Dual-Band Wearable Rectenna for Low-Power RF Energy Harvesting

B. Naresh, Vinod Kumar Singh, V. Bhargavi, Amik Garg and Akash Kumar Bhoi

Abstract In this paper, a dual-band textile rectenna is fabricated and tested to power the wireless and wearable sensor systems at 2.45 and 5.8 GHz. The wearable rectenna substrate is designed with a textile material and conductive element is a copper tap. Fabricated antenna has a size of 50 × 50 mm^2 and it is effortlessly bent on human body. The rectenna element is also fabricated on the same textile material and RF to DC conversation is investigated for power levels −20 to 15 dBm. The wearable antenna has experimentally measured impedance bandwidth of 40% for primary band and 51% for second band. The rectenna has maximum efficiency of 60% at −3 dBm (5.8 GHz) and 0 dBm (2.45 GHz).

Keywords Dual band · Rectenna · RF to DC · Wearable antenna Wireless sensor system

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1 Introduction

Solid dielectric substrate antennas are more common in use, they made with a printed copper on a dielectric substrate such as FR4 for low gain antennas, Duroid, Benzocyclo butane, Roger 4350, FR4-epoxy, Bakelite [1, 2]. These days researcher brings in new kind of dielectric materials are called textile materials. A coaxial feed textile antenna with wash cotton, curtain cotton, and jean cotton substrate materials are investigated in [3] with the help of HSFF software. E-shaped antenna with fleece fabric as a substrate is designed and manufactured for 2.25–2.75 GHz band in [4]. The main advantages of textile material are light in weight, easily foldable, and the most important one is it is wearable. The proposed textile antenna is designed with jeans as dielectric substrate and the radiating patch is designed with a copper tap. The development of textile-based antennas introduces a new type of communication system that is body-centric wireless communication [5, 6]. In this technology sensors or monitoring electronic devices are integrated into the clothing. Wearable antenna for military applications and the performance of the wearable antenna on the human body is presented in [7]. How this wearable antenna can improve the safety of the firefighters is introduce in [8]. A short range personal area network and body wireless communication design based on the textile antenna is in [9]. The power required to drive the electronic devices is supplied by a battery or a super capacitor. While using battery system as a power source there are some problems like recharging and also it required maintenance. So to overcome the problem energy harvesting is the best alternative.

Semiconductor design technology is at freezing pace in the twenty-first century. Consequently, devices are miniaturized; power levels have come down to micro- and nanowatts. So that energy harvesting from the surrounding environment is an active research area. Radio frequency (RF) is one of such energy harvesting method from the ambient. Harvested energy is used to drive the micropower devices which are integrated into the wearable system. RF harvesting mainly requires an antenna which receives RF energy and the rectifier which converts RF energy into DC voltage. Rectifying antenna for low-power applications at 2.45 GHz and rectenna circuit topologies for different power levels are also explained in [10]. The author in [11] fabricated the multi-energy harvesting system which scavenged through solar, RF, heat energy sources.

In this paper ultrawide dual-band textile antenna is designed and fabricated, the jeans cotton fabric is used to design textile antenna [12–15]. RF to DC rectification is investigated at 2.45 and 5.80 GHz; the rectifier circuit is intended for low power level ($E < 2$ V).

2 Antenna Configuration

The dielectric material has an important role in microstrip antenna when it comes to wearable antenna it must be flexible and lightweight so that the substrate material chosen is a cotton jeans. Textile antenna conducting path is designed by a foil tap of

Table 1 Antenna specification used in CST microwave studio

S. No.	Parameter	Value
1	Dielectric permittivity (ε_r)	1.7
2	Loss tangent	0.025
3	Textile thickness (mm)	1.0
4	Textile dimension (mm)	50 × 50
5	Partial ground plane (mm)	46 × 16
6	Circle 1 radius	8.0
7	Circle 2 radius	6.4
8	Microstrip feed line	20 × 4

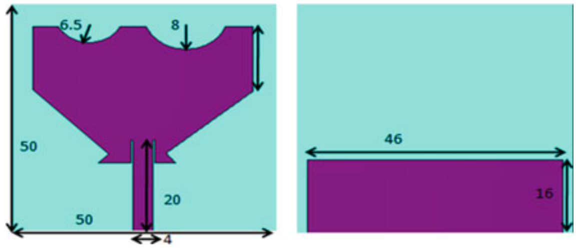

Fig. 1 Geometry of a compact circularly polarized rectangular microstrip antenna with a pair of truncated corners (all dimension in mm)

copper. The properties of the textile material are determined by conduction experiment and are reported in Table 1. Patch antenna patch dimensions are calculated by using Eqs. (1) and (2). The most significant future of the wearable antenna is, they can integrate into clothing to drive the smart electronic devices or the sensors. Before fabrication, the textile antenna was simulated in CST microwave studio 2010 environment. The designed antenna snapshot is depicted in Fig. 1 with front and back view.

$$W = \frac{C}{2f_0\sqrt{\frac{\varepsilon_r+1}{2}}};\ \varepsilon_{\text{reff}} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(\frac{1}{\sqrt{1+12\left(\frac{h}{w}\right)}}\right) \tag{1}$$

$$L = \frac{C}{2f_0\sqrt{\varepsilon_{\text{reff}}}} - 0.824h\left(\frac{(\varepsilon_{\text{reff}}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{\text{reff}}-0.258)\left(\frac{W}{h}+0.8\right)}\right). \tag{2}$$

3 Rectenna Design

The rectifying circuit design is initiated with a second-order low-pass filter which takes the form of impedance matching in between the textile antenna and diode. Matching is essential while working with low power levels; else harvesting efficiency will reduce by reflected power. The Schottky diode used in the RF to DC

Table 2 HSMS-285x PSPICE parameters

S. No.	Parameter	Units	HSMS-285x
1	B_V	V	3.8
2	C_{J0}	pF	0.18
3	E_G	eV	0.69
4	I_{BV}	A	3 E^{-4}
5	I_S	A	3 E^{-6}
6	N		1.06
7	R_s	Ω	25
8	$P_B(V_J)$	V	0.35
9	P_T (XTI)		2
10	M		0.5

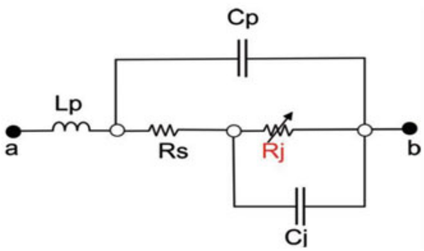

Fig. 2 Equivalent diode model with Spice parameters

conversion is HSMS2850 with a low threshold voltage of 150 mV [12]. The input impedance of the diode is a dynamic variable dependent on input RF power, in order to understand that diode performance a mathematical model of the diode undergoes detail analysis with spice parameters given in Table 2.

The diode input impedance is calculated from the zero-biased equivalent circuit of the diode as shown in Fig. 2, where L_p is the parasitic inductance, C_p—parasitic capacitance, and R_s series parasitic resistance. Junction capacitance C_j and R_j junction resistance, the junction resistance is a function of the applied bias current given by Eqs. (3) and (4). I_T is the sum of the diode saturation current (I_S) and diode bias current (I_B). The input impedance between terminals a and b in Fig. 2 is calculated for dual-band operating frequencies. The input impedance at 2.45 and 5.8 GHz are 219.4 and 41 Ω respectively.

$$R_J = \left(\frac{0.026}{I_T}\right) \tag{3}$$

$$I_T = I_B + I_S \tag{4}$$

LC filter elements are calculated separately for dual-band frequencies. While using this rectenna circuits for sensor applications, ripples in the output may cause failure or malfunction of the circuit because they are the most sensitive devices. Pass the smooth DC current to load after the rectification filters are necessary, they

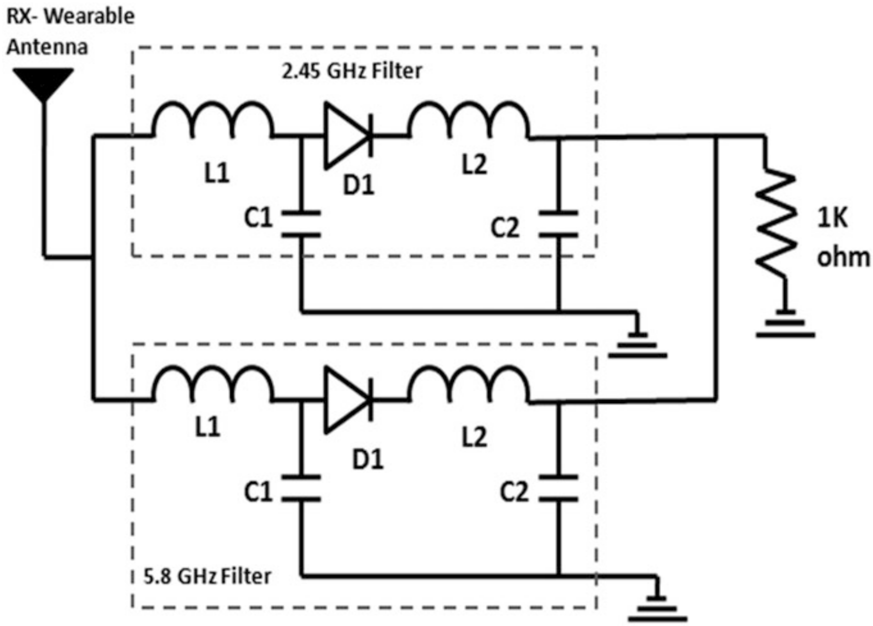

Fig. 3 Electrical circuit of rectenna

eliminate the ripples in the rectified direct current or voltage. The proposed rectenna has the output filter is a LC filter, aimed to diminish the AC frequency components. The proposed low-power rectenna electrical circuit is shown in Fig. 3. The circuit elements for 2.45 GHz are $L_1 = 1.42$ nH, $C_1 = 2.1$ pF, $L_2 = 4$ nH, and $C_2 = 45$ pF. The circuit elements for 5.8 GHz are $L_1 = 1.54$ nH, $C_1 = 0.27$ pF, $L_2 = 1.06$ nH, and $C_2 = 45$ pF.

4 Results and Discussions

The proposed antenna measurement is done in an anechoic chamber to find the parameters of the antenna in both bent and unbent conditions using vector analyzer (Agilent E5071C ENA). Figure 4 presents the comparative return loss measured in bent and flat condition along with simulated return loss of the antenna. Measured dual-bandwidths are 2.2–3.30 GHz (40%) and 4.0–6.73 GHz (51%). The primary band resonance frequency is 2.45 GHz with return loss magnitude of −17 and −21 dB is the return loss magnitude at 5.8 GHz. When antenna bent the bandwidths are reduced by a small amount due to fabrication tolerance and drapability of the textile material. In the bent condition, the resonance frequencies along with magnitudes are shifted. Resonance frequencies are shifted to words the lower frequency side in both the bands.

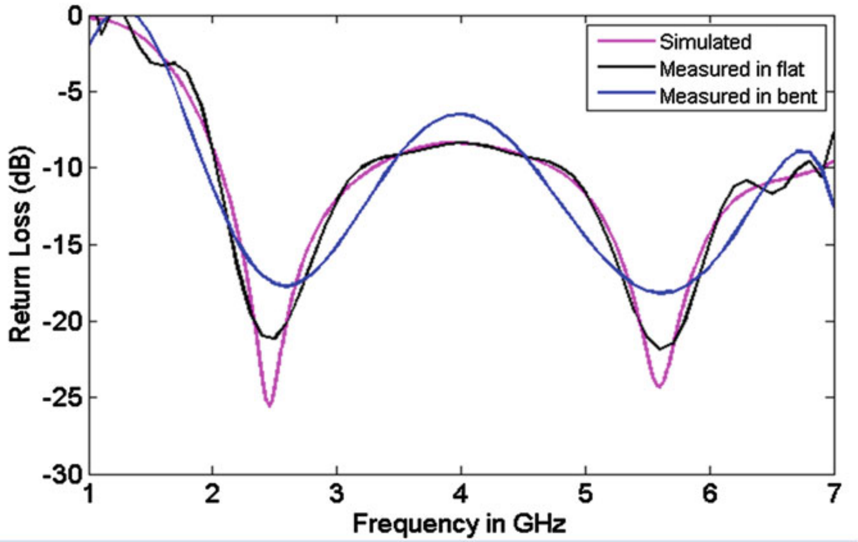

Fig. 4 Comparative return loss of the proposed antenna

The distance (D_r) between the transmitting horn antenna with the gain of G_{tX} = 11 dBi and the rectenna is 1 m. The Friis transmission Eq. (5) is used to find out the micro power available at rectenna terminals.

$$P_{rX} = P_{tX} G_{tX} G_{rX} \left(\frac{C}{4\pi D_r f_0} \right)^2, \tag{5}$$

where P_{tX} is the transmitting power at a given field strength E (mV/m); G_{rX} is the receiving antenna gain (3.5 dBi).

The constant C and f_0 are the velocity of light and frequency of the microwave. The output DC voltage (V_{outDC}) and overall efficiency (η_{EH}) of the rectenna against power density are calculated by Eq. (6).

$$\eta_{EH} = \frac{P_{outDC}}{P_{rX}} = \frac{V_{outDC}^2 / R_L}{P_{rX}} \tag{6}$$

Finally the simulated and measured overall efficiency of the rectenna is depicted in Fig. 5a, b. The measured maximum efficiency for flat rectenna is 60% is obtained at −3 dBm input power for a load of 1 kΩ at 5.8 GHz. The measured RF to DC conversion at 2.45 GHz is 54%. The rectenna efficiency is measured in bent condition too. From the measured return loss plot it is witness that in the bent condition the magnitude of S_{11} is reduced with effect the gain of the antenna and so efficiency is affected. The efficiency obtained in bent condition is 41.34% at 5.8 GHz and 45 for an input of −5 dBm.

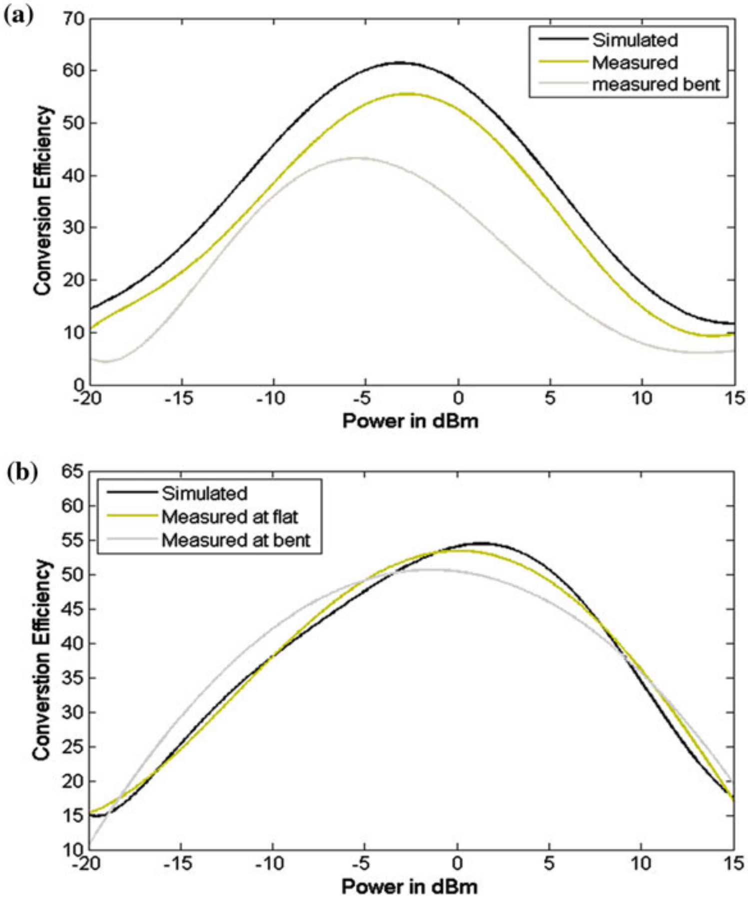

Fig. 5 **a** Measured and simulated overall efficiency versus input power levels at 5.8 GHz. **b** Measured and simulated overall efficiency versus input power levels at 2.45 GHz

From Eq. (6) DC power output is directly proportional to the square of the DC voltage and the effect of load resistance on power conversion efficiency is studied at dual bands. The harmonics at the output DC voltages has to be limited by connecting an LC filter at load side. The inductor in the filter controls the load current variations and output voltage variations are dampens by the capacitor. The capacitance value is chosen in such a way to limit maximum ripple in the output voltage is 10 mV at −5 dBm power level. The DC output voltages at the flat and bent position are 0.82 V (2.45 GHz) and 1 V (5.8 GHz) are shown in Fig. 6a. Finally, the low-power microwave energy harvester is fabricated on textile is depicted in Fig. 6b.

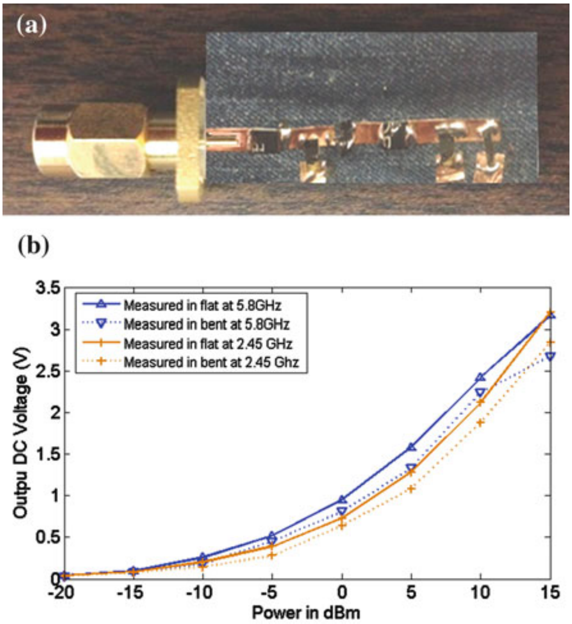

Fig. 6 **a** Fabricated 2.45 GHz rectenna on textile material. **b** Output DC voltages from rectifier

5 Summary

This paper works explain the design and manufacturing of the antenna with the textile materials and also its potential application in wearable wireless system. The textile antenna is made with jeans cotton as the substrate and copper tap as a radiating element. From the measured results the fabricated antenna has dual band in that first band covers the ISM bans 2.45 and 5.8 GHz. Proposed textile rectenna is tested for different micropower levels as −20 to 15 dBm. The wearable antenna has experimentally measured impedance bandwidth of 40% for primary band and 51% for second band. The rectenna has maximum efficiency of 60% at −3 dBm (5.8 GHz) and 0 dBm (2.45 GHz).

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