Simulation of electric field strength in liquid lens from the concentric interdigitate electrode pattern

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Abstract. In this paper, the electric field distribution in designed liquid lens were simulated and demonstrated. The concentric interdigitate electrode was designed to generate the non-uniform electric field. Consequently, two liquid material on electrode undergoes dielectrophoresis (DEP) phenomenon and forming curvature can confine the incident light. Such two immiscible liquids were studied in the criteria of significant difference in dielectric constant such as Δε≈20. To be specific, the higher dielectric constant liquid as a lens material was first considered comparing to the ambient one. The simulation results reveal that, with fixed electrode width of 25 µm, the increasing gap of electrode from 25 to 125 µm can increase electric field strength at the lens apex from 237 to 386 V/m. Interestingly, the electric field strength was enhanced up to 533 V/m when the electrode width was increased. When the lower dielectric constant liquid was used as lens material, the electric field strength at the fixed width of 25 µm was increased from 16 to 71 V/m as the increasing gap from 25 to 125 µm. However, the low electric field strength of 63 V/m was obtained at broaden width of electrode. In both cases, the electric field strength is not significantly increased at the larger width for all conditions. Our model can be benefit for promising liquid lens design in term of low energy, cost reduction and compact device.

1. Introduction
In the past, the focal length of lens system, which composed of several solid lenses, can be adjusted by mechanical actuation. Because of the limitation of fixed focal length of each lens and mechanical tuning, the conventional lens system is bulky and complex system complicated. Currently, the lenses installed in the modern device is required be small and compact due to space limitations. Thus, the variable focus lenses are an important optical component to focusing light on the microscale optical device such as cellular phone cameras, capsule endoscopes, microscope, and eyeglasses [1]. The focal tunable lens, also known as liquid lens, which focusing light based on the change of liquid curvature without mechanical moving parts, has been extensively interested due to the boundless possibilities in various applications. The lens, basically the interface between two liquid materials, is regulated by applying electric field exerted on dielectric materials. The lens curvature between two immiscible liquids can be adjusted in many methods such as pneumatic actuator [2], magnetic actuator [3], electro-wetting [4], and dielectrophoretic [5]. Each approach has its own advantage and disadvantage. For example, the pneumatic actuator method can be quickly adjusted of focal length, but the compartments require a large space. However, dielectrophoretic methods are the most attractive
approaches because of the direct voltage actuation with low power consumption and small sized device.

Dielectrophoresis (DEP) phenomenon has been widely applied to electric-control particles in a fluid suspending medium. In principle, DEP define the force of particle under a non-uniform electric field caused by an induced dipole-moment-form from applied voltage [6]. Thus, the DEP can be utilized to control small volumes of liquid with properly designed electrodes. Recently, the DEP phenomenon has been applied to the liquid lens [7]. Xiaoyin Yao, Jun Xia study the modeling liquid lens driven by DEP force to compare the difference of electric fields between DEP and EWOD liquid lens [8]. However, the understanding of how the electric field drives liquid to form a lens has not been fully studied. In this paper, we focused on simulation of electric field strength in liquid lens from the concentric interdigitate electrode pattern by DEP phenomenon.

2. Basic principles
The Electrostatics module describe for electric potentials, charges, and grounds by applying to different geometrical objects. The AC/DC Electrostatics module is governed by charge conservation and classical electrostatics, under static conditions, the electric potential \( V \), is defined by the equation (1) [9]:

\[
E = -\nabla V. \tag{1}
\]

Combining this equation with the relation of \( D = \varepsilon_0 E + P \) between the dielectric displacement \( D \) and the electric field \( E \), as the following equation:

\[
D = \varepsilon_0 (\nabla V) + P. \tag{2}
\]

It is possible to represent Gauss' law as the following equation:

\[
\nabla \cdot D = \rho, \tag{3}
\]

\[
-\nabla \cdot (\varepsilon_0 \nabla V - P) = \rho. \tag{4}
\]

In this equation (4), the physical constant \( \varepsilon_0 \) is the vacuum permittivity, \( \rho \) is the density of the space charge and \( P \) is the electric polarization vector. This equation describes the electrostatic field in dielectric materials. The electric field force along the surface of a lens curvature can be calculated from the gradient of an electrostatic potential, exhibit by means of Young-Laplace equation and Laplace law [10]:

\[
F = \frac{1}{2} \varepsilon_0 (\varepsilon_1 - \varepsilon_2) \nabla |E|^2, \tag{5}
\]

where \( F \) is the electric field force, \( \varepsilon_0, \varepsilon_1 \) and \( \varepsilon_2 \) is the dielectric constant in air, liquid 1(Polar) and liquid 2 (non-Polar), respectively, and \( E \) is the electric field. As mentioned above, all variables of the equation are the key limits to simulate the electric field, in order to provide accurate calculation results.

3. Electric field simulation
In this study, the concentric interdigitate electrode is designed to create a symmetrically non-uniform electric field, as shown in figure 1. The design of a circular aperture in the middle allows the light passing through the lens material which will cover the center of circular electrode. The electric field distribution in the designed liquid lens is simulated by using COMSOL Multiphysics® software with AC/DC Module to demonstrate the results in physics. The width and the gap of electrodes were varied
under dielectrophoresis (DEP) phenomenon. The boundary of electrode was set that the black electrode set to be ground and terminal with zero voltage and the red electrode set at 12 volts.

Schematic design of the model used in the simulations, shown in figure 2. In brief, the gold electrode, with 300 µm thickness was constructed on the 1-mm-thick glass substrate in the computational domain. A lens material, defined as “liquid-1” is represented by a blue semicircle, with height at apex of 2 mm and a horizontal length of 4 mm. The yellow rectangular represents lens-supporting material, liquid-2, in the chamber with the length of 6 mm and height of 3 mm. Here, we simulated the electric field under two conditions. The first consideration is, when Liquid-1 higher dielectric constant than liquid-2, defined as “1H2L”, otherwise “1L2H”.

The finite-element method (FEM) is used in our numerical simulation to find the strength and direction of the electric field in a liquid lens. The calculation of the distribution of the electric field carried out using COMSOL and Synchronize 3D model from the SOLIDWORKS software. In this experiment, the width and gap of the electrodes were varied from 25 to 125 µm, for example, the width is 25 µm, and the gap varies 25, 50, 75, 100 to 125 µm. A 3D computational domain of designed structure was divided into a mesh containing a finite number of Finer sized triangular elements. All physics parameters are essential to confirm the accuracy of this model.

4. Results and discussion
The distribution of electric field in both intensity and direction can be presented by 2D simulation. The strength of the electric field along the liquid interface were calculated and shown as the gradient of the electric potential, in y-z-planes. The red arrow indicates the direction of the electric field that exists from positive to negative of electrodes. The parameters of liquid 1 and 2 in this simulation were shown in the table 1. The electric field is widely distributed in the liquid-1 as shown in figure 3(a). On the other hand, the case of 1L2H, the distribution of electric fields is mainly in the area of liquid-2 due to higher electric constant, shown in figure 3(b). The magnitudes of the electric fields dramatically increase as the location approaches the electrode. The liquid interface at electrode in both simulation conditions show very strong electric field generation leading to contact angle change.
Table 1. Key parameters of liquid-1 and liquid-2 The value of dielectric constant and density.

|        | liquid-1 |        | liquid-2 |        |
|--------|----------|--------|----------|--------|
|        | dielectric constant | density (g/cm³) | dielectric constant | density (g/cm³) |
| 1H2L   | 47       | 1.26   | 2.7      | 0.97   |
| 1L2H   | 2.7      | 0.97   | 47       | 1.26   |

Figure 3. The distribution of electric field intensity at the electrodes in two fluids, at a voltage of 12 V and Electrode of width as 125 µm and gap as 25 µm, the gold layer thick 300 nm.

The distribution of electric field intensity was analysed by investigating the considered point to at a point 1 (define: x=0, y=2, z=-4) and at point 2 (define: x=0, y=2, z=4). The magnitudes of the electric field at the electrode width and gap of 25 µm in two liquids are shown in figure 4. In 1H2L, the results showed the high electric field magnitude of 240 V/m can be obtained from the liquid lens with a high dielectric constant as shown in figure 4(a). However, the low electric field magnitude of 16 V/m can be obtained in case of 1L2H, as shown in figure 4(b), that the liquid lens is a low dielectric media.

Figure 4. The electric field strength in a liquid, at a voltage of 12 V and the gold layer thick 300 nm, (a) 1H2L case and (b) 1L2H case.
Figure 5. The electric field strength at different electrodes size condition, (a) 1H2L case and (b) 1L2H case.

From figure 5, the electric field intensity at the apex of the liquid lens were considered at difference electrode size. In the case of 1H2L, with fixed electrode width of 25 µm, the gap increasing from 25 to 125 µm can increasingly generate the electric field strength at the lens apex from 237 to 386 V/m. Interestingly, the electric field strength was also enhanced up to 533 V/m when the electrode width increased, as shown in figure 5 (a). In case of 1L2H, the electric field strength at the fixed width of 25 µm was increased from 16 to 71 V/m as the gap increasing from 25 to 125 µm, as shown in figure 5 (b). In both cases, the electric field strength is not significantly increased at the larger width for all conditions. Thus, the limitation electrode widths for the concentric circle pattern is 125 µm in this lens structure.

5. Conclusion
The liquid lens was successfully modelled and simulated to obtained the electric field strength by the DEP force. Numerical results showed that the high dielectric media can provide the high electric field strength, which may cause the lens curvature change. The limitation of electrode gap and width is 125 µm for this electrode structure. Our showing model is a good guideline for the liquid lens fabrication in the future.

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