Efficient, Metamaterial-Inspired Loop-Monopole Antenna with Shaped Radiation Pattern

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Abstract—A new family of metamaterial-inspired monopole antennas is reported. Split-ring resonator (SRR) is introduced into the near field region of a monopole antenna. Four configurations are proposed by changing the position of the slot of the SRR. In each case, we obtain a new behavior and a new resonance frequency, in addition to that of the monopole. The results are presented for the return loss, efficiency, surface current and radiation pattern. Four prototypes are fabricated and measured. Good agreement between numerical and experimental results is demonstrated.

Keywords— planar monopole; metamaterial (MTMs); efficiency; multifrequency antennas; radiation pattern; reconfigurability; electrically small antennas (ESAs).

I. INTRODUCTION

The rapid progress of wireless devices for communication has increased the requirement of efficient, low profile, light weight and low cost electrically small antennas (ESAs). A variety of antenna has been engineered with metamaterials (MTMs) [1] and metamaterial-inspired constructs [2] in order to improve their performances in terms of efficiency [3-4] and bandwidth [5-6] or to achieve novel functions [7-8].

In this paper, we have used split-ring resonators cell (SRR) in order to enhance the efficiency of miniature monopole antennas and/or to shape their radiation pattern. Four configurations of antenna are studied by changing the position of the slot in the SRR loop. Each structure is composed of a monopole antenna with one split loop. This technique leads to a new resonance frequency lower than that of the monopole, a high efficiency and a shaped radiation pattern.

We should also mention the appearance of a new and important property: while miniature antennas are usually omnidirectional, the proposed configurations produce directive beams which are an attractive, but rare phenomenon.

II. PROPOSED ANTENNAS DESIGN

As shown in Fig. 1, The proposed structures consist of a monopole printed on a Rogers Duroid™ 5880 substrate of thickness 0.8mm, relative permittivity $\varepsilon_r = 2.2$ and mounted on a 200mm×200mm copper ground plane. In simulation, the antenna is excited by a lumped port of 50Ω input impedance. Then, rectangular slotted loop (SRR) is placed close to the monopole.

![Figure 1. Scheme of the first proposed antenna.](image)

Figure 2. Configurations of the four proposed antennas: (a): A1; (b): A2; (c): A3 and (d): A4.

We have studied four antennas by considering different configurations of the SRR cell (Fig.2). We have placed a slot in different side of rectangular SRR loop. For all the structures the dimension of monopole, the loop and the distance between monopole and SRR are constant. The monopole is designed to operate at 2.45GHz. All the dimensions are given in table I.
The prototypes are simulated, optimized, realized and finally characterized. Fig. 3 presents photos of the realized prototypes.

![Figure 3. Photo of the four realized prototypes.](image)

### III. RETURN LOSS

The return losses of the realized antennas are measured, using the network analyzer Agilent N5230A over the frequency range 1GHz-4GHz. Simulation results are obtained by ANSYS-HFSS software. Fig.4 represents simulated and measured return loss for different antennas. We can notice a good agreement between these results. Table II summarizes simulated and measured resonant frequencies, deduced from Fig. 4.

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Simulated resonant frequencies (GHz)</th>
<th>Measured resonant frequencies (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>1.606 2.455</td>
<td>1.635 2.445</td>
</tr>
<tr>
<td>A2</td>
<td>1.399 2.662</td>
<td>1.509 2.751</td>
</tr>
<tr>
<td>A3</td>
<td>1.744 2.566</td>
<td>1.803 2.591</td>
</tr>
<tr>
<td>A4</td>
<td>1.594 2.557</td>
<td>1.643 2.571</td>
</tr>
</tbody>
</table>

An important characteristic of the implemented resonators is their rectangular shape which maximizes the coupling to the monopole [9]. At low frequencies, it is well known that the monopole acts like a capacitor of effective value $C_{eff}$, whereas the SRR loop brings an effective inductance $L_{eff}$. Consequently, the combination of monopole and the SRR loop can form a series LC resonator with a new resonance frequency $f_0$ [5]:

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{1}{L_{eff}C_{eff}}}$$  \hspace{1cm} (1)
As shown in Fig.4, the proposed antennas operate at two resonant frequencies. For the A1 antenna (Fig.4.a) the first frequency $f_0 =1.606\text{GHz}$ corresponds to the resonance of the combination of SRR loop with the monopole, whereas the second resonance situated at $f_1=2.455\text{GHz}$, corresponds to the monopole antenna alone. We can notice small discrepancies between the measured and simulated return loss caused by the fabrication tolerances. We observe the same phenomena for the three other antennas: A2, A3 and A4.

IV. EFFICIENCY AND RADIATION PATTERN

Table III collects the simulated and measured overall efficiency (OE) of the four proposed antennas at the lower and the higher frequencies. OE is the ratio of the radiated power $P_{\text{rad}}$ to the input power $P_{\text{in}}$, as given by the following expression [3]:

$$OE = \frac{P_{\text{rad}}}{P_{\text{in}}}$$

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Simulated Overall Efficiency (OE %)</th>
<th>Measured Overall Efficiency (OE %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>$f_0$ 96.2 $f_1$ 95.8</td>
<td>$f_0$ 72.3 $f_1$ 82.6</td>
</tr>
<tr>
<td>A2</td>
<td>$f_0$ 94.8 $f_1$ 88.8</td>
<td>$f_0$ 82.1 $f_1$ 80.4</td>
</tr>
<tr>
<td>A3</td>
<td>$f_0$ 38.4 $f_1$ 82.7</td>
<td>$f_0$ 44.6 $f_1$ 77.3</td>
</tr>
<tr>
<td>A4</td>
<td>$f_0$ 39.1 $f_1$ 72.3</td>
<td>$f_0$ 40.2 $f_1$ 62.5</td>
</tr>
</tbody>
</table>

According to the table III, a high overall efficiency (OE) is obtained for the A1 and A2 antennas at the lower frequencies. For the A1 antenna the OE=96% at $f_0 =1.606\text{GHz}$ while for the same monopole without SRR, we obtain OE=11.85%. This is because the monopole is not matched at the frequency $f_0$. For the A3 and A4 antennas, we obtain a lower efficiency than that of the first two antennas at the lower frequencies, again, due to the bad impedance matching (high return loss shown in Fig. 4).

Fig.5 illustrates simulated surface current vectors and 3D radiation patterns of the four antennas at the resonance frequencies.

At higher resonance frequency (~2.5 GHz), the loop is not resonating, its current is weak and its function is disabled. The structure behaves like a single monopole antenna from both $S_{11}$ (Fig. 4) and radiation point of view.

At lower resonance (~1.6 GHz), the loop is highly excited and acts as a magnetic dipole. Its combination with the monopole antenna gives rise to an unusually directive beam (Fig. 5, A1, A2, A3 configurations). In A4 configuration, the overall vertical current is much higher than the horizontal one. The electric monopole behavior seems to overcome that of the magnetic dipole, leading to an axially symmetric radiation pattern which typical of monopole antennas.

We can explain in the same manner the impact of the surface current vector to the shape of the radiation pattern of the A2, A3 and A4.
In the case of the A1 antenna and at the frequency $F=1.606\,\text{GHz}$, we notice the presence of two high value currents on the loop: the first one is parallel to the monopole and the second one, perpendicular to it. Both currents are in phase and seem to form an "equivalent current" oriented approximately towards the $-30^\circ$ direction relative to the monopole (Z axis). We observe that the maximum directive beam is perpendicular to the axis of the "equivalent current". The same phenomenon is observed for the A2, A3 configurations.

![Diagram showing radiation patterns](image)

To check the simulation results, we present in Fig.6, the measured radiation pattern in (XOZ) and (YOZ) planes of the A4 antenna. These measurements are carried out in the anechoic chamber "SATIMO Stargate32". We can notice a good agreement between measured and simulated results.

![Simulated and measured radiation patterns](image)

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V. CONCLUSION AND FUTURE WORK

In this work, several efficient, metamaterial-inspired monopole antennas are presented. The studied structures are based on the association of a monopole antenna with a slotted loop (SRR cell). Four configurations are proposed by changing the slot position of the SRR. This technique leads to a new resonance frequency lower than that of the monopole, a high efficiency and a shaped or directive radiation pattern. These properties make the proposed antennas well suited for emerging multiband wireless applications.

Future works will address the extended study of a single structure with four agile slots creating an electronic reconfigurability of radiation pattern.

REFERENCES