MICROFABRICATED ELECTRODYNAMIC WIRELESS POWER RECEIVER FOR BIO-IMPLANTS AND WEARABLES

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ABSTRACT

This paper reports the design, modeling, fabrication, and characterization of a microfabricated receiver as part of an electrodynamic wireless power transmission (EWPT) system. This system differs from inductively coupled wireless power transmission (WPT) by employing low-frequency (<1 kHz) magnetic fields to deliver power over 10's of cm to multiple compact receivers in a cluttered environment. Herein we report the first-ever, chip-scale microfabricated EWPT receiver, which can output 2.5 mW of power under a 744 Hz, $550 \mu\text{T}_{\text{pk}}$ ac magnetic field (equivalent to 20 cm transmission distance). Compared to a previously reported prototype, the microfabricated device is 14.5x smaller (0.55 cm^3 vs. 8 cm^3), and offers a 2.1x increase in power density (4.6 mW/cm^3 vs. 2.2 mW/cm^3).

INTRODUCTION

WPT Challenges

The holy grail objective for wireless power transmission (WPT) is to achieve high efficiency, high power transmission to small power receivers at long distances (Fig. 1). Inductive coupling is well suited for efficient close-range transmission [1], but the efficiency decays quickly with the distance. Magnetic resonant WPT tries to increase distance while maintaining efficiency [2,3], but the system architecture is more complex. Additionally, there are both practical and safety concerns about the RF fields that exist between the transmitter and receiver. Specifically, any object that sits between the transmitter and receiver is subjected to relatively strong RF magnetic fields with frequencies typically ranging from 100's of kHz to 10 MHz. At these frequencies, unwanted eddy currents are generated in electrically conductive objects. At minimum, these eddy currents can attenuate or alter the fields used for power transmission. But worse, these eddy currents can cause undesirable or even unsafe heating in the intervening objects.

Therefore, there is a technology gap for mid-range (~ 10 – 100 cm) transmission to compact receivers, as is needed for Internet of Things (IoT) devices, wearables or bio-implants. Electrodynamic WPT (EWPT) has been proposed as a possible solution [4-7], wherein the magnetic fields from a transmitter (generally much lower frequencies than inductive or magnetic resonance methods) are used to excite the mechanical motion of a permanent magnet in the receiver. This mechanical motion is converted into electricity by one or more electromechanical transduction schemes.

Figure 1: Four competing design objectives for wireless power transmission (WPT).

EWPT Principle

The EWPT method presented here utilizes a receiver with a mechanically resonating permanent magnet embedded in a receiver coil, as shown in Fig. 2. The ac magnetic field generated by the transmitter couples via a torque with the receiver magnet, which torsionally oscillates. While oscillating around its axis, the magnet changes the magnetic flux in the receiver coil and generates an ac voltage by induction. The receiver coil can be connected to suitable power electronics to obtain a regulated dc voltage to charge a battery or directly supply a system.

Figure 2: System architecture of electrodynamic wireless power transfer (EWPT). The mechanically resonating magnet is sensitive to time-varying magnetic field from the transmitter and generates power in the receiver coil in which it is embedded.

The uniqueness of the EWPT method is that it operates at low frequency (10-1000 Hz) while maintaining a valuable power density. Considering the voltage V induced on the receiver coil, which is proportional to the time-rate-change of the flux $d\Phi/dt$, the reduction in voltage due to the lower operational frequency is counterbalanced by the much larger magnetic flux (and consequently flux change) produced by the mechanically moving permanent magnet. Furthermore, the lower frequency EWPT approach can safely operate with higher magnetic field strengths, since the admissible magnetic field strength for safe exposure of human is higher at lower frequency [8-9]. Most importantly, the low frequency of operation mitigates the field attenuation and parasitic heating effects that occur with RF fields. This makes EWPT suitable for transmitting power to multiple receivers in an environment crowded and cluttered with metallic objects such as a home, office, or automobile environment, or for powering safely deep biomedical-implants or wearables through human body.

Our research group has previously designed, built, and characterize various macroscale receivers to demonstrate the EWPT method [4-8]. In this paper, we present a significantly miniaturized receiver that utilizes micromachined silicon suspensions. Compared to previously utilized metal and polymer suspensions, the lower loss of the silicon suspension has the potential to increase the resonant amplitude of the receiver making it more responsive to lower magnetic fields, and therefore extending the power transmission distance.

Figure 3: Equivalent electrical circuit of an EWPT system and energy domain flow.

DESIGN OF MECHANICAL SUSPENSION

The EWPT system can be represented by an equivalent electrical circuit shown in Fig. 3. The energy from the source is flowing from the electrical domain through the transmitter coil, to the mechanical domain via the spring-mass-damper, and then back to the electrical domain through the receiver coil and the load. The two transductions between the electrical and the mechanical domains are achieved through electrodynamic coupling.

The chosen architecture, depicted on Fig. 4, integrates two suspensions attached to a frame on which two receiver coils are attached (not shown), and supporting a central platform on which two magnets are attached. Special care has been taken on the optimization of the mechanical suspensions. They are designed to be compact, allow only one degree of freedom around an axis of rotation, while setting the resonant frequency of the resonator through their rotational stiffness and allowing a large rotation of the magnet ($\pm 20^\circ$). The length of the suspension should be the smallest possible to minimize the receiver volume (i.e. higher power density), and to minimize the wiring far from the magnets where the fields are weaker (i.e. lower coil resistance leads to higher power).

Figure 4: Architecture of the micro-receiver, including the mechanical suspensions to be optimized.

The following prerequisites are chosen and used as inputs of the optimization: the size of the magnet (depending on a limited set of commercially available magnets), the resonant frequency, the maximal rotation amplitude of the magnet, and the wafer thickness and mechanical properties (Young's modulus and Poisson's ratio). The optimization should consider several other constraints and design objectives: the mechanical suspensions should be compliant in the desired mode (here one rotation), while rejecting other vibration modes around the frequency of interest; the stress at the maximum rotation amplitude should be lower than the yield stress adjusted by a multiplicative safety coefficient (chosen here as 0.2); the suspension length L_s should be minimal.

Different torsional suspension configurations are considered

as in [10] and [11] (Fig. 5): two simple torsional beams, two meander beams with their main axis perpendicular to the axis of rotation, and two meander beams with their main axis parallel to the axis of rotation. In this example, the three oscillators use the same magnet assembly (two $1/8'' \times 1/8'' \times 1/16''$ magnets) and resonate at the same frequency around 1 kHz. The challenge is to find a trade-off between a compliant enough structure with the right stiffness for the targeted frequency by changing the beam width and length, and the number of meanders when appropriate. The first configuration with simple torsional beams presents long beams to allow the targeted rotation amplitude. The second configuration, in which the meander beams work mainly in flexural mode, is much more compact, L_s being 1.76 times shorter, and the volume 1.5 times smaller. The third configuration, with beams working both in torsional and flexural mode, presents the most compact suspensions, and is consequently selected. Indeed, L_s is 2.36 times shorter and the volume is 1.77 times smaller than the first configuration. In this configuration, the resonant frequency could be widely adjusted by changing the number of meanders: with more meanders, the more compliant structure resonates at lower frequency, and the suspensions are shorter.

Figure 5: Torsional suspension beam configurations considered in the optimization of the design of the micro-receiver: simple torsional beams (a), meander beams perpendicular (b) and parallel (c) to the axis of rotation.

Once the suspensions are designed, the last element to be optimized is the receiver coil. To maximize the generated power, the winding should be as close as possible to the magnet without preventing its rotation. Moreover, the resistivity of the wire material should be the lowest possible, which is achieved with copper wire. The wire gauge does not significantly affect the generated power, meaning that a device with a large number of turns of thin wire will produce about the same amount of power as that using fewer number of turns of a thicker wire. However, it is

preferred to use a small wire diameter (i.e. more turns for a given volume) to obtain a significant enough voltage to ease the voltage regulation electronics.

MICROFABRICATION AND DEVICE ASSEMBLY

The fabrication process and assembly of the receiver are shown in Figs. 6 and 7. The serpentine torsion beams are formed by through-etching via DRIE a 200- μm -thick double-side-polished silicon wafer, using a 6- μm thick photoresist (Fig. 6ab). The 50 structures that fit on a 100 mm wafer are released during the same operation by etching the surrounding of their frames. Next, four Nd-Fe-B 1/8"×1/16"×1/16" magnets are assembled on the silicon platform (two on top and two on bottom). Since their magnetizations all point in the same direction, it is difficult to accurately position the magnet on the platform because they repel each other. The solution is to first demagnetize the magnets with a pulse magnetizer, assemble and glue them on the platform, and then re-magnetize the fully assembled structure with the pulse magnetizer (Fig. 6cdfg). Finally, the two receiver coils (AWG 40, 150 turns each, $\sim 17\ \Omega$ each) are wound on a sacrificial foam jig, glued, and then assembled on the silicon frame and connected in series (Fig. 6eh).

Figure 6: Device microfabrication process: DRIE etch of the suspension (a, b), magnets demagnetization, assembly and re-magnetization (c, d, f, g), and receiver coil fabrication and assembly (e, h).

Figure 7: Assembly of the micro-receiver: fabricated suspension (a, b), assembly of the magnets with the suspension (c), and fully assembled micro-receiver (d).

The final device is $10.8 \times 6.1 \times 8.3\ \text{mm}^3$ ($0.55\ \text{cm}^3$, $0.75\ \text{g}$), having a size and mass commensurate with common electronic components (Fig. 8ab). This represents a 14.5x volume reduction from the previous handmade macroscale receiver [6] (Fig. 8c).

Figure 8: Images of the microfabricated EWPT receiver: size comparison with (a) 5-cent coin and (b) electronic components; and (c) illustration of 14.5x decrease in receiver size compared to previous hand-made receiver.

EXPERIMENTAL RESULTS

The micro-receiver is characterized using a Helmholtz coil pair (28-cm diameter, 15-cm long, $1.2\ \Omega$ per coil, $0.74\ \text{mT/A}$). The Helmholtz coils are used in order to apply a purer (more spatially uniform and more controllable) magnetic field and without simultaneously applying a field gradient. Conversely, a typical transmitter coil (like used in [5]) produces both a field and a field gradient at any given distance, which cause a torque and force, respectively, acting on the receiver magnet. For preliminary testing purposes, we wanted to only subject the receiver magnet to a torque and not a force.

Fig. 9 presents the normalized open voltage while varying the excitation frequency from 200 to 780 Hz. The system presents a sharp peak, characteristic of an underdamped 2nd-order system (quality factor estimated to be 50). The maximum output, occurring at the resonant frequency of 744 Hz, is $0.95\ \text{V}_{\text{rms}}/\text{mT}$ in the linear regime.

Fig. 10 shows the actual time-average output power delivered to a resistive load (varied from 0.1 to 2000 Ω) while using a constant amplitude, $300\ \mu\text{T}_{\text{pk}}$ ac magnetic field. The power absorbed by the load tends to be low if its resistance is too low (low voltage) or is too high (low current) compared to the receiver coil resistance. The optimal load is about 50 Ω , expectedly close to the receiver coil resistance (34 Ω).

In a last experiment, the field is progressively increased to obtain the highest magnet rotation amplitude and highest power output. At a $550\ \mu\text{T}_{\text{pk}}$ field, the maximum transmitted power is found to be 2.55 mW ($0.59\ \text{V}_{\text{rms}}$ output). This magnetic field amplitude corresponds to a field produced at 20 cm by a 15-cm-radius coil supplied by 10 W input power. Above this field, the receiver suspension beams fractured as seen in Fig. 11. The maximum power density of the micro-receiver is $4.6\ \text{mW}/\text{cm}^3$,

which is 2.1 times higher than the power density of the last macroscale generation. Indeed, despite a smaller magnet, the small receiver resonates at higher frequency and still induces a larger power density, the generated power being proportional to the square of the frequency.

Figure 9: Normalized open-circuit voltage as a function of the frequency of the magnetic field.

Figure 10: Output power as a function of the resistive load under a $300 \mu T_{pk}$ ac magnetic field.

Figure 11: Fractured meander beam after a too high magnetic field amplitude.

CONCLUSION

In this work, we successfully demonstrate for the first time an EWPT system using a chip-sized partially microfabricated

receiver. We demonstrate 2.5 mW of power using a 744 Hz magnetic field with an amplitude of $550 \mu T_{pk}$, equivalent to a ~ 20 cm transmission distance for a typical 10 W transmitter coil. Compared to previous works, the microfabricated device is 14.5x smaller, and offers a 2.1x increase in power density (4.6 mW/cm^3). Future works will focus on further testing the device to improve the output power and developing the AC to DC receiver electronics.

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