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Bandwidth Enhancement for Low Frequency Meander Line Antenna

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Abstract—A simple and effective method of bandwidth enhancement for the printed meander line antenna (MLA) is proposed. This approach is characterized by symmetrically printing two meandering sections on both sides of a dielectric substrate and connecting them via shorting pins at the bottom of meandering sections, which are connected to a capacitive stripe for impedance matching. The illustrative equivalent circuit and the corresponding principle of bandwidth enhancement of this double-layered MLA are presented. The measured results of these double-layered and single-layered MLAs manifest the validity of our design approach.

1. INTRODUCTION

Miniaturization of antennas is highly in demand in modern wireless communication systems. This required characteristic poses challenge, especially when operated at low frequency, to the antenna engineers in some applications where omnidirectional radiation, broadband operation and relatively high gain are also desired simultaneously, thus arouses wide range of interest of many researchers [1–7]. MLA is an attractive candidate for a miniaturized antenna with omnidirectional radiation, considerable radiation efficiency and negligible cross polarization [8–10]. A MLA is constructed by continuously folding a conventional monopole/dipole antenna, which can also be printed on a dielectric substrate as a planar form. The resonant frequency and radiation efficiency of MLA can be approximately determined from the geometrical parameters using the equivalent model of a linear dipole antenna with inductive loading [11–13]. However, this conventional MLA exhibits a narrow impedance bandwidth and sensitive impedance matching [10, 12]. Some methods were proposed in the reported literature [14–17] to broaden the bandwidth of MLAs. A double rectangular loop structure was applied in [14] for bandwidth enhancement as well as size reduction, but this type of MLA is inconvenient to fabricate. In [15], a rectangular loop was loaded between the meandering sections and feed line to increase the impedance bandwidth. However, the overall height of this modified MLA is relatively high. A MLA consisting of two stripes, which was fed at the bottom of one stripe and grounded at the bottom of the other stripe, was proposed in [16]. This configuration produced a balance mode contributing to the impedance matching and an unbalance mode giving rise to the radiation. Hence, the impedance bandwidth can be broadened under some specified condition. Additionally, by employing the ascendant tapered configuration, the MLA can also effectively achieve wideband performance [17].

In this paper, an effective approach for bandwidth enhancement of low frequency MLA is presented. This novel method is mainly based on the quality factor theory of electronically small antennas and realized by linking two meandering stripes of MLA via shorting pins. In addition, a capacitive stripe is combined for impedance matching instead of an external matching network [18]. The illustrative equivalent circuit and the corresponding principle of bandwidth enhancement of the improved MLA are presented. Prototypes of single-layered and double-layered MLA are fabricated, and the measured results validate the effectiveness of this proposed approach.

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2. ANTENNA DESIGN AND ANALYSIS

2.1. Conventional Meander Line Antenna

The design of wideband MLA evolves from the conventional MLA (MLA1), whose configuration is shown in Fig. 1 (MLA1). The fundamental resonance of conventional MLA comes from the self-resonance of effective inductance and capacitance, where the input reactance equals zero, and the reactance slope is positive. The effective inductance can be primarily attributed to the self-inductance of the meandering sections, whereas the effective capacitance can be primarily attributed to self-capacitance between each meandering turns and capacitance existing between the meandering sections and ground plane [19]. The critical design parameters of conventional MLA include the width of the meander line (W_L), meander spacing (W_S), number of turns in the meander section (N), and overall antenna width (W). The first resonance of conventional MLA often produces very small input resistance, requiring impedance matching technique such as parallel matching stub, reactive network or impedance transformer, to be matched with 50 ohm feed line [20].

Parallel matching stub is applied here to demonstrate the performance of impedance-matched conventional meander line antenna, whose configuration is shown in Fig. 1 (MLA2). A shorting pin is employed to connect the parallel stub to the ground plane. These two MLAs are modeled and simulated in ANSYS HFSS software package, and their primary structural parameters are listed in Table 1 with other relevant parameters given as: the thickness of FR4 dielectric substrate ($\varepsilon_r = 4.4$) $h_d = 1.6$ mm; the width of feeding microstrip line $W_m = 3.2$ mm; the length of ground plane $L_g = 40$ mm.

Table 1. Structural parameters of conventional MLAs.

Parameters	W	W_L	W_S	L_S (for MLA2 only)
Value (mm)	55	2	0.5	13

The effect of this impedance matching technique is validated by the simulated reflection coefficients of MLA1 and MLA2, as plotted in Fig. 1. This improvement of impedance matching performance comes virtually from the variation of input impedance graphed in Fig. 2. The first resonance of the origin model (MLA1) appears near 420 MHz, where the input reactance equals to zero and the reactance slope is positive. By adding a parallel stub, the total inductance of the input impedance is increased, and a new resonance characterized by negative reactance slope (which is referred to as anti-resonance) is formed near the original self-resonance. As a result, the conventional MLA is well matched at 437 MHz with a bandwidth of 4 MHz for $S_{11} < -10$ dB, i.e., a fractional bandwidth of 0.92%, and the overall height and width of MLA2 are 0.14 and 0.08 respectively in terms of wavelength.

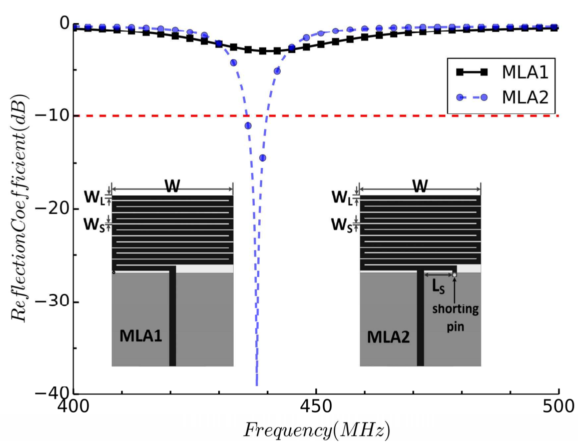


Figure 1. Configurations and reflection coefficient of conventional MLAs.

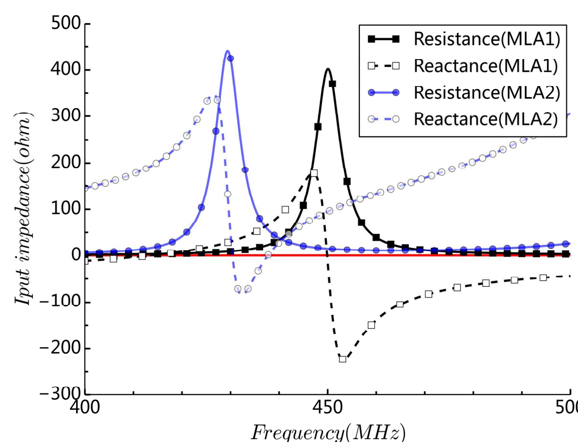


Figure 2. Impedance characteristics of conventional MLAs.

2.2. Capacitive Stripe-Loaded Meander Line Antenna

It is indicated from Fig. 1 and Fig. 2 that the impedance bandwidth can be broadened to some extent if the overall input impedance is decreased. However, this condition requires appropriate values of meandering width W_L and spacing W_S, which may be infeasible in the conventional fabrication process, with the overall antenna width and length constrained. The capacitive stripe is proposed in [18] to deal with this challenge and provide additionally an excellent solution for the arrangement of other modules (such as batteries) in some miniaturized wireless communication devices. The configuration of this type of loaded MLA (MLA3) is shown in Fig. 3.

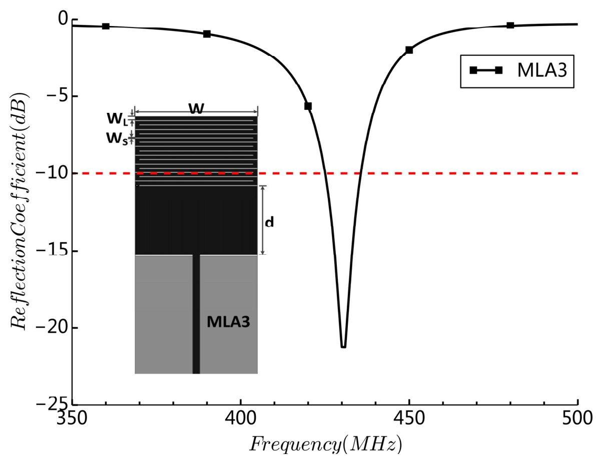


Figure 3. Configuration and reflection coefficient of MLA with capacitive stripe (MLA3).

A rectangular capacitive stripe with a width of W and length of d is inserted between the meandering sections and feed line for tuning the input impedance. The structural parameters of MLA3 are listed in Table 2. Note that the width of capacitive stripe is tuned to be $W = 52$ mm to make this MLA resonate near 433 MHz and its length is set to be $d = 40$ mm for impedance matching. Besides, the length of the ground plane (L_g) is increased to 75 mm to provide enough specular current on it.

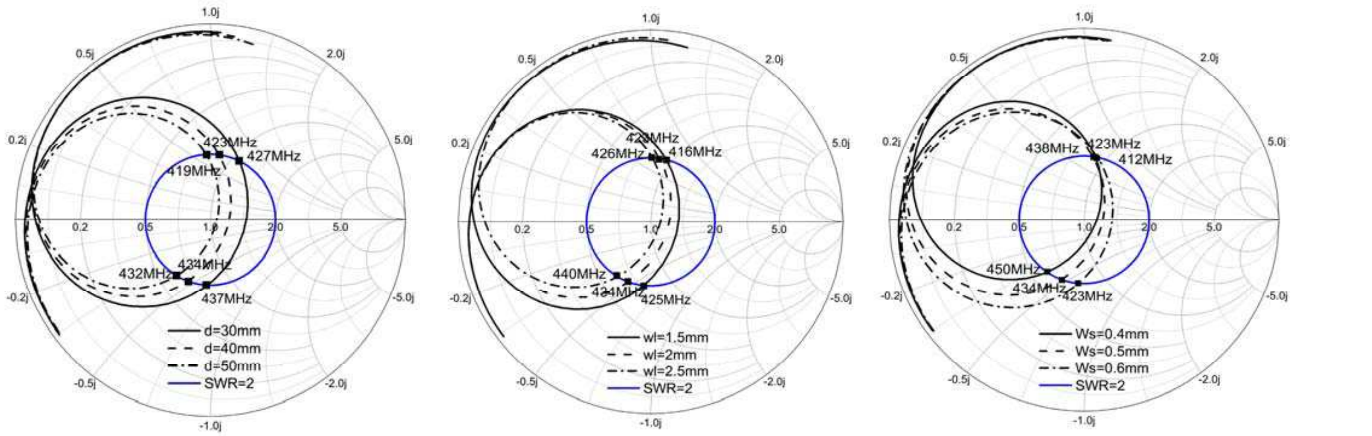
Table 2. Structural parameters of capacitive stripe loaded meander line antenna (MLA3).

Parameters	W	W_L	W_S	N	L_g	d
Value (mm)	52	2	0.5	6	75	40

As shown in Fig. 3, the MLA3 resonates at 431 MHz with a bandwidth of 10 MHz for $S_{11} < -10$ dB, which is considerably broader than that of MLA2. Accordingly, a conclusion can be drawn that the loading of capacitive stripe broadens the impedance bandwidth compared with MLA2.

The effect of capacitive stripe can be revealed more explicitly from the changing in the Smith chart by varying its length (d) as shown in Fig. 4(a). Obviously the input impedance becomes smaller, and the resonant frequency reduced slightly as d is increased, indicating that by introducing in the capacitive strip, the antenna is allowed to be self-resonant without the need of an extra matching network or tuning stub any more.

In Fig. 4(b), it is apparent that the input impedance decreases with the increase of W_L, and the resonant frequency rises by about 12 MHz. This can be attributed to the reduction of the antenna's equivalent inductance and the capacitance [18]. As a result, the change of the input impedance causes the decrease of the quality factor of the antenna, which consequently extends the impedance bandwidth from 9 MHz to 14 MHz. In Fig. 4(c), as the meander spacing W_S being tuned from 0.4 mm to 0.6 mm the antenna's input impedance shifts downward to the lower half of the Smith chart, indicating the increase of the antenna's capacitance and the reduce of the inductance, which makes the resonant frequency drop by 27 MHz, which means that the resonant frequency strongly depends on the value of W_S.



(a) (b) (c)

Figure 4. Effects of geometrical parameters on the impedance of MLA3. (a) Length of capacitive stripe (d). (b) Width of meander line (W_L). (c) Meander spacing (W_S).

2.3. Double-Layered Capacitive Stripe-Loaded Meander Line Antenna

To further broaden the impedance bandwidth, double-layered MLAs are designed on the basis of MLA3. Two meandering sections are printed symmetrically on both sides of the dielectric substrate, and a shorting pin is applied to connect them, as shown in Fig. 5. Two different configurations (MLA4 and MLA5) are used for comparing the effect of this method. For MLA4, only the meandering line is printed symmetrically on both sides of the dielectric substrate, and the shorting pin is placed at the beginning of the meandering line, while for MLA5, the meandering line and the capacitive strip are both doublelayered, hence the shorting pin is placed at the end of the feeding line, as shown in Fig. 5, which also shows the reflection coefficient of the two antennas compared with MLA3. Some geometry dimensions are given in Table 3.

It can be seen that the impedance bandwidths of double-layered MLA4 and MLA5 for $S_{11} < -10\,\text{dB}$ are broadened to 18 MHz and 16.5 MHz respectively from 11.5 MHz of single layered MLA3, which manifests the validation of the approach, along with the resonant frequency shifting upward a little which can be compensated by increasing the antenna size slightly.

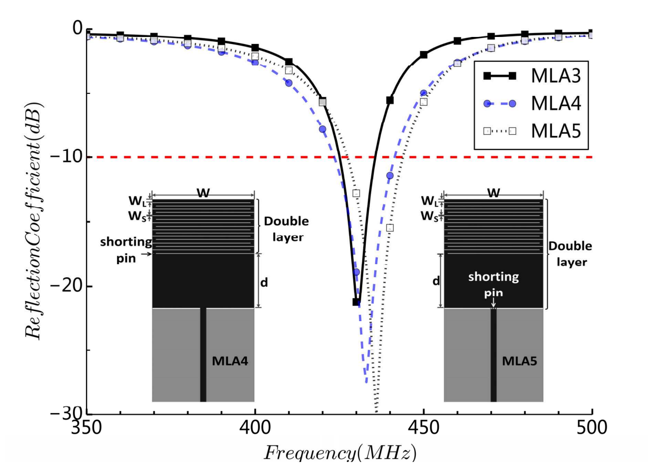


Figure 5. Configurations of double-layered MLAs and their reflection coefficient comparisons with MLA3, where MLA4 stands for the partially double-layered case and MLA5 means the entirely double-layered case.

Table 3. Structural parameters of double-layered MLAs.

Parameters	W	W_L	W_S	N	L_g	d
MLA4 (mm)	56	2	0.5	8	90	40
MLA5 (mm)	57	2	0.5	8	90	40

2.4. Equivalent Circuit Analysis

In fact, this explanation can be illustrated by the equivalent circuits of MLAs with single- and double-layered configurations, as shown in Fig. 6.

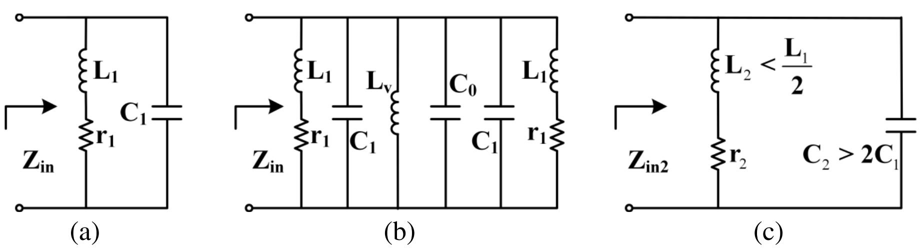


Figure 6. The equivalent circuit of (a) single-layered MLA, (b) double-layered MLA and (c) simplified form of double-layered MLA.

For the single-layered MLA (MLA3), considering the negative reactance slope near anti-resonance, a parallel resonant circuit is a simple and reasonable form to characterize its input impedance, as shown in Fig. 6(a). The inductor L_1 represents the effective inductance which can be mainly attributed to the self-inductance of the meandering sections, the capacitor C_1 denotes the effective capacitance that can be primarily attributed to self-capacitance between each meandering turns, and the resistor r_1 represents the radiation resistance. The input impedance seen from the end of the feeding line Z_{in} can be expressed as

$$Z_{in} = \frac{1}{1/\left(j\omega L_1 + r_1\right) + j\omega C_1} \tag{1}$$

which can be further derived as

$$Z_{in} = \frac{r_1 + j\omega\left(L_1 - Cr_1^2 - \omega_1^2 L_1^2 C_1\right)}{\left(1 - \omega^2 L_1 C_1\right)^2 + \omega^2 C_1^2 r_1^2} \tag{2}$$

By forcing the imaginary part of Z_{in} to be zero, the resonant frequency can be obtained

$$f_{01} = \frac{\omega_{01}}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{1}{L_1^2}\left(\frac{L_1}{C_1} - r_1^2\right)} \tag{3}$$

Since the quality factor of this antiresonant circuit can be determined as

$$Q_1 = \frac{\omega_{01} L_1}{r_1} = \frac{2\pi f_{01} L_1}{r_1} \tag{4}$$

Substitutes Equation (3) into Equation (4), we can obtain that

$$Q_1 = \sqrt{\frac{L_1}{C_1 r_1^2} - 1} \tag{5}$$

With the fact that narrow impedance bandwidth of an antenna is resulted from its inherent high quality factor ($Q_1 \gg 1$), we can infer that

$$\sqrt{\frac{L_1}{C_1}} \gg r_1 \tag{6}$$

Which makes r_1^2 in Equation (3) become negligible, obtaining

$$f_{01} \approx \frac{1}{2\pi\sqrt{L_1 C_1}} \tag{7}$$

Similarly, considering that two symmetrical sections are connected in parallel to each other by a shorting pin, the equivalent circuit of double-layered MLA (MLA5) can also be established, as shown in Fig. 6(b). The rLC circuit is duplicated with an addition of two extra terms, C_0 and L_v, where C_0 is used to describe the coupling capacitance between the two meandering sections, and L_v characterizes the inductance of the shorting pin.

For comparison, the equivalent circuit of MLA5 can be further simplified to the same form as that of MLA3 as shown in Fig. 6(c). So the quality factor and the resonant frequency of MLA5 would be written as

$$f_{02} \approx \frac{1}{2\pi\sqrt{L_2 C_2}} \tag{8}$$

$$Q_2 \approx \frac{1}{r_2}\sqrt{\frac{L_2}{C_2}} \tag{9}$$

Note that L_2 is much smaller than $L_1/2$ because a small inductance L_v is connected in parallel, while C_2 becomes larger than $2C_2$ ($C_2 = 2C_1 + C_0$), and r_2 changes approximately to $r_1/2$ which can lead to $Q_2 < Q_1$, and $f_{02} > f_{01}$. As a result, a conclusion can be drawn that impedance bandwidth is broadened and the resonant frequency is increased for double-layered MLA. It worth to point out that the augment of resonant frequency can be compensated by adjusting the size of meandering sections without increasing the overall height of MLA.

3. MEASUREMENT AND DISCUSSION

To demonstrate the validity of the proposed method, two MLAs are fabricated for comparison. The meandering sections are printed in a tapered configuration for further bandwidth enhancement, as shown in Fig. 7. Note that the shorting pin for doublelayered case is located at the connecting part of meandering sections and capacitance strip. Some primary structural parameters are listed in Table 4, where dw quantifies the width augment of meandering sections for the tapered profile. FR4 dielectric substrates ($\varepsilon_r = 4.4$) with a thickness of $h_d = 1.6$ mm is adopted here for both cases.

The simulated and measured reflection coefficients of the fabricated MLAs are plotted in Fig. 8. Good agreements between simulation and measurement are obtained. It can be seen from the measured results that the resonant frequencies of MLA6 and MLA7 are 418 MHz and 423 MHz respectively, therefore the overall size will be 0.25 wavelength in height and 0.1 wavelength in width for MLA6,

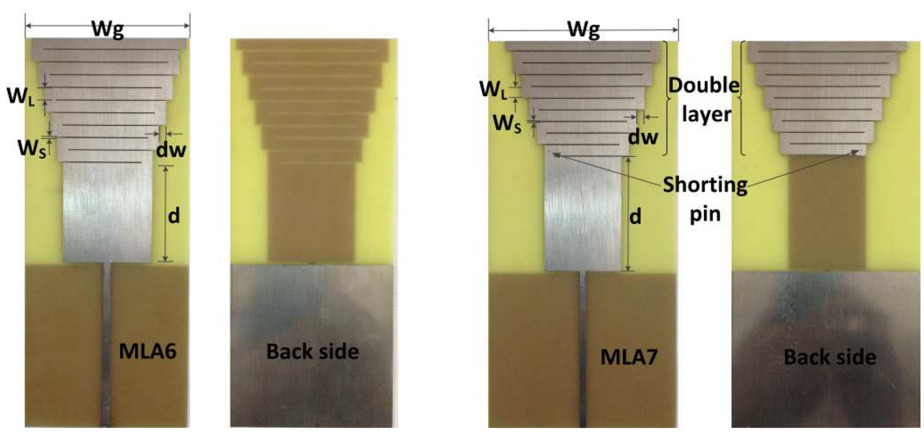


Figure 7. Photographs of fabricated MLAs, where MLA6 stands for the single-layered case, MLA7 refers to the double-layered case.

Table 4. Structural parameters of fabricated MLAs.

Parameters	W	W_L	W_S	N	d	W_g	dw
MLA6 (mm)	40	5	0.5	5	45	74.5	2.8
MLA7 (mm)	40	5	0.5	5	55	98.5	4

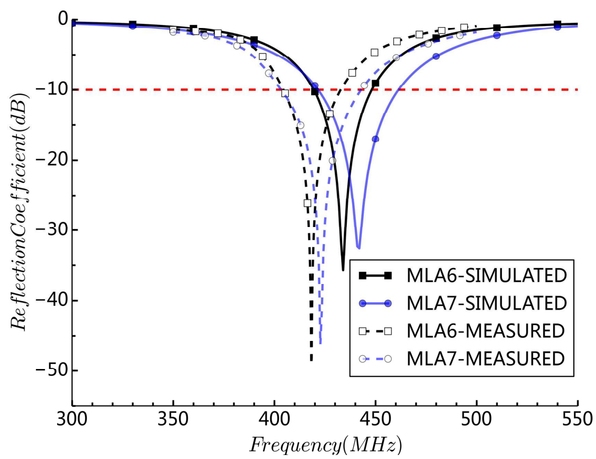
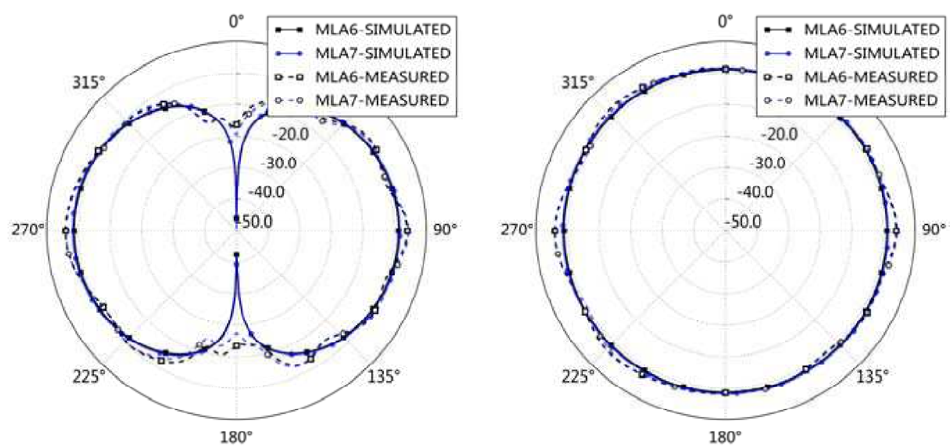


Figure 8. Reflection coefficient of the fabricated prototypes.



(a) (b)

Figure 9. Radiation patterns of the fabricated MLAs. (a) E-plane. (b) H-plane.

and 0.26 wavelength in height and 0.14 wavelength in width for MLA7. In contrast to the single-layered MLA, the fractional bandwidth of double-layered form is broadened by 2.7% (from 6.71% to 9.39%) for $S_{11} < -10$ dB (12 MHz), which means about 1.5 times as wide as the single-layered form's accomplished with a slight shift of resonant frequency. These variations are consistent with the conclusion drawn from the equivalent circuit analysis, manifesting the validity of the proposed approach. The measured resonant frequencies are shifted downward by about 15 MHz for both cases compared with the simulated ones, and this discrepancy can be attributed to the instability of dielectric substrates as well as the manufacturing error.

On the other hand, compared with MLA2, the fractional bandwidths of MLA6 and MLA7 are largely increased. Especially the MLA7's fractional bandwidth becomes almost 10 times, from original 0.92% for MLA to the present 9.39% by using a double-layered tapered meandering structure and introducing a capacitive stripe. The newly added capacitive stripe should also facilitate the integration design of certain miniaturized electronic devices and provide a more feasible structure of MLA considering the restrictions of fabrication, although it brings a little additional size to the whole antenna.

The measured radiation patterns for E-plane and H-plane at the resonant frequencies are plotted in Fig. 9, which shows that both prototypes fabricated yield monopole-like radiation patterns. It can be concluded that the radiation characteristics differ little for these configurations, which is ascertained by the negligible discrepancies of radiation patterns and peak gain within the operating bandwidth shown in Fig. 10.

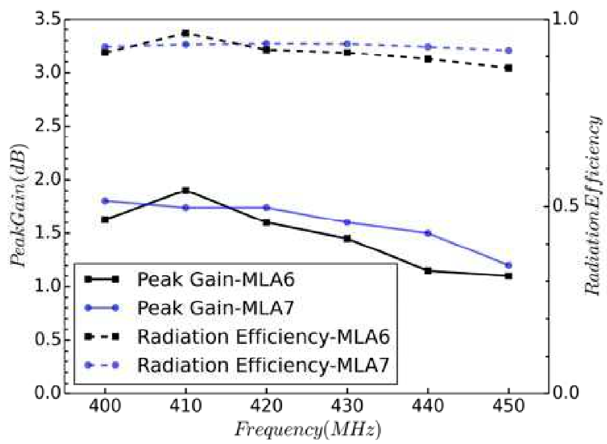


Figure 10. Peak gain and radiation efficiency curves of the fabricated prototypes.

It can be seen from Fig. 10, the radiation efficiency of the proposed antennas are quite high, and there was little difference between the single layered and double layered MLAs within the operating bandwidth. The trend of the peak gain is also in accordance with the trend of the radiation efficiency, which also ensures good radiation characteristics of the antennas.

4. CONCLUSIONS

In this paper, a novel and effective approach for the bandwidth enhancement of low frequency MLA in light of quality factor theory of electronically small antennas is presented. By connecting two meandering stripes of MLA via shorting pins, the quality factor of the double-layered MLA can be reduced compared with the single-layered MLA, which consequently broadens the impedance bandwidth. The illustrative equivalent circuits and the corresponding principle of bandwidth enhancement are presented. Prototypes of single-layered and double-layered MLAs are fabricated and tested, and the measurement results demonstrate the effectiveness of the proposed approach.

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