Design of a compact quasi-isotropic antenna for RF energy harvesting

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***Abstract*— In this paper, a compact quasi-isotropic antenna with enhanced bandwidth for radio frequency (RF) energy harvesting applications is presented. The quasi-isotropic pattern is achieved using split ring resonators (SRRs) and the folded dipole structure. Two folded split ring resonators (FSRRs) are implemented orthogonally to reduce the mutual coupling, and each resonance is placed closely to widen the bandwidth. The measured bandwidth is 5% with ka = 0.47. The measured gain deviations (Δ) are 4.6 dB and 4.0 dB at 863 MHz and 888 MHz, respectively.**

***Index Terms*— Electrically small antennas, electric dipole, magnetic dipole, isotropic antenna, RF energy harvesting, split-ring resonators**

I. INTRODUCTION

Recently, radio frequency (RF) energy harvesting has drawn attention as a battery-less energy source for sensor devices in wireless communication systems [1]. Since the ambient RF energy is randomly distributed and incomes arbitrarily, the receiving antennas with isotropic radiation pattern, which provides full spatial coverage, can be beneficial to harvest the ambient energy stably. Even though the design of an isotropic antenna is impossible [2], recent works have been conducted on quasi-isotopic antennas [3-6]. A general approach to design a quasi-isotropic antenna is implementing two crossed electric dipoles with 90-degree phase shift as shown in Fig.1(a). For example, two crossed dipoles which differs in length for phase delay are proposed in [3]. In [4], four monopoles are implemented with sequential feed network. The other way to design a quasi-isotropic antenna is using the electric dipole and the perpendicular magnetic dipole as shown in Fig.2(b). Following the Maxwell's equation, the omnidirectional patterns of the electric dipole and perpendicular magnetic dipole can be added as the electric field from each dipole (electric or magnetic current source) propagate with inherent 90-degree phase difference. In [5], the dielectric resonator with small ground plane is suggested as a quasi-isotropic antenna by exciting an electric dipole and magnetic dipole simultaneously.

Another important design factor to be considered for the RF energy harvesting antenna is the electrical size. As the electrical size of the previous works is not small, the authors proposed a compact quasi-isotropic antenna using split-ring resonators (SRRs) in [6]. The SRR, which are widely used as to make the electrical size of microwave components [7], can also be used as a quasi-isotropic antenna. The authors proposed the folded split-ring resonator (FSRR), which applies the folded dipole structure to the SRRs to improve the radiation characteristics and to match the input impedance to the 50-ohm coaxial cable [6]. However, its narrow band operation cannot cover the Korea cellular band (869-894 MHz) due to the high quality factor of the SRR.

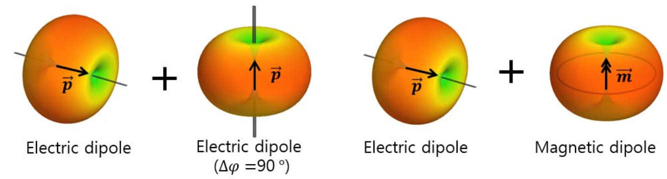

Fig. 1. The design of the quasi-isotropic antennas. (a) Two electric dipoles with 90- degree phase shift. (b) An electric dipole and magnetic dipole

This paper describes a bandwidth-enhanced quasi-isotropic antenna using two FSRRs which are implemented orthogonally. The bandwidth is increased by placing each resonance closely with little coupling. The details of the proposed antenna are discussed, and the experimental results show general agreement with simulated results.

II. QUASI-ISOTROPIC ANTENNA DESIGN

The configuration of the proposed orthogonal folded split ring resonators (OFSRRs) is shown in Fig. 2. The OFSRR antenna is composed of two perpendicular FSRR antennas, one on the horizontal (xz) plane with the outer conductor of the substrate and the other on the vertical (yz) plane with the inner conductor. The balanced port is set to directly feed both FSRRs through the via holes that connect the feeding points of the two elements. The horizontal and vertical FSRR elements are designed with identical parameters except the gap (gh, gv) and the parameters optimized with full electromagnetic (EM) simulator CST are listed in Fig.2. The operation of the FSRR can be analyzed as a tangential electric dipole moment and a normal magnetic dipole moment, which are excited at once [6, 8]. The radiation properties of the FSRR can be improved by increasing the width ratio (w2 /w1) of each SRRs as shown in Fig. 2.

The resonances of each FSRR is placed close together to enhance the bandwidth. The coupling between two FSRRs is reduced by implementing them orthogonally, which means the equivalent electric (or magnetic) dipole of the horizontal FSRR is orthogonal to the electric dipole (or magnetic) of the other FSRR. As a result, the proposed OFSRR can achieve the expanded bandwidth providing the quasi-isotropic pattern with

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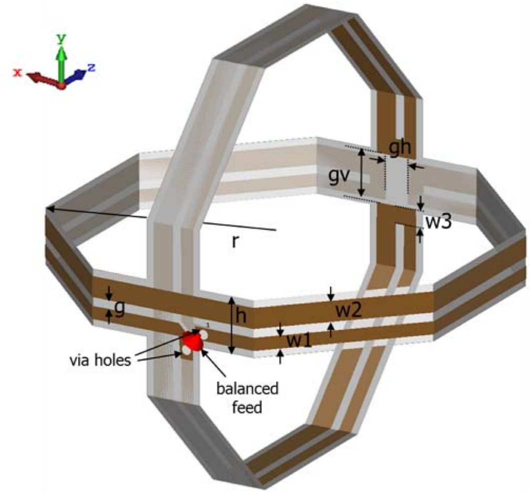
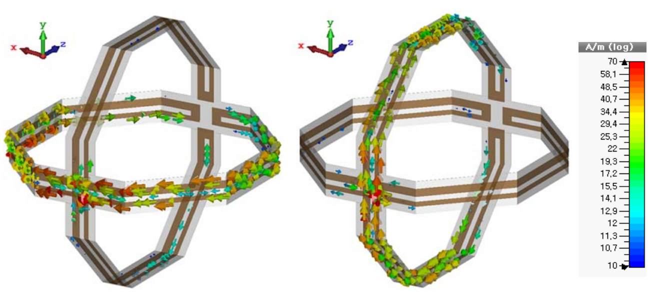


Fig. 2. Proposed antenna configuration with the design parameters. r = 26, w1 = 1.5, w2 = 2.4, w3 = 2, h = 6.5, g = 1, gh = 2.7, gv = 5.7 (unit:mm)

(a) (b)

Fig. 3. Photos of fabricated OFSRR antenna. (a) Perspective side view. (b) Perspective top view.



(a) (b)

Fig. 4. Simulated current distribution of the proposed OFSRR antenna. (a) At the first resonance (859 MHz). (b) At the second resonance (886 MHz).

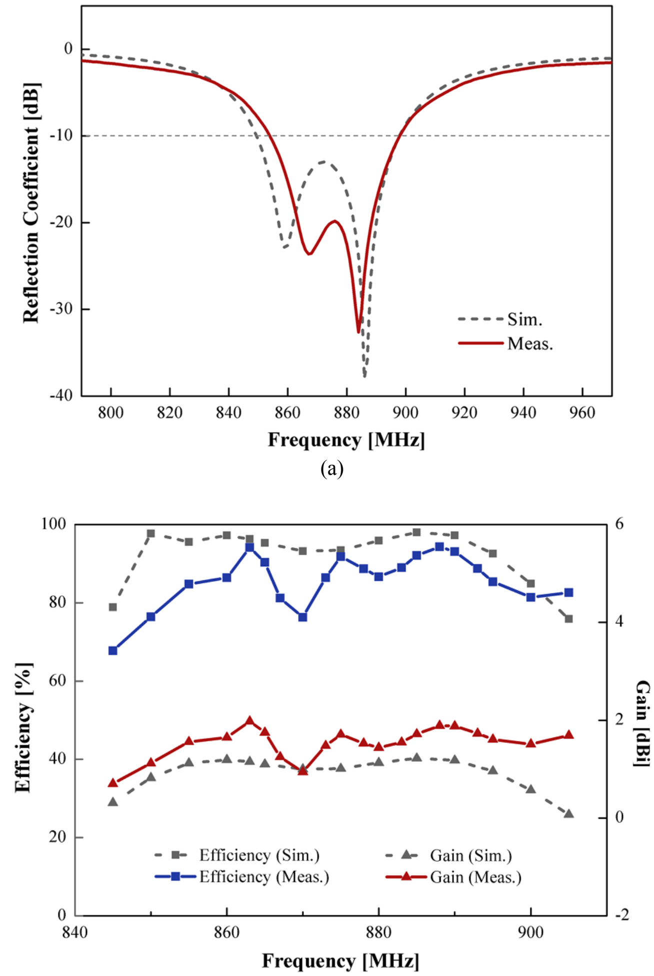


Fig. 5. Simulated and measured results of the OFSRR antenna. (a) Reflection coefficient. (b) Total radiation efficiency and maximum realized gain.

electrically small size.

The development figure of the proposed antenna is fabricated using the flexible printed circuit board (FPCB) process on the flexible substrate, Rogers ULTRALAM 3850 with 4 mils thickness, tan δ = 0.002, $\epsilon_r = 2.9$ and half ounce copper. The development figure is then folded and soldered at the side as shown in Fig. 3. A ferrite balun is used to support the balanced feed. The OFSRR antenna can also be fabricated using two printed circuit board (PCB) for better mechanical stability.

The simulated current distributions at each resonance are described in Fig. 4. The current distribution shows that the horizontal FSRR resonates only at the first resonance and operates as an equivalent electric dipole in the x-direction and as a magnetic dipole in the minus y-direction resulting in dual polarization on the xz-plane. Fig. 4(b) indicates that the vertical FSRR resonates only at the second resonance exciting an electric dipole on the y-axis and magnetic dipole on the x-axis leading to dual polarization on the yz-plane. The electric dipole and the magnetic dipole at each resonance provide a quasi-isotropic pattern as the omnidirectional patterns of the dipoles are added. In addition, the two electric dipoles or magnetic dipoles are perpendicular to each other, which means there would be little coupling although the two resonances are set close together.

III. Results and Discussion

Fig. 5(a) shows the reflection coefficient of the proposed antenna with the resonant points of the simulated values at 859 MHz and 886 MHz and the measured values at 868 MHz, 884 MHz. The measured 10-dB fractional bandwidth (FBW) is about 5% (854-898 MHz) and the electrical size is ka=0.47 at 868 MHz. In Fig. 5(b), the simulated and measured total radiation efficiency and maximum realized gain are plotted.

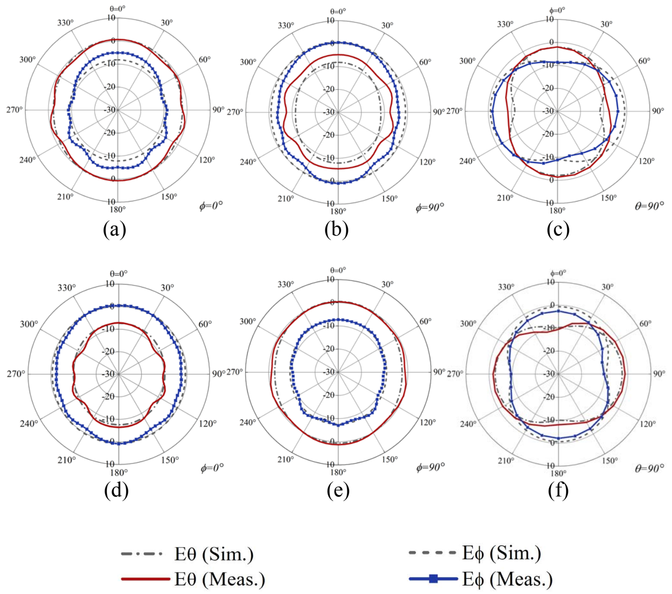


Fig. 5. Polar plot results of the proposed antenna. At the first simulated (859 MHz) and measured (863 MHz) resonances. (a) xz-plane. (b) yz-plane. (c) xy-plane. At the second simulated (886 MHz) and measured (888 MHz) resonance. (c) xz-plane. (d) yz-plane. (e) xy-plane.

TABLE I
COMPARISON WITH THE MEASURED RESULTS OF THE RECENT STUDIES

	This work		[4]	[5]	[6]	[7]
Electrical Size	0.47		1.16	1.63	1.05	0.41
Resonant Frequency [MHz]	863	888	2450	2450	2440	888
Measured Gain Deviation [dBi]	4.6	4	6.64	5.75	5.6	5.2
Bandwidth [%]	5		11	20.8	6.9	1.8

The measured total radiation efficiency is higher than 76.3% in the bandwidth with two peak values around 94 %. The measured maximum realized gain values are in the range of 0.94 to 1.98 dBi and normally higher than the simulated values as the uniformity of the quasi-isotropic simulated pattern is affected by the measurement environments. The simulated and measured results show good agreement despite of small discrepancies due to fabrication tolerances.

Fig. 5 presents the polar patterns of the proposed OFSRR antenna at both resonances. The measured patterns generally agree with the simulated results, except the stronger cross polarization caused by the reflection from the perpendicular element. Although the pattern nulls of the xy-plane are not clear due to strong cross polarization, it can be observed that the equivalent dipoles are aligned with the x-axis or y-axis at both resonances as explained.

The performances of the proposed antenna are compared in Table I with those in recent studies [4]-[7]. As shown in the table, the proposed antenna shows quiet small electrical size (ka = 0.47) with the minimum measured gain deviation values (4.6 dB, 4.0 dB) and enhanced bandwidth (5%), which is enough to cover the Korean cellular band. In addition, the proposed antenna can operate without a complex feeding structure as the antenna is based on equivalent electric and magnetic dipoles.

IV. CONCLUSION

The bandwidth-enhanced compact quasi-isotropic antenna based on an OFSRR is investigated in this paper. The proposed antenna can simultaneously excite the equivalent electric dipole and the perpendicular magnetic dipole at each resonance providing a quasi-isotropic pattern. The bandwidth is expanded by placing the two resonances close together with little coupling as the equivalent dipoles of each resonance align orthogonally. The concept of the folded structure is applied to enhance radiation properties. The FBW is 5% with measured resonant frequencies of 868 MHz and 884 MHz, and the measured gain deviation (Δ) values are 4.6 dB and 4dB at each resonance. The proposed antenna is a prominent candidate for a compact RF energy harvesting antenna covering the Korean downlink band with quasi-isotropic pattern.

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