Research Article

Design of Wideband Circular-Slot Antenna for Harvesting RF Energy

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The design of a wideband circular-slot antenna for RF signal harvesting is reported in this work. The proposed design frequency range accommodates the leading contributors to the available RF signals accessible by the RFEH node. These widely utilized frequency bands comprise GSM1800, UMTS2100, Wi-Fi2.450, and LTE2600. The antenna geometry comprises circular-ring radiating component filled with two orbital circular and rectangular slots. At the bottom plane, a pair of rectangular and semirectangular-circle slits are integrated. The antenna presented is designed on a double layer of 1.6 mm high FR4 substrate. The source antenna achieved a simulated and measured impedance bandwidth (BW) of 1.510 and 1.590 GHz, amounting to 68% and 73% fractional BW (FBW), covering -10 dB reflection coefficient ($|S_{11}|$) between 1.640 to 3.150 GHz and 1.550 to 3.140 GHz, in that order. The wideband circular-slot source antenna realized a maximum measured gain of 1.88, 2.13, 2.81, 3.22, and 4.32 dBi for 1.800, 2.100, 2.450, 2.650, and 3.20 GHz, respectively. The proposed design dimension on the printed board is 0.61 $\lambda_g \times 0.70 \lambda_g$.

The improved antenna gain is obtained from a circular parasitic patch coupled to the defected ground structure (DGS) for better RF energy harvesting in an ambient environment.

1. Introduction

The ability to handle high electromagnetic (EM) energy is one of the important features of antennae used for the RFEH module [1, 2]. RFEH technology has recently piqued the interest of researchers as an additional source of energy that provides an alternative solution to short-life batteries [3, 4]. Mobiles phones and other related wireless devices have been penetrating the market since 1980 [1, 5]. Hence, the rising demand for the long operational life of a battery remains an open challenge [6, 7]. In RFEH systems, a rectifying antenna (rectenna) harvests the energy via a combination of a source antenna and RF-rectifier [8, 9]. The source antenna picks up the incoming signals, which are then transformed by an RF-rectifier into a useable low power dc supply [10]. RFEH technology is considered among the sources of green energy by utilizing and shielding humanity from potentially harmful radiation [11]. Thus, wireless medical implanted devices (WMID) largely facilitated the emergence of applications in healthcare systems such as wirelessly capsule endoscopes, neural implants, retinal prostheses, various neural recording microsystems, spinal cord stimulators, and
intracranial pressure (ICP) monitors [12, 13]. Life-saving healthcare systems involve telemetry and supervision of the vital human body parts by the basic essential indicators for the evaluation, diagnosis, stimulation, and treatment process [14, 15]. RFEH antennae with wide operational BW and improved gain are desirable for an efficient RF harvester [16]. RF-spectral data from various research studies that have recently been reported shows a practical amount of energy for harvesting at GSM1800, UMTS2100, ISM2.4-Wi-Fi2.45, and LTE2600 spectrum [5]. It is a challenging task to design an antenna that can operate over a specific broad and compact spectrum for a particular application [17, 18].

Researchers have recently focused on developing ultra-wideband antennae with band rejection capabilities to minimize interference from narrow-band wireless applications [19, 20]. To attain the desired goal, several designs approach, such as inserting slits and slots of varying diameters, are being applied to the radiating components, feed line, and ground planes [5, 19]. The use of half (λ/2) [5] and a quarter (λ/4) [21] wavelength, open ended slits, and DGS [22, 23] are also reported for various wireless communications applications. The authors in [24] introduce a circular patch monopole antenna with an annular-ring structure at 5.80 GHz. The antenna demonstrates a 12.8% BW increment, and a gain of 5.70 dBi at a relatively high frequency compares to a typical monopole antenna. A monopolar broadband antenna is reported by the authors in [25]. With the introduction of metallic Vias, the antenna attains a BW of 18%, resulting in a peak realized gain of 6 dBi between 2.15 and 2.35 GHz.

Incorporating a feeding-loop results in about 65% BW as demonstrated by the authors in [26]. The antenna realized a peak gain in the span of 3 to 7.7 dBi between 1.320 and 2.60 GHz operating frequencies (f₀). Besides, the deployment of a complex feeding technique in the 3D structural model, a CPW broadband antenna with a square-slotted pattern is demonstrated by the authors in [27]. The design realized a FBW of 17.2% at 2.440 GHz. The concept of introducing slots and slits on the feed line and the bottom ground of the CPW antenna is reported to improve the BW by about 45% by the authors in [28, 29]. The authors in [30] explore the analysis of corner truncated antennae comprising U and L slots. A single feed probe is used in the design study where the various dimensions of the substrate height (h) were examined. The design attained a peak FBW of 14.0% at 4.05 and 4.15 GHz. The authors [31, 32] demonstrated the concept of integrating the feed line with slots and slits. The designs, respectively, realized a FBW of 4.70% and 17.70% for worldwide interoperability for microwave access (WiMax) and radio frequency identification (RFID) applications. The technique of fractal architectures deployed by the authors in [33–35] obtained a FBW of 22.50%, 0.78%, and 2.00%, respectively. Hence, the broadband antennae reported by the authors in [28, 29, 31] and [36] are generally designed with a complicated geometry that is difficult to actualize.

This work targets a wideband circular-slot antenna with an improved gain, having a simple and inexpensive geometry structure. The authors in [34, 37] demonstrated the concept of an electromagnetic coupling using a single feed line to maintain simple antenna geometry. A tilted rectangular and triangular wideband monopole printed antennae are exploited by the authors in [38, 39]. The designs reported a FBW of 51.40% and 62.00%, respectively. The designs also recorded a relatively low gain across the f₀, which renders them unsuitable for low-power RFEH systems. A low-profile source antenna with broad BW and enhanced gain is required for better RFEH in ambient terrain [1, 8, 11]. A broadband antenna for RFEH is presented by the authors in [40]. The antenna achieved a FBW of 23% at 2.45 GHz. The authors in [41] reported a narrow-band antenna for the RFEH application. The source antenna achieved a 10 dB BW of 30 MHz with a peak gain of 3.360 dBi at 2.45 GHz. Printed patch antennae are regaining recognition in the design of RF harvesters due to their conformability to planar and nonplanar surfaces, compactness, low-profile, light, and cheap manufacturing cost [1, 8, 11]. Patch antennae are also preferred due to their adaptability in terms of f₀, gain, radiation pattern, polarization, and matching BW. Therefore, the proposed design in this work maintains a trade-off between simple geometry structures, compact size, affordability, and improved performance.

In this study, a circular-slot wideband antenna is reported. The antenna is suitable for harvesting RF signals across GSM1800, UMTS2100, ISM2.4-Wi-Fi2.45, and LTE2600 spectrum. The proposed design achieved a total dimension of 50 mm × 56 mm matched through a 50 Ω transmission line (TL). The proposed design offers a wide f₀ of 1.640 GHz to 3.150 GHz with an improved gain applicable for RFEH systems. The remaining sections of this work are divided into the following. Section 2 outlines the proposed design antenna configuration. The findings are addressed in Section 3. The concluding remark is presented in Section 4.

2. Antenna Design

RF spectrum measurements were performed before coming out with the antenna design to determine the availability of RF ambient power in the environment. Figure 1 presents a
cross section of the received ambient RF power levels. The survey highlights the significance of five major spectrums with reasonable power levels for RFEH. As a result, the operational frequency for the proposed antenna is specified within 1.640 to 3.150 GHz, which covers GSM1800, UMTS2100, ISM2.4Wi-Fi2.45, and LTE2600 frequency bands.

The antenna presented in this paper is designed on a double layer of 1.6 mm height \((h)\) FR-4 substrates, having 4.7 dielectric constant \((\varepsilon_r)\), with 0.02 tangent loss \((\tan\delta)\). The material is adopted because it is inexpensive, available, and simple to fabricate. The proposed antenna comprises a circular-ring radiating element integrated with two additional circular and rectangular slots. Figure 2 presents design architecture and the parameters of the proposed wideband circular-slot antenna. Firstly, antenna architecture was a model using a circular microstrip planar antenna based on a closed-form equation as expressed in the following equation [42]:

\[
f_{lw} = 7.2 \left( \frac{9a + 4p}{4} \times k \right)^{-1} \text{GHz},
\]

where \(f_{lw}\) represents the lower cutoff \(f_o\), \(p\) is the gap of the feed line in (cm), \(a\) provides the radius of the circular patch in (cm) over a constant value \(k = 1.15\). Thus, “\(a\)” can be expressed as

\[
a = \left( \frac{3.20(GHz)}{f_{lw} \times k} \right) - \left( \frac{4}{9} \right)p.
\]

Solving for “\(a\)” at \(f_{lw} = 1.6\) GHz, and \(p = 0.5\) cm, \(a\) is computed to be 1.6 cm (16 mm). The width of TL is initially evaluated at 2.7 mm from the Wheeler’s closed-form equation [10] and then optimized at 2.8 mm. The calculated values from the model equation are transferred into a high-frequency structure simulator (HFSS) from ANSYS for further parametric tuning and optimization.

This section investigates the impact of various critical dimensional elements on the antenna’s performance, notably its radiation pattern, impedance BW, and gain. All simulations are conducted through HFSS. The first circular antenna structure (Design-#1) resonates at 2.2 GHz with an unsatisfactory \(|S_{11}|\). Circular structures tend to provide a steady flow of currents [15,33]. A DGS is introduced into the antenna structure to achieve a broader impedance BW between 1.600 and 3.100 GHz as depicted in Design-#2. A circular-ring structure is realized by introducing a 23 mm circular slot into the radiator, as shown in Design-#3. Two circular slots are added to the orbital section of the radiator to achieve a broader resonance across 2.320 to 2.910 GHz \(f_o\).

A good impedance matching is realized by extending rectangular slots from the bottom of the radiator. The DGS is also incorporated with a resonating circular parasitic patch to enhance the proposed antenna’s gain. The embedded circular patch on the partial ground resonates with the corresponding pair of circular slots counterpart on the left-hand side (LHS) of the radiator. Additionally, a pair of rectangular slots and a semirectangular-circle slit are carved on the bottom ground for a broader impedance BW as described in Design-#4. The addition of the slots and slits into the orbital sides of the structure is realized through considerable parametric analysis to maintain the antenna wideband characteristics with a reasonable gain. Hence, Figure 3 illustrates the procedures used to achieve the desired wideband circular-slot antenna.

**Figure 2:** Proposed wideband antenna design architecture: (a) top view and (b) bottom view.
The wideband circular-slot radiator is first excited with an upper circular slot along the LHS corner with a radius of \( r_1 \). The diameter of the slot was tuned at \( \lambda/4 \) of the medium resonance mode of 2.1 GHz. \( r_1 \) was then varied to investigate the effects of the slots on the antenna performance. Adjusting \( r_1 \) introduces a noticeable impedance mismatched along the 2.00 to 2.400 GHz. The diameter of the slots was then optimized at 16 mm, as shown in Figure 4(a). The lower circular slot with a radius of \( r_2 \) is integrated between the radiator and the feed line to further improve the upper resonance mode \( f_r \) between 2.320 and 2.910 GHz and also reduce the impedance mismatch. The diameter of the lower orbital slot were then gradually tuned at \( \lambda/8 \) of \( f_r \) at 2.45 GHz. Hence, \( r_2 \) of the slot demonstrates an improved antenna performance at 10 mm diameter, as shown in Figure 4(b).

The incorporation of the upper and lower circular slots to the radiator introduces an impedance mismatch to \( f_r \). As such, a vertical rectangular slot is raised from the center of the radiator to enhance the impedance matching across the wide \( f_r \). Rectangular stubs have been frequently employed in various literature to increase the resonance performance depending on their orientation [43–46]. Varying the length of the slot \( r \) has an impact on the impedance BW, which
distorts the antenna peak achievable gain. The impedance matching tends to improve as \( t \) slowly increases from 6.5 to 9 mm and deteriorates beyond 10 mm. A good impedance matching is realized by extending the length \( t \) of the rectangular slot from the bottom of the radiator at 9.30 mm, as demonstrated in Figure 5(a). Additionally, a circular parasitic patch is embedded into the partial ground to resonate with their corresponding pair of the radiator orbital circular slot to enhance the proposed antenna’s gain. A comparison of the circular parasitic patch with radius \( r_3 \) and the corresponding length \( t \) is illustrated in Figures 5(a) and 5(b).

3. Results and Discussion

Figure 6(a) presents the results of the simulated and measured \( |S_{11}| \) versus the frequency of the proposed wideband circular-slot antenna. The antenna’s measured \( |S_{11}| \) is in close agreement with the simulated data. The slight variation from the measured data is attributed to fabrication tolerance between the top and bottom view, the SMA source or connection loss, and soldering lead loss. The proposed design achieved -10 dB simulated and measured BW of 1.51 GHz over a frequency span of 1.640 to 3.150 GHz and 1.590 GHz between 1.550 and 3.140 GHz. The results findings cover a target \( f_o \), amounting to 68% and 73% of the simulated and measured FBW, respectively.

Figure 6(b) depicts the peak gain variation as a function of frequency. A maximum peak measured and simulated realized gain of 3.1 dBi and 3.2 dBi is attained by the antenna at 2.600 GHz over a range of the targeted \( f_o \). A peak realized simulated and measured gain of (1.93 dBi, 2.6 dBi, and 3.3 dBi) and (1.8 dBi, 2.1 dBi, and 2.7 dBi) is also achieved at 1.800, 2.100, and 2.400 GHz, respectively.
Figure 7 presents a 2D radiation plot across the four $f_o$. The results are simulated at 1.800, 2.100, 2.450, and 2.65 GHz, alongside $xz$-plane for ($\varphi = 0^\circ \mid 0^\circ < \theta < 180^\circ$) and $yz$-plane for ($\varphi = 90^\circ \mid 0^\circ < \theta < 180^\circ$), respectively. An almost omnidirectional radiation pattern is seen along $xz$-plane, whereas $yz$-plane portrays a dipole-antenna pattern at 1.800 and 2.100 GHz, and a directional antenna at 2.450 and 2.650 GHz.

Table 1 summarizes the antenna’s outcomes, which are compared with the related work in terms of their
description, electrical dimensions, FBW, and gain. The authors in [18, 24] realized a peak gain when compared to this work at the expense of a larger electrical dimension, lower FBW, and relatively higher $f_{oc}$. Besides, the proposed wideband circular-slot antenna demonstrates a good improvement with a broader $f_{oc}$ that covers four major RFEH spectrums. Furthermore, the antenna achieved a high gain across $f_{oc}$, which is important in energy harvesting applications. As a result, the antenna provides a good trade-off between FBW, compact size, gain, and cost.

The performance of the proposed wideband circular-slot antenna in an ambiance terrain is investigated in the Multimedia University, Cyberjaya campus. Figure 1 highlights the capability of the terrain for harvesting RF signals. The amplitudes of receiving RF signals vary based on the ambient circumstances. After evaluating the antenna parameters, a broadband RF-rectifier with a wide scale of input power is introduced to make a rectenna system. The RF-rectifier also operates between 1.780 and 2.620 GHz. The two components are connected by a straight-through SMA-male to a SMA-male RF adapter. The broadband rectenna is then put to the test in an ambiance setting. The proposed wideband circular-slot antenna is subjected to a variety of tests at different locations in the campus through the rectenna system. Generally, the locations are marked between 30 and 200 meters from a nearby position or BS. The measurements location is around 1 to 2 m above the surface level. As demonstrated in Figure 8, the proposed circular-slot antenna produces an output dc voltage $V_{dc}$ of 0.313 V via the wideband RF-rectifier output terminal.

4. Conclusion

Source antenna architecture presented in this paper is composed of a circular-ring radiating element loaded with two orbital circular and rectangular slots. A defected ground integrated with a pair of rectangular and semirectangular-circle slits is modeled at the bottom plane for enhancing the impedance matching BW. A circular parasitic patch resonating with its respective pair of radiator orbital slots is further added into DGS to improve the gain of the proposed antenna. The proposed wideband circular-slot antenna achieved a measured and simulated operational BW of 1.59 and 1.510 GHz, resulting to a 73% and 68% FBW, respectively. A peak measured and simulated realized gain of (1.8 dBi, 2.1 dBi, 2.7 dBi, and 3.1 dBi) and (1.93 dBi, 2.6 dBi, 3.4 dBi, and 3.2 dBi) is attained by the antenna at 1.800, 2.100,
2.450, and 2.650 GHz, in that order. The source antenna is implemented on the FR-4 board covering a size of 0.61 \( \lambda_g \times 0.70 \lambda_g \) [47].

**Data Availability**
The data used to support the findings of this study are included within the article.

**Conflicts of Interest**
The authors declare that they have no conflicts of interest.

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