A 2D optical ultrasound array using a polymer film sensing interferometer

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Abstract - A 2D optical ultrasound receive array has been investigated. The transduction mechanism is based upon the detection of acoustically-induced changes in the optical thickness of a thin polymer film acting as a Fabry Perot interferometer (FPI). A sensor head employing a medium finesse polymer film FPI has been fabricated and characterised. By illuminating the interferometer with a large diameter (12mm) laser beam and raster scanning a photodiode across the reflected output beam, a 2D ultrasound array was simulated. To demonstrate the concept, the ultrasound field distributions at various distances from the focus of a 5 MHz focussed ultrasound transducer were mapped. The system was also evaluated by performing transmission ultrasound imaging of several targets of known dimensions. The "array" aperture, defined by the dimensions of the incident optical field, was 12mm in diameter and spatially sampled in 0.1mm steps. Element sizes, defined by the photodiode aperture, were 0.4mm for the foucussed transducer measurements and 0.8mm for the transmission ultrasound images. The wideband (30MHz) noise-equivalent-pressure was 3kPa and the acoustic bandwidth 12MHz. It is considered that this approach has the potential to be used for transmission medical ultrasound, biomedical photoacoustic imaging and ultrasonic field characterisation applications.

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1. INTRODUCTION

There are a number of limitations associated with 2D piezoelectric ultrasound arrays. These include difficulties in fabricating acoustically small element sizes for use at MHz frequencies whilst still retaining adequate detection sensitivity. This is particularly so for phased arrays where, for optimum lateral spatial resolution, a near-omnidirectional element response is required necessitating an element size that is small in comparison to the acoustic wavelength. Sub-50µm element sizes are required for an isotropic response at 10 MHz, for example. To achieve this with adequate wideband detection sensitivity (<1kPa) using piezoelectric transducers represents a major challenge. Electrical crosstalk and the complexity that arises from the need to incorporate a large number of electrical connections within the footprint of the array head present further difficulties.

A solution may lie in optical methods whereby the incident acoustic field distribution, following an appropriate transduction process, is mapped on to an optical field. The spatial discretisation of the acoustic detection process can therefore be removed from the detection plane to a remotely located high-density array of optical detectors such as a photodiode array or CCD array. This offers intrinsic advantages in terms of the spatial sampling of the acoustic aperture. In particular, substantially smaller element sizes (in principle down to the optical diffraction limit of a few µm) and interelement spacings than can be achieved with piezoelectric arrays are possible.

Several approaches have been investigated. The detection of acoustically-induced changes in optical reflectance at a glass-liquid interface for 2D photoacoustic imaging[1] has been demonstrated. A system based upon fustrated total internal reflection due to acoustically induced displacement of silicon nitride membranes has been investigated for transmission ultrasound imaging.[2] Interferometric detection of acoustically-induced displacements across the surface of a pellicle[3] and the detection of changes in the optical thickness of a multilayer dielectric stack Fabry Perot (F-P) interferometer[4] and a glass etalon[5] have been described for ultrasound imaging and field mapping.

The use of a polymer film Fabry Perot sensing interferometer as an ultrasound sensor has also been studied extensively[6,7,8,9]. In this paper, we examine the feasibility of extending this approach to the development of a 2D optical ultrasound array[10]. An experimental system has been set up and used to map

2000 IEEE Ultrasonics Symposium Proceedings, pp1183-1186, 2000

the output of a focussed ultrasound transducer and perform transmission ultrasound imaging of various spatially calibrated targets.

2. Experimental set-up

A schematic of the experimental set-up for imaging ultrasound fields is shown in figure 1. The sensor head comprises a glass backing stub which was first coated on one side with a partially reflective aluminum coating. A 50µm thick polymer film (Parylene)[7] was then deposited followed by a second, fully opaque aluminium coating. The two aluminium coatings form the mirrors of the Fabry Perot interferometer. A wedge was formed on the optical input side of the sensor head to eliminate parasitic interference between the light reflected from the sensing film and that from the front face of the glass backing stub. This design, which approximates to a rigid-backed configuration, produces a $\lambda/4$ thickness mode resonance limited bandwidth of approximately 12MHz[8,10]. A 15mW laser beam of diameter 12mm was used to illuminate the sensing film. The light reflected from the sensing head was directed on to a 25MHz photodiode mounted on an x-y scanning stage.

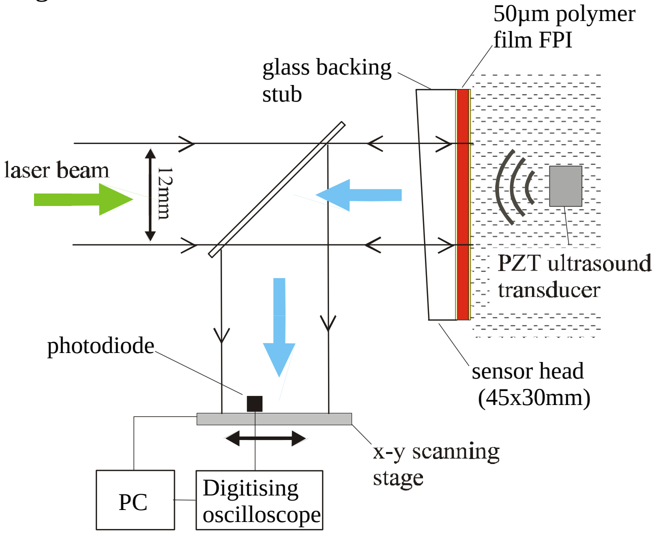

Figure 1 *Experimental imaging set-up*

Various pulsed PZT transducers were used as ultrasound sources. Acoustically induced changes in the optical thickness of the polymer film produce a corresponding change in the intensity of the reflected beam. By raster-scanning the photodiode over the area of the reflected optical beam, a representation of the lateral distribution of the acoustic field incident across the sensing head can be obtained. In its simplest form it is a 1-1 mapping so, to a first approximation, the effective acoustic element size and interelement spacing are simply those of the photodiode area and the scan increment respectively. The active diameter of the photodiode was 0.8mm. This was reduced to 0.4mm using a pinhole aperture for the transducer field mapping measurements shown in figure 5. Sensitivity was determined by referencing the sensor output with that of a calibrated PVDF membrane hydrophone giving a noise-equivalent-pressure of approximately 3kPa. A typical sensor output is shown in figure 2.

The system was evaluated by two methods. Firstly, by obtaining transmission ultrasound images of a variety of spatially calibrated targets. Secondly, by mapping the output of a 5MHz focussed ultrasound transducer at various distances from the focus.

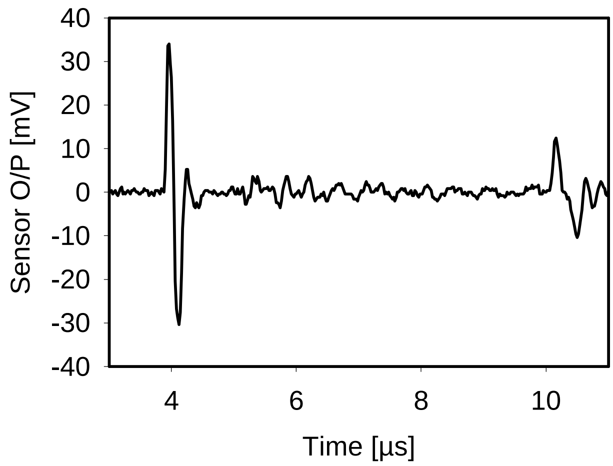

Figure 2 *Sensor output due to a signal from a pulsed 3.5MHz planar PZT transducer*

3. Results

3.1 Transmission ultrasound imaging

Images of two acoustically opaque targets were obtained. The first was a silicone rubber cross of the dimensions shown in figure 3. The second was a plastic mesh as shown in figure 4. The targets were placed between the sensor head and a 3.5MHz, 1” dia. planar PZT transducer and the photodiode scanned across the reflected sensor output beam. The scanned region was a 12 x 12mm rectangle and the scan increments were 0.1mm. The images were corrected for sensitivity variations across the sensor head.. Images (not shown) of the transducer output were also taken without the targets to confirm that the field distribution over the scanned area was acceptably uniform.

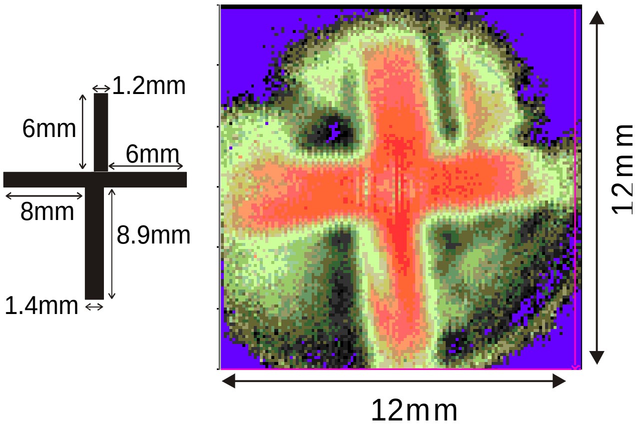

Figure 3 *Transmission ultrasound image of silicone rubber cross target (left.). Photodiode element size=0.8mm, scan increment=0.1mm.*

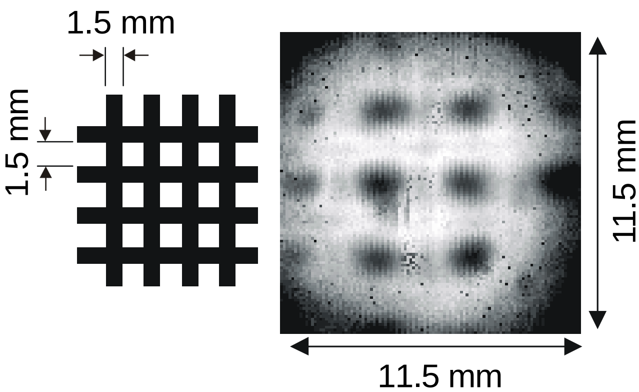

Figure 4 *Transmission ultrasound image of plastic mesh target (left.). Photodiode element size=0.8mm, scan increment=0.1mm, scanned area=11.5x11.5mm*

Figures 3 and 4 demonstrate the concept of mapping an acoustic field on to an optical beam showing that an "array" aperture with useful sensitivity of around 10mm diameter is possible. The target dimensions are comparable to the acoustic wavelength (0.4mm in water) used so rectilinear propagation cannot be assumed. Image resolution in this instance is therefore limited by diffraction of the acoustic field around the edges of the target rather than the photodiode element size.

4. Ultrasound field mapping

Figure 5 on the following page shows three images of the output of a focussed ultrasound transducer taken at various distances *z* from the focus. These clearly show the diverging beam profile of the transducer. The FWHM values obtained from the horizontal and vertical profiles agree with calculated 6dB beam widths. For example the calculated beam width at the focus (*z*=65mm) is 0.67mm. The beam width obtained from figure 5 for *z*=70.5mm which is slightly off the focus is 0.75mm. The discrepancy may also be due to the photodiode aperture which, although reduced to 0.4mm for these measurements, is still comparable to the dimensions of the field close to the focus. Nevertheless it does indicate that, for dimensions of around several hundred microns, the effective acoustic element size is defined by the dimensions of the optical detector element. Ultimately, the minimum acoustic element size will be determined by the contribution of acoustically-induced thickness deformations outside the optically defined "element" size and mode coupling effects. However, directivity measurements obtained using a polymer film sensing interferometer illuminated by the output of a 6µm core diameter optical fibre[7] indicated that sub-50µm effective radii are feasible suggesting acoustic crosstalk effects are small for these element sizes

3. Conclusions

The feasibility of a 2D ultrasound array based upon the FP polymer film sensing concept has been demonstrated . Uniform wideband frequency response, kPa acoustic pressure resolutions and the potential to sample 1cm diameter apertures with element sizes of 50µm suggest that the concept has excellent potential as an alternative to conventional ultrasound arrays. For any practical application however, two important modifications to the scheme described are required. Firstly, it is necessary to spatially resolve the optical field in parallel rather than physically scanning a single detector element. This could be achieved using a CCD array[1,2] or photodiode array. Secondly, a laser source of substantially higher power (~1W) would be required to achieve the objective of kPa detection sensitivities with, for example, 50µm element sizes.

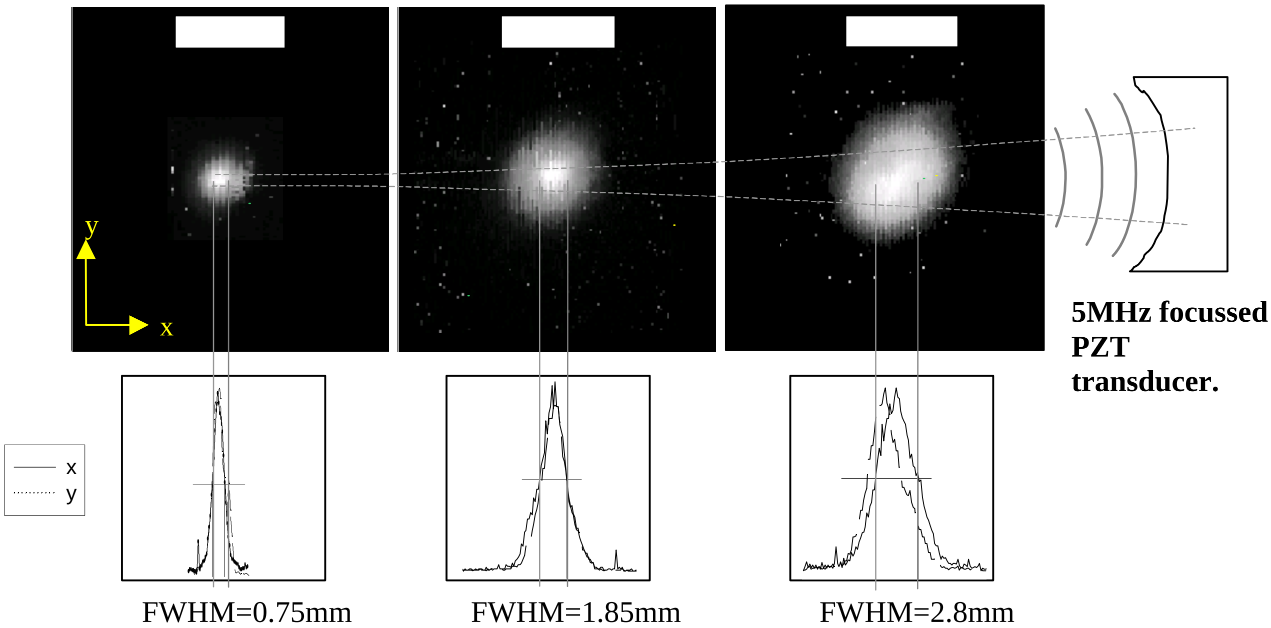

Figure 5 *Field distributions at 3 distances z from a 5MHz focussed ultrasound transducer. From left to right z=70.5mm, z=77.4mm, z=84.1mm. Transducer focal length=65mm, element dia.=25mm. Photodiode element size=0.4mm. Scan increment=0.1mm.*

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