DEVELOPMENT OF A 50MHZ FABRY-PEROT TYPE FIBRE-OPTIC HYDROPHONE FOR THE CHARACTERISATION OF MEDICAL ULTRASOUND FIELDS.

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1 INTRODUCTION

Modern diagnostic medical ultrasound equipment increasingly uses higher frequencies to improve spatial resolution. Higher power ultrasound (US) sources are also being used for therapeutic applications. These higher powered sources cause non-linear propagation of the US within the body and the subsequent harmonic distortion leads to a much wider frequency content of the signal being measured. Characterisation of the output of such devices requires a hydrophone with a broadband frequency response and an acoustically small element size to avoid spatial averaging. Any such hydrophone must achieve these two characteristics whilst retaining adequate sensitivity.

The devices presently used for this type of characterisation are piezoelectric PVDF needle and membrane hydrophones (A review of the current technology and techniques can be found in reference 1). Whilst development in fabrication techniques have allowed the production of needle hydrophones with small active areas (~40µm), the reduction in sensitivity as active element size decreases is still a limitation with this type of sensor.

Several alternatives to the needle hydrophone based on fibre-optic sensing methods have been suggested in the past. These techniques employ reflectometry[2], interferometry[3], diffraction[4], polarimetry[5], or the inclusion of Bragg reflectors[6] within the fibres to detect ultrasound.

In this paper we present an extrinsic optical fibre sensor based on a polymer film Fabry-Perot Interferometer (FPI). This is a development of previous work in which it was shown that this type of sensor can provide a bandwidth of 20MHz and a wideband noise equivalent pressure of 10kPa [7]. The concept has been advanced by making 3 key developments. Firstly a new range of fibre sensors was designed with bandwidths in excess of 50MHz. Secondly, in order to develop a relatively low cost system with the necessary robustness for practical field use, the operating wavelength region of the sensors has been shifted to the 1520-1600nm range. This enables the rapidly tuneable, stable and inexpensive fibre-coupled C-L band lasers developed for optical telecommunications applications to be used as the interrogating source. Finally, following the acoustic characterisation of an initial batch of the fibre sensors, we have shown that a modification of the fibre tip geometry can improve the frequency and directional response.

2 THE FABRY-PEROT BASED FIBRE-OPTIC HYDROPHONE SYSTEM

2.1 Sensor transduction mechanism

The fibre-optic hydrophones presented here are based on the optical measurement of acoustically induced changes in the optical thickness of a thin polymer film deposited onto the tip of an optical fibre. This is made possible by creating a Fabry-Perot (FP) cavity with the polymer film as the intracavity spacer. For an appropriate interrogating wavelength, the reflectance of the cavity is directly related to the thickness of the spacer. Thus, as the thickness is modulated by an acoustic pressure, so too is the reflectance of the cavity. The optimum operating (optical) wavelength, or bias point, of the sensor is found by measuring its Interferometer Transfer Function (ITF). This is achieved by measuring the reflectance of the cavity as a function of wavelength. The bias point is then chosen to be the point of maximum gradient on the ITF as depicted in Figure 1. At this point the sensor produces the highest sensitivity and linearity.

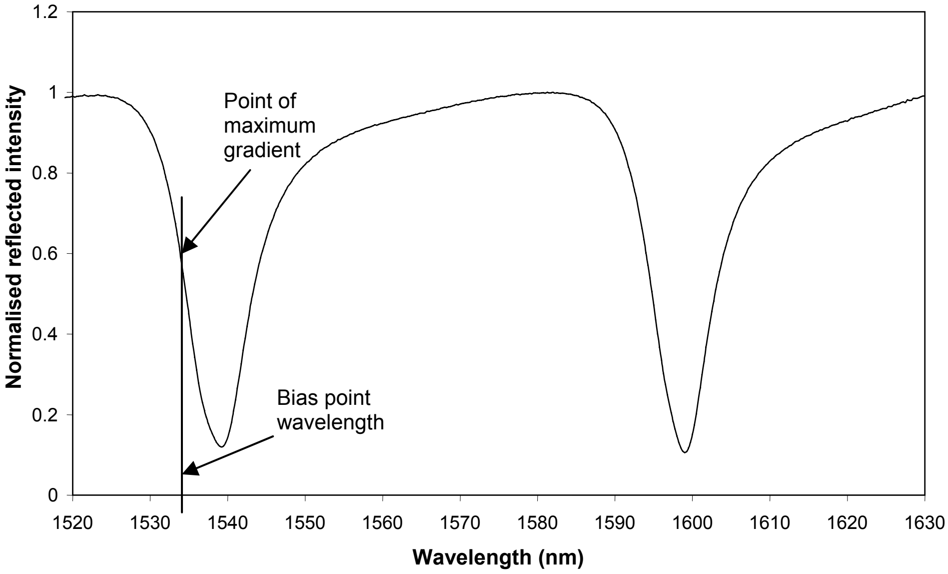

Figure 1 Measured interferometer transfer function for a fibre-optic hydrophone with a sensing layer of approximately 10µm

2.2 Sensor design and fabrication

In this paper, we present two fibre-optic sensor designs, both based on the Fabry-Perot interferometer. The first type is fabricated on the tip of a plane cleaved optical fibre. The second is fabricated on the tip of a tapered optical fibre.

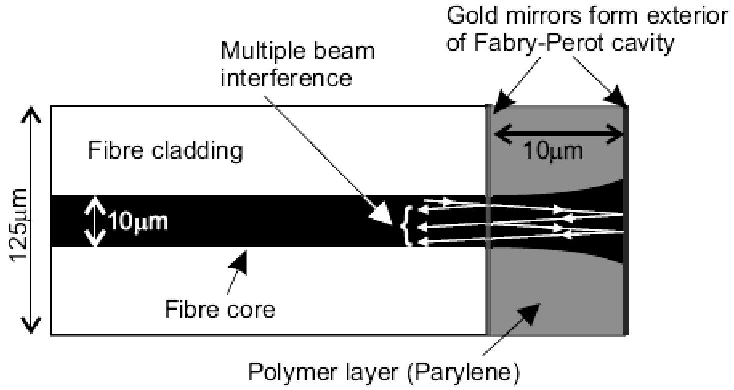

Figure 2 Schematic of the plane cleaved optical fibre sensor

Figure 2 shows a schematic of the plane cleaved optical fibre hydrophone. The sensing structure is deposited directly onto the tip of a plane cleaved single mode optical fibre (SMF28). The face of the fibre tip must be perpendicular to the optical axis of the fibre. This is necessary to minimise return losses from the sensor into the fibre. The Fabry-Perot cavity comprises a 10µm polymer film (Parylene) sandwiched between two gold mirrors. The first mirror is formed by the DC sputtering of

Gold onto the tip of the fibre. The desired mirror reflectivity is achieved by controlling the thickness of the gold coating. Once the first mirror has been deposited, the polymer spacer is vacuum deposited[7]. Parylene-C was chosen for the polymer as it has good optical clarity and offers a very conformal coating. This means that when deposited on to an optically flat surface (i.e. the tip of a plane cleaved optical fibre) both the contact surface and the exposed surface of the parylene will be flat. This is extremely important in the production of a high quality FP cavity. Parylene also has good mechanical properties with a low Young's modulus which helps to improve the sensitivity of the sensor. It can also be deposited under vacuum enabling sensors to be inexpensively batch fabricated. Following the deposition of the Parylene, the second gold mirror is deposited. The reflectivity of this mirror is set as high as possible to ensure a maximum return signal from the sensor. A final thin coating (~2μm) of Parylene is applied to encapsulate the sensor and improve robustness.

The polymer film thickness was chosen to be 10μm. Assuming the sensor approximates to a rigid backed configuration, this provides a theoretical bandwidth of 50MHz. The reflectivity of the first mirror was optimised using a numerical model of the ITF. The hydrophone's sensitivity is dependant on both the "visibility" of the interference fringe and also the maximum gradient of the ITF. From the model, it is apparent that a compromise must be struck between these values as an increase in the gradient can lead to a reduction in visibility and also a higher DC level at the bias point. The higher DC level can increase the optical noise generated by the photodiode and thus reduce the performance of the system.

Figure 3 shows a schematic of the tapered fibre hydrophone design. The decision to use a tapered sensor was made after preliminary results from the plane cleaved fibre showed a non-uniformity of frequency response. It has been previously shown[8] that the frequency response of a needle hydrophone is dominated by diffraction effects related to the tip geometry. The same reference also indicated that the frequency response could be flattened considerably by modifying the geometry of the hydrophone tip. It therefore seemed reasonable to conclude that tapering the tip of the sensor could also significantly improve the performance of these sensors. The tapered fibre hydrophone maintains the same transduction mechanism as that of the plane fibre, with the Fabry-Perot cavity being deposited in the same manner.

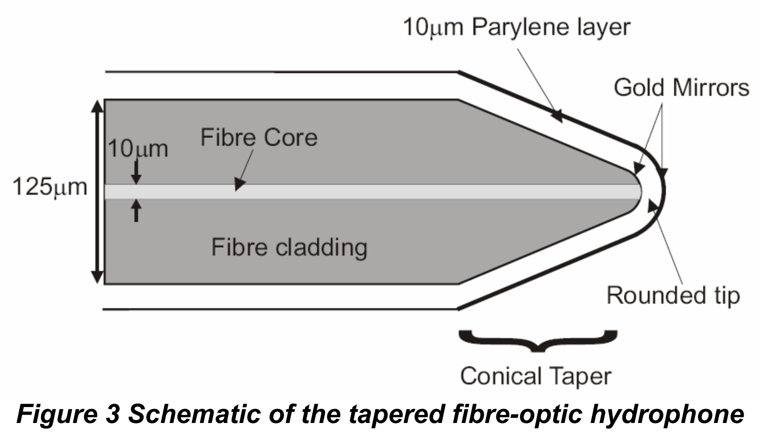

Figure 3 Schematic of the tapered fibre-optic hydrophone

2.3 Hydrophone system overview

A schematic of the hydrophone system can be seen in Figure 4. The light source for the system is a tuneable laser which operates in the telecoms C-L bands (1520-1600nm). 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 by a wideband InGaAs photodiode (having been routed back through the coupler). The bias point for the sensor is found by sweeping the laser through its wavelength range whilst recording the photodiode output in order to obtain the ITF. The laser is then tuned back to the maximum gradient of the ITF. The entire procedure is carried out under computer control.

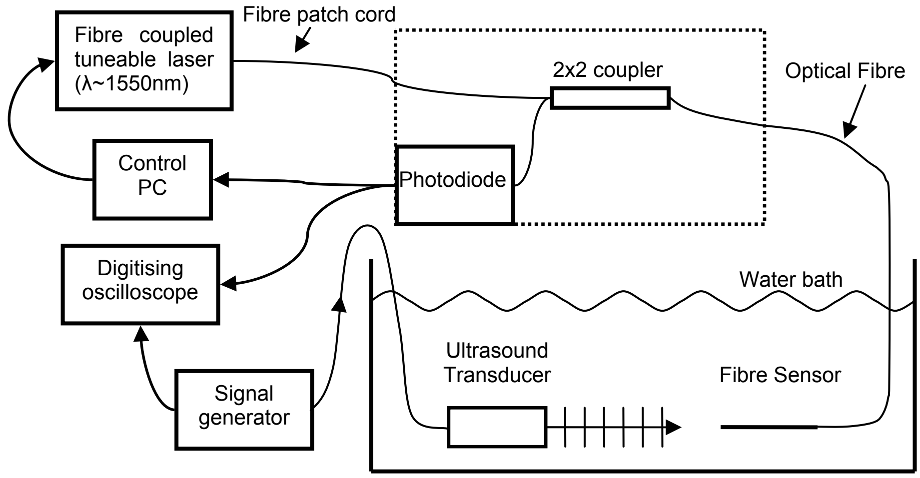

Figure 4 Schematic of optical fibre hydrophone system

3 ACOUSTIC PERFORMANCE AND CHARACTERISATION

3.1 Experimental setup

The frequency response and directivity of the sensor were investigated using a shocked wave tone burst as seen in Figure 5a. This was generated by driving a 1MHz transducer with a high amplitude signal. The resulting non-linear propagation leads to the distortion of the waveform and subsequently generated harmonics that occur at integer multiples of the fundamental.

3.1.1 Frequency response

The frequency response of the fibre sensors was determined using a substitution calibration technique. The acoustic signal was first measured using a PVDF membrane hydrophone of known frequency response. The measurement was then repeated using the fibre sensor. By comparing the frequency content of the signal measured with the fibre sensor to that of the membrane hydrophone, the fibre sensor’s frequency response could be determined. To ensure accuracy, both hydrophones were aligned to the acoustic beam axis using a 3-axis, computer controlled, motion control system. The hydrophones were positioned such that the time delay between the generation and detection of the ultrasound pulse was the same for each. These measures ensure that the frequency content of the acoustic signal being measured was the same in both measurements. (A full description of this technique and its specific advantages can be found in reference 9)

3.1.2 Directivity

The directional response of the fibre sensors was obtained by placing them in the shocked field described above. The hydrophone was aligned such that when it was rotated around its tip, the temporal shift of the measured waveform was less than 100ns. This prevents the tip of the sensor from being translated within the acoustic beam during rotation. This is a necessary requirement as the frequency content across the acoustic beam is non-uniform and any translation of the hydrophone tip during the experiment will result in an increase in measurement uncertainty.

3.2 Results

3.2.1 Sensitivity

The sensitivity of the fibre optic hydrophone is not only determined by the optical and mechanical properties of the sensing structure itself. It is also influenced by the output power of the laser as well as the performance of the photodiode. Indeed an increase in the laser output power will increase the sensitivity of the sensor. However, such an increase may also lead to increased noise on the photodiode. As such we use the noise-equivalent-pressure (NEP) of the sensor as a measure of sensitivity. We define this as *the acoustic pressure that provides a system signal-to-noise ratio of unity*. Thus the NEP is given by

$$NEP = \frac{N}{S} \tag{1}$$

where S is the senor sensitivity (mV MPa^{-1}) and N is the RMS value of the system noise voltage (mV). However, S is frequency dependent (see section 3.2.2), we therefore define S to be *the average sensitivity (in mV MPa^{-1})in the frequency range 1-20MHz*. We measured the NEP of the plane cleaved fibre sensor and found it to be 2kPa over a measurement bandwidth of 50MHz for a laser output power of 1mW. This is comparable to the NEP of a 200μm PVDF needle hydrophone[7]. The sensitivity of the tapered hydrophone was considerably lower than that of the plane cleaved fibre sensor. This is likely to be due to a higher level of optical loss introduced by the beam altering characteristics of the taper. This loss results in a lower level of light being reflected back into the fibre. As a result of this, the value of the NEP for the tapered fibres was approximately 50kPa.

3.2.2 Frequency response

Before looking at the frequency response of the fibre sensors, it is useful to look at the time-domain signals produced by fibre sensors and comparing them to that produced by the known standard (in this case the PVDF membrane hydrophone). The time domain signals from all the hydrophones used are shown in Figure 5. The plots reveal some structure within the signal from the fibre hydrophones which is not seen in the signal from the membrane hydrophone. This is indicative of a non-uniform frequency response. It can be seen that the signal from the tapered sensor contains slightly less high frequency ringing than is seen with the plane fibre hydrophone – indicating, perhaps, a more uniform frequency response.

The frequency response spectra are shown in Figure 6. Examination of the features of the spectrum from the plane fibre sensor reveals a potential link between the geometry of the sensor itself and the frequency response. The first major peak in sensitivity occurs at 24MHz, if we convert this to a wavelength, bearing in mind the speed of sound in water, we get 62.5μm. This is equal to the radius of the optical fibre. This suggests the presence of edge waves propagating across the tip of the sensor, and then arriving in phase at the sensing region. Similarly, the peak sensitivity at 32MHz corresponds to a wavelength of 68 microns in Parylene (the sensing layer) which is the equivalent of the total radius of the sensor (fibre plus Parylene). So this could arise from the same edge waves as the first peak, but this time propagating within the sensing layer

The spectrum from the tapered fibre also shows a major peak, this time at 14MHz. The corresponding wavelength of 100μm is of the same order as the fibre diameter and could, therefore, be related to the fibre geometry. On comparison with the results from the plane fibre, it can be seen that the tapered fibre has a more uniform response over the frequency range 20-50MHz.

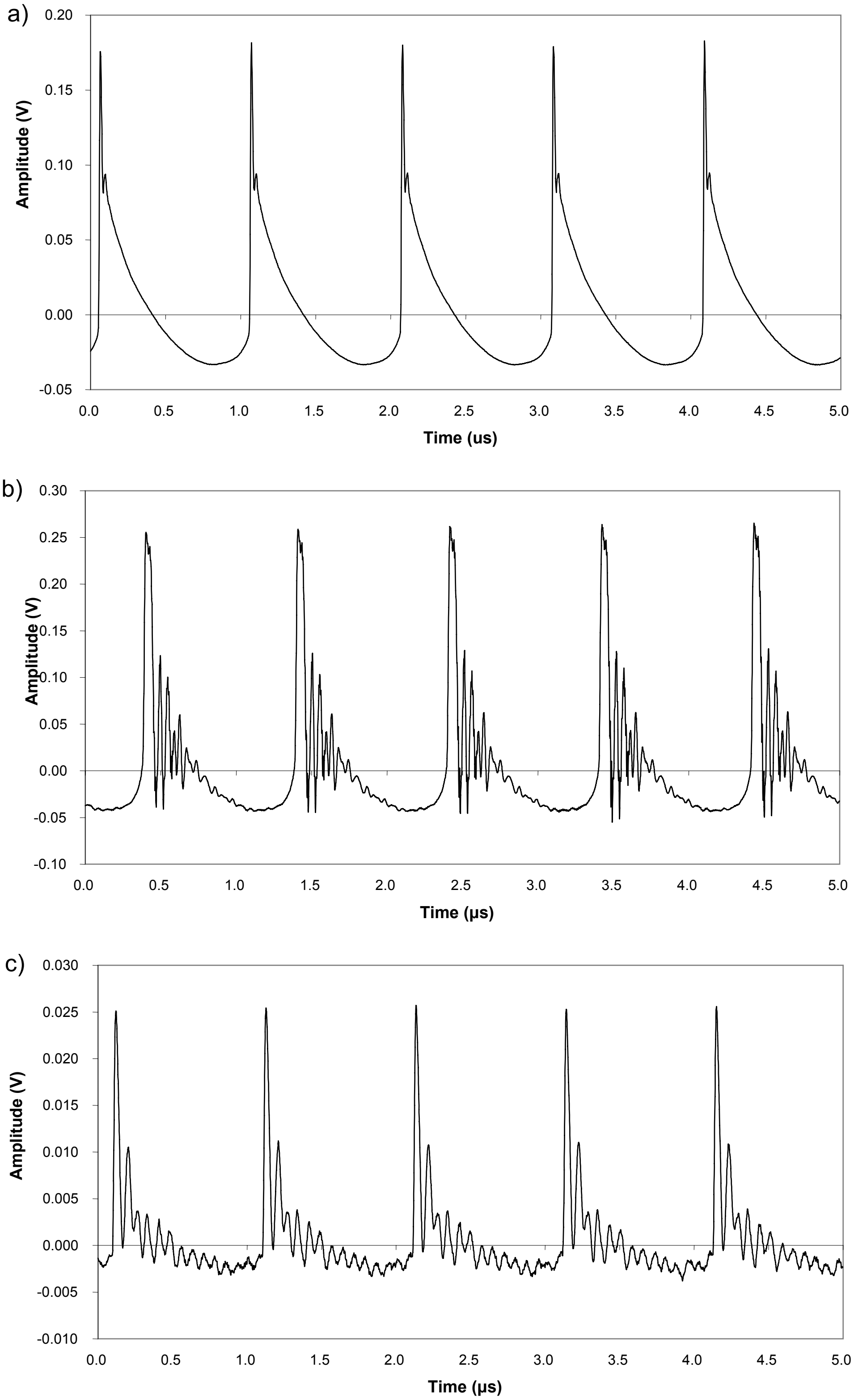

Figure 5 a)Time domain signal showing shocked wave as detected by a reference membrane hydrophone. b) Shocked wave signal acquired by a typical plane cleaved fibre hydrophone. c) Shocked wave signal acquired by a tapered fibre optic hydrophone.

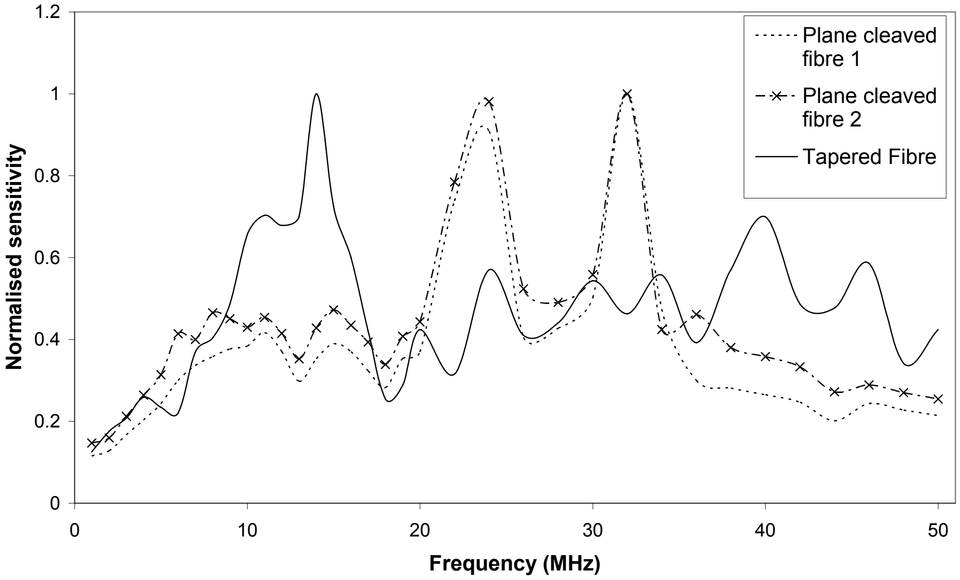

Figure 6 Frequency responses for two typical plane cleaved fibres and one tapered fibre hydrophone

3.2.3 Directivity

The directional response of both the tapered and plane cleaved fibre hydrophones can be seen in Figure 7 a) and b) respectively. For low frequencies (1-10MHz), the response of the plane fibre falls gradually and uniformly with angle, whilst not reaching a null in the range 0-90°. In this frequency range the acoustic wavelength (>150µm) is much greater than the expected active element size (We estimate the active element size to be given by the mode field diameter of the optical fibre, in this case that is on the order of 10µm). At 15MHz we see the sudden appearance of 2 nulls at +/-30°. According to the standard directivity model for a circular plane piston in a rigid baffle, this corresponds to the performance of a sensor of active element size 240µm – twice the diameter of the optical fibre. The response of the tapered hydrophone shows some improvement over that of the plane sensor. Here it is seen that although there are nulls in the response, they occur at a larger angle and are also significantly broader. The extent of the sensitivity drop is also considerably lower at around 15dB instead of 25. The structures seen in the responses are still the subject of our ongoing work.

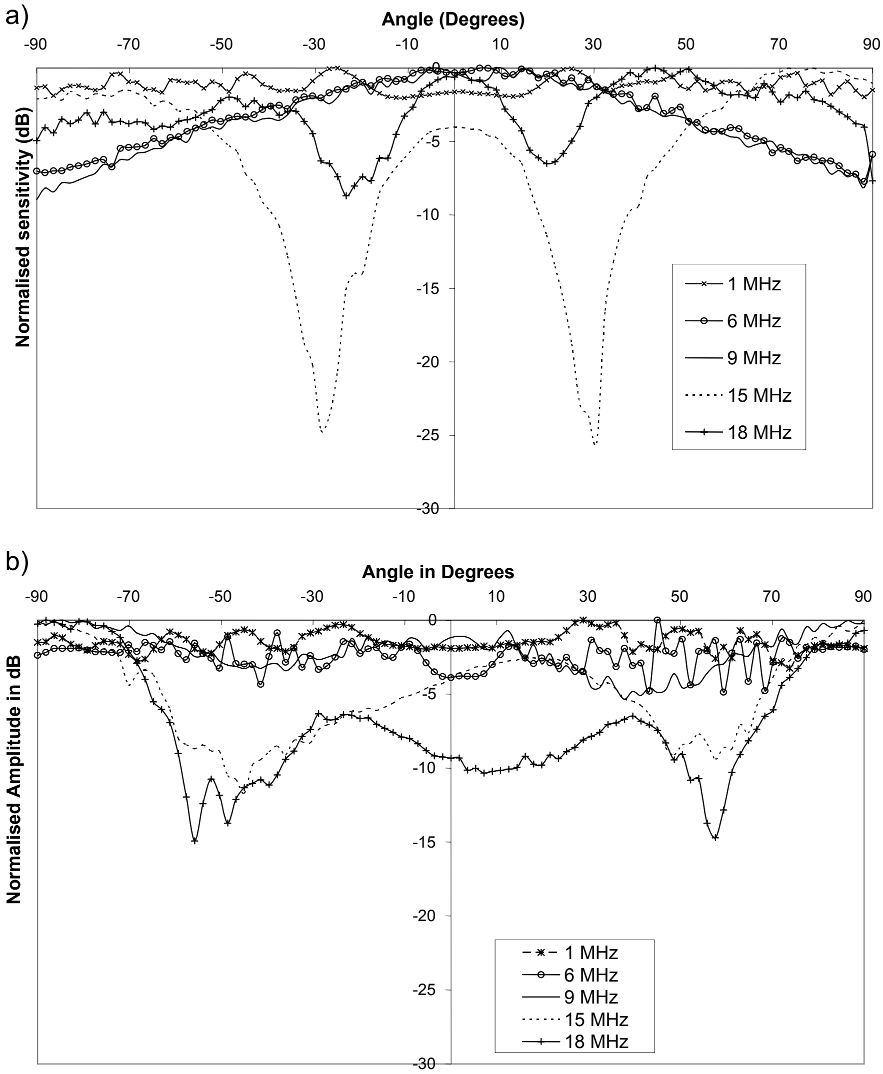

Figure 7 a) Directivity plot for a typical plane cleaved fibre hydrophone. b) Directivity plot for tapered fibre hydrophone

4 CONCLUSIONS

The aim of this work is to produce a fibre-optic hydrophone, with a bandwidth in excess of 50MHz, for the characterisation of medical ultrasound fields. We have presented two sensor designs, one based on a plane cleaved fibre tip and the other on a tapered fibre tip. The plane tipped fibre has shown a good sensitivity (NEP ~5kPa) and a bandwidth extending beyond 50MHz. By designing the sensor around a 1550nm single mode fibre, we have been able to use a tuneable laser designed for the telecoms industry. Such lasers are readily available and offer ruggedness and reliable operation at a reasonable price. The use of this type of laser has also allowed us to construct an entirely fibre-coupled system suitable for use in the field.

In an effort to improve the uniformity of response across the entire bandwidth of the sensor, we have introduced the use of a tapered optical fibre. This type of fibre is becoming more widely available “off the shelf” as the taper can form a lens at the tip of the fibre which is useful in some alignment applications. However, this lens effect has reduced the optical quality of our Fabry-Perot cavity and thus reduced the sensitivity of the hydrophone (NEP ~50kPa). This effect, however, is balanced by the apparent improvement in uniformity of the frequency response across the bandwidth as seen here.

Our future work on this project will involve using acoustic and optical modelling to investigate and improve the sensitivity, frequency response and directivity of the sensors. In doing this we hope to achieve an optimum sensor tip geometry giving high sensitivity and a uniform response over the bandwidth of the sensor.

5 ACKNOWLEDGMENTS

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