Antenna and Coil Design for Wireless Signal Detection and Charging of Embedded Power Active Contact Lens

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Abstract— **This paper presents a screen printed 2.4GHz antenna and induction charging coil for an active contact lens with a single large pixel user display and on-board 3.8V 5µAh rechargeable battery. The antenna traces are printed using silver conductive paste on a 25µm polyethylene terephthalate (PET) substrate. The incoming signal from the antenna feeds into an IC that amplifies and rectifies the signal. The coil provides wireless energy transfer to inductively charge a thin film battery [1] located on the contact lens. The printed antenna achieved a S11 of -4dB at 2.4GHz and a gain of -13 dB.**

I. INTRODUCTION

Technical advances in clear circuitry fabrication allows for an improved way of life by providing a real-time heads-up-display (HUD) for use on contact lenses. Integrating an easily viewable display with an external wireless biomedical sensing system allows for an immediate notification during a potentially health threatening event. In many situations, factors that attribute to those events are not immediately detectable by our senses (e.g. radiation and odorless fumes). Thus the individual must rely on external equipment as a safety measure. Such equipment should be unobtrusive such that it does not hinder one's ability to perform his or her task while also readily viewable to the user. Our system utilizes an external UV sensor that will transmit a wireless signal to the contact lens when it detects harmful intensities. On the contact lens a single pixel electrochromic display notifies the wearer once the UV threshold has been reached. Though our system is centered on a UV sensor, input from any sensor can be displayed as long as it provides a signal over the required threshold and is at 2.4GHz.

Various papers have investigated wireless energy as a means of power delivery to a contact lens. Pandey *et al.* [2] fabricated a contact lens with a single LED display powered by 2.4GHz. Cheng *et al.* [3] presented a 5.8GHz rectenna design focusing on increasing efficiency by using high Q passive components to impedance match the antenna to the rectifier. The drawback of RF scavenging is that the levels of energy present in the environment are small. In addition, the free space path loss causes the end-to-end efficiency of an RF scavenging system to suffer. The advancements over these systems that our system provides are: 1) the on-lens battery allows for operation even when an external supply is not being applied and 2) the coupled antenna and battery charger provides for more efficient power management.

This project primarily focuses on providing wireless signal detection using a loop antenna tuned to receive signals in the 2.4GHz ISM band. The antenna is coupled with an inductive coil and is used to inductively charge a thin film battery also located on the contact lens. An external UV sensor transmits a signal to the contact lens when the amount of UV radiation detected surpasses a certain threshold. The incoming signal and battery power management will be handled by a custom IC fabricated using the ON Semiconductor CMOS C5 0.6um process.

II. SYSTEM ARCHITECTURE

The main function of our contact lens is to warn the wearer when the work environment has been compromised as detected by an external sensor – we implemented an external UV sensor as a test application. To support its functionality, the contact lens must be able to: receive incoming signals from the sensor, manage the battery's power, and activate a display as a warning stimulus.

Reception of the wireless signal and inductive charging is handled by the printed antenna.

The purpose of the antenna is to receive the wireless signal transmitted by an external UV sensor and inductively charge the onsite battery. A custom chip manages battery recharge and turns on the display when a 2.4GHz signal is received by the antenna. The contact lens contains an electrochromic display than will turn from clear to a transparent blue to notify the wearer. Fig. 1 shows the overall system of the active contact lens.

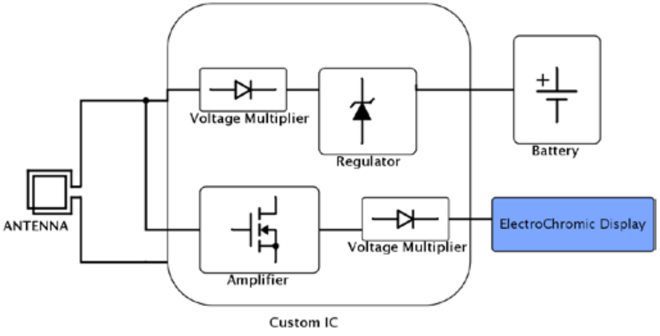

Figure 1. Active Contact Lens System Diagram

This work focuses primarily on the design of the antenna. There will be two modes of operation for the antenna; it will act as a receive antenna for a 2.4GHz wireless signal and perform as the tag coil for a 13.56MHz charging voltage.

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III. ANTENNA DESIGN

The antenna and battery charging coil were combined into a single device such that the coil will be inductive at our charging frequency of 13.54MHz and will be resonant at 2.4GHz. In addition, we limited the size of our antenna to a maximum diameter of 13mm in order to stay within the size of a contact lens and a minimum inner diameter of 6mm to avoid overlapping the pupil. The magnetic field generated by a circular loop is given by [4]

$$B_z = \frac{\mu_o I N a^2}{2(a^2 + r^2)^{3/2}} \tag{1}$$

where μ_0 is the permeability of free space, I is the current, N is the number of turns, a is the radius of the loop, and r is the distance from the center of the loop. Eq. 1 states that the magnetic field generated by the coil is increased by either having more turns or increasing the loop area. We must also consider the efficiency of the antenna when receiving a 2.4GHz signal which is determined by its radiation resistance and Ohmic resistance [5]. The radiation resistance Rr of an electrically small antenna is

$$R_r = 20(\beta^2 NS)^2 \approx 31{,}200\left(\frac{NS}{\lambda^2}\right)^2 \Omega \tag{2}$$

where N is the number of turns, S is the loop area, and λ is the wavelength. The Ohmic resistance of a loop constructed with wire is given by

$$R_w = N^2 \frac{2\pi b}{wt} R_s \tag{3}$$

where b is the mean loop radius, w is the trace width, and t is the ink film thickness. R_s is the surface resistance given by

$$R_s = \sqrt{\frac{\omega\mu}{2\sigma}} \tag{4}$$

where σ is the conductivity of the silver conductive paste. The antenna efficiency is given by

$$e_r = \frac{R_r}{R_A} \tag{5}$$

where R_A is the sum of R_w and R_r. Having a large radiation resistance will improve the efficiency of our antenna. Therefore, increasing inductance by having a larger inner diameter is a better choice than having more turns because a larger diameter increase the area of the loop and consequently its radiation resistance.

Our main focus was to optimize the dimensions of the coil such that it has a purely real impedance of 50Ω (input impedance of the chip) as we would like to avoid using lumped passive components for impedance matching. We expect a very low efficiency for our antenna because of its inherent design. First, the loop encompasses a small area which results in a low radiation resistance. Second, the silver conductive paste used for the traces has a high resistivity of $2.33\text{x}10^6$ S/m resulting in high ohmic losses.

Antenna parameters such as trace width and number of turns were determined using simulations done on Agilent's Advance Design System (ADS). The table below shows the antenna design optimized for size, efficiency, and S11 reflection coefficient.

TABLE I. PRINTED ANTENNA PARAMETERS

Outer Diameter (cm)	1.3
Inner Diameter (cm)	8
Trace width (µm)	250
Trace thickness (µm)	250
Number of turns	4

The antenna was created using the screen printing process. The substrate is a 25µm thick PET film as PET is a standard in screen printing. However, PET is an irritant and a more biocompatible material such as polydimethylsiloxane (PDMS) would be better suited for use in the eye. In the future, we plan on adapting the screen printing process and ink formulation to support printing on a PDMS substrate. The ink used to print the trace is 5052 Silver Conductive Paste from DuPont. Fig. 2(a) shows the simulated substrate model.

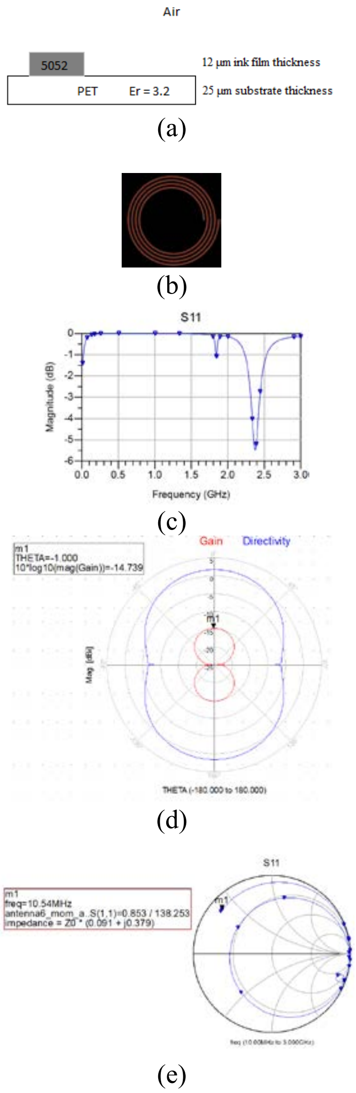


Figure 2. (a) Substrate model (b) Simulated Antenna (c) Simulated S11 matched at 50Ω (d) Simulated Antenna Gain (e) Antenna Inductance

Fig. 2 (b) shows the antenna layout in ADS. Fig. 2(c) shows the simulated reflection coefficient at 2.375GHz. Fig. 2(d) shows the simulated gain of the antenna. Fig. 2(e) shows a coil inductance of 286.6nH.

Simulations show identical results with a PDMS substrate even though PDMS has a lower dielectric constant of 2.5. The reason is that the substrate is not thick enough to drastically affect the operation of the antenna. However, simulations have to be performed when the antenna is on the eye. Fig. 3 shows the simulation model with the permittivity of the cornea [6] and anterior chamber [7].

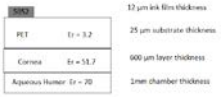
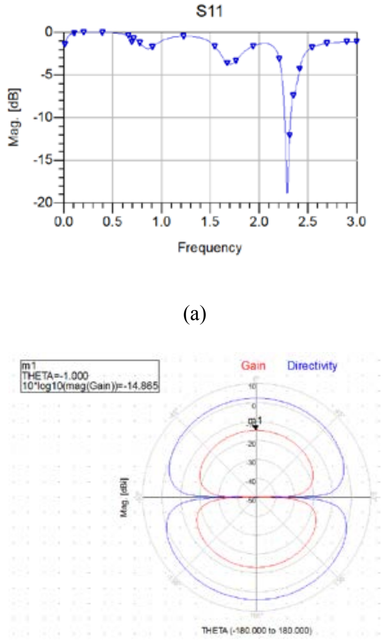


Figure 3. Substrate Model with Eye Tissue Parameters



(a)

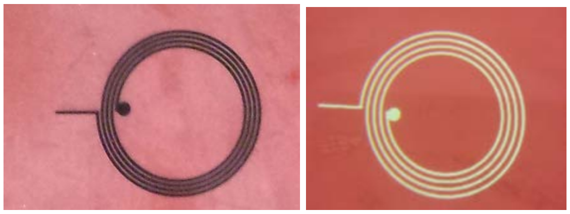
(b)

Figure 4. a) S_{11} of Antenna with Eye Tissue b) Simulated Antenna Gain

Fig. 4(a) shows a shift in the antenna's resonant frequency to 2.3GHz and having a much lower reflection coefficient. Fig. 4(b) shows a 0.1dB drop in gain when tissue is introduced the substrate.

A. Screen printing

The screen printing method allows us to rapidly prototype, test, and make necessary revisions all while supporting the use of transparent and flexible substrates. It is also an additive process eliminating the need for harmful etchants during fabrication. First, we create a photomask of our design using the Cyrel Digital Imager.



(a) (b)

Figure 5. (a) Antenna Mask (b) Exposed Screen

Fig. 5(a) shows the positive mask of our antenna. The design on the mask is UV-exposed onto a capillary emulsion which is a photosensitive polymer. The exposure time was 60 seconds with an intensity of 120LTU. The emulsion that has been exposed to UV will harden while the unexposed areas can be washed away using water to create a negative on the screen as show in Fig. 5(b). The red area is capillary emulsion blocks ink from flowing through while the yellow trace is the open mesh. A second exposure is performed without a mask to increase the durability of the emulsion to withstand more printing and cleaning cycles. These exposure settings were determined through trial and error. Low exposure intensities will not cause the emulsion to harden all the way through which causes the emulsion between the traces to wash away. Exposures that are too intense will undercut the photomask exposing portions of the traces resulting in thinner traces. We used a 405 size mesh in order to flow ink into openings that are hundreds of microns wide. The mesh size refers to the number of fibers in a linear inch, 405 meaning 405 fibers per linear inch which means each fiber has a diameter of 63.7μm. Rule of thumb states that the trace width should be at least three times greater than the mesh diameter [8]. Otherwise, the fibers themselves will impede the ink from flowing onto the substrate. The print the antenna, we used a ATMA AT-45FA Pneumatic Screen Printer.

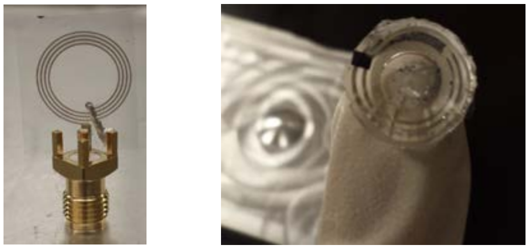


Figure 6. Printed Antenna and Assembled Lens with Newest Antenna

Fig. 6 shows the printed antenna. To access the inner feed point, we bridged a trace on over the coil with tape and silver epoxy.

IV. RESULTS

Fig. 7 shows the measured reflection coefficient of the printed antenna. The printed antenna was resonant just below 2.38GHz. The reflection coefficient is higher than the simulated results by 1 dB.

Figure 7. Printed Antenna S11 Measurement

We tested the gain of the antenna by transmitting a 2.4GHz 10dBm signal using a 5dB gain antenna at a distance of 42 cm. Fig. 6 shows a detected signal power of -33dBm or 0.5µW at the input of the spectrum analyzer.

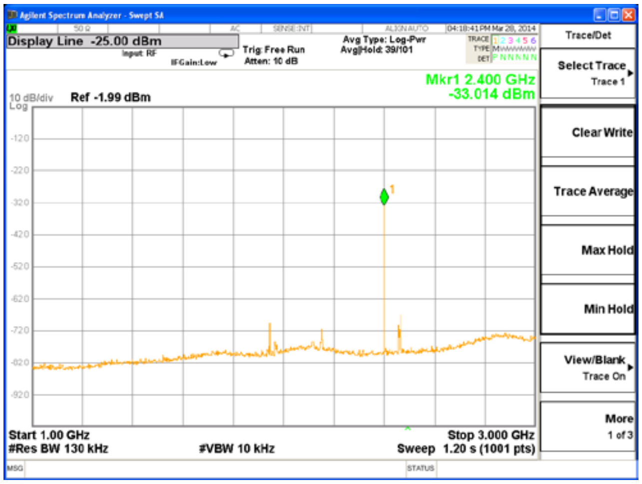


Figure 8. Signal Received Power by the Antenna

Friis transmission equation tells us that the power received is equal to the sum (in dB) of antenna gains and signal power subtracted from the path loss.

$$P_r(\mathrm{dBm}) = P_t(\mathrm{dBm}) + G_t(\mathrm{dB}) + G_r(\mathrm{dB}) - 20\log\ R(\mathrm{km}) - 20\log\ f(\mathrm{MHz}) - 32.44 \tag{6}$$

A distance of 42cm attenuates the signal by 32.7dB which means the signal right at the antenna has a power level of -17.7dBm or 17µW. |S11| of -4dB means that 60.2% of the power is accepted by the antenna resulting in 10.2µW of accepted power. Therefore, the efficiency of the antenna can be calculated to be 4.9% resulting in an antenna gain of -13dB which is 2dB higher than simulation. Differences in gain and |S11| may be because the ink film thickness of the actual antenna may be thicker than 12µm because the capillary emulsion applied on the screen is 30µm thick. Since the emulsion sits directly on top of the mesh, a thicker emulsion allows for greater ink concentrations to flow through the open areas of the mesh resulting in thicker ink film thickness and lower resistances. This lowered resistive loss also affects the overall impedance of the antenna which may explain the higher reflection coefficient seen by the VNA.

V. CONCLUSION

A dual purpose antenna was developed as a means of both wireless communication and inductive charging for an active contact lens. The screen printing fabrication process used to create the antenna allows for rapid iteration, as designs can easily be modified, printed, and tested. Results of the printed antenna on PET showed an $|S_{11}|$ of -4dB and an overall efficiency of 4.9%. While PET is an established and common substrate for screen printing, PDMS would be a more suitable substrate for a contact lens due to its biocompatibility and oxygen permeability. Therefore, future work on this project will involve adapting the printing process, such as ink formulation and surface treatment for the substrate, to support the PDMS substrate.

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