A Dual-Band Printed Electrically Small Antenna Covered by Two Capacitive Split-Ring Resonators

Lin Wang, *Student Member, IEEE*, Meng Qing Yuan, and Qing Huo Liu, *Fellow, IEEE*

***Abstract*—In this letter, we present a dual-band electrically small antenna (ESA) operating at 934 MHz and 1.55 GHz. The miniaturized radiation structure consists of a small ring and two concentric split-ring resonators on an FR-4 substrate. The resonant response of the proposed radiation structure is characterized by the coupling among two split-ring resonators and the small ring. A weak electric field interaction between two split-ring resonators is observed. This interaction provides an additional capacitance to further reduce the total dimension of the resonant electrical length. The calculated return loss of the proposed structure agrees well with the measured data. Measured radiation patterns are presented. The planar structure is promising for compact wireless devices and may find applications in wireless electrocardiograph sensors, multiband portable MIMO wireless systems, and RF energy-harvesting systems.**

***Index Terms*—Dual-band, electrically small antenna (ESA), electrocardiograph sensor, RF energy harvesting, split-ring resonator (SRR).**

I. INTRODUCTION

ELECTRICALLY small antennas (ESAs) are fundamentally important for modern wireless communication systems [1], RF harvesting systems, wireless radio frequency identification (RFID) systems, and wireless sensor networks [2]. Generally, the maximum dimension ($D_{\max}$) of an ESA is smaller than $\lambda/4$, where λ is the operating wavelength. $D_{\max}$ is smaller than $\lambda/2$ for dipole antennas, smaller than $\lambda/4$ for monopole, and smaller than $\lambda/3$ for loop antennas [3]. Wheeler [4] first identified the limitation of bandwidth of an ESA through the concept of radiation power factor. By employing the low-order TE and TM spherical wave modes, Chu calculated the minimum radiation power quality factor, or Q factor of an electrically small dipole, where the dipole is enclosed in a hypothetical sphere with a radius a [5]. In his calculation, a radiation Q for an ESA is defined by

$$Q = \begin{cases} \frac{2\omega W_{\rm e}}{P_{\rm rad}}, & \text{if } W_{\rm e} > W_{\rm m} \\ \frac{2\omega W_{\rm m}}{P_{\rm rad}}, & \text{if } W_{\rm e} < W_{\rm m} \end{cases} \tag{1}$$

where ω is the antenna radiation frequency, $W_{\rm e}$ and $W_{\rm m}$ are stored time-averaged electric field energy and magnetic field energy, respectively, and $P_{\rm rad}$ denotes the average radiated and dissipated power. Based on this definition, the approximate fundamental limitation of an ESA is

$$Q_{\rm Chu} = \frac{1}{ka} + \frac{1}{k^3a^3}. \tag{2}$$

McLean [6] further gave a more precise result of the minimum radiation quality factor for the circularly polarization case by the direct field method. From (2), the bandwidth of an ESA, defined by ω/Q, is a nonlinear function of the maximum dimension of the antenna structure. Consequently, an ESA with a narrow bandwidth results in a small radiation resistance and a low radiation efficiency.

Practically, various small antennas, such as folded monopoles, meandered dipoles and loops, and resistive or reactive loading antennas have been designed to approach the fundamental limitation [3], [7], [8]. For example, metamaterial-based electrically small antennas have been demonstrated to miniaturize the antenna structure with the proper radiation performance [9], [10]. In [10], a capacitively loaded loop is utilized as a reactance to realize impedance matching of the small loop antenna.

On the other hand, small-ring antennas, with natural compact structures, have become important aspects in microwave ring systems [11], [12]. For a multiple-input–multiple-output (MIMO) portable wireless system, multiple antennas, typically 2×2 or 3×3 units, are also required in the limited chassis space in order to achieve the spatial diversity capability. Although a dual-band planar dipole loaded with eight split-ring resonators (SRRs) has been proposed to partially solve this challenge in [13], this antenna is not compact in the horizontal direction. Moreover, it would be very difficult to integrate this antenna into the printed circuit board. Therefore, dual-band compact ESAs are highly demanded. Our objective in this letter is to provide a dual-band compact ESA unit suitable for ISM- and L-band applications in smart and portable wireless devices.

The structure of this letter is as follows. Section II describes the antenna geometry and design methodology. In Section III, experimental and simulation results are discussed. Finally, Section IV offers some suggestions for frequency switchable and tunable ESAs in smart device applications. In our study, Wavenology EM, a commercial full-wave analysis software package from Wave Computation Technologies, Inc. (WCT), is utilized to analyze and investigate the radiation performance of the proposed antenna [14].

II. ANTENNA STRUCTURE AND DESIGN METHODOLOGY

Fig. 1 presents the configuration of the dual-band electrically small antenna with two capacitive split-ring resonators. This ESA structure is fed by a high-performance 50-Ω coaxial RF subMiniature version B (SMB) connector. The inner conductor of this connector is connected to the right strip of the loop, and the outer pins of the connector are directly soldered to the left

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The authors are with the Department of Electrical and Computer Engineering, Duke University, Durham, NC 27708 USA (e-mail: lw85@duke.edu; orchestor@gmail.com; qhliu@ee.duke.edu).

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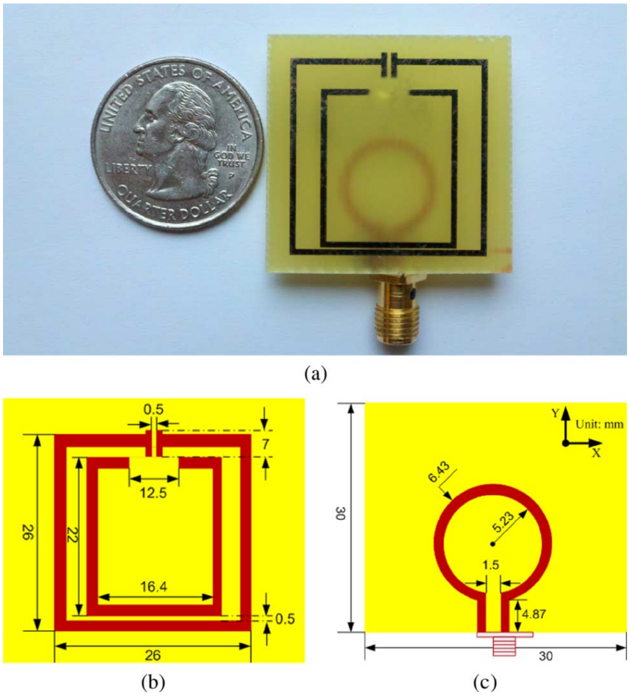

Fig. 1. Proposed antenna configuration. (a) Fabricated antenna prototype. (b) Geometry of the SRRs on the bottom. (c) Geometry of the loop on the top.

strip of the loop. The entire radiation structure has a sandwich shape as shown in Fig. 1(a). The top layer includes a small radiation loop, the bottom layer consists of two SRRs, and the central layer is the substrate. The small loop, which acts as the excitation of RF radiation, has a radius of 5.23 mm. The length of the feeding strips of the loop is 4.87 mm. Dual SRRs, which act as the magnetic coupling resonating structure, are printed on the bottom of the structure. The side length of the outer SRR is 26 mm, and the gap of the outer SRR is 0.5 mm. The dimension of the inner SRR is 16.4×22 mm^2, and the gap of the inner SRR is 12.5 mm. The low-profile structure of the loop and SRRs can be easily fabricated on the FR-4 substrate. Here, the substrate, with the dielectric constant of 4.2 and a loss tangent of 0.029, occupies a space of $30 \times 30 \times 1.8$ mm^3.

The proposed low-profile and compact antenna operates at dual-frequency bands. The fundamental idea is that two resonant modes are achieved through the field interaction among SRRs and the small loop. In this interaction, two capacitive split-ring resonators play the role of impedance matching to the small loop at both frequency bands. Impedance of various electrically small antennas can be matched through loading either spherical shells of homogenous, isotropic negative permittivity (ENG) material or a negative permeability (MNG) material with a zero input reactance. Therefore, this kind of antenna system may provide higher efficiency than traditional antennas. However, its antennas are not compact and mainly operate at a single frequency. In contrast to the antenna in [13], which occupies a large area through integrating four SRRs into an antipodal dipole, our dual-band sandwich design maintains a compact size.

It is well known that impedance matching is challenging for a small-loop antenna because of its small radiation resistance and large reactance. The inductive reactance of the small loop can be matched through capacitive loads. One of those capacitive loads can be realized by a split-ring oscillator. The gap in the split-ring oscillator provides the desired capacitance at the operating frequency. This capacitance and the inductance arising from the small-loop antenna form a pair of LC resonators. According to [12], the small-loop antenna generates a time-varying magnetic flux across the loop plane. This time-varying magnetic flux will induce the time-varying current at the SRR. In the side gap of the SRR, a large electric field energy is stored, and hence the small gap provides the capacitance of an LC resonator. Resonant frequencies of the dual-band ESA can be tuned through controlling the gap's separation of SRRs and the circumference of the ring antenna. We found that the low band is characterized by outside SRR and the high band is mainly affected by the length of the inside SRR. According to the equivalent circuit model of a split-ring resonator [15] and a small-ring antenna [12], the low-band resonant frequency is designed at 934 MHz for ISM applications, and the high band one is at 1.55 GHz for L-band applications.

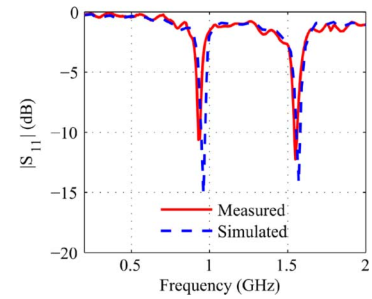

Fig. 2. $|S_{11}|$ comparison between measurement and simulation.

III. Results and Discussions

We fabricated, simulated, and measured the proposed dual-band ESA. The measured and simulated return loss of the proposed antenna are given in Fig. 2. Measured resonant frequencies are obtained at 934 MHz and 1.55 GHz, which are close to the simulated values. The measured return loss is about -10.7 dB at 934 MHz and -12.4 dB at 1.55 GHz. The simulated return loss shows good agreement with the measured value.

The relative radiation quality factor of this ESA $(ka = 0.36 < 1)$ with respect to the bandwidth is of fundamental interest. As we discussed in Section II, the overall size of the antenna structure, characterized by the wavelength at 934 MHz, is about $0.081\lambda \times 0.081\lambda$. Assuming that a minimum sphere encloses the entire antenna, the corresponding minimum radius a is 0.0573λ (18.38 mm). Therefore, from (2), the minimum radiation Q of the antenna is estimated to be around 24.29. The fractional bandwidth $(\mathrm{BW} = 3.61\%)$ is extracted from the experimental S-parameter data. Since the radiation Q is inversely proportional to the bandwidth, a Q_{rad} value of 27.72 is obtained for the low resonant frequency band. Small bandwidths are subjected to large Q-factors from the strong self-resonance of SRRs [13]. We also noticed that the computed radiation quality factor $(Q_{\mathrm{rad}} = 7.72)$ at the low-frequency band approaches the theoretical value $(Q_{\mathrm{Chu}} = 24.29)$. However, for the high-frequency band, the minimum radiation Q calculated from Chu's formula is 6.39. The radiation Q from the measured S-parameter increases to 18.02 with respect to the bandwidth of 5.55%.

To further illustrate the resonant interaction scheme between the ring antenna and SRRs, the electric field magnitude distribution is investigated. The electric field on the top of the substrate

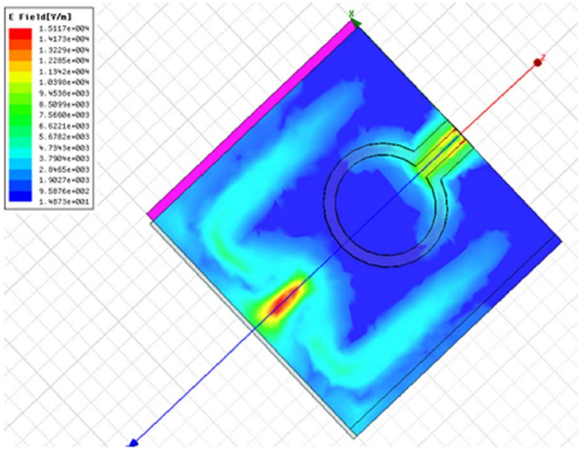

Fig. 3. Electric field distribution at 934 MHz.

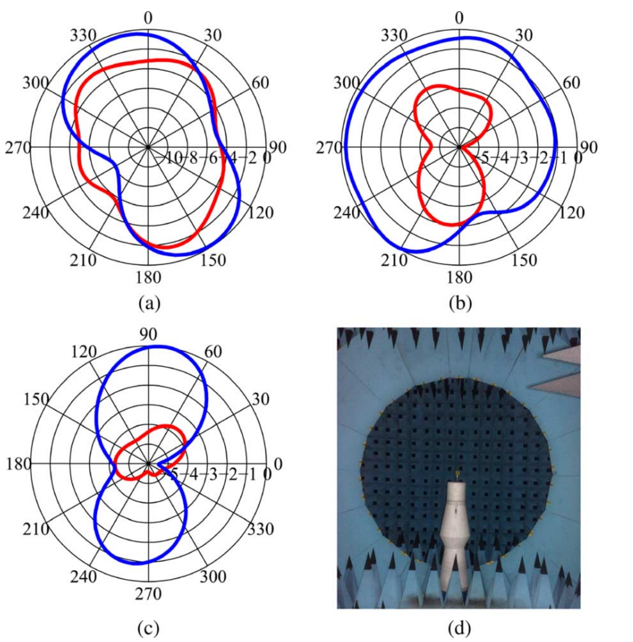

Fig. 4. Measured 2-D far-field radiation patterns. The light line denotes measurement at 934 MHz. The dark line denotes measurement at 1.55 GHz. (a) xy plane. (b) yz plane. (c) xz plane. (d) Antenna is measured by Satimo SG32 antenna measurement system.

is plotted in Fig. 3. We found the E-field distribution pattern resembles an M shape. In the middle of the M shape, the electric field shows a maximum intensity value, which directly verifies that the electric energy is mainly stored within the gap of SRRs. This stored electric energy in the gap partially provides the required capacitance for an LC resonance between the SRR and the small ring [13]. Second, the symmetrically decaying distribution of the electric field along the side gap between the inner and outer SRRs provides the additional electric field energy. The capacitance arising from this distributed electric field between two SRRs, unlike the capacitance generated by the gap, helps to reduce the antenna resonant length.

This dual-band electrically small antenna (DUESA) is measured by the Satimo SG32 antenna measurement system as shown in Fig. 4(d). Normalized far-field radiation patterns at 934 MHz and 1.55 GHz are presented in Fig. 4(a)–(c). Measured radiation patterns have a uniform symmetry. An approximately 15° offset is observed due to the experimental setup. The measured radiation efficiency of the antenna is 36.7% at the lower band. At the high-band resonant frequency of 1.55 GHz, the measured radiation efficiency increases to 43.6%.

IV. Conclusion

In this letter, we find passive split-ring resonators can be an important antenna miniaturization technique in designing multiband electrically small antennas. Through the magnetic field coupling between the ring antenna and two SRRs, two electric resonant paths are produced. At the same time, the antenna's electric length is reduced by the additional capacitance of gaps between two linear SRRs. Radiation patterns and efficiencies at both the low- and high-frequency bands are measured. Integrating with varactors, this compact configuration may apply to frequency switchable and tunable ESAs for various multiband wireless systems and wireless electrocardiograph sensors.

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References

[1] C. M. Roberts, "Radio frequency identification (RFID)," *Comput. Security*, vol. 25, no. 1, pp. 18–26, 2006.

[2] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: A survey," *Comput. Netw.*, vol. 38, no. 4, pp. 393–422, 2002.

[3] R. C. Hansen, *Electrically Small, Superdirective, and Superconducting Antennas*. Hoboken, NJ: Wiley-Interscience, 2006.

[4] H. A. Wheeler, "Fundamental limitations of small antennas," *Proc. Inst. Radio Engineers*, vol. 35, no. 2, pp. 181–181, 1947.

[5] L. J. Chu, "Physical limitations of omni-directional antennas," *J. Appl. Phys.*, vol. 19, no. 12, pp. 1163–1175, 1948.

[6] J. S. McLean, "A re-examination of the fundamental limits on the radiation q of electrically small antennas," *IEEE Trans. Antennas Propag.*, vol. 44, no. 5, pp. 672–676, May 1996.

[7] L. M. Si and X. Lv, "CPW-fed multi-band omni-directional planar microstrip antenna using composite metamaterial resonators for wireless communications," *Prog. Electromagn. Res.*, vol. 83, pp. 133–146, 2008.

[8] P. Jin and R. W. Ziolkowski, "Multiband extensions of the electrically small, near-field resonant parasitic z antenna," *Microw. Antennas Propag.*, vol. 4, no. 8, pp. 1016–1025, 2010.

[9] F. Qureshi, M. A. Antoniades, and G. V. Eleftheriades, "A compact and low-profile metamaterial ring antenna with vertical polarization," *IEEE Antennas Wireless Propag. Lett.*, vol. 4, pp. 333–336, 2005.

[10] A. Erentok and R. W. Ziolkowski, "Metamaterial-inspired efficient electrically small antennas," *IEEE Trans. Antennas Propag.*, vol. 56, no. 3, pp. 691–707, Mar. 2008.

[11] J. Y. Sze, C. I. G. Hsu, and S. C. Hsu, "Design of a compact dual-band annular-ring slot antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 6, pp. 423–426, 2007.

[12] K. Chang and L.-H. Hsieh, *Microwave Ring Circuits and Related Structures*, 2nd ed. Hoboken, NJ: Wiley, 2004.

[13] F. Herraiz-Martinez, L. Garcia-Munoz, D. Gonzalez-Ovejero, V. Gonzalez-Posadas, and D. Segovia-Vargas, "Dual-frequency printed dipole loaded with split ring resonators," *IEEE Antennas Wireless Propag. Lett.*, vol. 8, pp. 137–140, 2009.

[14] "Wave Computation Technologies, Inc. (WCT)," Wavenology EM, 2010 [Online]. Available: http://www.wavenology.com

[15] J. D. Baena, J. Bonache, F. Martin, R. M. Sillero, F. Falcone, T. Lopetegi, M. A. G. Laso, J. Garcia-Garcia, I. Gil, M. F. Portillo, and M. Sorolla, "Equivalent-circuit models for split-ring resonators and complementary split-ring resonators coupled to planar transmission lines," *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 4, pp. 1451–1461, Apr. 2005.