

ASYMMETRIC WIRELESS POWER TRANSFER WITH A FLEXIBLE CONTACT LENS INDUCTOR

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ABSTRACT

This paper reports the microfabrication of a Galinstan-based flexible coil on a contact lens and its preliminary use for wireless power transfer onto a smart contact lens. The Galinstan-based coil provides accommodation against physical deformation of a contact lens by maintaining electrical conductivity under strains due to its semi-fluidic nature. The fabricated Galinstan-coils successfully demonstrated post-deformation tolerance up to 166.67% strain. The fabricated contact lens prototype with a Galinstan-coil showed the maximum wireless power reception of 32.4 μW with a power efficiency of 0.75% from an external coil located 5 mm away within a frame of eyeglasses.

KEYWORDS

Wireless power transfer, flexible electronics, smart contact lens, Galinstan, polyethylene terephthalate.

INTRODUCTION

Smart contact lenses have been drawing recent interests because they can open up new potential pathways for various applications from the detection of biomarkers [1] to vision correction [2]. For those applications, they are expected to consume power ranging from a few micro-watts [3] to several milliwatts [4] to continuously monitor the status with sensors, operate actuators and wirelessly transfer data and signals. Meeting those power requirements remains as a grand challenge to enable practical contact lenses under strict constraints in size, power, and safety concerns.

To meet the power requirement, mainly three different approaches were pursued, including the use of a battery [5], an energy harvester [6] and wireless power transfer [7]. Among those approaches, the use of wireless power transfer seemingly remains the most promising to power contact lenses without limited lifetime (a battery) and limited power amounts in a tiny (1's cm^3) volume (an energy harvester). For example, an energy harvester, which utilized eyelid movement to induce magnetic power generation, produced a limited output power of 16.67 μW on a contact lens [6].

Wireless power transfer has previously been utilized to power contact lenses mainly through inductive coupling [8]. However, in practice, it showed some failures because the metalized inductor on a contact lens tended to show cracks and lose connectivity once the lens, consisting of soft materials, went through some deformation. This subsequently led to a significant drop in transferred voltages and thus the inductive coupling efficiency. Thus, it remains a critical challenge to improve the metal line stability considering the flexibility of a lens.

To achieve the conductivity under deformation, a metal line can be coated with a liquid metal, Galinstan, that provides a parallel conductive path and fill in cracks, if any.

This paper reports the fabrication, operation, and initial experimental wireless power transfer results of a Galinstan based contact lens inductor.

OPERATION PRINCIPLE

The Galinstan-based inductor maintains the electrical quality of the inductor with its liquid nature and minimizes the chance of failure. For an inductively coupled 2-coil wireless power transfer system, each of the primary and the secondary coils shows inductances and series DC resistances (Fig.1-(a)) that determine its quality factor by the following relationship-

$$Q_P = \frac{\omega_P L_P}{R_P} \quad (1)$$

$$Q_S = \frac{\omega_S L_S}{R_S} \quad (2)$$

where Q is the quality factor, ω is the operating frequency, L and R are the inductance and the series DC resistance of a coil respectively. Subscripts 'P' and 'S' refer to the primary and the secondary coils respectively. When a soft contact lens only with a solid-metal inductor is deformed, the metal line produces cracks leading to a sharp increase in resistance R_S and thus very low Q_S and eventually failing to wireless power transfer (Fig.1-(c)). However, when a contact lens with both solid-metal inductor ($4.1 \times 10^7 \text{ S/m}$ conductivity at 20°C for gold) and liquid-metal coating ($3.46 \times 10^6 \text{ S/m}$ conductivity at 20°C for Galinstan) are deformed, the liquid-metal coating connects the cracked metal line and sustains the conductivity of a coil.

FABRICATION PROCESS

Figure 2 shows the steps followed to fabricate the contact lens inductor. First, as a substrate, a thin polyethylene terephthalate (PET) sheet of 188- μm thickness was chosen due to flexibility and biocompatibility [9] (Fig.2-1). After being cleaned with acetone, isopropyl alcohol (IPA) and deionized (DI) water, it was cut into a desired coil shape of a 10-mm outer diameter, a 6-mm inner diameter and a 500- μm width by utilizing a CO_2 laser (VLS3.75, Universal Laser System)(Fig.2-2 and 3). The patterned PET substrate was thermoformed into the contact lens curvature by heat-pressing them at 150°C in a custom-made contact lens mold out of aluminum (Fig.2-4). The curved coil pattern was again cleaned in oxygen plasma (Technics PE II-A RIE plasma etching system) at 200 W for 2 minutes. After the plasma cleaning, the curved pattern was deposited with metal layers consisting of 10-nm thick chromium and 100-nm thick gold by a sputter (Denton 635 sputter system)

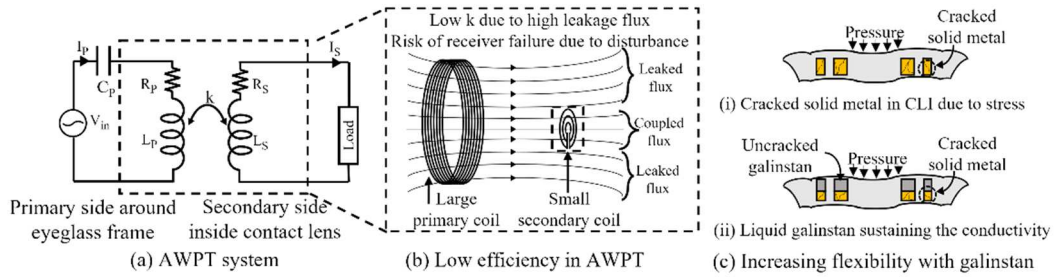


Figure 1: Problem in asymmetric wireless power transfer system and use of Galinstan to increase the flexibility

(Fig.2-5). Two ends of the metal-deposited pattern were connected to thin test wires using a conductive epoxy (MG Chemicals) (Fig.2-6). Next, the metal-deposited pattern was coated with Galinstan (Ga-68.5%, In-21.5%, Sn-10%, melting point -19°C) that was treated with an electrolytic NaCl solution to remove the oxide skin by the method discussed in [10]. Subsequently, the metal surface was coated with oxide-removed Galinstan by utilizing a 'selective wetting' method discussed in [11] (Fig.2-7). Separately, two polydimethylsiloxane (PDMS, Sylgard-184, Dow Corning) membranes were prepared by mixing PDMS with a curing agent in a 10:1 ratio, degassing it in a vacuum-desiccator and pouring it over the contact lens mold. A rapid curing was followed at 110°C for 10 minutes. Finally, the Galinstan-coated inductor substrate

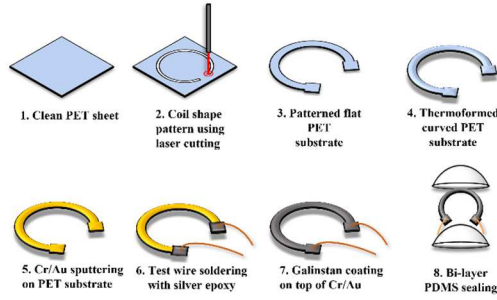


Figure 2: Fabrication process flow for the flexible contact lens inductor

was placed between the two PDMS lens membranes and pressed into a double-layered contact lens prototype (Fig.2-8).

The completed device is shown on Figure 3. The total diameter of the fabricated contact lens prototype was 13.42 mm, which is comparable to an average iris diameter of 13 mm. The height of the contact lens was 2.4 mm. An acrylic ring of 1.6 mm thickness was attached at the bottom of the contact lens to provide a rigid base for the experimental tests. To make a comparison, a conventional contact lens with a solid-metal inductor was also fabricated in the same method. The only difference in the fabrication was that they did not undergo the Galinstan coating in step 7 in Figure 2.

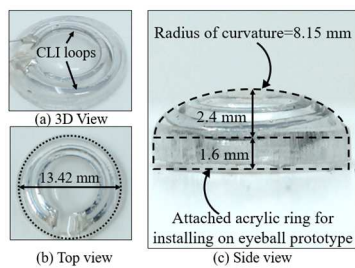


Figure 3: Fabricated contact lens prototype

TESTING METHODOLOGY

The fabricated Galinstan-coated contact lens was tested to evaluate the stability under deformation, inductive coupling efficiency with an external source coil and the resulting output power. The inductances of the coils for the experiments were measured using a Keysight E5061B impedance analyzer.

Stability of Conductance Under Deformation

To measure the stability of the fabricated Galinstan-coated contact lens inductor under deformation, the change in DC resistance was measured while the contact lens was gradually deformed by utilizing a vertical actuator. The contact lens prototype was placed under a drill bit that advanced downward in a vertical direction at a resolution of 0.5-mm height change. The deformation was performed by lowering the drill bit from 0 to 4 mm at every 0.5 mm difference which was controlled by utilizing the height adjusting knob. The deformation was measured by utilizing a camera from the side. During the deformation, the resistance of the Galinstan-coated contact lens inductor was monitored by an Agilent 34401A multimeter.

Coupling Coefficient and Range Measurement

The coupling coefficient of the Galinstan coated contact lens inductor was measured by placing the fabricated contact lens face-to-face to an eyeglasses-coil without any resonance tuning capacitor (Fig.4-(a)). The eyeglasses coil was manufactured by turning a low skin-effect Litz-wire [12] 24 times around an eyeglasses frame. The external coil was connected to a Keysight 33600A waveform generator that produced a sinusoidal input signal with a peak voltage of 10 volts with a 50-Ω input impedance. To sense the input current (I_{in}) through the external coil, a 1-Ω resistor was connected in series with the primary coil, while its voltage was being monitored by a high-precision oscilloscope (MSO-S 404a, Agilent Technologies). On the other hand, the contact lens inductor coil was connected to another channel of the oscilloscope while the open-circuit voltage (V_{oc}) across the contact lens inductor coil was measured. Once the input current (I_{in}) and the open-circuit voltage (V_{oc}) were measured, then the coupling coefficient k was calculated using the equations (3) and (4).

$$M = \frac{V_{oc}}{|\omega I_{in}|} \quad (3)$$

$$k = \frac{M}{\sqrt{L_P L_S}} \quad (4)$$

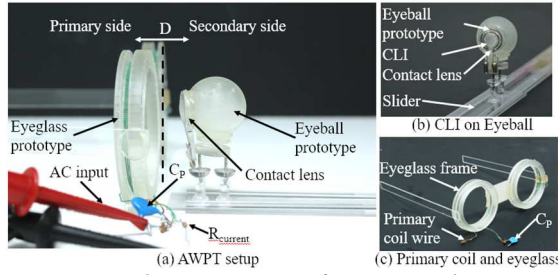


Figure 4: Wireless power transfer setup and components (a) primary and secondary side (b) eyeball prototype (c) eyeglass prototype

where M is the mutual inductance, L_P and L_S are the self-inductances of the primary eyeglass-coil and the secondary contact lens inductor coil, respectively, V_{OC} is the open circuited voltage across the contact lens inductor, I_{in} is the input current through the primary coil, and ω is the operating frequency. To measure the coupling coefficients over a distance, the primary coil was kept steady at a certain position, and the contact lens inductor was gradually drawn away from the primary coil from 5 to 60 mm.

Output Power Measurement

The transferred power amounts from an external coil to the contact lens coil was calculated by measuring the voltage across an over-dampening 1-k Ω resistor that was attached between the ends of the contact lens inductor coil. Note that the contact lens was attached onto a faux eyeball manufactured out of a polymeric plastic mimicking a close-to-real situation (Fig.4-(b)). Although it is conventional to match impedances between input and output, the 1 k Ω resistance was chosen to simulate non-ideal conditions. To boost the source voltage, the primary coil was connected to a 120-pF capacitor to tune a resonant frequency to 1.8 MHz (Fig. 4-(c)).

To calculate the output power efficiency, the measured voltage across the 1-k Ω resistor was plugged into the equation (5).

$$\eta = \frac{V_{out}^2}{V_{in} I_{in} R_L} \quad (5)$$

where η is the efficiency of received power at the load resistor, V_{out} is the peak output voltage across the load resistor, V_{in} and I_{in} are peak input voltage and current, and R_L is a load resistance (1 k Ω in this case). To also predict the possible output power for the impedance-matched 50- Ω impedance, the equation (5) was used with same V_{out} values and 50 Ω value for R_L .

RESULTS

The inductance and the resistance of the fabricated contact lens inductor were measured as 2 μ H and 3.56 Ω , respectively. The outside and the inside diameters of the 24-turn primary coil was 56 mm and 51 mm, respectively, with the measured inductance of 133 μ H and the measured resistance of 2.9 Ω .

Stability of Conductance Under Deformation

The Galinstan-based contact lens inductor of 2.4 mm height turned out to be stable, maintaining its resistance values from 3.56 Ω to 3.136 Ω by -11.91% change under

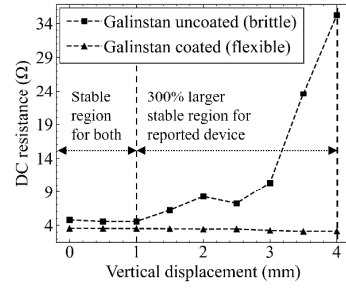


Figure 5: Effect of pressure on the contact lens inductor

an experimental deformation range from 0 mm (original shape at rest, 0% strain) to 4 mm vertically towards the base (166.67% strain) as shown in Fig.5. This is a significant improvement by nearly 4 times in terms of strain with a 300% larger window of stability range in comparison to the conventional Galinstan-less inductor, which remains stable only up to 41.67% strain at 1 mm deformation. The negative sign of the percent change of resistance indicates the decrease of resistance with increasing deformation, i.e., the applied pressure. These results confirmed our hypothesis that the increase in resistance due to the micro-cracks in the solid metal film can be minimized with the help of liquid metal.

Coupling Coefficient and Range

The measurement shows (1) that the coupling coefficient decreased sharply from 0.120% to 0.045% nonlinearly with increasing distances from 5 mm to 60 mm; (2) that the maximum coefficient was 0.12% at 5 mm distance between the eyeglasses and the contact lens; and (3) that at the 20-mm distance, which is considered as the nominal distance from the human eye to the eyeglasses and our interests, the coupling coefficient was measured as

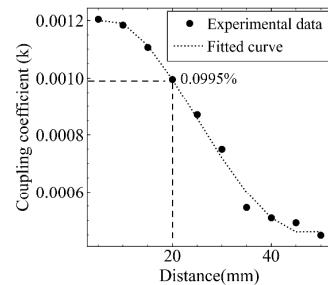


Figure 6: Coupling coefficient for increasing distance

0.0995%, which is reasonable considering the asymmetry between the two coils, as shown in Fig.6. Subsequently a fitted curve was produced, matching well to the experimental data, with the polynomial equation (6).

$$k = 22.1525D^3 - 1.7436D^2 + 0.018D + 0.001156 \quad (6)$$

where D is the distance between the primary and the secondary coils in meters.

Output Power for the Contact Lens Inductor

The transferred output power was measured as 32.4 μ W with non-matching impedance, as shown in Fig.7. The result, however, implies that the final output power transfer can be maximized to 102 μ W by nearly 20 times simply by matching the impedance in future testing. Additionally, the measurement results showed that the output rms voltages

were measured as 179.93 mV, as shown in Fig.7. The left vertical axis in Fig.7 shows the transferred output power, and the right vertical axis shows the output rms voltage across the 1-k Ω load-resistor. For the closest proximity

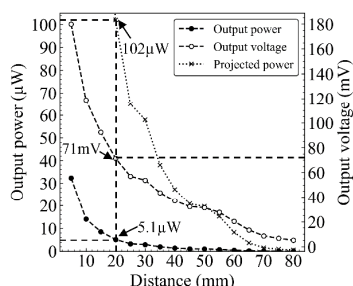


Figure 7: Output power, voltage, and projected power in the contact lens inductor for increasing distance

between the coils, the output voltage was measured as 179.93 mV, which resulted in the transferred power output of 32.4 μ W with a power-transfer efficiency of 0.75%. At the typical distance of 20 mm between the pupil and the eyeglasses, the output power was measured as 5.1 μ W. The maximum power output, with the potential use of the matching impedance (50- Ω impedance), was estimated as 102 μ W for 5 mm distance and 71 μ W for 20 mm distance, as shown from the dotted line in Fig.7.

These results indicated that the asymmetric wireless power transfer system, despite the issues of low coupling coefficients, could deliver >1 mW level of output power through wireless links if the secondary inductance is increased with higher number of turns with narrower width.

CONCLUSION

This paper reported the development of a contact lens inductor made in combination of solid gold thin film and liquid Galinstan. The use of Galinstan on top of a metal lines enabled the stability of the system under deformation of 4 mm. Despite the asymmetry in the dimensions between the primary and the secondary coils, the initial results showed successful wireless power transfer of 32.4 μ W. The resultant flexibility and the feasibility of wireless power transfer shows some promises toward flexible wearable microsystems.

ACKNOWLEDGEMENTS

This project was generously supported by NSF CPS grant 10053422. Microfabrication was carried out in the state-of-the-art Utah Nanofabrication facility in the University of Utah.

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