FINITE ELEMENT SIMULATION OF LASER BASED OPTICAL GENERATION OF ULTRASOUND

Shiwei Zhou[1], Paul Reynolds[2], Roland Krause[2] and John Hossack[1]

[1]Department of Biomedical Engineering, University of Virginia,
P.O. Box 800759, Charlottesville, VA 22908-0759
[2]Weidlinger Associates Inc, 4410 El Camino Real, Los Altos, CA, 94022

Abstract - There is growing interest in microscopic 2D arrays for very high resolution imaging. One approach, based on using a scanned laser for both generation and detection of acoustic waves, has been proposed by the University of Michigan ultrasound group [1]. Various design improvements have been advanced. These include: changing the thermoelastic source material (replacing Chromium with Polydimethylsiloxane (PDMS)) and eliminating the glass substrate (by replacing it with an all PDMS structure). In this paper we investigate the impact of these design changes and also consider the impact of laser spot size using PZFlex Finite Element Analysis (FEA) [2]. In particular, a thermoelastic coupling capability was introduced, and tested, in the FEA simulations.

I. INTRODUCTION

There is interest in extending the capabilities of ultrasound microscopes to frequencies higher than 50 MHz so as to perform realtime, non-invasive electronic biological tissue sectioning [3]. However, constructing 2D arrays suitable for these frequencies is very challenging. An alternative approach is based on using a laser to generate a tightly controlled source via the thermoelastic effect [4]. In the 2D array application, the laser would be scanned across the surface to sequentially address separate ‘elements’. The element size is approximately defined by the laser spot size and can therefore be made very small – approximately 25 microns across. The receive process involves using a laser beam to detect displacements on a reflective surface using interferometric techniques [5]. This receive process is exceptionally sensitive.

Historically, these structures were based on glass slides with a Chromium layer to provide both the thermoelastic effect and as the reflector for the receive interferometer. The glass slide poses an interesting problem since it exhibits low acoustic losses and therefore may provide a low loss channel for surface waves propagating outwards from the excited element and thereby resulting in the problems associated with inter-element crosstalk (typically sidelobes or otherwise degraded beam profile). Additionally, since the thermoelastic process is inherently inefficient there is considerable interest in examining possible improvements resulting from change in choice for the thermoelastic material. Buma *et al* [3] recently demonstrated a significant improvement by replacing the chromium layer with a carbon powder loaded PDMS. (PDMS is a silicone material.) In the interests of efficiency and in order to examine expected behavior at a microscopic scale, it was decided to apply Finite Element Analysis to the task of investigating the impact of various design parameters.

II. FINITE ELEMENT ANALYSIS

The finite element analysis package PZFlex [2] was chosen to simulate the generation of ultrasound in the stated structures since its explicit time-domain approach lends itself well to rapid analysis of broadband wave propagation problems. Additionally, a thermoelastic modeling capability was added to a pre-release version of the package.

Both the physical structure of the optical generation configuration and the load function were ideally suited to a 2D axisymmetric approximation, and consequently the time consuming nature of 3D calculations was avoided.

The model consisted of three layers: a glass or PDMS backing, a PDMS front layer, and a water load. The model extended multiple wavelengths in each direction before absorbing boundary conditions were applied to prevent unwanted echo signals. The model was discretized sufficiently to resolve all waves, shear and longitudinal, at the frequencies of interest.

The acoustic source was initially implemented as a 'box' of pressure, of identical size to beam penetration depth and radius. The pressure load caused rapid expansion of this 'box', thus generating a broadband function and stimulating wave propagation within the structure. An extrapolation boundary was placed in the water surrounding the pressure source and was used to record all pressure wave propagation data. PZFlex post-processing was then used to analytically extrapolate pressure at any location beyond the range physically modeled using data from the extrapolation boundary. The extrapolation technique is clearly more efficient than an all FEA mesh-based approach. (In any case it has proven to be good practice to test the extrapolation process in the very near field against an all FEA solution. Excellent agreement (to within numerical resolution based limits) has been obtained. Using this extrapolated data, beam patterns from -90 to 90 degrees, for a range of 50 mm from the device surface, were calculated for a variety of parameters and materials.

III. THERMOELASTIC MODELING

During the course of this investigation, a thermoelastic coupling option was added to PZFlex. A thermal source was specified within the physical structure (simulating the thermal energy conversion of the absorbed optical energy). PZFlex uses the thermal expansion coefficients of the relevant materials to calculate the material stresses generated, and consequently also obtain the resultant pressure waves.

Following the work of Timoshenko [6], the components of the linear strain tensor e_{ij} are the sum of contributions from the stress field (S) and the temperature field (T).

$$\varepsilon_{ij} = \varepsilon_{ij}^{(S)} + \varepsilon_{ij}^{(T)} \,.$$

Due to change from some reference temperature T_0 to the temperature T, the strain components are

$$\varepsilon_{ij}^{(T)} = \alpha(T - T_0)\delta_{ij}$$

where a denotes the linear coefficient of thermal expansion.

Combining these two equations together with Hooke's law yields

$$\varepsilon_{ij} = \frac{1}{2\mu}\left(\sigma_{ij} - \frac{1}{3\lambda + 2\mu}\delta_{ij}\sigma_{kk}\right) + \alpha(T - T_0)\delta_{ij}$$

This equation can then be inverted to give the thermoelastic constitutive equations

$$\sigma_{ij} = \lambda\delta_{ij}\varepsilon_{kk} + 2\mu\varepsilon_{ij} - (3\lambda + 2\mu)\alpha\delta_{ij}(T - T_0) \,.$$

Following implementation and validation of this option within PZFlex (pre-release), the thermoelastic option was used to attempt to analyze the effectiveness of the previous pressure load approach.

IV. SIMULATION RESULTS

The simulation conditions were chosen to broadly match those of the University of Michigan prototypes [1]. The laser spot was circular with a 25 micron diameter. Since the Chromium layer was a sputtered sub-micron thick layer it was practically negligible. However, we did model it as a one element (0.25 micron) thick layer in one model run. Practically, in the case of the thin Chromium layer, the thermoelastic effect was produced primarily by the adjacent water. In any case, the thermoelastic coefficient of Chromium is insignificant in comparison to that of water. The linear thermal expansion coefficients of the materials being used are shown below.

Material	Linear Expansion Coefficient (10^{-6} / K)
Glass	90
Chromium	6.5
PDMS	590
Water	210

The transient thermal excitation represented by the laser pulse was modeled as a half cycle of a sinusoid at 50 MHz (-6dB pulse length = 13.3 ns).

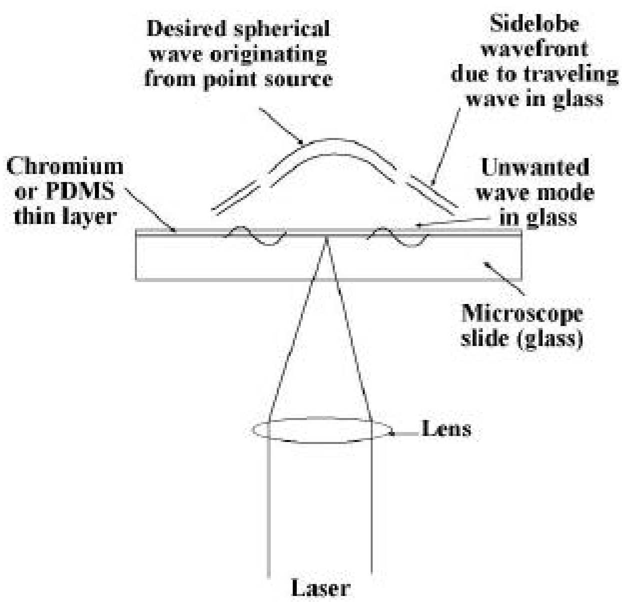

Figure 1 Configuration of the laser-based acoustic source

Figure 2 illustrates the beam pattern obtained using PZFlex for three different design configurations. One simulation includes the Chromium using a single element thick layer (0.25 micron). It is evident that the lines for this case and the case where the Chromium layer is ignored (and just the water heating is considered) are indistinguishable. The plot also illustrates theoretical results for both the rigid baffle and pressure release case [7]. In accordance with the observation made by the University of Michigan group [1], we see that the beam pattern is better modeled by the pressure release model. This model includes a cosine θ term that causes greater 'fall-off'. A minor sidelobe is evident in the cases where a glass slide is used. Glass has very low acoustic attenuation (3.6 dB/cm at 1 GHz (low power case) [8]) and therefore may be expected to sustain significant element crosstalk via either longitudinal or transverse solid (bulk or surface) waves. However, the acoustic mismatch between the two materials is poor (1.5 MRayl (water) versus 12 MRayl for glass). Therefore, only a small portion of the acoustic energy in the water, or PDMS, is coupled into the glass. Nevetheless, some of our FEA results (not illustrated here) clearly show the faster longitudinal wave and a slower surface shear wave that couples into the fluid load to form a sidelobe at approximately 40 degrees.

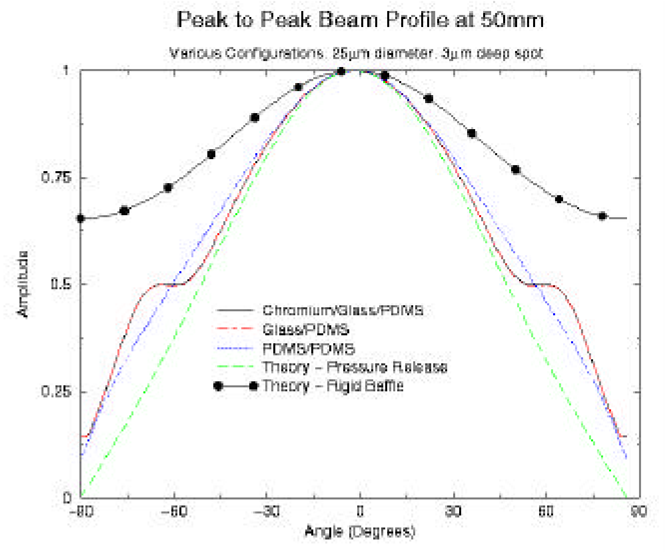

Figure 2 Beam profiles for different material configurations. Theoretical results are also illustrated.

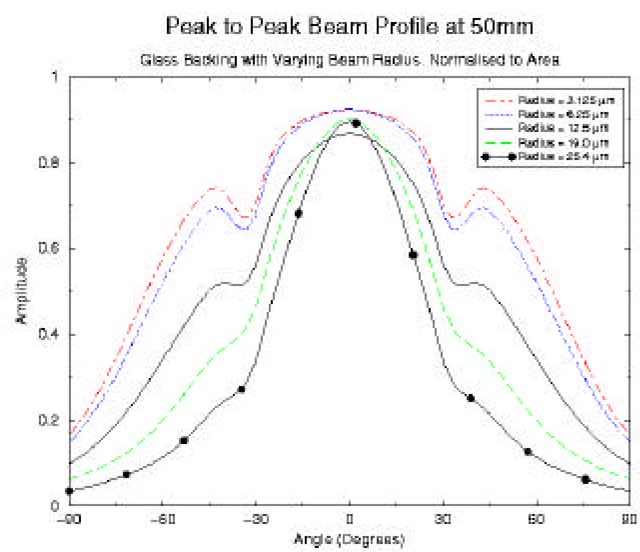

Figure 3 Beam profiles for different laser spot sizes (glass backing)

Figure 3 illustrates the beam patterns for different laser spot sizes. It is not very practical to experimentally vary the laser spot size to the extent we do here. However, the simulation provides some useful insights. We observe that as the laser spot size becomes smaller, the relative impact of the sidelobes becomes greater.

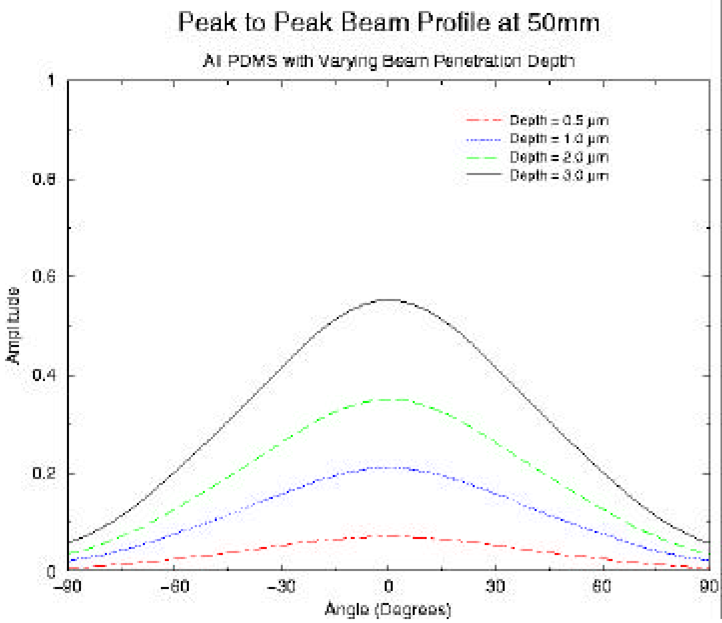

Figure 4 Beam profiles for different laser penetration depths (PDMS backing, PDMS / carbon thermoelastic region)

Prof. M. O'Donnell (University of Michigan) communicated to us that a design enhancement is in development that will eliminate any glass backing related problems. This improvement comprises replacing the glass backing support with a PDMS support. Thus, the entire structure is well matched to water and the channel for lateral coupling of acoustic energy is eliminated. Figure 4 illustrates the beam patterns for various laser penetration depths for a PDMS backing, PDMS (carbon powder loaded) active layer design. No sidelobe activity is observed for any laser penetration depth.

V. CONCLUSIONS

PZFlex FEA provides a useful tool for examining the impact of various design criteria in thermoelastic based transducers. We have observed that some limited sidelobe energy can occur in a glass substrate when one is used. However, if the glass is replaced with better well matched PDMS, the sidelobe activity is eliminated. We have also observed that sidelobe activity (when it does occur) is more significant, in a relative sense, for smaller laser spot sizes.

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