33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Eye-Surface Conformable Telemetric Structure for Polymer-based Retinal Prosthesis

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Abstract— **In this research, inductive telemetric structure for retinal prosthesis was developed based on Liquid Crystal Polymers. For power and data transmission into the polymer-based retinal implant which is conformable to eye surface, the designed coil was thermo-formed into convex shape. The geometric parameters of the coil were optimized using finite element method (FEM) simulations for maximizing coupling coefficient and quality factor. The electrical properties of fabricated coils were characterized and their power and data transmission performance was tested. The properties of deformed structure were compared to those of the planar structure. *In vivo* experiment were also conducted to confirm the functionality of telemetry system in implanted conditions as well as to estimate the influence of biological media upon link properties.**

I. INTRODUCTION

Retinal prosthetic devices are aiming to restore partial vision of blind patients with retinal disease like retinitis pigmentosa (RP) and age-related macular degeneration (AMD). The remaining retinal neurons are electrically stimulated by microelectrodes array implanted in the retinal space. A number of research groups have dedicated to develop the implantable retinal prosthetic devices [1-7].

One of the main objectives of retinal prosthesis researches is the totally implantable device that is thin, small, and long-term reliable. Slim and small dimension of the implanted device is essential especially for retinal prosthesis since the device is usually placed on the curved surface of eyeball; risk of infection and device failure is high since space is very limited and continuous movement of eyeball induces friction between the implant and tissue.

One of the efforts toward this objective is the development of Liquid Crystal Polymer-based retinal prosthesis [8], which is depicted in Fig 1. LCPs are biocompatible and mechanically stable materials that have very low moisture absorption (<0.04%), compared to conventional polymers like polyimide (2.9%) and parylene-C (0.1%). The entire system is monolithically fabricated using thermal bonding process, where whole components including electrode, system substrate, packaging, and coil are based on LCPs. LCP-based monolithic system can be as thin and flexible as conventional polymer-based system, but expected to be more long-term reliable in implanted condition than polyimide and parylene-C [8]. In addition, through a thermo-forming process, the entire system can be simply formed into convex shape to fit the curvature of eyeball so that the friction and discomfort of patients are minimized.

This implantable device requires stable power and data transmission for long-term chronic operation, and thus inductive coil should fit the eye-surface as well. Therefore, the goal of this work is, as a part of eye-attachable retinal prosthetic system, to develop a polymer-based telemetric structure that can conform to the curved surface of eyeball.

Wire-wound coils have been mainly used for powering the biomedical implants so far, but they have several disadvantages to be employed for retinal prosthesis because they are thick, stiff, and have limitation in miniaturization. Wire coils make integration with polymer-based system complicated.

Therefore, planar coils lithographically printed on polymer substrates are being developed by a number of researchers [9-11]. Planar coils have several advantageous features over wire-wound coils; they are thin and flexible, and can be fabricated as small as micron-scale using matured MEMS technologies providing accurate and uniform electrical properties. On top of that, polymer-based planar coils can be easily integrated into polymer-based substrate.

However, planar coils have less flexibility in design since they have limited space for placing conductor when compared to wire-based coils which can be wound tighter. Therefore, sophisticated design procedure is required for developing an efficient planar coil under the condition given by implantation environment.

In this research, LCP-based coil was designed to maximize the power efficiency and data communication distance for retinal implant. The geometric parameters of coils were decided using simulation tools based on finite element

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Manuscript received April 15, 2011. This work was supported in part by the Inter-University Semiconductor Research Center (ISRC) of Seoul National University; in part by the Happy tech. program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2010-0020847); in part by the Brain Korea 21 Project, the Department of Electrical Engineering, Seoul National University in 2011

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978-1-4244-4122-8/11/$26.00 ©2011 IEEE

method (FEM). Designed coils were fabricated and characterized, and then link performance was tested in laboratory condition as well as *in vivo* conditions. Coil was thermo-formed into convex shape, and then its properties were compared to flat coil before forming.

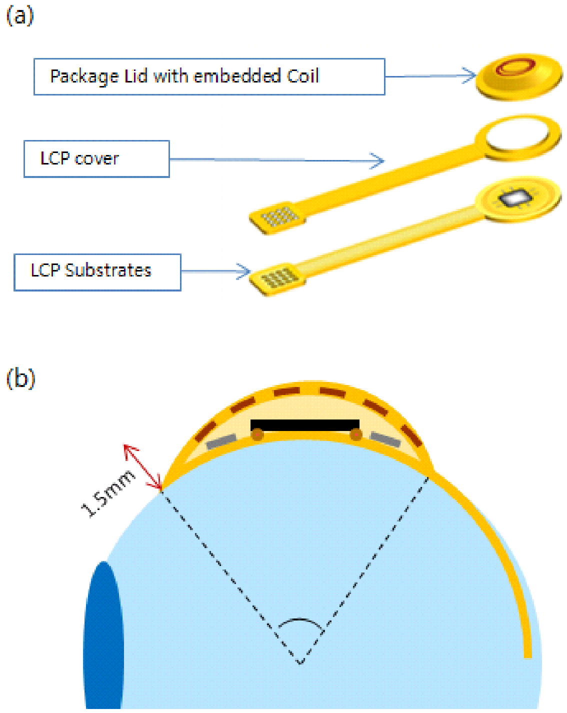

Fig 1 (a) The schematic of the LCP-based monolithic retinal stimulator. Whole system, including electrode substrate, coil and package, is fabricated using singe material so that fabrication is dramatically simplified. The planar coil will be embedded into the LCP package lid to reduce the system thickness. (b) The cross section of eyeball with retinal prosthetic device placed on the surface (not in scale).

II. METHODS

A. Coil Geometry and Simulation Tools

Maximum diameter of receiving coil is limited by the anatomically available space at which the implant is placed. In this research, maximum diameter of receiving coil is set to 10mm. For the given size of the receiving coil, other parameters including inner diameter of receiving coil, inner and outer diameter of transmitting coil, and the number of turns were decided using FEM-based simulation tools for maximizing the coupling coefficient and quality factors of coils, and minimizing the sensitivity to misalignment. Two kinds of simulator programs were used for this purpose: Fasthenry and HFSS (Ansoft, Pittsburgh, PA). HFSS provides more accurate results than FastHenry but more time is consumed for modeling and solving. Therefore, FastHenry was used for parametric sweep of variables whereas HFSS was used for verification of optimal values.

B. Thermo-forming

A LCP-based system can be thermo-formed into desired shape and size even after the whole fabrication process is finished. This enables the implanted devices to fit the shape of surrounding tissue so that tisssue damage and patient's discomfort is minimized.

In this research, fabricated planar coil was thermo-formed to fit the curvature of eyeball using aluminum mold consisting of male and female parts. Detailed procedure of applying heat and pressure of thermo-forning process is same as descibed in [8]. After the forming process, the electrical properties and link performance were measured, and then compared with planar coil before forming.

C. Fabrication and Measurement

Designed coils were fabricated on the 100 um-thick LCP substrate using conventional flexible PCB technologies. Their electrical characteristics were measured by precision impedance analyzer (HP4325) and compared with the simulation results.

Their link performance was tested by measuring the power efficiency and the maximum operating distance of stimulation circuit. Power efficiency was defined as P_2/P_1, where P1 is the amount of transmitted power and P2 is the power delivered to 1KΩ load connected to receiver coil. Maximum operating distance was measured connecting a stimulator (stimulator ASIC and surrounding circuitries like rectifier and regulator) to the receiver coil. The Maximum operating distance was defined as the gap between two coils above which stimulation ASIC cannot provide correct stimulation due to lack of power receiving or excessive errors in data decoding. PWM (Pulse Width Modulation) scheme was employed for data encoding and class-E amplifier with carrier frequency of 2.5MHz was used for power and data transmission.

Transmitting coil will be placed on the skin and less restricted in volume than receiving coil, thus it was fabricated by winding litz-wire, consisting of 6 individually insulated strands.

D. Performance testing in PBS and in vivo

In order to verify the performance of designed planar coil in implanted condition and to estimate the influence of biological environment upon the inductive link, experiments were performed in physiological saline (PBS) as well as *in vivo*. Biological media between coil pair, such as hair, skin, bone, body fluid or other tissues, can affect the electrical characteristics and performance of the inductive link. Accordingly it is important to evaluate the designed coil in physiological environment for estimating the performance of coil in real implanted condition and to take into account of additional capacitance produced by biological media. Quantitative analysis about the influence of physiological medium surrounding the coil, as well as integration with IC and polymer encapsulation has been performed in [12].

A PBS testing was conducted by introducing physiological saline solution (PBS) between transmitter and receiver coils. LCP-based planar coil was encapsulated PDMS and immersed in PBS in chalet, while transmitter coil was attached beneath the chalet.

In vivo animal experiment was performed using New Zealand White Rabbits. **오류! 참조 원본을 찾을 수 없습니다.**The fabricated coils were implanted in the rabbit's conjunctiva and scalp to quantify the influence of biological media on link characteristics of coil pair.

Change in link performance and frequency shift of resonance peak were measured, by varying the distance between coils and external tuning capacitance for both experiments.

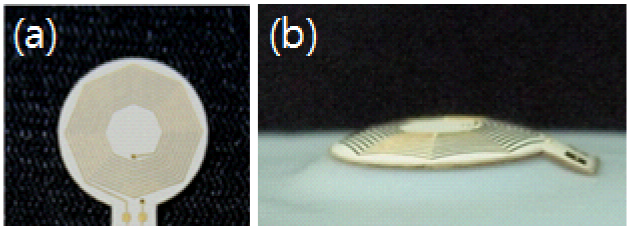

Fig 2 Fabricated receiving planar coil on LCP substrates. (a) is the LCP-based planar receiver coil of 10mm diameter. (b) shows the coil thermo-formed into convex shape to fit the curvature of eyeball of 22 mm diameter. .

III. RESULTS

A. Geometric Parameters and Electrical Characteristics

As a result of FEM simulations, the coil parameters were decided as summarized in Table I, and fabricated as shown in Fig 2 (a). The copper line was patterned on both side of LCP film and the width of each turn is 130µm, metal thickness was 18µm. Their simulated and measured characteristics were compared in Table 2. Quality factors Q of coil were calculated by $Q = \frac{\omega L}{R}$ at 2.5MHz. SRF is self resonance frequency of planar coil.

Comparing the simulated and measured data, it can be found that HFSS gives more accurate anticipation. FastHenry also provided fairly precise simulation results, but overestimated the quality factor. This coil pair showed approximately 25 % of power efficiency at 5mm distance, transferring energy and decodable data to stimulator ASIC up to 14 mm separation in the air.

B. Deforming

Using the thermo-forming process of LCPs, planar coil was successfully deformed into the curved shape as shown in Fig 2 (b). The diameter of curvature is 22 mm that is similar to the diameter of human eyeball. Measured electrical characteristics (Table III) showed approximately 3% increase in resistance and decrease in inductance after the forming process. However, no significant change in link performance was observed.

C. PBS and in vivo experiments

Tissue absorption of magnetic flux and the additional capacitance created at the interfaces of physiological layers can deteriorate the link performance. The results from PBS and *in vivo* experiments are shown in Table IV. Communication distance decreased to 12mm of *in vivo* from 14mm in air, and the power efficiency at same distance was reduced by approximately 5%. Shift of resonance frequency due to additional capacitance generated by introduction of physiological layers was shown to be less than 1%, which corresponds to the experiments of [12]. These results prove the feasibility of designed planar coil as a telemetry unit for LCP-based biomedical implants.

Table I
The geometric parameters of transmitter and receiver coils decided by simulations.

	Transmitter	Receiver
Outer Diameter (mm)	25	10
Inner Diameter (mm)	8	5
Turns	24	20
Coupling coefficient	0.154 (5mm distance)	

Table II
Comparison of simulation results and measured value of the designed planar coil

	Simulated		Measured
	FastHenry	HFSS	
L (uH)	3.5	3.06	2.75
R (Ω)	3.84	4.1	3.61
Q (at 2.5MHz)	14.3	11.6	12
SRF (MHz)	-	42	46

Table III
Change of electrical properties when the coil is deformed.

Forming	L (uH)	R (Ω)	Q (at 2.5MHz)
Before	2.75	3.61	12
After	2.7	3.7	11.5

Table IV
Comparison of the maximum operating distance of coil in air, in physiological saline, and under the conjunctiva of rabbit.

	In air	In PBS	*In vivo*
Maximum operating distance	14 mm	14 mm	12 mm

IV. CONCLUSION

Thin and flexible planar coil on LCP substrate was designed and fabricated for the LCP-based retinal prosthesis which is conformable to eye surface. Optimal parameters for coil geometry was found using FEM simulations such as FastHenry and HFSS. Fabricated coil characteristics were measured and their performance was tested in laboratory condition as well *in vivo* animal experiment in order to consider the influence of biological media between coils. Fabricated planar coil was deformed into curved shape by thermo-forming process to make the retinal implant conformable to curved surface of the eyeball.

REFERENCES

[1] M. S. Humayun, J. D. Weiland, G. Y. Fujii, R. Greenberg, R. Williamson, J. Little, B. Mech, V. Cimmarusti, G. V. Boemel, G. Dagnelie and E. Juan, “Visual perception in a blind subject with a chronic microelectronic retinal prosthesis,” *Vision Res*, vol. 43, pp. 2573-2581, 2003.

[2] E. Zrenner, "Will retinal implants restore vision?," *Science*, vol. 295, pp. 1022-1025, 2002.

[3] J. D. Weiland, W. Liu, and M. S. Humayun, "Retinal prosthesis," *Annual Review of Biomedical Engineering*, vol. 7, pp. 361-401, 2005.

[4] P. Walter, Z. F. Kisvárday, M. Görtz, N. Alteheld, G. Rossler, T. Stieglitz and U. T. Eysel, “Cortical Activation Via an Implanted Wireless Retinal Prosthesis,” *Invest Ophthalmol Vis Sci*, vol. 46, pp. 1780-1784, 2005.

[5] J.-M. Seo, S. J. Kim, H. Chung, E. T. Kim, H. G. Yu and Y. S. Yu, “Biocompatibility of polyimide microelectrode array for retinal stimulation,” *J Mater Sci Eng C*, vol. 24, pp. 185-189, 2004.

[6] H. G. Sachs, T. Schanze, M. Wilms, A. Rentzos, U. Brunner, F. Gekeler, and L. Hesse, “Subretinal implantation and testing of polyimide film electrodes in cats,” *Graefe’s Arch Clin Exp Ophthalmol*, vol. 243, pp. 464-468, 2005.

[7] D. B. Shire, S. K. Kelly, C. Jinghua, P. Doyle, M. D. Gingerich*, et al.*, "Development and Implantation of a Minimally Invasive Wireless Subretinal Neurostimulator," *Biomedical Engineering, IEEE Transactions on,* vol. 56, pp. 2502-2511, 2009.

[8] S. E. Lee, K. S. Min, J. Jeong, J. H. Kim, and S. J. Kim, "Monolithic encapsulation of implantable neuroprosthetic devices using liquid crystal polymers," *Biomedical Engineering, IEEE Transactions on,* to be published.

[9] S. Kim, K. Zoschke, M. Klein, D. Black, K. Buschick*, et al.*, "Switchable polymer-based thin film coils as a power module for wireless neural interfaces," *Sensors and Actuators, A: Physical,* vol. 136, pp. 467-474, 2007.

[10] W. Li, D. C. Rodger, E. Meng, J. D. Weiland, M. S. Humayun*, et al.*, "Flexible Parylene Packaged Intraocular Coil for Retinal Prostheses," in *Microtechnologies in Medicine and Biology, 2006 International Conference on*, 2006, pp. 105-108.

[11] M. Sawan, S. Hashemi, M. Sehil, F. Awwad, M. Hajj-Hassan*, et al.*, "Multicoils-based inductive links dedicated to power up implantable medical devices: modeling, design and experimental results," 2009.

[12] S. Kim, R. Harrison, and F. Solzbacher, "Influence of system integration and packaging for a wireless neural interface on its wireless powering performance," in *Engineering in Medicine and Biology Society, 2008. EMBS 2008. 30th Annual International Conference of the IEEE*, 2008, pp. 3182-3185.