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A quad-band antenna for multi-band radio frequency energy harvesting circuit

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ABSTRACT

In this paper, a compact planar CPW-fed antenna operating over the four frequency bands is proposed for RF energy harvesting applications. The proposed antenna includes five radiating elements and a stepped ground plane, occupies a total area of $48 \times 42\,\mathrm{mm}^2$. By virtue of stepped ground plane, the antenna exhibits a better impedance match compared to the antenna with the full ground plane. The measured $|S_{11}|$ better than -10 dB is obtained at the frequency bands GSM-900, GSM-1800, Wi-Fi 2.1 GHz and Bluetooth (2.4 GHz), showing its suitability for RF energy harvesting application. For this to be feasible, the developed antenna is matched with the rectifier at four desired frequencies using a compact quad-band matching network. The merit of the proposed rectifier circuit is it can be extended for n number of frequency the band by using only $3n$-1 number of lumped elements. To validate the design method experimentally, a prototype of a dual-band rectifier is also fabricated. The measured result demonstrates that the proposed dual-band rectifier circuit achieved the peak efficiency of 42% and 38% for 0.9 and 2.1 GHz, respectively at a load impedance of 4.7 kΩ.

1. Introduction

A rapid growth in the wireless technology made self-sustaining devices feasible through the RF energy harvester. Compared to other harvesting techniques like piezoelectric nanogenerators [1] and triboelectric nanogenerator [2], RF energy harvesting provides relatively continuous energy supply owing to the features of easy availability, and less independency on environmental effects. Energizing the sensor nodes through the RF energy harvester truly alleviates the problem of frequent battery replacement or it could eliminate the battery requirement altogether [3]. However, despite the revolutionary growth in wireless technology the ambient RF power density is small, hence severely limits the harvester efficiency, especially of harvesting circuit working on a single frequency band. Previously, lots of single band harvesters have been proposed [4–7]. The major drawback of such harvester is degraded performance due to a little shift in incident RF signal frequency from the optimal resonance frequency. In contrast to a single band, a wide-band energy harvester can promise a high output voltage by accumulating more RF signals from a number of frequency bands. However, the trade-offs might be a reduced conversion efficiency due to input impedance variation with frequency and input power, which makes difficult to retain the impedance match over a large frequency band [8,9].

To address this difficulty, it is preferable to harvest energy from several narrow frequency bands rather than a single large one. In literature, different topologies have been proposed for the multi-band energy harvesting circuit. These topologies mainly differentiated on the basis of their filter functionality. Three topologies which are widely used to design a multi-band energy harvester are shown in Fig. 1. Authors in [10,11] utilized the topology shown in Fig. 1(a), where several single band rectennas operating over the different frequency bands are stacked together to realize a multi-band energy harvester. The output of each rectenna is added using the dc voltage combiner. The main drawback of this topology is a large number of antennas, which increases the circuit complexity and cost. The circuit complexity is reduced to some extent in [12–14] by replacing several single band antennas by a wide-band antenna. In both topologies, RF branches that composed of matching network, rectifier and low pass filter can be increased to harvest more energy from a number of frequency bands, but with drawbacks concerning induced circuit complexity, increased size and cost. For instant, in [13,14] quad and hexa-band rectennas are proposed, where multiband matching networks were realized by stacking multiple number of single and dual band matching networks, respectively. Finally, a topology where a multi-band antenna stacked with a multi-band rectifier is proposed in this paper and shown in Fig. 1(c). A similar topology is utilized in [15–23] to design a multi-band harvesting circuit. Though the results presented were very appreciable, but the reported rectifiers were not extendable for more than

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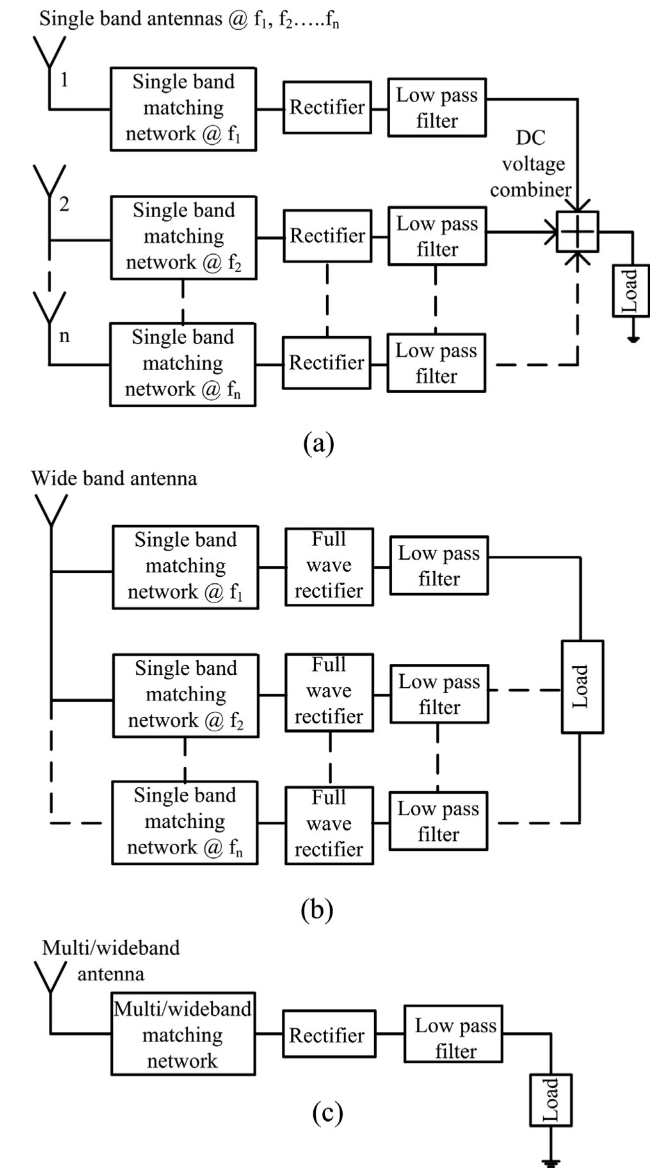

Fig. 1. Multi-band RF energy harvesters (a) using several single band antennas and matching networks (b) using a wide band antenna and several single band matching networks and (c) the proposed circuit.

two or three frequency bands due to the large size and complexity of the rectifier circuit. For example, a quad-band rectenna utilizing a quad-band antenna and a matching network is proposed in [16]. Although, the reported work is substantially focused on antenna design while the matching network was based on stacking of conventional stub matching sections which may increase the circuit size considerably. On the other hand, the proposed harvesting circuit is based on $1 \longrightarrow n$ frequency transformation method, which makes circuit to easy extend for a number of frequency bands using $3n-1$ lumped elements.

To investigate the frequency bands of maximum power density, some field measurements have been done in the university campus. After doing so, it is found that the maximum signal strength is available mostly at GSM-900, GSM-1800, WiFi 2.1 GHz and 2.4 GHz frequency bands. Hence, this work is mainly focusing on design and development of a compact quad-band antenna and its application in quad-band RF energy harvesting circuit. The multi-band rectenna starts with design of quad-band antenna followed by dual-band rectifier circuit and then combination of both.

2. Quad-band antenna design

As the demand for RF energy harvesting circuit to be compact and lightweight in order to integrate with modern wireless devices, therefore the selected antenna should be low profile and satisfy the multi-band operation. Previously, a variety of multi-band antennas employing different shaped of monopole radiating elements, various ground plane sizes has been proposed to achieve multi-band operation [24–32]. However, most of these antennas either have the complex structure or occupies large size. For instance, in [27] a microstrip fed quad-band antenna consisting of a double G-shaped radiator and slotted ground plane occupied the total size of $0.24\lambda_l \times 0.18\lambda_l$ (λ_l calculated at the lowest operating frequency of the antenna). Later, a triple band planar inverted-F antenna (PIFA) in conjunction with a parasitic element is proposed in [28] with a total size of $0.72\lambda_l \times 0.4\lambda_l$.

In this work, a simple low profile CPW-fed quad-band antenna is proposed. Consisting of five radiating strips and stepped ground plane, the antenna occupies a total area of $0.12\lambda_l \times 0.14\lambda_l$. The geometry of the proposed antenna are shown in Fig. 2(a). Here four rectangular shaped arms of different lengths are added one by one to the circular arc to produce different surface current paths and to generate four resonant modes.

All antenna parameters including all arms length, their relative position corresponding to the circular arc, step in ground plane were first iteratively approached and then optimized via simulation, using the 3-D simulator based on finite integration technique, CST Microwave studio. Both radiator and the ground plane are printed on one side of

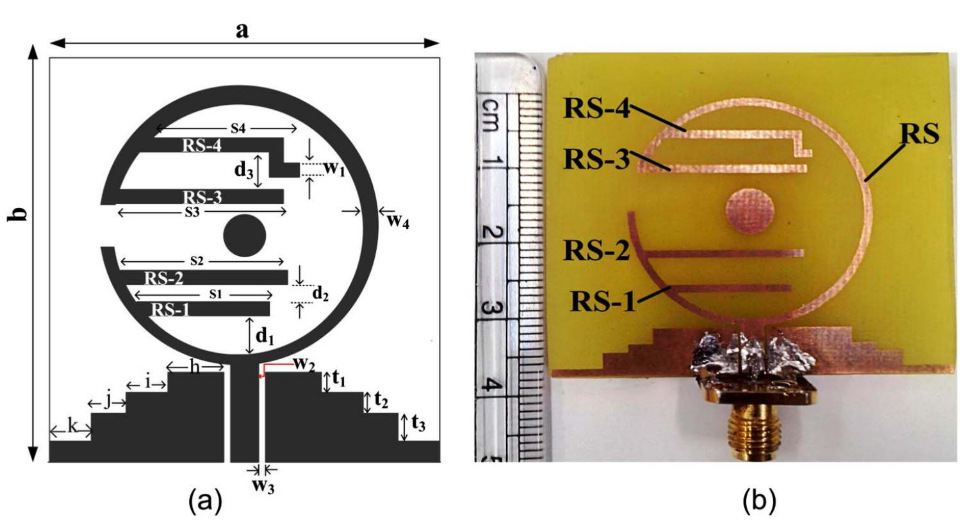

Fig. 2. Layout and fabricated antenna printed on FR-4 substrate.