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On the Impact of Material Losses on Radiation Efficiency and Matching Bandwidth of Electrically Small Antennas

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Abstract—This work demonstrates the material loss impact on ultra-small antennas. The material losses considered are the ones common for printed circuit board manufacturing technology, which are substrate loss (RO4003C) and metal loss (bare copper). The simulation performance for four variations of a shunt-fed circular antenna of ultra-small size with a maximum dimension of $\lambda/30$ is presented. The impact is analyzed for future investigations on radiation efficiency enhancements.

I. INTRODUCTION

Contrary to classical high data rate telecommunication systems, where a wide bandwidth is required, electrically small antennas (ESAs) offer a narrow bandwidth (NB) when engineered to favor radiation efficiency [1], [2]. However, the radiation efficiency enhancement of ultra-small antennas is very challenging, requiring a re-examination of the fundamental characteristics, such as the material properties. Internet of Things (IoT) devices are a great example of our interest in this work. NB-IoT is a narrowband data-transmission protocol for IoT devices, required to deliver lower data rates but with longer battery life [3]. For a NB-IoT-compliant device, a long-lasting battery life also requires energy optimization of electronics, including the desired ever-smaller antennas with the least possible losses. To analyze the effect of enhancing radiation efficiency, an ultra-miniature antenna is studied in this work. The ESA is of printed circuit board (PCB) technology, with a maximum electrical dimension of $\lambda/30$, corresponding to an electrical size ka of 0.1.

II. SHUNT-FED CIRCULAR ANTENNA LAYOUT

Fig. 1 shows the four variations of the ESA shunt-fed circular antenna. The antenna is printed on a single layer of a Rogers RO4003C substrate. The substrate has a thickness of 1.524 mm. The metallization is of bare copper, having a conductivity of $5.8 \cdot 10^7$ S/m and a thickness of 35 μm . The antenna is fed to the region marked in blue. A capacitor closes the circular ESA at the other end. The dimension label values in Fig. 1 are summarized in Table I. The four ESAs in Fig. 1 have the same dimensions, except for some dimensions that are different at the feeding part for matching to 50Ω impedance, also summarized in Table I. The four ESAs are optimized to operate at 868 MHz to match a 50Ω reference impedance. Accordingly, the maximum dimension occupied by the metallic part of the ESA is $L_1 = 11.52$ mm, which is equivalent to an electrical length of $\lambda/30$ at 868 MHz. The corresponding electrical size, ka , is 0.1, where “ k ” is the radian length equal to $2\pi/\lambda$, and “ a ” is the radius of the smallest sphere enclosing the metallic part of the antenna. The ESAs in Fig. 1 are labeled from {a} to {d}. The capacitive load values are indicated for each ESA. The reactive load calculation method is detailed in [3] and [4].

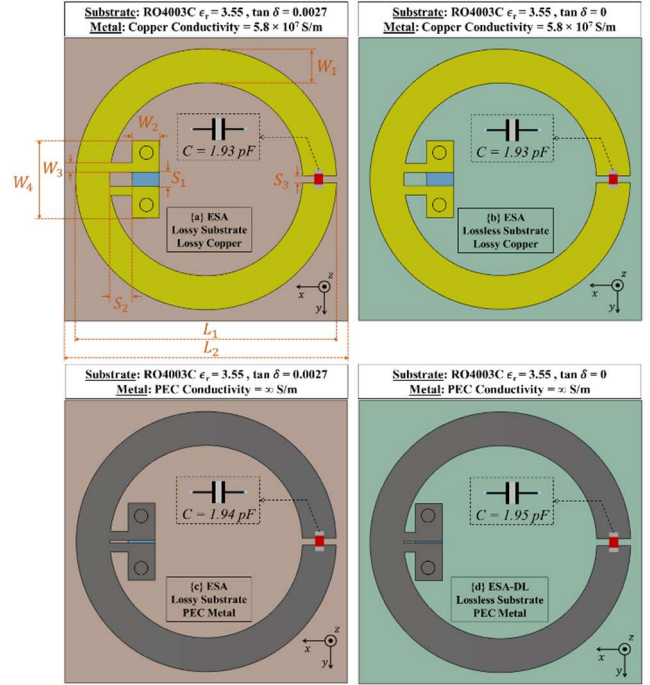


Figure 1. Compact shunt-fed circular antenna dimensions labels and the variations of the compact shunt-fed circular antenna.

TABLE I. SHUNT-FED CIRCULAR ANTENNA DIMENSIONS.

ESA Variation	Dimensions (mm)											
N	Sub.	Met.	S_1	S_2	S_3	L_1	L_2	W_1	W_2	W_3	W_4	
{a}	L	L	0.63	1.0	0.3	11.52	$\lambda/30$ at 868 MHz	12.52	1.5	1.2	0.4	3.41
{b}	LF	L	0.60	1.0								
{c}	L	LF	0.11	0.8								
{d}	LF	LF	0.07	0.5								

N: ESA number; Sub.: Substrate; Met.: Metal; L: Lossy; LF: Loss Free

The difference between ESAs {a}, {b}, {c}, and {d} is related to material lossy and lossless properties. ESA {a} has all material losses introduced, the copper losses and the substrate losses. ESA {b} has only copper losses with a lossless substrate (loss tangent is zero). ESA {c} has a lossless metal, using here the perfect electric conductor (PEC) (having infinite conductivity) and a lossy substrate. ESA {d} has a PEC metal and a lossless substrate, so no losses are present at all in this variation.

III. SIMULATION RESULTS

Fig. 3 shows the reflection coefficient plot for ESAs {a}, {b}, {c}, and {d}, and Fig. 4 shows the radiation efficiency and total efficiency. The -10 dB $|S_{11}|$ bandwidth and radiation efficiency at 868 MHz are summarized in Table II. From Table II, we can observe that ESA {b} with a lossless substrate

has a slightly higher radiation efficiency compared (shown in row 2) to ESA {a} (and a slightly lower bandwidth, row 1). However, ESA {c} with lossless metal has very enhanced radiation efficiency compared to ESA {a} and noticeably lower bandwidth. Notice that ESA {d} with completely lossless materials has 88.02% radiation efficiency (not 100%); this is due to the ESA's closely spaced opposing currents, starting to approach transmission lines that do not radiate.

The ESAs quality factor is provided in row 3 of Table II. By normalizing the quality factor to the radiation efficiency, we get the ideal quality factor in row 4. Notice that the ideal quality factors in row 4 should be equal. However, since the ideal quality factor is extremely high, minor simulation errors could provide such differences. The Chu quality factor lower bound is provided in row 5, and the ideal version is provided in row 6. Since the Chu lower bound considers spherical enclosures only, row 7 provides the ideal Gustafsson lower for a square of zero thickness and linear polarization, and row 8 provides the lossy version of this bound.

TABLE II. ESA VARIATIONS PERFORMANCE.

Row	ESA	{a}	{b}	{c}	{d}
1	-10 dB $ S_{11} $ BW (MHz)	1.187	1.115	0.166	0.094
2	RE η_r at 868 MHz (%)	7.42	7.89	51.49	88.02
3	QF [6] $Q = \frac{2}{FBW} \frac{ S_{01} }{\sqrt{1- S_{01} ^2}}$	487	518	3485	6155
4	Normalized QF Q/η_r	6569	6577	6769	6993
5	Chu [1] QF LB $Q_{Chu} = \eta_r \left(\frac{1}{(ka)^3} + \frac{1}{ka} \right)$	75	79.6	520	889
6	Normalized Chu QF LB Q_{Chu}/η_r	1010			
7	Ideal Gustafsson [7] QF LB $Q_{Gustafsson}$	1971			
8	Lossy QF $\eta_r \times Q_{Gustafsson}$	146	155	1015	1735

RE: Radiation Efficiency; QF: Quality Factor; LB: Lower Bound; FBW: Fractional Bandwidth; $|S_{01}|$: Reflection coefficient reference level for the FBW (-10 dB, linear 0.3162)

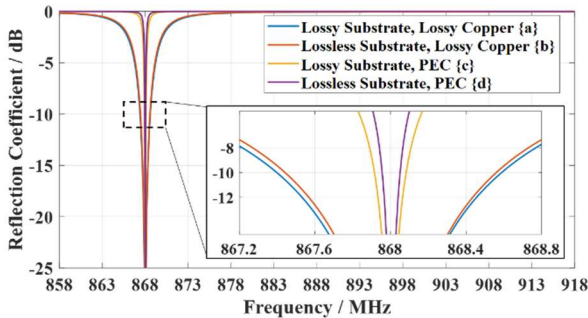


Figure 2. ESAs {a}, {b}, {c} and {d}: reflection coefficient.

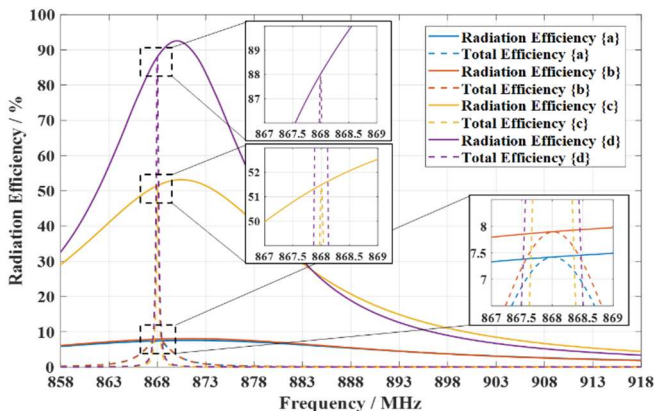


Figure 3. ESAs {a}, {b}, {c} and {d}: radiation efficiency and total efficiency.

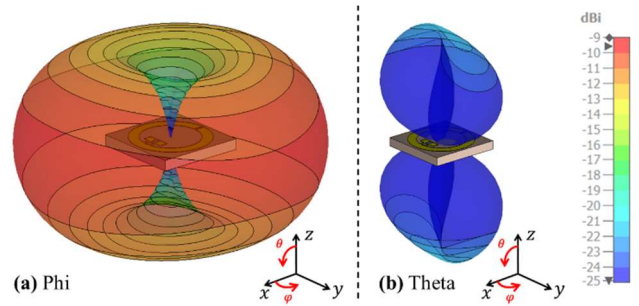


Figure 4. Radiation pattern for ESA {a} at 868 MHz, with realized gain scale: (a): Phi polarization component, (b): Theta polarization component.

The radiation pattern of ESA {a} at 868 MHz is shown in Fig. 4. The pattern shows magnetic-dipole radiation, with a maximum realized gain equal to -9.5 dBi dominated by the phi polarization and -21.35 dBi for the theta component.

CONCLUSION

An ultra-compact ESA was developed and studied, along with its material properties and variations. The ESAs are simulated, and it was observed that the metallic loss had a much higher impact on the antenna radiation efficiency compared to the low-loss substrate presented in the design. Moreover, the observed performances for all ESA variations confirm the balance between efficiency and bandwidth for a given antenna size, which compensates to give a constant ratio as predicted by the fundamental limits. This concludes that future work should be made on the antenna metallic part to enhance the antenna radiation efficiency. Possible solutions can be geometrical changes to the metal or the employment of more conductive materials. This work provides the first building block for radiation efficiency enhancement and will be followed in other studies.

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