Modeling and Optimization of the TAG lens

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ABSTRACT- The tunable acoustic gradient of refractive index (TAG) lens is a novel oscillating liquid lens that can vary its focal length at an ultra-high frequency. With the number of TAG lens applications rapidly increasing, there is a demand to improve the lens design such that its energy efficiency and optical performance are optimized. A TAG lens is a resonator consisting of a piezoelectric ring, a fluid filling the inside cavity, and an outer metal shell to enclose the system. Previous work from my group focuses on the fluid cavity and characterizes the lens by solving a 1D fluid mechanics problem. This 1D fluid model is sufficient to describe its basic mechanics. In this complicated system, we additionally require a deeper understanding of the coupling effects between various components. These coupling effects include the radial boundary condition imposed on the fluid cavity by the piezoelectric ring, the axial boundary condition imposed by the outer shell, and the associated interfacial acoustic wave scattering. In this study, I will formulate and simulate a 2D acoustic model to study these coupling effects. With this model, several improvements on the design of the TAG lens can be purposed. Experiments on various design parameters, such as the material of the outer shell, the thickness and aspect ratio of the piezoelectric ring, and the cooling of the lens will be performed to validate the model. Finally, the optimized TAG lens will be implemented as an ultrafast z scanner in the laser processing of transparent materials and 3D imaging systems.

1. INTRODUCTION

The TAG lens uses a piezoelectric transducer to radially excite an oscillating density gradient within a fluid-filled cylindrical cavity. This density gradient then induces a refractive index gradient. Since its invention in 2006, the TAG lens has been implemented in many imaging and manufacturing systems as a solution for extended depth of field. Applications include 3D imaging [1][2], wide-field microscopy for particle tracking velocimetry [3], and laser ablation of silicon with a z-scanner [4]. Previous research [5][6] from our group has solved the fundamental mechanics using a 1D model and optimized the refractive power from the fluid response in the TAG lens cavity. However, there are three assumptions of the 1D model (Fig.1(a)) that are unrealistic in a real TAG lens (Fig.1(b)). First, the radial boundary condition imposed on the fluid by the piezoelectric ring, a traction-free wall, is greatly simplified. In a practical TAG lens, the outer surface of the piezoelectric ring is fixed at several locations along its circumference by rigid pillars. Second, the finite length of the lens imposes boundary conditions in the axial direction. The outer shell acts as a closure to the system, inducing asymmetry in the vibration of both the piezoelectric ring and the filled liquid. Third, the role of the outer shell in confining the energy of the system also needs to be explained. This may relate to the energetic losses in the system. The above three mismatches impose new boundary conditions on the liquid, including the radial boundary condition by the clamped vibration of the piezoelectric ring, the axial boundary condition by the outer shell, and the acoustic wave scattering at each interface.

2. RESEARCH PLAN

I will model the TAG lens as an acoustic resonator. The radiation source of the acoustic field comes from the vibration of the piezoelectric ring. A TAG lens is at resonance if standing waves are formed inside the liquid cavity, and this should not be confused with the resonance of the piezoelectric ring itself. Both the piezoelectric ring and the fluid cavity oscillate under the constraint of the outer metal shell. The displacement of the piezoelectric ring is 5-7 orders of magnitude smaller than the diameter of the fluid cavity.

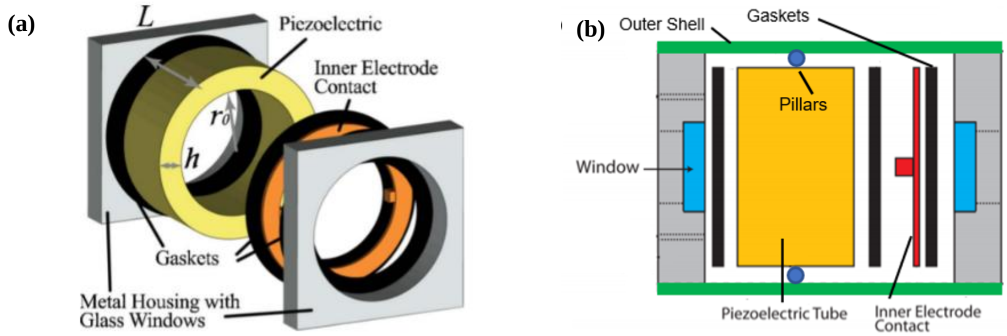

Fig.1 (a) Components of the 1D model of TAG lens (b) Components of a real TAG lens

The first step in solving the system is to consider its eigenmodes. These are the solutions to the linearized, source-free wave equation in the cylindrical coordinate: $\nabla^2\left(\frac{1}{Cs^2}P\right) - \frac{\partial^2 P}{\partial t^2} = 0$, where Cs is the speed of the sound and P is the acoustic pressure. The boundary conditions in this eigenvalue problem are given by the continuity of wave functions at the interface. The second step is to consider the source term from the vibration of the piezoelectric ring. This is solved from the coupled equations of mechanical stress T and electrical displacement D: $T_{ij} = c_{ijkl}S_{kl} + e_{lij}D_l$, $D_i = e_{ikl}S_{kl} + \epsilon_{ij}E_j$, where S is the strain, E is the electric field, and $c,\ e,\ \varepsilon$ are the tensors of elastic constants, piezoelectric constants and dielectric constants, respectively. The boundary condition at the inner wall is traction-free, and at the outer wall, it is clamped. The last step is to derive a particular solution to the inhomogeneous problem under the piezoelectric driving condition in step two.

The pressure acoustic model can be simulated in Comsol Multiphysics. Fig. 2 shows a preliminary simulation result on the coupling of the piezoelectric ring and the fluid cavity. Experimentally, various design parameters, such as the material of the outer shell, the thickness, and the aspect ratio of the piezoelectric ring can be optimized. For the optical performance, the figure of merit is the ratio of lens power to the electrical energy supplied to the system.

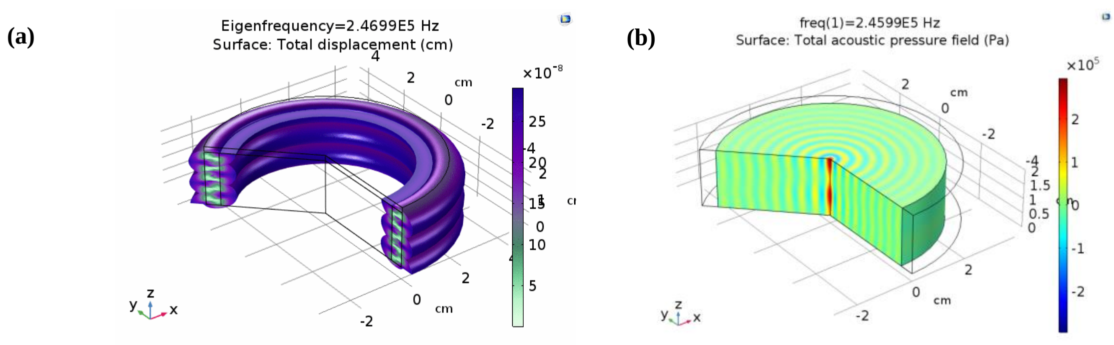

Fig.2 (a) Shape mode of a vibrating piezoelectric ring (b) Induced pressure acoustic field

3. WORK IN PROGRESS REPORT

Thus far, progress has been made in the following areas:

- Analytical solution: piezoelectric ring, resonator modes
- Numerical simulation: acoustic pressure in the fluid cavity driven by the piezoelectric response
- Experimentation: measurement of the impedance spectrum, study on the shell material

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