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1 µW-3.75 W Dual-Mode Near/Far-Field Wearable Wireless Power Transfer using a Hybrid Rectenna

Mahmoud Wagih, *Member, IEEE,*, Abiodun Komolafe, *Member, IEEE,*
Alex S. Weddell, *Member, IEEE,* Steve Beeby, *Fellow, IEEE,*,
School of Electronics and Computer Science, University of Southampton, Southampton, United Kingdom
{mahm1g15, aok1g15, asw, spb}@ecs.soton.ac.uk

***Abstract*—While far-field wireless power transfer (WPT) promises a long range of operation, it falls short on the DC power which can be provided. On the other hand, resonant near-field WPT suffers from a short wireless range. In this work, a dual-mode high/low-power near/far-field rectenna is demonstrated for the first time based on a flexible rectifier and a textile antenna. Based on a high-efficiency single-series rectifier, the far-field rectenna achieves a peak efficiency of 42.7% from an ultra-low power density of 0.43 µW/cm^2, with a 1 V DC output from 4 µW/cm^2. A high-power 6.78 MHz bridge rectifier is designed and implemented on a flexible textile-based substrate with a 10 dB return loss for inputs above 15 dBm. As a near-field receiver, the antenna could receive 3.75 W DC power at 5 cm from the transmitting coil, with an end-to-end efficiency of 30% inclusive of rectifier, coils, and power amplifier losses. Based on the proposed dual-mode antenna, textile-based wearables could be wirelessly powered dynamically using resonant near-field and radiative near-field WPT.**

***Index Terms*—Antenna, coils, GaN, inductor, rectifier, rectenna, supercapacitor, Magnetic Resonance (MR), wireless power transmission**

I. INTRODUCTION

As flexible "e-textile" wearables continue to generate interest for a range of different applications [1], enabling battery-free wearable devices through wireless power transfer (WPT) has been the focus of many research efforts [2]–[5]. Battery-less wearables have the advantages of a long lifetime and reduce the electronic waste generated upon their disposal.

On one end, far-field rectennas have been demonstrated using a multitude of wearable antennas ranging from omnidirectional monopoles [6], large-area patch and bow-tie arrays [4], [7], simultaneous wireless information and power transfer (SWIPT) microstrip rectennas [5], as well as flexible rectennas integrated with textile supercapacitors [8]. Wearable rectennas across the full frequency range from 433 to 26 GHz have demonstrated compliance with the Specific Absorption Radiation (SAR) limits for human exposure [5], [7], [9]. Moreover, the potential for operating at a few meters from a standard FCC-compliant source such as a Powercast transmitter or an RFID reader has been demonstrated [8]. On the other end, near-field wearable WPT has been demonstrated using a range of flexible, textile-based and printed coils for wearable near-field WPT [2], [10]–[12].

However, the aforementioned near- and far-field wearable WPT approaches were never demonstrated in a dual-mode system, capable of receiving power both using near-field resonant coupling and far-field radiation. To explain, while many rectifiers have been demonstrated for wearable far-field WPT using flexible materials [5], [7], [9], none have been aimed towards high-power Magnetic Resonance (MR) WPT. For instance, while textile coils have previously been used alongside a Qi transmitter and receiver [10], the power receiver circuitry was based on an off-the-shelf (COTS) Qi rectifier.

In this paper, a complete solution for wearable WPT both in the near-field, at 6.78 MHz, and in the far-field at 900 MHz is proposed to satisfy the different power budgets of wearable applications. Based on a miniaturized broadband wearable antenna integrated loaded with a coil [13], we demonstrate for the first time an all-flexible and textile-based wearable wireless power receiver with an output in excess of 3 W. With a sub-1 µW/cm^2 far-field power sensitivity and >3 W near-field power output with a 30% end-to-end efficiency, the proposed dual-mode presents state-of-the-art performance over both modes of operation.

II. ANTENNA, COIL, AND RECTIFIER DESIGN

To realize a hybrid dual-mode power receiver, a resonant inductive element and a radiative UHF antenna are required for near- and far-field operation, respectively. The far-field rectenna is based on a broadband antenna enabling it to maintain its response near the human body [4], [6]. The MR-WPT coil is implemented using embroidered Litz wires, enabling the coil to maintain the lowest possible series resistance using e-textile conductors which enhances the MR WPT efficiency. By surrounding the antenna with the square coil, the coil doubles as a resonator which contributes to the miniaturization of the antenna [14]. Fig. 1 shows the layout, dimensions, and photograph of the dual-mode antenna.

In far-field WPT, the key objective is maximizing the sensitivity for sub-1 µW/cm^2 power densities. A single-series microstrip rectifier based on the low-forward voltage SMS7630 Schottky diode is adopted in the design, previously shown to maintain the highest Power Conversion Efficiency

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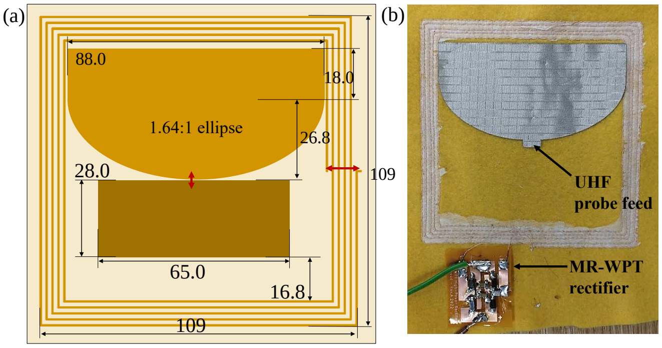

Fig. 1. Layout and photograph of the dual-mode rectenna: (a) antenna layout and dimensions in mm; (b) photograph of the antenna connected to the MR-WPT rectifier.

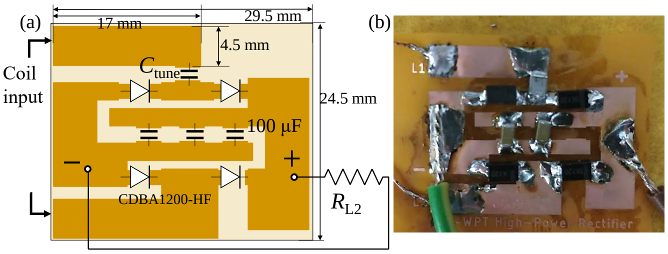

Fig. 2. The 6.78 MHz MR-WPT textile-based bridge rectifier: (a) layout and dimensions in mm; (b) photograph of the assembled rectifier.

(PCE) down to -20 dBm. For near-field WPT at 6.78 MHz, the frequency of “AirFuel Resonant”, a bridge rectifier is implemented on a flexible polyimide substrate and is integrated on the same textile substrate as the antenna, as shown in Fig. 1(b). A CDBA1200 Comchip Schottky diode is selected based on its 200 V reverse breakdown voltage, 1 A forward current, and relatively low series resistance and forward voltage drop under 15 Ω and 1 V, respectively. Surface-mount multi-layer ceramic capacitors with a 1.5 kV rating were chosen for the coil’s tuning capacitor (C_{tune}) on both the transmit and receive ends. The rectifier’s traces were designed with over 3 A current handling based on the 18 µm thickness of the flexible copper layer. Fig. 2 shows the layout and photograph of the near-field rectifier.

III. DUAL-MODE WPT CHARACTERIZATION

A. *S-parameter Measurements*

Prior to characterizing the power transfer and harvesting efficiency of the coil/rectenna, the s-parameters of the antenna and rectifier were measured using a Vector Network Analyzer (VNA) across both the High Frequency (HF) and Ultra High Frequency (UHF) bands. Fig. 3(a) and (b) show the Smith chart plots of the input impedance of the far- and near-field WPT components, respectively. For the UHF antenna, both the simulated (using CST Microwave Studio) and measured S_{11}/Z_{11} lie within the 10 dB return loss contour indicating a well-matched response; the antenna’s S_{11} bandwidth is also maintained in human proximity.

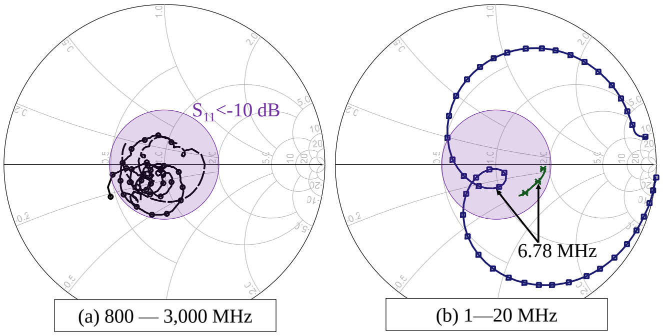

Fig. 3. Smith chart plot of the coil, rectifier, and antenna’s S_{11}: (a) simulated (dashed) and measured (solid+markers) UHF antenna S_{11}; (b) measured S_{11} of the critically-coupled coils and the rectifier at 15 dBm; shaded region indicates the 10 dB return loss contour.

Shown in Fig. 3(b) is the HF response. The MR WPT rectifier’s S_{11} response was measured at 15 dBm with a 40 Ω load; the load was determined based on Harmonic Balance (HB) simulations in Keysight ADS. The measurements were limited to a 15 dBm input power level due to the VNA’s maximum power output. The S_{11} of the coil was measured at critical coupling at about 5 cm away from a circular coil with a 9 cm radius and 9.6 µH inductance. From both Fig. 3(a) and (b) it can be verified that the 50 Ω matching is maintained across both the near- and far-field WPT interfaces of the dual-port dual-mode hybrid.

B. *Far-field 900 MHz WPT Characterization*

The rectenna is first characterized at 900 MHz using a wireless power source based on the VNA acting as a CW generator, a Mini-Circuits ZHL-4240W+ 1 W Power Amplifier (PA), an 8.8 dBi log periodic antenna, and a 3 dB attenuator to realize an Equivalent Isotropic Radiated Power (EIRP) of approximately 4 W (36 dBm). The rectenna was positioned at 2 m from the source, satisfying the far-field condition at 900 MHz, and connected to a 7 kΩ optimum load, based on an experimental and numerical (HB) load sweep. The power received by the antenna was measured using the VNA (through the S_{21}) before connecting the 50 Ω-matched rectifier to the antenna. The incident power density S at the antenna is calculated as

$$S = \frac{P_{\text{TX}} G_{\text{TX}}}{4\pi d^2}, \tag{1}$$

where $P_{\text{TX}} G_{\text{TX}}$ represents the source’s EIRP level and d is the rectenna-source separation.

Fig. 4 shows the simulated and measured PCE of the rectenna (based on the simulated antenna’s gain), alongside the DC power delivered to the load. The rectenna’s high sensitivity is evident through the high PCE for $S < 1$ µW/cm^2, with a net DC output down to 1 µW. For $S > 4$ µW/cm^2, the rectenna harvests over 100 µW DC power with over a 1 V output. Therefore, the rectenna is suitable for far-field WPT in the sub-mW range, and can complement the near-field power receiver designed for a higher power requirement.

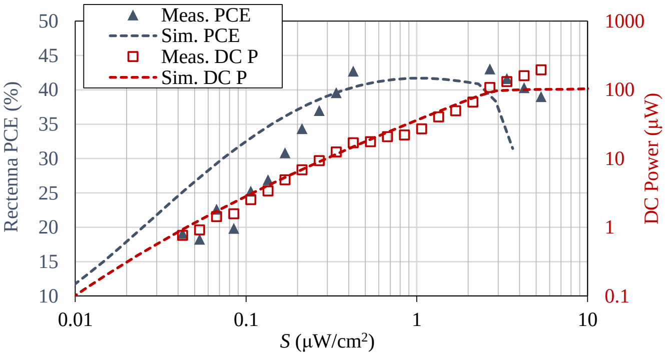

Fig. 4. Simulated and measured far-field WPT PCE and DC power output at 900 MHz with a 7 kΩ load.

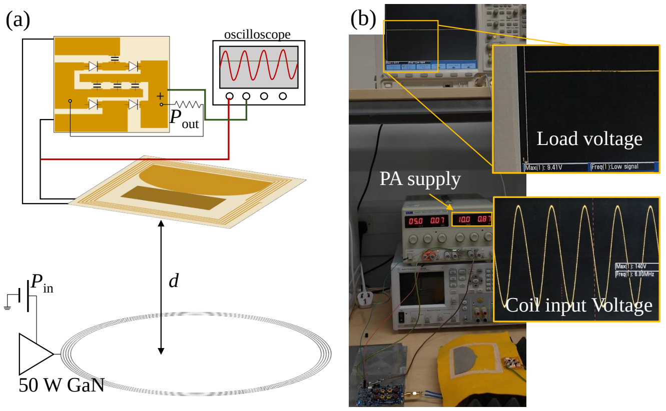

Fig. 5. The MR-WPT test setup: (a) block diagram; (b) setup photograph; inset shows the coil input and load voltage waveforms.

C. Near-Field 6.78 MHz WPT Characterization

The near-field WPT performance is characterized based on a commercially-available 50 W GaN class EF2 PA (GSWP050W) development kit. The SMA output of the PA is connected to a transmitting circular coil of a radius $r \approx 9$ cm. A low dielectric foam spacer is inserted between the transmitting coil and the receiving textile coil to maintain $d \approx 5$ cm, consistent with the VNA measurement setup used to measure the matched S_{11} in Fig. 3(b). The DC voltage across the load was monitored using an oscilloscope with a $\times 10$ probe. Fig. 5 shows the block diagram and photograph of the measurement setup of the MR WPT performance.

As the power output of the GaN PA could be adjusted through the DC voltage input, the input voltage was swept starting from the minimum input of 1 V to determine the maximum power level which could be handled by the receiving coil and rectifier. Fig. 6 shows the measured DC power output delivered to the load as a function of the DC power input to the PA. The PA's input power was calculated using the current draw at each 1 V bias increment. The end-to-end efficiency is therefore calculated as the ratio of the output DC power dissipating in the load to the input DC power to the PA. The input power sweep was repeated for a 40 Ω and 102 Ω loads, both shown in Fig. 6.

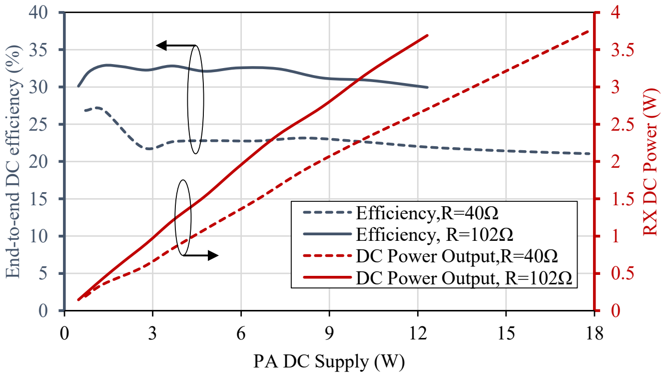

Fig. 6. Measured DC power delivered to the load and end-to-end efficiency as a function of the PA's DC input.

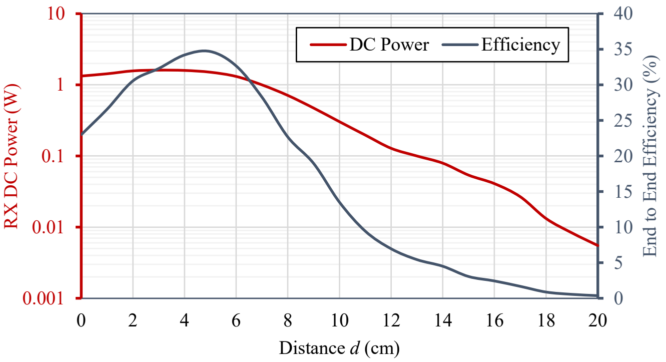

Fig. 7. Measured DC power delivered to the load and end-to-end efficiency for varying coil separation d, for an 8 V PA supply and 102 Ω load.

Up to nearly 3.8 W of rectified DC power, it can be seen that the rectifier maintains a nearly constant efficiency. To explain, the PA's efficiency is almost constant across different power levels and the coils represent linear and passive components. Above a DC power output of approximately 4 W, C_tune suffers from a temperature rise which ultimately limits the rectifier's operation and reduces the output voltage leading to the rectifier malfunctioning. Therefore, the proposed rectifier's power handling is limited to 3.75 W; this was demonstrated during more than 1 minute of continuous transmission with no damage to or overheating of the textile coils. The near-field measurement at a 3.75 W power output was also performed with the coil attached to the hand with no observable difference in the received power. To demonstrate human safety, the Specific Absorption Rate (SAR) has been simulated in CST using a layered tissue model showing under 0.5 W/kg absorption (averaged over 1 g tissue mass) for up to 10 W power input to the coil.

The impact of varying coils' separation on the end-to-end efficiency was investigated by varying the vertical separation d between 0 (coils separated by the substrate) to 20 cm. Fig. 7 shows the measured efficiency and DC power delivered to the load. The over coupling problem manifests for $d < 4$ cm, where the efficiency drops due to a higher current draw by the PA compensating for the lower S_{21} between the coils. In

TABLE I
COMPARISON WITH RECENT WEARABLE WIRELESS POWER RECEIVERS

	This work	[10]	[4]	[6]
Freq. (MHz)	**900; 6.78**	0.1-0.2	2,000-4,000	820
WPT Mode	**Radiative and MR**	Inductive (Qi)	Radiative	Radiative
Rectifier	**Textile-based**	Rigid COTS	Textile-based	Textile-based
Max power	**3.75 W**	1.51 W	10 µW	100 µW
End-to-end η_{MR}	**30%**	37%	N/A	N/A
RF S Sensitivity	**0.3 µW/cm^2**	N/A	4 µW/cm^2	0.2 µW/cm^2

under-coupled operation, it can be seen that the power output falls to 5.5 mW at 20 cm from the transmitting coil. At this range, it is typical for a 4 W RF power transmitter to induce a higher DC output in a rectenna [8], showing the transition range where radiative WPT starts to outperform MR WPT.

The proposed hybrid wireless power receiver is compared to state-of-the-art wearable wireless power receivers, which can only act as single-mode devices for either near- or far-field WPT, in Table I. As a near-field receiver, the achieved end-to-end efficiency is comparable with an earlier work using a standard (non-textile) Qi rectifier with textile coils [10]. Nevertheless, the proposed receiver is capable of generating at least double the DC power output, limited only by the lumped ceramic capacitor. Compared to far-field wireless power receivers, the sensitivity is in line with that of other single-mode sub-1 GHz textile rectennas [6], and is higher than that of rectennas operating at higher frequencies [4], demonstrating the suitability of the proposed hybrid power receiver for both near- and far-field operation.

IV. CONCLUSION

In this paper, a dual-mode near- and far-field wearable wireless power receiver was proposed based on a hybrid rectenna/coil. For the first time, a wearable wireless power receiver is demonstrated with a dynamic range starting from sub-mW operation (in the far-field) over a few meters, to >1 W WPT as an MR WPT receiver over a few centimeters. At 900 MHz, the rectenna achieves a state-of-the-art sub-1 µW/cm^2 sensitivity with a net DC output as low as 1 µW/cm^2. Enabling rapid and high-power charging of wearables, the near-field MR-WPT coil integrated within the rectenna is demonstrated receiving up to 3.75 W of DC power with an efficiency of 30% based on a commercial GaN PA and a textile-based bridge rectifier. Future work includes an improved near-field rectifier design, to overcome the current end-to-end efficiency limit.

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