Low-Profile Log-Periodic Monopole Array

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Low-Profile Log-Periodic Monopole Array

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***Abstract*—This paper presents a low-profile log-periodic monopole array antenna with end-fire radiation and vertical polarization. It consists of 15 monopole elements and a conductor-backed coplanar strip line as the feeding line. The monopoles are of the same height but loaded with top hats of different sizes to achieve the required resonant frequencies. A wideband transition from coaxial line to conductor-backed coplanar strip line is designed for the antenna feed. A prototype is fabricated and tested. Measured results show that an impedance bandwidth from 1.5 to 6.8 GHz (4.53:1) for VSWR <2.3 and a gain better than 4.5 dBi over the same operating frequency band are obtained while the antenna has a very low profile of only $0.047\ \lambda_L$ (λ_L is the free-space wavelength at the lowest operating frequency).**

***Index Terms*—End-fire radiation, log-periodic antenna, top-hat monopole.**

I. Introduction

IT HAS BEEN A challenge in recent years to design low-profile end-fire antennas with wide bandwidth and vertical polarization for communication systems used in aircrafts and vehicles. In these systems, there is usually a mounting platform of a large ground plane but the profile in the vertical direction is highly restricted due to aerodynamic and mechanical requirements. Only a few antennas are promising for such applications. Surface-wave antennas [1]–[4] are good candidates for end-fire radiation with wideband and vertical polarization. In [3], a flush-mounted surface-wave antenna was designed and a 4:1 impedance bandwidth for VSWR < 2 was achieved with an antenna height of $0.127\lambda_L$. However, its transverse dimension is very large ($1.54\ \lambda_L$), leading to an incompact structure. Recently, a surface-wave antenna employing a grounded ceramic slab ($\varepsilon_{r2} = 25$) was presented [4] and a low profile of $0.065\lambda_L$ was achieved due to the very high dielectric constant of the ceramic material used. A bandwidth of 2.95:1 was obtained by using a wideband surface-wave launcher. In [5], an H-plane ridged SIW horn antenna mounted on a large conducting plane was proposed. A wideband transition from a coaxial probe to SIW with three-step ridge was utilized to feed the horn antenna. An arc-shaped horn aperture loaded with dielectric was used to achieve a wideband of the antenna. The proposed antenna provided a 2.73:1 bandwidth with an antenna height of $0.07\lambda_L$. However, the antenna structure is a little complicated and the fabrication of the three-step ridge and the cone-shaped feeding pin inside SIW is difficult.

As one type of frequency-independent antennas, the log-periodic monopole antenna naturally has a wide bandwidth, can readily realize end-fire radiation, and is particularly suitable for being mounted on a large metallic platform. However, the height of conventional log-periodic monopole antenna is around $\lambda_L/4$ while the dipole version is around $\lambda_L/2$. Log-periodic monopole antennas have been investigated for many years since the pioneering work of Isbell [6]. In order to reduce the height of the log-periodic monopole antennas, a lot of techniques have been proposed. Typically, the arms of the antennas are meandered to minimize the physical dimension of the antenna [7]–[10]. In [7], a log-periodic dipole antenna with folded dipole element was designed and the reduced antenna arm length (half length of the longest dipole element) is $0.115\ \lambda_L$. In [9], a second-order Koch-fractal dipole antenna was proposed and the arm length of the miniaturized antenna is $0.167\ \lambda_L$. Another method to shorten the antenna arm length is through loading [11]–[15]. In [12], a T-top loaded dipole array antenna with an arm length of $0.125\ \lambda_L$ was presented. These techniques can reduce the arm length of the antenna, but the monopole array is not planar and may not be flush-mounted onto a metallic platform.

The top-hat loading of a monopole is known as a capacitive loading that helps to lower the resonant frequency and generate a more uniform current on the vertical post, resulting in an improved radiation resistance compared with a monopole of the same height without top loading. However, the resonant resistance is reduced due to its shortened antenna height. McLean [16] proposed a simple equivalent circuit model to estimate the impedance of a monopole loaded with a circular top hat. It is valid from dc, through the series resonant frequency, and nearly to the parallel resonance, showing a good agreement with experimental results. We recently designed a Yagi monopole antenna, which employed one driven and four parasitic top-hat monopoles to achieve unidirectional radiation. All the five elements are of the same height of $0.033\ \lambda_L$ [17], while achieving a broad bandwidth of 20.5%.

The low-profile log-periodic monopole antenna presented in this paper consists of 15 monopoles loaded with top hats of elliptical shape and the array is fed by a conductor-backed coplanar strip line. The monopoles are designed with identical heights, which are made possible by using different dimensions for the top-hats. The width of the coplanar strip line is varying along the way to achieve a good impedance match for the entire array. Two resistors are loaded at the end of both strip lines to absorb the residue power. A wideband transition

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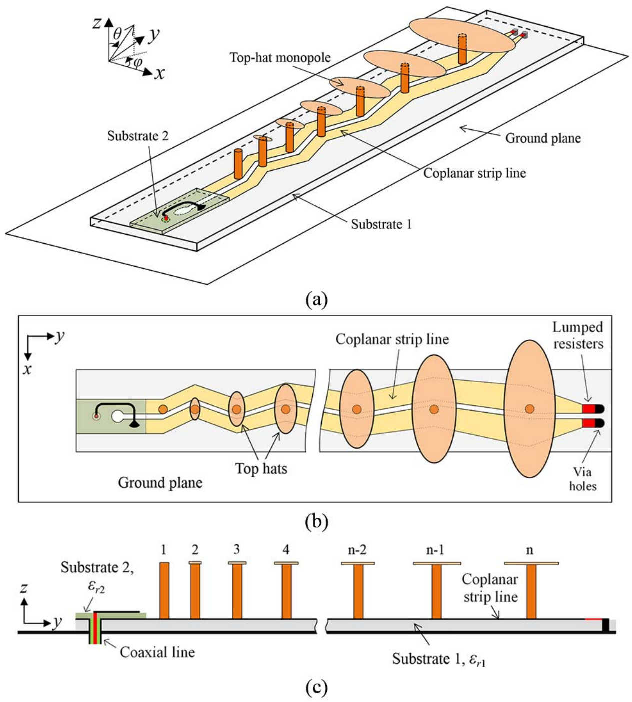


Fig. 1. Configuration of the proposed low-profile log-periodic monopole array antenna. (a) Perspective view. (b) Top view. (c) Side view.

from the coaxial line to the conductor-backed coplanar strip line is designed to feed the antenna. Our proposed log-periodic antenna has an obvious advantage that all the monopole elements are of the same height of $0.047\ \lambda_L$, resulting in a very low-profile and compact quasi-planar structure. In addition, it provides a wide bandwidth of 4.53:1 for VSWR < 2.3 and a gain better than 4.5 dBi over the entire operating band, showing its potential to be useful for aircrafts and unmanned aerial vehicles.

II. Description of the Array Antenna

The configuration of the proposed low-profile log-periodic monopole array antenna is shown in Fig. 1. It consists of 15 ($n = 15$) monopoles loaded with hats of different size and a coplanar strip line printed on the top layer of a conductor-backed substrate is employed to feed the monopole array. The monopoles are of the same height and aligned along a straight line to guarantee a nearly symmetric radiation pattern along the end-fire direction. The top hats are made to be of elliptical shape to avoid the overlap between two adjacent elements at low operating frequencies. The coplanar strip line is slightly bended to alternately feed the monopole elements so that a phase difference of 180° can be naturally satisfied between two adjacent elements across the slot of two strip lines. Two lumped resistors both of 100 ohms are used to absorb the residual power at the end of the strip lines. A wideband transition is designed from a coaxial line to the coplanar strip line to facilitate the measurements. The commercially available software ANSYS high frequency structure simulator (HFSS) is used for simulation in this paper.

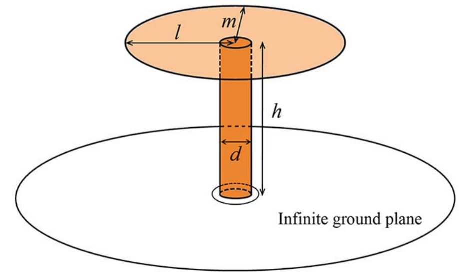


Fig. 2. Configuration of the top-hat monopole.

III. Design Considerations

The profile of a conventional log-periodic monopole antenna is determined by the height of the longest post, which is around a quarter wavelength at the lowest operating frequency. In order to significantly reduce the antenna profile, all the longer posts should be shortened. Our proposed low-profile antenna is unconventional since the heights of all the vertical posts are forced to be the same as that of the shortest one by invoking different loadings at the top end of the posts operating at different frequencies. The proposed monopole arrays hence exhibits advantages of low-profile and a quasi-planar structure. However, the radiation characteristics of the top-hat monopole should be different for different loadings, which may lead to matching problems and will be discussed in the following sections.

A. Top-Hat Loading

The array element of the proposed antenna is a top-hat monopole, as shown in Fig. 2. It consists of a vertical post of diameter d and height h, and is loaded with a top hat of elliptical shape. The long and minor axis of the hat are represented by $2l$ and $2m$, respectively. In order to simplify the element structure, we fix the ratio m/l as K for all the top hats, which are represented by l_i and m_i ($i = 1,\ 2,\ \ldots,\ n$).

The impedance characteristic of a monopole loaded with a top hat of circular shape can be estimated using the equivalent circuit model in [16]. It is noted that our monopole employs a top hat of elliptical shape and the main difference from the circular hat is the capacitance introduced by the top hat where the area of the hat plays an important role. The area of an ellipse is known as

$$s_{ell} = \pi l m \tag{1}$$

Substituting (1) into the formula representing the parallel plate capacitance C_a between the hat and the ground plane in [16], we obtain

$$C_a = \frac{\varepsilon_0 \pi l m}{h} \tag{2}$$

where $1 < l/h < 10$. The relationship between the top hat size and the resonant frequency as well as the resonant resistance of a top-hat monopole is shown in Fig. 3. It is seen that the resonant frequency can be lowered greatly by employing a large top hat loading at a given post height, indicating the possibility of forcing all the elements of a traditional log-periodic

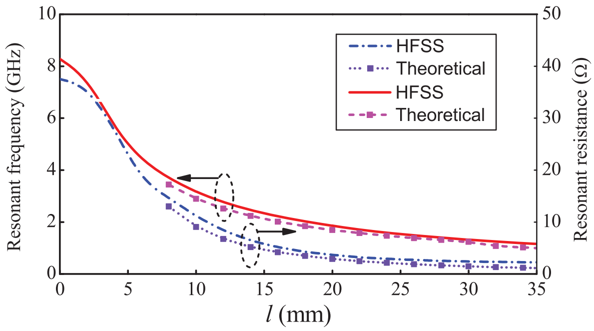


Fig. 3. Relationship between the top hat size and the resonant frequency as well as resonant resistance of the top-hat monopole in free space ($h = 8$ mm, $d = 1.6$ mm, $K = 0.4$).

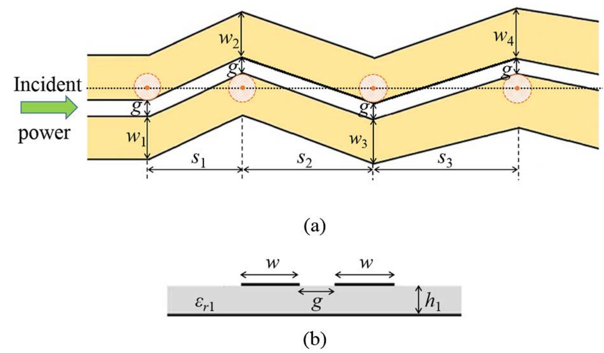


Fig. 4. Configuration of the conductor-backed coplanar strip line. (a) Top view. (b) Cross section.

monopole antenna to be of the same height. However, the resonant resistance is apparently decreased with the increase of the hat size. For example, a monopole with no top loading resonating at 8.2 GHz has a resonant resistance of 36.5 Ohms. By increasing the top hat size, the resonant frequency can be shifted to 2.05 GHz, with a resonant resistance of 4.3 Ohms. If a 4:1 impedance bandwidth is the design target, the resonant resistance of the largest element itself is nearly 1/9 of the smallest element.

Even though it is difficult to theoretically calculate the radiation resistance R of the final monopole array since the mutual impedance also plays an important role to determine R, it is expected that R at the lower frequency band is lower than that at the higher frequency band. The feeding line should therefore be tapered with lower characteristic impedance for matching of the antenna.

B. Log-Periodic Array

The log-periodic array is known as a frequency-independent antenna whose physical dimensions vary periodically with the logarithm of frequency. The active region of the antenna is near the elements whose lengths are around $\lambda/4$ and the role of active elements is passed from the longer to the shorter elements as the frequency increases. The energy from the active region traveling toward the longer inactive elements decreases rapidly so that very little energy is reflected from the truncated end. The shorter elements before the active region acts as shunt capacitive loading of the feeding line, forming the transmission region. The currents on the consecutive monopoles in the transmission region are in the opposite direction, contributing little to the overall radiation.

A log-periodic monopole array antenna having n elements (the longest monopole is the nth element) can be briefly described by a scaling factor τ and a spacing factor σ [6], [18], and

$$\tau = \frac{f_{i+1}}{f_i},\ \sigma = \frac{s_i}{4l_{i+1}},\ i = 1,\ 2,\ 3, \ldots,\ n \tag{3}$$

where f_i is the resonant frequency of the ith element and s_i is the spacing between the ith and the $(i+1)$th elements. l_i is the length of the ith element. The gain of a log-periodic monopole array is determined when τ and σ are given. A relatively higher gain can be obtained by choosing higher values of τ and σ. However, it leads to a larger antenna size and more elements. The scaling factor of the final log-periodic monopole array antenna τ is chosen as 0.88, with 15 elements in total. The initial spacing factor σ is chosen as 0.08, which together with τ will result in a gain of around 10.6 dBi for a conventional log-periodic monopole array [18]–[21].

C. Feeding Structure

For a log-periodic monopole antenna, an alternating feeding is required to achieve the backward end-fire radiation in the direction of the shorter monopoles. Typically, a microstrip line is adopted to feed the monopole array by optimizing the length of the strip between two adjacent elements to achieve the required phase difference [22]. In such a case, the microstrip line is usually longer than the element space and is necessarily bent to meet the required phase requirement, leading to an increased space occupation in the plane perpendicular to the monopoles.

In this paper, we employ a new conductor-backed coplanar strip line as the feeding line of the antenna, as shown in Fig. 4. It is slightly bent to be alternately connected with the vertical posts, which are aligned along a straight line to achieve nearly symmetric far-field radiation patterns and spaced by $s_1,\ s_2,\ \ldots,\ s_{14}$. The width of each strip section is linearly varied from w_1 to w_{15}. The gap between the strips is represented by g.

The currents on the two strips of the coplanar strip line are naturally out of phase when it is operating in its odd mode. Its characteristic impedance is determined by the strip width w, the gap g, the thickness h_1, and dielectric constant ε_{r1} of the substrate [23]. Fig. 5 shows the characteristic impedance of a coplanar strip line backed by a conductor. It is seen that the strip width acts as a more important role than the gap between the strips. Therefore, we vary the strip width instead of the gap to alter the characteristic impedance of the conductor-backed coplanar strip line to feed the final monopole array. The substrate thickness also affects the impedance significantly. If the impedance of the conductor-backed coplanar strip line is given, a narrower strip is used with a thinner substrate. For example, to achieve a 100-Ω line impedance ($g = 1$ mm), the strip width should be 4.1, 1.58, and 0.8 mm with a substrate of thickness

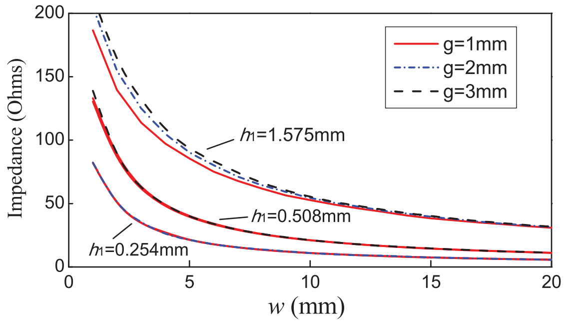


Fig. 5. Characteristic impedance of the conductor-backed coplanar strip line ($\varepsilon_{r1} = 2.2$).

1.575, 0.508, and 0.254 mm, respectively. Considering that the vertical posts of the monopoles are to be connected to the strips, the strip width should be at least equal to or a little larger than the post diameter.

D. Wideband Transition

A wideband transition from a coaxial line to the conductor-backed coplanar strip line is designed to excite the required mode of the coplanar strip that feeds the antenna, as shown in Fig. 6. It is a three-layered structure with an open-ended microstrip line on the top layer, a short-circuited coplanar strip line in the middle layer, which is then backed by a large ground plane on the bottom layer. The microstrip line is etched on the top substrate of dielectric constant ε_{r2} and thickness h_2, with a radial stub represented by a flare angle α and radius r_2. The coplanar strip line, etched on the bottom substrate of dielectric constant ε_{r1} and height h_1, is shorted at one end with its gap ended in a round shape of diameter r_1. A coaxial line of 50 Ohms protrudes into both substrates, with the inner conductor connected to the microstrip line of the same characteristic impedance on its end, and the outer conductor connected with both the ground plane and the shorted portion of the coplanar strip line. The electromagnetic energy traveling along the microstrip line is then coupled to the coplanar strip line by making the microstrip line going across the gap of the coplanar strip line.

The proposed transition can be considered as a two-port network, as shown in Fig. 6(d). If a uniform microstrip of length l_{mic} and a uniform conductor-backed coplanar strip stub of length l_{cbcps} are used, the lengths of both stubs should be $\lambda_g/4$ (λ_g is the guided wavelength of the microstrip line or the coplanar strip line) at the central operating frequency [24]. However, since the stubs are made nonuniform in this design to achieve a wider bandwidth and an improved flatness of the frequency response, the dimensions of the stubs should be optimized. The design procedures of the transition are given below.

1) Parameters of the substrate of the coplanar strip line are determined first. Since the coplanar strip line is used as the feeding line of the array, a substrate with a low dielectric constant of $\varepsilon_{r1} = 2.2$ and a low loss tangent of around 0.0009 over the operating band is chosen to minimize the material loss.
   On the other hand, according to [21], employing a feeding line with a relatively high characteristic impedance results in a higher radiation efficiency of the log-periodic dipole array. For the dipole array with $\tau = 0.88$, using a feed line with an impedance larger than 80 Ohms, can achieve a radiation efficiency higher than 95%. Although our proposed log-periodic monopole antenna uses a novel planar structure, the impedance of the employed feed line should still be chosen as high as possible. A substrate of thickness $h_1 = 1.575$ mm is selected considering the fact that the strip width will be very small if a very thin substrate is used, making it difficult to solder the post onto the strip based on Fig. 5.
2) A top substrate with a high dielectric constant of $\varepsilon_{r2} = 10.2$ is selected as the base of the microstrip line, which can help to suppress the leakage from the parallel plate mode at the coupling portion according to [25], and the top substrate thickness should be larger than 0.2 mm. A very thin substrate of thickness $h_2 = 0.64$ mm is selected to achieve a minimal discontinuity at portion 2-2′. The width of the 50-Ohm microstrip line is calculated as 0.6 mm.
3) The impedance match and operating bandwidth of the transition shall be determined by the dimensions of the radial stub of the microstrip line, the shorted portion of the coplanar strip line, and the spacing between them. A good performance can be achieved by some parametric study and a simple optimization.

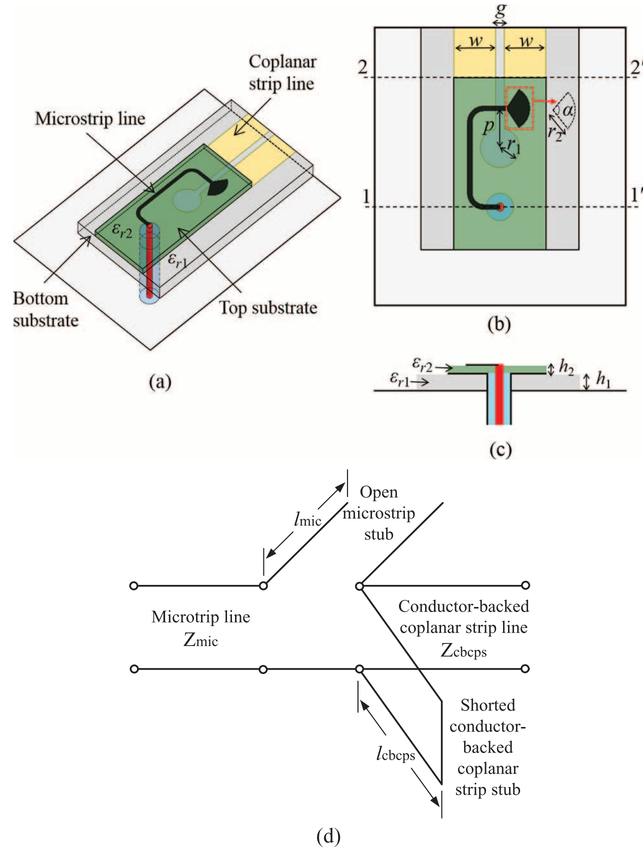


Fig. 6. Configuration and a simplified equivalent circuit model of the proposed wideband transition from the coaxial line to the conductor-backed coplanar strip line. (a) Perspective view. (b) Top view. (c) $1 - 1'$ cut plane. (d) Equivalent network.

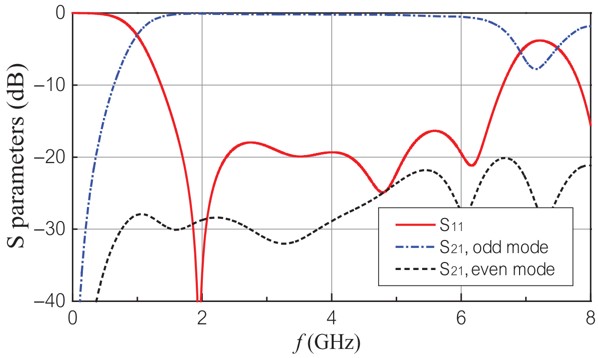


Fig. 7. S-parameters of the proposed wideband transition from coaxial line to conductor-backed coplanar strip line ($h_1 = 1.575$ mm, $h_2 = 0.64$ mm, $\varepsilon_{r1} = 2.2$, $\varepsilon_{r2} = 10.2$, $g = 1$ mm, $w = 6.5$ mm, $p = 5$ mm, $r_1 = 3$ mm, $r_2 = 3.4$ mm, $\alpha = 120°$).

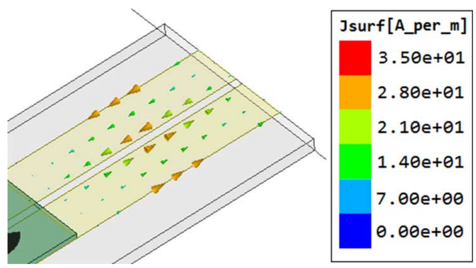
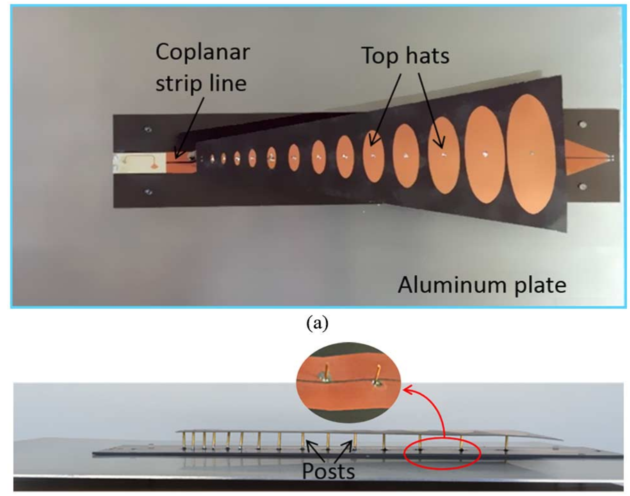


Fig. 8. Current distribution on the coplanar strip line of the transition.

Fig. 7 shows the S-parameters of the proposed wideband transition from a coaxial line to conductor-backed coplanar strip line. In the frequency range from 1.37 to 6.4 GHz, the reflection coefficient is better than -10 dB and the odd mode insertion loss is better than 1 dB. The even mode transmission is lower than -20 dB over the same band. Fig. 8 shows the current distribution on the coplanar strip line of the transition. It can be clearly seen that the currents on each side of the coplanar strip line are out of phase, demonstrating again that the coplanar strip line is working well in the expected odd mode for the antenna feed.



(a)

(b)

Fig. 9. Photo of the fabricated low-profile log-periodic monopole antenna. (a) Top view. (b) Side view and a large view of the connection of the vertical posts to the feeding line.

TABLE I
OPTIMIZED DIMENSIONS OF THE FABRICATED WIDEBAND LOW-PROFILE LOG-PERIODIC ANTENNA

Parameter	Value (mm)	Parameter	Value (mm)	Parameter	Value (mm)
h	8	w_{11}	15.8	m_{14}	29.9
h_1	1.575	w_{12}	16.7	m_{15}	35
h_2	0.64	w_{13}	17.6	s_1	5.0
p	5	w_{14}	18.1	s_2	5.8
g	1	w_{15}	18.3	s_3	7.2
r_1	3	m_1	0	s_4	8.5
r_2	3.4	m_2	1.3	s_5	9.5
d	1.6	m_3	2.8	s_6	12
w_1	6.5	m_4	3.6	s_7	14
w_2	6.6	m_5	4.5	s_8	15.7
w_3	8	m_6	5.7	s_9	16.9
w_4	9	m_7	7	s_{10}	17.8
w_5	9.9	m_8	8.6	s_{11}	20.3
w_6	10.8	m_9	10.6	s_{12}	23.7
w_7	12.2	m_{10}	13.5	s_{13}	25.5
w_8	13.1	m_{11}	16.6	s_{14}	29
w_9	14	m_{12}	20.4		
w_{10}	14.9	m_{13}	24.5		

IV. EXPERIMENTAL VERIFICATION

A prototype of the proposed log-periodic monopole antenna is fabricated and tested, as shown in Fig. 9. An aluminum plate of size 420 mm × 240 mm (2.1 $\lambda_L \times 1.2\ \lambda_L$) is employed as the platform of the antenna. Two lumped resistors of 100 Ohms are soldered at the end of the feeding line to absorb the residual power. A substrate of thickness 0.254 mm and dielectric constant 2.2 is used as the base of the 15 top hats. Copper posts are used to connect the top hats and the coplanar strip line printed on another substrate placed right above the aluminum plate. Spacings between the elements are optimized to achieve a good impedance match over the operating band. The final parameter values are $K = 0.4$, $\varepsilon_{r1} = 2.2$, $\varepsilon_{r2} = 10.2$, $\alpha = 120°$, and others can be found in Table I.

The simulated and measured reflection coefficients of the low-profile log-periodic monopole antenna are shown in Fig. 10. It is seen that the measured VSWR is lower than 2.3 from 1.5 to 6.8 GHz while the simulated one is smaller than 2 from 1.5 to 6.6 GHz. The slight difference between them may be attributed to the fabrication and assembly errors. Generally speaking, a very good agreement is achieved between simulated and measured VSWR results.

Fig. 11 shows the simulated and measured radiation patterns of the proposed antenna. It can be seen that the measured co-polarization patterns agree well with the simulated ones. The measure cross-polarization patterns are a little worse than simulated ones at some frequencies, which may be due to the improper soldering of the vertical posts. However, they are still better than -10 dB over the operating band. It may be mentioned here that the main radiation beam is quasi end-fire because of the finite ground plane used. A truly end-fire radiation can be obtained only when the proposed antenna has an infinitely large ground plane. Fig. 12 shows the simulated and measured gain and simulated radiation efficiency of the

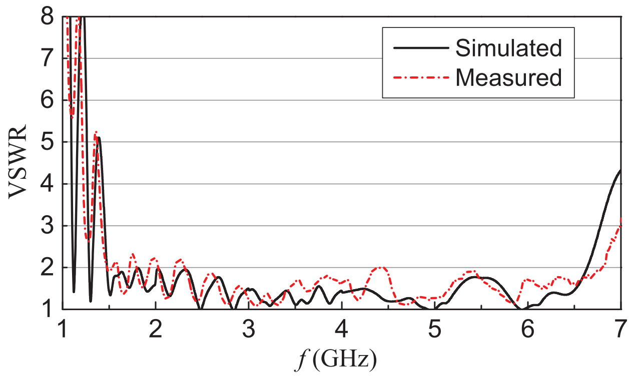


Fig. 10. Simulated and measured VSWRs of the low-profile log-periodic monopole antenna.

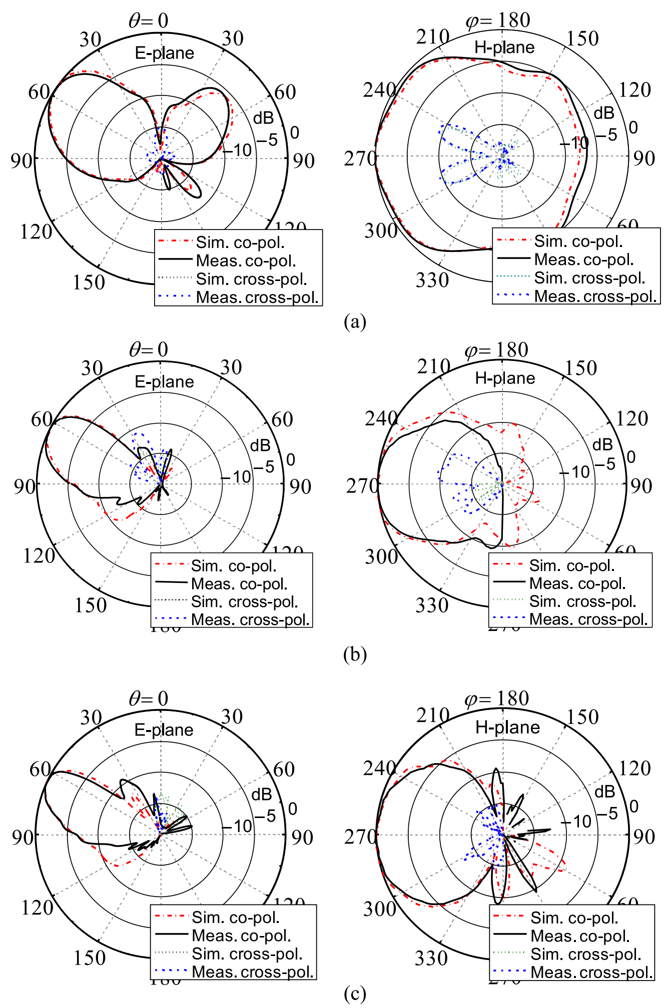


Fig. 11. Simulated and measured normalized radiation patterns of the low-profile log-periodic monopole antenna. (a) 1.5 GHz. (b) 3 GHz. (c) 6 GHz.

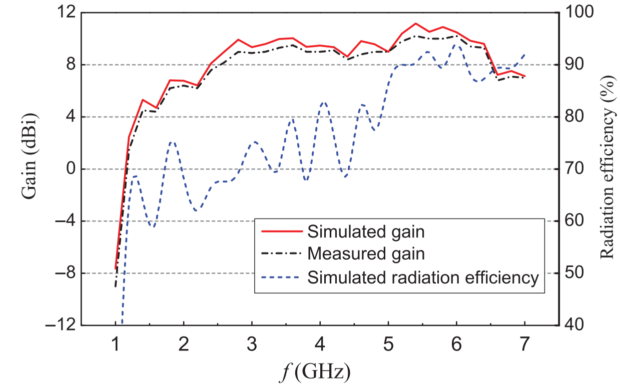


Fig. 12. Simulated and measured gains and simulated radiation efficiency of the low-profile log-periodic monopole antenna.

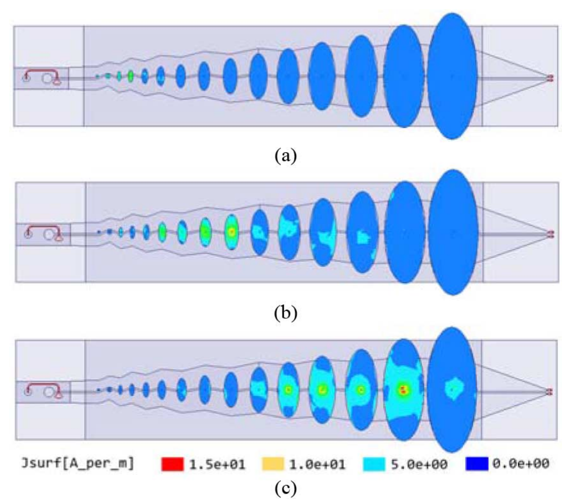


Fig. 13. Simulated current distribution (magnitude) on the top hats of the low-profile log-periodic monopole antenna. (a) 6 GHz. (b) 3 GHz. (c) 1.5 GHz.

antenna. It is seen that the measured gain is better than 4.5 dBi over the operating band with a maximum value of 10 dBi. The radiation efficiency is a little lower at the low frequencies as expected. However, an average value of 75% is obtained over the entire frequency band. It may be mentioned that our proposed array is different from conventional log-periodic arrays in terms of gain and radiation efficiency fluctuations. The gain of our proposed array is relatively low at low frequencies due to the larger absorptions at the array end and smaller radiation resistance of the loaded monopole in lower frequencies.

Fig. 13 shows the simulated current distributions on the top hats of the monopoles. It is seen that the active region of the array moves toward the monopoles with larger hats when the operating frequency decreases, as expected. There are about four active elements strongly excited at each of these three frequencies though other neighboring elements around the active region may also have a slight contribution to the array's radiation.

Table II shows a comparison between existing designs in the literature and our design. It should be mentioned that log-periodic dipole antennas in [7], [9], and [12] with low profile are also involved in the comparison considering that they have the possibility to be transformed into log-periodic monopole structures. It is obviously seen that our design provides the lowest profile among all these wideband vertically polarized antennas with end-fire radiation. The bandwidth of the antenna presented in [7] is wider than our proposed antenna. However, our design has a unique quasi-planar structure and can readily be made conformal.

TABLE II
COMPARISON OF WIDEBAND LOW-PROFILE ANTENNAS WITH END-FIRE RADIATION AND VERTICAL POLARIZATION

Reference	VSWR	Bandwidth	Gain (dBi)	Height (λ_L)
[7]	< 2.6	10:1	1.9–7.2	0.115
[9]	<1.93	4:1	4.3–8.3	0.167
[12]	<1.93	1.6:1	7–9.5	0.125
[4]	< 2.0	2.95:1	4–12	0.065
[5]	< 2.5	2.73:1	1.5–14	0.07
Our work	< 2.3	4.53:1	4.5–10	0.047

V. CONCLUSION

A wideband log-periodic monopole array with a very low profile of 0.047 λ_L, wide bandwidth of 4.53:1, and end-fire radiation has been presented. The monopole elements of the antenna are made of the same height by employing different top hat loadings. A wideband transition from the coaxial line to the conductor-backed coplanar strip line has been designed to feed the antenna array. A prototype of the antenna has been fabricated and tested. Measured and simulated results are in good agreement. The proposed antenna has a number of attractive features such as very low profile, planar structure, wide bandwidth, and light weight. It, therefore, should be potentially very useful in vehicular and airborne communication systems.

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