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Capacitive effect of coplanar electrodes partially outside the microchannel region for underwater microfluidic-based sensor

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This work aims to obtain the capacitance resulted from the coplanar electrode configuration meant to be used for underwater sensing application. Coplanar structure is proposed to overcome the complexity of parallel electrode microfabrication processes which require repeating process of layer deposition. Work is achieved through Finite Element Model (FEM) using ANSYS 12.1 and the result is compared with analytical equation for validation purpose. The model is then modified geometrically to investigate the effect of extending the electrodes beyond the microchannel region. This is due to a very small size of microchannel which sometimes requires the electrodes to be fabricated at larger dimension to increase the detection capability. The result shows that for the specified design (methanol as microfluidic material and PDMS as body structure), electrode width is not a dominant factor that contributes to the detection capability if located outside the microchannel region. Beyond the microchannel region, even the electrodes width is increased, the capacitance value seems to be decreasing.

[**Keywords:** Capacitive sensing, Micro fluidic-based, Coplanar electrodes, Underwater acoustic]

Introduction

In recent years, the use of capacitive mechanism for underwater sensing attracts significant attention among researchers due to the flexibility and performance improvement that offered by such technique[1-3]. Through the advancement in Capacitive Micromachined Ultrasonic Transducer (CMUT) technology, capacitive based device seems to be able to become an alternative in the underwater sensing world. Microfabrication advancement also benefits the micfrofluidic field by promoting its rapid protyping process[4]. Recently, microfluidic technology has opened up a new dimension for the capacitive based device meant to be used for underwater sensing, known as microfluidic-based underwater acoustic sensor[5]. The technology eases up the realisation of the membrane structure without having to undergo several repeated processes required by the conventional CMUT[6-7]. The use of polydimethylsiloxane (PDMS) as a membrane material in such process also has an added advantage to the underwater sensing such as the matched acoustic impedance properties between water and PDMS[8]. In such device, the main structures responsible for the sensing activity are the microchannel and sensing electrodes.Microfluidic technology enables the electrodes to be fabricated right under the microchannel. Any changes of dielectric occurs inside the microchannel is detected by the sensing electrodes. Previously, the sensing mechanism of such electrode configuration had been studied by several researchers to investigate the parameteric effect of electrode toward the capacitive response in such structure[9-12]. Nevertheless, all the previous works are only confined to coplanar electrodes which located exactly inside the microchannel region. So the objective of this paper is to further investigate the effect of electrode dimension if it is fabricated outside the microchannel region. This type of geometry is possible due to several factors. Firstly, at specific size of microchannel, there is a possibility to increase the sensitivity of the capacitive response by increasing the electrode width. Secondly, due to the limitation of available facilities, the coplanar electrodes sometimes need to be fabricated outside the microchannel region if the microchannel is made very small. Microchannel dimension needs to be as small as possible to promote the fluid movement. The different location of coplanar electrode underneath the microchannel region is depicted in Fig.1.

Materials and Methods

Design Consideration

Instead of having electrodes fabricated in parallel configuration (as in conventional capacitive sensor), both electrodes also can be arranged in the same plane (planar), where the movement of liquid above these electrodes creates a capacitive change under the existence of electric field between them. In microfluidic application, the coplanar electrode configuration finds its common use as a method to sense the capacitive change inside microchannel[9-10] Fig. 2 shows the difference in electrode arrangement between parallel and coplanar configuration.

Fig. 3 shows the schematic and actual device meant to be used for the underwater acoustic sensing. Through photolithography and softlitography processes, the microfluidic-based device with PDMS membrane and coplanar electrodes was fabricated.

The underwater acoustic testing used to verify the working of such device gave a resonance at frequency of 20 kHz. Availability of the fabrication facilities becomes the main factor of this electrodes configuration selection.Device was initially fabricated to predict the capacitive detection technique to be implemented in a microfluidic-based device for underwater application.Membrane structure was used as a sensing structure while the coplanar electrodes configuration was used to measure the amount of liquid moving inside the microchannel.Any movement of the liquid caused by the membrane deflection would create the dielectric changes inside microchannel.The changes hence produced a change of capacitance, which was used to measure the signal variable causing the deflection.In terms of sensing sensitivity, the mathematical equation for capacitive

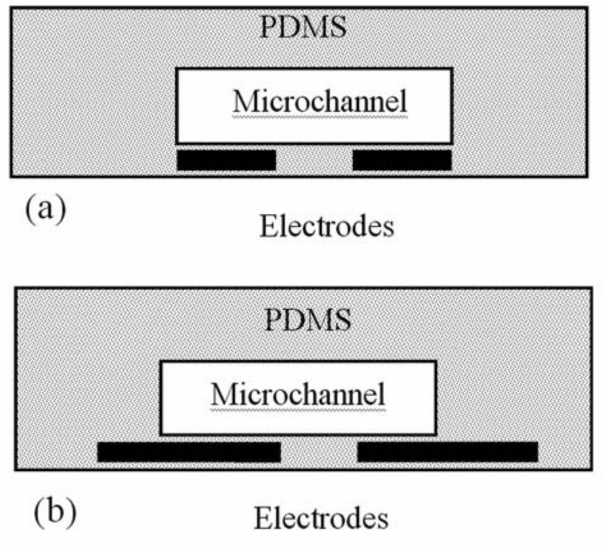
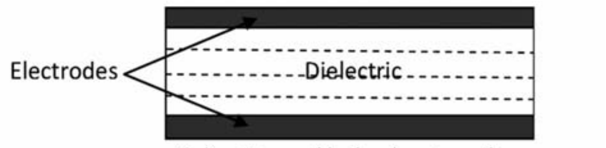
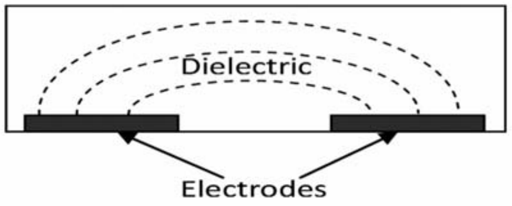


Fig.1—The diagram on the location of coplanar electrodes underneath the microchannel region (a) within microchannel region (b) partially outside the region
(a) electrodes totally interfacing with the microchannel
(b) electrodes partially interfacing with the microchannel



(a) Parallel electrodes



(b) Coplanar electrodes

Fig.2—Cross sectional difference between parallel and coplanar electrodes configuration. Figures also show the electric filed distribution for both structures.
(a) Parallel electrodes
(b) Coplanar electrodes

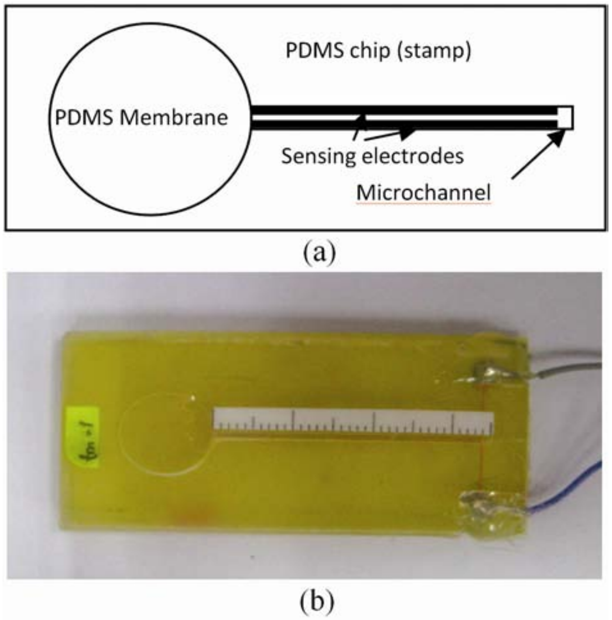


Fig.3—(a) Schematic diagram of underwater microluidic-based pressure sensor (b) Fabricated device [10,11]. The works however confined to the condition where the electrode structure lies within the microchannel width as depicted in Fig. 1 (a).

response inside the microchannel is derived by conformal technique[8] given by Equation 1.

$$c = \frac{2\varepsilon_r \varepsilon_o l}{\pi} ln\left[(1+\frac{w}{a}) + \sqrt{(1+\frac{w}{a})^2 - 1} \right] \quad \text{... (1)}$$

where ε_r is the dielectric constant, is ε_o the electric constant, l is the length of the electrodes, w is the width of electrodes and a is the half gap between electrodes.The work also shows that the equation is a good approximation for an aspect ratio, $w/a \gg 1$, but still valid for $w/a = 1$.Such configuration is previously used for the droplet detection where the electrodes constitute an interdigital structure.Previous works related to the coplanar electrodes also discussed on the effect of electrode width, separation gap and microchannel height to the capacitive response which give rise to the term such as penetration depth, T and effective width of electrode,w_{eff} [10,11]. The works however are confined to the condition where the electrode structure lies within the microchannel width as depicted in Fig. 1 (a).

This work has two main tasks. First is to verify the developed FEM model using ANSYS 12.1 by comparing it with the analytical solution from Equation 1. Secondly, is to use the model to investigate on the parametric effect of having electrodes located partially outside microchannel area as depicted in Fig. 1(b).

FEM Modelling

Through ANSYS, an electrostatic element, PLANE 121 was selected to represent PDMS and microchannel material. Material properties are given in Table 1.

By applying a suitable voltage difference, the capacitance produced was then extracted through CMATRIX command. Plot of electric field lines also obtained to observe the electric distribution within the structure configuration. In order to investigate the effect when the coplanar electrodes are partially located at the outside of the overlapping area to the microchannel region, the steps are summarised as follows:

Table 1—Material properties of the structure

Material	PDMS	Methanol
Dielectric Permittivity	2	32.64

1 Build a reference model dimension:
Microchannel size: 3 mm × 3 mm
Electrode width, w: 1 mm
Electrode separation gap, $2a$: 1 mm

At this dimension (w/a=2), the aspect ratio is still under the condition where equation 1 is still applicable. These electrode dimension also give the microchannel's minimum width of 3 mm to produce a structure where the coplanar electrodes lies exactly inside the microchannel region as in Fig. 1(a).

2 For validation purpose, the electrodes width is varied so that the aspect ratio, w/a varies from 1 to 15. However, for each electrodes width and separation variation, the coplanar electrodes were ensured to maintain their location within the microchannel region as in Fig. 1(a). This is important because the analytical equation to be used for comparison having such configuration assumption.

3 For the effect of electrodes partially outside the microchannel region (Fig. 1(b), the model dimension as given in step 1 was used as reference. By varying the electrodes width from 1.2 to 3 mm, while maintaining the rest of the parameter, the value of capacitance per unit length, C^* were computed using CMATRIX command.

4 Plot both result.

Results and Discussion

Model validation

Fig. 4 is the contour plot of the potential difference obtained from the simulation. It shows that for coplanar electrodes configuration, the voltage is not uniformly distributed inside the microchannel region. This is in contradiction with the voltage distribution for parallel electrodes configuration.

Fig. 5 shows the electric field distribution obtained for the model. The model was verified by comparing the C^* obtained from the model to that obtained from analytical equation. It is found that by increasing the electrode width within microchannel region, the

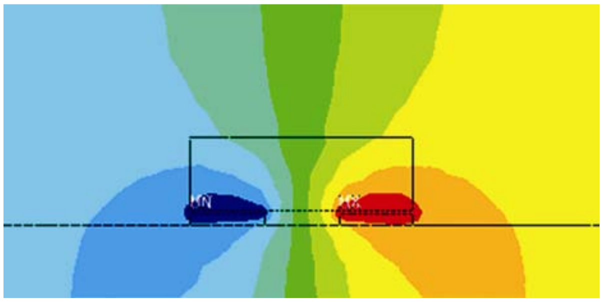


Fig.4—Voltage distribution of simulated FEM

electric field becomes closer to each other. The finding agreed with the theoretical discussion by[10].Fig. 6 shows the validation plot between the FEM and analytical equation for different aspect ratio.

FEM displays the same plot pattern or trend as compared to the analytical solution with the error decreasing from 17% to 7% for aspect ratio between 1 and 15. This is in agreement with the finding by[8]. This argument is used to justify the validity of the built model in obtaining the C^* for coplanar electrode configuration. The error could be resulted from the ignorance of electrode thickness which isnot accounted in the analytical equation.

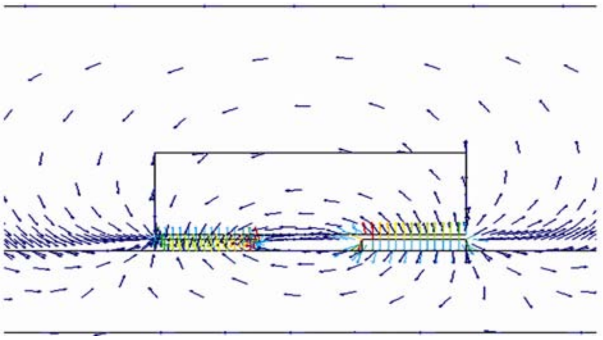


Fig.5—Electric field distribution of simulated FEM.

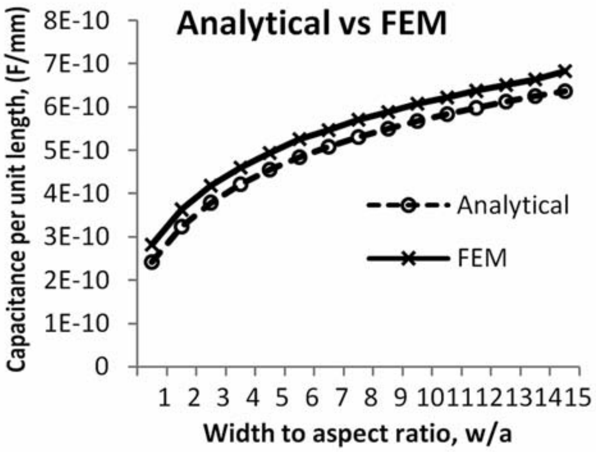


Fig.6—Analytical vs FEM

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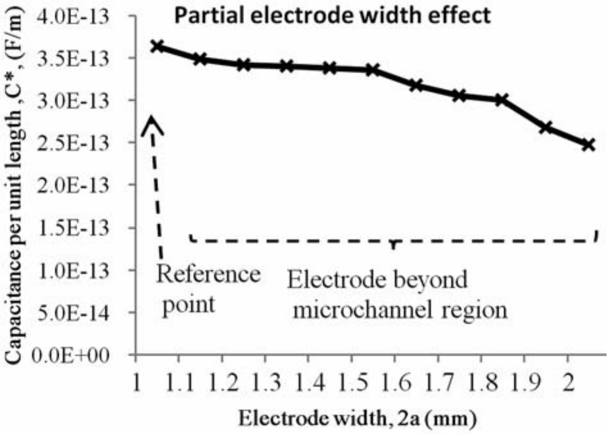

Fig.7—Capacitance per unit length vs electrode width (partially outside the microchannel).

Electrodes partially outside the microchannel

As explained in methodology section, there is a possibility that the electrode to be fabricated outside the microchannel region. Fig. 7 shows the effect of varying the width of the electrode on the capacitance per unit length, C^*. The reference is taken for electrode width equal to 1 mm. The reference C^* is equal to 3.64E-13 F/mm.This is the configuration where the electrodes are totally inside the microchannel region (Fig. 1(a)). Extending the electrodes beyond this area, the capacitance values begin to fall, indicating no significant effect resulted from this extension. It contradicts to the finding where the electrodes are extended within the microchannel region.

So, the finding suggests that due to the difference in material properties between the PDMS and microchannel's material (methanol), the electric field produced from the extension outside microchannel region gives no obvious effect to the overall capacitance response. Thus it indicates that other than electrode dimension, the material properties used for the device also need to be taken into account to improve the response effectively.

Conclusion

The capacitive sensing mechanism with electrode fabricated outside the microchannel has a limit that need to be considered before fabricating the structure. From the simulation, it is found that the extension of the electrode beyond the microchannel region will not contribute to the detection capability. At this point, material permittivity inside the microchannel is the main contributing factor towards higher capacitive detection.

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