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The Rectenna Design on Contact Lens for Wireless Powering of the Active Intraocular Pressure Monitoring System

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Abstract—**This paper proposed a wireless power harvesting system with micro-electro-mechanical-systems (MEMS) fabrication for noninvasive intraocular pressure (IOP) measurement on soft contact lens substructure. The power harvesting IC consists of a loop antenna, an impedance matching network and a rectifier. The proposed IC has been designed and fabricated by CMOS 0.18um process that operates at the ISM band of 5.8 GHz. The antenna and the power harvesting IC would be bonded together by using flip chip bonding technologies without extra wire interference. The circuit utilized an impedance transformation circuit to boost the input RF signal that improves the circuit performance. The proposed design achieves an RF-to-DC conversion efficiency of 35% at 5.8 GHz.**

I. Introduction

In general, the feature of contact lens is that it touches eyeball directly by using transparent polymers to correct the faulty vision. However, numerous literatures of the research recently dedicate placing biosensors on contact lens to detect various biomarkers of the eye without sheltering the pupil. Unlike the invasive implanted devices within the eye, using soft contact lens with biosensors to detect biomarkers for potential disease diagnosis is more convenient and safer. In 2003, the initial work [1] proposed a novel approach of intra-ocular pressure (IOP) measurement which has embedded strain gauge on a soft contact lens. At this stage, the device cannot work and be powered wirelessly. Later, B.A Parviz [2] presented a wirelessly-powered active single element display with an integrated system on the lens covering the situations in different environments such as in free space and in vivo on a rabbit [3]. Pedro.P et al. [4] realized the implantable active glaucoma intraocular pressure monitor that is a wireless powered sensor IC by receiving 13 dBm of RF power on cornea. In [5], the integrated system using RFID backscattering modulation technology with glucose sensor on the contact lens for wireless monitoring is presented. It consumes ultra-low power to drive the whole glucose chip system. However, the drawback of the above wireless powering works is their poor conversion efficiency of their RF rectifiers due to incomplete integration of the antenna and power harvesting IC. Thus, these devices require more external RF power for the desired transmission ranges. After introducing antenna for receiving RF power, the next two blocks being described are impedance matching network and RF rectifier. Generally, three methods can be applied in impedance matching network design, which are distributed components made by transmission lines [6] ,external lump components [7] and internal lump components [2] for 50 ohm standard impedance matching. The transmission line method occupies too much area for matching network in the system at 5.8 GHz. Then, the high-quality passive component on the contact lens is unavailable compared to that designed on PCB substrate. For complex conjugate matching method, arbitrary shape modification of the antenna for impedance tuning to match the chip impedance is prohibited due to the restricted area of the contact lens size for maintaining the antenna performance. Therefore, it is necessary to design the integrated passive impedance matching circuit between antenna and the multi-stage voltage multiplier. In summary, this paper develops a wireless power harvesting system in a contact lens integrating a custom-designed and high-efficiency power harvesting IC with embedded 5.8 GHz loop-antenna.

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II. Architecture

A. Overview

Figure 1 shows an active wireless IOP monitoring system with real-time operation. The *LC* resonating frequency of voltage control oscillator (VCO) corresponds linearly to variation of IOP and the 2.4 GHz loop antenna transmits oscillation frequency from VCO to external reader. The active pressure sensing system is micro-fabricated on the soft contact lens that it comprises 5.8 GHz rectenna, 2.4 GHz transmitting antenna, and intraocular pressure micro-electro-mechanical systems (MEMS) sensor with a VCO. Figure 2 represents electrical model of passive intraocular pressure sensor.

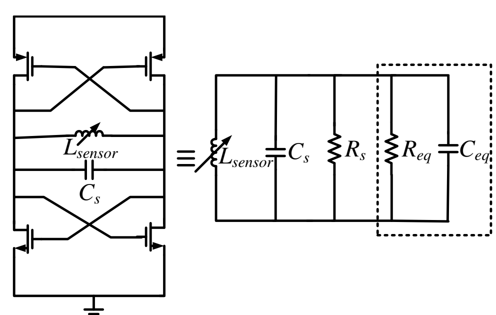


Figure 1. The proposed far-field wireless charging system for implanted devices.

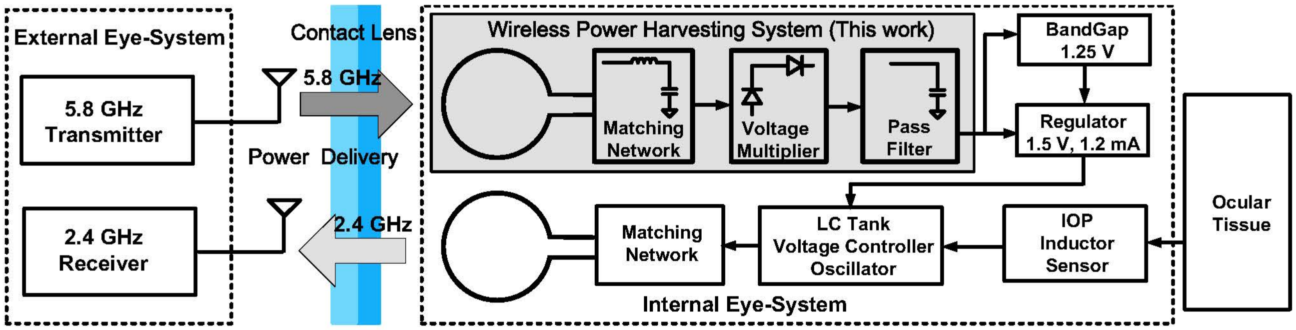


Figure 2. Proposed far-field Wireless Powering of the Active Intraocular Pressure Monitoring System

The inductor IOP sensor uses an electrical *LC* tank resonant circuit to detect the frequency variation, represented as

$$f_s = \frac{1}{2\pi}\sqrt{\frac{1}{L_{sensor}C_s} - \frac{R_s^2}{L_{sensor}^2}} \simeq \frac{1}{2\pi}\sqrt{\frac{1}{L_{sensor}C_s}}, \quad if \ R_s^2 << \frac{L_s}{C_s} \qquad (1)$$

where C_s is a capacitor fabricated on chip, and L_{sensor} is an inductor on contact lens using flip-chip bounding to connect IC pad. To have enough power for suitable operation of VCO with frequency tuning property, one of the main challenges on the contact lens of the IOP system is providing high output current for driving the active VCO to communicate with external reader. Thus, high-efficiency energy harvesting design in mW range is critical which will be discussed in detail in this paper.

B. *Loop Antenna Design*

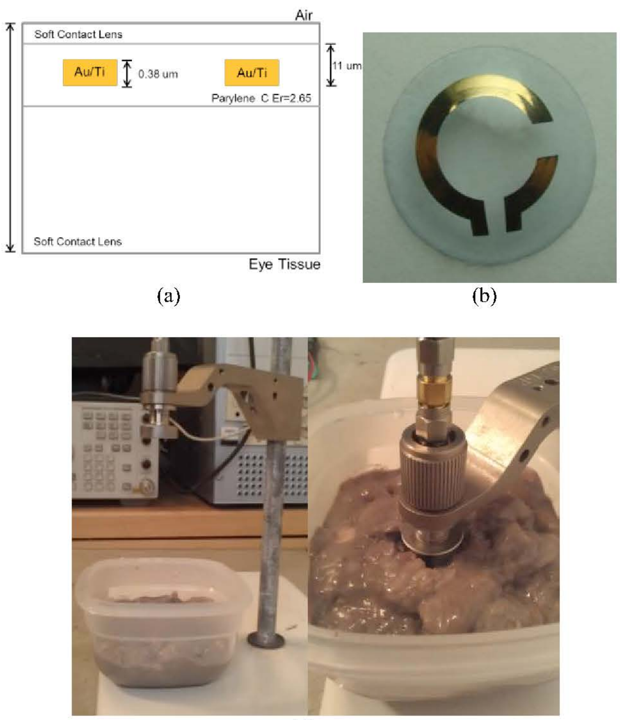


Figure 3. (a) Substrate model (b) Picture of a broadband loop antenna (c) Pig eye tissue and measurement setup.

Figure 3(a) illustrates the configuration of the proposed loop antenna at 5.8GHz. The proposed antenna is fabricated on a parylene C substrate, and comprises a horizontal wire loop with a gap. A gap on the loop antenna can lower the 1st resonance mode and increase the bandwidth without increasing antenna size. Figure 3(b) presents a photograph of a molded soft contact lens with the proposed antenna. The proposed antenna can be connected to the circuits by conductive epoxy glue [8]. Since the proposed antenna must be in contact with eye tissue during simulation and measurement, the mimicking of human eye tissue is also studied. Figure 3(c) shows the minced pig eye tissue was measured using an Agilent 85070E dielectric probe kit and an 8753E network analyzer.

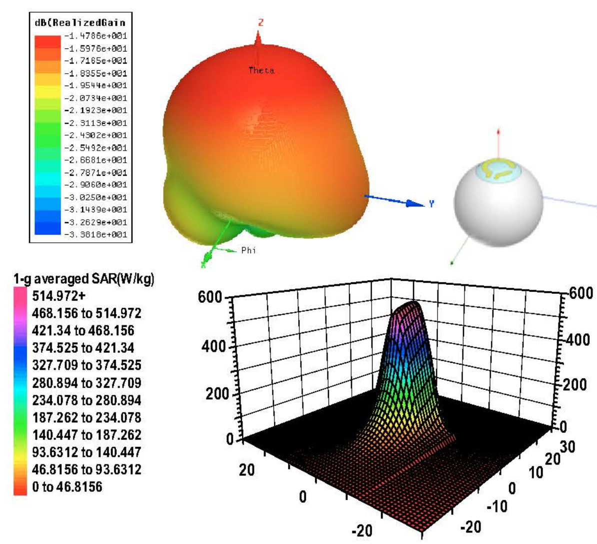
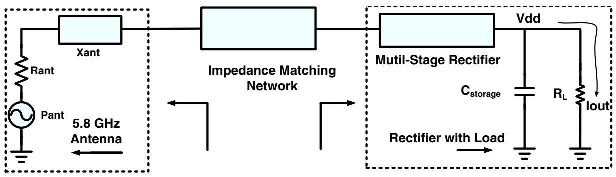


Figure 4. The 1-g average SAR distribution for proposed antenna with delivered power = 1 W.

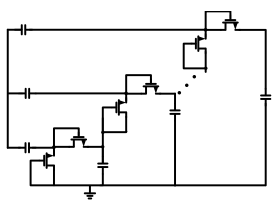
Figure 4 present the simulated three-dimensional far-field radiation pattern and 1-g average SAR distribution at 5.8 GHz for proposed antenna on eye tissue. When the proposed antennas are assumed to deliver 1 W, the maximum SAR values at 5.8 GHz is 514 W/kg. Therefore, the maximum allowable input power in-situ must be decreased to a suitable level (3.1 mW) to satisfy SAR regulations (1.6 W/kg) of ANSI/IEEE [9].

C. *5.8 GHz Impedance Matching Network and Rectifier Design*

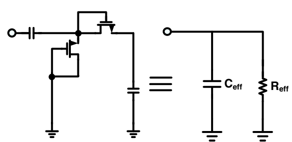
According to system specification, delivering a DC voltage of 1.5 V and a DC current more than 1.2 mA to load on the contact lens is necessary. Due to the size constraint on the cornea of eyeball, 5.8 GHz is thus chosen as power transmission band (antenna size is several cm), high efficiency power transmission in far field at this band is thus a challenge in this system. In order to keep the quite limited received RF power for IOP operation, sufficient conversion efficiency with enough output DC voltage is thus required.



(a)



(b)

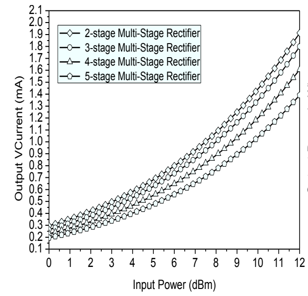


(c)

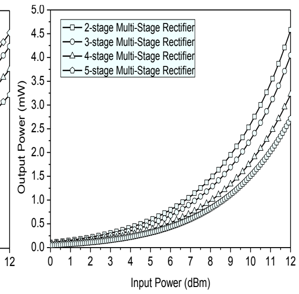
Figure 5. (a) Lump element Impedance Matching Circuit between the loop antenna and multi-stage voltage multiplier rectifier circuit. (b) the schematic of voltage multiplier RF rectifier (c) the equivalent circuit of multi-stages rectifier

According to the loop antenna design on the contact lens substrate, the impedance of the intraocular pressure monitoring system shall be transformed to 24.05-j62.77 by using lump integrated circuit components. Low loss and high-Q factor of passive components are the selection for increasing the bandwidth to tolerate any possible PVT (Process-Voltage-Temperature effect) variation or change on eye tissue liquid permittivity. The designed series inductor of the matching network circuit has a value of 2.2 nH with a quality factor of 10.47, and the parallel capacitor value of 349 fF with a quality factor of 25.2. Thus, the resonant frequency of the matching network circuit is well tuned to reduce the transformation loss between the loop antenna and power harvesting circuit at 5.8 GHz. The impedance matching circuit and rectifiers are both designed with ADS and HFSS. EM/Circuit co-simulation is done to avoid the parasitic effect from path and to improve the accuracy of high-frequency circuit design.

The main objective of the rectifier in IOP monitoring system on the contact lens is to provide dc output voltage of 1.5 V and output current of 1.2 mA for VCO operation. The native MOSFET device in TSMC-0.18 um process is thus chosen for inherently lower threshold voltage leading to higher conversion efficiency. By sweeping input RF power at perfect matching condition in Figure 5, varying stages of the rectifier can have different output current and power. Although the rectifier with more stages can achieve higher output voltage to the load, however, the output current and power are then decreased. Thus, to provide enough current (1.2mA) with enough high voltage to drive the active sensing circuitry of VCO, two-stage rectifier circuit is thus decided according to the results in Figure 6.



(a)



(b)

Figure 6. (a) Input power VS. Output voltage (b) Input power VS. Output power in various multi-stages rectifiers.

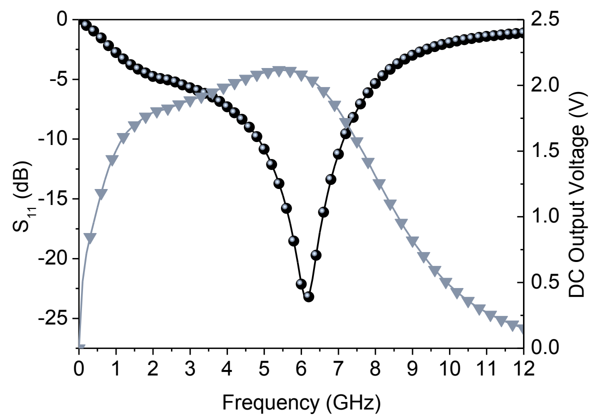


Figure 7. Simulation of the 5.8 GHz rectifier S_{11} & Output Voltage.

According to Figure 7, the S_{11} of 5.8 GHz rectifier circuit is measured at 10dBm input power level. In order to achieve the highest output current and voltage at 5.8GHz, the impedance is tuned to not perfectly match to 50ohm and the minimum return loss is nearby 6 GHz. The bandwidth of the circuit that is defined as the input return loss less than 10dB is around 2.2 GHz.

The power harvesting circuit is fabricated using a TSMC CMOS 0.18-um process with native device option. The fabricated circuit occupies an area of 450 um x 850 um. A photograph of the fabricated die is shown in Figure 8.

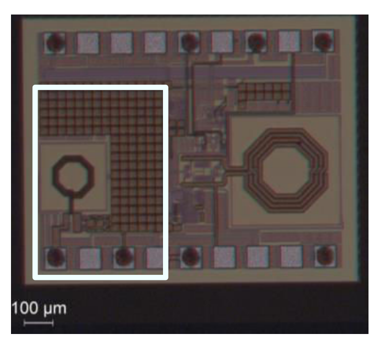


Figure 8. Micrograph of the fabricated intraocular pressure monitoring system IC

III. Discussion and Results

This study assembled a loop antenna with power harvesting IC on a parylene C substrate, shown in Figure 9.

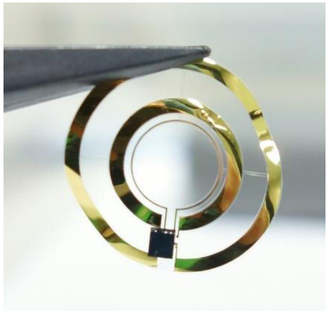


Figure 9. Photograph of the assembled contact lens.

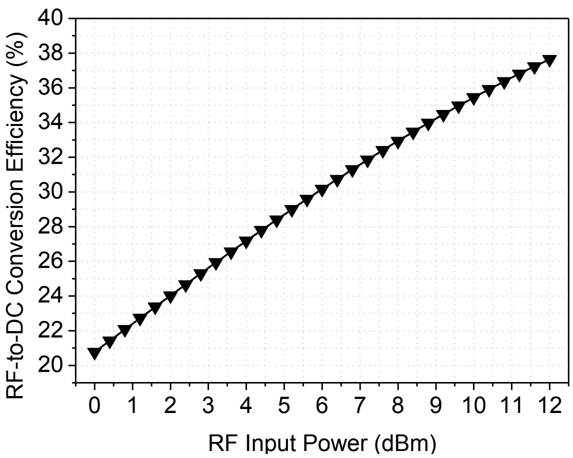


Figure 10. Simulation the efficiency of the power harvesting system.

Figure 10 shows the power conversion efficiency (PCE) obtained by varying input power simulation in the full IOP monitoring system. According to the simulation result, the 10 dBm input power can achieve PCE of 35.4 % and produce 1.5 V, 1.2 mA for supplying sufficient current for system. Due to the tradeoff between the output DC voltage and the RF-to-DC conversion efficiency, the 1.25 k-Ohm equivalent resistor load was selected as the load for conversion efficiency optimization design. Table I summarizes this work as compared with previously published works.

IV. Conclusion

This study describes the optimal design of a miniaturized antenna with power harvesting IC on soft contact lens. Also, the power harvesting IC is using the boosting technology to design the impedance matching network between the antenna and custom rectifier IC. The results also reveal that the proposed antenna also satisfies the 1-g average SAR regulation set by ANSI/IEEE in the MICS and ISM bands. The designed power harvesting system operates at 5.8 GHz having efficiency of 35% for 1.5 V/1.2 mA output power level to successful activating 2.4 GHz VCO.

Acknowledgment

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TABLE I. PERFORMANCE SUMMARY

	[3]	[5]	[4]	[10]	This work
Operator Frequency (GHz)	0.8-2	1.8	2.4	0.9	**5.8**
Antenna Gain (dBi)	-9	N/A	-6	N/A	**-17.5**
Requirement System Power (W)	129 u	3 u	1.5 m	18.4 u	**2.2 m**
Efficiency (%)	10	N/A	11.3	36	**35.1**
Load (ohm)	13.9 K	0.6 M	1k	N/A	**1.25**
External components	Zero	Zero	Cap Array	Matching network on PCB bord	**Zero**
est tissue	Rabbit eye	Air	Human eye	Muscle	**Pig eye**