A Compact Slot Loop Rectenna for Dual-Band Operation at 2.4- and 5.8-GHz Bands

Jiunn-Kai Huang
Department of Electrical Engineering
National Taiwan University
Taipei 10617, Taiwan
Bruce19902002@gmail.com

Shih-Yuan Chen
Graduate Institute of Communication Engineering
National Taiwan University
Taipei 10617, Taiwan
shihyuan@ntu.edu.tw

***Abstract*— A compact dual-band square slot loop rectenna fed by a microstrip line (MSL) for 2.4- and 5.8-GHz bands is presented. Instead of exploiting resonances of integer multiples of full wavelength in conventional dual- or multi-band slot loop antenna design, it is for the first time that the half-wavelength and one-wavelength resonant modes of MSL-fed slot loop antennas are exploited in the design of dual-band rectenna. Due to the distinct impedance behaviors at the two resonances, a matching circuit is inserted in between the rectifier circuit and slot loop radiator for simultaneous conjugate match at the two resonances. For verification, a prototype of the proposed compact slot loop rectenna for operation at 2.4- and 5.8-GHz bands is fabricated and tested. The conversion efficiencies of 49% and 66% are achieved, respectively. The prototype rectenna measures only 13 mm × 24 mm or $0.106\lambda_0 \times 0.196\lambda_0$ at 2.45 GHz.**

Keywords*— *dual-band, energy harvesting, rectennas, slot loop antennas, wireless power transmission.

I. Introduction

Nowadays, the battery life of an electronic device is the most dominant factor limiting its application. In particular, because more and more functions are embedded into a single mobile device, the demand for a longer battery life is even more difficult to fulfill. Rectifying antennas or rectennas, which can receive microwave power and convert it into useful dc power, has recently attracted much attention in wireless power transmission (WPT) and RF energy harvesting applications [1]-[2]. With an embedded WPT or RF energy harvesting module, the battery life of wireless sensors, hand-held devices, and even laptop computers could be extended. For all these applications, rectennas are the key component. On the other hand, several dual-band antennas have been proposed in the past decades for use in different wireless applications, which typically require backward compatibility and roaming capability among various wireless standards. The traditional dual- or multi-band slot loop antennas typically operate at resonances of the integer multiples of a guided wavelength, which inherently results in a larger antenna size [3], [4]. In this work, the MSL-fed dual-band slot loop antenna is first designed for operating at the half-wavelength and one-wavelength resonances, resulting in a smaller size and making it suitable for integration into a small device, such as wireless sensor or hand-held equipment, for wireless power transfer or energy harvesting. The simultaneous impedance matching at the two frequency bands is realized mainly by the parallel connection of a low-pass T-type matching circuit and a high-pass one. A compact dual-band rectenna is then obtained by combining the MSL-fed square slot loop radiator, the matching circuit, and a full-bridge boost converter, which can doubl く e the output dc voltage. The configuration of our proposed compact dual-band rectenna is depicted in Fig. 1.

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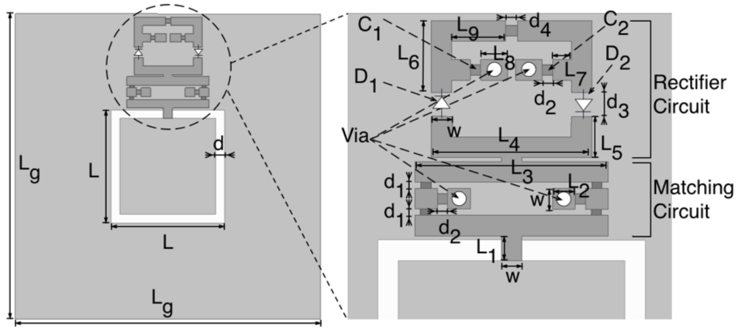
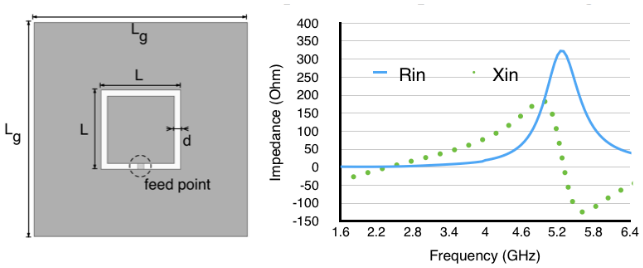


Fig. 1. Geometries of the proposed dual-band slot loop rectenna. (L_g = 35, L = 13, d = 1, w = 1, d_1 = 0.3, d_2 = 0.5, d_3 = 1.15, d_4 = 0.6, L_1 = 1.2, L_2 = 1.1, L_3 = 9.4, L_4 = 7.8, L_5 = 2, L_6=3.5, L_7 = 0.9, L_8 = 1.3, L_9 = 2.6, and h = 0.6. All in mm.)

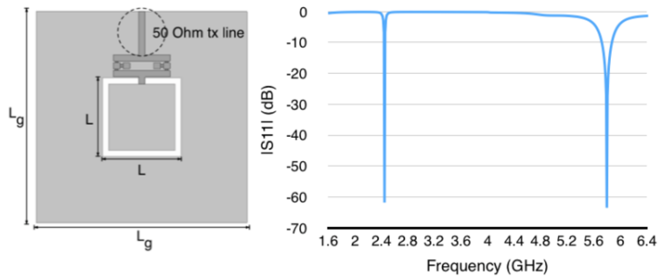
II. Dual-Band Slot Loop and Matching Circuit

The geometry and input impedance of an ideal square slot loop antenna are shown in Figs. 2(a) and (b), respectively. All the substrates used in this work are 0.4-mm FR4 slab (ε_r = 4.4 and tanδ = 0.02), while all simulations were carried out using Ansys HFSS. Clearly, the half-wavelength resonance of the slot loop occurs at 2.4 GHz and is a series resonance, while the one-wavelength resonance at 5.3 GHz is a shunt one. Due to the distinct behaviors of the impedance responses near the two resonances, a matching circuit is needed for dual-band matching. The geometry of the MSL-fed compact dual-band slot loop antenna including the matching circuit is illustrated in Fig. 3(a). The slot loop radiator is etched in the ground plane of the feeding microstrip line, while the matching circuit is formed by shunt connecting a low-pass and a high-pass T-type matching circuit as shown in Fig. 4. While the low-pass L-C-L T-type branch can match for the lower band, the high-pass C-L-C one can match for the upper band. All chip capacitors and inductors used in the prototype rectenna are from Murata, as also indicated in Fig. 4. To evaluate the antenna performance and acquire the upper bound of conversion efficiency for the rectenna, we first design the matching circuit such that the slot loop is matched for 50 Ω at both resonant frequencies. Later on, it will be designed for dual-band conjugate matching to the complex impedances of the rectifying circuit, which depends on the intended incident RF power level, the diode(s) in use,



(a) (b)

Fig. 2. (a) Geometry and (b) input impedance responses of ideal slot loop antenna. (L_g = 35, L = 13, d = 1. All in mm.)



(a) (b)

Fig. 3. (a) Geometry and (b) simulated $|S_{11}|$ response of the proposed MSL-fed dual-band slot loop antenna with the matching circuit.

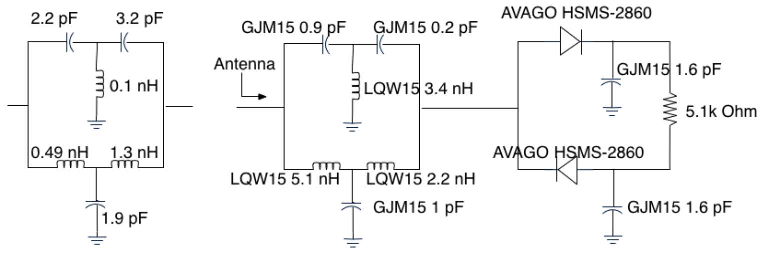
and the rectifier schematic. The schematics and element values used in the matching circuit for the two designs are shown in Fig. 4. Note that the targeted upper band is at 5.8 GHz, which is slightly higher than the inherent one-wavelength resonance (5.3 GHz) of the slot loop. This could also be mitigated by the above matching circuit. Fig. 3(b) reveals that a satisfactorily good matching is achieved at both targeted frequencies. The simulated radiation efficiencies of the antenna at the two frequencies are 54% and 79%, respectively.

III. Dual-Band Rectenna Design and Results

Based on the aforementioned dual-band slot loop antenna, a dual-band rectenna is developed simply by terminating the antenna with a dual-diode rectifier circuit, as shown in Fig. 4(b). The RF–to-dc conversion efficiency is a critical figure of merit for rectenna as well as for rectifier design. The RF-to-dc conversion efficiency ($\eta_{RF\text{-}dc}$) of a rectenna can be expressed as

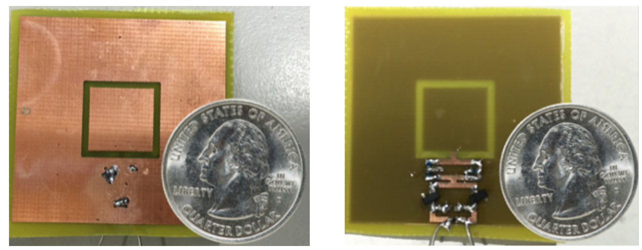
$$\eta_{RF-dc} = \frac{P_{dc}}{P_{RF}} = \frac{V_{dc}\times I_{dc}}{P_{RF}} = \frac{V_{dc}^2}{P_{RF}\times R_L} \tag{1}$$

where P_{dc} is the dc power measured at the load, P_{RF} is the received RF power of the rectenna, V_{dc} and I_{dc} are the dc voltage and current measured at the load, respectively, and R_L is the load resistance. The schematic of the rectifier used in this work is depicted in Fig. 4(b), and its layout is shown in Fig. 1. The rectifier circuit is composed of two parallel branches, each of which is formed by a diode (opposite polarities for the two branches) and a capacitor connected in series and to the common ground, and a load resistor connected in between the junctions of the two branches. Since the two branches can operate at different half cycles of the incident RF signal, higher conversion efficiency can be obtained. Moreover, the dc output voltage can double as well. The diodes used are AVAGO HSMS-2860, which possesses high detection sensitivity up to 35 and 25 mV/μW at 2.45 and 5.8 GHz, respectively, and the



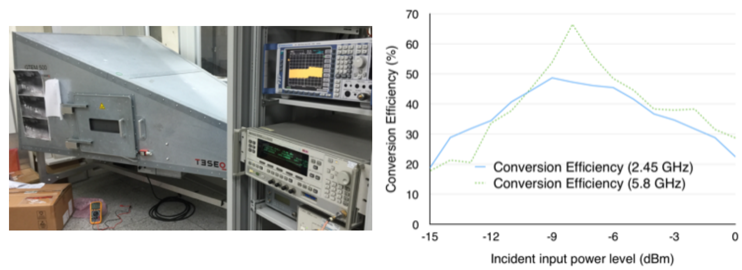
(a) (b)

Fig. 4. Schematics of (a) dual-band matching circuit for 50 Ω and (b) dual-band matching circuit plus rectifier circuit used in the prototype.



(a) (b)

Fig. 5. Photographs of the prototype rectenna. (a) Bottom and (b) top views.



(a) (b)

Fig. 6. (a) Experimental setup for conversion efficiency measurement and (b) measured results of the prototype rectenna.

capacitors used are the 1.6-pF GJM15 chip capacitor from Murata. The load resistance of 5.1 KΩ is adopted.

By combining the slot loop antenna, dual-band matching circuit, and rectifier, a compact efficient rectenna for dual-band operation is developed. Photos of the prototype rectenna are shown in Fig. 5. The prototype rectenna measures only 13 mm × 24 mm or $0.106\lambda_0 \times 0.196\lambda_0$ at 2.45 GHz. The conversion efficiency is measured in GTEM cell (GTEM500 from Teseq) as shown in Fig. 6(a), and the results are plotted in Fig. 6(b). Obviously, the maximum conversion efficiencies of 49% and 66% are achieved at 2.45 and 5.8 GHz, respectively, for incident RF power densitys of about -9 and -8 dBm.

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