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Thin film piezoelectric acoustic transducer for fully implantable cochlear implants

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ABSTRACT

This paper reports the development of a single cantilever thin film PLD-PZT transducer prototype. The device was experimentally characterized by attaching it on an acoustically vibrating membrane resembling the behavior of the eardrum. Acceleration characteristic of the sensor attached on the membrane was obtained by using a Laser Doppler Vibrometer (LDV) as the output voltage was measured by an oscilloscope. A voltage output of 114 mV was obtained, when the device was excited at 110 dB Sound Pressure Level (SPL) at 1325 Hz. This is the highest value for a thin film piezoelectric transducer in the literature to our knowledge. Using the results of a finite element analysis for this single-channel prototype, which are within 92% agreement with the experimental results, we performed an optimization study to propose a multi-frequency acoustic sensor to be placed on the eardrum for fully-implantable cochlear implant (FICI) applications. The proposed multi-channel transducer consists of eight cantilever beams. Each of these beams resonates at a specific frequency within the daily acoustic band (250–5000 Hz), senses the eardrum vibration and generates the required voltage output for the stimulation circuitry. The total volume and mass of the transducer are $5 \times 5 \times 0.2$ mm^3 and 12.2 mg, respectively. High sensitivity of the transducer (391.9 mV/Pa @900 Hz) enables transmission of strong signals to be the readout circuit, which can easily be processed. Expected to satisfy all the requirements (volume, mass, and stimulation signal at the hearing band) of FICI applications for the first time in literature, the proposed concept has a groundbreaking nature and it can be referred to as the next generation of FICIs since it revolutionizes the operational principle of conventional CIs.

1. Introduction

Cochlea, ossicles and eardrum together form one of the most elaborated structures in mammalians. It provides a very large frequency selectivity (20 Hz – 20 kHz) and sound perception (0–140 dB SPL), which makes ear the best acoustic sensor in nature. Unfortunately, this delicate structure of the cochlea also makes is prone to degradation without recovery. Approximately 15% of the world's adult population has some degree of hearing loss according to the World Health Organization (WHO). In total, there are 360 million people living with a hearing loss higher than 40 dB SPL as of 2015, 32 million of these patients are children [1]. The level of hearing loss can be classified as mild, moderate, severe or profound. For mild-to-moderate damage, a hearing aid can be used to restore the hearing loss with sound amplification [2]. Whereas, Cochlear Implants (CIs) can be utilized for the treatment of severe-to-profound hearing loss caused by irreversible damage of the hair cells [3].

CIs recover hearing to a certain extent by directly stimulating the auditory nerves via electrodes. The current commercial CIs has some drawbacks, such as high cost, the need for frequent battery charging/replacement and the requirement of wearing external components. These result in interruption of patients' access to sound, discomfort and an increased the risk of damage, especially when the CI is exposed to an aqueous medium (e.g. shower, pool) [4,5]. Furthermore, conventional CIs eliminate the entire natural hearing mechanism. However, operational parts of the hearing system, such as the eardrum and ossicles, can be utilized by new generation implantable components. As an example, the vibrations of the eardrum can be detected by acoustic sensors eliminating the need for an external microphone.

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Recent advancements in the field point out that solution of the above-mentioned issues lies in the next generation fully-implantable, self-powered and stand-alone CIs. Earlier studies focused mainly on accelerometer-based implantable middle ear microphones for next generation CIs [6–11]. However, such systems require external control and RF battery charging units. MEMS accelerometers can be used as implantable sensors [12] but they lack sensitivity and suffer from high power consumption. Thermal and electromagnetic sensors were also used as alternative approaches [13], however they have a limited output voltage and an undesirably high system noise. Piezoelectric transducers are widely used to convert mechanical vibrations directly into electricity without a need for an external source [14]. Although piezoceramic devices have been proposed as promising alternatives for CI applications [15,16], there are still major scientific and technical challenges. Recently, Jang et al. reported successful use of a piezoelectric cantilever array for stimulation of the auditory neurons in deafened guinea pigs [17]. Yet, the maximum output voltage (<50 μV) is well-below the lower limit that could be detected by an interface circuit without external amplification. Furthermore, the working frequency of the implemented sensor does not cover the audible frequency range for humans.

Here, we propose a multi-frequency thin film piezoelectric acoustic sensor concept to overcome the main bottlenecks of CIs, considering the limitations regarding volume, mass and stimulation signal. The sensor is to be placed on the eardrum for fully-implantable cochlear implant (FICI) applications. The design consists of several thin film piezoelectric cantilever beams, each of which resonates at a specific frequency within the daily acoustic band. The device will exploit the functional parts of the natural hearing mechanism and mimic the function of hair cells, where the signal generated by the piezoelectric transducers will be processed by interface electronics to stimulate the auditory neurons in the cochlea.

In this paper, we developed a single-channel Pulsed Laser Deposited-Lead Zirconate Titanate (PLD-PZT) thin film piezoelectric acoustic transducer to demonstrate the feasibility of the proposed concept. We verified that the voltage output of this single-channel device is sufficiently high to be detected and processed by a readout circuit without any external power source. Acoustic and electrical performances of the developed transducer were characterized, where the experimental results were used to construct a finite element model to be used in the optimization of the design parameters of the final device covering the complete daily acoustic band.

2. Design and modelling

The feasibility of piezoelectric transduction due to the eardrum vibrations has already been demonstrated in the literature [17]. However, implementation of the method to next generation CIs has significant challenges and requires an advanced design procedure should be followed considering several limitations.

In the proposed system, an array of piezoelectric cantilever is to be placed on the eardrum or ossicles to provide the signal for neural stimulation. The major challenge in the design of the piezoelectric cantilevers is covering the daily acoustic band with an adequate number of channels within the small volume of the middle ear. The piezoelectric sensor output is to be processed by an interface circuit and converted into stimulation pulses. The quality of sound perception will typically be improved as the number of the channels increases, due to the increased resolution of stimulation frequencies. However, this also increases the hardware complexity and the power consumption. Therefore, a balance should be sought between the sound perception level and the power consumption.

It has been reported that the average hearing performance increases up to 8 channels, and no further improvement is observed with higher numbers of electrodes (10–20) [18,19]. Furthermore, a recent study from our group demonstrates that 8-channel FICI systems can operate with sub-mW power dissipation [20]. Considering these, an 8-channel transducer is considered to be good enough for the proposed design to cover the daily acoustic band (250–5000 Hz) and to provide adequate spectral resolution [20–22].

The limited volume (<0.1 cm^3) [23] in the middle ear, the mass tolerance (<25 mg) [24] and the size (9 mm × 10 mm) [25] of the eardrum are the main limitations for obtaining an adequate voltage output for neural stimulation. Beker et al. reported that use of bulk piezo-ceramics can generate a significant amount of energy [26], where a single-channel device occupies a minimum of 5 × 5 mm^2 footprint due to impact of the relatively thick bulk piezoelectric layer on the design parameters. It is obvious that such a device in multi-channel configuration cannot satisfy the eardrum dimension limitation. The footprint may be reduced by stacking the single-channel bulk transducers on top of each other, which results in an increased mass. This results in an increase in the level of challenge due to the coupled motion with eardrum and leads to a lower vibration amplitude at the same acoustic input level [27]. Therefore, the usage of bulk piezoelectric transducers as multi-channel acoustic sensors is not convenient for FICI applications.

Thin film piezoelectric materials can be integrated with MEMS in the desired volume [23], which makes them a promising alternative for the application. Pulsed Laser Deposited (PLD) Lead Zirconate Titanate (PZT) is preferred among other thin film piezoelectric alternatives due to their superior ferroelectric and piezoelectric properties for acoustic sensing [28]. Using PLD-PZT, a more compact multi-channel piezoelectric acoustic sensor can be designed, where all cantilevers can be placed on a single layer. This is possible since the thin film fabrication procedure allows for reduction of both the cantilever size and the distance between individual cantilevers. Consequently, mechanical filtering for an adequate number of channels to cover the daily acoustic band within the 25 mg maximum loading requirement will be facilitated, ensuring that there is no significant effect on the ear drum acceleration.

Fig. 1 shows the proposed system for sensing the incoming sound with a close-up view of the piezoelectric cantilever beams, each of which resonate at a specific frequency within the hearing band. The cantilevers are placed facing each other with increasing/decreasing lengths to result in a smaller footprint. When an acoustic sound pressure impinges on the eardrum, the cantilever beam with the resonant frequency matching the excitation frequency starts to resonate. Consequently, the proposed system provides mechanical filtering and shows a frequency selectivity mimicking the natural operation of the cochlea. Center frequencies of the 8-channel filter are distributed between 250 and 5000 Hz as it is in the existing CIs, where frequencies below and above 1200 Hz are spaced linearly and logarithmically, respectively [29,30].

Fig. 2 illustrates a single cantilever beam structure. Lengths of the cantilever beam, the thin film PZT layer and the tip mass are critical optimization parameters to obtain a sufficiently high signal within the volume and weight limitations. Beam length is varied for obtaining the desired center frequencies and the cantilever beams arranged to face each other in such a way that the array fits into 5 × 5 mm^2 footprint. Tip mass usage is inevitable in order to tune the resonance frequency of the transducers and the induced stress level, which increases the vibration level and voltage output. Tip mass thickness is optimized and fixed at 150 μm to obtain the lowest center frequency (300 Hz). PZT length is another critical design parameter to maximize the voltage output. Results show that maximum output occurs when % 44 of the cantilever length is covered with the active piezoelectric layer [31]. For this reason, we also use this value for our cantilevers.