Compact Implantable Rectenna with Light-Emitting Diode for Implantable Wireless Optogenetics

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Abstract **─** In this paper, a compact rectenna which is capable to operate at 2.45 GHz for wireless implanted optogenetic stimulation is proposed. The rectenna consists of a monopole antenna and a rectifier circuit which drives the on-board blue light-emitting diode (LED). The presented rectenna is fabricated on 50 μm liquid crystalline polymer (LCP) substrate and has a dimension of 7 mm × 7.2 mm. The measured results of the rectenna embedded in the pork shows that the integrated LED can be lit wirelessly under the maximum permissible human exposure limit in controlled environments.

Index Terms **─** Flexible application, implantable antenna, LCP, rectenna, wireless optogenetic.

I. INTRODUCTION

With the rapid advances in flexible devices and biomedical telemetry [1-3], the battery-free wireless devices and optogenetics devices such as diagnostic measurement, stimulation and intervention devices [4-7] have been developed dramatically because they can be utilized to make incessant and non-invasive stimulating or monitoring. Wireless energy harvesting technology [8-10] also has been developed in last decade, which is essential for biomedical implanted device due to the fact that recharging or replacing the batteries of the tiny devices is inconvenient.

Various kinds of rectennas have been developed since the first experimental study of rectenna carried out in 1963 [11-13]. Several implantable rectennas have also been reported to provide electrical power to implanted device [14-15]. Recently an integrated injectable neural probe using microscale light-emitting diode (μLED) for optogenetic stimulation was developed [16]. Optogenetic stimulation has the advantage of using light to activate or silence the neurons which have been genetically sensitized to light with extreme precision. However, the rectenna used to drive the μLED in the wireless optoelectronic system in [16] was not implantable, which is very useful for the freely moving animal or human experiments. Up to now, few studies have investigated the rectenna which is both implantable and able to drive the LED.

In this letter, a compact implantable rectenna including a blue on-board LED for nerve stimulation application is presented. The rectenna embedded in the pork successfully lit the on-board LED at 2.45 GHz. Measured results of the rectenna showed that it could be used in optogenetic applications.

II. DESIGN AND FABRICATION

The presented implantable rectenna operating at 2.45 GHz is composed of a compact monopole antenna and a rectifier. Figure 1 displays the geometry of the proposed implantable rectenna along with its photo and dimensions. The rectenna has an overall size of 7 mm × 7.2 mm and is manufactured on double sided 18 μm copper clad Rogers ULTRALAM 3850 laminate which utilizes 50 μm liquid crystalline polymer (LCP) as the dielectric film. The dielectric constant and loss tangent of the substrate is 2.9 and 0.0025, respectively.

The antenna and rectifier were separately analysed by Ansys HFSS and Agilent Advanced Design System (ADS) software. The antenna consists of a simple folded radiating strip with the width of 2.2 mm and a short section of the line with the width the same as the width of the 50 Ohms feeding microstrip.

The implantable antenna needs to be put into test tissue to confirm its effectiveness. Recently the minced pork was confirmed that it is suitable to mimic the human skin and muscle between 100 MHz and 3 GHz [4]. Therefore the design of the implantable rectenna will be verified by embedding the rectenna into the pork as shown in Fig. 2 (a). The dimensions of the test pork were 85 mm × 80 mm × 45 mm.

The rectifying diode is essential in determining the RF-to-DC conversion efficiency of the rectifier. Basically, increasing the rectification stages can gradually improve the output voltage. However, the efficiency will decrease with the increase of the number of stages. Considering the voltage required to light a blue

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LED is approximately 2.4 V, the surface mount Schottky barrier diode pair HSMS-282C from Avago Technologies were chosen for the rectifier design.

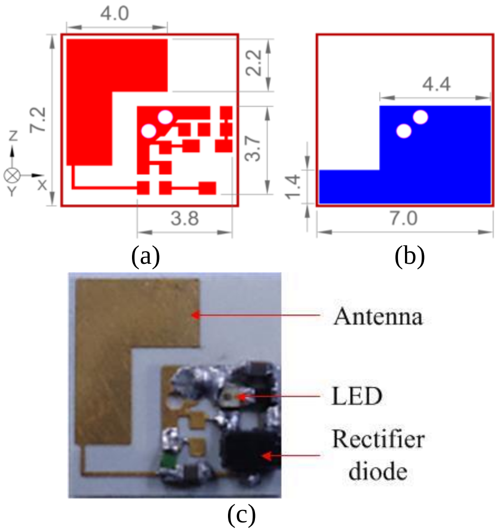
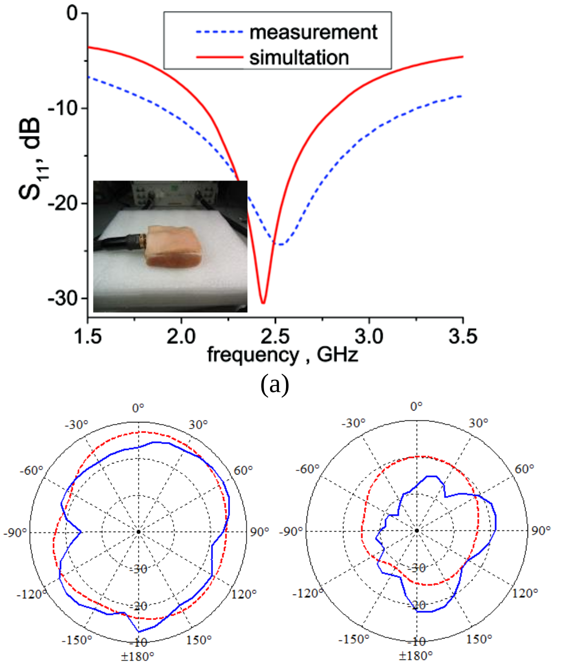


Fig. 1. Geometry of the proposed rectenna (dimensions in millimeters): (a) front view, (b) back view, and (c) photograph.



(b) XY plane (c) YZ plane

Fig. 2. Measured and simulated S11 and radiation gain patterns of the antenna embedded in the pork. (a) Measured and simulated S11 of the embedded antenna, (b) measured (blue line) and simulated (red line) gain patterns of the embedded antenna at XY plane, and (c) measured (blue line) and simulated (red line) gain patterns of the embedded antenna at YZ plane.

The schematic and photograph of the proposed rectifier circuit are presented in Fig. 3 (a). The dimensions of the rectifier circuit are 3.7 mm × 3.8 mm. The inductor L1 (= 1.6 nH) is used to improve the input matching of the rectifier. The capacitor C1 (= 39 pF) is a DC block capacitor. The diode D1 and D2 are the Schottky diode pair HSMS-282C. The capacitor C2 (= 1 μF) in a shunt configuration with respect to the load acts as a low pass filter, which isolates the load from unwanted RF signals. The surface mount diode D3 is a blue LED in series with the current limiting resistor R1 (= 2 KΩ).

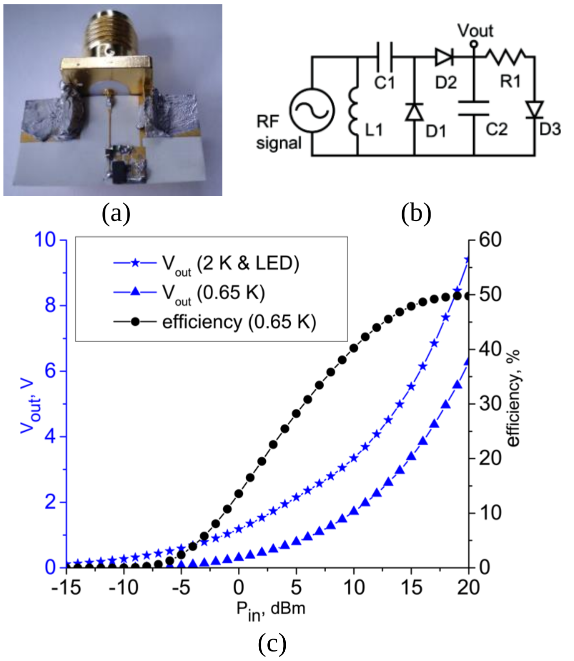


Fig. 3. Schematic and measured performance of the rectifier: (a) schematic, (b) photograph of the rectifier, and (c) performance of the rectifier.

III. RESULTS AND DISSCUSION

The fabricated rectenna, antenna and rectifier are coated with thin protective film of CRC Plasticote 70 for insulating them from the pork. The performances of the antenna were measured in an anechoic chamber. Figure 2 (a) shows the simulated and measured return loss of the antenna embedded into the pork. The simulation result of S11 agrees well with the measured S11 of the antenna. Figure 2 shows the measured radiation patterns of the antenna embedded in the pork at XY and YZ plane, respectively. The 2.45 GHz associated measured maximum radiation front gain of the embedded antenna is -12.9 dBi.

To measure the best efficiency of the rectifier, the LED was removed and the resistor R1 was chosen to be 0.65 KΩ. Figure 3 (b) shows the conversion efficiency of the rectifier as the function of RF input power when

R1 is 0.65 KΩ. The measured output voltages on the node Vout presented in Fig. 3 (a) were also shown in Fig. 3 (b). As can be seen in Fig. 3 (b), the output voltage Vout when both R1 (= 2 KΩ) and LED are loaded is higher than the output voltage when only R1 (= 0.65 KΩ) is loaded.

Figure 4 shows the photographs of the blue LED light-up demonstration when the rectenna was put on the surface of the pork and powered wirelessly. Figure 5 shows the power transmission efficiency (PTE) measurement setup for the proposed implantable rectenna. A blue lead LED and 2 KΩ lead resistor were used instead in order to facilitate finding out whether the LED is lit wirelessly. A power amplifier (power output from 0.02 W to 8.7 W) has been connected between the RF signal generator Agilent N9310A (power output from -20 dBm to 13 dBm) and a transmitting horn antenna with the gain of 5.1 dBi. The output power of the power amplifier was calibrated by the power meter Agilent N1912A. The rectenna was placed into the pork and the transmitting horn antenna was positioned at a distance of 10 cm in front of the rectenna. The PTE of the rectenna is defined as:

$$PTE(\%) = \frac{P_{DC}}{P_T} \times 100\% = \frac{V_{out} \cdot I_{out}}{P_T} \times 100\%, \quad (1)$$

where PDC is the DC output power, PT is the transmitting power of the power amplifier, Vout is the output voltage of the rectifier [4].

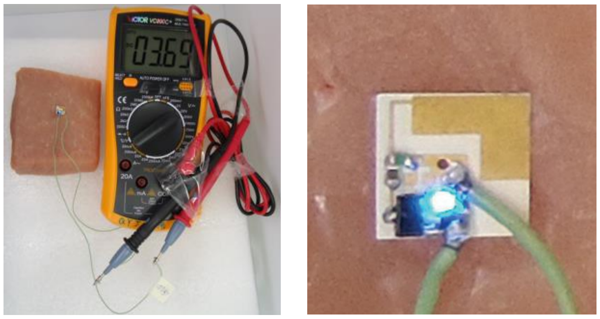
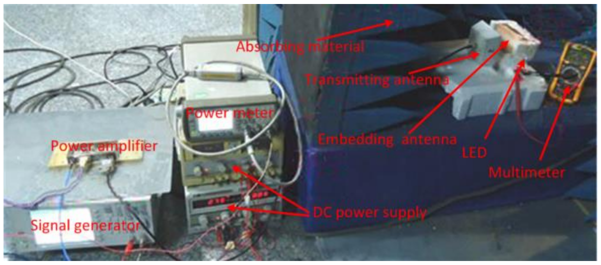
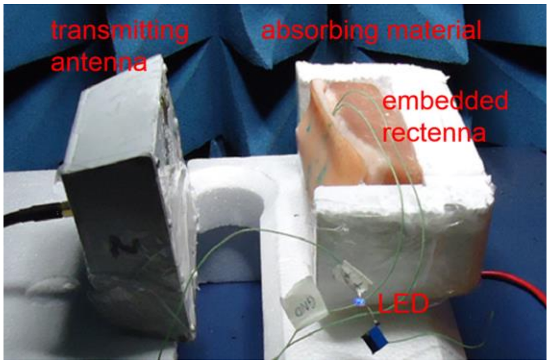

(a) (b)

Fig. 4. Photograph of the LED light-up demonstration for the rectenna: (a) photograph of the LED light-up demonstration, and (b) enlarged photograph of the wirelessly lit LED in the rectenna.



(a)



(b)

Fig. 5. Efficiency measurement system of the rectenna: (a) experiment setup of the efficiency measurement system, and (b) enlarged photograph of the transmitting antenna and the embedded rectenna with the lit LED.

The measured results shown in Fig. 6 are the measured output DC voltage and power transmission efficiency of the embedded rectenna as a function of the power density on the surface of the pork. The power transmission efficiency is low due to the free space loss, the biological tissue loss, the low antenna gain and the relatively low conversion efficiency of the detector. However, the blue LED begin to shine when the power density reaches 1.8 mW/cm^2, which is substantially lower than the maximum permissible human exposure limits (5 mW/cm^2) in controlled environments at 2.45 GHz based on the corresponding Federal Communications Commission (FCC) standard [6].

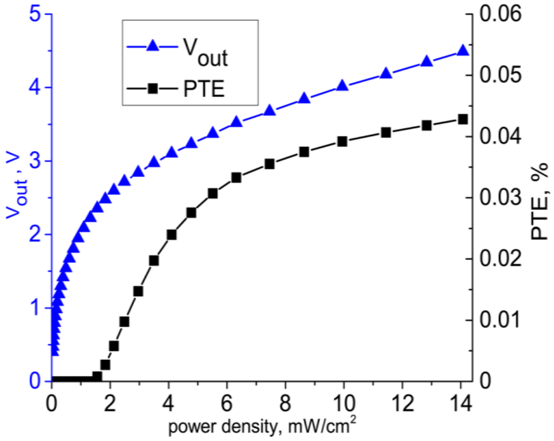


Fig. 6. Measured output DC voltage and power transmission efficiency of the embedded rectenna.

VI. CONCLUSION

In this paper, a compact implantable rectenna with a blue LED has been designed for optogenetics applications. The compact rectenna with the dimension of 7 mm × 7.2 mm operates at 2.45 GHz. The measured maximum gain of the antenna is –12.9 dBi. The design of the flexible rectenna was verified in the biomedical implantable environment through measuring the PTE of the rectenna. The measured results showed that the LED in the rectenna was successfully lit and the rectenna can be used in applications such as wireless optogentics. Due to the thin thickness and good flexibility property of the substrate of the rectenna, the proposed rectenna will be more flexible by implementing the rectenna using on-chip components instead of the surface mount components. We will fabricate the on-chip flexible rectenna for implantable electronics in the future work.

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REFERENCES

[1] Y. J. Qiu, Y. H. Jung, S. Lee, T. Y. Shih, J. H. Lee, Y. H. Xu, W. G. Lin, N. Behdad, and Z. Q. Ma, "Compact parylene-c-coated flexible antenna for WLAN and upper-band UWB applications," *Electronic Letters*, vol. 50, no. 24, pp. 1782-1784, Nov. 2014.

[2] Y. Lan, Y. H. Xu, C. S. Wang, Z. Wen, Y. J. Qiu, T. D. Mei, Y. Q. Wu, and R. M. Xu, "Flexible microwave filters on ultra thin liquid crystal polymer substrate," *IEEE MTT-S International Microwave Symposium*, Phoenix, AZ, USA, pp. 1-4, May 2015.

[3] S. Park, J. H. Ahn, X. Feng, S. D. Wang, Y. G. Huang, and J. A. Rogers, "Theoretical and experimental studies of bending of inorganic electronic materials on plastic substrates," *Advanced Functional Materials*, vol. 18, no. 18, pp. 2673-2684, Sep. 2008.

[4] C. H. Lee, S. K. Kang, G. A. Salvatore, Y. Ma, B. H. Kim, Y. Jiang, J. S. Kim, L. Yan, D. S. Wie, A. Banks, S. J. Oh, X. Feng, Y. Huang, G. Troester, and J. A. Rogers, "Wireless microfluidic systems for programmed, functional transformation of transient electronic devices," *Advanced Functional Materials 25*, pp. 5100-5106, Aug. 2015.

[5] E. R. Siuda, J. G. MaCall, R. AI-Hasani, G. Shin, S. I. Park, M. J. Schmidt, S. L. Anderson, W. J. Planer, J. A. Rogers, and M. R. Bruchas, "Optodynamic simulation of b-adrenergic receptor signaling," *Nature Communications*, 6:8480, Sep. 2015. DOI: 10.1038/ncomms9480.

[6] J. W. Jeong, J. G. McCall, G. Shin, Y. Zhang, R. AI-Hasani, M. Kim, S. Li, J. Y. Sim, K-I. Jang, Y. Shi, D. Y. Hong, Y. Liu, G. P. Schmiz, L. Xia, Z. He, P. Gamble, W. Z. Ray, Y. Huang, M. R. Bruchas, and J. A. Rogers, "Wireless optofludic system for programmable in vivo pharmacology and optogenetics," *Cell 162, 2015*, pp. 1-13, 2015.

[7] C. Dagdeviren, Y. W. Su, P. Joe, R. Yona, Y. H. Liu, Y. S. Kim, Y. A. Huang, A. R. Damadoran, J. Xia, L. W. Martin, Y. G. Huang, and J. A. Rogers, "Conformable amplified lead zirconate titanate sensors with ehanced piezoelectric response for cutaneous pressure monitoring," *Nature Communications*, article no. 4496, Aug. 2014. DOI: 10.1038/ncomms5496.

[8] R. G. C. Fuentes, A. C. Aparicio, E. Alarcon, "Energy buffer dimensioning through energy-erlangs in spatio-temporal-correlated energy-harvesting-enabled wiressless sensor network," *Emerging and Slected Topics in Circuits and Systems*, 4, pp. 301-312, 2014.

[9] Y. Wu and W. B. Liu, "Routing protocol based on genetic algorithm for energy harvesting-wireless sensor networks," *Wireless Sensor Systems*, vol. 3, pp. 112-118, 2013.

[10] C. Y. Song, Y. Huang, J. W. Zhang, S. Yuan, and P. Carter, "A high-efficiency broadband rectenna for ambient wireless energy harvesting," *IEEE Transactions on Antenna and Propagation*, vol. 63, pp. 3486-349, 2015.

[11] J. I. Moon, I. K. Cho, S. M. Kim, and Y. B. Jung, "Design of efficient rectenna with vertical ground-walls for RF energy harvesting," *Electronics Letters*, vol. 49, no. 17, pp. 1050-1052, 2013.

[12] A. Takacs, H. Aubert, L. Despoisse, and S. Fredon, "Microwave energy harvesting for satellite applications," *Electronics Letters*, vol. 49, no. 11, pp. 722-724, 2013.

[13] S. Ladan, A. B. Guntupalli, and W. Ke, "A high-efficiency 24 GHz rectenna development towards millimeter-wave energy harvesting and wireless power transmission," *IEEE Transactions Circuits and Systems I: Regular Papers*, vol. 61, no. 12, pp. 3358-3366, 2014.

[14] H. Fu-Jhuan, et al., "Rectenna application of miniaturized implantable antenna design for triple-band biotelemetry communication," *IEEE Transactions on Antennas and Propagation*, vol. 59, no. 7, pp. 2646-2653, 2011.

[15] Y.-L. Yang, C.-L. Tsai, and C.-L. Yang, "Enhancement of output voltage for novel dental rectennas," *2012 42nd European Microwave Conference (EuMC)*, pp. 321-324, 2012.

[16] T. I. Kim, et al., "Injectable, cellular-scale optoelectronics with applications for wireless optogenetics," *Science*, vol. 340, (6129), pp. 211-216, 2013.

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