Research Article

Compact Broadband Dual ZOR Antenna for Multiband Smart Mobile Phone Applications

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A compact broadband dual zeroth-order resonator (ZOR) antenna is proposed for multiband smart mobile phone applications. The theory of broadband zeroth-order mode and multimode technique is used to design the proposed antenna covering GSM850 (824–894 MHz), GSM900 (880–960 MHz), DCS1800 (1710–1880 MHz), PCS1900 (1850–1990 MHz), W2100 (1920–2170 MHz), LTE2300 (2300–2400 MHz), LTE2600 (2500–2690 MHz), and Wi-Fi (2400–2500 MHz) bands. In order to achieve broadband operations, the proposed antenna consists of a large ZOR and a small ZOR that can generate and merge resonant frequencies of the negative-order, zeroth-order, and positive-order modes. The overall size of the antenna is 40 mm × 6 mm × 3 mm. The performance of the antenna is verified by both full-wave simulations and experiments. The measured impedance bandwidths of 3:1 VSWR in the low and high bands are 210 MHz (0.81–1.02 GHz) and 1170 MHz (1.69–2.86 GHz), respectively. The antenna provides omnidirectional radiation patterns and measured radiation efficiencies exceeding 43.3% and 47.5% for low and high bands, respectively. The antenna performance applied to the commercial smart mobile phone device is also presented. The measured results show that it has the active performance of good total radiated power, total isotropic sensitivity, and specific absorption rate, which can meet the requirement of the smart mobile phone.

1. Introduction

Recently, there has been a great demand for compact built-in antennas that have small size with broad bandwidth, multiband operation, and good radiation performance because of the rapid development of modern wireless communication systems such as 2G, 3G, long term evolution (LTE), LTE-Advanced, and Wi-Fi. Conventional planar inverted-L antennas (PILAs) and planar inverted-F antennas (PIFAs) are widely used as built-in antennas for smart mobile phones [1, 2]. However, due to the limited available volume that could be allocated for the built-in antenna, it is very difficult to achieve multiband and broadband operation for the conventional antennas.

The metamaterial (MTM) is artificially engineered material with unique electromagnetic properties, such as antiparallel phase and group velocities and zero propagation constant at specific nonzero frequency [3, 4]. In particular, various double-negative (DNG), epsilon-negative (ENG), and

mu-negative (MNG) composite right/left-handed transmission line (CRLH-TL) structures provide a conceptual design method for implementing zeroth-order resonator (ZOR) antennas [5–10]. In recent years, various ZOR antennas using the CRLH-TL structure have been introduced for mobile phone applications [11–15]. Although these CRLH-TL ZOR antennas provide the advantage of multiband antenna design and size reduction, they typically suffer from narrow bandwidth which could not fully cover multiband and broadband for 2G, 3G, LTE, and Wi-Fi operations.

In this study, a compact broadband dual ZOR antenna is proposed for multiband smart mobile phone applications. By using the theory of broadband zeroth-order mode and multimode technique, the proposed antenna can work covering GSM850 (824–894 MHz), GSM900 (880–960 MHz), DCS1800 (1710–1880 MHz), PCS1900 (1850–1990 MHz), W2100 (1920–2170 MHz), LTE2300 (2300–2400 MHz), LTE2600 (2500–2690 MHz), and Wi-Fi (2400–2500 MHz) bands. The proposed antenna comprises a large ZOR (LZOR)

FIGURE 1: Equivalent circuit model for the ideal CRLH-TL unit cell.

FIGURE 2: (a) Geometry of the proposed compact broadband dual ZOR antenna. (b) Detailed dimensions of the helix feed line ($a = 19$ mm, $b = 5$ mm, and $c = 0.3$ mm).

and a small ZOR (SZOR) whose broadband characteristics are achieved by merging negative-order, zeroth-order, and positive-order resonant frequencies. Details about these studies are provided in the following sections.

2. Design Considerations

An equivalent circuit model for an ideal CRLH-TL unit cell is represented as the combination of a LH series capacitor C_{LH} , LH shunt inductor L_{LH} , and conventional RH-TL, as shown in Figure 1. The conventional RH-TL with characteristic impedance Z_0 and physical length d has intrinsic series inductor L_{RH} and shunt capacitor C_{RH} . In order to generate broadband ZOR, the dispersion curve of the LH and RH region must be designed to have a gentle slope. As the value of C_{LH} becomes smaller, the resonant frequencies of the negative-order modes are increased, whereas those of the positive-order modes are decreased [16]. Moreover, the bandwidths of the zeroth-order and positive-order modes are extended by introducing large value of L_{LH} and small value of C_{RH} [17]. Consequently, the broadband performance of the dual ZOR antenna can be accomplished by merging these resonant frequencies of the negative-order, zeroth-order, and positive-order modes.

The proposed antenna is designed based on broadband dual ZOR. It is fabricated on a 40-mm long, 6-mm wide, and 3-mm thick FR4 substrate whose relative permittivity is 4.4 and loss tangent is 0.024. The system circuit board is also fabricated on the FR4 substrate with the dimension of 50 mm $\times$ 100 mm $\times$ 0.8 mm. The dimensions of the system

ground plane and the nonground region are 50 mm $\times$ 90 mm $\times$ 0.8 mm and 50 mm $\times$ 10 mm $\times$ 0.8 mm, respectively. The geometry of the antenna is illustrated in Figure 2. The LZOR is composed of a large folded plate with a gap and two helix lines. The SZOR consists of a small folded plate, a helix line, and a vertical strip line. The configuration provides two LH series capacitors, resulting from the gap on the large folded plate and the coupling gap between the helix feed line and the small folded plate. At the same time, the helix lines and the vertical strip line provide the LH shunt inductors. The folded plates act like the conventional RH-TL with series inductors and shunt capacitors. The helix lines and the vertical strip line affect the zeroth-order resonant frequencies for GSM900 and DCS1800 bands, respectively. The gap on the large folded plate affects the first-negative-order resonant frequency for GSM850 band. Finally, the loop path from the feeding to the ground 1 through the helix lines affects the higher order resonant frequencies for PCS1900, W2100, LTE2300, LTE2600, and Wi-Fi bands.

Figure 3 shows the simulated VSWR of the proposed antenna with variations of the gap on the large folded plate and the vertical strip line. The antenna was simulated by using ANSYS HFSS full-wave simulator. As the gap on the large folded plate is changed from 4.5 to 7.5 mm, the first-negative-order resonant frequency is shifted from 0.78 to 0.86 GHz. However, the zeroth-order resonant frequency in the low band is hardly varied at 0.92 GHz. As the width of the vertical strip line is varied from 0.3 to 1 mm, the zeroth-order resonant frequency in the high band is shifted from 1.78 to 1.96 GHz. However, the higher order resonant frequencies are

FIGURE 3: Simulated VSWR of the proposed antenna with variations of (a) the gap on the large folded plate and (b) the vertical strip line.

hardly varied at 2.08 and 2.62 GHz, respectively. Thus, the bandwidth enhancement of the proposed antenna is accomplished by merging these resonant frequencies of the low and high bands.

The surface current distributions of the proposed antenna at each resonant frequency were analyzed and shown in Figure 4. Most of the surface currents at 0.82 and 0.92 GHz concentrate on the helix feed line and helix line because of the first-negative-order and zeroth-order resonant mode of the LZOR. Most surface current at 1.78 GHz is formed along the helix feed line and vertical strip line due to the zeroth-order resonant mode of the SZOR. At 2.08 and 2.62 GHz, relative strong surface currents exist around the helix line and helix feed line, respectively, due to the higher order resonant modes of the LZOR.

3. Experimental Results

Figure 5 shows the fabricated prototype antenna, and the simulated and measured VSWR of the antenna are shown in Figure 6. The measured results were obtained using KEYSIGHT E5071C vector network analyzer. According to the measured results, the zeroth-order resonant frequencies were 0.94 and 1.82 GHz in the low and high bands, respectively. The first-negative-order resonant frequency in the low band was 0.84 GHz, and the higher order resonant frequencies in the high band were 2.1 and 2.4 GHz. In addition, the measured impedance bandwidths (3:1 VSWR) in the low and high bands were 210 MHz (0.81–1.02 GHz) and 1170 MHz (1.69–2.86 GHz), corresponding to approximately 22.95% and 51.43% fractional bandwidths, respectively. The slight difference between the simulated and measured results was observed. This is mainly due to the fabrication tolerance resulting from the structural parameters such as the helix line, coupling gap, and FR4 substrate.

The measured radiation gain patterns of the fabricated antenna at 0.84, 0.94, 1.82, 2.1, 2.4, and 2.69 GHz are plotted

in Figure 7. The radiation patterns in x - y plane were nearly omnidirectional characteristics as a dipole antenna. The measured peak gains at 0.84, 0.94, 1.82, 2.1, 2.4, and 2.69 GHz were 0.21, 0.69, 1.63, 0.95, 2.59, and 1.62 dBi, respectively. The measured radiation efficiency was 45.8% at 0.84 GHz, 52.9% at 0.94 GHz, 68.8% at 1.82 GHz, 53.2% at 2.1 GHz, 68.5% at 2.4 GHz, and 59.4% at 2.69 GHz. The measured radiation efficiency and peak gain over the operating bands are shown in Figure 8. The peak gain varied from -0.27 to 1.23 dBi in the low band and from 0.28 to 2.96 dBi in the high band. The radiation efficiencies were above 43.3% and 47.5% in the low and high bands, respectively.

The proposed antenna applied to the commercial smart mobile phone device was also studied. The device can work covering GSM850, GSM900, DCS1800, PCS1900, and W2100 bands. The antenna was equipped at the bottom of the device, and the antenna area is shown in Figure 9. The size of the device was 58 mm $\times$ 115 mm $\times$ 14 mm. The active performances of the proposed antenna and the original antenna of the device such as total radiated power (TRP), total isotropic sensitivity (TIS), and specific absorption rate (SAR) were measured and compared. The TRP and TIS were measured in an anechoic chamber, and the SAR (1g SAR) was measured using SPEAG DASY4 SAR measurement system. The 1g SAR limit is 1.6 mW/g in a 1g average mass in the shape of a cube. The antenna input powers of GSM850, GSM900, DCS1800, PCS1900, and W2100 bands were 33, 33, 30, 30, and 23 dBm, respectively. The measured TRP and TIS in free space, with a hand phantom, and with a head phantom at each operating band are presented in Table 1. The measured SAR values with the left and right head phantoms at each operating band are also shown in Table 1.

Figure 10 shows a comparison of the measured TRP, TIS, and SAR values of the proposed antenna and the original antenna of the device. For all five bands, the TRP and TIS of the proposed antenna were equal to or better than those of the original antenna. The SAR values of the proposed antenna

FIGURE 4: Simulated surface current distributions of the proposed antenna at (a) 0.82, (b) 0.92, (c) 1.78, (d) 2.08, and (e) 2.62 GHz.

were higher than that of the original antenna except for W2100 band. The reason is that the head TRP of the proposed antenna is higher than that of the original antenna. Despite the same reason, the SAR values of the proposed antenna in W2100 band were substantially reduced. It seems that the surface currents concentrate on the helix line due to the higher order resonant modes of the LZOR, so that the electromagnetic field of the antenna spreads to the system ground due to

changes in the ground condition. The SAR values of the proposed antenna were below 0.88 mW/g in all five bands, and considerably lower than the 1 g SAR limit. This clearly shows that the proposed antenna is less dependent on the ground condition of the device than the conventional antenna structure. Thus, the measured results show that it has the active performance of good TRP, TIS, and SAR, which can meet the requirement of the smart mobile phone.

TABLE I: Measured TRP, TIS, and SAR values of the proposed antenna and the original antenna of the device.

Band	GSM850	GSM900	DCS1800	PCS1900	W2100
TRP [dBm]					
Free					
Original	25.68	27.18	24.79	26.65	20.42
Proposed	28.53	28.72	25.68	26.70	20.60
Hand					
Original	19.63	19.89	22.61	22.43	16.94
Proposed	22.80	24.82	23.26	23.35	17.47
Head					
Original	21.25	23.00	20.02	22.42	17.06
Proposed	24.17	23.57	21.70	23.52	17.51
TIS [dBm]					
Free					
Original	-100.65	-97.50	-105.35	-105.77	-106.17
Proposed	-102.76	-103.16	-105.67	-105.93	-106.68
Hand					
Original	-88.01	-86.80	-101.49	-102.00	-103.11
Proposed	-94.15	-95.60	-102.57	-102.85	-103.17
Head					
Original	-97.75	-95.86	-100.60	-102.79	-103.39
Proposed	-97.84	-97.48	-102.14	-103.38	-103.51
SAR [mW/g]					
Left					
Original	0.24	0.44	0.32	0.36	1.46
Proposed	0.58	0.68	0.35	0.41	0.88
Right					
Original	0.22	0.38	0.20	0.25	0.77
Proposed	0.52	0.62	0.25	0.34	0.76

FIGURE 5: Photograph of the fabricated prototype antenna.

4. Conclusion

In this study, a compact broadband dual ZOR antenna was proposed and investigated for GSM850, GSM900, DCS1800, PCS1900, W2100, LTE2300, LTE2600, and Wi-Fi operations. In order to achieve broadband operations, the proposed antenna is composed of a LZOR and a SZOR that can generate and merge resonant frequencies of the negative-order, zeroth-order, and positive-order modes. The measured impedance bandwidths of 3:1 VSWR in the low and high bands are

FIGURE 6: Simulated and measured VSWR of the proposed antenna.

22.95% and 51.43%, respectively. The antenna provides omnidirectional radiation patterns and measured radiation efficiencies exceeding 43.3% and 47.5% for low and high bands,

FIGURE 7: Measured radiation gain patterns of the proposed antenna at (a) 0.84, (b) 0.94, (c) 1.82, (d) 2.1, (e) 2.4, and (f) 2.69 GHz.

FIGURE 8: Measured radiation efficiency and peak gain of the proposed antenna.

FIGURE 9: Photograph of the commercial smart mobile phone device for the active performance measurement.

respectively. In addition, the proposed antenna applied to the commercial smart mobile phone device has good active

performance of TRP, TIS, and SAR, which can meet the requirement of the smart mobile phone. The configuration of

FIGURE 10: Comparison of the measured active performances of the proposed antenna and the original antenna of the device. (a) TRP. (b) TIS. (c) SAR values.

the antenna is flexible to achieve compact size, good radiation performance, and broadband operation. Therefore, the proposed antenna can be easily integrated in various multi-band smart mobile phones and used for multimode wireless communication devices.

Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

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