Nano-ultrasonic sensors

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Introduction:

Ultrasonics and ultrasonic sensors are widely used in numerous applications:
- Medical imaging and diagnosis
- Industrial imaging and measurement, especially non destructive testing
- Chemical, force, pressure and mass sensing [especially SAW sensors and quartz microbalances]

For conventional, piezo-transducer based ultrasonics:
- Typical frequencies are 1-100MHz
- This gives typical wavelengths of 50µm-5mm
- Typical transducer ~ matchbox size (10-30000mm^3)

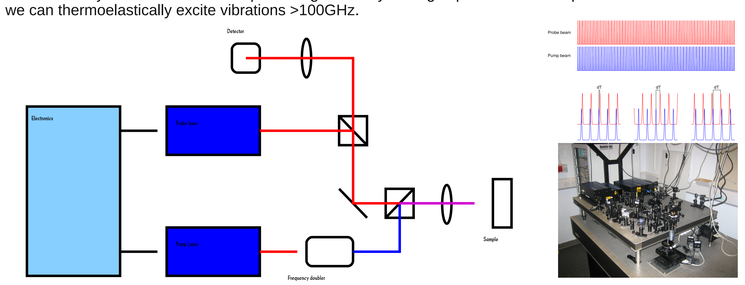
Nano-ultrasonics provides a technology platform for these applications at the nanoscale:
- Typical frequencies 1-100GHz
- Typical wavelengths 50nm-5µm
- Sizes down to ~100nm.

A key motivation is that smaller transducers allow smaller sensorsleading to better spatial resolution. Smaller sensors can also be used to access smaller environments such as the interior of cells. Nano-transducers could obtain ultrasonic resolutions higher than that of optical microscopes because the ultrasonic wavelength is smaller than that of visible light.

At the nanoscale there are significant basic technical problems to overcome, for instance, electrical connections are not possible due to the size, electronics in the GHz is difficult and the attenuation of ultrasound rises very fast with frequency (1900db/mm at 4GHz). The answer is to use fs lasers, laser ultrasonics and ps ultrasound techniques coupled with nano-ultrasonic transducers.

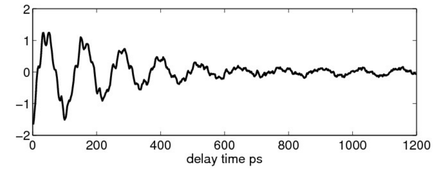
Pump-probe techniques:

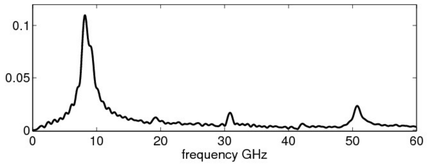
To overcome the physical and bandwidth restrictions of electrical / electronic interfaces to nano-ultrasonic transducers we are using dual pulse fs lasers. The "pump" pulse is used to activate the transducer and a second "probe" pulse is used to read the transducer.
The probe pulse is timed to occur after the first pulse is used to "strobe" the measurement (down mix the signal to DC). By adjusting the time delay between the pulses the entire ultrasonic signal can be observed. We use a dual laser ASOP system to scan the complete range of delays at high speed. The laser pulses have THz bandwidth and we can thermoelastically excite vibrations >100GHz.



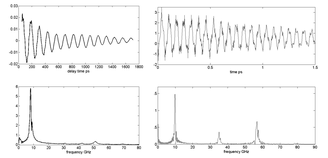
Nano-transducer results:

These results show the ultrasonic response of nano-transducers using the dual laser ASOPs system. These sandwich sturctures were excited using 150fs pulses at a wavelength of 390nm and the response was observed using pulses at a wavelengths of 780nm.





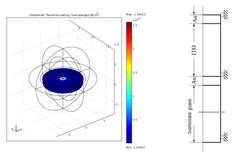
We have been able to show different response from these devices depending on the exact layer thickness used during fabrication and the details of the method of attachement to the samples. The Q of oscillation can be quite high and the damping can also yeild information about the sensor environment.



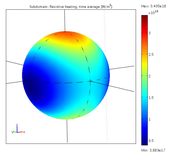
Transducer design:

Nano-ultrasonic transducers are designed to be both *optically* and *elastically resonant*. Can be any shape but have made "sandwich" and spherical structures.

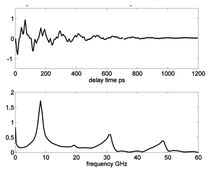
They are designed to absorb light at one wavelength and convert this absorbed heat into stress and vibration.

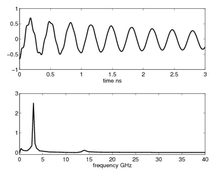


Analytical and mixed FE models were used to predict and optimise the mechanical behaviour of the structures

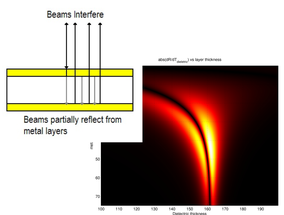


Models predict vibrational modes and frequency response and help to optimise the choice of materials for efficient transfer of optical energy into mechanical vibration.

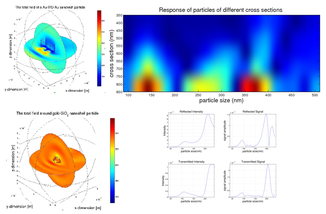




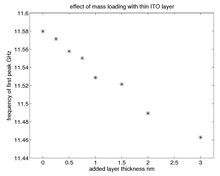
They are designed to resonantly scatter light at a 2nd wavelength. When the the transducer is perturbed by mechanical vibrations the scattering cross-section is changed and the motion of the transducer can be measured by observing the change in the optical scattering cross-section.

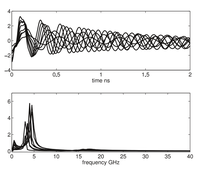


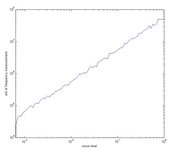
Analytical and FE models are used to predict and optimise the optical properties of the structures. FE becomes increasingly important for non symmetric structures and as the structures become sub-optical wavelength in size.



The models can also be used to predict and optimised the structure's response to the environment, for instance by increasing or decreasing the sensitivity to mass loading or by designing in additional vibrational modes. Comparing these with the noise performance of the instrumentation demonstrates that the right structures can exhibit high sensitivity to mass loading which is required for high sensitivity chemical detection.

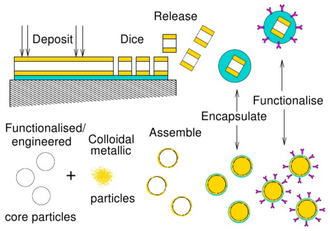


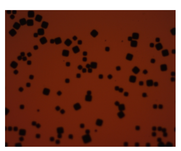


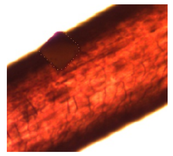


Transducer fabrication:

Nano-transducers can be fabricated using lithography (top down techniques) or molecular self assembly (bottom up techniques)



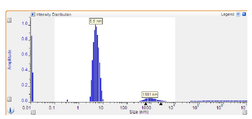


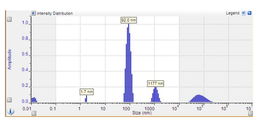


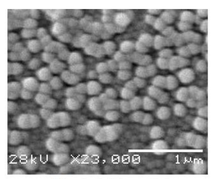
Top down techniques give excellent control and uniformity to some aspects of the fabrication process and can produce modest numbers of sensors (10^6 sensors per batch is possible). However, it becomes more challeging to fabricate smaller devices and is compairitively expensive.

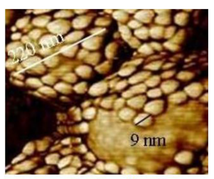
Molecular self-assembly provides an inexpensive way to fabricate large numbers of sensors (10^{12} sensors per batch is possible). It is simple to make small devices but process control is difficult so it is challenging to produces sensors with the optimal performance. It is also difficult to handle these small sensors and locate them in the instrument.

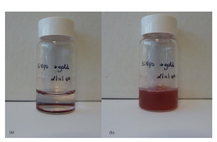
These structures where made using functionalised 185nm silica beads coated with 10nm colloidal gold particles. A single batch can produce >10^{12} sensors. The process is inexpensive but careful process control is required to produce devices with uniform size and shape.

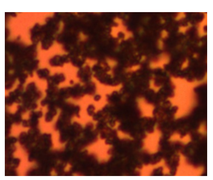










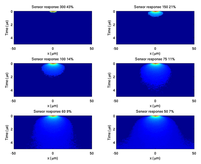


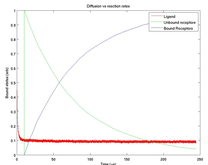
Effective size and resolution of sensors:

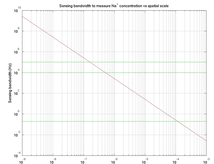
As a sensor becomes smaller the spatial resolution of the measurand increases because it senses a smaller volume. However in gaseous or liquid environment the effective size of the transducer is limited by diffusion and the response time of the sensors. For large sensors this is not particularly important and the diffusion distance is usually insignificant compared with the detector size. For very small sensors the diffusion distance can be the dominant scale for calculating measurement volumes.

Diffusion distances vs response time:

The speed of the nano-transducers is practically limited by the data acquisition time (but ultimately determined by signal-to-noise factors and the amount of optical power the sample can take without damage). However, the speed of sensing is ultimately limited by the chemical processes required for the target measurand to interact with the sensors and this can be slower than the instrumentation or diffusion at these scales.
As an example a typical pH meter with a response time of a few seconds and a size of a few mm is sensing a layer a fraction of a mm around it.
A nano-ultrasonic transducer 100nm across operating at 10kHz is sensing a volume of ~5um, many times its size.
To sense a volume equivalent to its size it would have to operate at ~100MHz - much faster than the chemical interaction at its surface.







Conclusion:

We have demonstrated the world's smallest ultrasonic transducers and investigated how they might be used as an ultrasonic chemical sensor. One target is to sense the intracellular environment at high resolution, however, diffusion limits the spatial resolution of nano-sensors because their speed cannot increase fast enough to keep pace speed of diffusion over small distances.

The ultimate limitation on the temporal response of these devices is not the ultrasonic response of the sensors nor the speed of data aquisition or the instrumentation but the the time taken for the sensor to interact chemically with the environment and bond to the target ligand. This is a fundamental limitation for very small chemical sensors. This means that free nano scale chemical sensors are not likely to achieve nanometre resolution for sensing in liquids.

Apart from chemical sensing, these devices could be used to probe the mechanical / elastic properties of small structures such and nano-engineered materials and cells. In these circumstances where diffusion and chemical interaction is not a factor the resolution is limited only be the ultrasonic wavelengths or the size of the devices.

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