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Characterization of Planar Based Electrode Piezoelectric Micromachined Ultrasonic Transducer for Underwater Sensor Application using FEA Simulation

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Abstract: This paper presents a simulation and characterization of piezoelectric macromachined ultrasonic transducer (PMUT) based on planar electrodes. This small scale device with low power consumption is important as an underwater sensor. However, PMUT has a low sensitivity problem. Thus, PMUT based on planar electrodes are designed to improve the sensitivity of the PMUT. The designs are simulated using Finite Element Analysis (FEA) COMSOL Multiphysics 5.0. It is based on planar electrodes, cavity and multilayer membranes which can improve the transmitting and receiving sensitivity of ultrasonic transducer. The targeting application is for an underwater sensor with the range frequency in between 300 kHz to 800 kHz. Two characterizations are studied which are transmitting voltage response (TVR) and open circuit receiving response (OCRR). Three parameters are investigated namely the piezoelectric material, the thickness of PZT5H and electrode area. In simulation results, aluminium nitrate (AlN) has the highest in both TVR and OCRR. For the different PZT5H thicknesses, the highest transmitting sensitivity is obtained at the thickness of 300 µm meanwhile for highest receiving sensitivity is obtained at the thickness of 500 µm. It is found that the electrode area at 0.3 mm x 0.3 mm has the highest in both transmitting sensitivity and receiving sensitivity. Based on the targeted frequency design, PZT5H with a thickness of 200 µm and the electrode area of 0.5 mm x 0.5 mm is the most appropriate one.

Keywords: Finite element; Open circuit receiving response; Planar based electrode PMUT; Transmitting voltage response; Underwater sensor.

1. INTRODUCTION

Ultrasonic Transducer (UT) has a capability to transmit and receive an ultrasonic signal in underwater. It has been used in many underwater applications such as underwater communication [1], underwater object detection and recognition [2] and underwater imaging [3]. All these applications have their own specifications of ultrasonic transducer. For underwater applications, the UT can be placed at the middle of the ocean or at the bottom of the ocean. It is difficult as the device requires power and energy whereas there is no direct power can be supplied to the UT. Therefore, the UT must be designed for low power consumption and has an ability in transmitting and receiving signal. Therefore, a piezoelectric micromachined ultrasonic transducer (PMUT) has been designed because of their micro scale device. The micro scale device has been used for a low power consumption and short range detection. However, a micro scale transducer device has low transmitting sensitivity and low receiving sensitivity as well.

Several researchers have studied the improvement sensitivity towards transmitting and receiving an ultrasonic signal. An array of smart PMUT has been designed with epitacially grown functional eutectic $Pb(Zr_{0.52}Ti_{0.48})O_3$ lead zirconate titanate (PZT) thin film on Si(111)/ γ - Al_2O_3(111)/SrRuO3(111) substrates to obtain high sensitivity. An array of 8 x 8 channel circular shaped has been designed for getting high density diaphragm [4]. A realization of arrays consisted of flexural piezoelectric transducers has been designed for low-frequency underwater. The transducer arrays consist of a flexural circular shape cells and each cell is a piezoelectric unimorph. Furthermore, the circular shape has only one edge and the flexural membrane will actuate at the middle of membrane. Therefore, it will provide more sensitivity to the transducer [5].

Thao *et al.* [6] designed a PMUT based on island shaped structures. The top electrode, polyimide and piezoelectric element, PZT are considered as a diaphragm of PMUT. It will work as flexural and give high displacement for high sensitivity.

Polyimide is function to cover PZT etch area. The shape of top electrode is round shape. In results, the used of Polyimide has reduced the capacitance and increased the output sensitivity. Sun *et al.* [3] also designed a PMUT using a flexural method but with a rectangular shape of diaphragm with less symmetric. In [6], a round shape for membrane design was used whereby it was a symmetrical shape and degenerated modes that lead to low output. The rectangular shape with ratio width to length can generate more modes and increase the output capability [7]. The results showed the increment amplitude and improvement in bandwidth. The bandwidth for symmetrical shape is narrow compared to rectangular shape. But this shape is difficult to be designed as optimization is required.

Luo *et al.* [8] designed a PMUT with cavity to improve the sensitivity. PMUT with cavity will give more displacement and large effectiveness area as compared to without cavity in [3] and [6]. The diaphragm consists of multiple membranes such as a top electrode, a piezoelectric layer, a bottom electrode and an elastic layer. Cavity has been located under these multiple membranes. The finite element method (FEM) simulation results have been shown that a large area of diaphragm responded and generated high output. The output sensitivity has shown that the PMUT with cavity has higher amplitude as compared to PMUT without cavity at same resonance frequency. Kusano *et al.* [9] has designed a PMUT with cavity but in different shape. The hexagon shape has been proposed in designing the diaphragm and improved more sensitivity. The results have shown the hexagon shape has a higher displacement amplitude compared to circular shape. Thus, the output sensitivity of hexagon shape was higher compared to circular shape. Wang *et al.* [10] has designed a PMUT with a cavity in thin membrane. The thin membranes were supported by a top electrode, a piezoelectric layer, a bottom electrode and an elastic layer. The results have shown that the output sensitivity was higher compared to [6].

This paper proposes a single PMUT with planar electrodes in multi membranes that consists of a polydimethylsiloxane (PDMS), a piezoelectric layer and planar electrodes. This design will improve the low sensitivity in transmitting and receiving an ultrasonic signal that occurred by ultrasonic transducer. The cavity and planar electrodes are the new techniques have are introduced for improvement. Section 2 describes a design of PMUT and FEA simulation setup. Section 3 demonstrates a FEA simulation results of PMUT with discussions. Finally, a conclusion remark is given.

2. METHODOLOGY

This section discusses the design of a PMUT and the methodology. In the design section, the electrode planar circuit and a polarization of piezoelectric is discussed. Then, in simulation setup section, FEA simulation setup using COMSOL Multiphysics 5.0 is described.

2.1 Theory

A PMUT is used to transmit and receive an acoustic wave or an ultrasonic wave through the medium such as air, fluid or solid based on sensing element piezoelectric material. A piezoelectric material has an ability to transduce an acoustic wave (mechanical form) to electric field (electrical form) or vice versa. When a piezoelectric material with a stress from an acoustic wave that hit the membrane, it can create an electric field. The relationship between the mechanical form and the electrical form inside the piezoelectric is called piezoelectricity. Piezoelectricity can be described mathematically using the material's constitutive equations.

Piezoelectric materials become electrically polarized if their membrane subjected to a strain. The atoms are displaced from their seat if the membrane has been deformed caused by the electric dipoles within the material. The crystal structures also give an average macroscopic dipole moment or electric polarization. This is called a piezoelectric effect. The constitutive equation represented the strain-charge is as

$$\begin{aligned} S &= s_E T + d^T E \\ D &= dT + \varepsilon_T E \end{aligned} \tag{1}$$

where S is the strain, T is the stress, E is the electric field, and D is the electric displacement field. The material parameters, s_E, d and ε_T correspond to the material compliance, the coupling properties and the permittivity of the material respectively. Next, the stress-charge constitutive form is obtained as

$$\begin{aligned} T &= c_E S - e^T E \\ D &= dS + \varepsilon_S E \end{aligned} \tag{2}$$

where the material properties, c_E, e^T, and ε_S have relationships with the parameter s_E, d and ε_T as

$$\begin{aligned} c_E &= s_E^{-1} \\ e^T &= d s_E^{-1} \\ \varepsilon_s &= \varepsilon_o \varepsilon_{rT} - d s_E^{-1} d^T \end{aligned} \tag{3}$$

COMSOL Multiphysics consists of three element physics that can be used to evaluate and analyse a PMUT structure in term of transmitting activities and receiving activities. It involves two mechanical elements namely acoustic wave and solid material, and one electrical element which is electrostatic. The underwater acoustic wave takes into account the acoustic-structure boundary which is pressure acoustics in governing wave equation as

$$-n\left(-\frac{1}{\rho_c}(\nabla p_t - q_d)\right) = -nu_{tt}$$
$$F_A = p_t n \tag{4}$$

where u_{tt} is the structure acceleration, n is the surface normal, p_t is the total acoustic pressure, and F_A is the load (force per unit area) acted on sensing membrane. The electrostatic in dielectric material has a relationship with a charge density as

$$\rho_p = -\nabla . P \tag{5}$$

where P is polarization and ρ_p is the charge density.

2.2 Design

Design of a PMUT circuit is based on planar a electrodes circuit, consisting of contact pad, electrodes and polyimide. The shapes of planar electrodes are square as shown in Figure 1. The planar electrodes consist of a Polyimide-Copper-Polyimide sandwich structure. The electrodes and contact pads are not covered by polyimide because the electrodes are adhered to piezoelectric material meanwhile the contact pads are soldered with an external wire. The contact pads are used to provide or bring out the voltage from the electrodes. The schematic diagram is shown in Figure 1. The multilayer membranes consists of PDMS, piezoelectric material and planar electrodes.

The PDMS is placed at the top of PMUT and worked as matching layer for water and piezoelectric material. The piezoelectric material is placed at the bottom of PDMS and worked as a sensing element. Figure 2 shows a cavity between polyimide and piezoelectric layer to increase an output sensitivity. A cavity consists of air that traps in between polyimide and piezoelectric layer. Air is less density and compressible that let the piezoelectric membrane bending at a maximum displacement. If the membrane can have a large bending, it increases the strain inside piezoelectric material. Thus, the output sensitivity will improve. The polyimide is used as an insulator and elastic element to increase the flexural of membrane. A PMUT with high flexural membrane will increase sensitivity as compare to the PMUT without a flexural membrane. The schematic of PMUT is shown in Figure 2.

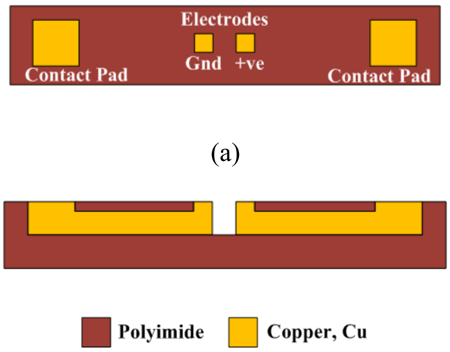

Figure 1. Schematic diagram of top view Planar Electrodes, (a) top view, and (b) side view

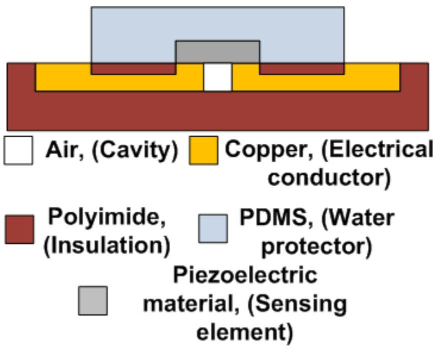

Figure 2. Schematic diagram of side view PMUT multilayer membranes

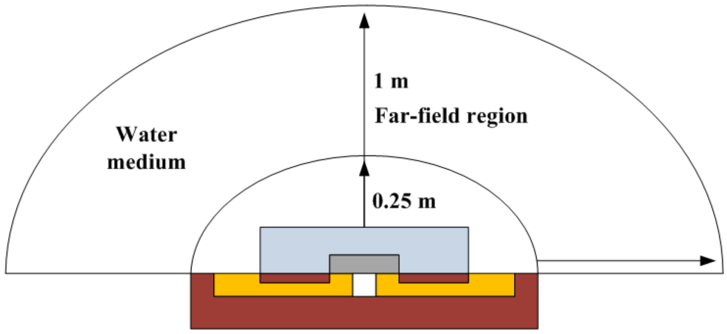

Figure 3. Simulation setup for underwater PMUT

2.3 Simulation Setup

A FEA simulation has been setup for the PMUT to characterize its frequency response, a transmitting voltage response (TVR), a receiving sensitivity (OCRR) and operation bandwidth. The PMUT parameters which are the piezoelectric material, the thickness of PZT5H, and the electrode size were investigated. Figure 3 shows the simulation design setup for an underwater PMUT. The far-field region represents the water. It is set up to 1 meter as a limit strength for high-frequency an acoustic wave can travel in shallow water.

In a global definition, pressure, P_{rms} = 1/(0.000001)[V/µPa] and root mean square voltage, V_{rms} = 1 V were set to the parameter box. In the component section, five equations have been included in the variable box. Equations (6) – (10) represent the receiving voltage (RV), pressure far-field location ($pfar1$), root mean square pressure (P_{rms}), TVR and OCRR respectively.

$$RV = intop\left(\frac{es.JZ}{es.omega \times 0.0005 \times 4.06 \times 10^{-6}}\right) \tag{6}$$

$$pfar1 = (0,0,1) \tag{7}$$

$$P_{rms} = \sqrt{0.5 \times pfar1 \times conj(pfar1)} \tag{8}$$

$$TVAR = 20\ log_{10}\frac{P_{rms}}{V_{rms}} \tag{9}$$

$$OCRR = 20\ log_{10}\frac{RV}{P_{rms}} \tag{10}$$

where $intop$ is integral evaluation on sensing element, $es.omega$ is electrostatic current measurement, $es.Jz$ is a current density and $pfar1$ is a far-field pressure. The geometry is designed as shown in Figure 3, and all material properties are set as given in Table 1. On the other hand, all parameters of PMUT geometry design is shown in Table 2, which were set in the geometry box.

Table 1. Mechanical properties of all PMUTs' materials

Properties / Material	Density (kg/m^3)	Speed of sound (m/s)	Young's modulus (GPa)	Poisson's ratio
Water	1028	14530	na	na
PDMS	969	1119	0.5	0.5
Copper	8960	4660	128	0.36
Polyimide	1420	2440	7.5	0.35
Aluminum nitrate (AlN)	3300	11050	340	0.24
Lead zirconate titanate (PZT5H)	7800	4560	78	0.31
Polyvinylidene Fluoride (PVDF)	1780	2250	8.3	0.08
Quartz	2650	5800	76.5	0.18
Zinc oxide (ZnO)	5680	6336	120	0.446

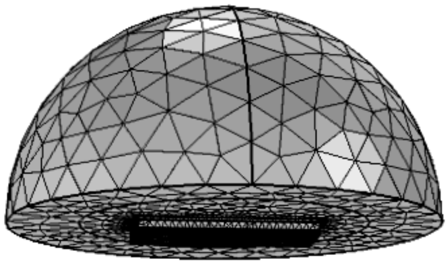

Figure 4. Mesh analysis setup

Table 2. All parameters of PMUT geometry design

Material \ Geometry properties	Thickness (mm)	Length (mm)	Width (mm)
PDMS	0.1	2.5	2.6, 2.8, 3.0, 3.3, 3.5
Piezoelectric material (varied)	0.028, 0.05, 0.11, 0.2, 0.3 and 0.5	0.5	0.6, 0.8. 1.0, 1.3, 1.5
Electrodes (positive electrode and ground electrode) (varied)	0.034	0.5	0.1, 0.3, 0.5, 0.8. 1.0
Contact pads (left and right contact pad)	0.034	2.0	2.0
Electrical path	0.026	0.3	4
Polyimide (varied)	0.026	2.5	16.6, 16.8, 17, 17.3, 17.5

Relationship between three components of physic which are pressure acoustic, solid mechanics, electrostatics and acoustic-structure is studied in the simulation. Next, a proper mesh analysis is selected including size and type of mesh. In this simulation, the size was selected as normal and tetrahedral was selected as the type of mesh. The mesh setup is shown in Figure 4. Three parameters that were studied were piezoelectric material, the thickness of PZT5H and the area of electrodes. The piezoelectric materials that were simulated were Aluminium Nitrate (AlN), Polyvinylidene Fluoride (PVDF), Lead Zirconate Titanate (PZT5H), Quartz and Zinc Oxide (ZnO). All the geometric parameters of the materials are shown in Table 2. The characterizations of TVR and OCRR were shown in the simulation results. From that, the performances in terms of resonance frequency and operation bandwidth were obtained.

3. RESULTS AND DISCUSSION

Two output responses were obtained from the simulations conducted on a PMUT. TVR was obtained from the output of transmitter meanwhile OCRR was obtained from the receiver. The TVR simulation results for different types of piezoelectric materials are shown in Figure 5. The results showed that AlN has the highest transmitting sensitivity (176 dB rel. 1μPa/V) followed by PZT5H, PVDF, ZnO, and the lowest transmitting sensitivity is Quartz. The AlN has the highest TVR as its Young's modulus is the highest as compared to all other materials. As the Young's modulus is a property of elastic material, high Young's modulus will increase the elasticity of the material. Therefore, strain will occur more inside the AlN and created high power during transmitting. In addition, the speed of sound of AlN is much closer to water, and the ultrasonic wave created by PMUT is easily transmitted through the water medium. However, PZT5H has a resonance frequency at 325 kHz which is a suitable piezoelectric material for the targeted design in the medium frequency range in between 300 kHz to 800 kHz.

The OCRR simulation results for different types of piezoelectric materials are shown in Figure 6. The results showed that the AlN also led the others in high receiving sensitivity. These are followed by PZT5H, ZnO, PVDF and Quartz. The OCRR and resonance frequency for AlN are 2 dB rel 1V/μPa and 1050 kHz respectively. The AlN performed better as its dielectric constant is lower as compared to the others. The dielectric constant for AlN is 8.9 whereas for PZT5H is 3450. The dielectric constant of a material is a property to permit the acoustic wave to penetrate its membrane. Besides, AlN has a high Young's modulus that gives stress inside the material and produces high voltage as well as high receiving sensitivity. The PZT5H is the second-highest as their mechanical coupling is the highest among the others. The OCRR and resonance frequency for the PZT material were -8 dB rel 1V/μPa and 425 kHz respectively. Mechanical coupling is a property of capability to convert the mechanical property to electrical property. A higher mechanical coupling will result in a more efficient in conversion of ultrasonic wave to voltage. Mechanical coupling for PZT5H is 70 while the AlN is 8.5.

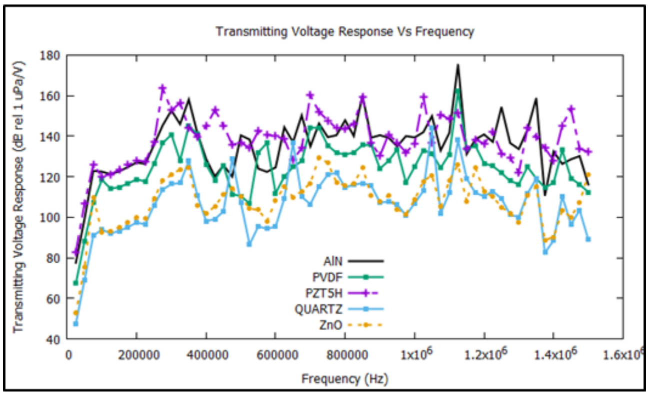

Figure 5. TVR for different piezoelectric materials

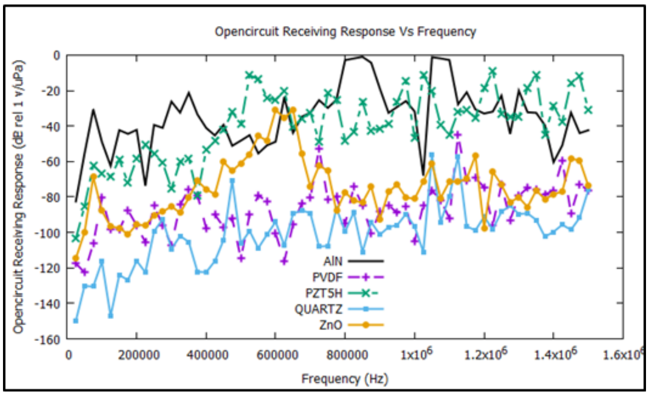

Figure 6. OCRR for different piezoelectric materials

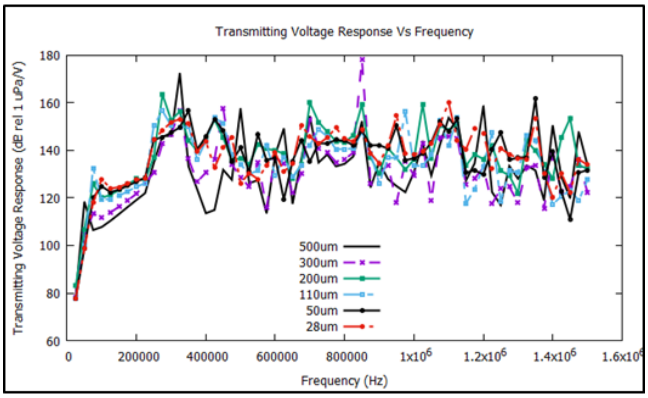

Figure 7. TVR for different thicknesses of PZT5H

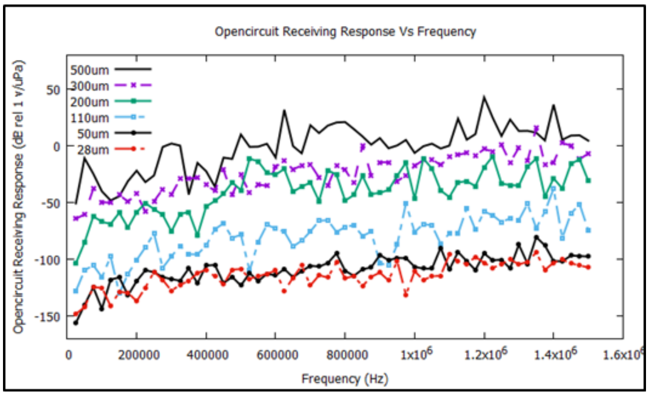

Figure 8. OCRR for different thicknesses of PZT5H

Subsequently, PMUT with PZT5H was studied as its resonance frequency for both transmitting voltage response and receiving voltage response is in the targeted operation frequency design (i.e., 300 kHz to 800 kHz). Furthermore, their transmitting sensitivity and receiving sensitivity were also in the targeted frequency design. In this simulation, the variable of PZT5H thicknesses was studied to configure out the best thickness of PZT5H that can produce a good resonance frequency and sensitivity for transmitting and receiving. The parameter of geometry models has been explained in the methodology section.

The TVR simulation result for different thicknesses of PZT5H is shown in Figure 7. The result shows the highest transmitting sensitivity was obtained with the thickness of 0.3 mm following by the thickness of 0.5 mm, 0.2 mm, 0.11 mm, 0.028 mm and 0.05 mm. The transmitting sensitivity and resonance frequency for the thickness of PZT5H at 0.3 mm are 180 dB rel. 1μPa/V and 875 kHz respectively. The best thickness for PZT5H in the targeted frequency design were 0.5 mm and 0.2 mm, which resonance frequencies of 350 kHz and 325 kHz respectively.

The OCRR simulation results for different thicknesses of PZT5H are shown in Figure 8. The highest receiving sensitivity was obtained by a thickness of 0.5 mm and followed by 0.3 mm, 0.2 mm, 0.11 mm, 0.05 mm and lastly 0.028 mm. The receiving sensitivity and resonance frequency for the thickness of PZT5H at 0.5 mm is 35 dB rel. 1μPa/V and 1200 kHz respectively. The best suitable PZT5H thickness for the targeted frequency design is 0.200 mm because the other PZT5H thicknesses were outside of the targeted frequency design. The resonance frequency for the thickness of PZT at 0.2 mm is 425 kHz.

Finally, simulations of different area sizes of the electrode were conducted. The TVR simulation results for different sizes of the electrode are shown in Figure 9. The results showed that the highest transmitting sensitivity was obtained by an electrode area at 0.3 mm x 0.3 mm and followed by electrode area 0.5 mm x 0.5 mm, 1.0 mm x 1.0 mm, 0.8 mm x 0.8 mm and 0.1 mm x 0.1 mm. The transmitting sensitivity and resonance frequency for electrode area at 0.3 mm x 0.3 mm are 170 dB rel. 1μPa/V and 1350 kHz respectively. It was found that the electrodes area of 0.5 mm x 0.5 mm was suitable for the targeted frequency design, although it was the second highest in transmitting sensitivity. The transmitting sensitivity and resonance frequency for electrode area at 0.5 mm x 0.5 mm are 168 dB rel. 1μPa/V and 325 kHz respectively.

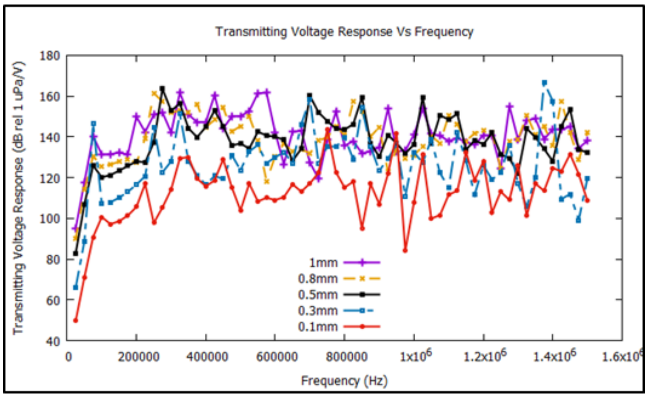

Figure 9. TVR for different electrode area

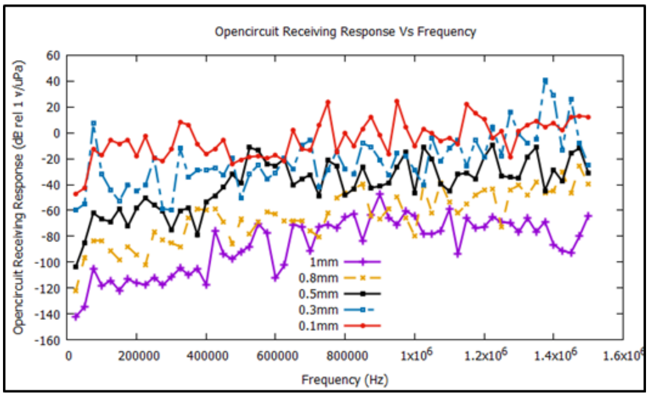

Figure 10. OCRR for different electrode area

The OCRR simulation results for different sizes of the electrode are shown in Figure 10. The results showed that the electrode area at 0.3 mm x 0.3 mm has the highest receiving sensitivity as compared to others. These were followed by electrode area 0.1 mm x 0.1 mm, 0.5 mm x 0.5 mm, 0.8 mm x 0.8 mm and 1.0 mm x 1.0 mm. The receiving sensitivity and resonance frequency for 0.3 mm x 0.3 mm are 40 dB rel. 1μPa/V and 1350 kHz respectively. The best suitable electrode area design for the targeted frequency was 0.5 mm x 0.5 mm as the other electrode area designs are outside of the targeted frequency design. The receiving sensitivity and resonance frequency for 0.5 mm x 0.5 mm are -8 dB rel. 1μPa/V and 425 kHz respectively.

4. CONCLUSION

This paper has presented a design of PMUT based on the planar electrode and characterized using FEA simulation COMSOL Multiphysics 5.0. In piezoelectric material characterization, AlN has been shown to be the highest in both TVR and OCRR. In the characterization of different PZT5H thicknesses, the highest transmitting sensitivity has been obtained by the thickness of PZT5H at 0.3 mm, whereas for highest receiving sensitivity has been obtained by the thickness of PZT5H at 0.5 mm. Analysis of different sizes of electrode area has shown that the electrode area at 0.3 mm x 0.3 mm has the highest in both transmitting sensitivity and receiving sensitivity compared to the others. However, as the targeted frequency design was in the range of 300 kHz to 800 kHz, PZT5H was selected as the sensing material. In this case, the thickness of PZT5H is 0.2 mm and the electrode area is 0.5 mm x 0.5 mm.

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REFERENCES

[1] S. Sadeghpour, M. Kraft and R. Puers, Coupled piezoelectric bulk-micromachined ultrasound trasndcuer (cpb-mut): An ultrasound transducer with enhanced pressure response in liquid and dense medium, *Proceedings of 2019 IEEE International Ultrasonics Symposium*, Glasgow, 2019, 1099–1102.

[2] G. Grelowska and E. Kozaczka, Underwater acoustic imaging of the sea, *Archives of Acoustics*, 39, 2014, 439–452.

[3] C. Sun, Q. Shi, M. S. Yazici, T. Kobayashi, Y. Liu, and C. Lee, Investigation of broadband characteristics of multi-frequency piezoelectric micromachined ultrasonic transducer (MF-pMUT), *IEEE Sensors Journal*, 19(3), 2019, 860–867.

[4] M. A. Matin, K. Ozaki, Y. Numata, D. Akai, K. Sawada and M. Ishida, Quantifying modal shapes in smart piezoelectric ultrasonic transducer array: Modeling and experiment, *Proceedings of 2013 IEEE Sensors Conference*, Maryland, 2013, 1–4.

[5] A. S. Savoia, B. Mauti and G. Caliano, A low frequency broadband flextensional ultrasonic transducer array, *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 63(1), 2016, 128–138.

[6] P. N. Thao, S. Yoshida and S. Tanaka, Development of mechanically-robust piezoelectric micromachined ultrasonic transducer (pMUT) with island-shaped PZT monocrystalline thin film, *Proceedings of 20th International Conference on Solid-State Sensors, Actuators and Microsystems Eurosensors XXXIII*, Berlin, 2019, 833–836.

[7] Tao Wang, T. Kobayashi and C. Lee, Broadband piezoelectric micromachined ultrasonic transducer (pMUT) using mode-merged design, *Proceedings of 10th IEEE International Conference on Nano/Micro Engineered and Molecular Systems*, China, 2015, 238–242.

[8] G.-L. Luo and D. A. Horsley, Piezoelectric micromachined ultrasonic transducers with corrugated diaphragms using surface micromachining, *Proceedings of 20th International Conference on Solid-State Sensors, Actuators and Microsystems Eurosensors XXXIII*, Berlin, 2019, 841–844.

[9] Y. Kusano, G.-L. Luo and D. A. Horsley, Spurious mode free hexagonal PMUT array, *Proceedings of 20th International Conference on Solid-State Sensors, Actuators and Microsystems Eurosensors XXXIII*, Berlin, 2019, 238–241.

[10] H. Wang, Y. Yu, Z. Chen, H. Yang, H. Jiang and H. Xie, Design and fabrication of a piezoelectric micromachined ultrasonic transducer array based on ceramic PZT, *Proceedings of 2018 IEEE Sensors Conference*, New Delhi, 2018, 1–4.