Multi-channel thin film piezoelectric acoustic transducer for cochlear implant applications

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***Abstract*—This paper presents a multi-channel piezoelectric acoustic transducer that is working within the audible frequency band (250- 5500 Hz). The transducer consists of eight cantilevers with thin film PLD-PZT piezoelectric layers. The transducer is well suited to be implanted in middle ear cavity with an active volume of 5×5×0.6 mm^3 and mass of 4.8 mg excluding the test frame. Finite Element Method (FEM) is used for modelling cantilever resonance frequencies and piezoelectric outputs. This model and shaker-table experiments are in good agreement on the frequency (97%) and output voltage (89%) values. Transducer can generate up to 139.36 mV$_{pp}$ under 0.1 g excitation at 316 Hz, which is the highest reported output voltage from a piezoelectric acoustic sensor to the best of our knowledge.**

Keywords— cochlear implant; MEMS based acoustic sensor; thin film PZT

I. INTRODUCTION

Human ear is a magnificent acoustic sensor with sound perception on a wide frequency selectivity (20 Hz – 20 kHz) and very high dynamic range a wide frequency selectivity a (0-140 dB SPL). Unfortunately, World Health Organization (WHO) reports 466 million people have hearing loss worldwide, and 34 million of them are children [1]. Patients with severe sensorineural hearing loss may hear again with cochlear implants (CI). CIs can recover hearing to a certain degree by bypassing the damaged hair cells and other members of the hearing system. The CI electrode inside the cochlea stimulates the nerves directly using a number of channels corresponding to certain frequency bands. However, conventional CIs have major drawbacks such as requirement of daily battery recharge/replacement, high cost, risk of damaging outer components when exposed to water, and aesthetic concern of patients particularly children and young users [2], [3].

Fully Implantable Cochlear Implant (FICI) systems, on the other hand, have a potential to solve most of the problems by eliminating the external components of a CI such as microphone, signal processor, and external battery. Many studies have been reported on using energy harvesters as internal power sources [4]–[6] developing new interface circuits to decrease the power requirement [7]–[9], and compact acoustic transducers for sound detection in middle ear[8], [10]–[14]. FLAMENCO[1] concept combines a commercial CI electrode with piezoelectric energy harvesters [4], [5], ultra-low power interface circuit [7], and multi-channel piezoelectric acoustic transducers [10] with all parts to be implanted inside the middle ear cavity to form a whole FICI system.

This paper presents development of the multi-channel piezoelectric acoustic transducer for the FICI application. Next section explains the design methodology and fabrication steps of the transducer. In the third section, results from the vibration experiments are compared with the simulation model and similar transducers from the literature. In the conclusion, achievements and future work are described.

I. DESIGN, MODELLING AND FABRICATION

An acoustic transducer for FICI system has to meet several requirements which are: area, volume, mass, frequency range and output level. In order to sense the incoming sound, transducer can be placed on eardrum or ossicles. Nonetheless, volume of the middle ear (1 cm^3) [15] and area of the eardrum (9 × 10 mm^2) [16] restrict the dimensions of transducer. Moreover, adding mass on the eardrum affects the vibration characteristic. This additional mass effect has been studied in the literature, and it was shown that loading maximum of 25 mg mass on the ear drum results 3 dB decrease in the vibration amplitude [17]. Besides, stimulating whole daily acoustic band is the other challenging issue. In a healthy cochlea, thousands of hair cells transform sound vibrations with frequencies from 20 Hz to 20 kHz to electrical signal and stimulate the nerves. Unfortunately, due to wide frequency range and limited dimensions, any artificial device could not replace the function of hair cells completely. Therefore, defining number of sensing channels and placing the center frequencies gain

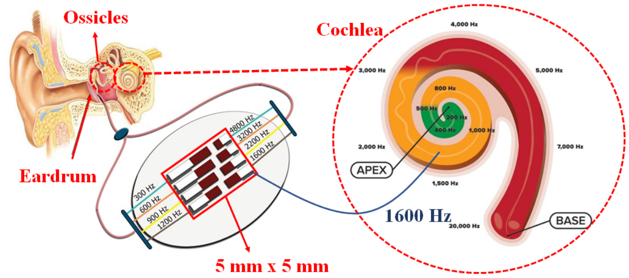

Fig. 1. The proposed system for sensing the sound with close-up views of the cochlea and the cantilever array [10].

[1]A Fully- Implantable MEMS-Based Autonomous Cochlear Implant, ERC Consolidator Grant, Project ID: 682756.

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importance. Last consideration for the design is the output level of the channels, where the state-of-the-art neural stimulation interface circuit requires a minimum signal level of 100 µV from each channel [7]. All these requirements must be satisfied while designing acoustic transducer for FICI applications.

Fig. 1 shows the previously reported transducer concept by our group to overcome the aforementioned problems [10]. A single-channel prototype was fabricated and demonstrated to show functionality of the model. In the present study, a multi-channel prototype has been developed with several cantilever beams with different resonance frequencies. These frequencies are defined similarly as in the conventional CIs, which are placed at 250 Hz to 6 kHz; and distributed linearly below 1200 Hz and logarithmically above 1200 Hz [18]. A recent study on CI channel numbers shows that hearing performance increases up to 8-channels and no significant improvement is observed with higher number of channels [19], therefore an 8-channel design has been used. Each channel consists of a Si based cantilever with a piezoelectric layer close to its fixed end. The resonance frequencies of the cantilevers depend on stiffness and mass of the beams. Stiffness of the beam can be decreased to lower the resonance frequencies by increasing the length of the beam. However, due to area/volume limitations of the middle ear, this approach is not feasible. Adding mass on the tip of the cantilever can be used to obtain lower frequencies. In addition to lowering the resonance frequency, adding mass on tip increases the mechanical stress on the beam which is used for generating voltage by using piezoelectric effect. Thin film PLD-PZT is preferred as a piezoelectric material due to its superior ferroelectric and piezoelectric properties among other piezoelectric materials [20]. The proposed acoustic transducer not only produces larger output signal but also provides widened dynamic range.

In order to design the system with these specifications, a finite element model is established in COMSOL Multiphysics. The final structure of the 8-channel system fit into 5×5×0.6 mm^3 and 4.8 mg without the testing frame. These dimensions are much lower than previously mentioned limitations, providing design flexibility on packaging. Besides the channel output signal levels are arranged to provide the minimum sensing level and wide dynamic range requirements.

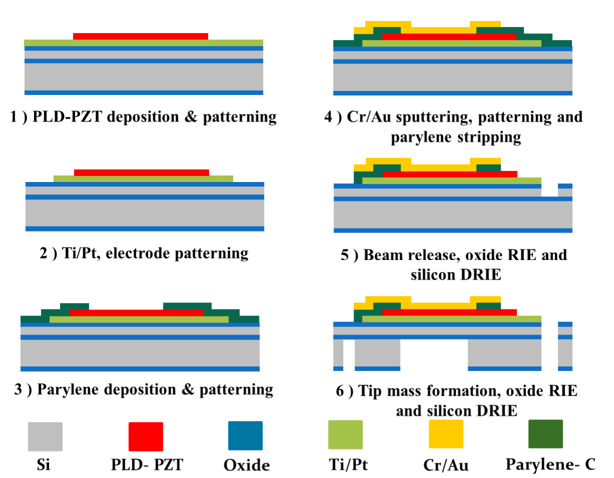

Fig. 2. Fabrication flow of the transducer.

Transducers are fabricated on 4-inch (100 orientation) SOI wafer (15 µm device / 2 µm oxide / 600 µm handle layers). Using SOI wafers provide controllable cantilever and mass thicknesses; key parameters of resonance frequency. A 6-mask fabrication process is developed (Fig. 2). Initially, 500 nm thick thermal SiO_2 layer is deposited for isolation of electrodes. Then, Ti/Pt (10/100nm) is sputtered as bottom electrode. Thin film PLD-PZT is deposited by Solmates (SMP-700 PLD) and patterned by special etchant provided by the firm (Fig.2-1). The bottom electrode is patterned using hot aqua-regia solution (Fig.2-2). Parylene-C (1 µm) is deposited for isolation between top and bottom electrodes and patterned using reactive ion etching (RIE) (Fig.2-3). Cr/Au (30/400nm) is used as top electrode layer (Fig.2-4). Cantilever beam and tip mass are formed by etching SiO_2 with RIE and silicon layers with deep reactive ion etching (DRIE) processes on both front and backside of the wafer (Fig. 2-5,6). All steps of the process are completed below 115 °C, which is below the poling temperature (200 °C) of PLD-PZT.

II. Result and Discussion

Fabricated devices were characterized on a shaker table under constant acceleration. A custom test holder and PCB were used to mount the transducers on the shaker table (Fig. 3). Transducer can generate up to 139.36 mV_{pp} under 0.1 g excitation at 316 Hz, which is the highest output voltage for similar size acoustic sensors in the literature to the best of our knowledge. Output voltage of other channels change between 7.18 mV_{pp} and 86.15 mV_{pp} under 0.1 g excitation while their resonance frequencies distributed between 647.3 Hz and 5767.2 Hz which can be seen in Fig. 4 and Table 1. These output characteristics are also consistent with the simulated model of the transducer. Fig. 5 shows both simulation and experimental characteristics of the second channel to visualize the consistency.

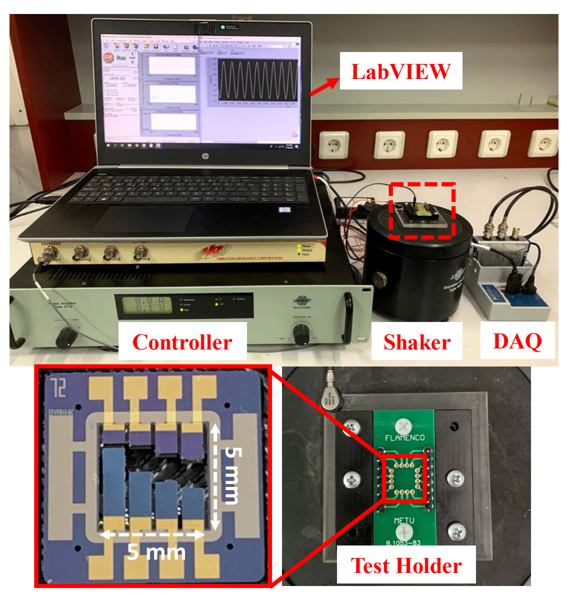

Fig. 3. Shaker table test set up and close-up view of the fabricated 8-channel transducer.

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TABLE I. SIMULATION AND EXPERIMENATAL RESULTS OF FABRICATED TRANSDUCER

Channel	Simulation		Experiment	
	Frequency (Hz)	*Voltage (mV_{pp})*	*Frequency (Hz)*	*Voltage (mV_{pp})*
1	316.4	141	316.4	139.36
2	648.0	90.1	647.3	86.15
3	990.1	45.3	988.3	42.84
4	1325.0	23.9	1321.0	22.15
5	1714.9	16.7	1735.8	14.68
6	2429.2	21.6	2452.3	20.13
7	3524.3	38.8	3497.8	36.58
8	5574.0	7.6	5767.2	7.18

Experimental results show that fabricated devices meet the requirements of the multi-channel piezoelectric acoustic transducer which can be placed on eardrum or ossicles. Each of the 8-channels of the transducer resonates in the audible frequency range and generates the highest output voltage in the literature which provides system a wide dynamic range. Output levels of channels vary between 7.18 mV_{pp} to 139.36 mV_{pp} in the vibration test, because of the different tip mass dimensions and resonance frequencies. To compare the vibration characteristics of each channel, the transducer is tested under the same acceleration level, 0.1g, on all tests. Depending on the frequency, this acceleration level on the eardrum corresponds to different sound levels. For instance, 0.1g acceleration level approximately equals to 100 dB at 600 Hz, 90 dB at 1 kHz and 80 dB at 5kHz [8].

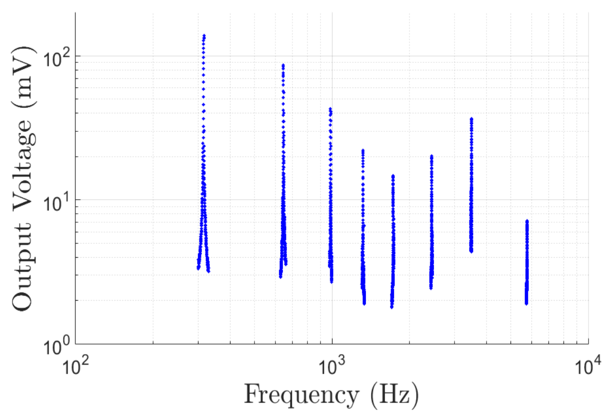

Fig. 4. Shaker table results of the fabricated 8-channel transducer under 0.1g acceleration.

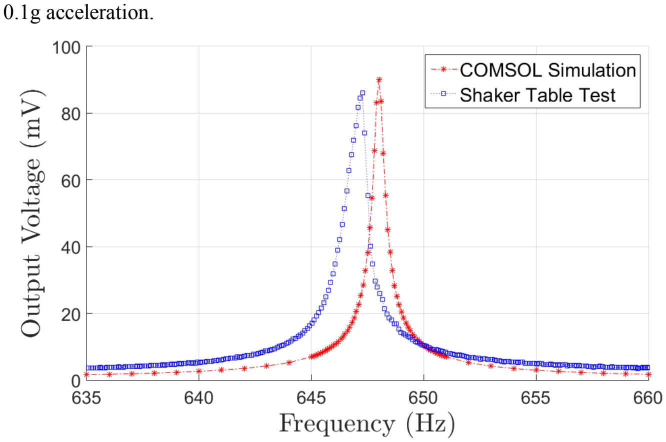

Fig. 5. Experimental result and simulation of second channel of the transducer.

TABLE II. COMPARISON OF THE FABRICATED TRANSDUCER WITH THE STATE-OF-THE-ART TRANSDUCERS FOR FICI APPLICATIONS

Study	Frequency Range	Excitation	Maximum Output Voltage
[10]	1325 Hz	110 dB	114mV @1325 Hz
[11]	2.92-12.6 kHz	101.7 dB	4.06 mV @7040 Hz
[12]	1617 Hz	0.6 g	200 mV @1617 Hz
[13]	281-673 Hz	1 g	9.6 mV @366Hz
This work	316-5767 Hz	0.1 g≈110dB[a]	139.36 mV @316Hz

[a] Corresponding sound level is extrapolated from [8].

Table 2 shows the performance comparison for vibration characteristics of state-of-the-art transducers in the literature. Considering the design parameters, this study provides the best performance by supplying the highest voltage, the widest frequency, and dynamic range.

III. CONCLUSION

In this study, modelling and experimental results of the multi-channel thin film PLD-PZT transducer concept is presented for FICI applications. This device mimics the hair cell by filtering incoming sound into frequency divisions with array of cantilever beams to stimulate the auditory nerves while using vibration of the ear drum and ossicles. Fabricated 8-cantilever transducers provide highest output voltage level (139.36 mV_{pp} at 316.4 Hz under 0.1g) in the literature while the mass and volume of the system are kept well below the limitations of middle ear cavity. Thus, the transducer can be modified for more channel numbers if needed. In consequence, proposed method and fabricated multi-channel transducer validates next generation FICI concept.

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References

[1] "Deafness and hearing loss," *World Health Organization* [Online]. Available: https://www.who.int/news-room/fact-sheets/detail/deafness-and-hearing-loss. [Accessed: 22-Jun-2019].

[2] M. K. Cosetti and S. B. Waltzman, "Cochlear implants: current status and future potential," *Expert Rev. Med. Devices*, vol. 8, no. 3, pp. 389–401, May 2011.

[3] F. G. Zeng, S. Rebscher, W. Harrison, X. Sun, and H. Feng, "Cochlear implants: system design, integration, and evaluation," *IEEE Rev. Biomed. Eng.*, vol. 1, pp. 115–142, 2008.

[4] L. Beker, O. Zorlu, N. Goksu, and H. Kulah, "Stimulating auditory nerve with MEMS harvesters for fully implantable and self-powered cochlear implants," in *2013 Transducers & Eurosensors XXVII: The 17th International Conference on Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS & EUROSENSORS XXVII)*, pp. 1663–1666, 2013.

[5] A. Koyuncuoğlu *et al.*, "Bulk PZT Cantilever Based MEMS Acoustic Transducer for Cochlear Implant Applications," *Proceedings of Eurosensors*, vol. 1, no. 4, p. 584, Aug. 2017.

[6] P. P. Mercier, A. C. Lysaght, S. Bandyopadhyay, A. P. Chandrakasan, and K. M. Stankovic, "Energy extraction from the biologic battery in the inner ear," *Nature: Biotechnology*, vol. 30, no. 12, pp. 1240–1243, Dec. 2012.

[7] H. Ulusan, S. Chamanian, B. Ilik, A. Muhtaroglu, and H. Kulah, "Fully Implantable Cochlear Implant Interface Electronics With 51.2-µW Front-End Circuit," *IEEE Trans. Very Large Scale Integr. Syst.*, pp. 1–9, 2019.

[8] D. J. Young, M. A. Zurcher, M. Semaan, C. A. Megerian, and W. H. Ko, "MEMS Capacitive Accelerometer-Based Middle Ear Microphone," *IEEE Trans. Biomed. Eng.*, vol. 59, no. 12, pp. 3283–3292, Dec. 2012.

[9] M. Yip, R. Jin, H. H. Nakajima, K. M. Stankovic, and A. P. Chandrakasan, "A Fully-Implantable Cochlear Implant SoC With Piezoelectric Middle-Ear Sensor and Arbitrary Waveform Neural Stimulation," *IEEE JSSC*, vol. 50, no. 1, pp. 214–229, Jan. 2015.

[10] B. İlik, A. Koyuncuoğlu, Ö. Şardan-Sukas, and H. Külah, "Thin film piezoelectric acoustic transducer for fully implantable cochlear implants," *Sensors Actuators A: Physical*, vol. 280, pp. 38–46, 2018.

[11] J. Jang *et al.*, "A microelectromechanical system artificial basilar membrane based on a piezoelectric cantilever array and its characterization using an animal model," *Sci. Rep.*, vol. 5, p. 12447, 2015.

[12] B. İlik *et al.*, "Thin Film PZT Acoustic Sensor for Fully Implantable Cochlear Implants," *Proceedings of Eurosensors*, vol. 1, no. 4, p. 366, 2017.

[13] P. Udvardi and J. Ferencz, "Spiral-Shaped Piezoelectric MEMS Cantilever Array for Fully Implantable Hearing Systems," *Micromachnies,*vol. 8, no. 10, 2017.

[14] C. Zhao, K. E. Knisely, and K. Grosh, "Modeling, fabrication, and testing of a MEMS multichannel aln transducer for a completely implantable cochelar implant," *TRANSDUCERS 2017 - 19th Int. Conf. Solid-State Sensors, Actuators Microsystems*, pp. 16–19, 2017.

[15] D. J. Carpenter, D. L. Tucci, D. M. Kaylie, and D. O. Frank-Ito, "Disagreement in middle ear volume estimation between tympanometry and three-dimensional volume reconstruction in the context of tympanic membrane perforation," *Journal of Otology.*, vol. 12, no. 2, pp. 74–79, Jun. 2017.

[16] S. A. Gelfand, *An Introduction to Psychological and Physiological Acoustics*, 5th ed. Essex, UK: Informa Healthcare, 2010.

[17] S. Nishihara, H. Aritomo, and R. L. Goode, "Effect of Changes in Mass on Middle Ear Function," *Otolaryngol. Neck Surg.*, vol. 109, no. 5, pp. 899–910, Nov. 1993.

[18] K. Arora, *Cochlear Implant Stimulation Rates and Speech Perception*, in *Modern Speech Recognition Approaches with Case Studies*, InTech, 2012.

[19] N. B. H. Croghan, S. I. Duran, and Z. M. Smith, "Re-examining the relationship between number of cochlear implant channels and maximal speech intelligibility," *Cit. J. Acoust. Soc. Am.*, vol. 142, p. 537, 2017.

[20] M. D. Nguyen, M. Dekkers, H. N. Vu, and G. Rijnders, "Film-thickness and composition dependence of epitaxial thin-film PZT-based mass-sensors," *Sensors Actuators A: Physical.*, vol. 199, pp. 98–105, Sep. 2013.

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