Compact Tri-Band Monopole Antenna with Dual Quasi-Lumped Resonators

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Abstract

A compact tri-band coplanar waveguide (CPW)-fed monopole antenna is proposed. By introducing dual quasi-lumped series resonators, the monopole antenna shows two additional resonance modes at lower frequencies, where it is electrically small when compared to the guided wavelength. The antenna is designed for the GPS, 2.4-GHz WLAN, and WiMAX applications.

Keywords : Tri-band, Monopole antenna, Coplanar waveguide (CPW)-fed, Quasi-lumped resonators

1. Introduction

With the fast development of wireless services, such as the global positioning system (GPS), wireless local area network (WLAN), and worldwide interoperability for microwave access (WiMAX), modern portable devices urge for integration with multiple wireless applications. A conventional multiband antenna uses several resonating paths to cover the desired frequency bands [1]. However, it suffers from the bulky size and is unsuitable for portable handheld devices. To miniaturize the antenna size, a variety of compact monopole antennas have been developed [2]-[4]. The monopole in [2] uses only one resonator to generate two frequency bands. Another design utilizing the open-loop resonators as parasitic element for multiband operation was discussed in [3]. Furthermore, a miniaturized multiband monopole antenna using metamaterial transmission-line has been studied [4].

In this paper, we propose and investigate a compact tri-band CPW-fed monopole antenna, covering the spectra including the GPS band (1.575 GHz), the 2.4-GHz WLAN band (2.4 - 2.48 GHz), and the WiMAX band (3.4 - 3.7 GHz). The prototype is developed based on a planar monopole with an operating band at 3.6 GHz. Dual quasi-lumped series resonators are then added to the monopole to generate two additional resonance modes. With the help of the quasi-lumped resonators, two extra frequency bands, operating at the GPS and WLAN frequencies, are introduced. In the meantime, the size of the antenna element, $10.5 \times 15.5\ mm^2$, is small when compared to the operating frequency. It makes the proposed design categorized as an electrically small antenna at low frequencies. The design concept, operation principle, and simulated and experimental results are discussed throughout the paper.

2. Antenna Design

Fig. 1 shows the layout of the proposed antenna. A low-cost FR4 substrate ($\varepsilon_r = 4.3$, $\tan \delta = 0.02$, and $h = 1.6$ mm) was used. The prototype design begins with a conventional planar monopole operating at the WiMAX band (3.6 GHz). For the purpose of antenna miniaturization, the size of the radiator and ground plane are kept unchanged throughout the manipulation. To introduce two additional bands at the GPS and 2.4-GHz WLAN frequencies, two series resonators, formed by quasi-lumped components, are etched on the monopole radiator without any extra occupied size. As the quality factors of the quasi-lumped resonators are relatively high, the two resonance modes are limited to narrowband operations, making them especially suitable for GPS and WLAN applications. Fig. 2(a) and (b) shows the equivalent circuit model of the proposed antenna. The quasi-lumped resonators are formed by the meander line inductors (L_1 and L_2), interdigital capacitors (C_1 and C_2), and the straight-line inductor L_3. The additional inductor accounts for the current flow on the remaining part of the plate; the resistor R represents the radiation resistance. A complete circuit model is plotted in Fig. 2 (b). The reactive loadings on the monopole are equivalent to a pair of series resonators, parallel connected with each other in the model. The resonance frequencies are:

$$f_1 = 1/2\pi\sqrt{C_1(L_1 + L_3)} \quad (1)$$

$$f_2 = 1/2\pi\sqrt{C_2(L_2 + L_3)} \quad (2)$$

It should be emphasized that due to the lack of a shunt inductive path to the ground plane, this design cannot be viewed as a zeroth-order resonator in the short-ended case. The radiation efficiencies at the two frequencies, which are not very high, support the above claims. This observation contradicts to the claim in [4].

By adjusting the lengths of the meander line inductors and interdigital capacitors, the resonance frequencies of the two resonators can be controlled independently. It should be noted that the inductor L_3 is fixed for the monopole mode at 3.6 GHz. The resonance frequency (f_1) caused by the outer series resonator is designed for the GPS band at 1.575 GHz; meanwhile, the resonance of the inner resonator (f_2) contributes to the operation band at the WLAN radio of 2.4 GHz. The tapered profile at the bottom of monopole plate is used for achieving impedance matching. The surface current distributions on the radiators are demonstrated in Fig. 3 for all three modes. The currents are mainly concentrated on the corresponding resonators for the GPS and WLAN applications; on the other hand, at 3.6 GHz, the proposed antenna functions as if a conventional monopole antenna.

3. Experimental Results and Discussion

The proposed monopole is simulated using HFSS. Due to the resonator loading, the SMA adaptor should be included in the simulation to account for the parasitic coupling. The dimensions of the antenna are optimized as w_g = 15, w_{feed} = 1.6, w_a = 8, l_g = 16, l_{feed} = 5, l_a = 10.5, and s_{feed} = 0.5. The remainder parameters are l_1 = 2, l_2 = 5.4, l_3 = 0.4, l_4 = 1.75, l_5 = 0.5, l_6 = 1, l_7 = 2, l_8 = 0.8, l_9 = 1.3, l_{10} = 2.75, l_{11} = 0.3, l_{12} = 2.9, l_{13} = 3.15, w_1 = 2.4, w_2 = 0.2, w_3 = 1.3, w_4 = 0.9, w_5 = 1.7, and w_6 = 3. All units are in millimeter. The line width and gap width in the meander line inductors and interdigital capacitors are both 0.25 mm. The angles of inclination, shown in Fig. 1(b), are θ_a = 30° and θ_b = 48°. A comparison of the simulated and measured $|S_{11}|$ is displayed in Fig. 4. The measurement was taken by an Agilent network analyzer E8363B. The frequency shift in the WLAN band is caused by the fabrication variation. According to the measured results, the operating bands with $|S_{11}|$ < -10 dB are from 1.57 - 1.62, 2.27 - 2.33, and 3.24 - 4.45 GHz. At the WiMAX band, the somewhat impedance mismatch in the monopole mode is due to the nonideal unbalanced current on the connecting coaxial cable. Fig. 5 indicates the xz- and yz-plane normalized radiation patterns of the proposed antenna at all three frequencies. The data were measured in an anechoic chamber by the NSI-700S-90 scanner at National Taiwan University of Science and Technology. The measured peak gains are 0.31, -0.91, and 2.87 dBi at the 1.58, 2.3, and 3.6 GHz. The radiation efficiencies, according to the measurement, are 26.9, 26.7, 52.3 %.

4. Conclusion

A tri-band compact monopole antenna, loaded with a pair of quasi-lumped resonators, is proposed in this paper. The new design is a CPW-fed uniplanar structure with a low-cost via-free fabrication process. The reactive loadings on the monopole antenna function as two series resonators to introduce dual low-frequency modes at 1.575 and 2.4 GHz. The size of antenna element is only 10.5 × 15.5 mm^2, which is 0.0045 λ_0^2 at the lowest operating frequency. It can find applications in modern smart portable devices.

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Acknowledgments

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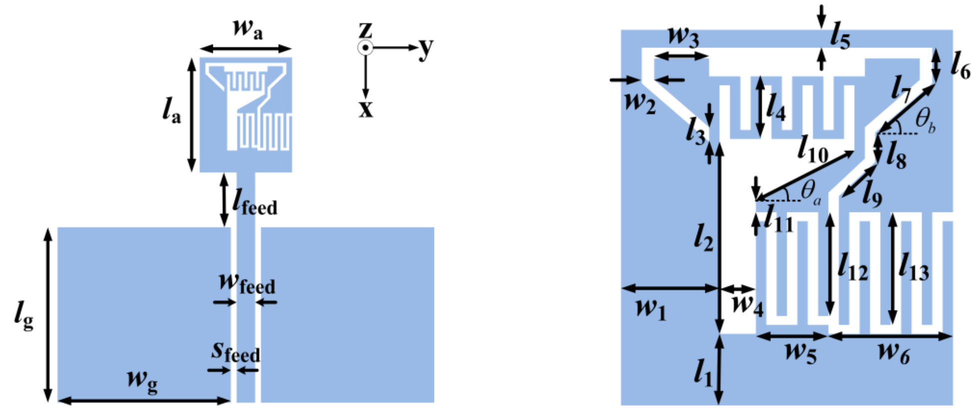
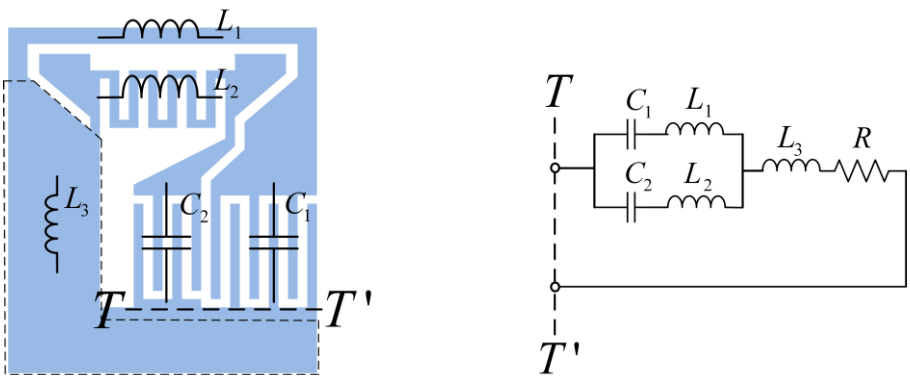


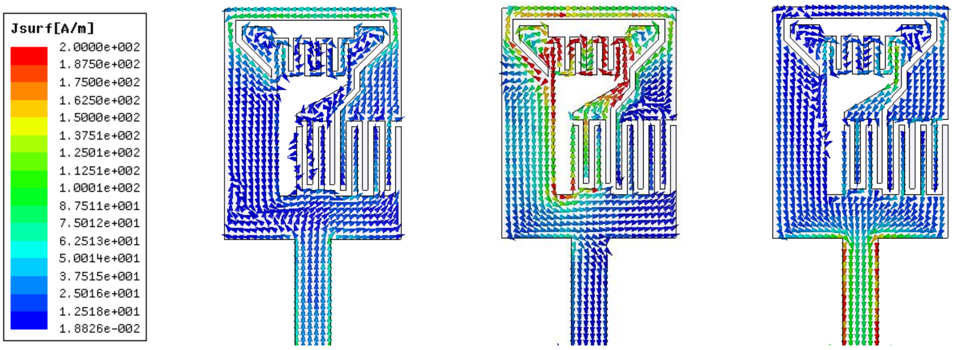
(a) (b)

Figure 1: The Proposed Tri-Band Compact Monopole with Dual Quasi-lumped Resonators: (a) The Whole Structure; (b) An Enlargement of the Resonators.



(a) (b)

Figure 2: The Equivalent Circuit Model of the Proposed Monopole Element: (a) Individual Components; (b) the Whole Circuit Model.



(a) (b) (c)

Figure 3: Surface Current Distributions on the Radiator at (a) 1.575, (b) 2.4, and (c) 3.6 GHz.

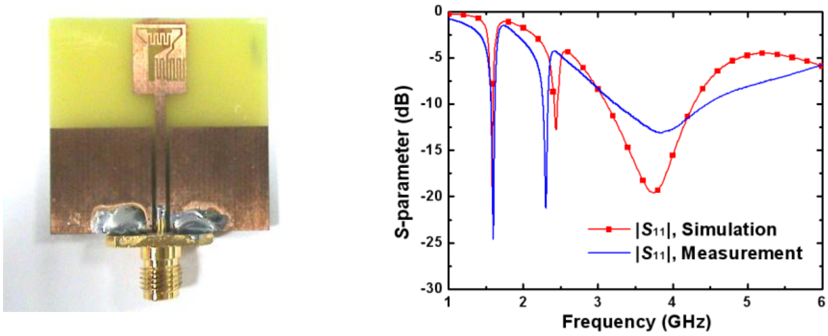
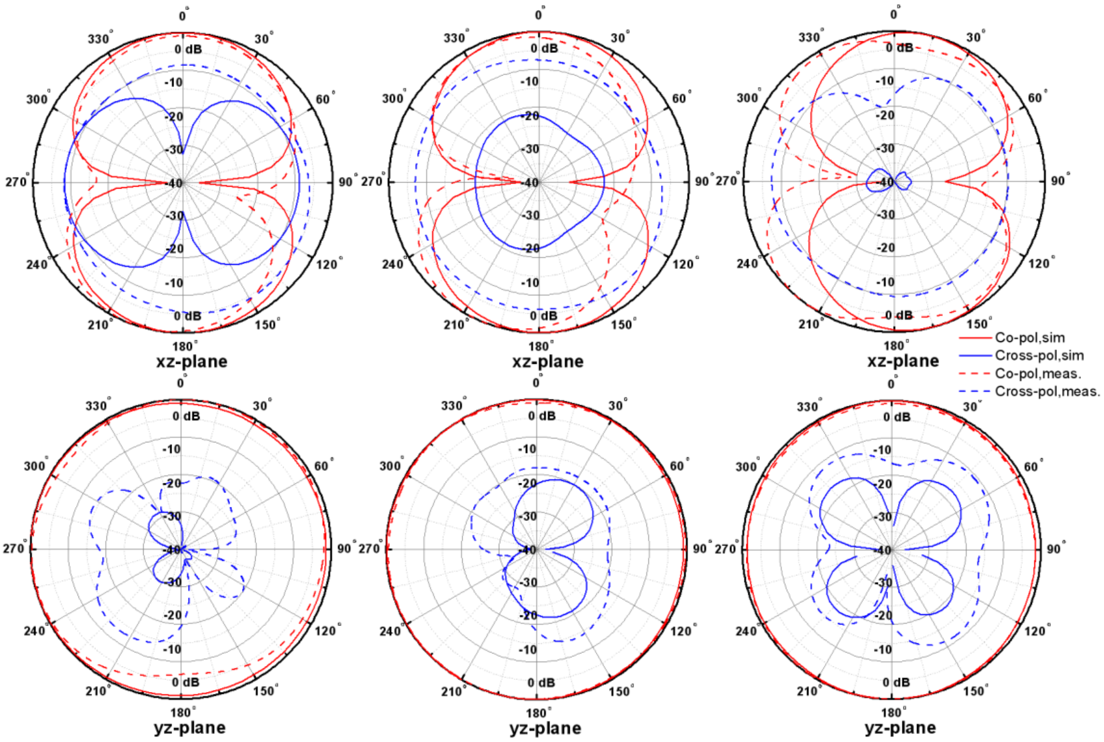


Figure 4: The Simulated and Measured $|S_{11}|$ of the Proposed Antenna.



(a) (b) (c)

Figure 5: Simulated and Measured Normalized Radiation Patterns of the Proposed Antenna in the xz- and yz-plane at (a) 1.58, (b) 2.3, and (c) 3.6 GHz.