Miniature Antenna for RF Telemetry through Ocular Tissue

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Abstract — In this study, we experiment with the feasibility of wireless telemetry using a miniature wireless system fully implanted within the eye. Of significant importance is the ability to transmit signals from miniature packaged systems without undue absorption of signals. Theoretical calculations found the attenuation through the eye to be -4.5 dB in the far field region, indicating that low power transmission systems can be implemented. Through the use of multilayer integrated Low Temperature Co-fired Ceramics (LTCC) packages, telemetry data through the eye was collected and compared to transmission in free space. In animal studies done using porcine eyes, we were able to successfully transmit and receive from the implanted device in the near field and far field regions measuring 2 dB and 6 dB of power reduction respectively.

Index Terms — Biomedical applications of EM radiation, biosensor, biomedical telemetry, microstrip antennas, LTCC package.

I. INTRODUCTION

Technology advances allow for miniaturization of devices that were inconceivable just a decade ago. With this miniaturization, engineering solutions for medical treatments are becoming a reality. Biomedical applications introduce a new array of challenges and drive innovation in miniaturized telemetry systems. As the size of wireless implants decreases, data transmission approaches fundamental limits. Packaging space is reduced and advanced integration techniques are needed.

In addition to ultra-low power circuit design, package hermeticity, and biocompatibility, other issues dealing specifically with wireless telemetry must be addressed. To improve biological acceptance and reduce side effects such as swelling, infection, and discomfort, implants are fabricated as thin and small as possible. For ocular implants in the treatment of glaucoma, a thickness of less than 350 µm is desired representing a difficult challenge for today’s system-in-a-package technology. These minute sizes pose a significant challenge to wireless telemetry especially in terms of antenna design. Optimal antenna size is inversely proportional to frequency so theoretically, antenna size could be reduced if the chosen carrier frequency was increased. Unfortunately, in biomedical implants, biological tissue attenuation is proportional to frequency. The design must simultaneously account for the tissue attenuation and also miniaturize the antenna while maximizing the efficiency.

This work focuses on developing a device used in ocular implants, shown in Fig. 1, for glaucoma. Glaucoma stems from a buildup of intra-ocular pressure (IOP) that can cause damage to the optic nerve and eventually lead to blindness. This device is proposed to provide an accurate 24-hour continuous IOP monitoring system. Continuous recordings allow for proper diagnosis and treatment of elevated pressure levels, beyond what is possible today. A hybrid prosthesis device that can both record and actively reduce pressure could significantly reduce the incidence of blindness in glaucomatous patients. The device must be small enough to enable implant feasibility right beneath the surface of the eye, and reduce physical side effects. The device must also have minimal power consumption due to the limited total energy storage. An electromagnetic (EM) model was used to predict the attenuation of the ocular tissue to optimally design the wireless transmitter.

An integrated system in a package is proposed in this paper, with the multilayer capabilities of an LTCC package used for miniaturization of the complete system. Specifically, a loop antenna fed with a partially embedded feed was designed to optimally radiate at 2.4 GHz with the corresponding ceramic packaging dielectric. Using a 2.4 GHz voltage controlled oscillator, a signal was transmitted through the antenna, out of the eye, and successfully picked up by an external receive antenna. The result is that the attenuation through the eye is minimal and that low power transmission should be possible leading to an implantable sensor tag.

Fig. 1. Implanted device in a porcine eye. The package is pushed to the side of the eyeball in the proper monitoring location during testing (not shown).
helps was found to be 1 mm beneath the surface. This small depth about 80% of the layer thickness, which through experiments
The hybrid device is implanted within the sclera at a depth of
suprachoroidal space, where it drains into the venous system.
aqueous humour outflow from the anterior chamber to the
pressure, uses the venous pressure differential to promote
between the anterior chamber and the suprachoroidal space.

specific condition of glaucoma, the implant will be inserted
relative permittivity (\(\varepsilon\)) of 50, a dielectric loss (\(\varepsilon''\)) of 19, and
\(\mu\) of 1, and \(\sigma\) of 3 S/m. The loss tangent of the eye is relatively high compared to traditional microwave materials; therefore the loss surrounding the antenna is a concern and care is taken to design an antenna without significant electric field stored in the near field of the package.

Several assumptions were made in this approximation to allow for feasibility of calculations. A plane-wave analysis was assumed to hold. From the structure of the eye and the location of the implant, it is fair to assume that we are transmitting through one homogeneous layer of sclera tissue. Lastly, we assume that rabbit ocular tissue has very similar properties to that of porcine for this experiment and eventually that of human for the final device. This is a fair assumption considering the biological similarities between closely related vertebrate mammals. A more accurate study requires a near-field analysis which is significantly more complicated for this implantation. Although the model uses several assumptions, the approximations allow us to understand how the EM fields are affected and where the attenuation effects originate. This simplified approximation is benchmarked against measurement from radiation inside and outside of the eyeball to determine the suitability.

The model begins with a derivation of skin depth from the wave equation [2]. Using the dielectric properties of the rabbit ocular tissue, we calculate the skin depth at 2.4 GHz to be 13.2 mm. In addition to transmission loss through ocular tissue and air, the interfaces between the package and biological tissue and air cause additional losses. The wave impedance mismatch at the antenna-eye interface and the eye-air interface causes reflections leading to decreased power transfer. The interface between two media with different dielectric properties along with the device is shown in Fig. 2. Since the power transmitted from the antenna can be measured, we can determine the power of the signal at the edge of the eye-air interface by first assuming a lossless medium. Using known values, the power reduction effects of the ocular tissue can be calculated and predicted. Using the Matlab program along with the dielectric properties of rabbit cornea tissue from [1], the calculated power reduction through a 1 mm depth at 2.4 GHz is -4.5 dB.

III. ANTENNA DESIGN

The area and thickness constraints of the implant along with the chosen frequency of operation are the most challenging aspects for the antenna design. The area allowed for the antenna has a maximum length of 6 mm (< 5% of the 2.4 GHz wavelength), drastically reducing the efficiency. Furthermore, the thickness requirement of the board only allows for minimal spacing between the antenna and metal traces, pads, and ground plane.

The relatively high loss tangent of the surrounding ocular tissue meant that it was desirable to minimize the electric field in the near-field region. Therefore, we devised a complex design, shown in Fig. 3, utilizing a predominately inductive feed structure to optimally couple the RF signal to the outside loop surrounding the perimeter of the substrate which maximizes our usage of the limited substrate and promotes magnetic field storage. The efficiency of our antenna is relatively low, mainly due to the size constraints; however, there are still notable advantages in this design. Benefits include ease of fabrication in LTCC as an embedded antenna combined with matching circuitry, and the ability to transfer data and inductively couple power using the same structure.
Ansoft HFSS™ is used to perform a full wave simulation to optimize this structure by locating the ideal feeding position and determine the proper feeding component dimensions. The software is also used to simulate the coupling effect, where the currents travel from the transmitter output port, through the feed, and magnetically couple to the outside loop. The simulated gain is 0.0153 (-18.15 dB) with an efficiency of 1.13%. The input reflection coefficient, $S_{11}$, is $0.051 + j0.635$ before incorporating the matching network. The matching network is implemented using a shunt 2.4 pF capacitor transmitting through a series 7.9 nH inductor to achieve a standard 50 Ω match.

IV. FABRICATION AND PACKAGING

The final design of our device contains a capacitor array for internal power storage, an integrated circuit with a rectifier for powering, and an embedded antenna. LTCC is a suitable option for assembling this complete system due to its multilayer and integration capabilities. In addition, LTCC provides a high dielectric allowing for miniaturization of the antenna. Dupont 951 was chosen as a demonstrator because of the relative ease of processing; however, the concept shown here is adaptable to other LTCC substrates while maintaining similar performance and size.

Cadence software is used to draw the layout and define shapes and locations of interconnects, vias, and the antenna. The structure consists of a 10 mil and a 2 mil thick layer of Dupont 951 tape. The 10 mil thick layer provides a durable back to the structure. The antenna is screened on the 2 mil thick layer while the routing is done on the 10 mil layer. In the design layout for the glaucoma board, three main components are added to the finished printed board. A cavity is formed in the substrate where we place the sensor that measures ocular pressure. The integrated circuit (IC) chip is placed right next to the pressure sensor, which records, processes, and transmits the data from the sensor. Next to the IC and sensor is an array of surface mount components use for power storage and matching. Aside from all these components are pads for test structures, to adjust and test the performance of the device. The antenna must account for these interconnects and ground planes for the surface mount components, sensor, and IC.

In the final implementation of the implanted device, a chip has been designed and fabricated through MOSIS using the AMIC5 0.5 µm process. Both package scale integration and chip scale integration are necessary. The details of the IC and sensor will be reported elsewhere; however, the radiative properties through the eye are the basis for this current study.

V. METHODS AND EXPERIMENT

In order to verify that transmitting from a tiny antenna in the eye to an external receiver is feasible; an experiment was devised in which the LTCC antenna was implanted in a freshly excised porcine eye. The goal was to determine the attenuation due to the less than ideal antenna and high loss within the eye.

To test the embedded antenna transmission capability in the LTCC package, we used a MAX2753 surface mount 2.4 GHz voltage controlled oscillator (VCO) from Maxim Integrated Products. This VCO has -11 dBm of output, which ensures that enough power will be received to extract the total loss of the transmit path. The VCO was soldered onto the LTCC board with the antenna matching network components using a solder paste method. This VCO mimics the function of the IC that will be the eventual oscillating source. DC wires were then soldered to the oscillator leads to provide power and frequency control. The implant was then coated with epoxy to insulate test-leads during the experiment. This will have the effect of shielding some of the fields from the influence of the tissues on the embedded antenna, and the effect should be further investigated.

This LTCC board was then implanted in the porcine eye for the test. Eyes were obtained both from the Weldon School of Biomedical Engineering and from Butler Meat Processing in Lafayette, IN. The eyes from both sources were obtained at most a few hours after euthanasia. In the cases where immediate use was not possible, the eyes were placed in saline solution and stored at 4°C for no more than 24 hours to minimize changes in the dielectric properties.

During the experimental procedure the eye was first placed on a surgical cutting board. The surrounding skin was cut and separated from the eyeball. An incision was made adjacent to the optic nerve and the opening was enlarged with a scalpel. The aqueous humor and lens were extracted and the implant was inserted through the incision. The antenna was pushed to the front of the eye and positioned just to the side of the pupil behind the cornea and sclera tissue. The final device will be implanted in a less intrusive manner and in a living subject, but will end up in approximately the same location, 1 mm to 1.5 mm below the surface of the eye. Without the larger surface mount VCO and wires, the device will be significantly smaller. The implantation procedure of the end product will consist of an incision made at the front of the eye where the device will be inserted right beneath the surface.

The rest of the experimental setup consists of a receive patch antenna connected to an Agilent E4404B Spectrum Analyzer to measure the transmitted power. The patch antenna

![Fig. 4. LTCC board size comparison with a penny.](image-url)
is representational of an antenna that can be used in a portable external device whose purpose will be to wirelessly communicate and charge the implant within the eye. The porcine eye with the implanted LTCC module was placed specific distances away from the receive antenna, as shown in Fig. 5, and the spectrum analyzer was used to obtain power measurements. This experiment was repeated with the same LTCC transmit module implanted in different eyes. Ultimately, the data from the separate tests correlated well, indicating the test is repeatable.

VI. DATA AND ANALYSIS

The final mode of operation expects a patient to routinely charge and download data from the implant by holding an external device close to their eye. The numerous data measurements from several implantation experiments are averaged and plotted in Fig. 6. By applying the Friis formula, the patch antenna has gain of 5.29 dBi with the transmission power of -11 dBm, the fabricated miniature antenna gain can be calculated to be -18.45 dBi (efficiency = 1.05%), which is slightly worse than simulated gain. This could be due to an imperfect matching network.

The results showed 1.75 dB and 1.93 dB of power reduction through the ocular tissue at close distances of 1 and 2 inches, respectively, while a 5.89 dB reduction was seen at a distance of 6 inches from the eye. The insignificant power reduction in close distances can be explained by near field coupling of the magnetic field of the antennas. At 1 to 2 inches, the radiation is not an established plane wave and is still in the near field. Thus, the EM wave is dominated by the magnetic component which is not altered by the permittivity mismatches and dielectric loss of biological tissues. Since the permeability of biological tissue is essentially identical to that of free space, the magnetic waves see no boundaries and face little attenuation. At further distances around 6 inches, the far-field electrical component of the wave becomes dominant and the power reduction from transocular affects is seen. For the glaucoma system specifications, the output power is designed to be -60 dBm for low power-consumption operation, and an external receiver with a sensitivity down to -140 dBm is desired. Countering the attenuation of 6 dB from the tissue and from free space transmission path loss, the receiver can be placed in 10.4 meters away using a 5 dBi receive antenna. The relatively low loss of the implanted antenna gives a promising future for miniature implanted ocular devices.

Fig. 5. Embedded antenna transmitting through the eye to a receive antenna 2 inches away.

Fig. 6. Experimental measurements of transmitted power.

V. CONCLUSION AND FUTURE WORK

The experiment was done using an off the shelf VCO to validate the efficacy of the antenna embedded in LTCC and to demonstrate transocular transmission. An integrated circuit has been fabricated through MOSIS using the AMIC5 0.5 µm process consisting of on-chip electronics and a 2.4 GHz transmitter. The chip was recently received back from MOSIS and initial tests show that the transmitter meets the necessary requirements of power output and frequency for our application. The on-chip circuitry rectifies and regulates the voltage from the power coupling inductor, processes and stores pressure measurements, and wirelessly transmits to an external device. This study shows that the RF transmit power can be sufficiently low for a miniature device and that the RF sensor tag concept is possible for the Glaucoma application.

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REFERENCES