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A Compact Printed Seven-Band Monopole Antenna for Vehicle-mounted T-BOX

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Abstract—A seven-band antenna for vehicle-mounted T-BOX with a compact structure is proposed and studied. The proposed antenna is composed of a monopole branch and a ground branch. In addition, a slot is embedded in the monopole branch for bandwidth enhancement. By using 0.25- and 0.5-wavelength modes, the lower band (824–960 MHz) and higher band (1710–2690 MHz) are covered. The working mechanism is analyzed based on S-parameters and surface current distributions. The attractive merits of the proposed antenna are that the structure is compact with a small ground, and no lumped element is used. The measured results show that the antenna can cover the lower band of GSM850/900 and the desired upper band of DCS1800/PCS1900/UMTS2100/LTE2300/2500. The measured efficiencies are also presented.

1. INTRODUCTION

Internet of Vehicles (IoV) enables interaction among vehicles, cloud server, and users in a way that we are able to closely connect the cyber world with the automobile [1]. As one of the most important parts of IoV, Telematics Box (T-BOX) is the hinge of the connection between car and human, and it can also be seen as a terminal system. To upload car state and realize remote control function, a 3/4G communication standard needs to be applied in T-BOX. So, frequency bands such as GSM850/900/DCS1800/PCS1900/UMTS2100/LTE2300/2500 should be covered as many as possible by the antennas of T-BOX. Besides, a compact antenna structure is also a common requirement due to limited space and complex electromagnetic environment in vehicle and T-BOX. Moreover, compared with the antenna used for data card, a much smaller ground is provided here, because the computer can always be a ground when the antenna is working in the latter case. Therefore, it is a big challenge to design a T-BOX antenna with multi-band/wideband and small size [2, 3].

There are many types of antennas studied for modern mobile terminals. In [4], the bandwidth was increased by arc-shaped slot and DGS. A matching circuit has been proposed in [5, 6] to cover the lower band. In [7], multi-branch was used to create multi-mode, and the bandwidth was also widened by coupled feeding. The antennas proposed in [4, 7] were designed in a monopole shape, but they were not suitable for a T-BOX application for their large ground size. With metal rim radiated as main radiator, a loop structure was realized in [8], by selecting short point and feeding point suitably, and a broad bandwidth can be realized. Reconfigurable antenna is also an effective way for bandwidth enhancement, but this technology is not universally applicable. A diode in [9] helps the antenna realize reconfigurable operation. However, the structure is too complicated.

In this paper, a compact printed seven-band monopole antenna for vehicle-mounted T-BOX is proposed and studied. The proposed structure not only occupies a small no-ground area of 48 mm × 19.5 mm on the circuit board but also shows a simpler structure. All the simulations have been done by ANSYS electromagnetics suite 17.1.

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The rest part of this paper is organized as follows. In Section 2, the geometry and detailed dimensions of the proposed antenna are described. In Section 3, the working mechanism of the proposed antenna is analyzed based on the surface current distribution and parameters analyses. In Section 4, the measured results are presented to verify the proposed design. Finally, conclusions are drawn in Section 5.

2. PROPOSED ANTENNA CONFIGURATION

Figure 1 shows the geometry of the proposed compact printed seven-band monopole antenna at the right position of the system circuit board, and detailed dimensions of the antenna are also given. The length and width of the antenna structure are 48 mm and 19.5 mm, respectively. The system ground plane is pasted on a 1-mm-thick FR4 substrate. To fit the T-BOX, there are two rectangular openings etched on the lower edge of the PCB. The size of the PCB is 91 mm × 19.5 mm × 0.8 mm. The proposed antenna consists of a ground branch and an inverted C-shape monopole branch with an L-shaped slot. As shown in Fig. 1, the ground branch is a straight strip (the length $L3$ is 14 mm) and 3 mm away from the feeding point A. To cover the band GSM850, the inverted C-shape monopole nearly covers three-quarter of the none-ground's margin, and an L-shaped slot is also embedded in the monopole to extend electrical length for the same reason.

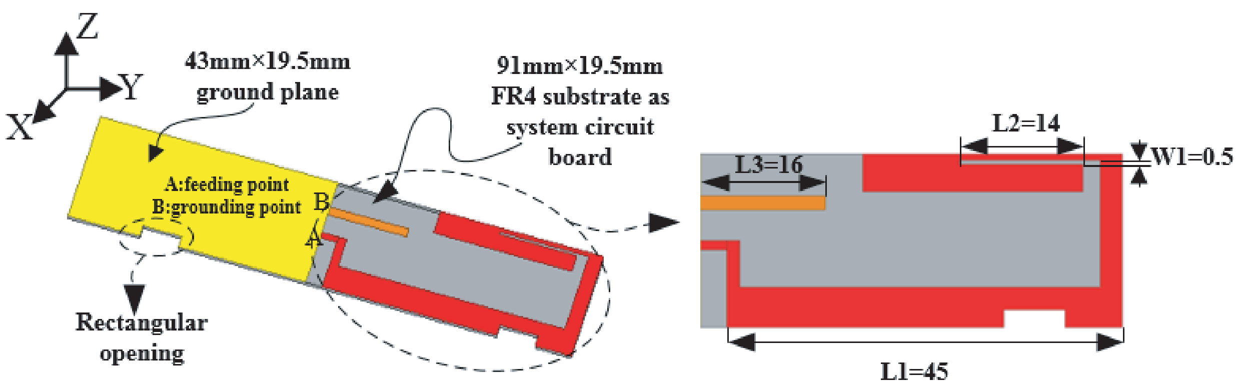


Figure 1. Geometry of the proposed antenna structure and detailed dimension (Unit: mm).

3. ANALYSES OF THE PROPOSED ANTENNA

In order to understand the proposed seven-band monopole antenna, the functions of the monopole branch, L-shaped slot and ground branch are analyzed. S parameters and surface current distributions are used to analyze the working mechanism of the proposed antenna.

3.1. The Analysis of the L-Shaped Slot and Ground Branch

To study the functions of the monopole branch, the L-shaped slot and ground branch, following cases, i.e., Ant 1 (the monopole branch), Ant 2 (L-shaped slot etched on the monopole branch) and the proposed antenna, as shown in Fig. 2(a), are analyzed. The simulated results of S_{11} of Ant 1, Ant 2 and the proposed antenna are shown in Fig. 2(b).

Figure 2(b) shows that, for Ant 1, there are three resonance frequencies. They are at around 1 GHz, 2.2 GHz and 2.8 GHz. When an L-shaped slot is added in Ant 1, Ant 2 is formed. At the lower band, Ant 2 can cover the GSM850 band, but the matching is poor at the higher band. Thus, with the help of an L-shaped slot, Ant 2 can cover most part of the desired lower band and part of the higher band. In order to improve the performance of higher band, a ground branch is introduced, and the proposed antenna is formed. The ground branch can produce another higher resonance and broaden the higher frequency band of the antenna, thus both the desired lower and higher bands are realized.

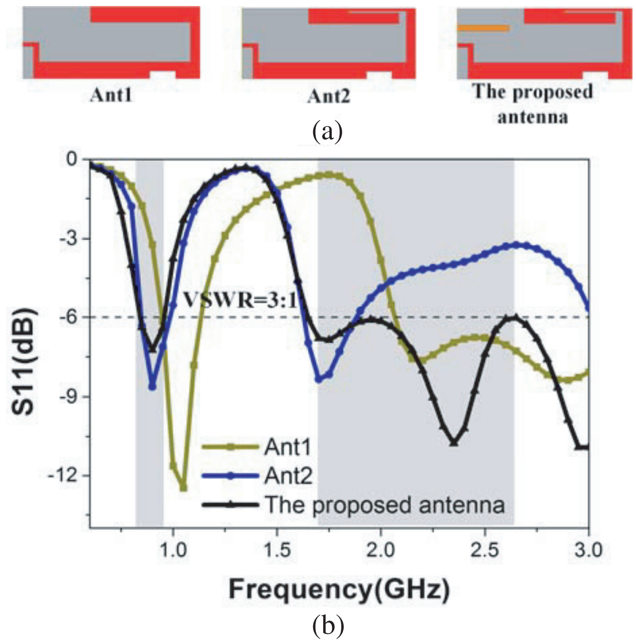


Figure 2. (a) Structures of the Ant 1, Ant 2 and proposed antenna. (b) Simulated S_{11}.

3.2. The Surface Current Distributions

To understand working modes of the proposed antenna, surface current distributions are studied. Simulated current distributions of the proposed antenna at 0.9 GHz, 1.75 GHz, 2.35 GHz and 2.95 GHz are shown in Fig. 3. Fig. 3(a) shows that at 0.9 GHz, the main current is on the monopole branch, and the current is maximum from A to B, thus, the monopole branch works at the 0.25-wavelength mode of the AB section at 0.9 GHz. Besides that, the L-shaped slot does increase the electrical length of the lower band from Fig. 3(a). Fig. 3(b) shows that the current on monopole is maximum at D and minimum at C, thus, the monopole works at the 0.5-wavelength mode of the CD section at 1.75 GHz. Fig. 3(c) shows that at 2.35 GHz, the current is zero at E, thus the monopole works at the 0.5-wavelength mode of the EF section. Fig. 3(d) shows that at 2.95 GHz, the current is zero at G, H and I, and the maximum current is at J, K and L, respectively. So the ground branch works as the 0.25-wavelength mode at 2.95 GHz. In addition, the ground branch also works as the 0.25-wavelength mode at 2.35 GHz, which increases the bandwidth of the higher band.

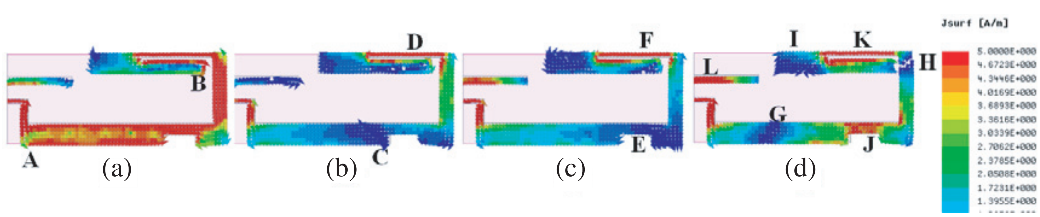


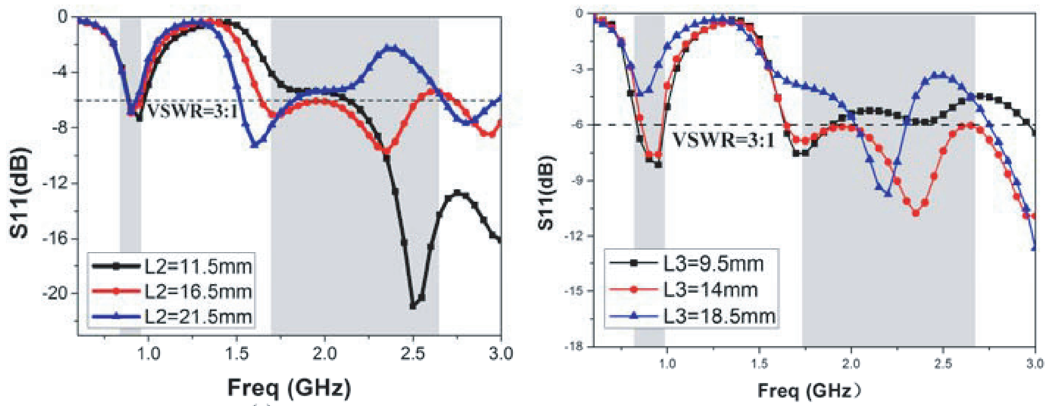
Figure 3. Simulated surface current distributions of the proposed antenna (a) 0.9 GHz. (b) 1.75 GHz. (c) 2.35 GHz. (d) 2.95 GHz.

Based on the above results, we can get some conclusions as follows. At the lower band, the working bands are realized by the 0.25-wavelength modes of the monopole branch with an L-shaped slot. At the higher band, the 0.25- and 0.5-wavelength mode of the monopole branch and the ground branch work together to cover the desired higher band.

3.3. Parameter Analyses

To better understand the working mechanism of the proposed antenna, some parameters about the L-shaped slot and ground branch are analyzed. As shown in Fig. 1, the parameters of $L2$, and $L3$ are related with the lengths of the L-shaped slot and ground branch.

According to Fig. 4(a), the value of $L2$ influences the bandwidth of the lower band and the matching in higher band. When $L2$ becomes greater, the resonance frequencies decrease in both lower and higher bands, but the matching in higher band becomes worse. Considering the bandwidth and matching, $L2 = 14\,\text{mm}$ is chosen.



(a) (b)

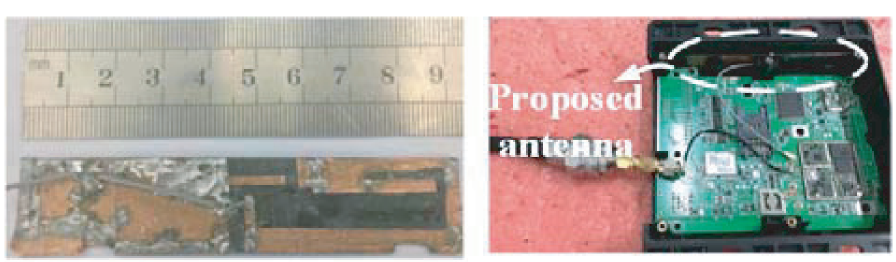
Figure 4. (a) Simulated S_{11} with different length of $L2$. (b) Simulated S_{11} with different length of $L3$.

From Fig. 4(b), when $L3$ becomes larger, matching towards higher band is improved by a coupling loop formed by monopole branch and ground branch. However, as a longer $L3$ will change the resonant mode of the coupling loop, the higher order mode will resonate beyond the band of interest which decreases the bandwidth of the higher band. Moreover, a longer $L3$ also leads to a deterioration of lower band. Considering both the bandwidth and matching, $L3 = 14\,\text{mm}$ is chosen.

4. MEASURED RESULTS AND DISCUSSIONS

A prototype of the proposed antenna is fabricated according to the dimensions shown in Fig. 1. A photo of the fabricated antenna is given in Fig. 5(a). The VSWR is obtained by vector network analyzer (VNA), and the radiation performances are measured in an anechoic chamber. Fig. 5(b) shows the antenna working environment, and the antenna is put in a vehicle-mounted T-BOX.

Figure 6 shows the simulated and measured VSWRs of the proposed antenna. The simulated VSWR ≤ 3 impedance bandwidths are 140 MHz (0.82–0.96 GHz) and 1.35 GHz (1.65–3.00 GHz) at



(a) (b)

Figure 5. (a) The photo of the fabricated antenna. (b) Antenna working environment.

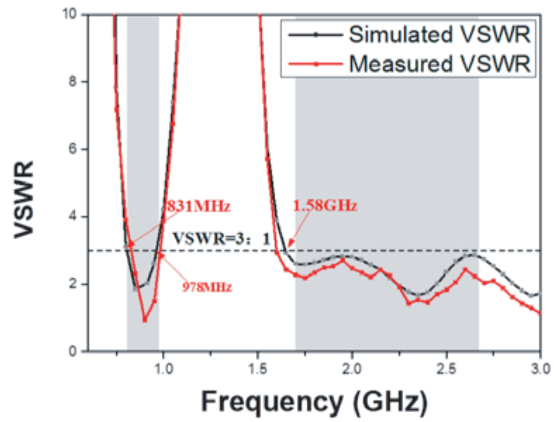


Figure 6. Simulated and measured VSWR of the proposed antenna.

the lower and higher bands, respectively. The measured VSWR $\leq$ 3 impedance bandwidths are 147 MHz (0.831–0.978 GHz) and 1.42 GHz (1.58–3 GHz) at the lower and higher bands, respectively. The simulated and measured VSWRs coincide with each other well. The slight difference may be caused by manufacture errors and dielectric loss. The antenna covers the lower band GSM850/900 and the desired upper band of DCS1800/PCS1900/UMTS2100/LTE2300/2500.

The measured efficiency of the proposed antenna ais shown in Fig. 7(a). It can be seen that the corresponding measured efficiencies at the lower and higher bands are 48.7%–58.2% and 76.4%–87.3%, respectively. Fig. 7(b) illustrates the radiation gain of the proposed antenna. The gain varies in a range of 1.1–1.95 dBi at the lower band and in a range of 0.98–2.05 dBi at the upper band. The variations of gain values within the bands of interest are lower than 0.85 dBi and 1.07 dBi, respectively.

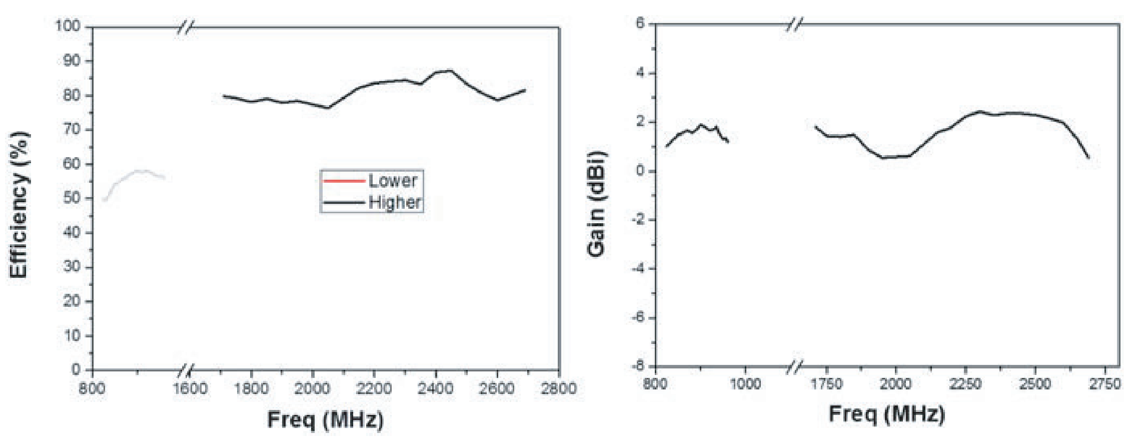


Figure 7. (a) The measured efficiency of the proposed antenna. (b) The measured gain of the proposed antenna.

Figure 8 presents the measured radiation patterns of the antenna. It can be seen that the antenna exhibits dipole-like behavior at 0.9 GHz, 1.75 GHz and 2.35 GHz, respectively. Table 1 shows the comparison between the proposed antenna array and some other antennas reported for terminal handsets. From this table, it is obvious that the proposed antenna has a small ground with acceptable radiation performances.

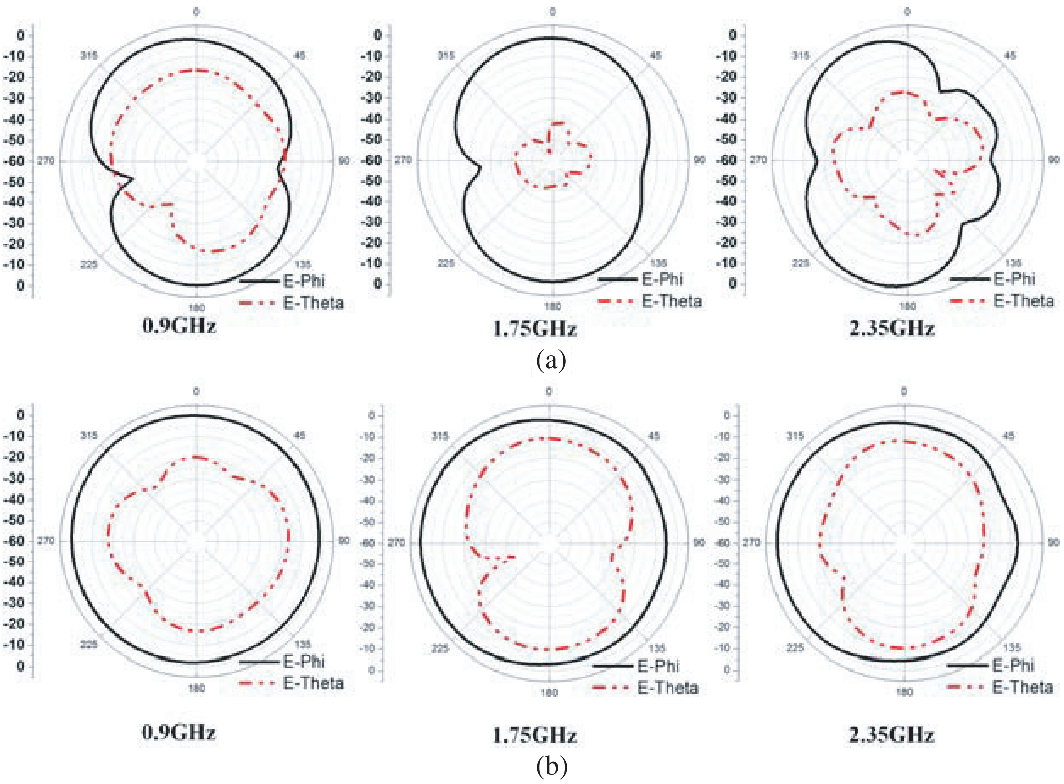


Figure 8. Measured radiation patterns of the proposed antenna in (a) XOY plane, (b) XOZ plane at three frequencies: 0.9, 1.75 and 2.35 GHz. (Unit: dBi).

Table 1. Comparison between the proposed and the referenced antennas.

Reference	Frequency (MHz)	Ground size (mm)	Antenna size (mm)	Efficiency (%)	Gain (dBi)
[5]	704–960; 1710–2690	$60 * 105$	$25 * 25$	40–53 (lower band); 41–70 (higher band)	−0.6–0.5 (lower band); −1.5–1 (higher band)
[10]	880–960; 1710–2600	$110 * 40$	$11 * 39$	65–69 (lower band); 59–70 (higher band)	Not mentioned
[11]	824–960; 1710–2170	$115 * 56.5$	$15.5 * 56.5$	60–70 (lower band); 60–78 (higher band)	0.5–1.3 (lower band); 0.5–2.3 (higher band)
[12]	824–960; 1700–3800	$60 * 125$	$32 * 8 * 5$	54.5–75 (lower band); 68.3–90 (higher band)	−0.3–5.12 (lower band); −0.56–4.78 (higher band)
Proposed	824–960; 1710–2690	$43 * 19.5$	$45 * 19.5$	48.7–58.2 (lower band); 76.4–87.3 (higher band)	0.98–2.05 (lower band); 0.85–1.07 (higher band)

5. CONCLUSIONS

This paper presents a seven-band monopole antenna with the size of 48 mm × 19.5 mm × 0.8 mm for Vehicle-mounted T-BOX. The proposed antenna consists of a ground branch and a monopole branch. The proposed antenna is designed without using any lumped element. The measured VSWR ≤ 3 impedance bandwidths are 147 MHz (0.831–0.978 GHz) and 1.42 GHz (1.58–3 GHz) at the lower and higher bands, respectively. It covers the GSM850, GSM900, GSM1800, GSM1900, UMTS, LTE2300, and LTE2500 bands. Within the two bands, the measured efficiencies are 48.7%–58.2% and 76.4%–87.3%, respectively.

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