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Design and fabrication of nanoscale ultrasonic transducers

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Abstract. 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 discuss the design and fabrication of nanoscale ultrasonic transducers. The transducers rely on optical and mechanical resonances, they can be used to generate and detect high frequency ultrasound in a sample. The mechanical and optical performance of the devices have been extensively modelled using both analytical techniques and finite element modelling. This allows the fine tuning of the design parameters to ensure optimised performance for the experimental configuration. The devices can be fabricated in a number of ways, we present one method for building these types of devices, a ‘top down’ approach where plate structures are built up and patterned using standard photolithographic techniques. This method produces nanoscale devices in one dimension only (the others being a few microns) but produces excellent devices for testing in situ and for comparison to the models as they are easy to handle and measure. Approaches for reducing the other dimensions to the nanoscale will also be considered.

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 femtosecond 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 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 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.
These devices rely on optical resonances and therefore require 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 change causing a variation in the measured intensity at the detector. We have approached the creation of these transducers from a ‘top down’ direction, where ‘top down’ means building the structures from the top, a layer at a time. The produced resonating layer structure 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 pump beam light absorbed in the metal layers. Because the absorption of the laser light 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.

The frequencies produced by the transducer vary with the thickness of the layers used. Figure 3 and 4 show the changes to the dominant frequency component as the layer thickness varies. In figure 3 the ITO layer thickness is kept fixed at 160nm and the gold layer is varied. We see a shift in the frequency from 14 – 9.5 GHz. Figure 4 shows the case where the gold layer is kept fixed at 20nm and the ITO layer is varied. Again, we see the frequency shift by a significant amount 13 – 9 GHz. This allows some tuning of the device to operate at a specific frequency by carefully choosing the layer thicknesses.
The fact that the devices are so sensitive to the layer thicknesses means that this can be used as a transduction method. Figure 5 shows the effect of adding a very thin layer of material to the top gold layer of a device. In this case the added thin layer was ITO as this is optically transparent to the pump beam and would therefore not affect the location of the generation of the sound waves. As the thickness of the loading layer is increased we see that the resonance peak shifts by a small but measurable amount.

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 transducer. The two reflected beams then interfere with a strength that is dependent on the metal layer separation. The acoustic field will change the separation of these partial mirrors, and so the optical path difference between the beams will change 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 6. The plotted quantity is the sensitivity of the device \( \frac{dI}{dt} \) i.e. the change in the reflectivity with respect to the mirror separation. From figure 6 we can see that for a gold:ITO:gold sandwich the best sensitivity is achieved with a 40nm gold layer and 160nm ITO layer, although there are broad range of device configurations that have good performance.

Figure 6. Sensitivity of the gold:ITO:gold transducer from the analytical model

To model the devices as they get smaller a full 3D FEM model is required. In this case the input field is incident on the device in the positive \( x \) direction, with the device layers extending in the \( x \) direction, the transverse size of the device can be varied (\( y,z \) direction) as shown in figure 8. We then calculate the reflected and transmitted far field spectra. This is achieved using a near field to far field transformation.

To obtain the sensitivity we calculate the scattering cross section \( C \) as a function of separation \( S \) and then differentiate this to get \( dC/dS \) which is our “sensitivity” measure (i.e how much the signal changes when the transducer is squeezed by the ultrasound). This is then repeated for different device layer thicknesses and transverse sizes. We find that as the devices get smaller and smaller (i.e. the transverse
size gets smaller so there is less of the device interacting with the input field) then the sensitivity peak shifts to longer probe wavelengths. If the wavelength is fixed then the sensitivity will reduce as the device size is reduced. To keep optimal performance the device configuration must be changed. The change is required as the refractive index of the filling material (ITO in this case) starts to have reduced influence on the response, such that eventually the optimal point depends most strongly on the refractive index of the surrounding medium (air or water). As the refractive index of the medium is less than that of ITO the devices must be made thicker as the transverse size decreases. This can be seen in figure 9 which shows a plot of the sensitivity peaks of the devices shifting to thicker layer sizes (particle size) when the cross section of the devices reduce.

![Response of particles of different cross sections](#)

**Figure 8.** Effect of reducing the transverse size of the devices – the sensitivity peaks shift to taller device sizes

### 4. Manufacturing the devices

We have fabricated the devices using standard photolithography techniques to produce patterned substrates. Use of a sputer allows the gold and ITO layers to be deposited on the patterned substrate. This 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 lateral device size of ~5 microns and a few million devices per run. Using a better photolithography process or employing a different dicing technique (such as focused ION beam or E-beam lithography techniques) 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.
Figure 9. Optical image of transducers in situ and released and reattached on a glass substrate

Figure 9 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.

We measured a 10 micron transducer on top of a glass substrate that had a polystyrene buffer layer. The buffer layer has two purposes, firstly to provide acoustic isolation for in-situ measurements, thus increasing the length of time the signals exist, and secondly as a way to release the devices into solution. The recorded signal is shown in figure 10 after the coincidence peak and background have been removed.

Figure 10. Experimental result from 10 micron patch transducer

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 difference in the actual mechanical properties of the layers. The oscillations in the experiment are longer lived than for the modeled result. This is likely due to the inclusion of the buffer layer and the reduction of acoustic energy lost into the substrate that it provides.

To demonstrate the influence of the surroundings on the response of the transducer we have measured a set of devices in both air and water (figure 11). The water layer acts as a mass loading layer and as such influences the mechanical resonance of the device causing the measured frequencies to shift.
Figure 11 shows that the signals levels are reduced in water significantly compared to the levels obtained in air. There are a number reasons to explain this; firstly for the water layer to be included an additional cover slip was added with standoffs to trap a water layer of ~300-400 microns above the transducers. This will have reduced the amount of pump and probe light reaching the transducers reducing the size of the generated waves and reducing the detection signal to noise ratio. Secondly water is very attenuating at high frequencies [4] and so we expect to see a reduction in signal level with much stronger damping and for the high frequency peaks.

Figure 12 shows the spectrum of the traces for the air and water experiments, we see that the main peak has shifted down by ~300MHz and the 50 GHz peak which was clear in the air case is no longer visible above the noise. More averaging was used in the water case to improve the chance of seeing these attenuated peaks but they have been damped to such a level that they are still not visible.
6. Future Directions

The devices that have been made and tested have only been nanoscale in one dimension. In the future we hope to reduce all dimensions to the nanoscale. This could be achieved by using other patterning techniques such as improved photolithography processes or ebeam lithography or focused ion beam techniques. We have also 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. The gold shell acts as the partially reflecting layers and the clear soft inner silica core acts as the separation layer.

The advantage of using the self assembly approach is that it is easier to make small devices, but the difficulty arises in controlling the distribution of sizes so that most of the batch produced are within the correct size range for good operation at our laser wavelength.

We have manufactured devices with a core size of ~180nm and a 10 nm gold shell (Figure 13) but the distribution of sizes is still quite high. Testing of these devices is ongoing.

![Figure 13. Self assembled nano particle transducers, the gold particles can be seen coating the silica core](image)

As well as reducing the size we will need to improve our handling techniques for these small devices so that they can be reattached for measurements. In the future we hope to encapsulate and functionalise the devices so that they can be used for site specific measurements. This will increase their utility as transducers considerably as the ability of the transducers to only attach to the things we wish to measure will be very useful.

7. Conclusion

We have modelled, fabricated and tested an ultrasonic / optical transducers of approximately 200nm in height and with lateral dimensions of 10-5 microns in size. The transducers can be liberated from the base substrate and attached for non contact measurements. These transducers produce and detect ultrasound at frequencies in the 5-50GHz range. They have been remotely excited and probed using femtosecond lasers. We have the ability to manufacture even smaller devices using molecular self assembly.

8. References

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