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A Radiating Near-Field Patch Rectenna for Wireless Power Transfer to Medical Implants at 2.4 GHz

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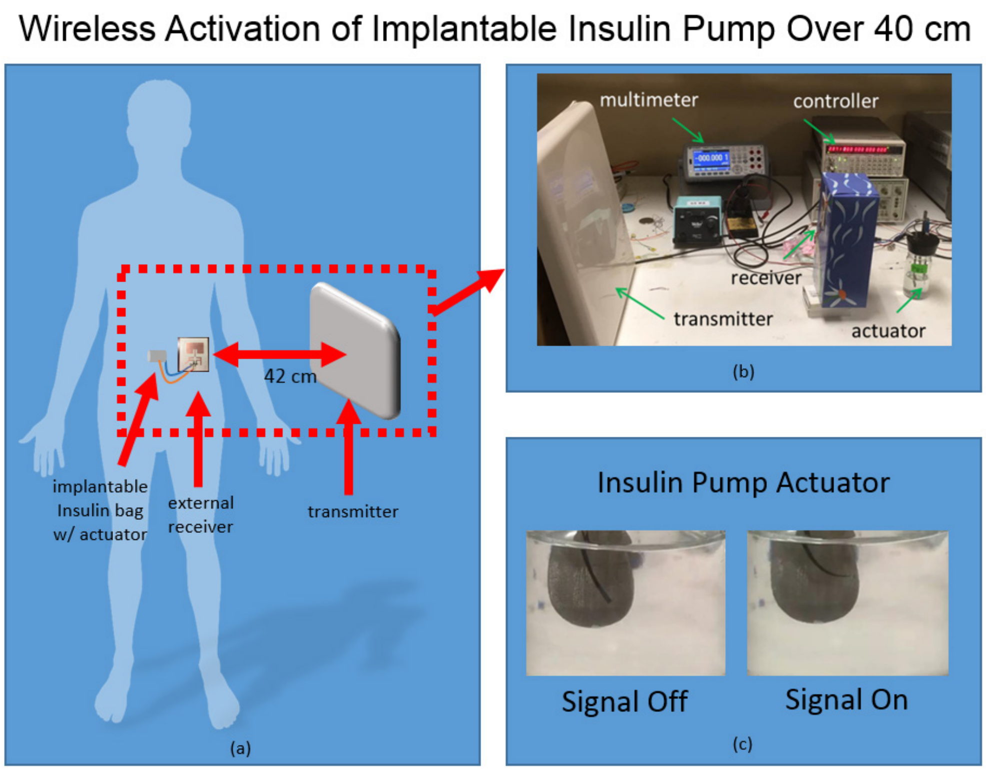

Visual Summary. (a) Illustration of application: transmitter delivers power wirelessly to on-body rectenna, which activates insulin pump, (b) test bench experiment, (c) wirelessly activated insulin pump arm

Take-Home Messages

- Power is delivered wirelessly to the body over substantial distance (42 cm) using a new near-field wireless powering approach that is position-insensitive.
- A small rectifying antenna (rectenna), located external to the body, is presented and experimentally validated as a means of delivering power up to 1.2 mW.
- The targeted application is that of wireless power delivery for recharging or activating medical implants (such as insulin pumps) using a RF source placed at a sufficient distance from the human body.
- The significance of this work lies in the demonstration of near-field antennas to power/recharge wireless implants (sensors or stimulators) in an unobtrusive manner.

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Abstract A radiating near-field method of recharging and activating medical implants using a 2.4 GHz rectifying patch antenna (rectenna) is designed and tested. Traditional near-field charging uses magnetically coupled coils, but these are highly sensitive to misalignments between the transmitter and receiver. In contrast, the proposed design employs the principles of wireless power transfer (WPT) using radiating antennas. These antennas provide a misalignment-insensitive power delivery method, even when the receive antenna footprint is small (27.5 mm x 19.75 mm). A misalignment analysis is performed up to 15 cm, showing a maximum loss of 7.5 dB. As a proof-of-concept demonstration, a rectenna receiver was fabricated consisting of a patch antenna attached to a radio frequency (RF) rectifier. This integrated rectifier is a voltage quadrupling circuit that provides RF-DC rectification with efficiency of 40% at 0 dBm. For validation, a real-time actuation of a medical drug pump is demonstrated using only wirelessly transmitted power with no additional power storage elements.

***Keywords* — wireless power transmission, medical implant, drug pump, near-field**

I. Introduction

TRADITIONALLY, most wearable or implantable medical devices (e.g., sensors, pacemakers, etc.) necessitate battery replacement [1]. However, this can be impractical or infeasible for hospital patients or the elderly. An example would be an insulin pump that would be embedded underneath the skin; the replacement of such a battery would be both an encumbrance to the patient, as well as a medical hazard due to the repetitive surgeries it would require. As an alternative, a wireless RF system may be used to safely and wirelessly transmit power to such a medical device [1]. Additionally, such an RF system would serve as a sanitary means of medical powering without the need for invasive operations.

Advances in antenna miniaturization, circuit design, and biocompatible materials are bringing forward new opportunities for unobtrusive diagnosis and patient care using wireless implantable devices [2]. It was reported that there are several million individuals using implanted medical devices like pacemakers [3]. With most of these devices, the typical method of powering them is to use Lithium batteries, although some use other methods of power generation, including piezoelectric, electrostatic, ultrasonic transducers, and optical charging [1]. In this paper, we propose a different method for powering implantable sensors. This method is less sensitive to misalignment as it relies on using wireless power transfer (WPT) in the radiated near-field to delivery power to a device on or in the body. Indeed, midfield wireless power transmission has been thoroughly investigated by Poon et al., as a viable means of WPT for medical applications [4]; however, instead of utilizing spirals and coils as the means of power reception, this work utilizes patch antennas in the radiating near-field. A comparison of other midfield works is presented in Section III.

Wireless powering of devices has been extensively researched since the early 1990s. Chang et al. developed efficient rectenna designs at low powers, achieving 82% for a 50-mW rectenna design [5,6]. Popović and Hagerty researched the recycling of ambient RF signals, as well as developed modern rectenna matching techniques [7,8]. Volakis and Olgun demonstrated the wireless powering of a sensor using only ambient WiFi energy [9,10]. Costanzo et al. has been notable for her work in near-field inductive links as well [11, 12].

Two approaches have been, generally, considered for WPT: 1) near-field coupling, and 2) far-field radiation. Near-field coupling operates on the principle of nearby magnetically coupled coils that resonate at low frequencies (0.3-30 MHz) [1]. Indeed, since the 1960's, the concept of wirelessly powered medical implanted has been explored [18]. But although inductive links have been capable of delivering high levels of power [19], misalignment and sensitivity to coil adjustments has been a major challenge [1]. Coil separations of 1-2 diameters tend to maximize the coil quality factor [20] and lateral misalignment can cause severe degradations, limiting the effectiveness when the coils are misaligned.

Far field radiation is suitable when using opportunistic RF signals such as WiFi and television [9]. Key to harvesting these ambient RF signals is the introduction of high efficiency rectification circuits that turn-on even though incoming signals are of very low power, viz. on the order of μW. Typically, ambient power from WiFi or television range from -20 to -40 dBm [10], depending on the distance from the RF source. Several studies have been conducted on rectifier efficiencies at the 2.4 GHz range

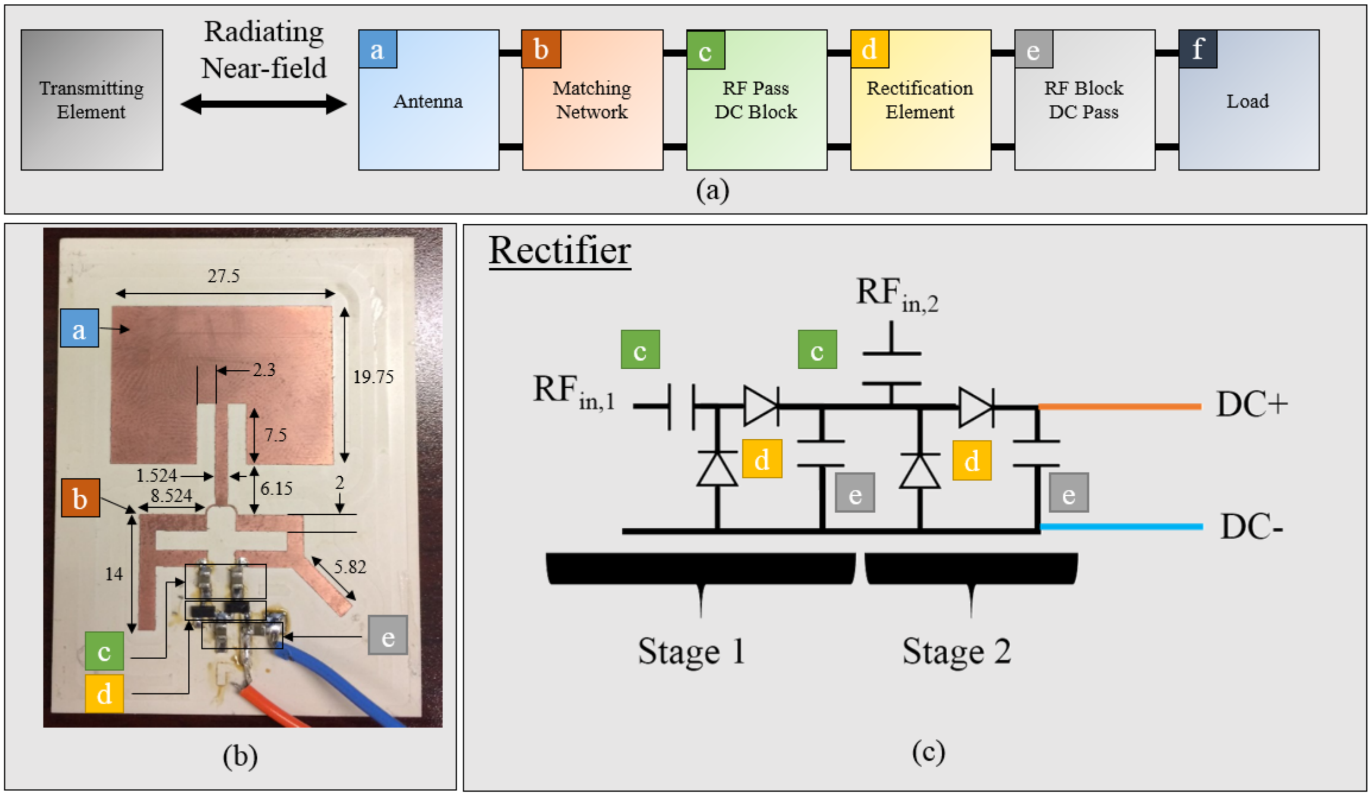


Fig. 1. (a) RF chain of the rectenna system, (b) fabricated rectenna circuit showing dimensions (all dimension are in mm), (c) circuit schematic of the equivalent voltage quadrupling rectifier

[13], some examples in literature include 57% at 0 dBm [14], 66.8% at 10 dBm [15], 70.4% at 0 dBm [16], and 72.8% at 8 dBm [17].

However, most of these systems employ a single diode or voltage doubler as the rectifier; this work presents a novel voltage quadrupler that achieves a maximum efficiency of 47.7% at 11 dBm and 40% at 0 dBm, which we demonstrate to deliver a sufficient voltage to operate an insulin pump wirelessly over 42 cm. Additionally, most midfield designs thus far have considered only spiral or coil antennas for transmission [30-32]; herein we present a patch antenna which provides a high tolerance to displacement while occupying a small footprint.

In this paper, we propose a new method to wirelessly power sensor devices from near-field radiating patch antennas. The proposed radiating method overcomes alignment issues between the exterior transmitter and receiver. This is achieved by relying on radiation, rather than direct coupling between the device and the RF source. To test the operation in the radiating near-field region, a patch rectenna is developed and tested at 2.4 GHz.

II. Methods and Procedures

A. Rectenna Design

Previous works demonstrated wireless power transmission at WiFi frequencies for over-the-air wireless power transmission across large distances [21]. Herein, we present all components of a rectenna on a single Printed Circuit Board (PCB) for operation at WiFi frequencies and in the near-field.

The basic components of the proposed rectenna are illustrated in Fig. 1(a). It includes:

1) Transmitting element. This is typically placed outside the body and close to the skin. It is generally a transmitting coil, but in our case we use a patch array as the external transmitter in order to establish a proper radiating near-field.

2) Receiving antenna. This is responsible for receiving the electromagnetic energy wirelessly.

3) Matching network. This transforms the antenna impedance to match that of the rectifier.

4) RF Pass/DC Block element. This allows the RF signal to pass to the rectifying elements, but blocks backward DC flow (typically modeled with a series capacitor or shunt inductor).

5) Rectification elements. These are ideally diodes, whose non-linear response is capable of producing a DC component as well as various harmonics that are filtered.

6) RF Block/DC Pass element. This is responsible for passing the DC signal to the load while blocking the RF signal (modeled as a series inductor or shunt capacitor).

7) Output load. This can represent a battery, sensor, medical device, etc., and is usually modeled as a resistor.

The rectenna patch element was designed to operate at 2.4 GHz. For this proof-of-concept demonstration, it occupied a footprint of 27.5 x 19.75 mm^2 and was fed by a 50 Ω source. Though outside the scope of this work, further miniaturization of the patch can be performed using high-permittivity substrates and meandering techniques [22]. For example, a similar patch on a substrate with dielectric constant ε_r=12.2 would shrink the overall size roughly 25%. When implanting directly beneath the skin, the high dielectrics of the body will provide a means of shrinking the patch down significantly as well [23]. Additionally, the active circuitry may be folded onto the back of the patch, as in [24], to reduce the overall size by another 50%.

The rectification circuit, shown in Fig. 1(c), consists of three main components: 1) RF Pass/DC Block series capacitors at the input, 2) diode elements for rectification, and 3) RF Block/DC Pass shunt capacitors at the output. The equivalent circuit of the rectifier is shown as a two-stage voltage doubling rectifier.

An RF splitter was further added at the terminal of the patch element, to divide the RF signal between a right and a left matching branch. The purpose of the two branches was

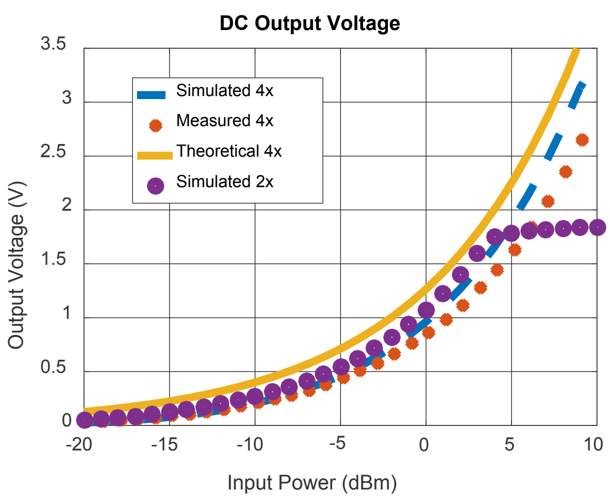


Fig. 2. Simulated, measured, and theoretical output voltage from voltage quadrupler, and simulated output from a voltage doubler

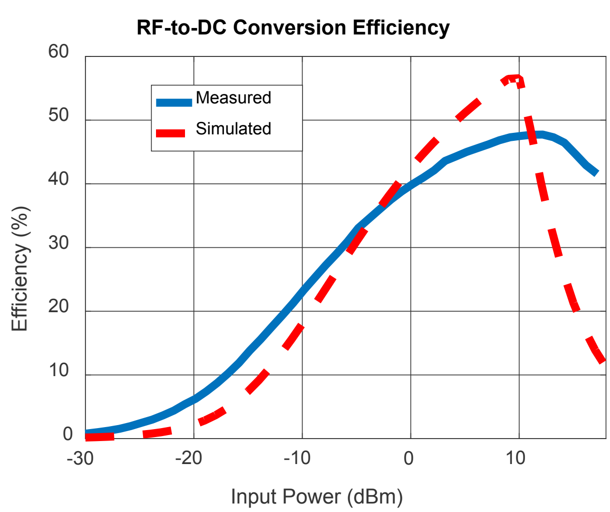


Fig. 3. RF-to-DC conversion efficiency of the voltage quadrupling rectifier

for additional fine-tuning made possible by the open transmission line stubs. Using these tunable components, any frequency offset (due to the narrow bandwidth of the patch antenna) can be corrected. We note that this splitter is necessary for voltage quadrupling. Another such circuit is a Villard quadrupler, as in [25]; however, the Villard rectifier necessitates a balun, adding unwanted extra bulk.

Fig. 2 shows the simulated, measured, and theoretical output voltage from a voltage quadrupling rectifying circuit, as well as a simulated voltage doubler. The theoretical output voltage is simply four times the peak voltage of the input signal assuming 50 Ω input power. The simulated and measured traces for the quadrupler simply show the DC voltage across the output resistor. The simulated voltage doubler shows similar performance at lower powers; as can be seen, it fails to rectify efficiently at higher powers.

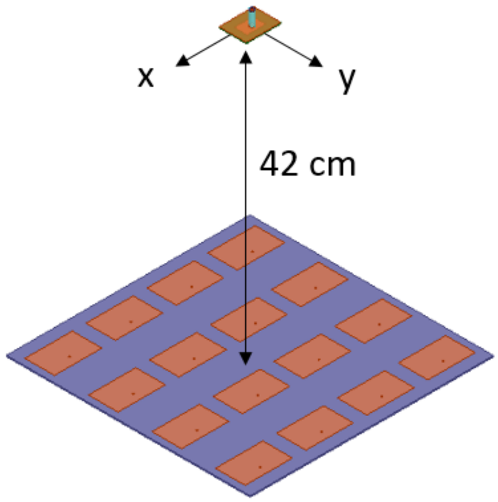
We remark that the insulin pump in this case requires a minimum of 1 V in order to oxidize. Indeed, the voltage quadrupler was chosen in order to provide the highest possible voltage to the implantable insulin pump. The insulin pump polymer, upon oxidation, expels cations causing the actuation arm to shrink. The higher the input power, the faster the actuation arm turns on. As such, the 'turn on' power of the implantable pump according to Fig. 2 is approximately 0 dBm.

The voltage quadrupler was fabricated on a Rogers TMM10 substrate having a dielectric constant ε_r=9.2, and a loss tangent tanδ=0.0022. We note that the high dielectric permittivity was chosen to help realize a small rectenna size. The thickness of the substrate is 60 mil, and 0.1 μF was used for every capacitor. Further, the rectifier diodes were Skyworks SMS7630 [26]. These diodes offer excellent performance for the expected power range [27]. The load in this case is a 1.8 kΩ resistor, which was found experimentally to be the approximate resistance of the insulin pump.

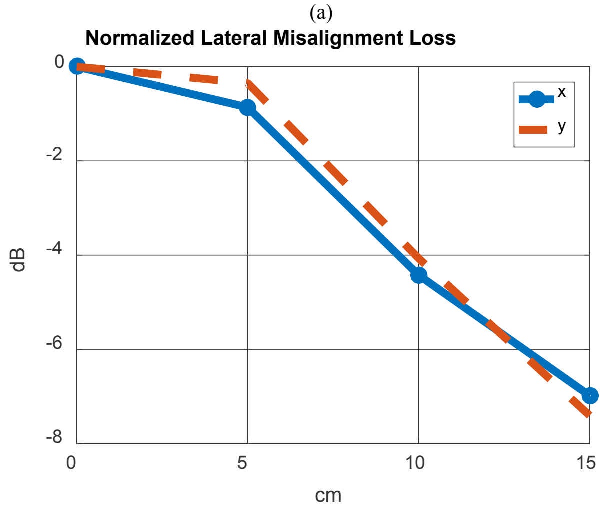
The rectifier shown in Fig. 1(b) was first fabricated as a stand-alone unit and tested to determine its efficiency. The rectifier was then fed by a signal generator at various power levels to measure the RF-to-DC conversion efficiency. The load was always 1.8 kΩ. With minor tuning between the simulated and fabricated models, the conversion efficiency, calculated as $\eta=DC_{out}/RF_{in}$, is shown in Fig. 3. A coaxial-to-microstrip feed provided the input power for RF_{in}, while the voltage across the output resistor provided DC_{out}. As seen, we achieved a maximum simulated efficiency of 55%, and a measured efficiency of 47.7% at 11 dBm.

B. Radiating Near-Field Measurements

The transmitting patch array measured approximately 34x33 cm^2 while the receiving patch was the same dimension as the one shown in Fig. 1(b). The separation distance was fixed at 42 cm as shown in Fig. 4(a). This distance was chosen because it places the receiving rectenna in the radiating near-field, which occurs between



(a)



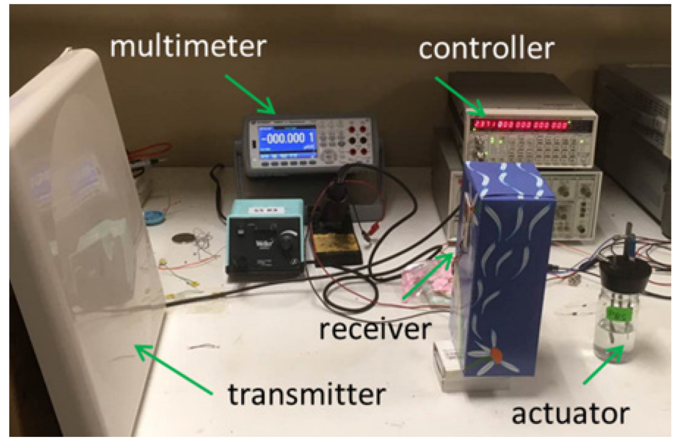
(b)

Fig. 4. (a) Illustration of the transmitting and receiving antenna in the lateral misalignment test, and (b) lateral misalignment loss as a function of offset distance when the vertical separation is fixed to 42 cm

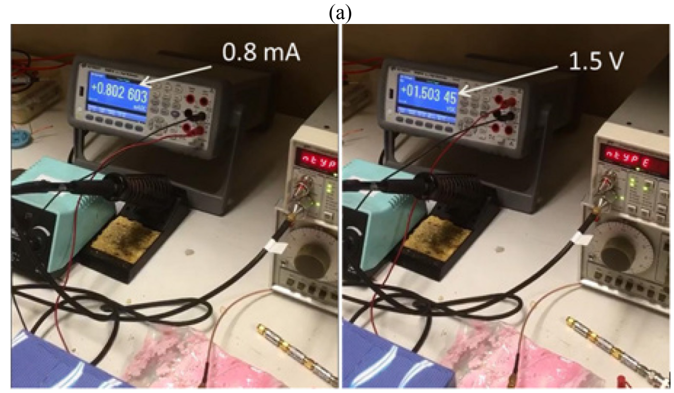
$$0.62\sqrt{\frac{D^3}{\lambda}} < x < \frac{2D^2}{\lambda} \quad (1)$$

where D is the longest dimension of the antenna, and λ is the wavelength at 2.4 GHz [28]. In this case, D is assumed to be the distance from the first patch to the last patch, as described in [33]; that is, the cut along which the patches are excited. When the receiving antenna is a distance outside this range, then it will be in the far-field.

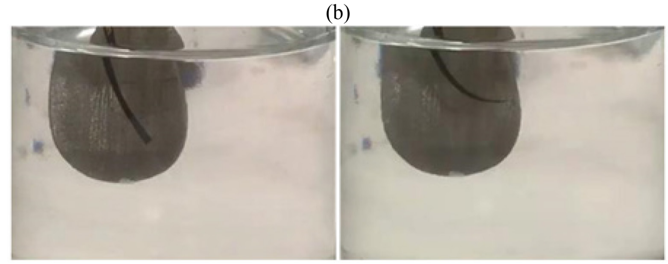
The received power from the transmitting array was then measured as the receiving patch was swept in the x and y directions. Fig. 4(b) shows the loss due to the separation (42 cm) and lateral misalignments in the radiating near-field. When misaligned by 15 cm, an additional 7.5 dB of path loss is added. A table with comparison to coil studies (of comparable size) found in literature is included in Table I. We remark that similar or lower misalignment loss is seen for a smaller receiver size, making the radiated near-field approach very suitable for on-body medical applications.



(a)



(b)



(c)

Fig. 5. (a) Radiating near-field rectenna setup, (b) measured voltage and current across 1.8 kΩ load, (c) actuated medical pump

TABLE I
COMPARISONS OF LATERAL MISALIGNMENT STUDIES IN LITERATURE

Ref.	Rx Antenna	Separation Distance (cm)	Tx Size (cm^2)	Rx Size (cm^2)	Loss (dB)
[35]	Coil	10	1017.9	7.1	11.3
[34]	Spirals	18	254.5	63.6	4.2
This Work	Patch	42	1122	5.4	7.5

III. RESULTS

To assess the performance of the given rectenna structure, a transmitter and receiver were connected to a controllable power supply, as shown in Fig. 5(a). A possible clinical application is the case where the patient stands near the external transmitter to activate the implanted pump. We note that the external transmitter is a linearly polarized patch array with a nominal gain of 19 dBi, and the transmitting power was set to 16.49 dBm. Thus, the entire EIRP was 35.49 dBm. This EIRP level is just below the FCC limit for a point-to-point link of 36 dBm [29].

The receiver rectenna was placed at a distance of 42 cm

TABLE II
COMPARISON OF THE PROPOSED VERSUS REPORTED MIDFIELD WPT SYSTEMS

Ref.	Antenna Type	Antenna Footprint (cm^2)	Rectifier Type	Scenario	Transmission Distance	Power Delivered	Source Power
[32]	Coil	0.03	Voltage Doubler	Implanted	5 cm	125 µW	0.5 W
[31]	Spiral	6.35	Single Diode	Implanted	6.5cm	4 mW[a]	1 W
[30]	Loop	0.90	-	Implanted	5-6 cm	173 µW	0.5 W
[4]	Coil	0.12	Voltage Doubler	Implanted	5 cm	200 µW	0.5 W
This Work	Patch	5.4	Voltage Quadrupler	Free-Space (fully-implantable operation envisioned)	42 cm	1.2 mW	44.5 mW

All WPT systems in this table were intended to power medical devices.
[a]Simulated

(see Fig. 5(a)) and optimally angled and positioned to the transmitter, reducing the path loss and multipath effects. A multimeter was then connected to the output of the rectification circuit across the 1.8 kΩ resistor placed in series and parallel set-up. The measurement is shown in Fig. 5(b), and the goal was to extract the current and voltage across at the output of the rectifier. We found that a constant current of 0.8 mA and voltage of 1.5 V was delivered using the wireless transmitter and rectenna receiver. As such, the amount of power delivered was 1.2 mW over this distance. A comparison of this work compared to other works in the midfield that deliver power to a medical device is shown in Table II.

The specific implantable pump was intended to squeeze a small pouch of insulin when located inside the body. The polypyrrole (PPy) actuation arm is shown in Fig. 5(c), and is submerged in phosphate buffered saline (PBS) solution, which provides cations (mostly Na^+) for the actuation. PBS is found naturally in the body, and is a conductive fluid in the blood stream. The left side of this figure shows the arm with no RF illumination, and on the right the actuated PPy arm is bending after the successful reception of the near-zone RF power illumination.

IV. CONCLUSION

A radiating near-field RF Harvester (rectenna and source/transmitter) was designed and built, showing up to 47.7% efficiency at 2.4 GHz. Using a transmitting antenna/source located in the radiated near-field zone of the rectenna, a total of 1.2 mW was delivered across 42 cm. A misalignment analysis was performed showing a maximum of 7.5 dB when offset by 15 cm.

This type of wireless power delivery offers a robust alternative to the position-sensitive coils, traditionally used for medical wireless power transfer. In the future, this rectenna design can be miniaturized even further by placing the rectifier behind the rectenna on a multilayer substrate and implanting under the skin. The miniaturized rectenna circuit could then be embedded onto the insulin pump and integrated with all components in a single system-in-package (SiP) medical device.

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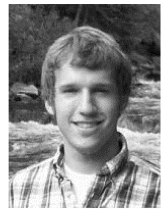

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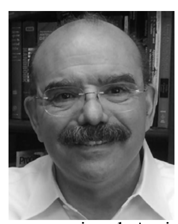
Dr. Kiourti has received several awards and scholarships, including the IEEE Engineering in Medicine and Biology Society (EMB-S) Young Investigator Award for 2014, the IEEE Microwave Theory and Techniques Society (MTTS) Graduate Fellowship for Medical Applications for 2012, and the IEEE Antennas and Propagation Society (AP-S) Doctoral Research Award for 2011. She is currently serving as an Associate Editor for the IEEE Transactions on Antennas and Propagation.



John L. Volakis (S'77-M'82-SM'89-F96) was born on May 13, 1956 in Chios, Greece and immigrated to the U.S.A. in 1973. He obtained his B.E. Degree, summa cum laude, in 1978 from Youngstown State Univ., Youngstown, Ohio, M.Sc. in 1979 from The Ohio State Univ., Columbus, Ohio and the Ph.D. degree in 1982, also from the Ohio State Univ.

Prof. Volakis started his career at Rockwell International (1982-84), now Boeing. In 1984, he was appointed Assistant Professor at The University of Michigan, Ann Arbor, MI, becoming a full Professor in 1994. He also served as the Director of the Radiation Laboratory from 1998 to 2000. From January 2003 to Aug 2017 he was the Roy and Lois Chope Chair Professor of Engineering at the Ohio State University, Columbus, Ohio and served as the Director of the ElectroScience Laboratory from 2003 to 2016. Effective August 2017 he is the Dean of the College of Engineering and Computing and a Professor in the Electrical and Computer Engineering at Florida International University (FIU).

Over the years, he carried out research in antennas, wireless communications and propagation, computational methods, electromagnetic compatibility and interference, design optimization, RF materials, multi-physics engineering, millimeter waves, terahertz and medical sensing. His publications include 8 books, 400 journal papers, nearly 750 conference papers, 26 book chapters and 17 patents/patent disclosures. Among his co-authored books are: Approximate Boundary Conditions in Electromagnetics, 1995; Finite Element Methods for Electromagnetics, 1998; 4th edition Antenna Engineering Handbook, 2007; Small Antennas, 2010; and Integral Equation Methods for Electromagnetics, 2011). He has graduated/mentored nearly 90 doctoral students/post-docs with 41 of them receiving best paper awards at conferences. His service to Professional Societies include: 2004 President of the IEEE Antennas and Propagation Society (2004), Chair of USNC/URSI Commission B (2015-2017), twice the general Chair of the IEEE Antennas and Propagation Symposium, IEEE APS Distinguished Lecturer, IEEE APS Fellows Committee Chair, IEEE-wide Fellows committee member & Associate Editor of several journals. He was listed by ISI among the top 250 most referenced authors (2004), and is a Fellow of IEEE and ACES. Among his awards are: The Univ. of Michigan College of Engineering Research Excellence award (1993), Scott award from The Ohio State Univ. College of Engineering for Outstanding Academic Achievement (2011), IEEE AP Society C-T. Tai Teaching Excellence award (2011), IEEE Henning Mentoring award (2013), IEEE Antennas & Propagation Distinguished Achievement award (2014), The Ohio State University Distinguished Scholar Award (2016), and The Ohio State Univ. ElectroScience George Sinclair Award (2017). He is a fellow of the Applied Computational Electromagnetics Society.