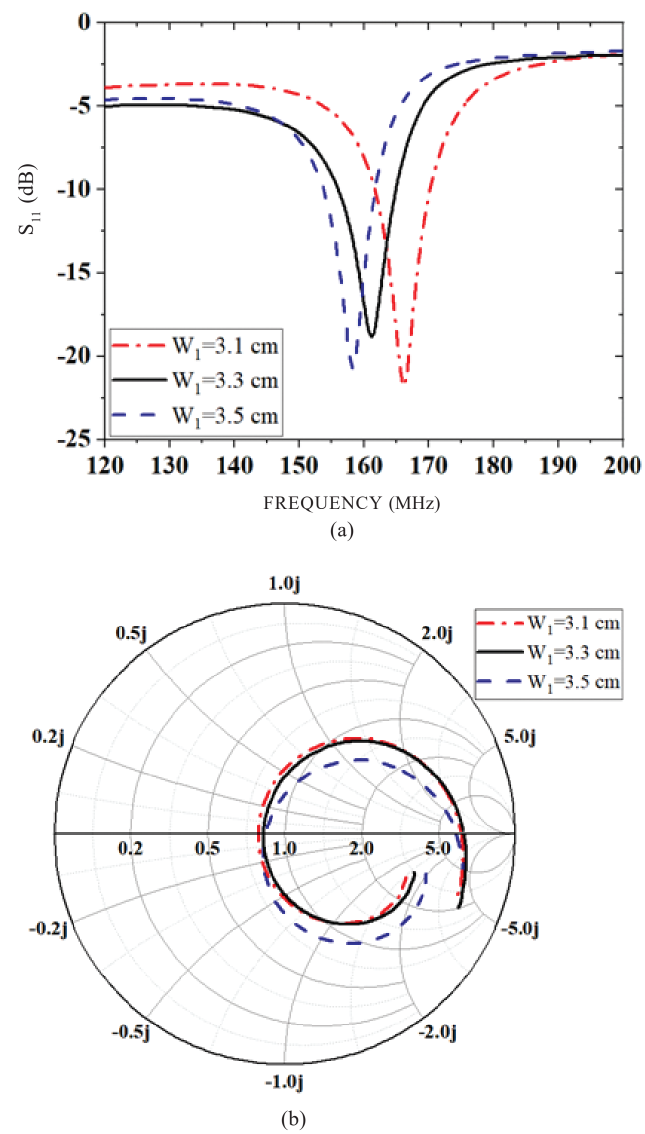
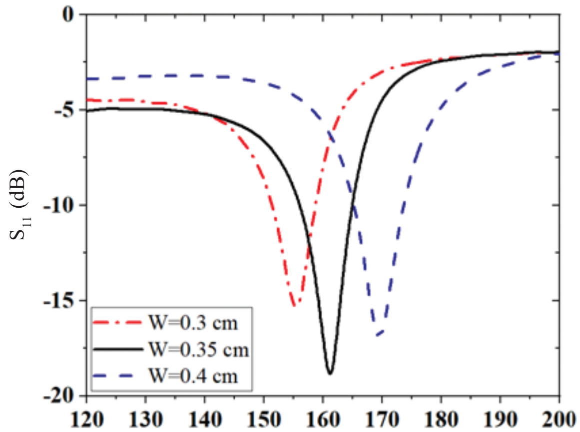
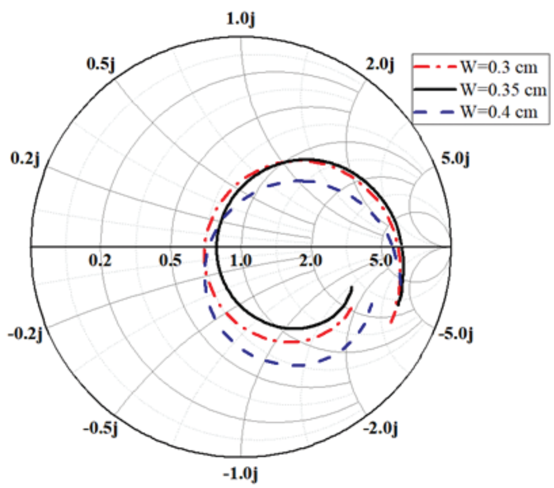


Figure 6. Effect of the variation of the driven meander sections width W_1 on (a) reflection coefficient S_{11} (dB) and (b) input impedance loci plots.



(a)



(b)

Figure 7. Effect of the variation of the driven meander line width W on (a) reflection coefficient S_{11} (dB) and (b) input impedance loci plots.

to 0.4 cm. At W = 0.35 cm, significantly better reflection coefficient value is obtained for the resonance frequency 161 MHz. This is mainly due to the input impedance matching of the monopole line with microstrip feed line, which can also be noticed from input impedance plots as shown in Fig. 7(b).

4.4 Effect of Variation in Ground plane Width W_g and Length L_g

Similarly, the dimension of the ground plane was varied and return loss and input impedance versus frequency were noted. The ground plane length L_g = 4.5 cm and W_g = 17 cm are chosen for good matching at desired resonance frequency and bandwidth (BW) of the antenna.

5. COMPARISON OF SIZE REDUCTION WITH NUMBER OF SEGMENTS

To study the reduction in overall size of the antenna with number of segments symmetrical to the feed line axis (the addition of 'U-shape' segments) into LPMA, dimension of the antenna is optimised for desired frequency of 161 MHz. In Table 3, the number of U-shape segments, overall area, reflection coefficient, and percentage reduction in the size

Table 3. Percentage change in reduction of MLPMA size.

Number of segments (N)	Area (L_s x W_g) cm^2	S_{11}(in dB) at 161 MHz	Reduction in size with respect to LPMA (per cent)
LPMA	60 × 27	-33.4	--
2	57 × 25	-29.3	12.0
4	55 × 23	-27.6	21.9
6	54 × 22.5	-24.8	25.0
8	52 × 22	-22.1	29.4
10	49 × 22.5	-19.3	31.9
12	48 × 20.5	-18.6	39.3
14	47.5 × 19.7	-18.5	42.2
16	47.2 × 18.5	-18.4	46.1
18	45.2 × 18	-18.3	49.8
20	44.7 × 17.3	-18.0	52.3
21	44 × 17	-17.5	53.8
22	43 × 16.5	-13.0	56.0
24	42 × 16	-12.2	58.0

of the MLPMA is given. Addition of every new segment helps reduction in the physical size keeping the resonance length of the line approximately same. With increase in number of segments, the degradation in reflection coefficient value is observed because of increase in discontinuity in the line sections. At N = 21, the reasonably good reflection coefficient value -17.5 dB is obtained with size reduction of 53.8 per cent. Reduction in the size can be further obtained by increasing the segments but the design has to be compromised with further deterioration in reflection coefficient. The overall dimension of the proposed structure with N = 21 is 44.5 × 17 × 0.16 cm^3. In Fig. 8, it can be observed that initially reduction in the size is significant. However, with more number of segments, reduction in size observed to be less significant as the dimension of the U section becomes smaller.

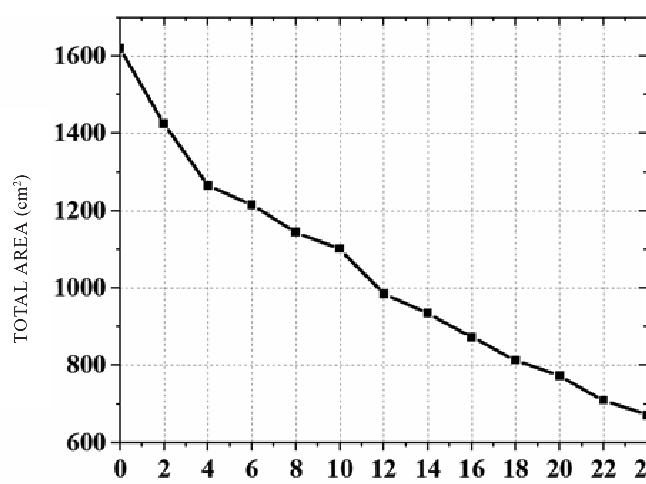


Figure 8. Reduction in area with increase of segments N of the MLPMA.

6. EFFECTS ON THE ANTENNA PERFORMANCE AFTER MOUNTING ON SATELLITE PANEL

The effects of satellite panel on the antenna performance, once it is deployed, has also been investigated. The satellite panels to which the antenna is mounted is considered as perfect ground plane, which will be perpendicular to the plane of the antenna. Different-sized mini and micro-satellite panels ranging from 30×30 cm^2 to 100 × 100 cm^2 are considered[8] and effects have been studied using software simulations. When the ground plane size increases the radiation pattern becomes unidirectional in E-plane, whereas it remains omnidirectional in the H-plane. With minor adjustment in the spacing between satellite body and the feed of the antenna leads to good input match at the centre frequency. The gain of the antenna becomes 2.9 dBi with radiation efficiency of 93 per cent at the centre frequency. The increase in gain is due to increase in radiation in the forward direction.

7. EXPERIMENTAL VERIFICATION

Figure 9 shows the photograph of the fabricated MLPMA with 21 sections of meandered structure obtained through methodology presented in section 4. The proposed antenna is fabricated on a single layer commercially available FR4 substrate. A 50 Ω SMA connector is soldered to the feed line of the antenna, which is backed by ground plane. The properties of antenna are measured in a reflection free environment using Keysight's Fieldfox Microwave analyser (Model No: N9916A) and radiation pattern measurement setup. The comparison of the simulated and the measured reflection coefficient plots are as shown in Fig. 10. The simulated resonance frequency of 161 MHz is in good agreement with measured one of 160.5 MHz. There is a small difference between the simulated and

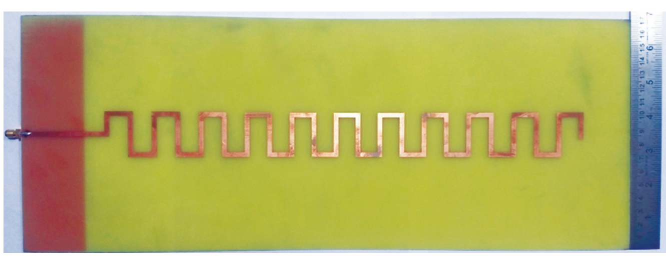


Figure 9. Photograph of the fabricated MLPMA.

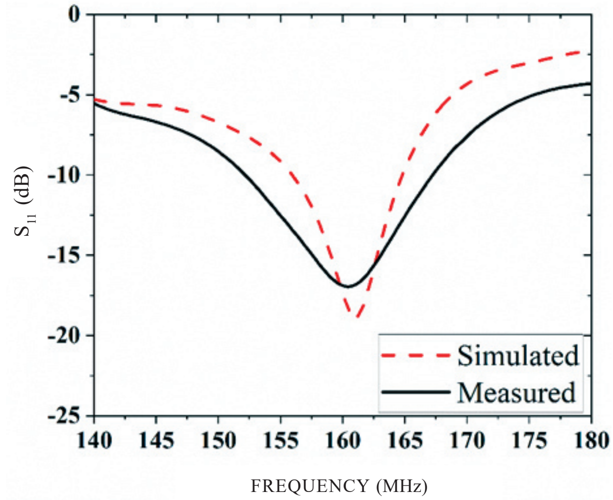


Figure 10. Simulated and measured reflection coefficient S_{11} (dB) of the MLPMA.

the measured values, which is attributed to the dielectric constant difference of the commercially available FR4 substrate, fabrication and measurement errors. The measured BW is 15 MHz, which is higher than simulated BW of 8.9 MHz. The measured value of reflection coefficient at the 161 MHz is slightly high, which dampens the resonance increasing the BW. Figure 11 compares the simulated and measured normalised radiation patterns in E and H plane at 161 MHz. In both the planes, the co-polarisation levels are much stronger than their respective cross-polarisation level by greater than 40 dB. In the E-plane, the radiation pattern is a 'Figure of 8', where as in the H-plane, it is an omnidirectional. There is reasonable agreement between simulated and measured radiation patterns with the measured beam-width of 82°, while the simulated value is 84°. The gain of the antenna measured at 160.5 MHz is 1.87 dBi which is 1.8 dBi in simulation. These characteristics of the proposed MLPMA meets requirements of the SB-AIS, which requires vertical polarisation, low gain (around 1.5 dBi) and wide beam-width. The wide beam-width keeps the satellite and on-board ship antenna in beam, irrespective of the pitching and rolling of a ship due to adverse sea conditions[2].

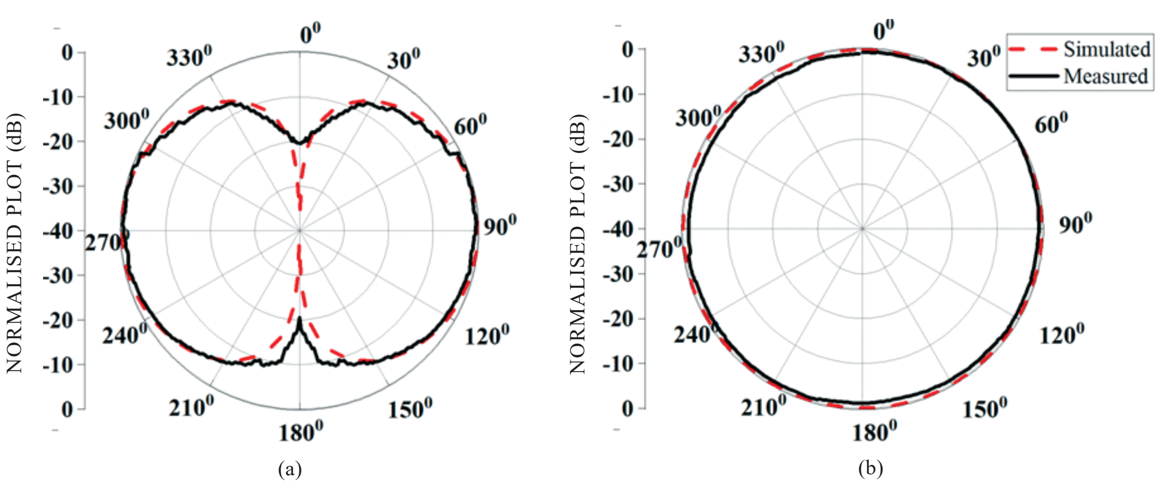


Figure 11. Simulated and measured radiation patterns of the MLPMA in (a) E-plane (b) H-plane.

Table 4. Performance comparison with reported configurations for SB-AIS application

Ref.	Antenna configuration	Gain (dBi)	Dimensions (H×W) cm^2	Comment
[4]	Wired monopole antenna	2.14	NG	Requires support to deploy it to be straight
[5]	CFRP helical antenna	NG	H= 400	Bulky, Needs special mechanism for maintaining stability
[7]	Array of patch antennas	2.45	50 × 50	Bulky, Needs high precision while fabrication
[9]	Short monopole capacitively coupled to shortened quarter-wavelength printed line	-11.6	1 × 9	Bulky, very low gain
Proposed	MLPMA	1.87	44.5 × 17	Simple, low-profile, light

The performance of the proposed MLPMA is compared with earlier reported configurations as shown in Table 4. It has been observed that, the proposed antenna has simple structure, occupies relatively small space. The gain is relatively low but it satisfies SB-AIS requirements.

8. CONCLUSIONS

A compact printed monopole antenna is proposed for satellite based AIS applications in this paper. By meandering the conductor of the monopole, the overall size of the antenna is reduced. The reduction in size of about 53.8 per cent is obtained as compare to conventional SLMA with similar characteristics at 161 MHz. The prototype of the proposed antenna is fabricated and results are validated. Experimental results shows that the antenna possesses omnidirectional radiation pattern in azimuthal plane, making it suitable for SB-AIS on-board application.

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In the current study, he helped in the fabrication and measurements. He has also carried out data collection and writing manuscript with inputs from all authors.

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In the current study, he simulated the design using CST microwave studio simulation tool and optimised design parameters. He also evaluated hardware performance and compared results.

Mr Rahul Keley received BTech (Electrical and Electronics) from Naval College of Engineering, Lonavala, India and MTech (Radar and Communication) from DRDO-Defence Institute of Advanced Technology, Pune. Currently, he is a serving officer in Indian Navy. His area of research involves: Microstrip antennas, AIS systems, conformal antennas.
In the current study, he carried out pilot studies, collected initial data and carried out initial analysis. He also provided statistical advice and overall guidance required in execution of experiments.

Dr K.P. Ray is MTech (Microwave Electronics) from University of Delhi and PhD from Department of Electrical Engineering IIT, Bombay. Presently he is a Professor, Dean Research and head of the Department of Electronics Engineering, Defence Institute of Advanced Technology, Pune. He worked in the areas of RF and microwave systems/components and developed expertise in the design of antenna elements/arrays and high power RF/microwave sources for RADAR and industrial applications. He has published over 350 research papers in journals and conference proceedings. He holds 3 patent and filed three patent.
In the current study, he conceived the idea of the proposed compact printed antenna for SB-AIS and finalised antenna specifications, formulated procedure for optimisation of the design, guided in measurements and approved the final result and manuscript.