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Design and Performance Analysis of Pattern Reconfigurable MIMO Antennas for Mobile Smartphones

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Abstract

This paper presents compact pattern reconfigurable antennas for mobile handsets in MIMO configuration. Each antenna of the MIMO configuration being coupled fed monopole in meandered form is capable of covering several cellular frequency bands in the range of 1.75 – 2.67 GHz including 4G – LTE, 2G – GSM, 3G – UMTS and WLAN. The MIMO antennas are printed diagonally at the left and right no-ground portions on the top layer of the substrate to enhance the isolation performance. The substrate used is FR-4 with relative permittivity of 4.35 and loss tangent of 0.02. The volume of the substrate is 120 x 65 x 1.6 mm^3 with each antenna occupying an area of 26.5 x 14.5 mm^2. The pattern reconfigurability is achieved by connecting and disconnecting a 4.5 x 2 mm^2 metallic strip using the p-i-n diode switch. The antennas are pattern reconfigurable in the frequency range of 1.9 – 2.1 GHz. The isolation achieved is better than 16 dB over all the frequency bands covered by each antenna. A prototype has been fabricated and tested. The simulated and measured results show a good performance of the MIMO antennas.

Index terms

Mobile Handset, Reconfigurable antenna, Multiple Input Multiple Output (MIMO), printed monopole

1. Introduction

With the development of modern communication standards such as Universal Mobile Telecommunication System (UMTS) and Long Term Evolution (LTE), the mobile communication becomes more convenient with the capability of supporting voice and large sized data communications simultaneously [2], [3]. Modern day users are not only able to access and download data on the mobile handset, but also can enjoy the high quality video streaming. However, an increase in the communication interference has taken place due to the changes in the terrain's environment such as the presence of large buildings and obstacles and the increase in the number of users. This largely degrades the quality of the communication link. Multiple Input Multiple Output is the key technology that has been developed more than 10 years ago which utilizes the signal scatterings from the obstacles in favour of communication quality [4]. MIMO technology assures a high data rate, increased channel capacity and enhanced coverage without requiring additional channel bandwidth [2]. The benefits of MIMO technology can be exploited by designing such antennas which have the capability of changing the radiation pattern thereby assuring a good signal level in all communication scenarios. Such antennas are referred to as pattern reconfigurable antennas in literature. The implementation of such antennas is not yet successful in mobile handsets due to the decoupling issues that appear when dealing with a compact volume of a mobile handset. So there is a strong need to develop such antennas in mobile handsets to make voice and large sized data communication work faster and more reliably.

Several designs of handset antennas have been proposed in [5]-[21] of which most of the designs are of reconfigurable antennas. However, these designs tend to be part of frequency reconfigurable antennas. A design of frequency and beam reconfigurable antenna using optical switches is presented in [5]. The antenna is a printed dipole antenna with a coplanar waveguide (CPW) to coplanar stripline (CPS) transition as a feed to the antenna. Two silicon photo diode switches are used at the arms of the dipole. The activation of the switches is done using infrared laser diodes through optical fiber to shift the operating frequency and the beam of the radiation pattern. Though the proposed design is very simple and easy to implement, its narrow bandwidth makes it not suitable for multiband mobile handsets. Another design of reconfigurable antenna for mobile handsets is presented in [6]. The proposed design operates in two modes which are PIFA and loop modes. The switching between the modes is done using PIN diode switches. A drawback in the proposed design is its height that extends above the ground by 6 mm, which makes the design not suitable for sleek handsets. Also, since the design is frequency reconfigurable, it cannot be implemented to achieve pattern reconfigurability from a mobile handset. A design presented in [8] covers two frequency bandwidths with one bandwidth ranging from 700-960 MHz, and the second bandwidth ranging from 1.7-2.7 GHz. The operating band reconfigurability is achieved using micro-electro-mechanical switches (MEMS). Though the design proposed in this work is compact, however the use of MEMS switches in mobile handsets is never suitable due to its high insertion loss, a high biasing voltage (50-70V) and a complex matching network. A fairly compact design of the reconfigurable antenna has been presented in [11]. The proposed antenna is composed of two strips and a coupling branch. Strip 1 contributes to the resonance at 2 GHz, whereas strip 2 contributes to the resonance at 980 MHz, and the coupling branch improves frequency bandwidth. A p-i-n diode is used to control the conducting length of strips for achieving operating band reconfigurability. The antenna however is not suitable for achieving pattern reconfigurability on a mobile handset. Another design of the frequency reconfigurable antenna presented in [12] is switched by the p-i-n diode for operating in PIFA and loop modes. A few more recent designs of the reconfigurable antennas have been presented in [17]-[21]. A pattern reconfigurable antenna in MIMO configuration for mobile applications is shown in [18]. The antennas possess decent pattern reconfigurable characteristics along with a good isolation performance, but the cellular coverage is limited due to its narrow bandwidth with a resonance at 2.36 GHz only. Also the antennas are placed at a height of 6 mm above ground plane, which makes the design not suitable for slim mobile devices. Another design presented in [19] is of pattern reconfigurable antennas. The proposed design is compact and printed but the operating bandwidth is 5.15 – 5.35 GHz which is not suitable for cellular handsets. Most of the designs discussed above are of frequency reconfigurable antennas and few designs of pattern reconfigurable antennas with limited cellular coverage were also discussed. There is a strong need to develop multiband and pattern reconfigurable antennas for achieving best throughput and signal level from a mobile handset in a dense and scattered propagation environment.

In this paper, two linearly polarized MIMO antennas printed diagonally on FR-4 substrate have been presented. The antennas are monopoles that are meandered to have a compact volume. An additional metallic strip is connected to each antenna using p-i-n diode switch for achieving pattern reconfigurability.

2. Antenna Design

The antennas are designed and simulated in CST Microwave Studio®. The simulated model of the MIMO antennas is shown in Fig. 1. The antennas are meandered monopoles fed through coupling and etched diagonally at the no-ground portion on the top layer of the substrate. Two metallic strips of area 4.5 x 2 mm^2 are also etched and connected to the monopoles using Infineon BAR 50-02V p-i-n diode switches. The diode switches are soldered in Gap_1 as shown in Fig. 1. The p-i-n diode is biased using a variable DC power supply with a voltage of 0.95V and current set to 20 mA. The connectivity of these strips reconfigure the radiation pattern without altering the return loss performance. Coilcraft fixed value inductors are soldered in Gap_2 to choke the RF current from flowing into the biasing wires. The value of the inductance is 56 nH and has been selected through computer simulations. The fabricated prototype of the antenna is shown in Fig. 2. It can be seen that the biasing wires of the p-i-n diodes run through the bottom layer of the substrate which comprises the ground plane. The connection between the p-i-n diode and the biasing wires is made through via holes, drilled from the bottom layer to the biasing pads on the top layer of the substrate. This reduces the effects of the biasing wires on the radiation characteristics of the MIMO antennas. The volume of the substrate used for the design is 65 x 120 x 1.6 mm^3 with each antenna printed on a small area of 14.5 x 26 mm^2. The material used for the substrate is FR-4 with relative permittivity of 4.35 and loss tangent of 0.02.

Fig. 1. Simulated Model of the reconfigurable MIMO antennas for mobile handsets. [Units: mm]

Fig. 2. Fabricated prototype of the reconfigurable MIMO antennas for mobile handsets.

3. Simulation and Experimental results

The design of the proposed reconfigurable MIMO antennas for mobile handsets is simulated in CST® Microwave Studio. For validation of the simulated results, the prototype was tested in the Antenna Laboratory at Queen Mary, University of London. The s-parameters were obtained by connecting the antennas to Anritsu® vector network analyzer (VNA), whereas the radiation pattern measurements in either 'ON' or 'OFF' state were conducted inside the anechoic chamber. The measurement setup was very carefully established to minimize any possible interference. However, some discrepancies may incur due to the fabrication imperfections and the presence of the biasing circuitry. For the purpose of analysis and comparison, the simulation data files from CST® Microwave Studio and the measurement data files from the network analyzer were extracted and post processed in Matlab®. The simulated and the measured results will be presented and discussed in the sub-sections.

3.1 Return Loss

The return loss curves of the reconfigurable MIMO antennas are shown in Fig. 3. It can be seen from the return loss curves that the MIMO antennas are radiating with a 6 dB bandwidth of 1.75–2.67 GHz. The measured return loss corroborates with the simulated one. However, a minor shift in the frequency was observed due to the possible imperfections in the fabrication of the antennas and tolerances in the specifications of FR-4 substrate. S-parameters of only one antenna are shown as both the antennas are identical. Each antenna is thus capable of covering GSM 1800 (1.71-1.88 GHz), GSM 1900 (1.85-1.99 GHz), UMTS (1910-2170 MHz), WLAN (2.4-2.48 GHz), LTE band number 2-4, 9-10, 15-16, 23, 30 (1.70-

2.36 GHz) and LTE band 7 (2.5-2.69 GHz) [23].

Fig. 3. Return loss of the reconfigurable MIMO antennas for mobile handsets.

3.2 Decoupling

Isolation curves for the MIMO antennas are shown in Fig. 4. The MIMO antennas are exhibiting a measured isolation better than 16 dB over the whole frequency bandwidth. This is due to the placement of antennas in diagonal configuration which isolated the two antennas in the farfield. The diagonal separation between the antennas is 76 mm which is nearly 0.6 λ at the resonant frequency of 2.23 GHz. The farfield distance of each MIMO antenna can be calculated by using the longest dimension of the antenna which is its vertical length. The vertical length of the antenna is 32.5 mm which gives a farfield distance of 15.7 mm. The antennas are thus placed in each other's farfield, however being placed in mirrored configuration the antennas radiate in opposite directions. Also the antennas being placed in diagonal configuration are highly isolated in polarization thereby enhancing the decoupling performance. This results in a low correlation between the farfields of the antennas leading to a better isolation as compared to the other configurations. Simulations have shown that the isolation between the proposed MIMO antennas improves by increasing the diagonal spacing.

Fig. 4. Isolation curves for the reconfigurable MIMO antennas for mobile handsets.

3.3 Antenna Currents

The MIMO antennas proposed in this work are meandered monopoles with two additional metallic strips. These strips connect or disconnect for achieving the reconfigurability of the radiation pattern. Each metallic strip is connected and disconnected using a p-i-n diode switch that is soldered using conductive epoxy. When the p-i-n diode is forward biased, a shorting path is established between the antenna and the metallic strip and the strip starts radiating. This can be seen from the current distribution shown in Fig. 5. The amount of current on the metallic strip in the 'OFF' state of p-i-n diode is very less, whereas a significant current started flowing on the metallic strip in the 'ON' state which largely shifts the radiation pattern. This change in the magnitude of the current flowing on the metallic strip leads to a shift of radiation pattern in the bandwidth of 1.9 – 2.1 GHz. It can also be seen that the amount of current flowing in the ground plane is very less except the current on the upper edge. This minimizes effect of electronic components on the current distribution of the antennas and the ground plane.

Fig. 5. Current distribution of the reconfigurable MIMO antennas at different frequencies.

3.4 Radiation Patterns

The simulated 3D radiation patterns in either ‘ON’ or ‘OFF’ state at different frequencies are presented in Fig. 6. It can be seen that the radiation pattern in the ‘ON’ state of p-i-n diode is different from the radiation pattern in the ‘OFF’ state. This can be validated by the current distributions shown in Fig. 5. The distribution of current in the ‘ON’ state is different from the current distribution in the ‘OFF’ state. In the ‘OFF’ state, the magnitude of the current flowing on the upper edge of the ground plane is larger than the current in the ‘ON’ state. Also, the amount of current flowing through the metallic strip in the ‘OFF’ state is much lower than the ‘ON’ state where a large amount of current starts flowing through the metallic strip. These changes in the distribution of current generate pattern diversity. A parametric analysis on the length and width of the metallic strip is included in a later section.

Fig. 6. 3D radiation patterns of the reconfigurable MIMO antennas for mobile handsets.

The radiation pattern measurements were performed in both x-z and y-z planes. The p-i-n diode was biased using a variable DC power supply with a current set to 20 mA and voltage to 0.95 V. The radiation patterns of only one antenna are shown in both ‘ON’ and ‘OFF’ states as the two antennas of the MIMO configuration are symmetrical. The normalized co-polar (theta plane) and cross-polar (phi plane) radiation patterns of the MIMO antennas at different frequencies in x-z and y-z planes are shown in Fig. 7 and Fig. 8 respectively. The simulated and measured radiation patterns agree with some discrepancies occurred mainly due to the fabrication limitations and the measurement procedure which involves the use of biasing wires, connection cables and connectors. The antennas are pattern reconfigurable predominantly in the frequency bandwidth of 1.9 – 2.1 GHz.

Fig. 7. Radiation patterns of the reconfigurable MIMO antennas for mobile handsets in x-z plane.

Fig. 8. Radiation patterns of the reconfigurable MIMO antennas for mobile handsets in y-z plane.

3.5 Gains and Efficiencies

The simulated and measured gains and efficiencies of the MIMO antennas at different frequencies are listed in Table I and Table II respectively. The measured gain is calculated by the gain comparison method using a standard gain horn [24]. Whereas, the efficiencies are measured using the Wheeler Cap Method [25]. The simulated and measured values corroborate a good performance of the MIMO antennas. It can be seen that the value of efficiency at 2.24 GHz is higher than the efficiency at 1.80 GHz. This is because the return loss at 1.80 GHz is poorer than the return loss at 2.24 GHz. A good return loss ensures a better efficiency and vice versa.

Table 1 Simulated and Measured Gains of the reconfigurable MIMO Antennas

Table 2 Simulated and Measured efficiencies of the reconfigurable MIMO Antennas

3.6 Diversity Gain

The diversity gains of the antennas at different frequencies are evaluated using the statistical models summarized in [26]-[27]. The diversity gains are calculated from the post processing in CST® Microwave Studio. The cross polarization ratio (XPR) values used in the simulation are 5 dB for the indoor and 1 dB for the outdoor environment. Also, the mean elevation angles m_V and m_H, of the vertical and horizontal polarized wave distributions, used in the simulation are 100 for the indoor and 200 for the outdoor environment. Finally, the standard deviations of the horizontal and vertical polarized wave distributions are also required which are 150 for the indoor and 300 for the outdoor environment. The statistical model used for the elevation is Gaussian whereas, for the azimuthal plane the uniform model is used. The values of diversity gains, for indoor and outdoor environments, mentioned in Table III present a good diversity performance of the MIMO antennas. This is due to a better isolation between the MIMO antennas which enhances the diversity gain.

Table 3 Diversity Gains of the reconfigurable MIMO Antennas

4. Parametric Analysis

A parametric analysis was performed on the feed gap by changing its value from 0.83 mm to 1.63 mm and the effect on the s-parameter was observed. Another parametric analysis was carried out on the length and width of the extended metallic strip which contributes to the reconfigurability of the radiation pattern. The parametric analysis is only performed in the ‘ON’ state of the p-i-n diode when the metallic strip contributes to the reconfigurability of the radiation pattern. Each parametric analysis will be discussed in later subsections.

4.1 Coupling Gap of the Feed

A parametric analysis was performed on the coupling gap of the feed. This gap is represented as Gap_3 in the antenna design. It can be seen from the s-parameter curves in Fig. 9 that the gap value of 1.23 mm gives a better 6 dB bandwidth and a better return loss performance when compared to the other values of the coupling gap.

Fig. 9. Effect on the return loss by varying the coupling gap of the feed.

4.2 Length of Extended Metallic Strip

Another parametric analysis was performed on the length of the extended metallic strip which contributes to the reconfigurability of the radiation pattern. The length of the strip was changed from 0 mm to 4.5 mm. It can be seen from Fig. 10(a) that the effect of the change in length on the return loss is negligible and the 6 dB bandwidth stays nearly the same. The width is kept at the proposed value of 2 mm.

The effect of the variation of length on the radiation pattern is shown in Fig. 10(b) which shows that the change of length controls the directivity of the antenna. The length of 4.5 mm is selected as it gives a considerable change in the directivity without altering the frequency bandwidth. Also, if the length of the extended metallic strip is varied using the diode switches, the radiation pattern reconfigurability can be achieved in more than one direction. This can be seen from Fig. 9(b), where the direction of maximum radiation changes at each value of length.

Fig. 10. Effect on (a): the return loss and (b): the radiation pattern by changing the length of the extended metallic strip.

4.3 Width of Extended Metallic Strip

A parametric analysis was also performed on the width of the extended metallic strip which contributes to the pattern reconfigurability. The width of the strip was changed from 1 mm to 4 mm and the effect on the return loss and the radiation pattern was observed. It can be seen from Fig. 11 that the effect of changing the width on the return loss and the radiation pattern is almost negligible. The length is kept at the proposed value of 4.5 mm.

Fig. 11. Effect on (a): the return loss and (b): the radiation pattern by changing the width of the extended metallic strip.

5. Conclusions

A pair of printed and compact pattern reconfigurable MIMO antennas for mobile handsets was presented in this paper. The antennas are meandered monopoles fed through coupling for a small volume. Each antenna is wideband covering GSM 1800/1900, UMTS, WLAN, and several LTE frequency bands. Each antenna shows the reconfigurability of the radiation pattern in the bandwidth of 1.9 – 2.1 GHz. The pattern reconfigurability is achieved by connecting or disconnecting the additional metallic strip using the p-i-n diode switch. The simulation and measurement results strongly agree with minor discrepancies. The measured decoupling is better than 16 dB for all the frequency bands covered by the MIMO antennas. The proposed MIMO antennas present a good example of pattern reconfigurable antennas for modern mobile handsets. However, modified designs can be made to cover cellular frequency bands below 1 GHz and to achieve pattern reconfigurability in multiple frequency bandwidths. Moreover, the SAR analysis of the design will be included in future works.

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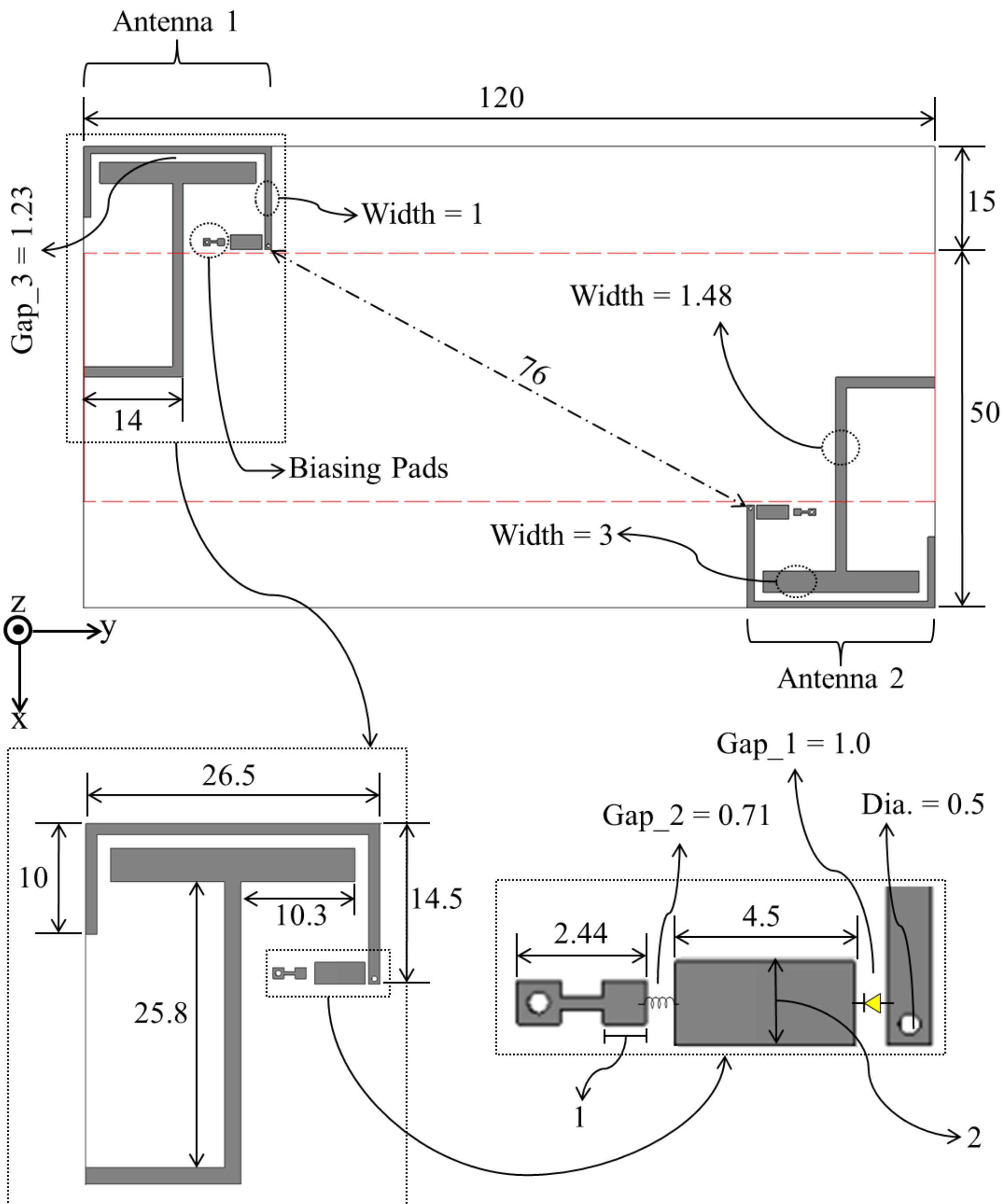


Fig. 1. Simulated Model of the reconfigurable MIMO antennas for mobile handsets. [Units: mm]

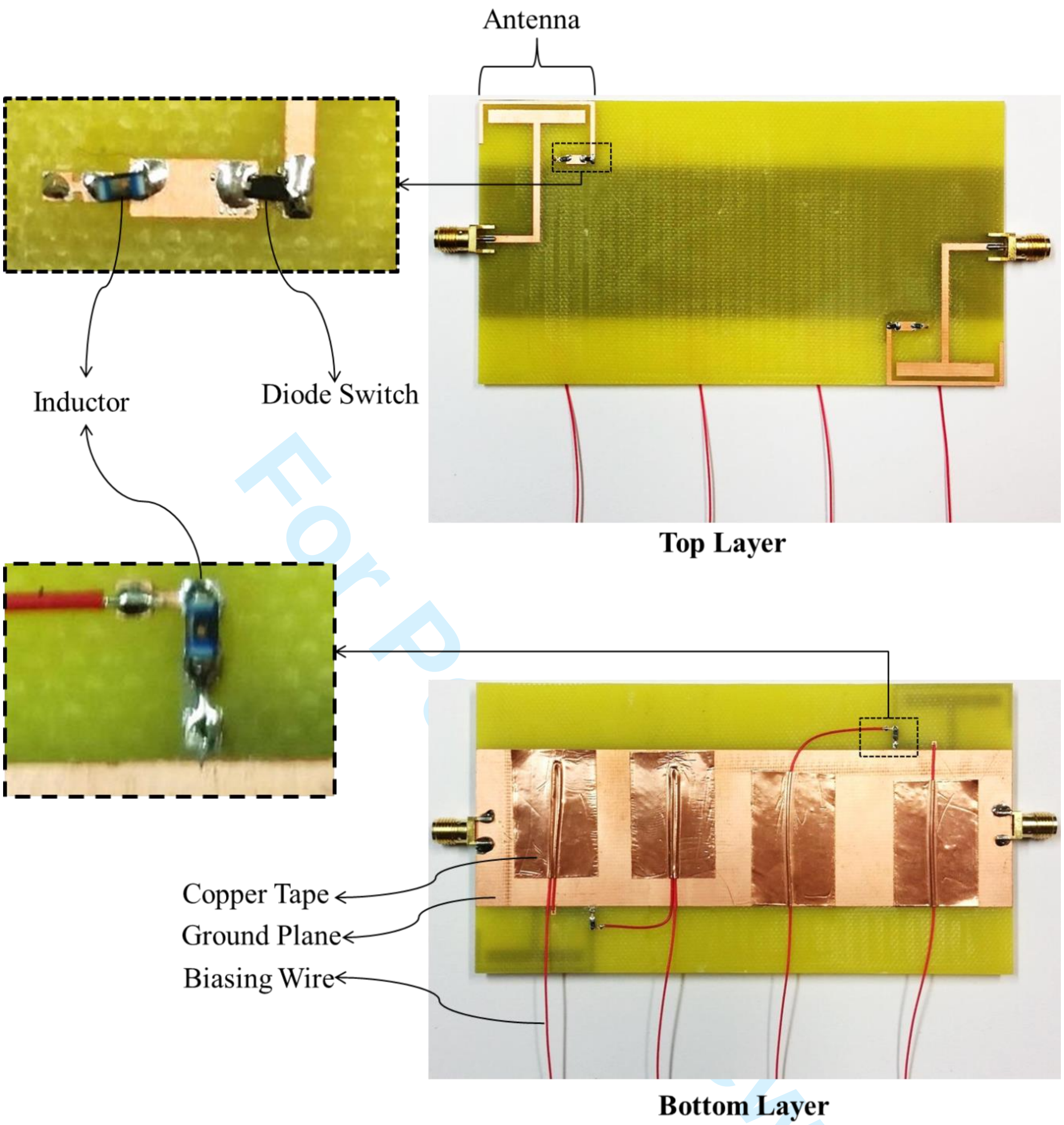


Fig. 2. Fabricated prototype of the reconfigurable MIMO antennas for mobile handsets.

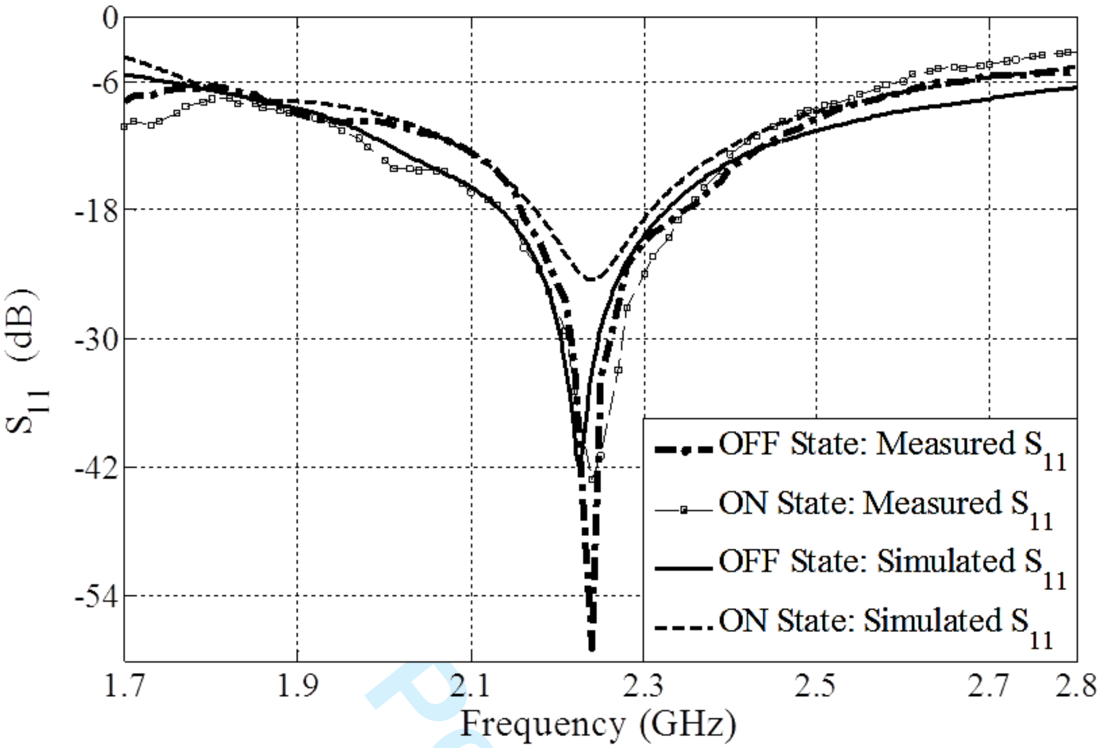


Fig. 3. Return loss of the reconfigurable MIMO antennas for mobile handsets.

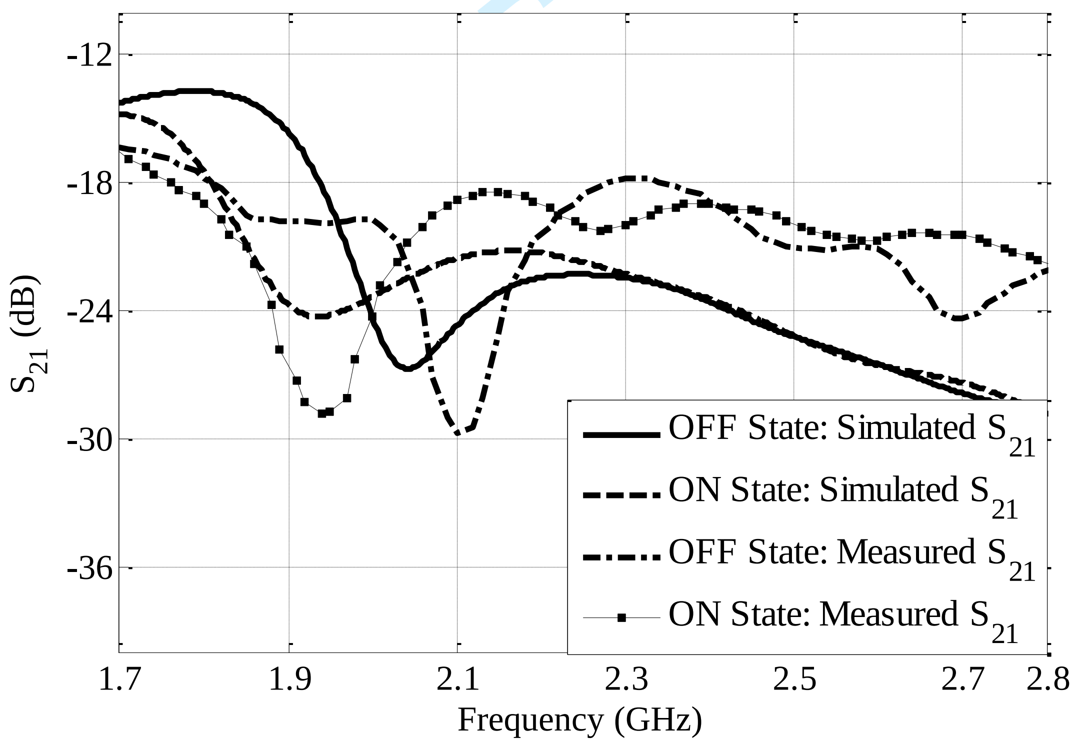


Fig. 4. Isolation curves for the reconfigurable MIMO antennas for mobile handsets.

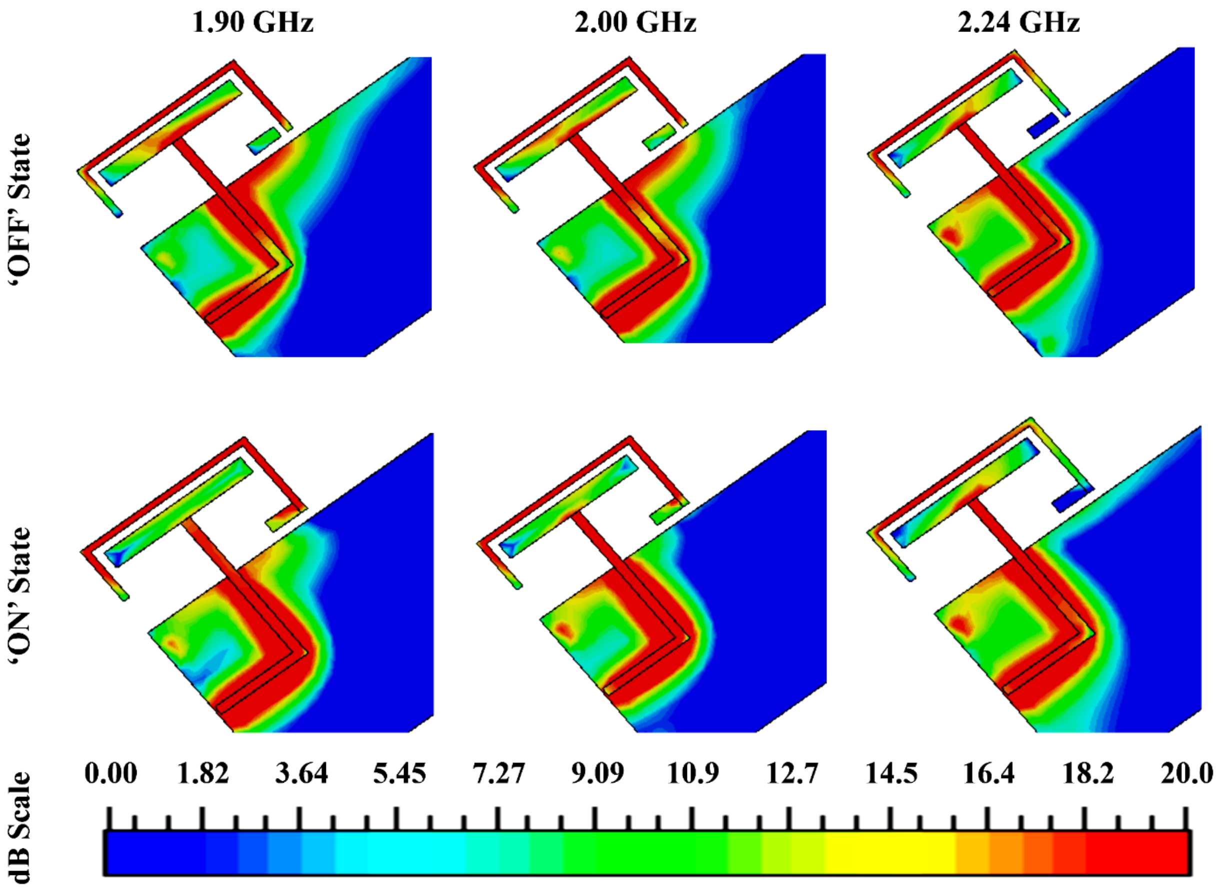


Fig. 5. Current distribution of the reconfigurable MIMO antennas at different frequencies.

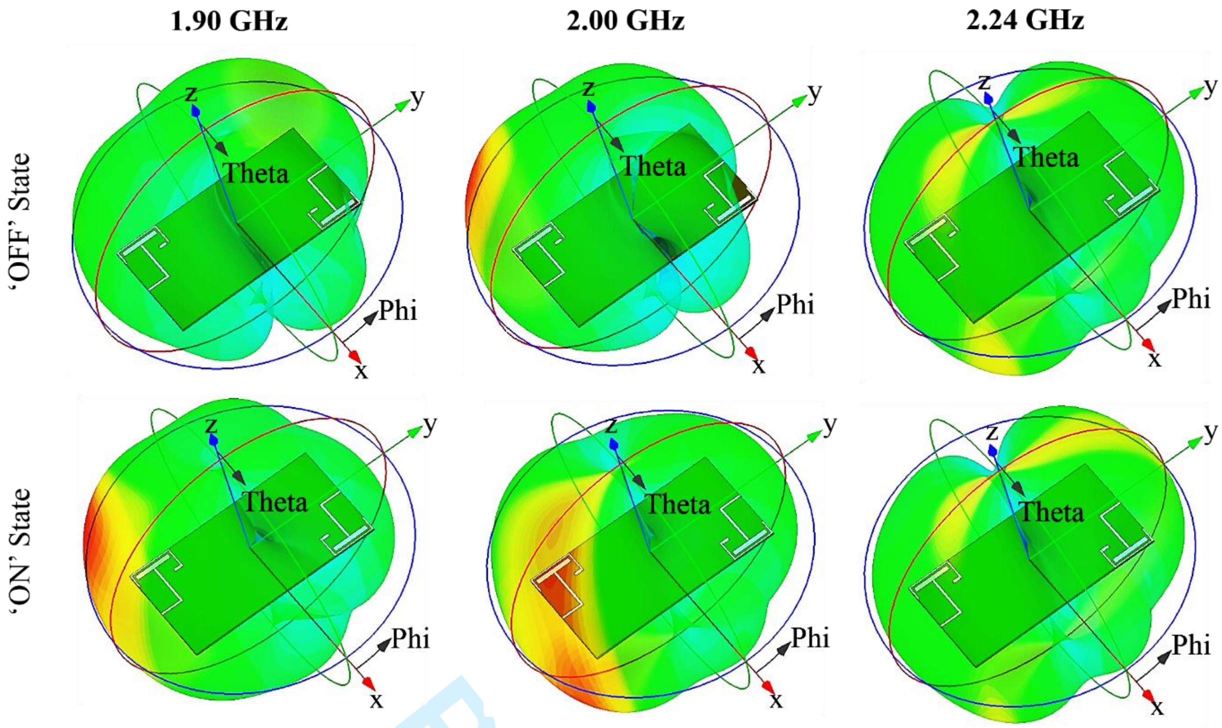


Fig. 6. 3D radiation patterns of the reconfigurable MIMO antennas for mobile handsets.

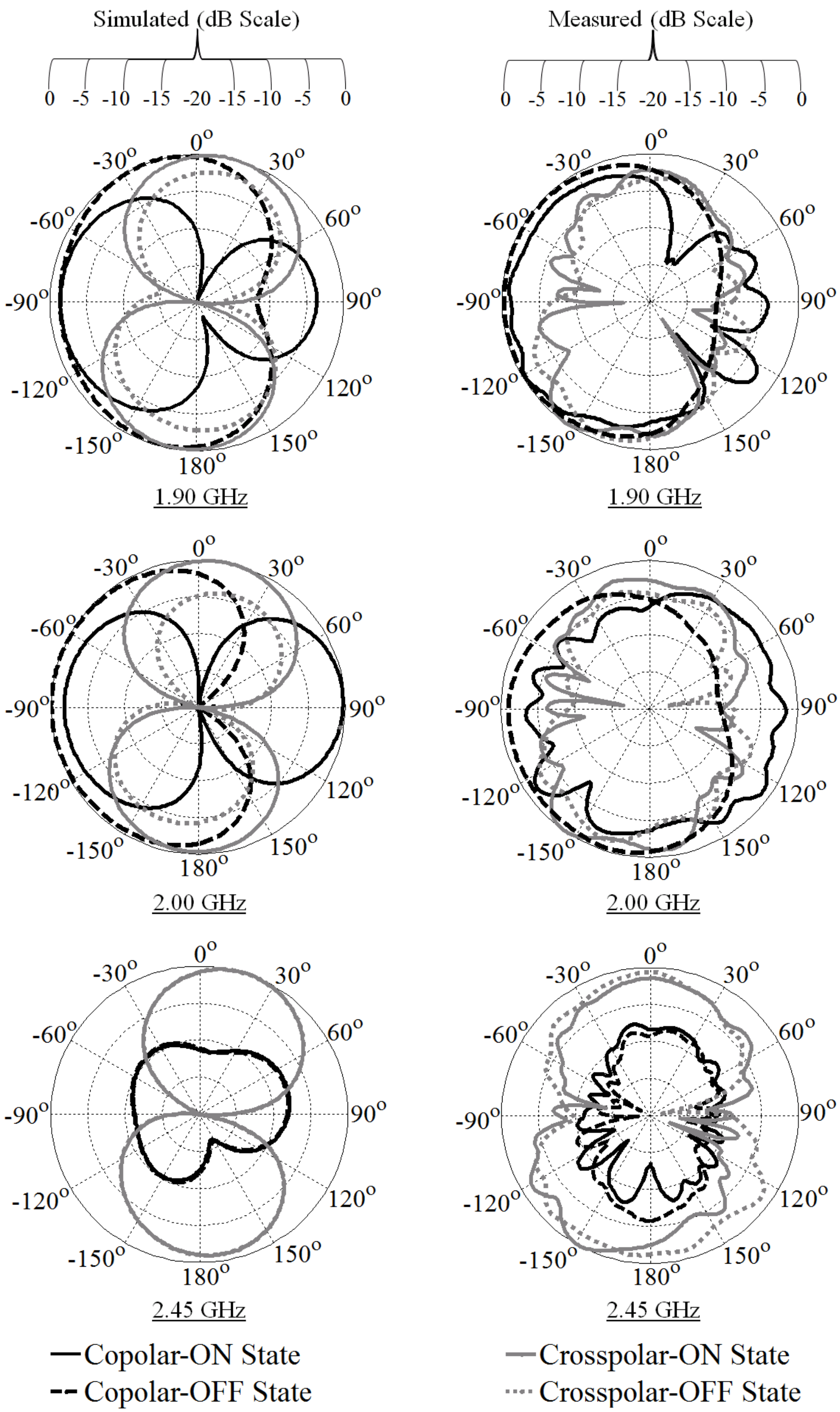


Fig. 7. Radiation patterns of the reconfigurable MIMO antennas for mobile handsets in x-z plane.

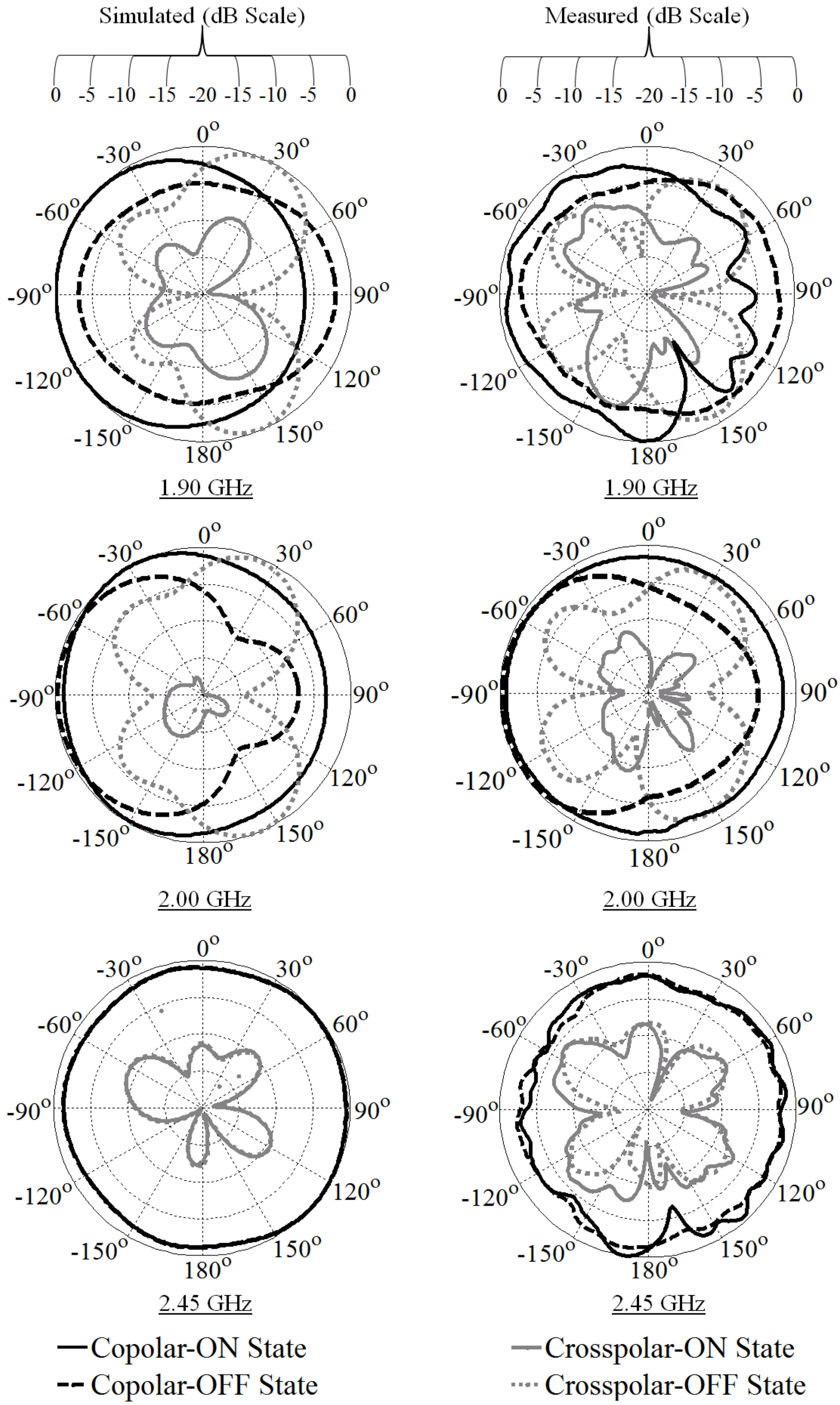
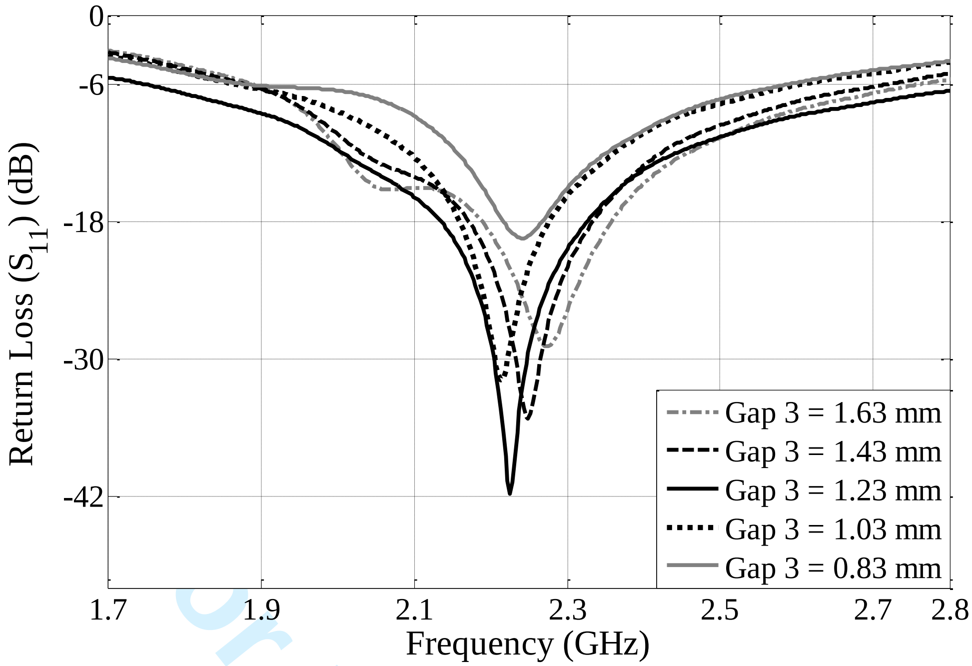


Fig. 8. Radiation patterns of the reconfigurable MIMO antennas for mobile handsets in y-z plane.



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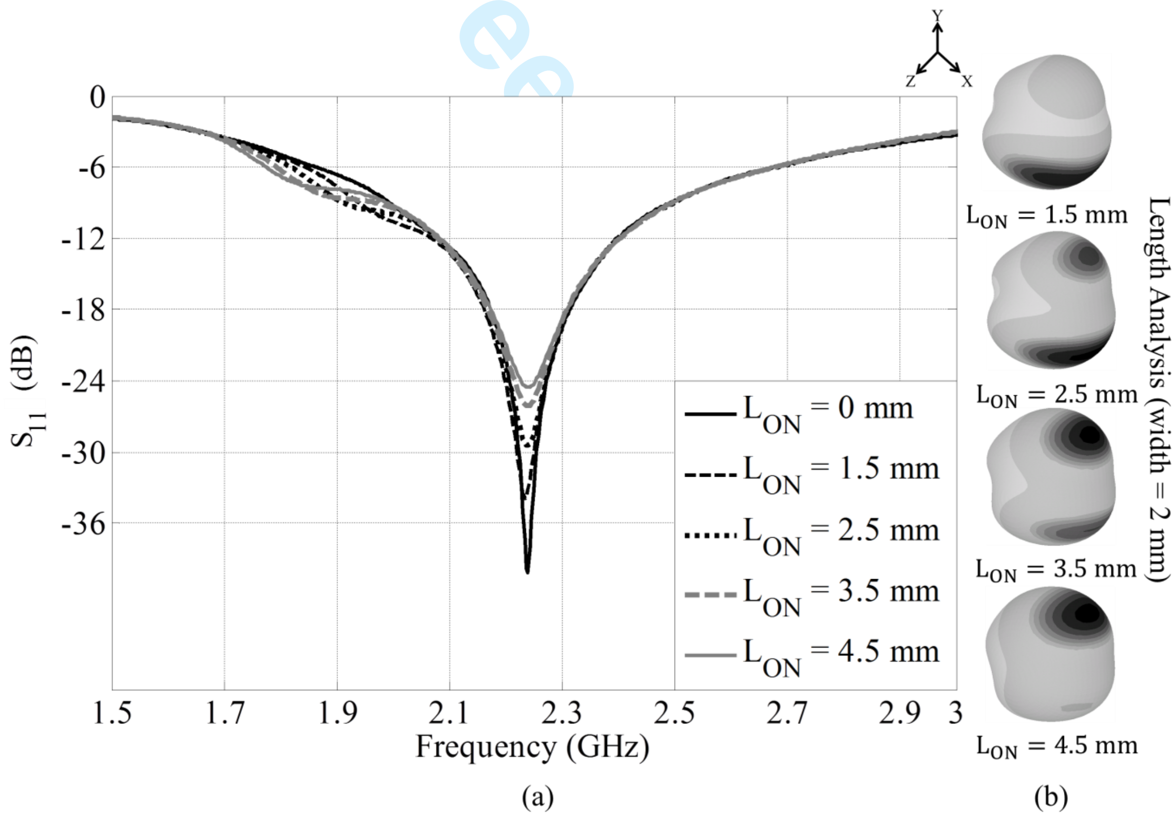

Fig. 10. Effect on (a): the return loss and (b): the radiation pattern by changing the length of the extended metallic strip.

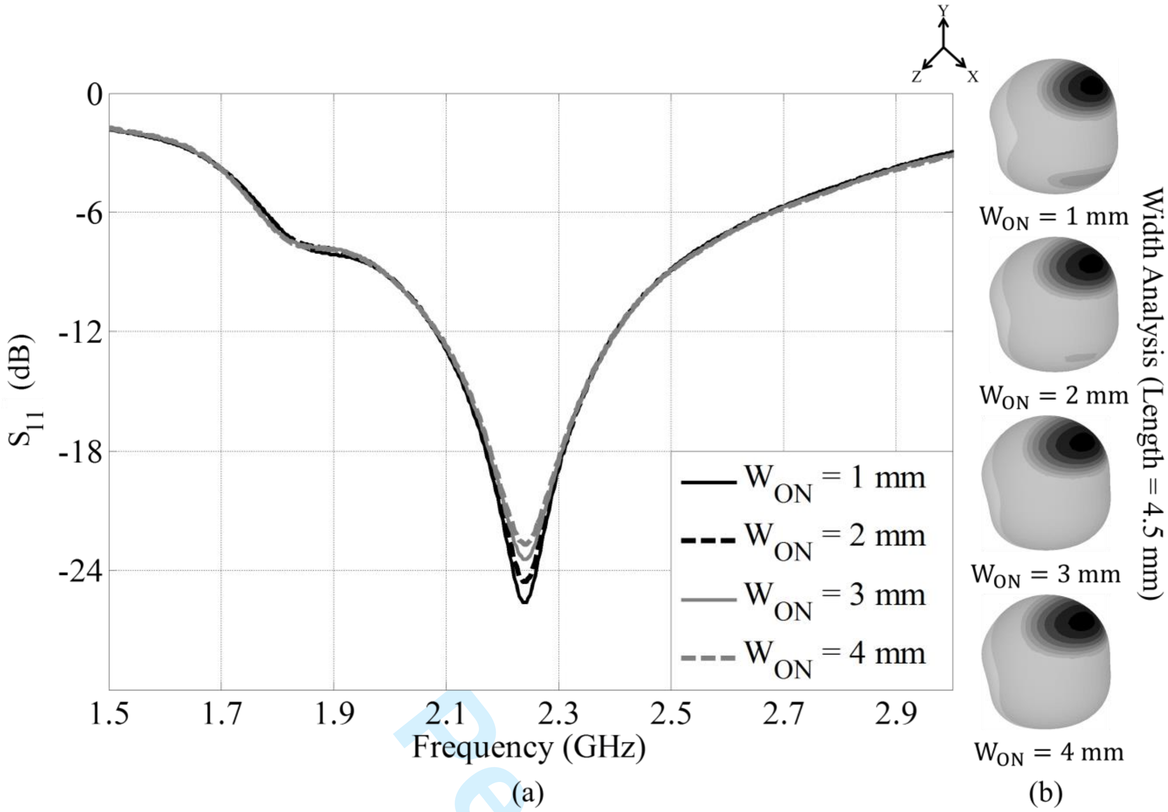

Fig. 11. Effect on (a): the return loss and (b): the radiation pattern by changing the width of the extended metallic strip.

Table 1 Simulated and Measured Gains of the reconfigurable MIMO antennas

Freq. (GHz)	Gain (dBi)			
	'ON' State		'OFF' State	
	Simulated	Measured	Simulated	Measured
1.80	1.17	0.96	1.60	1.31
1.90	1.54	1.19	1.47	1.12
2.24	1.84	1.53	1.76	1.64
2.45	1.24	0.92	1.12	0.83

Table 2 Simulated and Measured efficiencies of the reconfigurable MIMO antennas

Freq. (GHz)	Efficiency (%)			
	'ON' State		'OFF' State	
	Simulated	Measured	Simulated	Measured
1.80	53	46	62	56
1.90	71	64	63	58
2.24	81	75	81	73
2.45	70	63	68	64

Table 3 Diversity Gains of the reconfigurable MIMO antennas

Freq. (GHz)	Diversity Gain (dB)			
	'ON' State		'OFF' State	
	Outdoor	Indoor	Outdoor	Indoor
1.80	9.95	9.89	9.57	9.34
1.90	9.95	9.88	9.69	9.58
2.24	9.94	9.97	9.93	9.90
2.45	9.91	9.84	9.94	9.97