Design of Miniaturized Antenna and Power Harvester Circuit on the Enucleated Porcine Eyes

Hui-Wen Cheng, Tsung-Chi Yu, Hong-Yi Huang, Ssu-Han Ting, Tzuen-Hsi Huang, Jin-Chern Chiou, and Ching-Hsing Luo

***Abstract*—This letter describes a prototype of a miniaturized rectifying antenna (rectenna) design for the wireless powering of an ocular device. In contrast to the conventional on-lens loop antenna, this letter presents a loop antenna with stepped structures for optimal impedance to the rectifier. The return loss of the antenna less than -15 dB at 3 GHz is accomplished in a contact lens with a diameter ranging from 10 to 15 mm. Additionally, the radio frequency (RF) rectifier and voltage-boosting network (VBN) are optimized to enhance the power conversion efficiency (PCE) by using the voltage boosting technique. Experimental results indicate that the optimal rectifier, which is fabricated with the TSMC 0.18-μm process, produces a dc output voltage of 2.94 V and a conversion efficiency of 31% across a resistive 3.5 kΩ load with an input power of $+9$ dBm. Moreover, the rectenna under the experiment with an enucleated porcine eye can be powered wirelessly with a transmitting device at a distance of 4 cm. The output power is 2.01 mW with a transmitting power of $+32$ dBm for the wireless ocular physiological monitoring (WOPM) system. Importantly, this letter demonstrates the feasibility of an optimal miniaturized on-lens rectenna design, capable of overcoming the RF power attenuation on the ocular tissue to increase the delivering distance and reduce the transmitting power.**

***Index Terms*—Contact lens, microelectromechanical systems (MEMS), radio frequency (RF), rectifying antenna (rectenna).**

I. INTRODUCTION

INVASIVE and noninvasive methods of long-term monitoring for eye condition have received considerable attention recently to examine the feasibility of using bio-telemetry systems such as examining various eye diseases or in identifying biomarkers of the tear fluid. Implantation of extremely compact planar meander-line dipole antennas as an intraocular radiation element for a retinal prosthesis [1] and an active glaucoma monitor implanted into the cornea for intraocular pressure measurement [2] are examples of invasive methods. Meanwhile, examples of noninvasive methods (e.g., glucose sensing [3] and intraocular pressure monitoring [4]) involve the use of sensors on contact lenses, as illustrated in Fig. 1. Importantly, sufficient electrical power must be generated by harvesting radio frequency (RF) energy to the wireless powered portable and wearable monitoring devices to ensure long-term and flexible monitoring in order to collect data unobtrusively. For example, Fig. 2 schematically depicts the block diagrams of a wireless ocular physiological monitoring (WOPM) system. This system is integrated heterogeneously with a power harvester, RF communication circuits, miniaturized antenna, and biosensors fabricated with microelectromechanical systems (MEMS) technology. Chow *et al.* [2] designed an implantable active glaucoma intraocular pressure monitor integrated by a wireless powering device on the cornea, in which the peak efficiency is 11.3%. That design is inadequate for compact integration, owing to the use of an externally discrete capacitor in order to upgrade the efficiency of the antenna. Otis *et al.* [5], [6] developed a wirelessly powered, active single-element display with an integrated system on a lens, in which a peak efficiency is 10% by using the loop antenna with conjugate impedance-matching method. The peak efficiency is decreased due to the usage of an eight-stage rectifier to increase the output voltage. Given the limitation of the contact lens size as well as the ability to maintain the antenna performance in a restricted area, designing a conventional loop antenna for impedance tuning to match the rectifier impedance is rather difficult. In sum, the above works require additional transmitting power for the desired transmitting ranges.

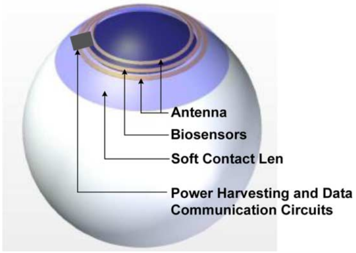

Fig. 1. Conceptual diagram of an active contact lens system for the wireless ocular physiological monitoring applications.

This letter presents a prototype of a miniaturized rectifying antenna (rectenna) operated at 3 GHz without external passive elements. Fabricated with MEMS technology, an on-lens loop antenna with stepped structures is impedance-matched for

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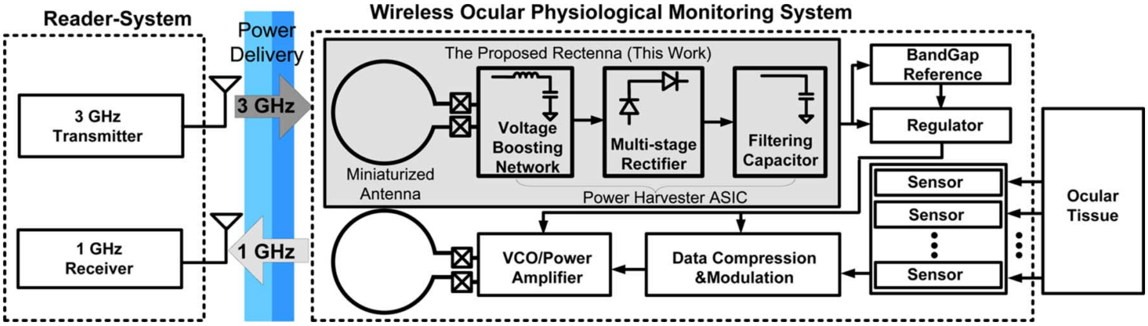

Fig. 2. Block diagrams of a wireless ocular physiological monitoring system.

the desired resonance frequency. Additionally, optimized efficiency of the power harvester application-specific integrated circuit (ASIC) is achieved using the voltage boost technique. Moreover, integration of the miniaturized antenna on an enucleated porcine eye with the power harvester ASIC is tested under physiological conditions to verify its reliability.

II. OVERVIEW OF THE PROPOSED POWER HARVESTER SYSTEM

The integrated rectenna includes a miniaturized antenna on a contact lens, passive voltage-boosting network (VBN), multistage rectifier, and filtering capacitor, as shown in the shaded area of Fig. 2. The proposed miniaturized antenna must be implemented within the volume of a commercial contact lens that normally has a diameter of 10–15 mm and a total thickness of 200 μm. The proposed design demonstrates the feasibility of a prototype of contact lens containing only the Parylene-C layers without the hydrogel layers. Parylene-C is used as the insulation and substrate material of the contact lens, owing to its biocompatibility, flexibility, and high gas permeability.

Due to the on-lens constraints of the area, thickness, and clear-vision space for leaving the pupil unobstructed, a maximum diameter of 12 mm ($\sim$12% of the 3-GHz wavelength) is allowed for the antenna. With a tradeoff analysis between the size of contact lens, efficiency of small antenna, and ocular tissue attenuation, 3 GHz is selected as the center frequency of RF power transmitting [2]. The proposed WOPM system attempts to provide 2 mW of dc power. By taking account of the possible conversion, reflection, and bonded wire losses, an input power of +9 dBm (7.94 mW) is desired. To ensure accurate simulation of the proposed rectenna, a human eye model (i.e., a diameter of 23 mm sphere) is established by High Frequency Structure Simulator (HFSS) software and simulated with permittivity and conductivity of a human eye [7].

A. Design of a Stepped Loop Antenna

A loop antenna at the receiving end is generally excited by a magnetic field. A magnetic field may yield less loss than that of an electric field when it propagates near human tissue with a high dielectric loss. Based on the transmission line theory, the operating frequency of a stepped loop antenna is determined to be 3 GHz with its equivalent resonator model. In Fig. 3(a), the radiating element consists of four planar patches. The four planar patches are preformed to interfere with the current phase distribution in order to implement 50 Ω at the feeding point within the constrained area [8]. The stepped loop antenna is fabricated using the traces of composite biocompatible metal materials (titanium and gold) on a polymer (Parylene-C) substrate based on a MEMS technology [Fig. 3(b)]. Fig. 3(c) shows the photograph of the stepped loop antenna.

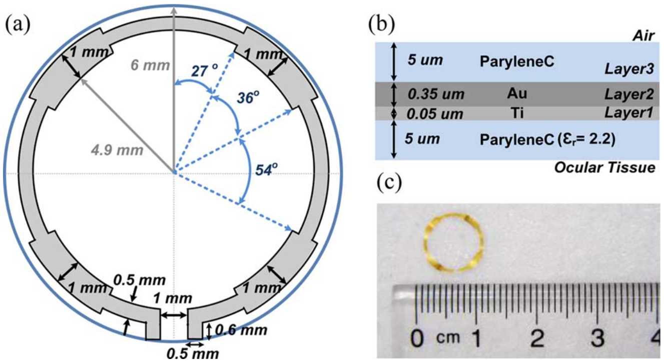

Fig. 3. (a) Structure of the proposed contact lens stepped loop antenna. (b) Layer structure of the miniaturized antenna. (c) Photograph of the stepped loop antenna insulated with parylene-C.

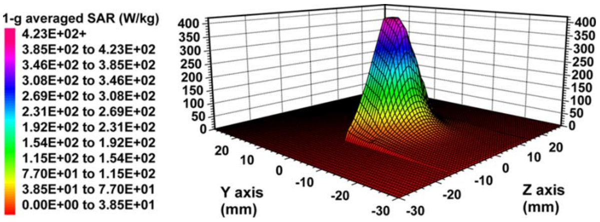

Fig. 4. Simulated SAR value of the stepped loop antenna.

Due to the high absorption rate of an ocular tissue, the radiation efficiency of 0.302% is then diminished [9]. The radiation pattern of the stepped loop antenna designs that the maximum directly is in the eye view. Although the stepped loop antenna used in this work is a receiving antenna, additional transmitting characteristics are described here for reference. Fig. 4 displays the simulated 1-g average specific absorption rate (SAR) for the distribution profile in the level of W/kg, which has a peak SAR value of 423 W/kg. To comply with biological safety requirements of average RF exposure to the eyes, the IEEE standard specifies exposure limits at 10 W/kg (10 MHz–10 GHz) [10]. Additionally, the measured peak gain of the designed stepped loop antenna is -15 dBi.

B. Impedance Matching Network and Rectifier Design

Based on a consideration of the limited volume available for high integration, the external passive components on lens are not

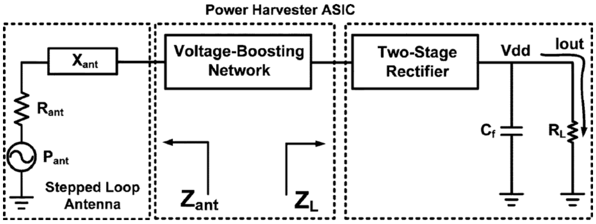

Fig. 5. Voltage-boosting network between the stepped loop antenna and the power harvester ASIC.

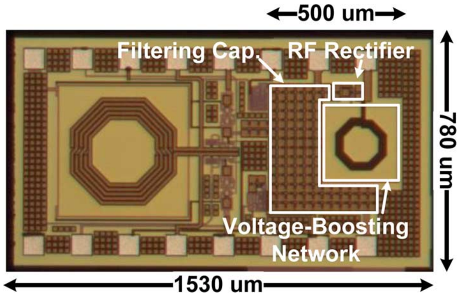

Fig. 6. Micrograph of power harvester integrated circuit.

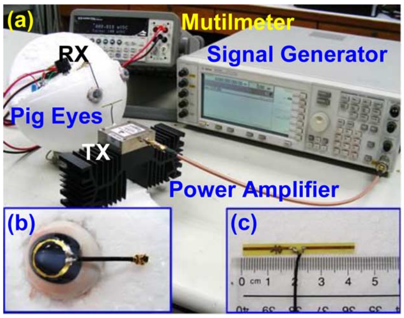

Fig. 7. (a) Enucleated porcine eye measurement setup. (b) Contact lens with stepped loop antenna on the enucleated porcine eye with a miniature coaxial cable length of 2 cm. (c) Transmitting dipole antenna.

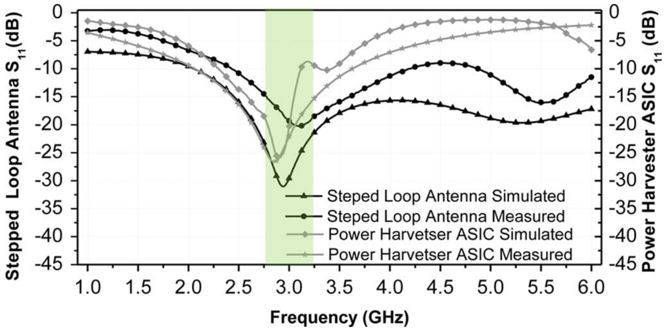

Fig. 8. Simulated and measured S_{11} of the on-lens stepped loop antenna on the enucleated porcine eyes and power harvester ASIC.

preferred warranting the design of a power harvester ASIC fabricated with TSMC 0.18-μm process. In the rectifier design, the power conversion efficiency (PCE) is the most effective means of evaluating the rectifier circuit, which is affected by circuit topology, diode-device parameters, operation frequency, input RF-signal amplitude, and output loading conditions. The overall efficiency η of the rectifier can be evaluated by

$$\eta(\%) = \frac{P_{\mathrm{DC}}}{P_{\mathrm{r}}} \times 100\% = \frac{V_{\mathrm{DC}}^2}{R_L \cdot P_{\mathrm{r}}} \times 100\% \tag{1}$$

where $\mathrm{P_{DC}}$ denotes the output dc power, $\mathrm{P_r}$ represents the power received by the rectifier, V_{DC} refers to the output dc voltage, and R_L is the load resistance. This work utilizes the native threshold transistors with a lower threshold voltage to eliminate the voltage drop of the diode-connected MOSFET for enhancing sensitivity of the rectifier. Although increasing the number of stages enlarges the output voltage, it decreases efficiency due to the voltage drop of each stage of rectifier. Thus, two stages are implemented to keep its high efficiency but to increase the output voltage by maximizing the charge delivered to the load resistor of 2.5–3.5 kΩ. To improve the power harvester ASIC performance, the input RF signal at the input node of the two-stage rectifier is boosted using the voltage boosting technique [11]. The voltage gain is accelerated by an optimal passive VBN to provide the maximum PCE of the rectifier, as shown in Fig. 5. Notably, an on-chip MIM filtering capacitor ($C_{\mathrm{f}} = 125$ pF) is highly desired to suppress the high-frequency supply noise and prevent large voltage drops. According to the simulation results, the equivalent impedance Z_L at the loaded rectifier input is 54.46-j77.44 Ω. This finding suggests that the impedance Z_L is inherently capacitive and can be designed to match the input impedance of the stepped loop antenna by a series inductor of 4.7 nH. Therefore, the available voltage gain of designed impedance is 1.97 to increase input voltage at a specified load.

Fig. 6 shows a photograph of the fabricated die, which includes the power harvester ASIC in the right part and another circuit in the left part. The power harvester ASIC is designed with the ADS EM/Circuit and Momentum cosimulation to include the parasitic effect from the layout traces and improve the accuracy of a high-frequency response.

III. EXPERIMENT

Enucleated porcine eyes that were kept moist for transportation (<3 h) were used in this experiment. Porcine eyes were used owing to their dielectric properties close to those of human eyes [4]. In the experiment, the eyes were placed in a Styrofoam eye-holder plate with the cornea facing toward the transmitting device [Fig. 7(a)]. The wireless power regulation capability was quantified by evaluating the on-board power harvester ASIC and on-lens stepped loop antenna [Fig. 7(b)] under the environment setup shown in Fig. 7(a). The adopted transmitting antenna with 0.2 dBi gain at 3 GHz is a dipole antenna [Fig. 7(c)], which was built on an FR4 printed circuit board (PCB) substrate. The largest dimension of the dipole antenna is 42 mm. The ZVE-3W-83+ power amplifier was driven by a signal generator (Agilent E54855A) and connected to the transmitting dipole antenna in order to operate as the RF powering source. This experiment also examined the distance effect by varying the distance between the enucleated porcine eye and the transmitting dipole antenna in the line of sight.

IV. RESULTS AND DISCUSSION

Fig. 8 shows the simulated and measured S_{11} of the on-lens stepped loop antenna [Fig. 7(b)] and power harvester ASIC. Obviously, the proposed stepped loop antenna and ASIC achieve an impedance bandwidth of 825 and 800 MHz, respectively, at a return loss $\geq$ 15 dB, which is well matched at around 3 GHz.

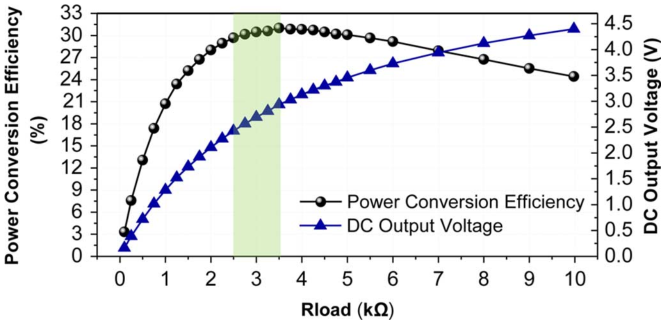

Fig. 9. Measured efficiency and output voltage of the power harvester ASIC versus varying load.

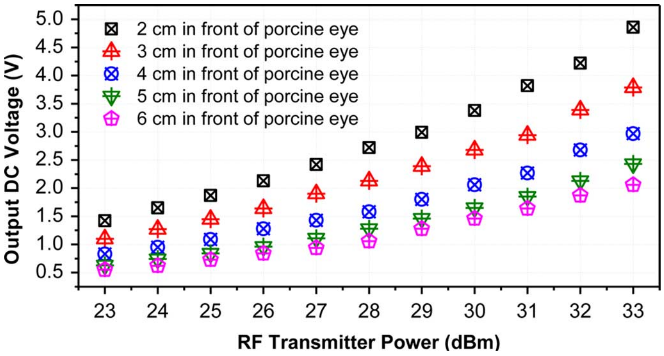

Fig. 10. Comparisons of the output dc voltages of the rectenna at variation distance.

Fig. 9 plots the efficiency of the power harvester ASIC for various load resistances ranging from 1 to 10 kΩ. A 3-GHz RF signal with an input power of +9 dBm was directly fed to the power harvester ASIC. Within the specific load range (i.e., from 2.5 to 3.5 kΩ), PCE over 30% and an output voltage ranging from 2.43 to 2.94 V can be achieved. The highest efficiency of up to 31% can be obtained at 3.5 kΩ load, together with an output power of 2.46 mW. The above results indicate that the measured output power satisfies the proposed WOPM system dc power requirement of 2 mW.

This letter also examines the voltage regulation capability of the proposed stepped loop antenna and power harvester ASIC. Fig. 10 summarizes the measurement results by varying the output power level and the distance between the receiving rectenna and transmitting device. In the distance range of from 2 to 6 cm, the regulated output dc voltage can obviously exceed 2 V across a 3.5-kΩ resistor as the transmitting power is +33 dBm. However, the required transmitting power level is +26 dBm if the powering distance is fixed at 2 cm. According to the required specific power of the proposed WOPM system, an experiment is performed using a +32-dBm RF source to provide a power capability of 2.01 mW at a distance of 4 cm for a 3.5-kΩ resistor load.

Table I summarizes and compares the experiment results of the proposed rectenna integration to those in previous works, indicating that the proposed rectenna integration has a higher conversion efficiency and longer operating distance under a similar transmitting power level than those of previous works.

TABLE I
COMPARISONS OF ON-LENS RECTENNA TO PREVIOUS WORK

Reference	[2]	[6]	This work
Operator Frequency (GHz)	3	0.8-2	3
Transmit Power (dBm)	+32	+35	+32
Transmit Antenna	Horn	Dipole	Dipole
PCE (%)	11.3	10	31
Generated Power (W)	37 *u*W^{*a}	125 *u*W	2.01 mW
External Components	Capacitor^{*b}	None	None
Operating Distance (cm)	5	2	4
Test Tissue	Rabbit eye	Rabbit eye	Porcine eye

*a: across 27 kΩ load. *b: to upgrade the antenna performance.

V. CONCLUSION

This letter demonstrates the feasibility of an optimal on-lens miniaturized stepped loop antenna and power harvester ASIC integration to improve the RF signal absorption and regulation efficiency for a WOPM system. According to measurement results of the enucleated porcine eye, the integrated rectenna obtains an output power of 2.01 mW from an incident 3-GHz 32-dBm EIRP RF signal at a distance of 4 cm. In addition, the proposed power harvester ASIC exhibits an optimal PCE of 31% by favorable on-chip impedance matching. As for future research, the compact integration of our proposed stepped loop antenna and power harvester ASIC by flip-chip technology rectenna is a highly promising solution for powering a WOPM system embedded into contact lens.

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