A Fabry-Perot fibre-optic hydrophone for the measurement of ultrasound induced temperature changes

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***Abstract*— A wideband fibre optic hydrophone system based on a polymer film Fabry-Perot interferometer has been developed for the measurement of ultrasound fields. The sensor transduction mechanism is based upon the interferometric detection of acoustically-induced changes in the optical thickness of the polymer film. The system is also sensitive to temperature change due to thermal expansion of the polymer film. This permits the sensor to be used to measure temperature changes caused by ultrasound exposure. The advantage of this concept is that it offers the prospect of providing simultaneous measurement of ultrasound fields and induced temperature changes at the same spatial location. Characterisation of the thermal performance of the sensor shows its response to be linear up to 65 °C and the resolution nominally 0.25 °C. Ultrasonically induced temperature rises of 50 °C above ambient were measured when insonating with a HIFU transducer. The response time of the sensor is currently limited to approximately 120 ms due to the tuning speed of the laser.**

I. INTRODUCTION

Ultrasound induced heating is an important effect in two broad areas of medical ultrasound. Firstly, in diagnostic ultrasound it is important that heating is avoided as it can lead to tissue damage and even necrosis [1]. Secondly, in therapeutic ultrasound, where treatment relies on localised temperature increases either to destroy tissue (e.g. tumors [2]) or to encourage reparation (e.g. physiotherapy [3]). In both cases it is important to have knowledge of the underlying relationships between the acoustic parameters of the ultrasound field and the corresponding heating effects (and vice-versa). At present, experimental investigations of such effects require two measurement devices, one for acoustic measurements and one for thermal measurements. This makes it impossible to simultaneously measure temperature and pressure at the same spatial location.

In previous work [4], [5], a fibre-optic hydrophone based on a polymer film Fabry-Perot interferometer has been developed and shown to have a wide bandwidth (>50 MHz), high sensitivity (NEP = 2 kPa) and small optically defined element size (10 μm). In this paper, the use of this sensor to measure both acoustic signals and ultrasonically induced heating is presented.

II. THE HYDROPHONE SYSTEM

The hydrophone system setup can be seen in Fig. 1. The light source for the system is a tuneable laser operating in the telecomms C band (1528-1564nm). This provides the input light to the sensor via a 2x2 coupler. After passing through the coupler, the light is transmitted via the fibre downlead directly to the sensing element at the tip of the sensor fibre. The reflected light (which is modulated by the ultrasound) is then detected at the photodiode (having been routed back through the 2x2 coupler). The operation of the laser (i.e. wavelength tuning) is controlled by a PC.

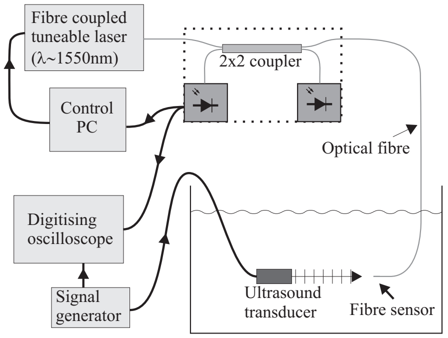

Fig. 1. *Schematic of the fibre-optic hydrophone system*

The sensor itself comprises a Fabry-Perot interferometer formed by sandwiching a polymer film between two gold mirrors, the first of which is semi-reflective.

The first gold mirror is deposited onto the tip of the fibre by DC sputtering. The reflectivity of the mirror is controlled via its thickness. Following this, a 10 μm thick film of Parylene-C is deposited under vacuum to form the polymer sensing layer. After the sensing layer is deposited, the 2nd gold mirror is sputtered onto the tip to complete the sensor structure. Finally, a thin ($< 2\mu$m) layer of Parylene is deposited to protect the 2nd mirror and improve robustness. A full description of the fabrication process can be found in reference [4].

A. *Acoustic transduction mechanism*

The optical power reflected from the sensor is dependant upon the relative phases of the optical fields reflected from

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each of the gold mirrors. Phase, in turn, is dependant on the optical thickness of the polymer layer and the wavelength of the incident light. The relationship between phase and reflected power is known as the interferometer transfer function (ITF). As an ultrasound wave arrives at the sensor, the acoustic pressure results in a change in the optical thickness of the polymer film and hence a change in phase. This produces a change in the optical power reflected back into the fibre.

For maximum acoustic sensitivity, the system is biased to the optimum operating point which corresponds to the peak phase derivative of the ITF. This is achieved by measuring the ITF (by tuning the laser through it's wavelength range and measuring the reflected optical power) and then returning to the wavelength corresponding to this peak derivative. This process is carried out automatically by the system software.

B. Thermal measurement mechanism

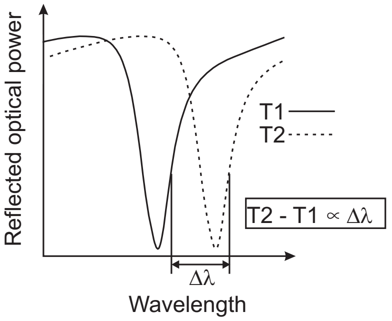

Fig. 2. *As temperature (T) changes, so does the wavelength corresponding to the peak phase gradient. Measurement of $\Delta\lambda$ allows calculation of ΔT*

The sensor's thermal sensitivity is based on the detection of thermally induced thickness changes in the polymer film. These thickness changes typically happen on a much slower timescale than those induced by an ultrasound field. The phase of the ITF is dependant on both the thickness of the polymer layer and the optical wavelength. It follows that a temperature change will shift the bias point along the wavelength axis. This can be seen in figure 2. The shift can be directly related to the temperature change. Continuous measurement of the ITF (by repeatedly scanning the laser wavelength) allows for real time monitoring of ultrasound induced temperature changes. For this to be successful, it is necessary to have a laser which is rapidly tuneable so that the sensor's ITF can be measured in the shortest time possible.

III. EXPERIMENTAL METHOD

In order to induce significant temperature changes for the sensor to detect, a fibre hydrophone was cast in a cylindrical silicone rubber[1] mould. The silicone acted as an acoustic absorber and the absorbed energy caused an increase in temperature. A thermocouple probe was also embedded in the same mould at a lateral distance of approximately 1 cm from the fibre tip. The thermocouple was used to verify that ultrasound induced changes in temperature were occurring. A schematic of the setup can be seen in figure 3.

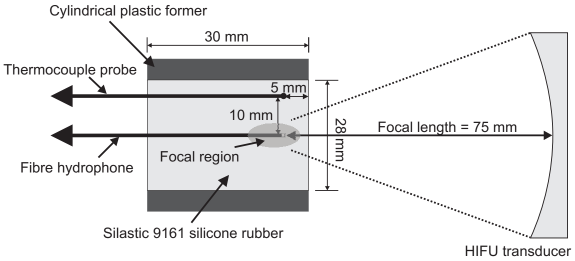

Fig. 3. *Schematic of fibre and thermocouple alignment within silicone rubber mould*

Two sets of heating experiments were carried out. Firstly, a planar transducer (typically used for calibrating needle and membrane hydrophones), which generated a non-linearly propagating tone burst, was used. In these experiments, the silicone rubber mould was aligned such that the fibre sensor's tip was on the acoustic beam axis. This was achieved by measuring the amplitude of the acoustic field and moving the sensor on a 3 axis, computer controlled translation system. The temperature rise was varied by changing the mark-space ratio of the transducer. Since the heating produced was relatively slow, it was possible to capture an oscilloscope trace of the acoustic signal immediately prior to commencing temperature monitoring.

Secondly, a high intensity-focussed ultrasound (HIFU) transducer was used to induce faster, higher temperature changes. The transducer operated at a frequency of 1.1 MHz and had a focal length of 75 mm, the resulting focal region was on the order of several millimetres. Since the temperature changes induced by the HIFU transducer occurred on a much shorter timescale than those with the planar transducer, it was not possible to measure the acoustic field prior to the temperature measurements. The fibre was aligned with the focal point of the field by knowledge of the focal length of the transducer and the approximate location of the fibre sensor within the silicone rubber.

In order to quantify the temperature changes, it was first necessary to calibrate the sensor to relate a given wavelength shift to a change in temperature. This was achieved by placing the silicone rubber mould in a beaker of water and slowly heating it. The temperature measurement from the thermocouple was then compared to the wavelength shift from the fibre sensor.

IV. RESULTS

A. Thermal calibration

The data from the thermal calibration can be seen in figure 4. The wavelength shift as a function of temperature is seen to be linear up to a temperature of approximately 40 °C above ambient (in this case 25 °C). Above this temperature change, the response becomes non-linear. However, it is possible that the thermal properties (i.e. range of linear thermal expansion)

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[1] Dow-Corning Silastic 9161 silicone rubber

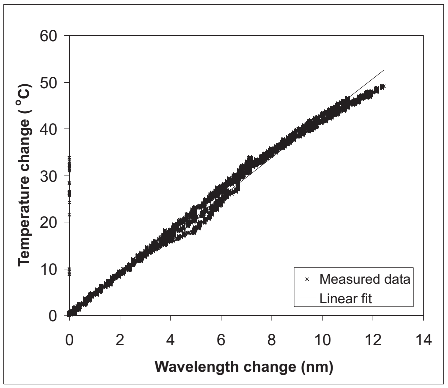


Fig. 4. *Thermal calibration plot*

of the silicone rubber in which the fibre is embedded may influence the temperature response of the sensor.

B. Planar transducer

In the first experiments, a planar transducer generating non-linear tonebursts and operating at a fundamental frequency of 1 MHz was used. To produce a significant level of heating a mark space ratio of 1:9 was employed. The waveform of the field in the water immediately before the surface of the silicone rubber can be seen in figure 5(a).

The silicone rubber absorbed a significant proportion of the energy in the beam. This is illustrated in figure 5(b) which shows the measurement made by the embedded fibre optic hydrophone. It can be seen that all of the energy in the higher harmonics has been absorbed leaving just the fundamental frequency (1MHz) of the transducer.

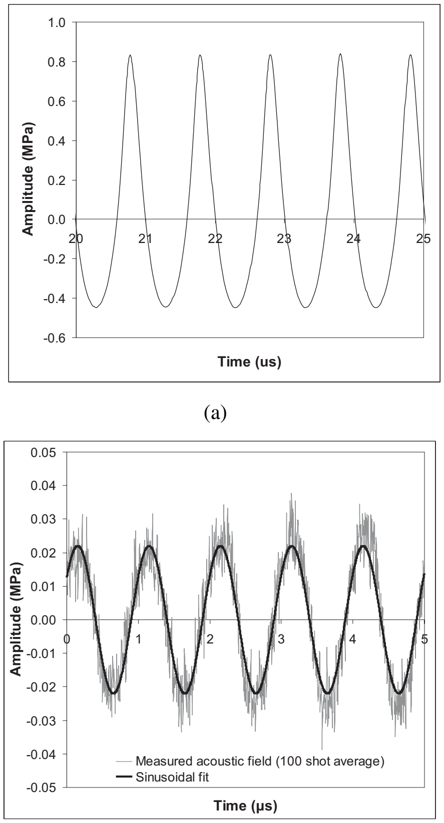
The results of the heating with the planar transducer can be seen in figure 6. The basic form of the temperature rise appears to agree with expectations as it follows an approximately exponential rise during insonation and a similar exponential fall after the transducer is switched off.

The maximum temperature rise recorded by the fibre sensor for this insonation was approximately 12 °C above the ambient temperature (28 °C). However, the thermocouple is seen to exhibit less of a temperature change, recording a maximum of 4.8 °C above ambient. This also agrees with the expectations since the thermocouple is significantly off-axis, thus the heating local to the probe will be less than at the fibre tip.

Another feature of the fibre sensor data is the apparent discretisation of the temperature/wavelength values. At this stage the origin of this is not fully understood. However, it could be related to a *stick-slip* thermal expansion where a certain level of stress is required for the sensor to overcome some inherent inertia and expand/contract. This may arise from differential thermal expansion of the Parylene and the surrounding silicone rubber.

C. HIFU transducer

In order to induce larger temperature changes, a HIFU transducer was used. Two sets of data are shown in figures 7(a) and 7(b). In 7(a), the transducer was operated in CW mode with a peak to peak amplitude of 90 V. At this setting, the heating effect was considerably greater than that achieved with the planar transducer, with a maximum temperature rise of 35 °C (relative to the water tank ambient of 29 °C. The figure also shows that the temperature measured by the thermocouple peaks after the transducer is switched off. This is due to the fact that the heating effect would have been very highly concentrated close to the fibre. Once the transducer was switched off, the heat slowly dissipated causing a continued increase in temperature close to the thermocouple.



(a)

(b)

Fig. 5. *Acoustic signal measured by a)a PVDF membrane hydrophone (active diameter 0.4mm) at the surface of the silicone rubber cast and b) the fibre-optic hydrophone 5 mm inside the silicone rubber.*

In figure 7(b) the transducer was again operated in CW mode, this time with a peak to peak amplitude of approximately 150 V. Here the heating was more rapid with a temperature change of nearly 45 °C in just 25 seconds.

On closer inspection of the peak in measured temperature change (figure 7(b)), the temperature appears to decrease slightly before the transducer is switched off. The figure also shows that after cooling, the temperature change becomes negative, suggesting that the silicone rubber finishes at a temperature approximately 10 °C below the ambient temperature of the water tank. Such a change is clearly non-physical. It is believed that this was caused by a change in the mechanical

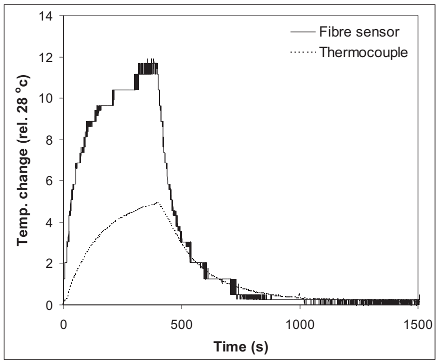


Fig. 6. *Temperature evolution with planar transducer*

properties of the silicone rubber, brought about by the extreme heating. This change in mechanical properties may have led to an increase in static pressure close to the fibre sensor, which would be indistinguishable from a decrease in temperature.

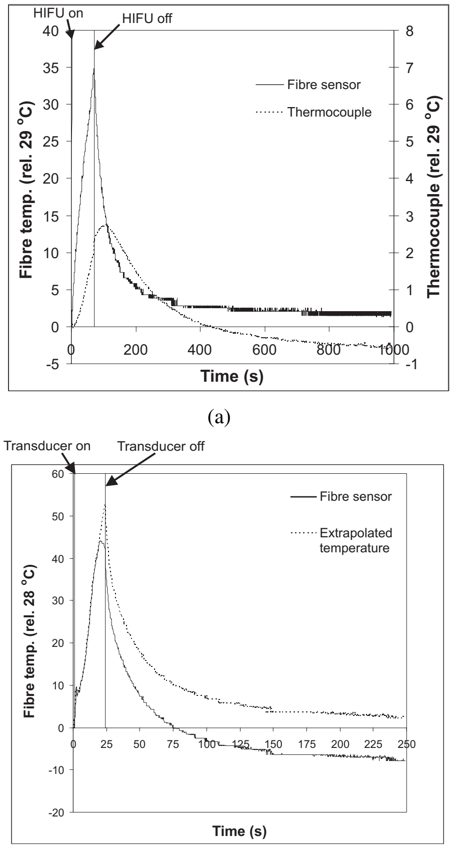
Assuming that this is what happened, it is reasonable to extrapolate the curve to find the actual temperature attained at the fibre sensor. Assuming the gradient of the temperature rise to be constant over the short time of the discrepancy, a maximum temperature rise of 52 °C is seen. This is shown by the dotted line in figure 7(b).

V. CONCLUSION

In this paper, the Fabry-Perot fibre-optic hydrophone has been shown to be suitable for making measurements of temperature rises induced by ultrasound fields. The sensor's response to temperature changes has been shown to be linear up to a temperature of approximately 65 degrees with a resolution of 0.25K. However it is important to note that the the surrounding silicone rubber may have influenced the linearity. As a part of the future work, an investigation of the linearity of the temperature response with the sensor in different materials (such as air and tissue-like gels) is planned.

Whilst it has not been directly measured in this work, the sensor should have a short rise time. As the shift in wavelength is related to the change in thickness of the sensor, and the sensing layer is very thin (10 μm), the time taken for the sensing layer to change thickness should be very small. Work using a similar sensor and sensing layer thickness was carried out by Laufer *et al*[6] indicated rise times of less than 150 μs. Despite this fundamental limit, the rise time of the current system is limited to significantly longer rise time as it takes 120 ms to tune the laser in order to measure the transfer function. However, it should be possible to significantly reduce this by modifying the method used to track the wavelength shift.

The ability to measure both the ultrasound field and any associated heating could prove useful in several areas of ultrasound, for example the characterisation of the output of diagnostic medical transducers. Other potential applications include investigations of heating in, for example, tissue or tissue-like phantoms with HIFU fields. In both applications the ability to relate temperature changes to acoustic pressures, and also vice-versa, would be of great benefit.



(a)

(b)

Fig. 7. *Temperature evolutions using the HIFU transducer a) in CW mode with a peak to peak amplitude of 90 V pk-pk and b) in CW mode with a peak to peak amplitude of 150 V pk-pk*

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