Compact Dual-Band Tapered Open-Ended Slot-Loop Antenna For Energy Harvesting Systems

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Abstract: In this study, a compact dual-band combined loop-slot planar antenna is proposed. (1) Background: multi-function antennas are desired for wireless communication to cover the desired frequency spectrum. (2) Methods: the proposed antenna consists of a semi-rectangular open-ended loop (OEL) operating at the lower frequency band 920 MHz, an open-ended slot (OES) transmission line that provides resonance at the higher band 2.4 GHz, and a feeding port using the asymmetric coplanar strip (ACS) line. The ACS is used to excite the antenna to achieve dual-band performance. The overall dimensions of the fabricated prototype are $32.5 \times 53.5 \text{ mm}^2$ ($0.1 \lambda_o \times 0.16 \lambda_o$), where $\lambda_o$ represents the free-space wavelength at the lower frequency. (3) Results: from the calculations, the antenna shows two impedance bandwidths (estimated at $-10 \text{dB}$) of 30 MHz (920–950 MHz) and 300 MHz (2.2–2.5 GHz) to cover the ISM band (920 MHz) and 2.45 GHz WiFi bands, respectively. Indeed, the antenna has stable radiation patterns and achieves peak measured realized gain of 1.8 dBi in the lower band and 4.2 dBi in the higher band. (4) Conclusion: the antenna shows the merits of low profile structure, single-layer, and low-cost fabrication. The proposed antenna not only achieves incremental increase in radiation efficiency, but also provides a lightweight, and small footprint.

Keywords: asymmetric CPW; dual-band; energy harvesting; loop; slot

1. Introduction

With the great advancement in wireless communication technology and personal wireless communications, there is a constant demand for antennas with multi-functions. Multiband antennas that are simultaneously operating at different frequency band are preferred for several practical applications. For instance, wireless mobile services, satellite communication, biomedical diagnosis, and energy harvesting applications [1,2]. The license-free Industrial-Scientific-Medical (ISM) frequency bands located at 0.9, 2.4, and 5.8 GHz are usually exploited to support wireless power transfer (WPT) technology. Currently, the RF energy transfer in ISM Bands is not only promising, but it also becomes a reality as some pioneer companies propose several full kits: Powercast Corporation, AnSem, and MicroChip, to name a few [3]. However, there is still a great demand to make the RF energy transfer an appropriate, low cost and easy-to-use solution to sufficiently powering the remote wireless nodes. One of the most critical points concerns the harvesting capability of the RF modules is the design of a compact, simple, dual-band, and lightweight antenna.

At present, 0.92 and 2.45 GHz frequency bands are more attractive because of their good performances of data speed and anti-environment jam ability [4,5]. The 0.92–2.45 GHz ISM bands are very common and widely used for different applications, like Radio-frequency Identification (RFID), local area networks, and many other wireless services, like Bluetooth. Therefore, the power that is
emitted into the environment is adequately large when compared to other applications. This power can be recycled and utilized for energy harvesting [6,7]. The antenna plays a key role in the harvesting of electromagnetic energy. It is used to harvest electromagnetic waves in space and transform them into electric currents to be processed further. Nevertheless, there are some challenges for developing an antenna to harvest power efficiently at both bands. For instance, the operation mode and frequency differences between 0.92 and 2.45 GHz are too large to properly achieve dual-band structures [8–10].

Owing to the greater demand for applications in these frequency bands, several attempts have been made with the purpose to design compact and an efficient antennas operating in these bands [11–17]. To meet the dual-band requirements, more recent evidences highlighted the design of a dual-band antenna. For instance, Sun et. al introduced a wide band Yagi-Uda antenna to cover a wide band from 1.8–2.1 GHz. Although the proposed antenna can harvest the power from DCS-1800 and UMTS-2100, it does not cover 0.9 GHz [18]. A slot-loaded dual-band $\lambda_o/2$ folded dipole antenna is reported in [19] to serve the energy harvesting system at 0.9/2.45 GHz. The folded dipole is utilized to shrink down the antenna size and operates at 0.9 GHz, whilst a slot is etched from the folded dipole to generate the second band at 2.45 GHz. Although the antenna has achieved a dual-band operation, it employs double-layer configuration. Dual-band electrically small antenna (ESA) operating at 934 MHz and 1.55 GHz is presented in [20]. The structure of this antenna is based on a loop that excites two different sizes of split-ring resonators to achieve dual resonant structure. Additionally, a compact planar dual-band antenna based on the monopole structure for UHF and ISM bands is reported in [21] with a large size.

A dual-band antenna for energy harvesting application has been designed and investigated in [22] to operate at 1.95 and 2.45 GHz. The antenna has achieved a good enhancement in antenna gain. The measured results showed a gain of 8.3 and 7.8 dBi at 1.95 and 2.45 GHz, respectively. In [23], a dual-port triple-band L-probe microstrip patch rectenna design for ambient RF energy harvesting using the GSM900, GSM-1800, and UMTS-2100 bands is described. The design is based on stacking two single-port patch antennas back-to-back in order to implement a compact dual-port patch antenna with high isolation between ports.

The previously reported antennas are not simply integrated with wireless applications, despite the previous attempts that were conducted to solve the antenna compactness and poor radiation pattern at the lower frequency band. Indeed, the reported designs were not straightforward and they require rigorous mathematical analysis. Therefore, dual-band compact and high efficient antennas are highly recommended. The objective of this study is to introduce a simple dual-band compact loop-slot combined architecture suitable for RFID, Wi-Fi, and energy harvesting applications.

In this paper, a compact 0.92 GHz and 2.45 GHz dual-band combined loop/slot antenna is proposed in order to generate good radiation and electromagnetic wave propagation at the specified frequencies. The OEL and OES are used to provide the microwave propagation at 0.92 GHz and 2.45 GHz, respectively. The OEL is a trapezoidal rectangular shape with a total length of $0.7\lambda_g$ at 0.92 GHz. Additionally, the OES is based on a tapered slot, the overall length is $\lambda_g/2$ at 2.45 GHz.

This paper is organized, as follows: the structure and configuration of the antenna are introduced in Section 2 as well as antenna analysis. In the same manner, discussions are carried out to investigate the operation principle of the antenna. The experimental results and comparison are presented in Section 3. In the last part, the manuscript is summarized with the conclusions.

2. Antenna Design Architecture

In this section, the operating principle of the antenna and parametric sweep analysis is illustrated. The dual-band characteristic is realized using two different type resonant modes of the loop-slot antenna, namely, a loop basic mode in the lower band and a slot basic mode in the higher band. It is wise to state the antenna design polarization characteristics whether it is preferred for the EH system design or not. For the ambient energy harvesting, a high-efficient rectennas are desirable for energy harvesting to intercept more power from the radiated electromagnetic energy and hence maximize the output DC
power. This feature can be achieved using different methods. Solutions to high conversion efficiency rectenna is mainly dependent on the receiving antenna design where the influence of receiving antenna on system performance (in terms of conversion efficiency and working distance) is of significance. The receiving antenna can either be designed to have high-gain, multi-polarized, multi-beam, ... etc. A high-gain antenna is preferred for the longest distance applications. Furthermore, a circularly polarized (CP) antenna is desirable to receive electromagnetic energy from different polarization to improve the total conversion efficiency. Therefore, a wide-band and high-gain CP antenna is a good candidate to collect energy from random polarization at different operating frequencies for RF energy harvesting.

On the other hand, in case of dedicated RF energy harvesting where the transmitting source features are well-known to the receiver, the aforementioned characteristics are not critically important. The receiving antenna will be designed to have the typical polarization of the transmitting antenna. In our case, the transmitting antenna is a high gain linear polarized Yagi antenna. Therefore, the receiving antenna was designed to also have linear polarization. This ensures a large power conversion between the Tx and Rx side.

2.1. Description of the Antenna Structure

The antenna is composed of a notched rectangular loop which contributes to the OEL configuration (identified by ABCDEFA structure), slotted parallel transmission line that handles the operation of OES (identified by CDEFGHIC structure), and an ACS strip feed line. As shown in Figure 1, the OEL is divided into two segments with small gap separation. Normally, the loop antenna resonates (with a purely real impedance) when the perimeter of the loop approaches one wavelength is comparable to 920 MHz. The first segment has an L shape and it represents a quarter wavelength defined by \((L_{p1} + L_{p2})\). The other segment is composed of trapezoidal shape defined by \((L_{p4} + L_{p5} + L_{p6})\) that is connected with a curved transmission line \((L_{p3})\) to tune the input impedance. The total length of the trapezoidal shape is a half wavelength. Each segment is loaded with an open slot, so the total length of the loop antenna can be reduced and resonance frequency is tuned to the desired frequency of operation.

On the other hand, the OES is created by extending the ground plane along with side-by-side to the trapezoidal shape. The higher resonance is obtained by adjusting the length of the slotted transmission line \(L_{p6}\).

The antenna is fed by using ACS that has a single lateral ground. The ACS fed method is used to reduce the size of the antenna and improve its performance. The ACS configuration provides similar benefits of CPW fed antenna in addition to more compactness. In case of ground width more than the width of the feed line, the characteristic impedance of ACS that achieves 50\(\Omega\) is calculated according to the following equations [24]:

\[
Z_0 = \frac{60\pi}{\sqrt{\varepsilon_{\text{eff}}}} \frac{K(k)}{K'(k')}
\]

\[
k = \frac{0.5W_g}{g + W_f}, \quad k' = \sqrt{1 - k^2}, \quad \varepsilon_{\text{eff}} \approx 1 + (\varepsilon_r + 1)/2
\]

and \(\frac{K(k)}{K(k')}\) is called an elliptical integral, and equal to

\[
\begin{align*}
\frac{K(k)}{K(k')} &= \begin{cases} 
\frac{\pi}{\ln \left( \frac{1 + \sqrt{1 - k^2}}{1 - k^2} \right)} & 0 \leq k \leq 1 \\
\frac{1}{\pi \ln \left( \frac{1 + \sqrt{1 - k^2}}{1 - k^2} \right)} & 1 < k \leq \frac{1}{\sqrt{2}} \\
\frac{\pi}{\ln \left( \frac{1 + \sqrt{1 - k^2}}{1 - k^2} \right)} & 1 < k \leq 1 
\end{cases}
\end{align*}
\]
Figure 1. Geometry of the proposed antenna, all dimensions existed on the antenna are given in mm. The dimensions are given, as follows: \( W = 32.5, L = 53.5, L_{g1} = 20, W_{g1} = 6.78, W_{g2} = 6.97, L_{p1} = 41, L_{p2} = 10, L_{p3} = 8, L_{p4} = 12, L_{p5} = 43, L_{p6} = 26, W_{p1} = 4.65, W_{p2} = 3, W_{p3} = 5, W_{p4} = 3.6, W_{p5} = 7, W_{p6} = 2.5, S_{1} = 1.36, S_{2} = 2, S_{3} = 2.22, S_{4} = 2, W_{f} = 1.28 \). All units are given in mm. The circular red points indicate the position of each alphabet. These letters are identified to simply describe the antenna structure in the context.

2.2. Parametric Sweep Analysis

In order to understand the proper operation of the proposed antenna, a parametric study is examined, as shown in Figure 2. As mentioned earlier, a parallel L strip line is inserted alongside the main radiator, so the antenna configuration can produce a dual-band feature. The length of such transmission line is \( L_{p1} \) and is optimized for the best performance. This parameter is varied from 25 to 45 mm with a step of 5 mm. The corresponding S11 is shown in Figure 2a. It is noted from the figure that, the lower resonance frequency is significantly affected by changing \( L_{p1} \). In the same manner, the higher resonance frequency has no change but the matching is improved. The value of \( L_{p1} \) is optimized to be 41 mm, which produces the best matching condition at 0.92 and 2.4 GHz.

Similarly, the parameters of the OES antenna are studied. The length of the open stub \( L_{p6} \) and slot separation width \( S_{3} \) are tuned, as given in Figure 2b,c. Both of the parameters affect the impedance matching level at the higher frequency. As expected, there is a minimal change of S11 at the lower frequency where both parameters significantly affect the antenna performance at the higher frequency band. The optimized values of \( L_{p6} \) and \( S_{3} \) are given as 26 and 2 mm, respectively. For further clarification, two antennas were developed, so that we can simply understand the antenna operation. The S11 of the Ant.1 and Ant.2 is illustrated in Figure 3a. The blue curve represents Ant.1. As can be observed, this antenna does not utilize an L-section, so it produces a single resonance at 2.4 GHz. In order to allow this configuration exhibit a second resonance at 0.92 GHz, rectangle L metal strip is inserted to form the OEL antenna (Ant. 2). This L-strip is extended alongside with the main radiator and ended with a separation gap of 0.3 mm. This gap acts as a capacitive reactance, so the total length of the radiator at the resonance frequency can be reduced by approximately 45%.
Figure 2. Parametric study of the open-ended slot antenna, (a) parametric study of the side-arm length, \( L_{p1} \) is the length of the arm; (b) variation of the open stub length, \( L_{p6} \), which adjust the level of impedance matching; and, (c) changing of the slot width \( S_3 \), this parameter doesn’t alter the resonance frequency, but it controls the impedance matching.

Figure 3. Performance of the antenna structure, (a) Reflection coefficients of Ant. 1 and Ant. 2, where Ant.1 represents the nominal case without the side arm that is parallel to the main radiator, and Ant. 2 represents the developed antenna structure to achieve dual-band operation by exploiting a parallel segment to the main trapezoidal radiator; (b) surface current of the antenna at 0.92 GHz and 2.45 GHz.
The surface current distribution is indicated Figure 3b to investigate the radiation pattern. The current is basically concentrated inside the loop antenna and almost no current flow in the ground plane. This explains that the proposed antenna behaves as a loop antenna at the lower band frequency. On the other hand, the surface current distribution at the higher frequency is illustrated in the right side of Figure 3b. It is observed that the current is flowing through the main radiator and ground plane. The L-arm of the main radiator acts as a director that concentrates beam in the end-fire direction at the higher band.

The radiation efficiency of the antenna is demonstrated using the following method. The proposed antenna is considered as a small antenna because it achieves the condition of small antennas \( ka < 1 \) (where \( k = \frac{2\pi}{\lambda} \) and \( a \) is the half of maximum antenna dimensions). Therefore, the Wheeler cap method has been selected to calculate the measured radiation efficiency for the proposed antenna [25–27]. The radiation efficiency of the proposed antenna is shown in Figure 4c. In the lower band, the average peak efficiency is less than 70%, while the higher band efficiency exceeds 70%.

3. Experimental Results and Simulation

The geometrical configuration of the proposed antenna has a simple, single layer and compact structure. The antenna uses a commercial cheap FR4-epoxy substrate with a thickness of 1.6 mm, a relative permittivity of 4.6, and a loss tangent of 0.02. The antenna has a profile size of \( 32.5 \times 53.5 \text{ mm}^2 \). The antenna is a planar type-based structure and its fabrication is very simple using either mechanical (CNC) or chemical (photolithography) techniques. The chosen approach in our case is the mechanical fabrication method, which provides a clean and high precise fabricated prototype. The fabrication is done using a mechanical etching process with a 100 \( \mu \text{m} \) resolution. The inner conductor of the input SMA connector is connected to the main strip of the loop, and the outer pin of the connector is directly soldered to the right side metal. The fabricated antenna is shown along with the S11 Figure 4a.

The properties and performance of the proposed antenna are predicted and optimized through electromagnetic simulation software in the Ansoft HFSS environment. The measured return loss, as shown in Figure 4a, indicates clearly that the proposed antenna has a multiband characteristic. Two resonant frequencies are located at 0.92 GHz and 2.45 GHz, with the return losses exceeding 20 and 22 dB, respectively. When compared with the simulated results, the measured reflection coefficient achieves good agreement in both the resonant frequency and bandwidth. It is noted that the higher band resonant frequency is slightly shifted toward the lower frequency region. This is attributed
to the dielectric constant fluctuation with frequency, and the parasitics that are produced form the connecting port.

On the other side, the realized antenna gain is illustrated in Figure 4b. The gain is plotted for the lower band from 0.9 to 1 GHz, and extended from 2.2 to 2.6 GHz at the higher band. While the simulated peak antenna gain at 920 MHz is 2 dBi, the corresponding peak value at 2.4 GHz is 5 dBi. In contrast, the exact measured gain at the lower band is 1.8 dBi, while that at the higher band is 4.2 dBi. The gain was estimated at the end-fire antenna direction. It is apparent from the curves that both measured and simulated results are slightly matches. The slight mismatch between measurement and simulation results are not significant. This mismatch is due to the solder connection of the fabricated antenna that is not considered in the simulation. Furthermore, the resolution of CNC machines is another factor for this little bit mismatch. Although this little bit mismatch, the antenna still covers the proposed bandwidths.

The most important antenna characteristic is the radiation pattern. The radiation pattern of the proposed antenna is experimentally tested and compared with the simulation results, as shown in Figure 5. The radiation pattern at the lower band resembles the conventional small loop antenna which is given like a figure of eight in the XY plane and omnidirectional in the XZ plane. In contrast, the directional end-fire radiation pattern is achieved at the higher band, because the ground plane acts as a reflector.

Several metrics are compared against similar research work existing in literature to evaluate the benefits of the proposed design, as depicted in Table 1. The comparison reflects that the proposed antenna offers several merits in terms of compactness, gain, low cost and simple architecture. The proposed antenna provides a compact footprint as compared to the architecture introduced in [11,12]. Moreover, it is obvious that the proposed antenna provides a reasonable high realized gain at both operating bands. The proposed antenna has a size of 32.5 × 53.5 mm². This size is considered to be a compact structure with respect to the lower resonance frequency (920 MHz). Nevertheless, the size might further reduce by using either a metamaterial structure or developing new patterns to realize the antenna with the same performance over a much-reduced footprint. The antenna can be employed to collect the electromagnetic energy in order to feed to a rectifier for RF-DC energy conversion. This application doesn’t necessitate a specific alignment, but it can achieve similar performance in either broadside or end-fire coordinates.

**Figure 5.** Antenna normalized simulated and measured radiation patterns at lower (0.92 GHz) and higher (2.4 GHz) band frequencies.
Table 1. Comparison of this study with the relevant research work in literatures.

| REF | f, GHz | Gain dBi | BW, MHz | Efficiency, % | Ant. Config. | Size, mm² | Substrate |
|-----|--------|----------|---------|---------------|--------------|-----------|-----------|
| [11] | 0.9, 2.4 | ~ve | N/A | 20, 40.8 (Rectenna) | meander monopole | 46 × 30 | RO4003 |
| [12] | 2.45, 5.8 | 1.46, 3.83 | N/A | 67, 59.5 (Rectenna) | sickle-shaped | 44 × 33 | FR4 |
| [18] | 0.92, 2.4 | 2, 3.5 | 80, 100 | 40, 35 (Rectenna) | shorted TLs | 45 × 80 | RO5880S |
| [21] | 1.8, 2.1 | 11, 14 | 100, 100 | 37, 43 (Antenna) | quasi-Yagi broadband array | 190 × 100 | RO5870 |

This work 0.92, 2.4 2,5 30, 300 70, 73 OEL, OES 32.5 × 53.5 FR4

4. Conclusions

This study has explained a new method to design compact, high-efficient, dual-band combined antenna that can work simultaneously at lower band 0.92 GHz and higher band 2.4 GHz. The antenna is based on a simple combined OEL and OES. The structure has low-cost fabrication and a single-feed network. It is demonstrated that the overall antenna gain is 1.8 dBi and 4.2 dBi at 0.92 and 2.4 GHz, respectively. The antenna is designed and optimized to capture the energy from the ambient environment at the radio frequency range of ISM 900 MHz and Wi-Fi bands 2.45 GHz. This antenna is also highly desirable for system flexibility. Because the proposed antenna has compact architecture, it can be considered as an important candidate for low-power RF energy harvesting. The planar structure is promising for compact wireless devices and it can find applications in wireless energy harvesting.

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