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Design of Ultrasonic MEMS Transducer for Temperature Sensor

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ABSTRACT

There are numerous temperature sensors available having diverse characteristics depending upon their actual application. This paper aims to discuss the miniaturized size of ultrasonic transducer based temperature sensor. Both transmitter and receiver for this ultrasonic Micro-Electronics Mechanical Systems (MEMS) based temperature sensing device are of piezoelectric material. Prior to fabrication of ultrasonic MEMS device, design and simulation are extensively used to avoid wastage of time and test the workability of a system without much expenditure. COMSOL Multiphysics 4.4 is a versatile tool and is used to design and solve the transducer device with 3D partial differential equations. In this paper, the piezoelectric transducer is designed with Lead Zinconate Titanate (PZT) which can be used as thin film. The proposed device relies on propagation of 40 KHz ultrasonic waves in air medium with varying temperature. This indicates that by using this principle high temperature sensing devices can be fabricated.

Keywords: ultrasonic, temperature sensor, MEMS, PZT

1. INTRODUCTION

High-temperature sensing is mandatory in many fields such as major sectors of industries, including material production and processing, power plants, automotive, transportation and aerospace. Piezoelectric is sensing gaining popularity on the grounds of its compact size, low cost and fairly modest signal conditioning compared to other available techniques for high-temperature sensing [1]. For majority of processes efficiency increases with increase in temperature. Hence the ability to operate at high temperature is a vital aspect for thermal sensors. Numerous approaches have been adopted for fabrication of piezoelectric transducers that can operate at high temperatures, such as application of waveguides in order to remove the transducer from the high temperature element under inspection or the use of piezoelectric materials with comparatively high Curie temperatures in order to permit the transducers to function at higher temperatures [2-4].

Considerable research has been conducted on fiber optic, piezoresistive, capacitive and piezoelectric sensors for high-temperature applications [5-7]. Fiber optic sensors have gained popularity on behalf of applications involving operation at higher temperature as a result of their insusceptibility to electromagnetic intrusion and elevated temperatures of operation. Though sensors of this variety entails distinct packing in order to guard the fiber tips and wires which are very fragile in nature. Mechanical failure of this kind of sensors may occur due to inconsistency of thermal expansion coefficient of both the fiber and packing materials which curbs the use of fiber optic based sensors in high temperature environment [8]. Along with problematical procedure of manufacture, optic based sensors have a costly and challenging system for signal processing which are some of the key shortcomings limiting its usage [9-10]. Piezoresistive sensors utilizes the variation in resistance combining with the reaction to foreign turmoil namely acceleration, pressure or force. Generally, piezoresistive materials are less vulnerable to hindrance caused by electromagnetic waves. On the contrary the integral temperature dependency of materials upon resistivity

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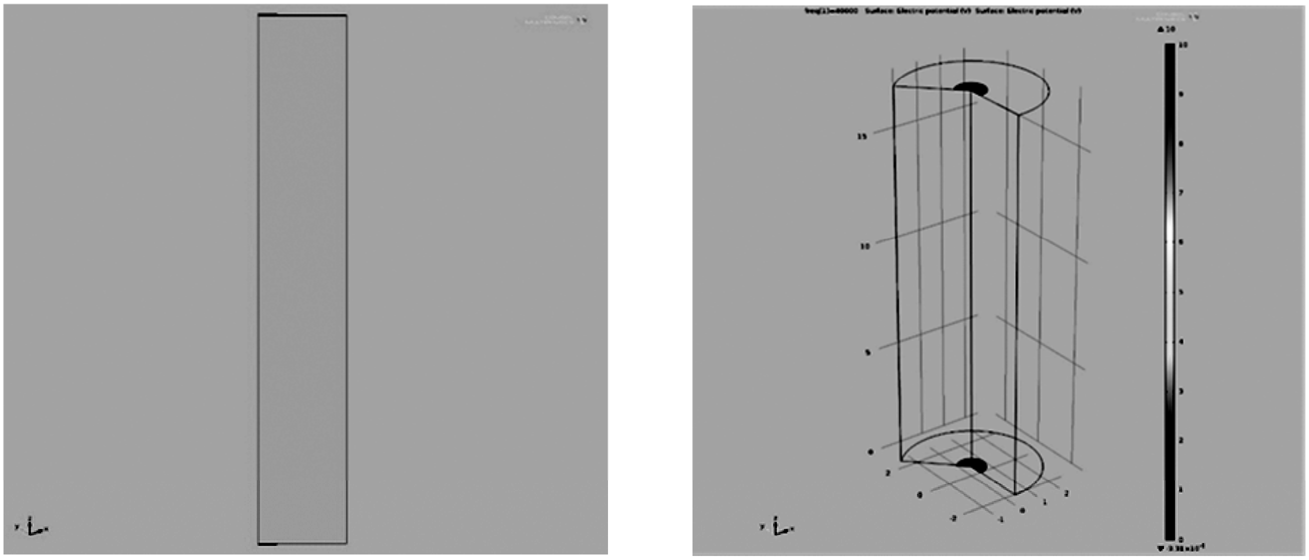
can lead to imprecisions at high temperatures [11-12]. Capacitive sensors have the added advantage of high resolution, small thermal drift and decent noise performance. Nonetheless, they suffers from inadequate robustness and are easily affected by parasitic capacitance equivalent to that of the sensor [13-15]. Conventional methods of sensing using piezoelectric material has widely been practiced in sensing various parameters like chemicals, vibration, distance, pressure and mass. Temperature sensing is however a new concept which is dependent on thermal properties of piezoelectric material and the propagation of ultrasonic wave in air medium.

In this present work, the ultrasonic Micro-Electro Mechanical Systems (MEMS) device technology is used to develop a miniaturized transmitter and receiver. Ultrasonic MEMS technology has recently emerged as an alternative objective that offers enhancements such as a substandard voltage requirement, flexible geometries and mixing of various resonant frequencies for integration with auxiliary microelectronics circuits. The designed acoustic transducers is based on the fundamental piezoelectric property. Piezoelectric materials generate ultrasonic waves that have large piezoelectric coefficient, moderately larger dielectric constant and a very high electromechanical coupling coefficient. The aforementioned parameters facilitate the propagation of the generated ultrasonic waves through the air medium. As a result of large electromechanical coupling coefficient it has a broader bandwidth [16].

For the purpose of transmitter and receiver the versatile material Lead Zinconate Titanate (PZT) is used. It has an exclusive semiconducting property and shows excellent piezoelectric behavior [17]. PZT can operate over a wide range of frequencies for transmitting and receiving and can also be cut into a large variety of shapes and sizes that can be customized to meet specific requirements and application [18]. It has low drive and high output and also possesses good mechanical and acoustic coupling [19]. Since MEMS experiments are time consuming and are carried out at an expense of resources are consequently preferred to be done through a multidisciplinary simulation platform. The platform used is COMSOL Multiphysics 4.4

2. MODEL GEOMETRY OF ULTRASONIC TEMPERATURE SENSOR

In this simulation study, the Piezoelectric Devices module was used to design MEMS ultrasonic Temperature Sensor in which a parameterized geometry was created with the addition of Predefined materials to the



(a) (b)

Figure 1 (a): 2D axis- symmetric model geometry showing the structure of air medium as well as PZT sample, (b) 3D View of the model.

model from the material browser. The 2D axis-symmetric package in COMSOL Multiphysics 4.4 was employed in the simulation work of the device. Comparatively small size piezoelectric film is used as ultrasonic transmitter and receiver. The air medium is considered as a cylindrical structure of 5.2 cm diameter and 17.5 cm height. During simulation, the ultrasonic wave generated by the model is assumed to be transmitted through the air medium. The physical properties of the medium changes with change the temperature which also impacts the propagation of ultrasonic wave.

3. MATHEMATICAL CALCULATION

In the air medium, altering temperature affects many parameters such as speed of sound and air density. Speed of sound (c) is directly proportional to temperature (T) [20]. It can be given as follows

$$c = c_0 * \sqrt{\left\{1+\left(\frac{T}{273.15}\right)\right\}} \tag{1}$$

In terms of temperature it can be written as

$$T = \left(\left[\frac{c}{c_0}\right]^2 - 1\right) * 273.15 \tag{2}$$

Where c_0 is speed of sound at 0ºC which is equivalent to 331.3 m/s.

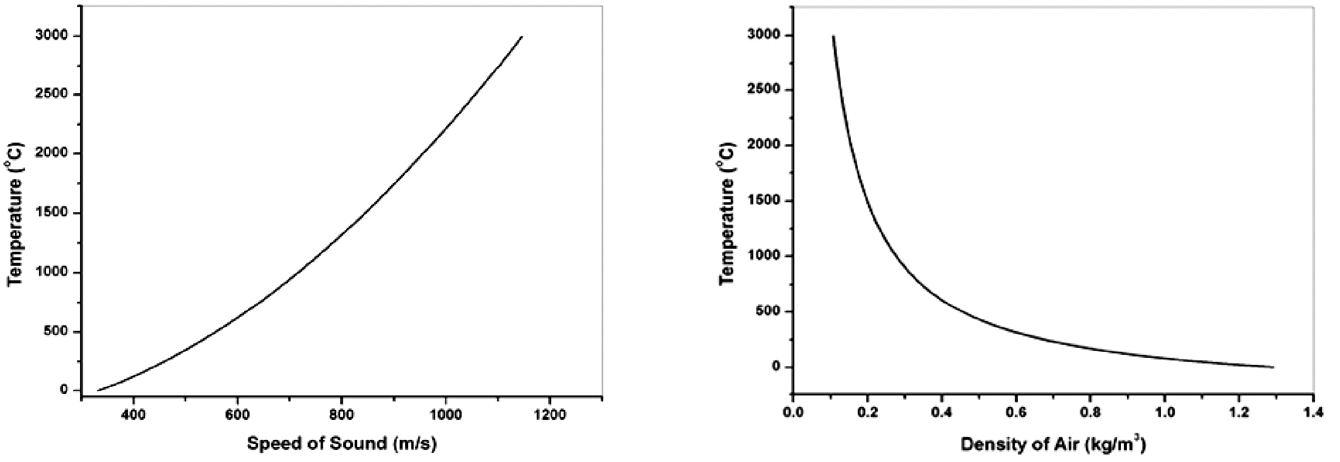
However, Density of Air (ρ) is inversely proportional to temperature (T) [21]. Atmospheric pressure (P) and specific gas constant (R) for dry air are constant.

$$\rho = \frac{p}{\left\{R\left(273.15+T\right)\right\}} \tag{3}$$

In terms of temperature it can be written as

$$T = \left[\frac{p}{\rho R} - 273.15\right] \tag{4}$$

Plots for Equation 2 and Equation 4 can be seen in Fig. 2(a) and 2(b)



(a) (b)

Figure 2: (a) Speed of sound vs. Temperature, (b) Air Density vs. Temperature

4. RESULTS AND DISCUSSION

The piezoelectric ultrasonic transmitter produces an acoustic wave that propagates in the air medium all the way to the receiver. The geometry of the medium plays an important role in choosing the correct operating frequency for the transmitter.

4.1. Frequency Optimization

The operating frequency of the transmitter is varied from 20 KHz to 80 KHz. The optimum transmitting pressure and generated voltage is obtained at optimized frequency of 40 KHz as shown in Fig. 3. Hence the operating frequency is kept constant at 40 KHz.

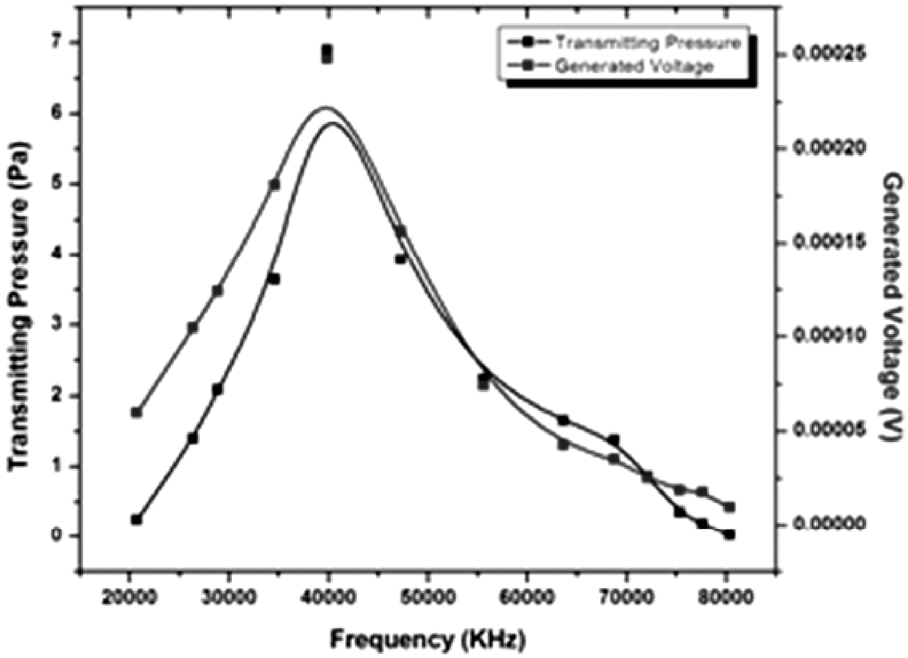
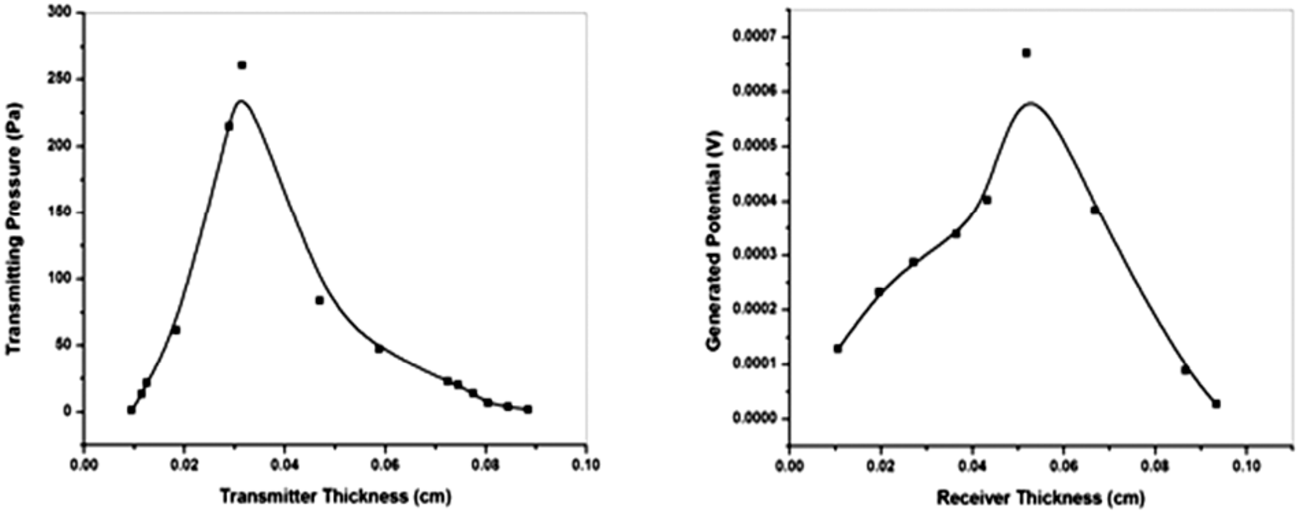


Figure 3: Frequency optimization

4.2. Effect of sample width and thickness on fundamental frequency

At an optimized frequency of 40 KHz and a constant width of 0.5475 cm the thickness of the transmitter and the receiver are varied from 0.01 cm to 0.0885 cm. The transmitter and the receiver is optimized at



(a) (b)

Figure 4: (a) Transmitter thickness optimization (b) Receiver thickness optimization

0.0315 cm for maximum transmitting pressure and 0.0515 cm for maximum generated voltage as shown in Fig. 4(a) and Fig. 4(b) respectively.

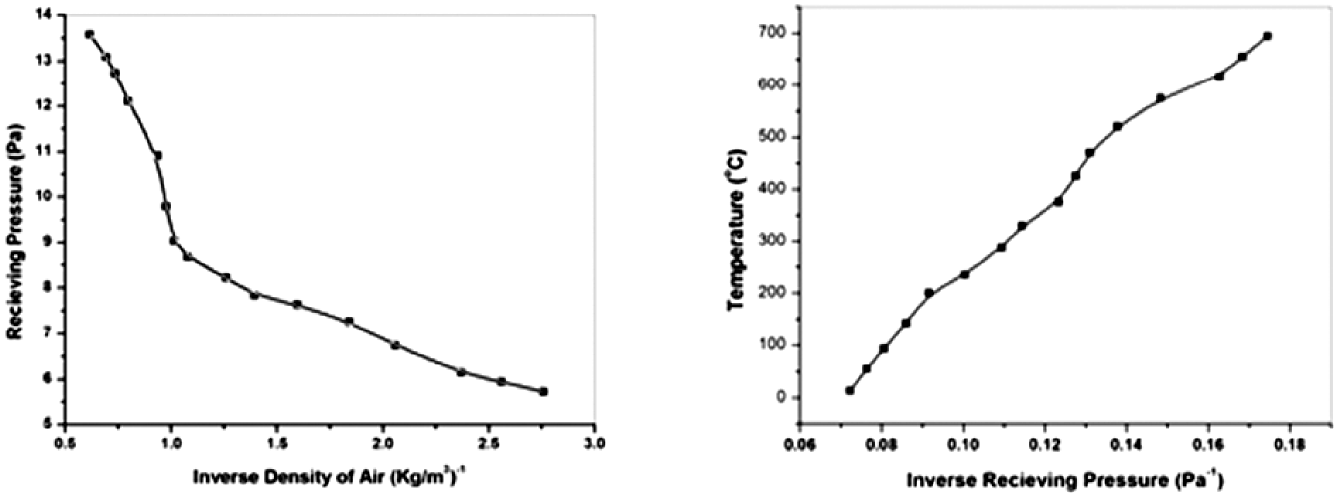
4.3. Study of Receiving Pressure and Generated Voltage at the Receiving End

The cross-sectional 2D axis symmetric geometry model of piezoelectric MEMS transmitter is maintained by changing the medium density and speed of sound with varying temperature and keeping the shape and size intact. Fig. 5(a) shows that the receiving pressure decreases when the inverse of air density increases. Hence the receiving pressure decreases with decreasing density of air inside the transmitting medium. Fig. 5(b) shows that the receiving pressure is inversely proportional to temperature. So, with increasing temperature, density decreases but the receiving pressure diminishes.

Generated Potential (V) is solely dependent on piezoelectric material property such as voltage sensitivity of Material (), receiving pressure (P) and thickness of the receiver (t).

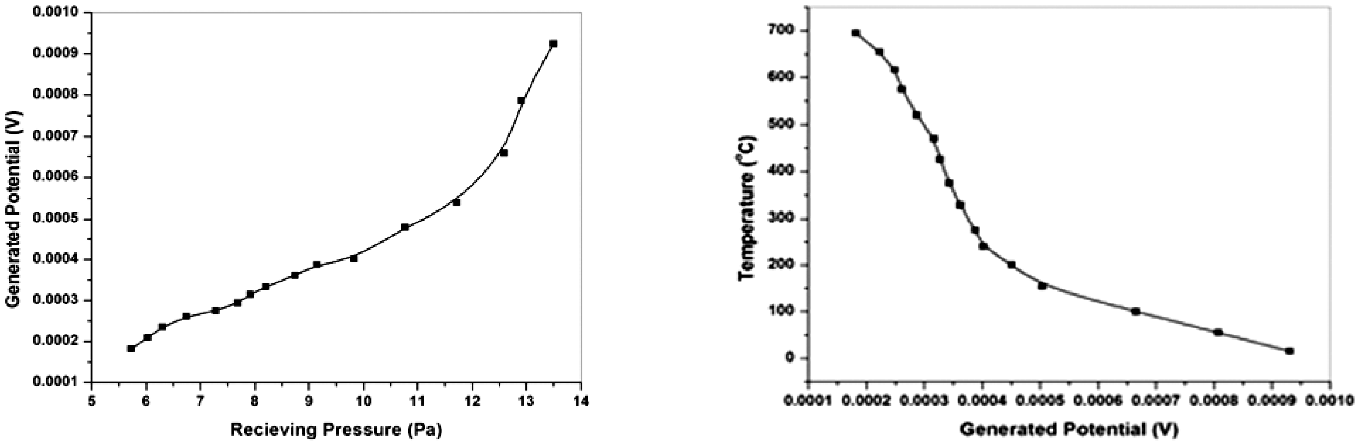
$$V = S_v . P . t \tag{5}$$

Fig. 6(a) shows the relationship between receiving pressure and generated potential. As voltage sensitivity and receiver thickness are constant, generated potential is directly proportional to receiving pressure which is clearly indicated in Fig. 6(a).



(a) (b)

Figure 5: (a) (Air Density)-1 vs. Receiving Pressure, (b) (Receiving Pressure)-1 vs. Temperature



(a) (b)

Figure 6: (a) Receiving Pressure vs. Generated Voltage, (b) Generated Voltage vs. Temperature

By comparing the plots from Figure 5(a), Figure 5(b) and Figure 6(a), it becomes clear that the generated voltage at the receiver end decreases as at the temperature rises, which can be seen in Figure 6(b). Hence from the generated potential the temperature can be determined.

5. CONCLUSION

PZT based ultrasonic MEMS transducers are designed by using COMSOL Mutiphysics tool. From results of simulation it is found that the less pressure generates as temperature increases. It has quite significant pressure which can be utilized as an ultrasonic temperature sensor. However it looses it's piezoelectric property beyond a temperature of 700ºC. Other piezoelectric materials can be used in place of PZT for sensing higher temperature.

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