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A Wideband Fractal Planar Monopole Antenna with a Thin Slot on Radiating Stub for Radio Frequency Energy Harvesting Applications

M. M. Fakharian*

Faculty of Engineering, University of Garmsar, Garmsar, Iran

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ABSTRACT

In this paper, for energy harvesting applications a design of a wideband planar monopole antenna is proposed using fractal geometry and inserting a thin slot on radiation patch. The proposed antenna is optimized at various stages during its design. Moreover, a parametric study is done for understanding sensitivity of important design parameters in the design process of the antenna. The designed antenna operates at 10-dB impedance bandwidth from 0.92 to 2.58 GHz (fractional bandwidth of 95%) with low profile structure and compact size of 65 × 65 × 0.8 mm^3, acceptable return losses, stable radiation characterizes and reasonable gains. A potential application of the antenna as a receiving antenna for harvesting systems has been carried out inside the laboratory as the harvested power from ambient radio-frequency (RF) energy. This wideband antenna has a good potential to harvest RF energy of available signals in the GSM-900, GSM-1800, and Wi-Fi bands, and can be used as a part in DC power supply modules of low power sensor networks.

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1. INTRODUCTION

Nowadays, wideband antennas are used in various wireless applications such as in multimedia devices, smart phones etc. Apart from these applications, wideband antennas can be also used as an important component for radio frequency (RF) energy harvesting systems [1]. The RF energy harvesting can be applied as a power supply for a number of the low power electronic devices such as wireless sensor nodes, in order to either replace or even to recharge the the devices' battery. The wideband feature in the antennas in these systems helps in scavenging ambient RF energy from the incoming signal may come from different frequency channels from 0.8 to 2.5 GHz covering GSM900, GSM1800, and Wi-Fi bands of the surrounding environment [2]. Furthermore, the available RF energy can be from various powers and different directions. Hence, an appropriate wideband antenna with a single structure and an omni-directional pattern with stable radiation pattern is required for such systems to have higher RF energy harvesting efficiency from the ambient.

In the last decade, ranges of antenna for energy harvesting applications have been proposed such as patch antenna [3], spiral antenna [4], dipole antenna [5], slot antenna [6], metamaterial antenna [7], and so on. These antenna designs have narrowband [5, 8], multiband [9, 10], or wideband [1-4, 11-14] operations. A single narrow band design produces low conversion efficiency for low-power levels of input power density and not very proper for wireless energy scavenging applications. A multiband or a wideband design can capture more power from the existing signals of different standards from RF energy sources in air and then produce more output power than that a narrowband antenna. But, it was already discussed in literature [15] that wideband antennas are desirable rather than multiband antennas, because they have easier design, and they are interoperable among countries, whose assignment plans of frequency can be diverse among them.

Corresponding Author Institutional Email: *fakharian@fmgarmsar.ac.ir* (M. M. Fakharian)

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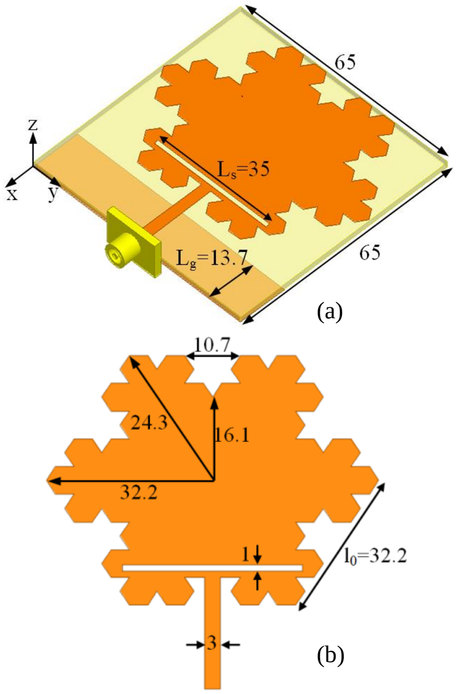


Figure 1. Structure of the proposed antenna (a) side view (b) radiating patch (dimension: mm)

So far, several planar wideband antennas are reported in the literature for RF energy harvesting applications [2-3, 12-14]. A wideband printed log periodic dipole array antenna is proposed by triangular shaped dipoles [2]. The antenna covers the 10-dB impedance bandwidth from 0.570 to 2.750 GHz, but the size of antenna is very large and the pattern is not omnidirectional. Di Carlo et al. [3] dealed with a circularly polarized (CP) microstrip monolithic antenna operating at 868 MHz with fractional bandwidth of 5% for wireless power transfer. But they achieved impedance bandwidth which is not adequate and its pattern is not uniform and omnidirectional. A wideband CP antenna is designed by Adam et al. [12]. The frequency band of this antenna is achieved from 1.73 to 2.61 GHz that is not very suitable for scavenging, furthermore the pattern in not uniform due to the asymmetric structure of the antenna. An antenna is presented by merging a 2×2 array with a tapered antenna [13]. The antenna has 6-dB impedance bandwidth of 720–1300 MHz and 1630–3630 MHz, but its pattern is not omnidirectional and uniform across the entire bandwidth. A wideband bent triangular monopole planar antenna is proposed for this application [14]. The antenna has a 10-dB impedance bandwidth from 0.85 to 1.94 GHz, but this bandwidth is not sufficient for harvesting application. Therefore, a simple and compact planar wideband antenna with uniform and omnidirectional radiation pattern necessities to be developed for wireless energy scavenging.

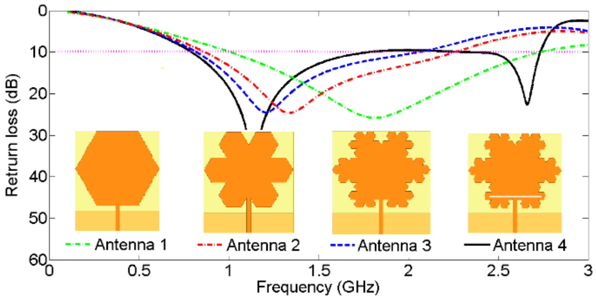


Figure 2. Development stages and the corresponding simulated return loss of the antenna

In this paper a wideband fractal planar monopole antenna is presented. The fractal geometry is based on an iterative Koch snowflake up to second iteration. The compact structure and ease configuration are the main advantage of this fractal monopole antenna [16-18]. In the proposed antenna, wideband function is expanded by inserting a rectangular thin slot on the fractal radiating stub, so a multiresonance characteristic can be produced, especially at the higher band. Good impedance bandwidth and uniform omnidirectional radiation pattern are acquired in the interest frequency band. Measured and simulated datas are shown to validate the practicality of the proposed fractal antenna configuration for RF energy harvesting.

2. ANTENNA DESIGN AND SIMULATION

The proposed planar antenna based on a fractal structure with etching a thin slot on it is shown in Figure 1. The antenna is designed on a low-cost FR4 substrate with a relative permittivity of 4.4, thickness of 1.6 mm, and loss tangent (tan δ) of 0.02. A modified 2nd iteration of Koch snowflake fractal radiation patch with an embedded rectangular-shaped thin slot on it is fed by a 50-Ω microstrip line. The ground plane is modified to partial rectangular plane to enhance the desired impedance bandwidth and omnidirectional radiation pattern characteristics as a monopole antenna. The antenna performance is analyzed and optimized using 3D Ansoft HFSS EM software [19].

The development stages of the antenna are shown in Figure 2, and the corresponding simulated return loss curves are shown in same Figure 2. The 1st antenna consists of a radiator with a hexagon-shaped, a microstrip feed-line with 50Ω impedance, and a rectangular ground plane. In the 2nd antenna, first fractal iteration is implemented to radiator of the 1st antenna, and also in the 3rd antenna, second fractal iteration is implemented to previous antenna. As shown in Figure 2, the resonant frequency of the fractal antenna decreases with the increase in the number of iterations, although it reduces its impedance bandwidth. In order to understand the cause of this phenomenon, the following equations can be considered. The perimeter length (l_{perim}) and the effective area (A) of the proposed modified fractal patch geometry, at indentation angle 60° and at iteration n, are found in literature [20].

$$l_{perim}(n)=4\left[\frac{2}{3}\left(\frac{5}{3}-\cos 60\right)\right]^{n} l_0 , \tag{1}$$

$$A(n)=\left[1-4\left(\sum_{i=1}^{n}\frac{4^{i-1}}{9^{i}}\right)\cos 60 \sin 60\right] l_0^2 . \tag{2}$$

As shown in these formulas, the perimeter or the overall electrical length of the antenna increases with increasing the number of iterations so the decrease in resonant frequency stems from that. On the other hand, the enclosed area of the fractal antenna decreases with iteration increasing. Therefore, the ratio of perimeter length to enclosed area is large when more iteration is implemented in the fractal geometry, so the impedance bandwidth decreases with this extending of iteration. Finally, at the 4th antenna, a thin rectangular slot is applied to the radiating patch. This technique increases bandwidth, especially at the end of the frequency band [21]. Indeed, this thin slot is used for the new resonance excitation function, and hence multi-resonance characteristics with wider impedance bandwidth can be created. As shown in Figure 2, the operating band of the antenna is improved and shifts from 1–2.73 GHz to 0.78–2.73 GHz as develops design of the antenna, so completely covering the RF energy scavenging interesting bands. Antenna 4 is the final proposed antenna. The optimized geometrical parameters of the final proposed antenna are illustrated in the same Figure 1.

To understand the operation theory of the proposed antenna at the wideband performance, the current distributions at three frequencies are shown in Figure 3. Figure 3(a) shows the surface current dis- tributions at 0.95 GHz. As shown in this figure, the electric current is strengthened around the edges of the interior of the thin slot and on the entire feed line of the fractal-shaped radiating patch. Consequently, the antenna performance is dependent on these sections mainly near the resonance frequency at 0.95 GHz. It is observed in Figure 3(b) that the current distributions are more concentrated on the lower section of the feed line and around two sides of the thin slot at 1.85 GHz. Figure 3(c) shows that the current distributions are concentrated on the bottom part of the feed line and on the edges of the interior and exterior of the thin slot at 2.45 GHz.

To understand the influence of the antenna physical dimensions on the bandwidth characteristics. The return loss curves for two important parameters are shown in Figure 4. Figure 4(a) shows the effect of slot length (Ls) on the impedance matching of the proposed antenna. It is indicate that by inserting the thin slot with suitable dimensions on the radiation stub, additional resonance is excited at the higher band. It is clear that with increasing of Ls from 33 to 36 mm, the upper resonance frequency decreases. On the other hand, it is shown in Figure 4(b) that by increasing rectangular ground length (Lg) from 11.7 to 15.7 mm, the lower frequency of the bandwidth decreases. This figure also shows that for smaller values of Lg, the antenna return loss deteriorates.

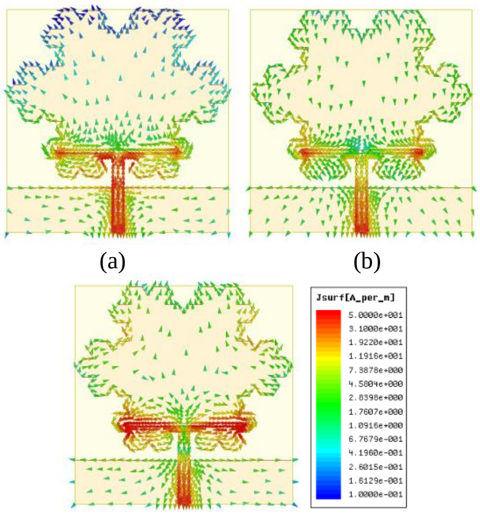


Figure 3. The simulated current distributions of the propsed antenna at three frequencies. (a) 0.95 GHz, (b) 1.85 GHz, and (c) 2.45 GHz

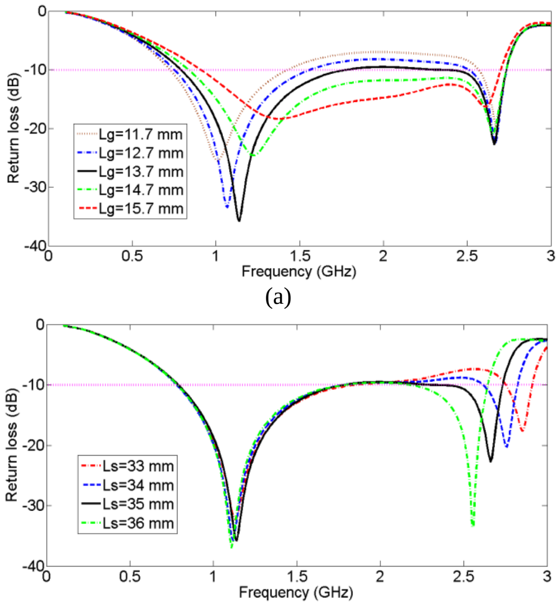


Figure 4. Effects of Lg and Ls on the antenna return loss of the antenna. (a) Lg and (b) Ls

3. ANTENNA FABRICATION AND MEASUREMENT RESULTS

In order to validate the simulated results, the proposed fractal monopole antenna is fabricated and its impedance bandwidth, radiation and power spectrum characteristics are measured. Figure 5 shows photographs of the fabricated prototype. In the following, the experimental results are given, discussed, and compared with the simulated results.

In Figure 6, it is presented a comparison between the simulated and measured return losses of the proposed antenna which appear to be in relatively good agreement. The discrepancies between the simulated data and measured result are almost due to fabrication tolerances and misalignments, including the dimensional error of the antenna and the nonconformity of the actual dielectric permittivity of the substrate. Moreover, it can be attributed to the calibration errors resulting from the vector network analyzer, measurement setup and connecting coaxial cables. Measured result shows that the proposed fractal antenna can cover a frequency range from 0.92 to 2.58 GHz (95%, 10-dB impedance bandwidth). Thus, it covers the most interest bands for harvesting application.

The measured radiation pattern along H(x-z) and E(y-z) planes for three different frequencies 0.95, 1.85, and 2.45GHz are presented in Figure 7. As seen in this figure, the radiation patterns are nearly stable and uniform at the different frequencies. As well as, it is also seen that the antenna maintains omni-directional pattern in the H-plane and bi-directional pattern in the E- plane over the frequency band.

The increase in cross-polarization level at high frequencies is almost by reason of the excitation of hybrid current distribution on the antenna radiator patch. The measured gain and simulated radiation efficiency of the antenna are also shown in Figure 8. The antenna achieved an average gain of 0.9 dBi over the operating frequency, and the maximum value of 3.1 dBi which occurs at 2.7 GHz. It should be noted that the antenna gain is reasonable over the working band respecting the compact size and omnidirectional behavior of the proposed antenna. Besides, the efficiency of the antenna is almost stable with the growth of frequency, while the value of gain increases for higher frequencies. The following values of simulated efficiency are obtained of 84.8, 79.12 and 78.37% at 0.95, 1.85 and 2.45 GHz, respectively.

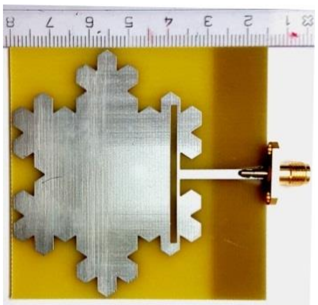


Figure 5. Prototype of the fractal monopole antenna

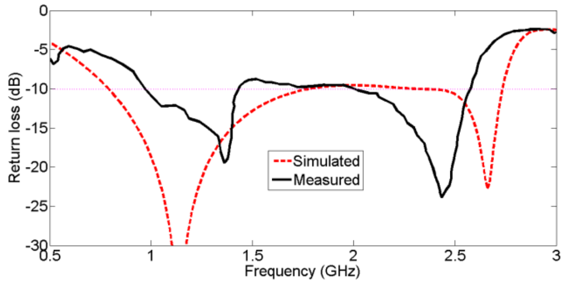
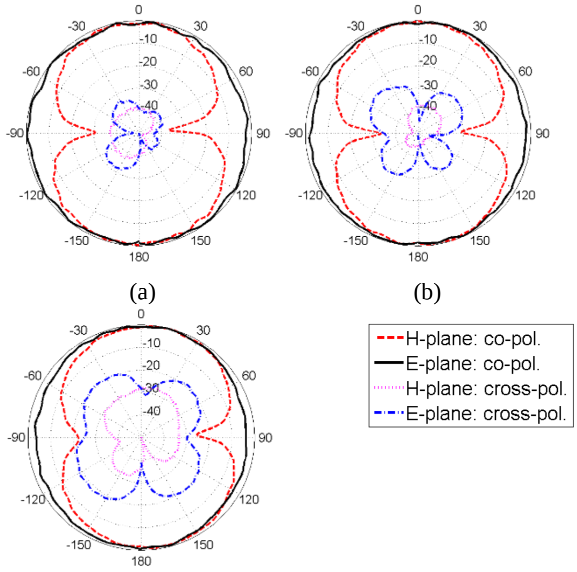


Figure 6. Simulated and measured return losses of the proposed antenna



(a) (b)

(c)

Figure 7. Radiation patterns of the proposed antenna in the H- and E-planes at a) 0.95 GHz, b) 1.85 GHz, and c) 2.45GHz

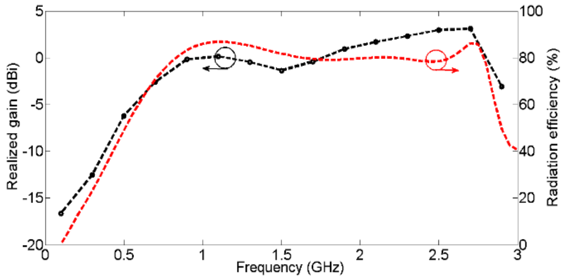


Figure 8. Measured gain and simulated radiation efficiency of the proposed design

To evaluate the performance of the proposed wideband antenna in a realistic measurement of the harvested power, a spectrum analyze is connected to the antenna for integrating the power spectrum over bandwidth. An indoor laboratory environment is selected with a relatively low ambient RF power density to conduct the test. Nearest cell phone tower site is about 600 m away from the laboratory and a Wi-Fi router is near to the position of test. The received power in dBm in term of frequency is shown in Figure 9. It is clear that the power is mostly distributed at three frequency bands which are GSM-900, GSM-1800, and Wi-Fi with average power levels of -46, ،-32, and ،-33 dBm, respectively. It should be noted that the measured total power in the band received by antenna is variable as a function of time.

The performance comparison of the designed antenna with other relevant designs available in the literature is presented in Table 1. Antenna parameters such as Impedance Bandwidth, Electrical Size, Peak Gain, and Efficiency for given dielectric constant of substrate are shown. It is obvious that the proposed antenna has design superiority over many designs in terms of compactness and bandwidth for the designed frequency bands. Compared to results reported by Alex-Amor et al. [4], impedance bandwidth of the antenna is reduced that it is because of reduction in the total area of the proposed antenna.

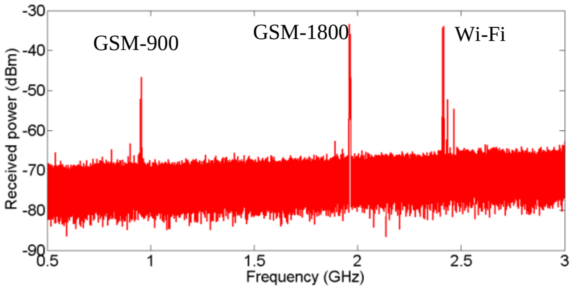


Figure 9. Measured power spectrum by the proposed antenna inside the laboratory

TABLE 1. Comparison of the designed antenna with related works in literature

Ref.	Description	Impedance Bandwidth (GHz), (%)	Electrical Size	Max. Rad. Efficiency (%)	Peak Gain (dBi)	Substrate, εr
Proposed	Fractal monopole with inserted slot	0.92-2.58, (95%)	0.2 × 0.2 λ_0 (0.92 GHz)	83.3	3.1	FR4, 4.4
[4]	Archimedean spiral	0.35-16 (192%)	0.23 × 0.24 λ_0 (0.35 GHz)	98	-	FR4, 4.7
[7]	Metamaterial with EBG structure	5.03- 6.04 (18%)	0.83 × 0.83 λ_0 (5.03 GHz)	50.4	8.6	FR4, 4.2
[11]	Dual-polarized cross-dipole	1.8-2.5 (33%)	0.42 × 0.42 λ_0 (1.8 GHz)	70	4.2	FR4, 4.4
[12]	Electromagnetically-fed CP	1.73-2.61 (40%)	0.38 × 0.38 λ_0 (1.73 GHz)	-	8.7	FR4, 4.6
[14]	Bent triangular omnidirectional	0.85-1.94 (79%)	0.31 × 0.27 λ_0 (0.85 GHz)	75	2	FR4, 4.4

The proposed wideband antenna is developed to array configuration based on a microstrip-to-slot-line transition feeding network in literature [22]. In this design, a wideband rectifying circuit using two-branch matching circuits by applying a full-wave rectifier circuit and an optimized coupled-line is presented to match with the ambient wireless signals in the low power density. A series-mounted Schottky diode HSMS-285C from Avago is applied for the rectifier circuit owing to its low turn-on voltage condition and small junction capacitance for a low input signal. Therefore, the proposed design can be used for efficiently harvesting RF energy from the ambient environment with appropriate RF-to-DC conversion efficiency.

4. CONCLUSION

A low-cost wideband fractal antenna with embedded a thin slot was proposed particularly for ambient RF energy harvesting. The antenna is capable of operating in a wide range from 0.92 GHz to 2.58 GHz, as the measurement results. Using fractal structure in radiating patch causes miniaturized dimension of antenna and the thin slot in the radiating patch is applied for the bandwidth enhancement of the antenna. The designed monopole antenna shows omnidirectional radiation patterns and responsible gains for different frequencies over the bandwidth range. Moreover, in order to estimate the incoming power level, a test is carried out with the antenna inside the laboratory. These results cause the conclusion that the major role of the harvested power comes from the cellular bands and wi-Fi router, especially from 1.8 and 2.4 GHz.

5. ACKNOWLEDGMENT

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Persian Abstract

چکیده

در این مقاله، یک آنتن مونوپل مسطح باندوسیع بر پایه هندسه فرکتال و تعبیه یک شکاف نازک بر روی پچ تشعشع‌کننده برای کاربردهای برداشت انرژی RF طراحی شده است. آنتن پیشنهاد شده در روند طراحی، در چندین مرحله بهینه شده است. علاوه بر این، یک مطالعه پارامتری به منظور درک حساسیت برخی پارامترهای مهم در روند طراحی آنتن، انجام شده است. آنتن طراحی شده دارای پهنای‌باند امپدانسی ۰/۹۲ تا ۲/۵۸ گیگاهرتز (پهنای باند کسری ۹۵٪) با یک ساختار فشرده به اندازه ۶۵ × ۶۵ × ۰/۸ میلیمتر مکعب است. همچنین آنتن دارای بهره و مشخصات تشعشعی قابل قبول و پایداری است. قابلیت کاربردی آنتن به عنوان یک آنتن دریافت‌کننده برای سیستمهای برداشت انرژی، داخل محیط یک آزمایشگاه تست شده است. آنتن باندوسیع طراحی شده، قابلیت خوبی در برداشت انرژی باندهای در دسترس GSM-900، GSM-1800 و Wi-Fi دارد که میتواند به عنوان یک بخش در ماژول تغذیه توان DC در شبکه‌های حسگر کم‌توان به کار برده شود.