Characteristics of optimized fibre-optic ultrasound receivers for minimally invasive photoacoustic detection

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ABSTRACT

A range of miniature (125µm o.d.) fibre optic ultrasound sensors based on the use of interferometric polymer optical cavities has been developed for minimally invasive photoacoustic imaging and sensing applications. It was observed that by careful selection of both the fibre tip and cavity geometry it is possible to achieve exceptional acoustic performance. Specifically, rounding the tip of the fibre to remove the presence of sharp diffractive boundaries enables a well behaved frequency response along with a near omnidirectional response at frequencies in the tens of MHz range to be achieved. The use of a plano-convex rather than a planar cavity provides high finesse and therefore detection sensitivity. Thus, by using a plano-convex cavity formed at the tip of radiused single mode fibre it was possible to realise a miniature ultrasound detector with a bandwidth of 80MHz, a noise-equivalent pressure of 40Pa (over a 20MHz measurement bandwidth) and a near omnidirectional response at frequencies as high as 30MHz. These characteristics suggest this type of sensor could find applications in interventional medicine for guiding needles or catheters, as mechanically scanned photoacoustic imaging probes or in laser scanning OR-PAM.

1. INTRODUCTION

Photoacoustic methods have significant potential in interventional medicine where a miniature sensing or imaging probe is inserted into the body for diagnostic, therapeutic or guidance purposes. A specific configuration of interest comprises a needle or catheter containing a fibre for delivering the excitation laser light and a miniature ultrasound receiver for detection[1,2]. This type of look-ahead transmit-receive probe could be used, for example, to guide needle or catheter based interventional procedures or as a mechanically scanned photoacoustic imaging probe. Realising such a device requires a highly miniaturised, broadband (tens of MHz) ultrasound detector. This presents a significant challenge when using conventional piezoelectric detectors. Fabricating and connectorising piezoelectric elements can become challenging as their dimensions become smaller and the ultrasound frequencies become higher. Additionally, it can be difficult to achieve sufficient detection sensitivity with small piezoelectric elements. Ultrasound receivers based on the Fabry Perot (FP) polymer film sensing concept[3] offer the prospect of overcoming these limitations. This type of sensor can provide high sensitivity and bandwidths extending to several tens of MHz. It can also readily be formed at the tip of a single mode optical fibre[4] allowing fabrication of highly miniaturised (125µm o.d) electrically passive detectors in a flexible probe-type configuration.

The first generation fibre-optic FP ultrasound sensors employed a planar FP sensing cavity deposited on to the tip of a plane cleaved single mode fibre[4]. However they suffered from several limitations. These included modest sensitivity due to beam walk-off which limits the cavity finesse and a non uniform angle-dependent frequency response due to diffraction effects around the fibre-tip. In this paper, a new generation of fibre-optic sensors that overcomes these limitations is

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described. Two key developments have been made. First, instead of using a planar FP cavity, a plano-convex[5] cavity is employed. This provides much higher optical confinement enabling the cavity finesse and therefore the sensitivity to be increased very significantly. Second, by carefully modifying the geometry of the fibre end-face, the influence of diffraction can be reduced enabling far superior frequency response and directional characteristics to be achieved.

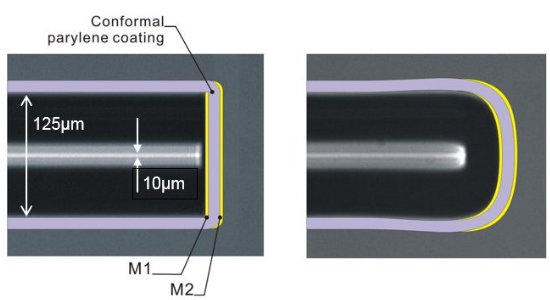
Several sensor designs were fabricated, characterised and their acoustic performance compared with each other. Section 3 describes those based on a planar FP sensing cavity and section 4 describes those employing the more sensitive plano-convex cavity.

2. OVERVIEW

The sensors described in this study comprise an optical interferometric cavity consisting of a micron-scale polymer spacer sandwiched between a pair of mirrors. The cavity is formed on the tip of a single mode optical fibre, interrogated using light emitted by a 1550 nm continuous wave laser[5] and optimally biased by tuning the interrogation wavelength to the edge of the cavity resonance[5]. Under these conditions an acoustically-induced modulation of the cavity optical thickness produces a corresponding modulation in the reflected optical power which is detected by a photodiode. A range of sensor designs with different fibre tip and cavity geometries were fabricated and comprehensively characterised by measuring their sensitivity, frequency response and directivity as described in the following two sub-sections.

3. PLANAR FP SENSING CAVITY

In the first instance, fibre probes comprising a planar Fabry Perot (FP) sensing cavity formed on the tip of a 1550nm single mode SMF-28 optical fibre (core/cladding diameters: 10µm/125µm) were fabricated. Two designs distinguished by the different fibre-tip geometries shown in Figure 1 were investigated. The first comprised a plane-cleaved fibre (with the buffer removed) on to which a dielectric coating was deposited to form the first mirror (M1) of the cavity (Figure 1(a)). A 12µm thick Parylene C polymer spacer was then vacuum deposited on to the tip followed by deposition of the second mirror (M2). Both mirror reflectivities were nominally 98%. Finally, a protective Parylene C coating (not shown) was deposited over the entire structure to prevent water ingress. The second design employs a rounded tip as illustrated in Figure 1(b). This geometry was motivated by the notion that smoothing the edges of the fibre tip may yield improved frequency response and directional characteristics by avoiding the sharp diffractive boundaries of the plane-cleaved design[6,7]. The tip of the fibre was rounded by melting it in a controlled manner using the arc discharge from a fusion splicer. The polymer spacer and cavity mirrors were deposited on to the fibre tip as described above. Although the tip is not perfectly flat, its radius of curvature is sufficiently large that the sensing cavity geometry can be regarded as being planar over the 10µm diameter of the fibre core.



(a) (b)

Figure 1 Planar FP Parylene C polymer cavities formed at the distal end of (a) a plane-cleaved fibre and (b) a rounded-tip fibre. M1 and M2 are the cavity mirrors on either side of the conformal Parylene spacer. The figures are composite images comprising a greyscale microscopy image of the fibre tip (acquired prior to fabricating the cavity) and a schematic representation of the cavity spacer and mirrors.

3.1 Cavity transfer function

Figure 2 shows the cavity wavelength transfer function of a typical rounded-tip fibre sensor (Figure 1(b)). This was obtained by sweeping the wavelength of the interrogation laser and recording the reflected optical power. For this sensor, the cavity thickness was 12μm, the reflectivity finesse F_R was 73, and the visibility V was 0.3 – similar values were obtained for the cleaved-tip geometry. Both F_R and V are well below the theoretical values that would be achieved with a planar cavity illuminated by a collimated beam. This is because the Rayleigh range of the beam emerging from the 10μm single mode fibre core is approximately 50μm. After only a few round trips within the cavity the beam becomes divergent, walks-off and does not fully couple back into the fibre core. This in turn limits the practically achievable finesse and thus the sensitivity.

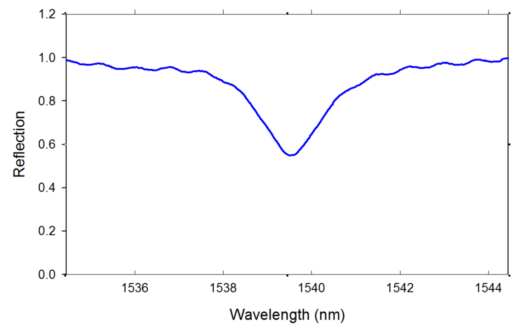


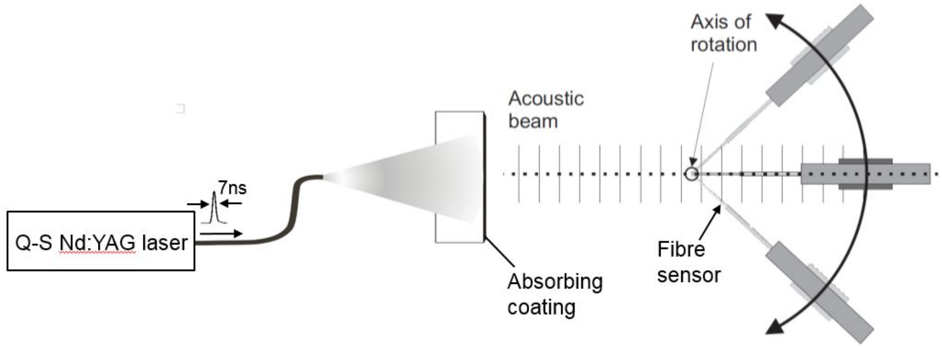
Figure 2 Cavity transfer function of a 12μm planar FP cavity deposited on to a rounded-tip fibre. F_R=73, V= 0.3.

3.2 Noise-equivalent pressure

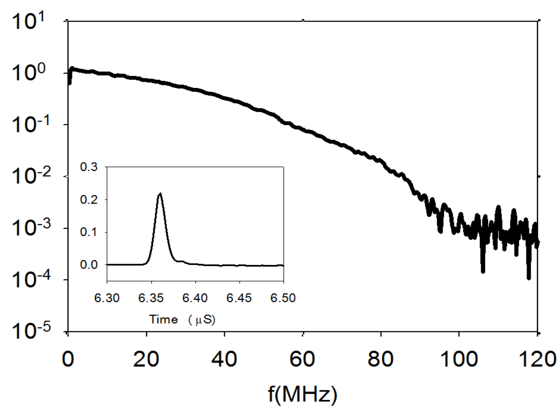
The detection sensitivity or noise-equivalent pressure (NEP) is defined as the acoustic pressure that provides a system signal-to-noise ratio of unity. To determine the NEP, the output of the fibre sensor under test was compared to that of a calibrated 130MHz (-3dB bandwidth) planar FP sensor of known sensitivity. The noise was measured over a 20MHz measurement bandwidth without signal averaging – note that peak rather than rms noise figures are quoted as the former provides a more realistic indication of the smallest signal that can be detected when measuring broadband signals in the time domain. The maximum NEP of the rounded-tip sensor design over the frequency range 18-25 MHz was 200Pa over a 20 MHz measurement bandwidth. The plane-cleaved fibre-tip sensor provided a similar NEP. Although such an NEP is respectable it is distinctly non optimal owing to the beam walk-off effects that arise in planar FP cavity discussed in section 3.1.

3.3 Frequency response and directivity

A laser generated ultrasound sound was used to measure the frequency response and directivity as shown in Figure 3(a). The source comprised a 10mm thick PMMA substrate coated on one side with highly absorbing black spray paint. The disk was illuminated by the output of a fibre-coupled Q-switched Nd:YAG laser emitting 10ns pulses at 1064nm. The diameter of the laser beam incident on the absorber was 30mm. This resulted in the generation of planar acoustic waves with a broadband frequency content in the range 1-80MHz as illustrated in Figure 3(b). The fibre-optic sensor was mounted on a rotating stage with its tip located on the axis of rotation.



(a)



(b)

Figure 3 (a) Experimental arrangement for measuring frequency response and directivity using a laser generated ultrasound source. (b) Acoustic frequency spectrum of time domain signal (inset) generated by the source.

The frequency response was obtained by orientating the fibre-optic sensor at normal incidence to the laser generated ultrasound source. The detected time-resolved signal was recorded, its acoustic frequency spectrum calculated and divided by that of the source. The latter was measured independently using the calibrated 130MHz planar FP sensor referred to in the previous section which is of known frequency response. Figure 4 shows the measured time-resolved signals and frequency responses of both sensor designs. The plane-cleaved sensor time-domain signal is distorted and exhibits significant ringing. These characteristics manifest themselves in the frequency response which, although broadband with a response extending to 80MHz is highly non uniform with multiple irregularly spaced features. These features arise from the interaction of the incident plane wave, its reflection from the fibre tip and the diffracted edge waves propagating across the fibre endface in the surrounding fluid, polymer spacer and the fused silica fibre. Each of these different wave components propagate across the fibre tip at different wave speeds and arrive at the core where they interfere with each other. FTFD modelling[6] has shown that it is the frequency dependent interaction of all of these waves that is responsible for the complex structure in the frequency response. Clearly such a response is undesirable for photoacoustic imaging and sensing applications as it will compromise spatial resolution and introduce artefacts. By contrast the edge wave components are significantly reduced in the rounded-tip sensor as it lacks the sharp diffractive boundary of the plane-cleaved sensor. It therefore provides a more uniform, well behaved frequency response. This is reflected in the time-domain signal which exhibits significantly less ringing and distortion than the plane-cleaved sensor.

The frequency dependent directivity of the two sensor designs is shown in Figure 5. The plane-cleaved design exhibits both reduced bandwidth with increasing angle and significant angular dependence. By contrast, the rounded-tip sensor retains its wide bandwidth to much greater angles (~70^0) and exhibits much less angular sensitivity at all frequencies.

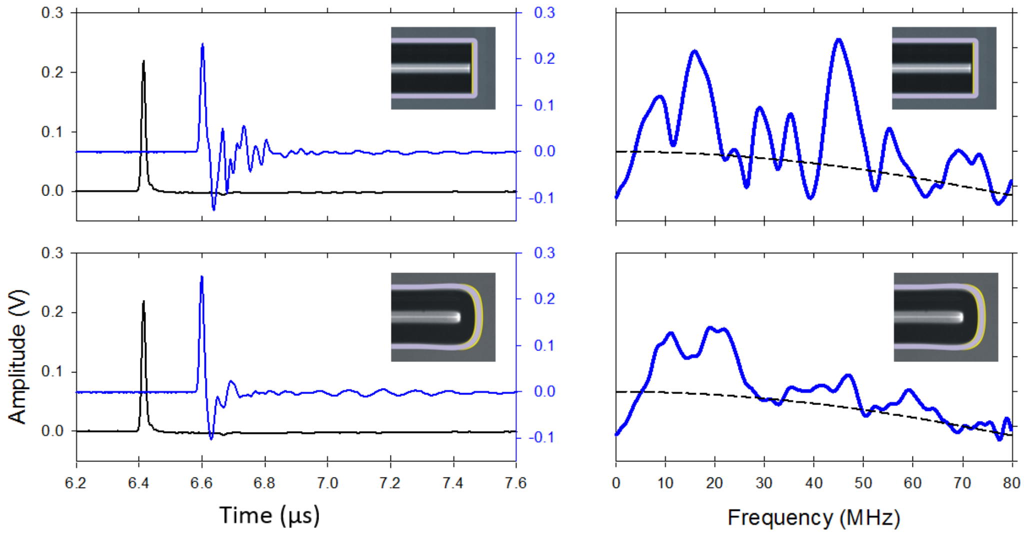


Figure 4: Impulse responses (left) and frequency responses (right) of plane-cleaved (top) and rounded-tip (lower) sensors with planar FP cavities. In the left hand figures, the blue line represents the response of the sensor to the acoustic pulse (black line) produced by the laser generated ultrasound source. In the right hand figures, the blue solid line represents the sensor frequency response. The dotted line represents the frequency response of a planar FP sensor cavity of the same thickness but infinite lateral extent.

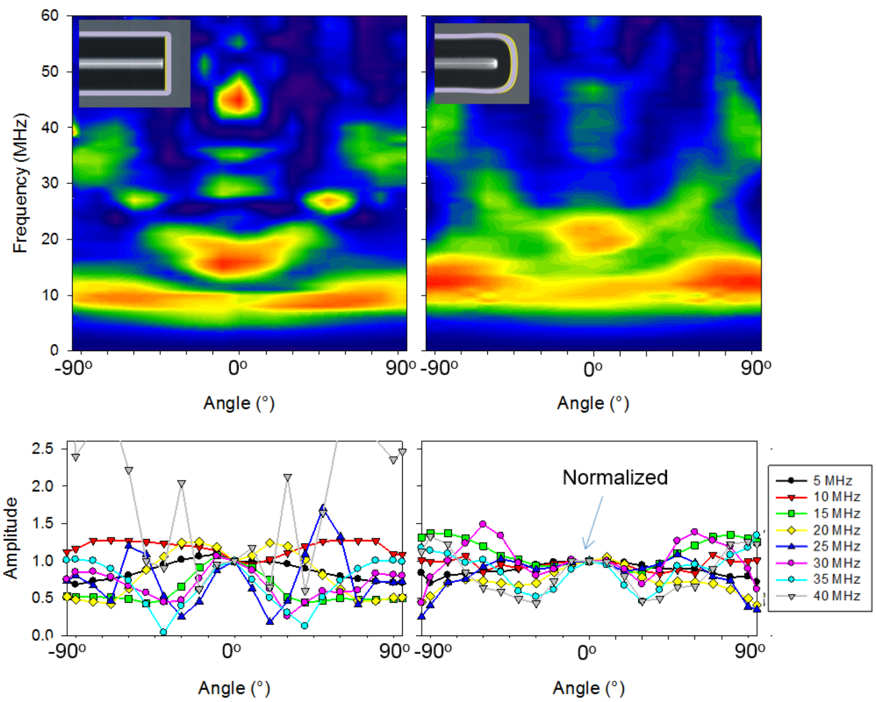


Figure 5 Directional response of plane-cleaved (left) and rounded-tip (right) sensors with planar FP cavities. The colour maps in the top row show the frequency response as a function of angle. The graphs in the lower row show horizontal profiles through the colour maps at specific frequencies normalised to the response at normal incidence.

4. PLANO-CONVEX SENSING CAVITY

As described in the previous section, a limitation of a planar sensing cavity is that the divergent nature of the beam emerging from the single mode core of the fibre walks-off thus limiting the cavity finesse and therefore sensitivity. In essence the problem is one of insufficient optical confinement. To address this, the use of a cavity in which the outer mirror surface is convex was explored. Matching this mirror surface to the wavefront curvature offers the prospect of achieving much greater confinement and realising a finesse that approaches the theoretical maximum. The two designs shown in Figure 6 were investigated. These comprise plano-convex cavities formed on the tips of plane-cleaved and rounded fibres. Unlike the planar cavities described in section 3, the spacer is an optical epoxy formed using a precision dip coating process. The cavity mirrors were formed in the same way as the planar cavity mirrors described in section 3 and had the same reflectivities (98%).

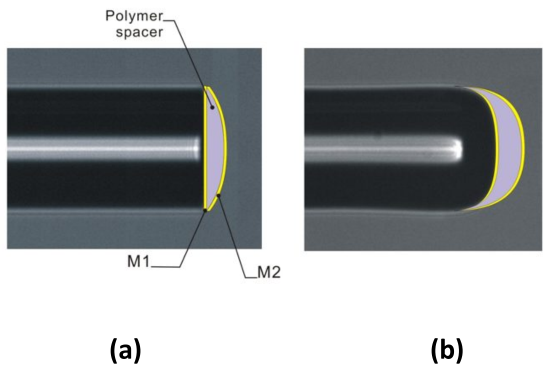


Figure 6 Plano-convex polymer cavities formed at the distal end of (a) a plane cleaved fibre and (b) a rounded-tip fibre. M1 and M2 are the cavity mirrors on either side of the polymer spacer. The figures are composite images comprising a greyscale microscopy image of the fibre tip (acquired prior to fabricating the cavity) and a schematic representation of the cavity spacer and mirrors.

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4.1 Cavity transfer function

The cavity transfer transfer function of a representative rounded-tip plano-convex cavity (Figure 6 ((b)) is shown in Figure 7. For comparison the transfer function of the planar cavity in Figure 2 is also shown. The plano-convex cavity provides more than a factor of 5 higher finesse (F_r=381) than the planar cavity (F_r=73) as well as improved visibility due the significantly higher optical confinement it provides. A similar finesse was also measured with the plane-cleaved-tip plano-convex design ((Figure 6 ((a)).

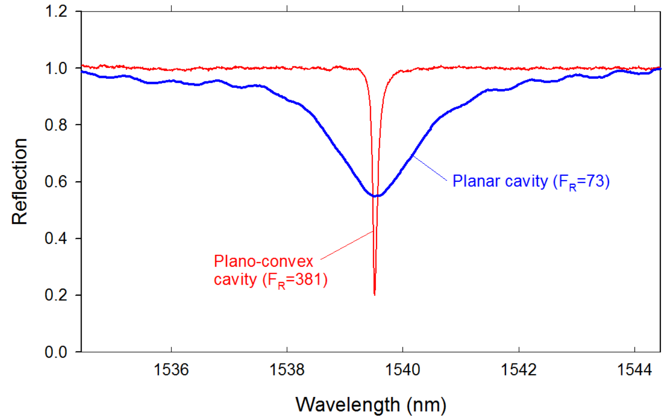

Figure 7 Cavity transfer function of a 20.5µm thick plano-convex cavity formed on a round-tip fibre (red line). For comparison the transfer function of the 12 µm planar FP cavity (Figure 2) is also shown (blue line).

4.2 Noise-equivalent pressure

The maximum measured NEP of a representative rounded-tip plano-convex cavity (Figure 6 (b)) was 40Pa over the range 9-15MHz over a 20MHz measurement bandwidth. This represents a factor of 5 higher sensitivity than the planar cavity sensor described in section 3. Based on the differences in thickness of the two cavities (factor of 1.7) and finesses (factor of 5) the sensitivity should be a factor of 8.5 higher. The discrepancy is likely to be due to the significant differences in the frequency response characteristics of the two sensors making the comparison inevitably approximate. Nevertheless, it is evident that the plano-convex cavity provides a very significant increase in detection sensitivity.

4.3 Frequency response and directivity

Figure 8 shows the measured impulse and frequency responses of the two plano-convex sensor designs. The plane-cleaved sensor time-domain signal is broadened, distorted and exhibits significant ringing. These characteristics produce a correspondingly bandlimited, variable frequency response that is of comparable non-uniformity to that of the plane-cleaved planar FP sensing cavity design (Figure 4). This is perhaps unsurprising as both designs possess the sharp diffractive boundaries provided by the cleaved fibre tip. The rounded tip design shows a significantly improved time domain signal in the sense that the pulse duration is shorter, is less distorted and exhibits less ringing. This is reflected in its frequency response characteristics which show a smoother less structured response with a bandwidth extending to 80MHz. Although the frequency response exhibits significant variations over the entire frequency range, the response varies fairly smoothly without the very sharp peaks and troughs of its plane-cleaved fibre tip counterpart (Figure 8, upper right). Moreover the bandwidth appears to be appears to be higher. These features are reflected in the corresponding time-domain signal. Its pulse width is narrow and there is less ringing than the signal shown in Figure 4 (lower left)

The directional response is shown in Figure 9. The plane-cleaved sensor exhibits very significant variations, particularly for frequencies beyond 10 MHz. By contrast the rounded-tip sensor shows much lower directional sensitivity. Indeed for frequencies up to 35MHz, the response is almost omnidirectional. Compared to its planar cavity counterpart (Figure 5, upper right image) which shows significant bandwidth reduction with increasing angle, the bandwidth of the plano-convex rounded-tip sensor appears to be largely independent of angle extending to 60MHz at angles as high as 80^0.

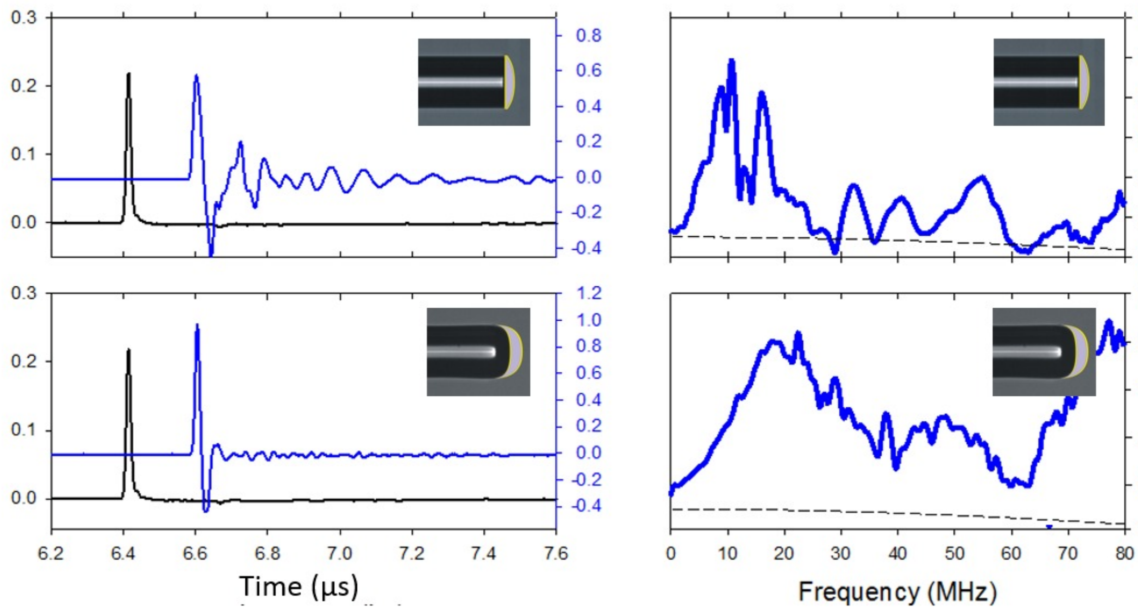

Figure 8 Impulse (left) and frequency responses (right) of plane-cleaved (top) and rounded-tip (lower) sensors with plano-convex cavities. In the left hand figures, the blue line represents the response of the sensor to the acoustic pulse (black line) produced by the laser generated ultrasound source. In the right hand figures, the blue solid line represents the sensor frequency response. The dotted line represents the frequency response of a planar FP sensor cavity of the same thickness but infinite lateral extent

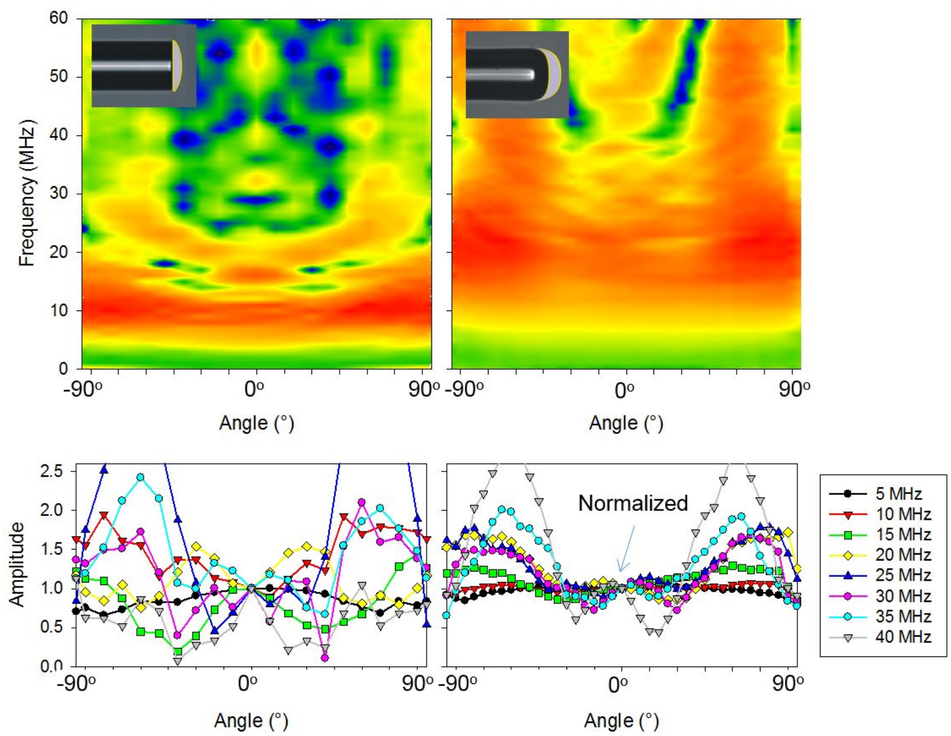

Figure 9 Directional response of plane-cleaved (left) and rounded-tip (right) sensors with plano-convex cavities. The colour maps in the top row show the frequency response as a function of angle. The graphs in the lower row show horizontal profiles through the colour maps at specific frequencies normalised to the response at normal incidence.

5. CONCLUSION

A range of miniature fibre optic sensors have been fabricated and characterised. It has been demonstrated that optimising the geometry of the fibre-tip and the sensing cavity enables significant improvements in acoustic performance to be achieved. By rounding the tip of the fibre in order to avoid sharp diffractive boundaries, it is possible to achieve a significantly smoother broadband frequency response than previously possible. In this study particular attention was paid to measuring directional response. Often overlooked, it is of crucial importance for many applications. For example, to achieve high image SNR and fidelity in photoacoustic tomography or phased array ultrasound imaging, a near omnidirectional response that permits the detection of acoustic waves arriving from sources distributed over a large angular aperture is essential. Another application that requires low directional sensitivity is laser-scanning OR-PAM in which the photoacoustic waves are detected using a single stationary planar detector offset from scan area[8]. To obtain an adequate field-of-view without incurring excessive acoustic attenuation the detector must be situated in close proximity to the sample and this requires the detector to have a large acoustic acceptance angle. As well as demonstrating that the frequency response and directivity can be improved, significant increases in sensitivity have been achieved through the use of a plano-convex cavity. For example the rounded-tip plano convex fibre sensor provides an NEP in the tens of Pa range and thus orders of magnitude more sensitive than a piezoelectric receiver of comparable bandwidth and directional characteristics.

In summary, these sensors may find applications in photoacoustic and ultrasound sensing and imaging. Their small size and broadband response lends them to minimally invasive high resolution imaging applications where a flexible, electrically passive detector that can be inserted into a needle is required. Their omnidirectional response makes them suitable for photoacoustic tomography, phased array ultrasound imaging and laser-scanning OR-PAM. The potential to obtain extremely high sensitivity using ultra-high finesse plano-convex cavities may also make them useful for deep tissue imaging application such as photoacoustic breast imaging.

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