3D imaging of buried microstructures in a slab using picosecond acoustics

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1. Introduction

Imaging buried structures is a diverse and widely studied problem, with applications ranging from geology to medical imaging to structural flaw detection[1]. A number of variations of the technique have been demonstrated, such as those using X-rays[2], positrons[3] and acoustic waves[4]. The contrast mechanism of each type of imaging depends on the type of wave and its interaction with the material. Systems based on acoustic waves are useful in many applications because of their simplicity, low cost, safety, and non-destructive nature. Such systems typically use pulse-echo time-of-light techniques, such as in medical ultrasound. However, diffraction, interference and mode conversion effects increase the complexity of the acoustic signals, and limit applicability and achievable image resolution. Studying wave propagation in different structures could potentially lead to the achievement of better image quality and more useful information about particular structures.

In this work we use simulations to investigate the propagation of GHz acoustic waves in micro-scale slabs and attempt to probe the internal structures by measuring the acoustic transmission. The complexity of the resulting wave patterns, including diffraction and interference, means that traditional computed tomography approaches (which typically assume zero or little diffraction and attenuation) are not always appropriate. However the utilization of different excitation/detection schemes provide complementary information that can be used to reconstruct the structure.

2. Simulation

We performed 3D numerical simulations of bulk acoustic wave propagation in a rectangular aluminium slab containing buried polystyrene spheres of different sizes and distributions. The excitation source was chosen to model experimental conditions for laser-induced thermoelastic excitation of acoustic waves at GHz frequencies. From the simulated time-resolved output we extract the acoustic wave fields and inspect the surface displacements and strains at the perimeter of the sample. We use the data taken on the sample perimeter to infer the sample's interior structure.

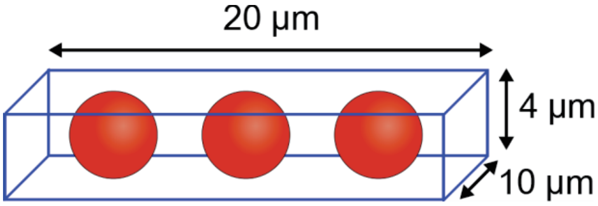

Fig. 1 Diagram of a test sample consisting of a 4 μm thick aluminium slab containing buried 4 μm diameter polystyrene spheres.

Fig. 1 shows an example of such a structure, in this case consisting of a 4 μm thick aluminium slab containing 3 buried spheres arranged in a line, each with a diameter of 4 μm. The sample is excited at different positions on its surface with different source geometries. **Fig. 2** shows examples of the propagation of 12 GHz bulk acoustic waves inside this structure. The acoustic field, $f(\mathbf{r},t)$, is represented by snapshots of the local dilation (relative volume change), $\Delta V/V$. The waves are excited by a planar source distribution on the front face of the sample. The image shows a cross-section in the x-y plane of the acoustic propagation through both the aluminium and the polystyrene spheres. The acoustic field inside the spheres shows diffraction resulting from the surface curvature. Acoustic transmission through the spheres is seen to be relatively low. On the far surface of the slab there are regions of high amplitude, corresponding to acoustic paths with no obstacles, and regions of low amplitude—acoustic "shadows"—corresponding to acoustic paths in which an obstacle impedes the wave propagation. The transition between the two regions is quite sharp because of the relatively short acoustic wavelength and clear interface between the spheres and substrate. By measuring the field amplitude on the sample surface, we can identify features that make up the internal structure of the sample: choosing appropriate boundaries between the high and low amplitude regions defines the boundaries

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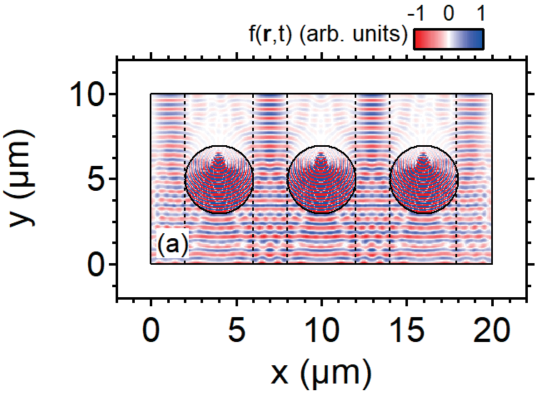

Fig. 2 Cross-sectional views of simulations of 12 GHz acoustic waves propagating in a 4 μm thick aluminium slab containing buried microspheres. The dotted lines indicate boundaries of the obstacles as determined by the acoustic shadows. Excitation is by a planar source at the y=0 face.

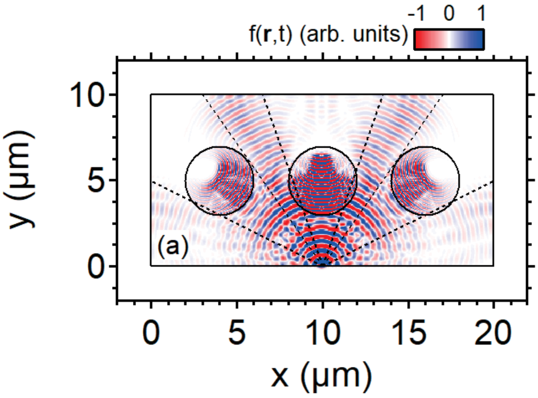

Fig. 3 Cross-sectional views of simulations of 12 GHz acoustic waves propagating in a 4 μm thick aluminium slab containing buried microspheres. The dotted lines indicate boundaries of the obstacles as determined by the acoustic shadows. Excitation is by a 0.5 μm diameter point source at the y=0 face and centred with respect to the structure.

of the obstacles in the acoustic path. In Fig. 2 such boundaries are indicated by the dotted vertical lines. Corresponding simulations can be performed with excitations on the remaining faces, and by combining the results of the different simulations we can determine the location and approximate size of the spheres.

Complementary information can be obtained by changing the excitation geometry. For example, **Fig. 3** shows the result of excitation with a 0.5 μm diameter spot. The smaller spot size means that there is a diverging wavefront and wide illumination of the sample. In this case the position of the excitation can be scanned over the surface so that different regions of the sample can be illuminated by the acoustic field from different angles. In Fig. 3 the excitation is at the centre of the front face of the sample, but corresponding simulations can be performed with the excitation spot at different positions on the same face, as well as over the remaining faces. In a similar way to the planar excitation, the approximate location and size of the buried objects can be obtained.

In a more complicated structure, it may be appropriate to combine results from both planar and spot excitations, as well as different source positions and sizes. Through broadband excitation and Fourier analysis we can also compare the results at different frequencies: while higher frequencies generally offer the potential for greater spatial resolution, they are also limited by higher attenuation.

Conditions for reliably identifying object boundaries and the limitations of this approach will be investigated. The results of the simulations will be used to guide future development of experimental studies of similar samples using an optical pump-probe system.

3. Conclusion

In this work we demonstrate the imaging of internal structures of micro-scale slabs by measuring the transmission of acoustic waves. With appropriate choice of excitation conditions for the sample under consideration, we are able to determine the size and location of buried microspheres. By comparing results from different structures and excitation schemes, we will identify the relevant features and limitations of the technique. The results will be used to spur further theoretical development as well as experimental implementation.

References

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