Design and fabrication of ultrasonic transducers with nanoscale dimensions

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Design and fabrication of ultrasonic transducers with nanoscale dimensions

R Smith[1], A Arca[1], X Chen[1], L Marques[2], M Clark[1] , J Aylott[2], M Somekh[1]

[1]Electrical Systems and Optics Research Division, Faculty of engineering, University of Nottingham, UK.
[2]School of Pharmacy, University of Nottingham, UK

Richard.j.smith@nottingham.ac.uk

The development of nanometre sized ultrasonic transducers is important in both biological and industrial applications. The small size can be important in its own right or necessary in order to generate acoustic waves with nanometric wavelengths. Potential applications of nanotransducers range from embedded sensors through to sub optical wavelength acoustic imaging. In this paper, we show the generation and detection of ultra high frequency acoustic waves using nanometre scaled optical ultrasonic transducers. The optical and mechanical properties of these devices have been modelled using finite element modelling (FEM) and analytical techniques. The models allow the fine tuning of the design parameters to enhance both the acoustic and optical performance of the transducers. The devices were fabricated by evaporating the required metal and transparent layers onto a substrate, and then surface patterning of the device was created by laser machining or photolithography, thus allowing close comparison between model and experiment. We discuss the transducer design process and the effect of the coating parameters and how these affect the operating frequency and efficiency of the devices. We discuss the possibility of using molecular self assembly to produce even smaller devices.

1. Introduction

Nanometre sized ultrasonic transducers are important in both biological and industrial applications. The small size is necessary in order to generate nanometric wavelengths or access small structures such as cells. There has been much interest in the vibration of micro[1] and nano[2] objects excited by fs laser pulses and the presented transducers build on this work. The transducers we introduce in this paper act as simultaneous optical and ultrasonic resonators designed so that they couple from the optical to the ultrasonic and vice versa. We have realised these in planar structures using Fabry-Pérot optical resonators and are developing spherical transducers using optically and ultrasonically resonant nanospheres (see figure 1a). There are a number of different approaches to producing these small scale structures and in this paper we shall focus on one method for building the planar devices. At this time the devices are nanoscale in one dimension only and we will discuss methods to reduce the size of the devices to be nanoscale in all dimensions. The devices have been modeled so that the parameters governing their behaviour could be tuned to produce a device that is effective from a mechanical and optical point of view. We have produced devices to be measured in a pump probe picosecond ultrasound system[3], where a pump pulse is absorbed by the sample and generates an acoustic wave packet. The probe beam monitors the sample at different time delays to measure the interaction of the propagating acoustic wave with the sample.

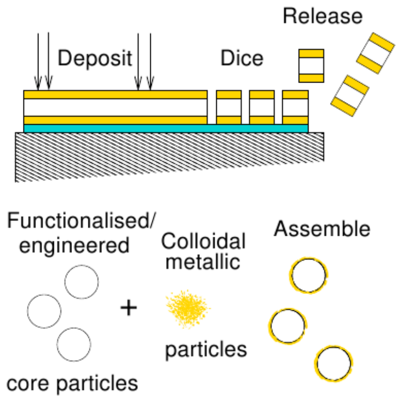


Figure 1. Two approaches to producing nano transducers

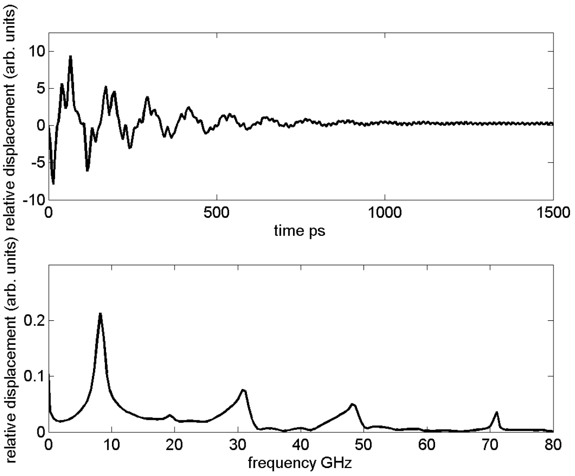


Figure 2. FE simulated ultrasound signal generated on nanostructure device

These devices rely on optical resonances and therefore rely on the presence of partially reflecting mirrors sandwiching an optically transparent filling. The incident light reflects and scatters off the partially reflecting boundary layers and interfere. The sensitivity of the device depends on the energy ratio of the reflected beams and the device size. If the size changes (for example due to the presence of an acoustic field) then the phase of the reflected components changes causing a change in the measured intensity at the detector. We have approached the creation of these transducers from a ‘top down’ direction, where ‘top down’ means be building the structures from the top, a layer at a time. The produced resonating layer structure that can then be patterned via photolithography or diced up using laser machining or focused ion beam techniques. Once diced the transducers can then be liberated from the substrate into solution.

2. Mechanical operation

The transducers generate ultrasound thermoelastically from the light absorbed primarily in the metal layers. Because the absorption in these layers is not uniform we use an EM FE model to predict this. The model calculates where in the structure the laser pulse is absorbed, knowing where and over what time scale the energy is absorbed the model can work out the change in temperature throughout the structure and from that the mechanical motion that arises. For the gold:ITO:gold structure we find that most of the light is absorbed in the top gold layer, which is as expected as gold is very absorbing at the pump laser wavelength of 400nm.

The result from the mechanical model for a structure of gold:ITO:gold:glass substrate (40nm:160nm:40nm:inf) is shown in figure 2 below, the figure shows the difference in displacement between the two gold layers. We observe a decaying oscillating signal composed of 3 or 4 main frequency components. The frequencies that are present are related to the round trip times of the acoustic waves through the structure.

3. Optical operation

The devices operate in a manner similar to that of a Fabry-Pérot interferometer. The layer structure is designed such that the top metal layer is a partial reflector allowing the probe beam to penetrate through the structure and reflect off the bottom layer of the structure. The two reflected beams then interfere with a strength that is dependent on the mirror separation. The acoustic field is assumed to change the separation of these partial mirrors, i.e. the optical path difference between the beams, hence creating a difference in the strength of interference. The individual thicknesses of the films are designed to give the optimum change in the reflectivity for a given change in mirror separation/radius, while maintaining desirable acoustic properties. When the transducers are bigger than the probe beam spotsize, they can be modelled analytically under the infinite width assumption using Fresnel coefficients. The result of this analytical optical model is shown in figure 3. The plotted quantity is the sensitivity of the device (d*I*/d*t*) i.e. the change in the reflectivity with respect to the mirror separation. From figure 3 we can see that for a gold:ITO:gold sandwich the best sensitivity is achieved with a 40nm gold layer and 160nm ITO layer.

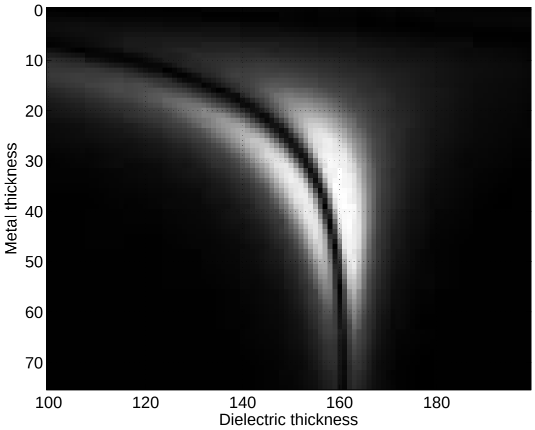


Figure 3. Sensitivity from analytical model

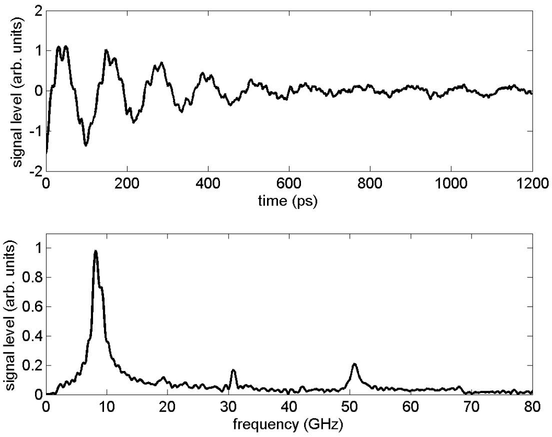


Figure 4. Experimental result from 10 micron transducer

4. Manufacturing the devices

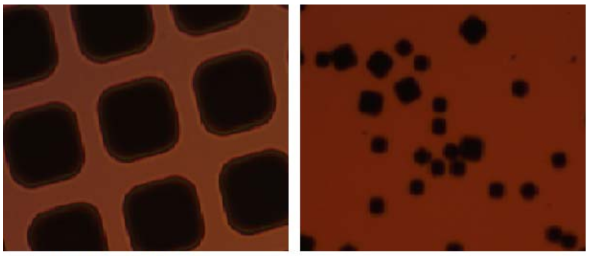
We have fabricated the devices using standard photolithography techniques to produce patterned substrates of the required films, which can be measured in situ or released from the substrate into solution. This approach allows very fine control over the devices made. It allows easy monitoring of the devices and allows *in-situ* measurements to be made before release to fine tune the design and fabrication process. However, the size and total number of devices made is limited, which in our case leads to a minimum device size of ~ 5 microns and a few million devices per run. Using a better photolithography process or employing a different dicing technique could produce transducers with lateral nanoscale dimensions.

5. The first prototype transducers

We have fabricated and tested a set of planar transducers. The experiment is based around an ASOPS [3] laser from Menlo Systems. This uses two femtosecond lasers that are jointly controlled with a set of high speed electronics to control the repetition rates of the two lasers. The electronics allow one laser to be locked at 100 MHz repetition rate and the other laser to be locked at 100 MHz + 10 KHz. This means that the lasers provide the equivalent of a 10 ns delay line sweep every 100 microseconds. The pump and probe beams are focused to the same location on the top of the transducer and probe response is recorded as the delay is swept. We measured a 10 micron transducer on top of a glass substrate that had a polystyrene buffer layer to provide acoustic isolation. The recorded signal is shown in figure 4 after the coincidence peak and background have been removed.

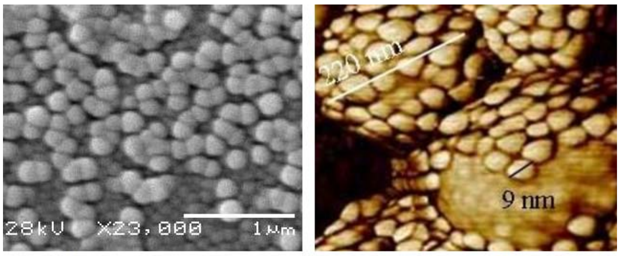
The signal is very similar to the modeled result in figure 2. The differences are likely due to slight variations in actual layer thicknesses and the mechanical properties. The oscillations in the experiment are longer lived than for the modeled result. This is likely due to the model not including the buffer layer and so acoustic energy is lost into the substrate more quickly than in the experimental case.

Figure 5 shows an optical image of the 10 micron patches and a lower magnification image of a mix of 5, 10 and 20 micron patches reattached to a glass slide after being lifted off into solution. This shows that the transducers survive the lift off process and can be reattached successfully.



10 micron patches Assortment of patches re-attached

Figure 5. Optical image of transducers in situ and released and reattached on a glass substrate



gold coated sillica particles zoom showing gold coating

Figure 6. Gold coated silica nanoparticle transducers

6. Future Directions

To reduce the transducer size still further we have started to tackle this problem from another direction – that of self assembled nanoparticles. We have made a series of particles with thin gold coating shells around a transparent core. These transducers are essentially a spherical version of the transducers we have already tested. These have a core of 180nm and a 10 nm gold shell (Figure 6). Testing of these devices is ongoing. In the future we intend to encapsulate and functionalize the particles increasing their utility as transducers.

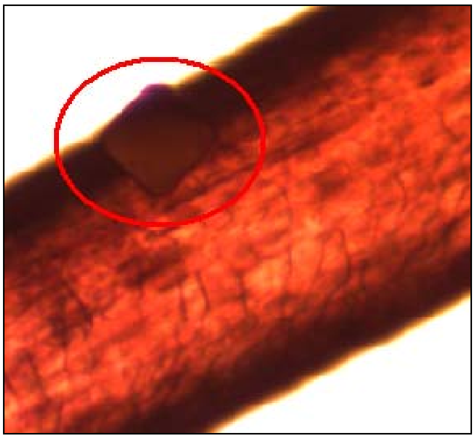


Figure 7. Transducer (highlighted) on a human hair

7. Conclusion

We have modelled, fabricated and tested an ultrasonic / optical transducer approximately 10-5 microns in size. The transducers can be liberated from the base substrate and attached for non contact measurements (see figure 7 where we attached a transducer to a human hair). These transducers produce and detect ultrasound at frequencies in the 5-30GHz range and they were remotely excited and probed using fs lasers. We have the ability to manufacture even smaller devices using molecular self assembly and have presented out first prototypes of spherical transducers of ~200nm in size.

References

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