Design of Dual-Band Circular Microstrip Patch Antenna with Slot for Energy Harvesting Applications

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Abstract: In this paper, a small-sized dual-band circular microstrip patch antenna along with an integrated slot is introduced for RF energy harvesting purposes. The introduced antenna includes a circular patch and a slot, which allows the antenna to work in two operating bands in addition to being very compact. The presence of a slot makes a larger path for the effective current, which leads to the miniaturization of the antenna and excitation of the lowest operating band. After designing the size of the antenna, the circular patch is able to resonate at the highest band of 4.94 GHz. Through optimal design of the slot shape, the lowest resonance frequency of 2.19 GHz is achieved, which allows the antenna to be used in harvesting the ambient RF energy from ISM and WLAN band sources. The antenna has been designed on a cheap FR-4 substrate having a dielectric constant of 4.4. The simulation results show great performance of the antenna in terms of impedance matching with a return loss less than -10 dB in both operating bands, VSWR near to 1, stable radiation properties, and acceptable gain, which makes it able to harvest the RF power efficiently.

Keywords: RF Energy Harvesting; Dual Band; Circular Patch; FR4; Slot Loaded Antenna

Introduction

The rise in wireless communications technology and Internet of Things (IoT) has led to an increase in the need for self-sustaining electronic devices. Traditional battery-based methods involve constant replacement or recharging of the batteries, which adds to the cost in addition to limiting the lifetime of the remotely operated sensing system. RF energy harvesting is considered to be a viable solution since it harnesses electromagnetic energy available in the environment and converts it into electrical energy. The ambient RF energy from Wi-Fi, WLAN, Bluetooth, mobile communication systems, and ISM band transmitters constitutes a continuous supply of energy, which could be utilized for powering electronic devices.

The antenna is one of the most important parts of an RF energy harvesting system, as it plays an important role in capturing and converting the incident electromagnetic waves into electrical energy. Microstrip patch antennas have found increasing popularity for energy harvesting systems due to their low profile, lightweight construction, easy manufacturing process, flexibility, and compatibility with printed circuit board technology. Circular microstrip patch antennas are amongst the various shapes of microstrip patch antennas which are compact, symmetric in nature, and have simple feed arrangements.

RF energy harvesting innovations in recent times have been oriented towards designing compact multiband antennas that can harvest energy from various frequency bands simultaneously. Dual-band antennas working in the frequencies of 2.19 GHz and 4.94 GHz have become very popular owing to the fact that they function in the Industrial, Scientific, and Medical (ISM) frequency bands, which have many

RF signals from Wi-Fi, WLAN, and other wireless communication systems. Various methods like slots, DGS, metamaterials, parasitic structures, and fractal geometry have been used to make multiband antennas smaller in size.

Of these techniques, the slot loading technique is among those that have been found to be very efficient in achieving several resonances without having to increase the size of the antenna. This is because the addition of the slot in the radiating patch or the ground plane results in an alteration in the current distribution and the generation of extra resonance modes.

This research proposes a novel dual-frequency circular microstrip patch antenna embedded with slots for RF energy harvesting purposes. In the design of the antenna, an inexpensive FR-4 substrate ($\varepsilon r = 4.4$) is used, and two resonant frequencies, namely 2.19 GHz and 4.94 GHz, are achieved. A circular patch is used to generate the high-frequency resonant frequency, while the slot generates the low resonant frequency by increasing the effective length of the antenna. The proposed design offers a satisfactory performance regarding the impedance match, gain, radiation patterns, and VSWR value around unity at both frequencies. The simulation results of the antenna design are obtained using CST Studio Suite software. The results prove the capability of the antenna for ambient RF energy harvesting in IoT applications and wireless sensor networks.

Related work

The use of RF energy harvesting has received much focus recently as an additional method of power supply to low-power electronics devices, wireless sensor networks, and IoT devices. The effectiveness of the design of the RF energy harvesting system is highly dependent upon the design of the antenna that is used, as the antenna should have high gain, be compact, have good impedance matching, and operate efficiently in one or more bands. Therefore, much effort has been placed on the design of compact multiband microstrip antennas to harvest RF energy.

One of the first battery-less RF-powered sensing systems was introduced by [1], which shows the possibility of using RF signals in the environment as a power source. [2] developed a highly effective energy harvesting system based on Wi-Fi with a frequency of 2.45 GHz, whereas [3] offered a detailed analysis of RF energy harvesting technologies, stressing the role of antenna design, impedance matching, and rectifier efficiency. [4] Developed a dual-frequency rectenna to harvest RF energy from both GSM and WLAN bands, proving the benefits of multiband systems compared to single-band systems. In the same way, [5] surveyed wireless communication systems with RF energy harvesting technologies, pointing out the increasing interest in the development of compact multiband energy harvesting antennas. [6] suggested a highly efficient rectenna that uses a dual-frequency antenna array, whereas [7] considered the latest progress in RF energy harvesting antennas.

Slot-loaded microstrip antennas have gained popularity because of their capability to reduce their size and provide multiband operations through the manipulation of the current distribution on their surfaces. [8] presented a compact dual-band circular microstrip antenna with slots loaded for wireless communications purposes, showing that the use of slots reduces the antenna size while providing extra resonances.

The slot-loaded microstrip antenna is gaining popularity because it offers the benefit of creating small antennas capable of operating on multiple bands through modification of the surface current pattern. [8] created a novel dual-band circular microstrip antenna having slot loading for use in wireless communications. This showed that slots increase the effective length of the electrical path and create additional resonance modes.

Antenna [10] presented a rectangular-shaped microstrip patch antenna using parallel slots for medical telemetry applications to illustrate that slotting is effective in impedance matching and miniaturization without compromising radiation efficiency. Subsequently, [12] suggested a robust antenna using silicon rubber material, using concentric circles for biomedical telemetry applications. Their contribution focused on the benefits of flexible dielectric materials in designing small-sized antennas.

In addition to this, further developments related to small-size flexible antennas have been made in [11], where the analysis and development of a small-size flexible antenna operating at 6.5 GHz for wireless sensor networks have been conducted. The proposed antenna exhibited good impedance bandwidth along with a good radiation pattern.

In a more recent study, [13] provided a systematic review on the design of energy harvesting antennas for self-powered biosensors in the biomedical field. This systematic review reviewed recent advancements in rectenna designs, multi-band energy harvesting antennas, flexible substrates, metamaterials, and impedance matching, along with the future directions for further investigation in small-sized wearable energy harvesting devices. In a related study, [14] described an approach to the design of a 2.4 GHz elementary resonator unit cell for the application of a rectenna using metamaterials.

Though there have been many designs of multiband antennas discussed in the scientific literature, a significant number of such designs use multilayered substrate materials, metamaterials, and complex feeding structures, which complicate the manufacturing process and are costly as well. Moreover, there are some antennas designed in very small sizes, but lack bandwidth and efficiency because of miniaturization. Hence, it is necessary to design a simple, inexpensive, and compact dual-band antenna that can efficiently harvest ambient RF energy available from the commonly used frequencies of the 2.19 GHz and 4.94 GHz ISM bands. The circular microstrip patch antenna with a slot satisfies all these criteria by providing compact size, simple structure, good impedance match, stable radiation pattern, and easy manufacturing process.

Method, Experiments, and Results

The geometry of the dual-band circular microstrip patch antenna that is suggested for application in RF energy harvesting systems is shown in Fig. 1. In the presented dual-band circular microstrip patch antenna, there is a circular radiating patch located on the upper layer of the dielectric substrate, as well as a slot in the ground plane placed on the bottom part of the substrate. The circular patch is excited via a 50 Ω microstrip feed line, while the ground slot serves as an extra resonator for obtaining two-frequency operation of the antenna. Thanks to the presence of the circular patch and the ground slot, the antenna is able to operate at two frequency bands at the same time. The antenna is fabricated from FR-4 substrate with $\varepsilon_r = 4.4$ and $h = 1.6$ mm.

Geometry-wise, the entire antenna geometry resides within a compact planar configuration, which makes the antenna ideal for integration within the RF energy harvester, wireless sensor nodes, and Internet-of-Things modules. Here, the circular radiating patch acts as the main resonating element that produces the high resonant frequency, while the slot cut on the ground plane helps in increasing the effective surface area, which produces an extra low-frequency resonance. Feeding of the antenna is accomplished via the microstrip transmission line, which is aligned with the centre of the antenna. Dimensions of the circular patch, feed line, and ground slot have been optimized in CST Studio Suite.

The slot that is incorporated into the ground plane is used to disrupt the current flow and make the antenna electrically longer without physically increasing its size. This technique helps in achieving miniaturization of the antenna along with generating the dual-band characteristics. With the optimized shape of the slot, a resonance in the lower frequency band occurs at 2.19 GHz, while resonance in the circular patch takes place at 4.94 GHz, thus receiving RF signals present in ISM and WLAN bands. The antenna dimensions are chosen by conducting parametric studies to obtain good impedance matching and gain in both frequency bands.

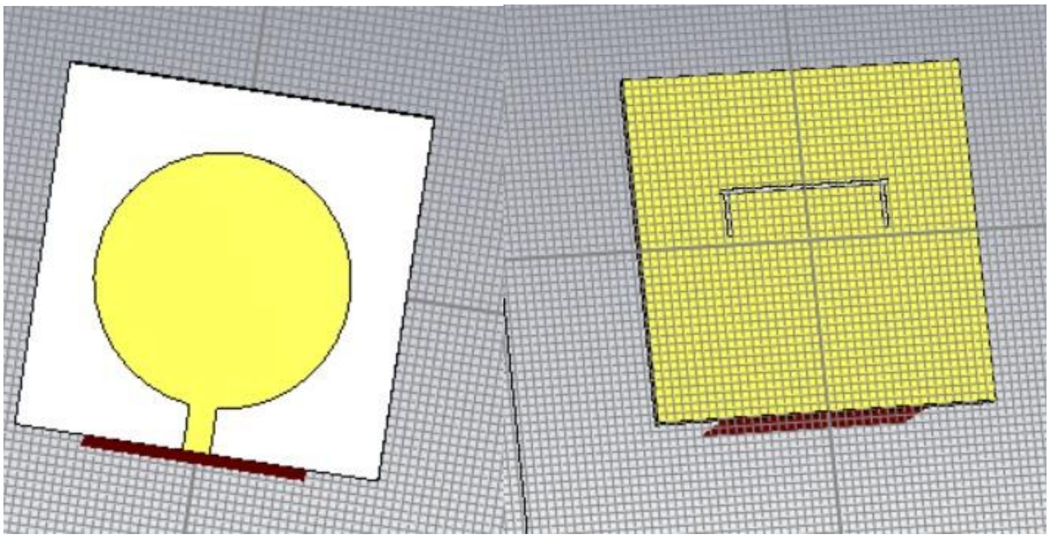

Figure 1. Top View and Bottom View of the microstrip patch.

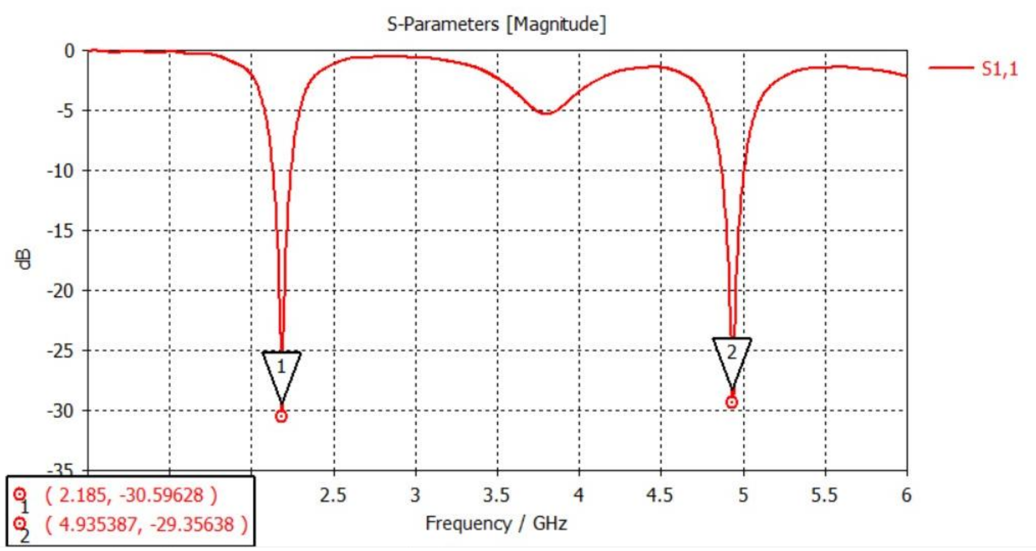

Figure 2. Simulated return loss characteristics at 2.18 GHz and 4.93 GHz

Simulation results regarding S11 characteristics of the proposed dual-band circular microstrip patch antenna are illustrated in Figure 2. The antenna shows two resonant modes around 2.19 GHz and 4.94 GHz, corresponding to the lower and upper operating bands, respectively. The corresponding minimum simulation results regarding return losses are −30.60 dB at 2.19 GHz and −29.36 dB at 4.94 GHz, which reveal good impedance matching between the antenna and the feeding source. The first resonant mode occurs mainly due to the slot introduced in the design of the antenna, which elongates the current path and helps to achieve miniaturization of the antenna, while the second one occurs due to the presence of the circular patch. The proposed antenna shows satisfactory return loss levels below the commonly used −10 dB level at both operating bands and is therefore suitable for use in dual-band RF energy harvesting applications. It can be seen from the result that the absence of the circular patch considerably diminishes the higher order resonant mode.

Conclusion

Design and analysis of an ultra-compact dual-band circular microstrip patch antenna having an embedded slot structure for RF energy harvesting have been successfully carried out. The dual-band performance of the proposed antenna is achieved at 2.19 GHz and 4.94 GHz owing to the combination of the circular radiating patch and the optimal configuration of the slot, while keeping a small size, light weight, and reduced cost by using the FR-4 substrate material. From simulation results obtained in CST Studio Suite, it can be seen that there is good impedance matching of the antenna with return loss values less than –10 dB, a nearly unity value of VSWR, a stable radiation pattern, and reasonable gain values at both operating frequencies. This ensures efficient reception of ambient RF signals belonging to ISM and WLAN frequency bands, making it a potential choice for RF energy harvesting applications. Because of its small size, ease of fabrication, and good performance, the proposed design may be successfully incorporated into wireless sensor networks and other IoT devices. Future research will involve the fabrication and testing of the antenna, validation of the simulation results, and incorporation with a highly efficient rectifier circuit to make an effective rectenna.

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