Compact Triple-band Planar Monopole Antenna with Single Metamaterial Unit

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Abstract— In this paper, we present a novel design for compact triple-band planar monopole antenna by integrating with a single metamaterial unit. The single metamaterial unit (single loop ring resonator which can exhibit three resonances) is set as part of radiation patch. The whole antenna structure including the metamaterial inspired patch and optimized ground plane contribute to an eight-like radiation pattern due to the monopole antenna configuration. Such antenna is first numerical analyzed and optimized by finite element method based simulator (Ansoft HFSS V14), and then the fabricated antenna sample are measured within a commercial near field measurement system (Satimo SG 32). Both numerical and experimental results demonstrate that the designed antenna exhibits three distinct operating frequencies and the eight-like radiation patterns at such three frequency bands are all obtained. At the same time, a compared conventional monopole antenna with the same dimensional sizes is also analyzed. Results show that the metamaterial inspired antenna has more compact size. The proposed novel antenna can be flexibly used for modern wireless communications including both stationary and portable terminal areas.

1. INTRODUCTION

In recent years, due to the breakthrough of modern wireless communications such as the wireless personal communications, near field communication, radio frequency identifications, wireless sensor networks, as well as the internet of things, the developments of compact and multi-band/multi-mode communication components have been the main barriers in such science and engineering area. In particularly, the first component used to send/receive the electromagnetic wave signals is the antenna. To achieve the miniaturization and multi-band/multi-mode requirements, comprehensive researches have focused on the multi-band antennas and/or ultra-wideband antennas. For the virous kinds of reported multi-band antennas, monopole antenna can attract most considerations in recent research progress, because of the compact sizes, flexible configurations, low fabrication costs, and well radiation characteristics. Some of the monopole antenna configurations are, for examples, circular ring patch antenna [1], I-shaped/U-shaped slot defected planar antenna [2], spirograph planar antenna [3], and spiral ring resonators inspired antenna [4]. These multi-band monopole antennas were achieved by designing virous resonator configurations to enhance operating frequencies, improve radiation pattern and at the same time reduce cross-polarization characteristics.

On the other hand, since the first realization of the so called metamaterial in 2000 [5], it has been proposed that the metamaterial can be widely used for designing novel antenna to improve most of the characteristics of conventional antennas [6]. For the monopole antenna integrated with metamaterial, some novel configurations have been reported elsewhere, e.g., the band-notched UWB planar antennas [7] with a modified complementary split-ring resonator, and the metamaterial-inspired dual-band monopole antennas [8]. Taking into deep consideration for the previously mentioned metamaterial-inspired dual-band antenna, two different resonators were integrated as the radiation part to achieve dual-band properties. In this paper, we propose two novel configurations of planar monopole antennas consisting of a single-loop resonator (SLR) as part of the radiation patch and fed with coplanar waveguide (CPW) and microstrip transmission lines, respectively. We also compare the operating frequency band and radiation characteristics with the conventional single band antennas to show the excellence of our proposed antennas. The SLR used in this paper has three distinct resonances states [9], which can be used to achieve the three operating frequency bands in the ranging of 2.4 to 6 GHz. We perform both numerical and experimental method to discuss such antennas. The proposed triple-band antennas possess compact size and exhibit very well eight-like radiation patterns and low cross-polarisations, which have potential applications for wireless communications.

2. ANTENNAS DESIGN AND FABRICATIONS

The schematic geometries of the two proposed metamaterial inspired triple-band antennas and the corresponding conventional single-band monopole antennas are shown in Fig. 1 respectively. The SLR considered as the half part of the radiation patch is placed on the upper side of the whole patch. From previous numerical analysis, there is a huge impedance mismatch between the resonator and the conventional 50-Ω feed line. Therefore, the bottom part of the patch is used to match the impedance between the SLR resonator and the feed line. The whole radiation patch is printed on a 0.8 mm-thick Rogers 4003 substrate (dielectric constant $\epsilon_r = 3.55$ and loss tangent $\tan\delta = 0.0027$) with a dimension of $D \times L = 30\,\text{mm} \times 22\,\text{mm}$. For the first antenna fed by CPW, the ground plane and SLR are printed on the same side of the substrate and the dimensional parameters are optimized as shown follows, by Ansoft HFSS software, $a = 13.1\,\text{mm}$, $b = 13.6\,\text{mm}$, $c = 6.4\,\text{mm}$, $w_1 = 1.9\,\text{mm}$, $w_2 = 0.85\,\text{mm}$, $w_3 = g_3 = g_4 = 0.4\,\text{mm}$, $h = 7.5\,\text{mm}$, $g_1 = 0.2\,\text{mm}$, and $g_2 = 0.3\,\text{mm}$. For the second antenna fed by microscript line, the ground plane is placed on the opposite side of the substrate and its dimensional parameters are the same as the first antenna, except that $w_1 = 1.8\,\text{mm}$ and $w_2 = 1.1\,\text{mm}$ for the impedance match. At the same time, the corresponding conventional signal band monopole antennas for the two kinds of fed lines are also designed with the same radiation patch size and ground plane size as shown in Figs. 1(a) and (c). Finally, through standard printed circuit board fabrication techniques, all of the four antennas are fabricated. In both simulation and measurement procedures, the 50-Ω micro-miniature coaxial connectors (operated from DC to 6 GHz) are used to simulate and test the antennas for reducing the effects of connectors on the antennas.

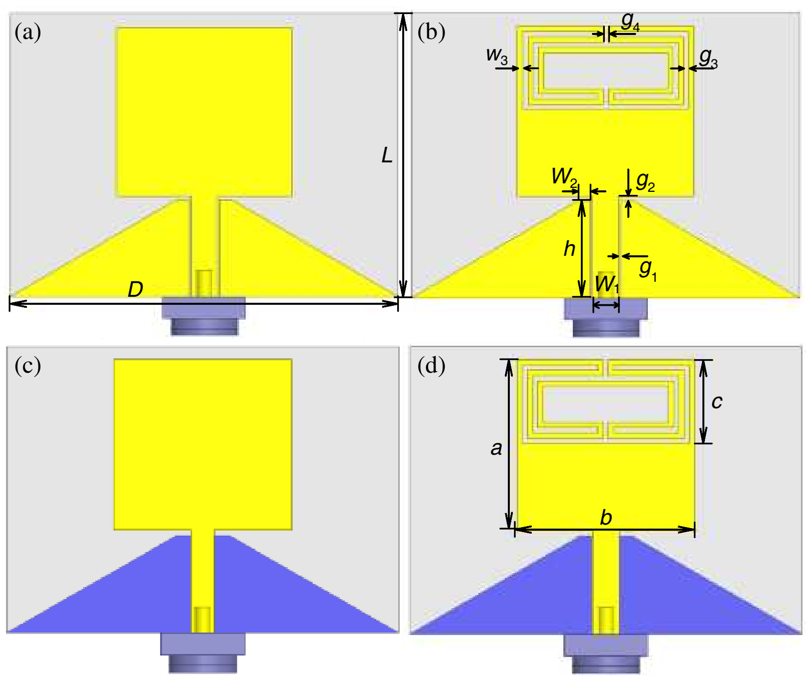

Figure 1: Schematic representations and the geometries of (a) conventional single-band monopole antenna fed by CPW, (b) metamaterial inspired triple-band antenna fed by CPW, (c) conventional single-band monopole antenna fed by microscript line, and (d) metamaterial inspired triple-band antenna fed by microscript lin.

3. SIMULATIONS AND MEASUREMENTS

Firstly, the simulated and measured reflection properties of the four proposed antennas are shown in Fig. 2. It can be known that, for the metamaterial inspired antennas, both the numerical and experimental results show three dips around 2.4, 3.85 and 4.9 GHz for the CPW fed antenna, and 2.4, 3.9 and 5.05 GHz for the microscript fed antenna. The simulated and measured results shown in Figs. 2(a), (c) and (b), (d) imply a good agreement between such two results. In the higher frequency band (4.5–6 GHz), there are slight frequency shifts for both kind of metamaterial inspired antennas. These shifts are mainly resulted from the mutual coupling introduced by connectors and soldering in the experiment at high frequencies. From the measured results, one can obtain three

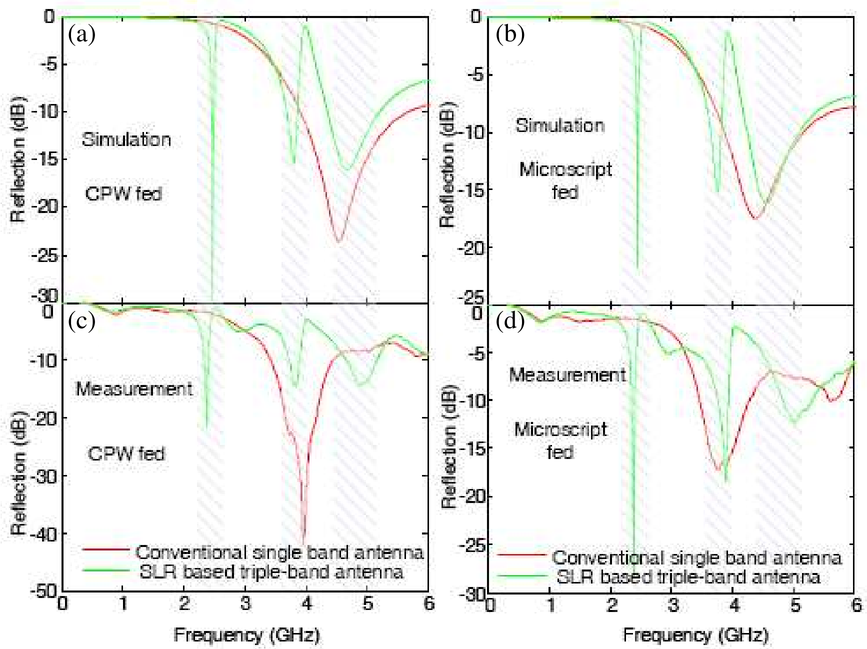

Figure 2: Simulated reflection results for the (a) CPW fed and (b) microscript fed conventional monopole antenna and metamaterial inspired triple-band antenna, and measured reflection results for the (c) CPW fed and (d) microscript fed conventional monopole antenna and metamaterial inspired triple-band antenna. The shadow areas are corresponding to the bandwidth of 10 dB reflection.

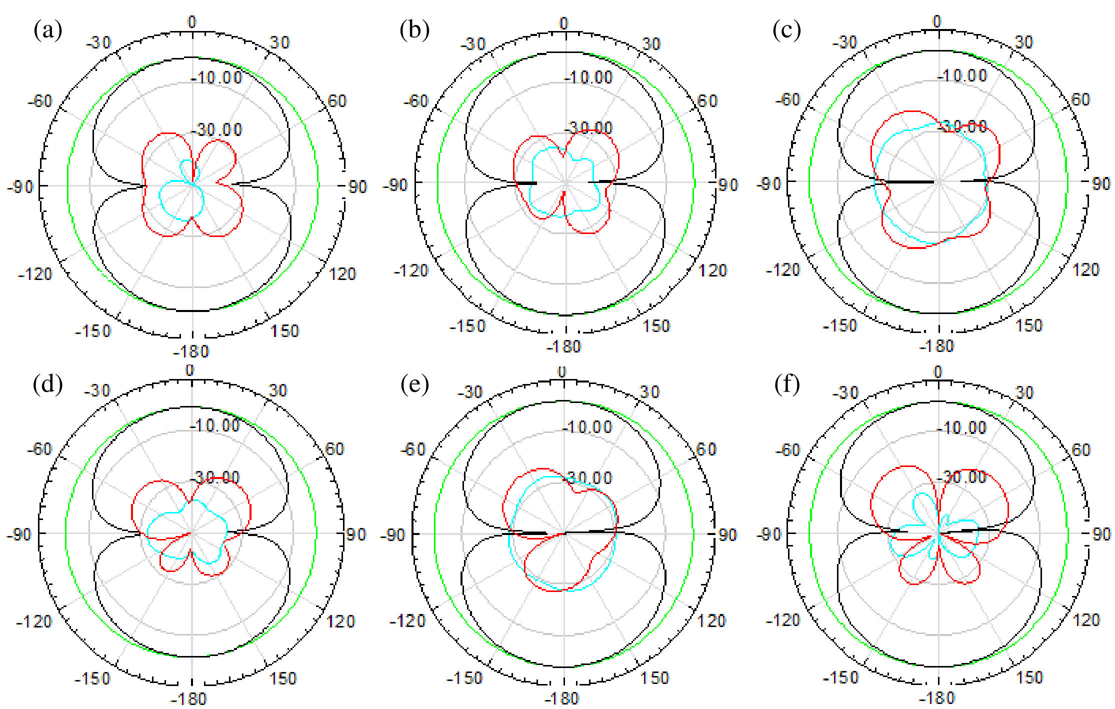

Figure 3: Simulated radiation patterns for the two metamaterial inspired triple-band antennas. (a)–(c) For the CPW fed antenna at corresponding reflection dips. (d)–(f) For the microscript fed antenna at corresponding reflection dips. Black line: co-polarisation E-plane; Blue line: cross-polarisation E-plane; Green line: co-polarisation H-plane; Red line: cross-polarisation H-plane.

distinct operating bands with 10 dB return loss: 2.33–2.42, 3.72–3.9 and 4.65–5.18 GHz for the CPW fed antenna, and 2.33–2.43, 3.75–3.95 and 4.82–5.31 GHz for the microscript fed antenna, respectively. On the other hand, the simulated and measured reflection results for the conventional monopole antenna show only one transmission dip located in the range of 3.8–5 GHz. It means that our proposed metamaterial inspired antenna can operated a very lower frequency with the same antenna size for the conventional antenna. Therefore the proposed antenna has a compact size property.

Figure 3 shows the simulated co-polarisation and cross-polarisation radiation pattern characteristics for the two metamaterial inspired antennas at three corresponding reflection dips. It can be seen that, at the three frequencies, both the two antennas exhibit typical eight-like radiation patterns in the co-polarisation E-plane, whereas in the co-polarisation H-plane they possess nearly omnidirectional radiation patterns. Moreover, the cross-polarisation radiations of the proposed antennas are very low for all the patterns. For examples, there is a 30 dB below the co-polarisation E-plane over $\pm 45^{\circ}$ range for the first antenna and 25 dB for the second antenna. And there is a 20 dB below the co-polarisation H-plane over the omnidirection for the two antennas, at all the three frequencies. These radiation patterns indicate an excellent polarisation purity and the such patterns are kept very well when integrated with metamaterial unit in the radiation patch. Moreover, it is seen that for both the CPW and microscript fed antennas, they have similar radiation patter at all the three frequencies. Therefore such kind of antenna can be integrated flexibly in to other CPW and/or microscript integration circuits.

To further characterize the designed antennas, we measured the peak gain total and efficiency in a commercial near field measurement system (Satimo SG 32), for the four antennas as comparisons. Table 1 shows the measured Peak gain total and efficiency at the corresponding reflection dips for all the four antennas. It can be seen that all of the antennas at each frequency have the same gain level. However, at higher operating frequency, the efficiency dropped down slightly. This is because the loss at such higher frequency is larger than in the lower frequency. From the above simulated and measured results, we can conclude such metamaterial inspired antenna can be easily used to modern wireless communications.

Table 1: The measured peak gain and efficiency properties for the four antenna samples.

Antenna	CPW fed single band antenna	CPW fed triple band antenna			Microscript fed single band antenna	Microscript fed triple band antenna		
Frequency (GHz)	4.0	2.4	3.85	4.9	3.8	2.4	3.9	5.05
Peak Gain Total (dBic)	3.4	3.7	3.0	3.2	3.5	3.2	3.4	4.2
Efficiency	0.57	0.58	0.45	0.38	0.56	0.53	0.48	0.47

4. CONCLUSION

In this paper, compared with two conventional monopole antennas, two novel metamaterial inspired compact triple-band antennas consisting of a SLR as part of the radiation patch and fed with CPW and microstrip transmission lines, respectively, are discussed through numerical simulations and experimental demonstrations. The proposed two antennas exhibit comparable radiation pattern with the conventional monopole antennas, including very well eight-like radiation patterns and low cross-polarisations, and high peak gain total and efficiency. Such antennas have potential applications for modern wireless communications and can be integrated flexibly in to other CPW and/or microscript integration circuits.

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