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Control of Optically Generated Ultrasound Fields Using Binary Amplitude Holograms

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***Abstract*—To obtain high resolution ultrasound images, transducers able to operate at high frequencies are required. Optically generated ultrasound utilising the optoacoustic effect is a promising alternative to piezoelectric transducers to achieve this. To use optically generated ultrasound for imaging, a method to spatially steer and focus the acoustic pulses is desirable. In this paper, the use of binary amplitude holograms to focus broadband ultrasound pulses generated by a pulsed laser was investigated. This was done experimentally with patterned absorbers and in simulation. It was found that applying two or more laser pulses applied to a hologram at its design frequency was sufficient to form a focus. The position of this focus could be moved in 3-D by changing the hologram. Additional focal points to those designed for were also found in both the simulation and experimental data. These were generated by constructive interference of harmonics of the pulsing frequency. Simulations found that increasing hologram resolution and applying greater numbers of laser pulses to the hologram decreased the volume of the primary focal point, and that the volume of this focus decreased more rapidly with increasing laser pulse numbers at higher hologram resolutions.**

I. Introduction

Piezoelectric transducers are ubiquitous in biomedical ultrasound. Despite their suitability for many applications, the fabrication of piezoelectric arrays operating at frequencies above 50 MHz still poses significant problems, for example, in producing arrays with sufficiently small element pitches, and eliminating acoustic and electric cross-talk between elements [1]. Optically generated ultrasound (OGUS) is an alternative to piezoelectrics in which a thin absorbing layer emits ultrasound following optical irradiation. This modality can produce pulses with bandwidths of 100s of MHz, and the array element size and spacing can be flexibly changed by altering the focus of the incident optical pulses. Additionally, holographic patterns of pressure can be generated and used to control the 3-D ultrasound field as an acoustic analogue to optical holography. This works by patterning the incident light field or absorbing layer in which the ultrasound is generated with a holographic pattern. The initial pressure distribution generated in a 2-D plane is then in the shape of this hologram. The waves then propagate outwards and constructively and destructively interfere to reproduce the desired acoustic fields. This is illustrated in Fig. 1. In principle, if a spatial light modulator (SLM) is used to control the incident pattern of the light field, this effectively creates a large 2-D optoacoustic array with tens to hundreds of thousands of separately controllable elements.

Previous work in this area by Meyer et al [2] demonstrated that narrowband acoustic pulses (10s kHz) could be generated optically by harmonically modulating the incident laser intensity. It was shown that by combining this with a SLM to control the spatial pattern of the incident light field, several results from optical holography could be reproduced acoustically. Earlier, several works by Sharples et al on surface acoustic waves (SAWs), for example [3], showed that this can be extended to broadband ultrasound and pulsed lasers if multiple laser pulses are applied with a temporal spacing matching the acoustic hologram design frequency. The incident light field was patterned with an SLM into a series of concentric arcs. A 1064 nm Q-switched mode-locked Nd-YAG laser able to produce envelopes of 30 sharp pulses with a 12.1 ns pulse spacing (82 MHz) repeated every 0.2-1 ms was used to generate the ultrasound. By matching the spacing of the concentric arcs projected by the SLM to the wavelength of a 82 or 164 MHz SAW in the material being tested, the SNR of the acoustic signal at the focus was improved by a factor of 80.

The objective of this work was to verify that OGUS pulses can be focused at arbitrary points in 3-D by using binary amplitude holograms and rapidly applied laser pulses, and to investigate the effect of different experimental parameters of the holograms and the laser source on the 3-D wavefield generated by the hologram.

II. Computer Generated Holograms

The binary amplitude holograms used in this work were calculated by ray-tracing. For each hologram, the position of the desired focal point relative to the 2-D hologram, the acoustic design frequency, and the corresponding acoustic wavelength in the medium were defined. The pressure $p(x, y)$ on the surface of the 2-D hologram was then calculated assuming the focal point was a monochromatic point source oscillating at the design frequency, where

$$p(x, y) = \frac{1}{r}\sin(\frac{2\pi r}{\lambda} + \Phi) \quad (1)$$

Here r is the distance from the focal point to each position on the hologram surface, λ is the acoustic wavelength, and Φ is an arbitrary phase offset. For multiple focal points, the pressure on the hologram surface was calculated by superimposing the responses. A binary amplitude hologram was then calculated by thresholding $p(x, y)$, with positive values set to 1 and negative values set to 0. Example binary holograms generated using this method are shown in Figs. 1 and 2. It was verified in two ways that the holograms produced acoustic wavefields with the desired distribution of focal points when optically excited: experimentally using patterned absorbers, and by simulation using the k-Wave acoustics toolbox [4].

III. Laboratory Experiments

A. Absorber Fabrication

The holograms calculated were 30 × 30 mm, had a single focal point on the centre axis at 3 cm, and were designed

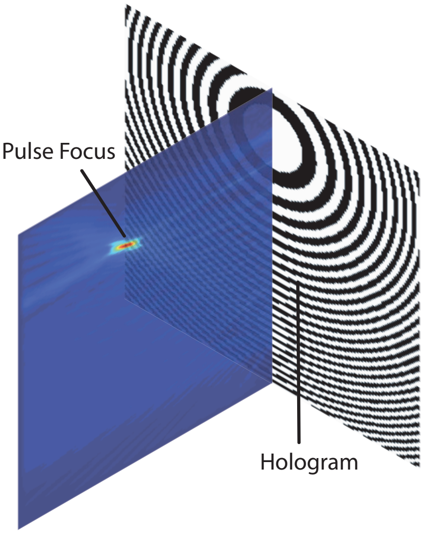

Fig. 1. Outline of the configuration used for simulations of hologram fields. Holograms are inserted as a 2-D plane into the simulation and the 3-D wavefield from these patterns simulated for different temporal inputs. The pressure over the domain is recorded and the size of the pulse focus seen in the figure is evaluated with a volume metric.

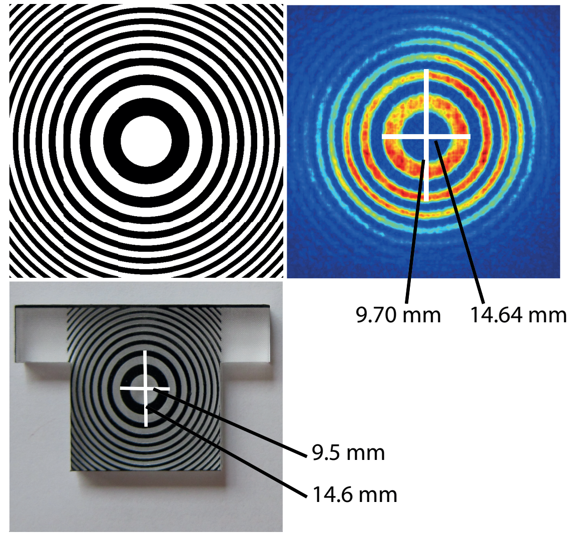

Fig. 2. Top left: Hologram used for experiments and simulations. Top right: Maximum pressure generated from the absorber in the experimental measurements identified in the back-propagation of the data. Bottom Left: Example patterned absorber fabricated using laser cutter. Annotations are the sizes of the first two hologram rings measured on the fabricated hologram and in the back propagated data.

for a frequency of 3 MHz. The holograms were fabricated from 50 × 30 × 5 mm transparent PMMA slides. These were coated with a thin layer of black spray paint (Super Satin, Plasti Kote, Valspar, US). A laser cutter (VLS4.60, Universal Laser Systems, US) was used to etch the hologram from the absorbing layers. A photograph of one of the holograms is shown in Fig. 2.

B. Field Measurements

A fibre coupled Q-switched Nd:YAG laser (Ultra, Big Sky Laser Technologies, Bozeman, MT) was used to excite the absorbers. This had a wavelength of 1064 nm, a pulse length of 8 ns, and a repetition rate of 20 Hz. Pulse energies of ∼35 mJ were delivered to the absorbers. Measurements of the generated acoustic field were performed in a 40 × 40 × 60 cm test tank with a two axis computer controlled positioning system (Precision Acoustics, Dorchester, UK). A calibrated PVDF membrane hydrophone with a thickness of 15 μm and 0.4 mm active element was used to record the pressure (Precision Acoustics, Dorchester, UK).

The absorber was suspended 20 mm inside the edge of the tank, and the membrane hydrophone was suspended approximately 20 mm away from the absorber. The laser fibre tip was placed 8 cm from the tank edge and manually aligned with the absorbing layer. A concave lens with a 40 mm focal length was placed 6 cm from the fibre tip to expand the beam. The radius of the beam at the edge of the tank was ∼12.5 mm. The experimental set up is shown in Fig. 3. Signals were recorded over a 30 × 30 mm plane parallel to the absorber axis using a step size of 0.3 mm. Time domain signals were recorded at each position using a digital oscilloscope with a sampling rate of 400 MHz and 50 averages.

The Q-switched laser was unable to produce a train of pulses at the desired 3 MHz repetition rate. So, to verify whether the ultrasound would focus with repeated laser pulses,

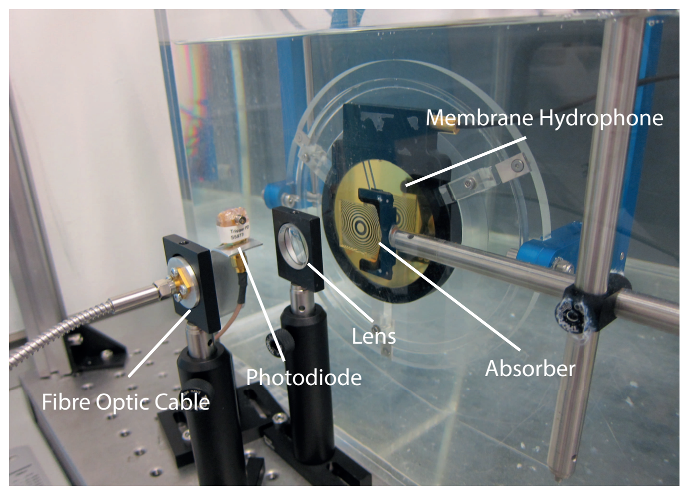

Fig. 3. Experiment set up for field measurements from patterned absorbers showing fibre optic cable, photodiode, lens, holographic absorber, and membrane hydrophone.

30 additional pulses were created in the time domain signals. This was done by adding the data recorded at each point to itself translated by multiples of 0.33 μs. This temporal spacing corresponds to a 3 MHz pulsing frequency.[1]

To calculate the 3-D wavefield of the hologram from the planar measurements, k-Wave was used to forward and back propagate the data by 90 and 25 mm respectively. Prior to this the data was spatially up-sampled to a grid spacing 0.05 mm to support frequencies up to 15 MHz in the simulation, low pass filtered at 15 MHz, and temporally down-sampled to a step size of 20 ns to improve computational efficiency. Linear

[1]The experimental data presented here assumed the acoustic pulses generated would be identical if generated by multiple laser pulses with a narrow temporal spacing.

acoustic propagation was assumed as the maximum recorded pressure was 59 kPa.

C. Simulation of Hologram Fields

The acoustic field generated by the hologram was also simulated using the k-Wave toolbox. The simulation was carried out in a 12 x 3 x 3 cm domain with a grid spacing of 0.05 mm and using a time step of 20 ns. The absorber pattern was input as a 2-D source distribution in the y-z plane at one end of the domain. Laser pulses were represented temporally as impulses at a single time point. 30 of these pulses were applied in the simulation at a frequency of 3 MHz to match the number added to the experimental data.

The effect of the parameters of the hologram and laser source on the properties of the resulting wavefield were investigated through simulations within the framework summarised in Fig. 1. The change in the ultrasound field induced by varying the number of laser pulses and the hologram resolution was evaluated. This was done by simulating the pulses generated by 3 equivalent holograms calculated with pixel sizes of 0.088, 0.176, 0.352 mm respectively. The number of successive laser pulses in the simulation was changed between 2-30. The size of the focal spot was measured in each simulation using a volume metric calculated by evaluating the number of voxels in which the maximum pressure exceeded 50% of the maximum pressure in the simulation. Other parameters were also evaluated, for example, changing the phase offset in Eq. (1), the threshold used to create the hologram, and the pulsing frequency of the laser.

IV. Results

The calculated hologram, the fabricated absorber, and the pressure generated by the laser in the experiment identified in the back propagation of the data are shown in Fig. 2. Figure 2 also shows the dimensions of the first two absorber rings calculated in both the back propagated data and on the fabricated hologram. The two are within 3% of each other, which confirms the accuracy of the back propagation. It can be seen from the initially generated pressure in Fig. 2 that the absorber was incompletely illuminated. Additionally, the variation across this plane indicates the gaussian profile of the beam caused the pressure generated to vary over the hologram. Both of these factors will have influenced the experimental data relative to the simulation.

The results of the simulations measuring the effect of varying the hologram resolution on the volume of the ultrasound focus are shown in Fig. 4. This shows that increasing the resolution of the hologram and the number of pulses decreases the size of the focal spot. Additionally, the volume of the focus decreases and converges to a steady volume more rapidly with number of laser pulses as the hologram resolution increases. The volume of the focus converges at $\sim$15, $\sim$19 and $>$30 pulses for pixel sizes of 0.088, 0.176 and 0.352 mm respectively for a 1 MHz hologram.

The maximum intensity projection of the 3-D field from both the experimental data and the simulation data is shown in Fig. 5(a)-(b). Both show the acoustic field is focused at 3 distinct points along the central hologram axis at 3 different depths. Figure 5(c)-(e) shows that the spectra of the pulse is constrained to the pulsing frequency and its harmonics. The first focal point at $\sim$3 cm is the design focus of the hologram and confirms that the 3-D position of the ultrasound focal point can be controlled. The latter two focal points are caused by the first and second harmonics of the pulsing frequency. This is visible in the spectra in Fig. 5(c)-(e). These show the maximum frequency in the spectra at the three foci are 3, 6 and 9 MHz respectively. These focal points occur where the path length difference from each absorber ring is approximately equal to the acoustic wavelength. So, if the broadband acoustic pulse contains multiple harmonics then several of these additional focal points will be present in the wavefield. A similar effect was observed in simulation where the depth of the focal point for a hologram could be changed by pulsing it at different frequencies. The additional foci do not occur when using monochromatic CW source as a simulation input.

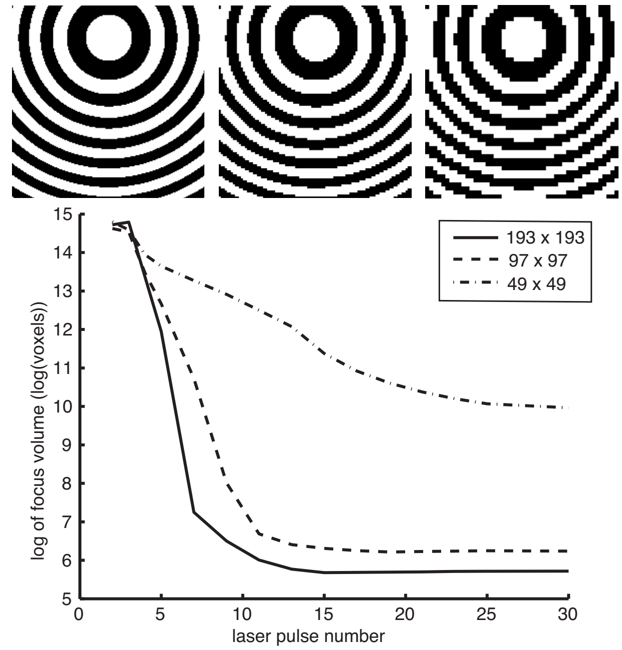

Fig. 4. Change in the volume of the ultrasound focus with the number of optical pulses for three equivalent holograms with resolutions of (1) 0.088 (2) 0.176 (3) 0.352 mm. The three holograms are shown above the graph.

There is a small offset in the position of the focal points between the experimental data and the simulation. This offset is systematic so could have arisen from erroneously identifying the hologram plane in the measurement data. The frequency with the maximum amplitude in the spectra at each focal point is the same for both the simulation and experimental data. However, there are differences between the simulation and experimental data in the amplitude for the other harmonics. These arise possibly due to differences between the flat spectral pulse used as a simulation input and the spectrum generated from the absorber in the experiment.

V. Summary and Discussion

This study has demonstrated numerically and experimentally that binary amplitude holograms can be used to focus broadband optically generated ultrasound pulses at an arbitrary depth. This relies on being able to generate multiple broadband

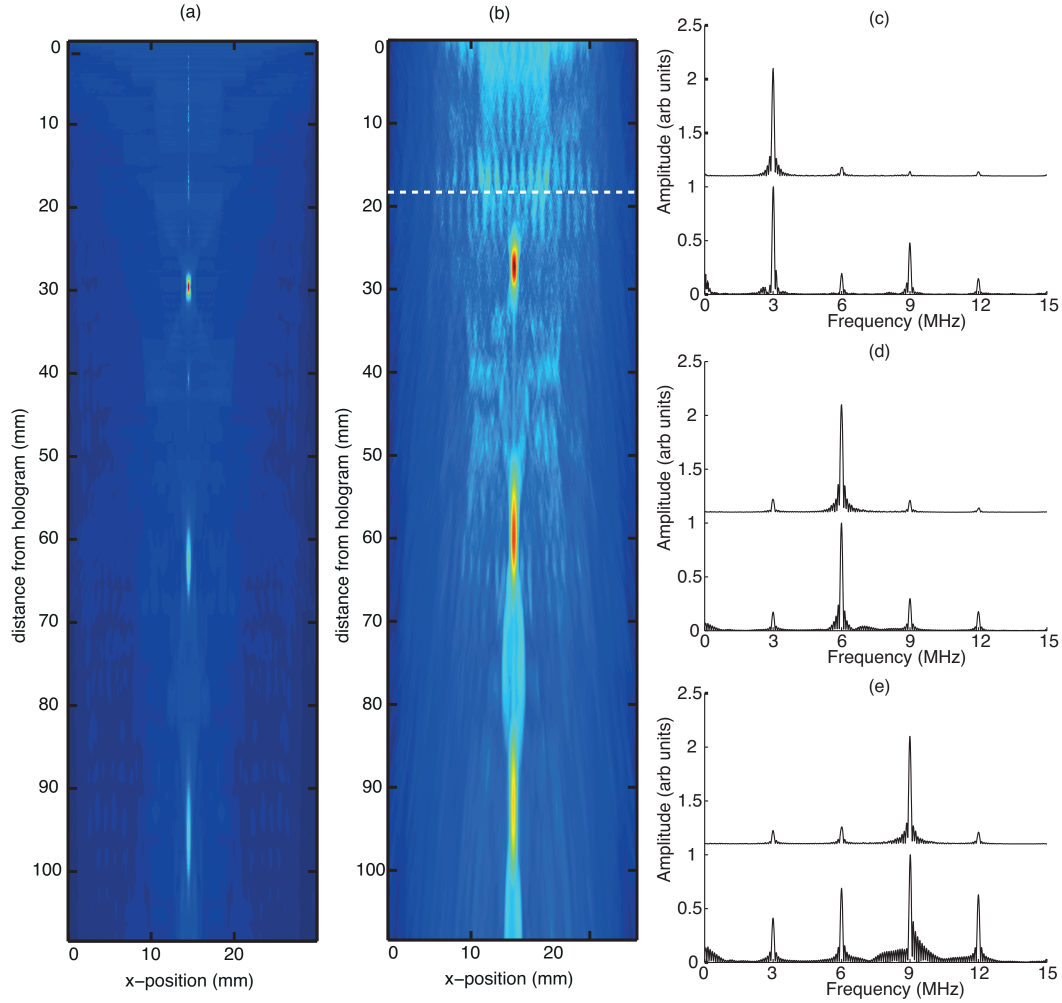

Fig. 5. Maximum intensity projection of 3-D ultrasound wavefield produced by a binary amplitude hologram in (a) simulation, and (b) experiment. In (b) the white dotted line is the measurement plane of the data. (c) (d) and (e) are the spectra of the pulse at the three foci in the experiment and simulation field. Each spectra is normalised, experiment spectra is translated up by 1.1 relative to simulation. The three graphs correspond to (c) first focal point (d) second focal point (e) third focal point

pulses at the hologram design frequency with a rapidly pulsed laser. This was verified by both experimental and simulation data. It was found, however, that use of a broadband ultrasound source results in multiple additional focal points further away from the hologram caused by harmonics in the pulse spectra. It was also shown that as the number of pulses or the hologram resolution reduces, the focal region becomes larger.

The approach used here of creating the holographic pulses by patterning the absorbing layer is somewhat inflexible. The depth of the ultrasound focus can be controlled after fabrication by changing the pulsing frequency but its lateral position cannot be changed. In future work the patterned absorber could be replaced by a SLM. This can modulate the light field incident on a homogeneous absorber, such that ultrasound is excited from only part of the absorber. The pattern projected by this SLM could be flexibly changed allowing for adaptation of the holographic pattern. In principle, this system combined with a laser source capable of generating multiple narrowly spaced pulses could allow the focus and spectrum of the ultrasound pulse to be controlled in 3-D and adapted in real-time. This could form a 2-D optoacoustic array with tens to hundreds of thousands of elements [2] with a range of possible applications including high frequency ultrasound imaging in 3-D.

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