A Compact Quasi-Isotropic Antenna Based on Folded Split-Ring Resonators

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***Abstract*—In this letter, an electrically small quasi-isotropic antenna using folded split-ring resonators is investigated. The antenna is based on split-ring resonators (SRRs) to achieve a quasi-isotropic radiation pattern using the electric and magnetic dipole current of the SRR. Interdigital capacitors are used to make the size more compact, and magnetic coupling of a folded structure is applied to improve the radiation characteristics of the SRR antenna. The electrical size of the antenna has ka = 0.41 at 888 MHz and 1.8% of fractional bandwidth. The measured gain deviation (Δ) is 5.2 dB and the measured radiation efficiency is higher than 81% in the bandwidth.**

***Index Terms*—Electrically small antennas, electric dipoles, isotropic antenna, magnetic dipoles, split-ring resonators (SRR).**

I. Introduction

IN RECENT years, antennas with an isotropic radiation pattern have become attractive for certain applications such as radio frequency identification (RFID), wireless access points (APs), aerospace applications, and radio frequency energy harvesting, as they provide full spatial coverage that can be beneficial for maintaining stable link connections. Designing an ideal isotropic antenna with polarizations in every direction is not possible [1]. However, quasi-isotropic antennas have been proposed in recent research [2]–[8]. A general way to design a quasi-isotropic antenna is to use orthogonal electric or magnetic dipoles that provide omnidirectional radiation pattern, as shown in Fig. 1. For instance, a quasi-isotropic radiation pattern is obtained by two perpendicular electric dipoles [2], or four monopoles with a sequential phase feeding network [3]. On the other hand, in [4], a dielectric resonator antenna using an electric dipole combined with an equivalent magnetic dipole generates quasi-isotropic pattern without any complex feeding network as there is a 90° phase difference between the radiated fields of an electric and magnetic dipole [9]. However, the quasi-isotropic antennas mentioned above are not electrically small enough to apply to compact wireless platforms.

An electrically small antenna is desirable for the electrically small size of device platforms. Many recent studies have taken advantage of metamaterials (MTMs) to achieve electrically small size of the antennas [10]–[14]. Particularly, the split-ring resonator (SRR) structure, one of the MTMs, is commonly used in various ways in designing passive elements such as antennas [13]–[22]. For example, in [15], the several types of SRRs are used to miniaturize the electrical size of antennas with high radiation efficiency. However, the feeding structures of these SRR antennas are complex and bulky due to the poor radiation characteristics of the SRR structure.

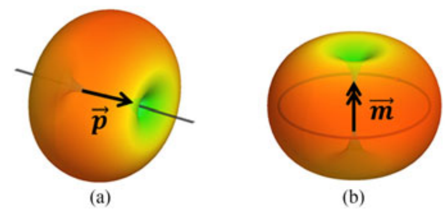

Fig. 1. (a) Radiation pattern of an electric dipole. (b) Radiation pattern of a magnetic dipole.

In this letter, an electrically small quasi-isotropic antenna that uses folded split-ring resonator (FSRR) is presented. The compact and simple SRR is used as it can generate an electric dipole and magnetic dipole simultaneously, thereby providing the quasi-isotropic radiation pattern. The magnetic coupling of the folded structure is applied to improve the radiation characteristics of the SRR antenna. The details of the design are described and discussed with general agreements of simulated and measured results.

II. Antenna Design

The configuration of the proposed antenna is shown in Fig. 2(a). The antenna was designed on the Rogers ULTRALAM 3850 flexible substrate with thickness = 25 μm, $\varepsilon_r = 2.9, \tan\delta = 0.002$, and half-ounce copper. The proposed antenna is based on the SRR structure to take advantage of its benefits, such as the quasi-isotropic radiation pattern and the electrically small size of the resonator. However, the input impedance of the single SRR is too low for direct feeding to a 50-Ω coaxial cable. The radiation characteristics of the single SRR are improved by applying the concept of folded dipole, which uses magnetic coupling of closely spaced dipoles [23]. According to the transmission line and antenna mode analysis of the half-wave folded dipole in [23], the input impedance can be increased by a factor of n^2 when there are n elements of closely spaced half-lambda dipoles. Thus, the radiation characteristics

Manuscript received March 9, 2016; revised May 5, 2016; accepted May 22, 2016. Date of publication May 27, 2016; date of current version February 27, 2017. This work was supported by the Bio-Mimetic Robot Research Center funded by the Defense Acquisition Program Administration and the Agency for Defense Development under Grant UD130070ID.

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Digital Object Identifier 10.1109/LAWP.2016.2573849

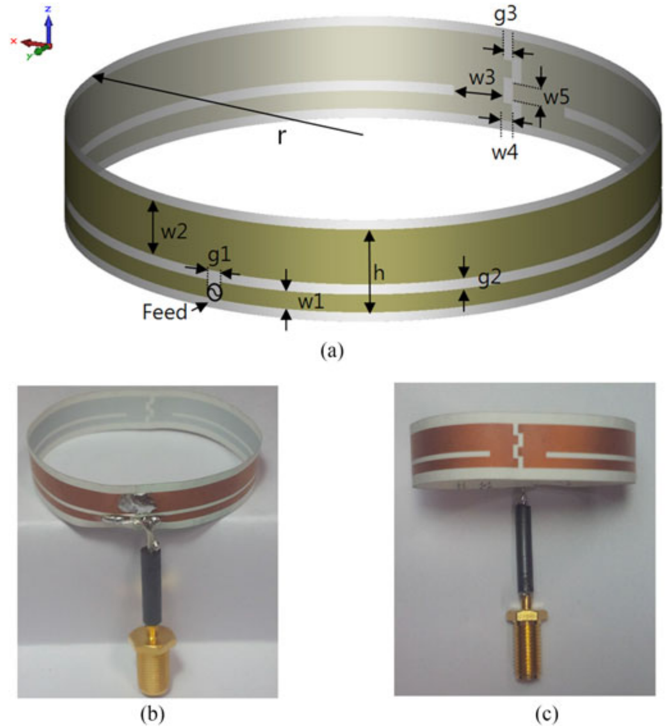

Fig. 2. (a) Geometry of the proposed antenna. (b) Perspective view of the fabricated antenna. (c) Rear view of the fabricated antenna.

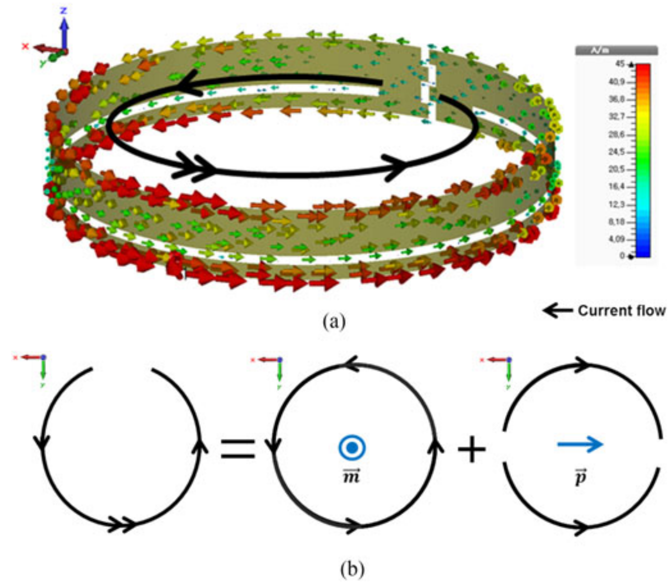

Fig. 3. (a) Simulated surface current on the proposed antenna in perspective view at 886 MHz. (b) Current distribution analysis of the proposed antenna as a magnetic dipole mode and electric dipole mode in top view.

TABLE I
DESIGN PARAMETERS OF THE PROPOSED ANTENNA

Symbol	Quantity [mm]	Symbol	Quantity [mm]
r	22	w1	1.4
h	6.5	w2	4.3
g1	1	w3	4
g2	0.8	w4	0.7
g3	0.8	w5	1.4

of the single SRR were improved by applying the folded structure, as shown in Fig. 2(a). The ratio of the width of the lower SRR (w1) and the upper SRR (w2) is chosen to match the input impedance as 50 Ω.

The FSRR is then made more compact by providing capacitive loading using the interdigital capacitors (IDCs) at the end of two arms, where the voltage would be maximum. The resonance frequency of the FSRR can be easily tuned by controlling the dimensions of the IDCs. The length (w4), width (w5), and the gap (g3) of the IDCs are determined to set the resonance frequency as 886 MHz. The size of the FSRR is $44 \times 44 \times 6.5\,\text{mm}^3 (0.13 \times 0.13 \times 0.02\,\lambda^3)$ or ka $= 0.41$. The values of the parameters are optimized using a CST full electromagnetic (EM) simulator and are listed in Table I.

The proposed FSRR antenna is fabricated through a flexible printed circuit board (FPCB) process with the flexible substrate. The perspective view and rear view of the fabricated antenna are shown in Fig. 2(b) and (c), respectively. The FSRR antenna with the flexible substrate is soldered at the front center to form a circular shape. The inner and outer conductors of the coaxial cable are connected to the left and right sides of the feeding gap (g1), respectively. The proposed antenna has a balanced feeding structure by putting ferrite beads on the outer conductor, which are used to prevent the current from flowing through the coaxial cable and disturbing the radiation of the antenna.

III. RESULTS AND DISCUSSIONS

The proposed antenna shows a quasi-isotropic radiation pattern, as the SRR structure can excite a magnetic dipole ($\vec{m}$) and an electric dipole ($\vec{p}$) simultaneously. The operation of FSRR antenna can be analyzed by its current distribution. Fig. 3(a) shows the simulated current distribution of the proposed antenna, and Fig. 3(b) describes the current analysis of an FSRR antenna as a magnetic dipole mode and electric dipole mode, which are current distribution of a small loop and loaded short dipoles with equal magnitude of maximum current. If the current of the magnetic dipole mode and electric dipole mode are combined, the total current would be the same as the current distribution of the FSRR antenna, which shows a maximum at the feeding region and almost disappears at the gap of the IDCs. Thus, the FSRR antenna can be considered as a sum of the magnetic dipole in the z-direction and electric dipole in the x-direction. The two dipoles showing omnidirectional radiation patterns compensate their pattern nulls, thereby providing the quasi-isotropic radiation pattern.

It is worth mentioning that the radiation of the FSRR antenna with an electric dipole and magnetic dipole differs from that observed with the magnetoelectric dipoles that provide a unidirectional radiation pattern [24], [25]. The former excites an electric dipole and a magnetic dipole simultaneously, while the latter excites two dipoles with 90° phase differences. Therefore, the radiated electric field of the FSRR would not be canceled

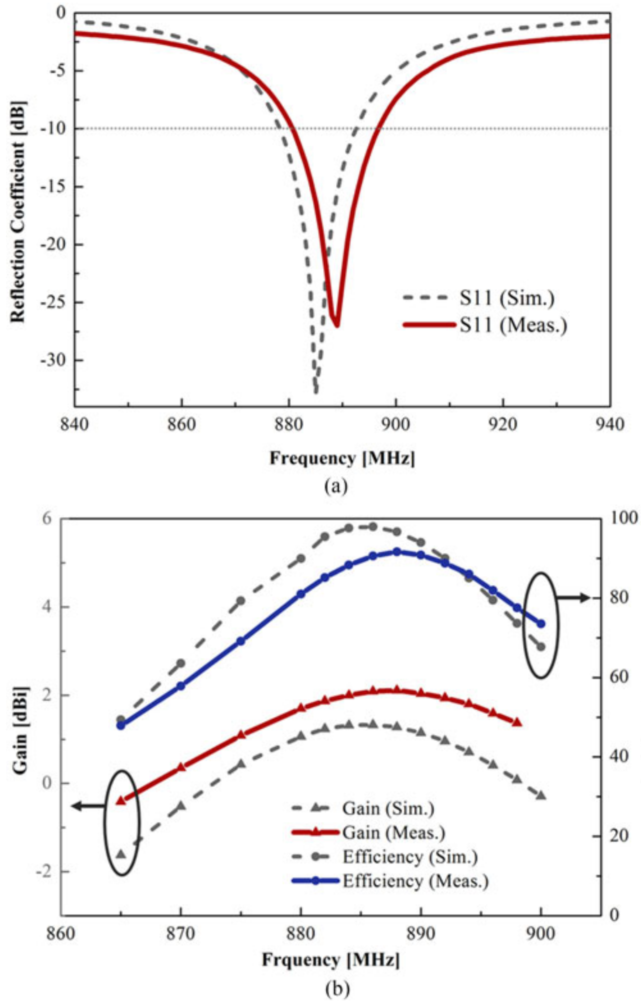

Fig. 4. Simulation and measurement results of (a) input reflection coefficient and (b) maximum realized gain and total radiation efficiency.

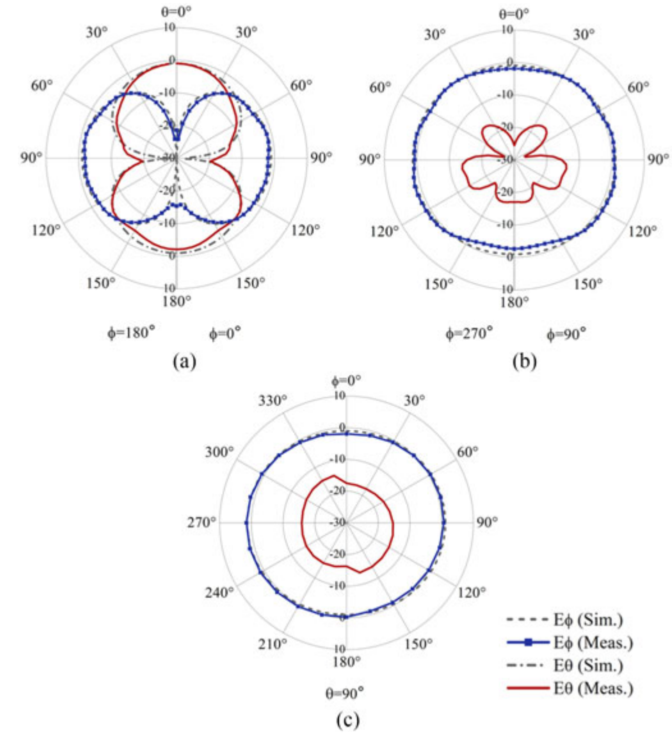

Fig. 5. Simulated (886 MHz) and measured (888 MHz) radiation patterns of the proposed antenna. (a) *xz*-plane. (b) *yz*-plane. (c) *xy*-plane.

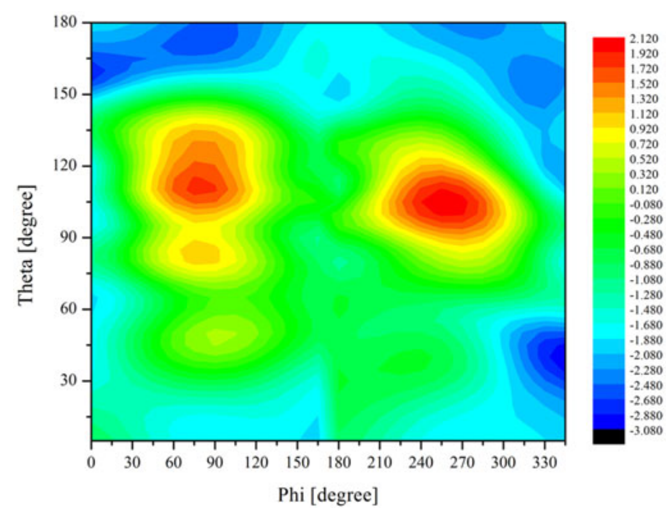

Fig. 6. Measured gain contour of the proposed antenna.

out, and it forms a quasi-isotropic radiation pattern with dual polarization in the *x*- and *y*-directions.

The simulated and measured reflection coefficients of the proposed antenna are shown in Fig. 4. The resonance frequency of the fabricated antenna is 888 MHz, and the resonance frequency of the simulation result is 886 MHz. As shown in Fig. 4(a), the measured 10-dB bandwidth is 1.8% (881–897 MHz). The simulated and measured values of the realized gain and total radiation efficiency are plotted in Fig. 4(b). The measured gain of the fabricated FSRR antenna varies in the range of 1.6– 2.1 dBi in the bandwidth, whereas the gain of the simulated one varies from 0.4 to 1.3 dBi. The measured gain shows higher value than the simulated one as a result of the nonuniform radiation pattern, which is caused by measurement tolerances. The peak value of the measured total radiation efficiency is 91% with a lower bound of 81% across the bandwidth. The simulated and measured results of the FSRR antenna show reasonable agreements although small discrepancy arises due to fabrication tolerances.

The simulated and measured radiation patterns in elevation (*xz*, *yz*) plane and azimuthal (*xy*) plane are shown in Fig. 5 at the resonance frequency of 886 and 888 MHz, respectively. Based on the polar plot result in the *xz*-plane as described in Fig. 5(a), the radiation of two dipoles can be observed by the E_θ component of the *x*-directed electric dipole and the E_ϕ component of the *z*-directed magnetic dipole. The electric fields generated from the electric and magnetic dipole radiate with dual polarization along the *x*- and *y*-directions. In Fig. 5(b) and (c), the E_θ components appeared only in the measurement results, due to unexpected scattering in the experimental environments. As shown in Fig. 5, the simulated gain deviation is 2.3 dB with 1.33 dBi maximum gain and –1.01 dBi minimum gain. The simulated gain deviation value is less than 3 dB, which is the

TABLE II
COMPARISON OF EXPERIMENTAL RESULTS OF THE QUASI-ISOTROPIC ANTENNAS

	This work	[2]	[3]	[4]
Resonant Frequency (MHz)	888	2450	2450	2440
Electrical Size	0.41	1.16	1.63	1.05
Measured Gain deviation (dB)	5.2	6.64	5.75	5.6
Fractional Bandwidth (%)	1.8	11	20.8	6.9
Operation Principle	Electric dipole with magnetic dipole	Two electric dipoles	Four electric monopoles	Electric dipole with magnetic dipole

theoretical limit of gain deviation when it is based on two ideal point sources [4], since the proposed antenna does not generate two ideal point sources.

Fig. 6 shows the measured gain contour of the proposed antenna at 888 MHz. The maximum gain appears around the *y*-axis, where omnidirectional radiation patterns of the electric dipole and magnetic dipole are overlapped. The measured gain deviation is 5.2 dB with 2.12 dBi maximum gain and –3.08 dBi minimum gain, as depicted in Fig. 6.

Table II lists the antenna performances of the proposed FSRR antenna compared to recently studied quasi-isotropic antennas [2]–[4]. As the table shows, the proposed antenna is the most compact in terms of the electrical size $(\mathrm{ka} = 0.41)$ with a minimum value of the measured gain deviation $(\Delta = 5.2\ \mathrm{dB})$, despite its lack of any requirement for complex feeding structures.

IV. CONCLUSION

A compact quasi-isotropic antenna using FSRR is presented in this letter. The proposed antenna is based on the single SRR structure, which can excite the magnetic dipole and orthogonal electric dipole at the same time to form the quasi-isotropic radiation pattern. The folded structure and capacitive loading of IDCs are applied to the single SRR to improve its radiation characteristics and make the electrical size more compact. The resonance frequency of the FSRR antenna is 888 MHz, and the 10-dB bandwidth is 1.8% with at least 81% of total radiation efficiency. The electrical size is $\mathrm{ka} = 0.41$, and the measured gain deviation is 5.2 dB, which are remarkable results compared to those of recently reported studies. The operation of the proposed antenna is verified experimentally with reasonable agreements. Therefore, the proposed antenna can be used as a promising candidate for compact wireless communication systems with quasi-isotropic radiation features.

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