Miniature fibre optic probe for minimally invasive photoacoustic sensing

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ABSTRACT

A miniature (175 µm) all-optical photoacoustic probe has been developed for minimally invasive sensing and imaging applications. The probe comprises a single optical fibre which delivers the excitation light and a broadband 50 MHz Fabry-Pérot (F-P) ultrasound sensor at the distal end for detecting the photoacoustic waves. A graded index lens proximal to the F-P sensor is used to reduce beam walk-off and thus increase sensitivity as well as confine the excitation beam in order to increase lateral spatial resolution. The probe was evaluated in non-scattering media and found to provide lateral and axial resolutions of < 100 µm and < 150 µm respectively for distances up to 1 cm from the tip of the probe. The ability of the probe to detect a blood vessel mimicking phantom at distances up to 7 mm from the tip was demonstrated in order to illustrate its potential suitability for needle guidance applications.

Keywords: Photoacoustic sensing, fiber optic sensor, minimally invasive surgery, needle guidance

INTRODUCTION

Photoacoustic (PA) sensing [1,2] has significant potential in interventional medicine for applications in which a miniature probe is inserted into the body via a needle or catheter for diagnostic or guidance purposes. Conventional PA probes typically employ an optical fibre for delivery of the excitation laser light and a piezoelectric ultrasound receiver for detecting the PA waves. However, this approach presents several technical challenges, particularly for applications that involve probe insertion via a fine needle or cannula and thus require a highly miniaturized device (<500 µm). With piezoelectric based PA probes, it is difficult to achieve this level of miniaturization due to the need to offset the opaque detector from the delivery fibre. Achieving adequate wideband detection sensitivity with the small element sizes required for a miniature probe can also be challenging. Moreover, technical complexity makes it difficult to manufacture at low unit cost for single-use.

In this study, we report a highly miniaturized (175 µm outer diameter) all-optical, forward-looking PA probe. The probe consists of a single optical fibre for delivering the excitation light and a wideband transparent planar Fabry-Perot (F-P) ultrasound sensor at the distal end of the fibre for detecting the PA waves. The transparent nature of the sensor avoids the need to offset it from the fibre tip allowing realization of a PA probe with an unprecedented level of miniaturization limited only by the diameter of the delivery fibre. Previously, a dual clad 1550 nm fibre has been used to realize a similar concept with the single mode core of the fibre being used to deliver the sensor interrogation light and the excitation light being delivered via the inner multimode cladding [1]. In the current study we describe an alternative design in which the core of a standard 1550 nm single mode fibre is used to deliver both the interrogation and excitation beams. In addition, a GRIN lens is inserted between the distal end of the fibre and the FP sensor. The GRIN lens serves two purposes. Firstly, it increases the confinement of the interrogation beam within the FP cavity thereby allowing higher finesse and thus sensitivity to be achieved. Secondly, it reduces the lateral extent of the excitation beam thus narrowing the lateral field of view and increasing the beam intensity. In this paper, we describe the fabrication of the probe, its optical and acoustic characterization and evaluation using a blood vessel mimicking phantom.

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PROBE FABRICATION AND CHARACTERISATION

The probe was fabricated using a three step process. Initially, a section of coreless silica fibre (CSF) was fusion spliced to the tip of a single mode fibre (SMF-28) and polished back until its length was ~ 312 µm. A 50 µm core diameter graded index multimode fibre (GRIN MMF) was then spliced to the CSF and polished back until its length corresponded to ½ pitch (~ 610 µm) [3]. The FP polymer film sensor was subsequently deposited on to the polished tip of the GRIN MMF [4] as shown in figure 1. The FP sensor mirror reflectivities were ~98% and the spacer thickness was 21.5 µm.

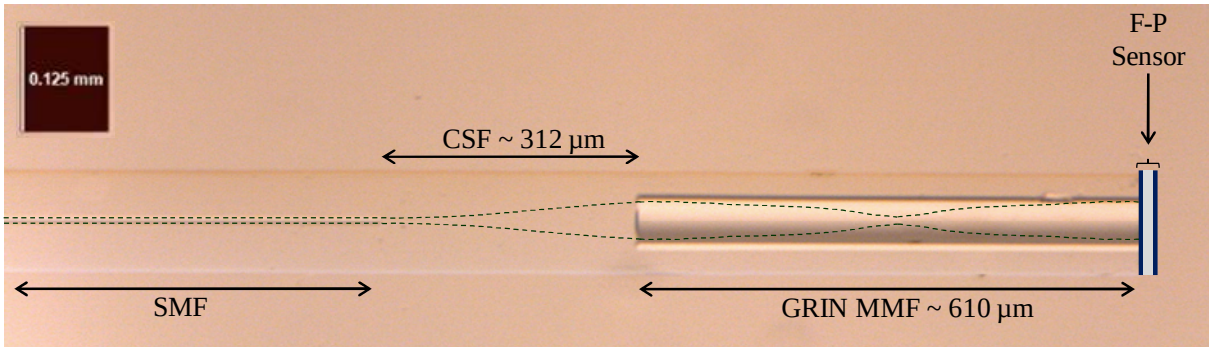

Figure 1. Micrograph of the fabricated probe with the SMF, CSF and GRIN MMF. The green dotted line shows the propagation of the beam through the probe.

Figure 2(a) shows the wavelength interferometer transfer function (ITF) of the probe and figure 2(b) shows its derivative (the wavelength sensitivity) which proves a measure of acoustic sensitivity. For comparison, the ITF and wavelength sensitivity of a nominally identical FP sensor deposited directly on to the tip of a plane cleaved single mode fibre (termed the "SMF probe") are also shown in figure 2.

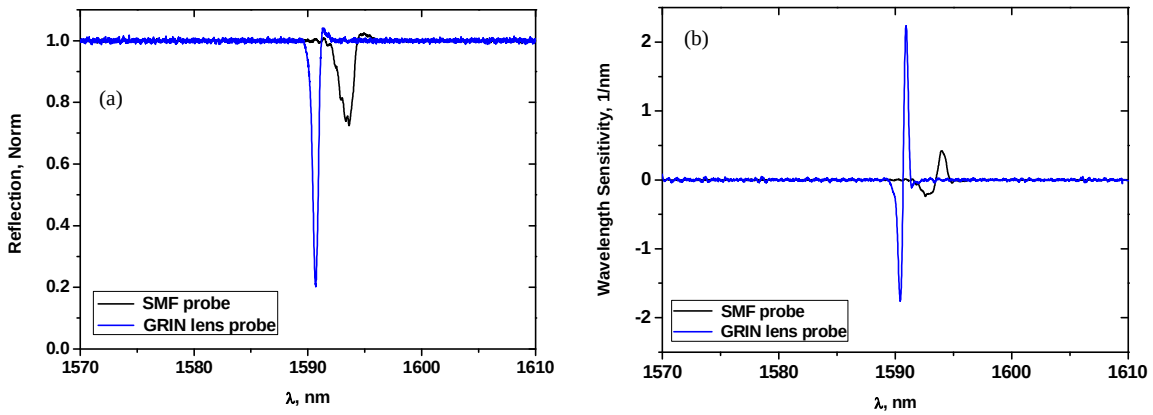

Figure 2. (a) ITF & (b) wavelength sensitivity of probes fabricated using SMF (black line) & GRIN lens (blue line).

The design beam waist diameter (in air) at the tip of the GRIN lens probe at 1550 nm was ~ 40 µm compared to 10.5 µm at the tip of the SMF fibre. It can be observed from figures 2(a) and (b) that there is a significant improvement in the fringe visibility and wavelength sensitivity in the case of the GRIN lens probe. This is due to the larger beam diameter

and thus the increased Rayleigh range obtained with the GRIN lens probe which reduces the interrogation beam walk-off within the FP cavity.

To measure the noise equivalent pressure (NEP) of the two probes, a calibrated pulsed 3.5 MHz planar PZT transducer was used. The peak NEP of the GRIN lens probe was ~ 520 Pa for a measurement bandwidth of 20 MHz. The maximum values of the wavelength sensitivities and the NEP values of the two probes are compared in Table 1. It is evident that the GRIN lens probe has better sensitivity and a lower NEP than the SMF probe. The frequency response of the probe was measured using a laser generated ultrasound source as described in reference [1]. The frequency response is shown in figure 3 illustrating a wideband response in excess of 40 MHz. The non-uniform nature of the frequency response is a consequence of the interaction of the incident acoustic wave, its reflection from the fibre tip and the edge waves propagating across the fibre endface [5].

Table 1. Comparison for the wavelength sensitivity and estimated NEP for the probes.

	SMF probe	GRIN lens probe
Design Beam Waist (μm)	10.4 (MFD)	~ 40.0
Wavelength Sensitivity (/nm)	0.42	2.24
NEP at 20 MHz BW (kPa)	3.05	0.52

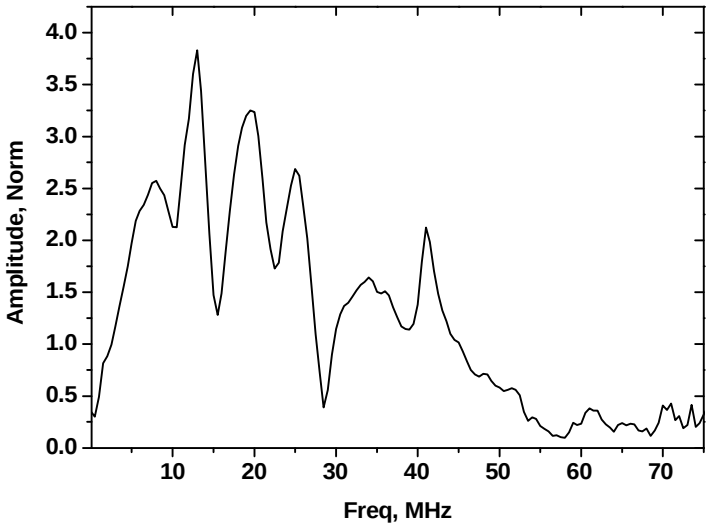

Figure 3. Frequency response of the GRIN lens probe.

PHOTOACOUSTIC SENSING PROBE

The excitation and interrogation laser beams are launched into the GRIN lens probe downlead using a standard wavelength division multiplexer (WDM) coupler as illustrated in figure 4. The excitation laser source was a dye laser

pumped by a frequency doubled Q-switched Nd:YVO_4 laser (Elforlight, UK) providing nanosecond pulses. The laser was operated at a wavelength of 580 nm with a pulse repetition rate frequency of 3 kHz and a pulse energy of 200 nJ at the fiber output. The interrogation laser used was an external cavity laser with a tuning range from 1500 – 1640 nm. The PA probe was connected to the common port (port 3W) of the WDM coupler. The output from the excitation laser which was coupled into a single mode fibre was transmitted through port 1W of the WDM coupler to the probe. The interrogation of the probe was via port 2W of the WDM coupler using a fibre optic circulator. The reflected light from the FP sensor was guided through port 2W of WDM coupler and redirected to the photodetector through the circulator port 3C.

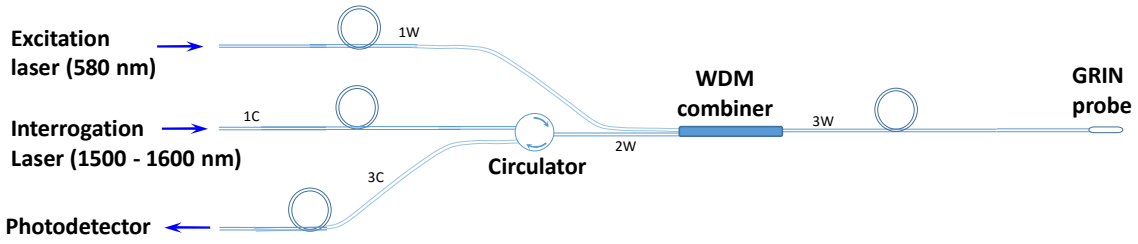

Figure 4. Schematic of the optical fibre system use to deliver the excitation and interrogation light to the probe tip.

To estimate the lateral resolution in non-scattering media, the probe was linearly scanned in steps of 2 µm across a thin highly absorbing ribbon of width ~ 400 µm and thickness of ~ 30 µm immersed in water as illustrated in figure 5(a). This procedure was repeated for different distances between the tip of the probe and the phantom. For each case, the amplitude of the PA signal was plotted as function of position (along X-axis as shown in figure 5a). The amplitude variation along the edge of the ribbon was taken as the edge spread function (ESF) from which the line spread function (LSF) was calculated. The lateral resolution was then taken to be the FWHM of the LSF which varied from 20 µm to 100 µm for depths ranging from ~0.5 mm to 10 mm as illustrated in figure 5(b).

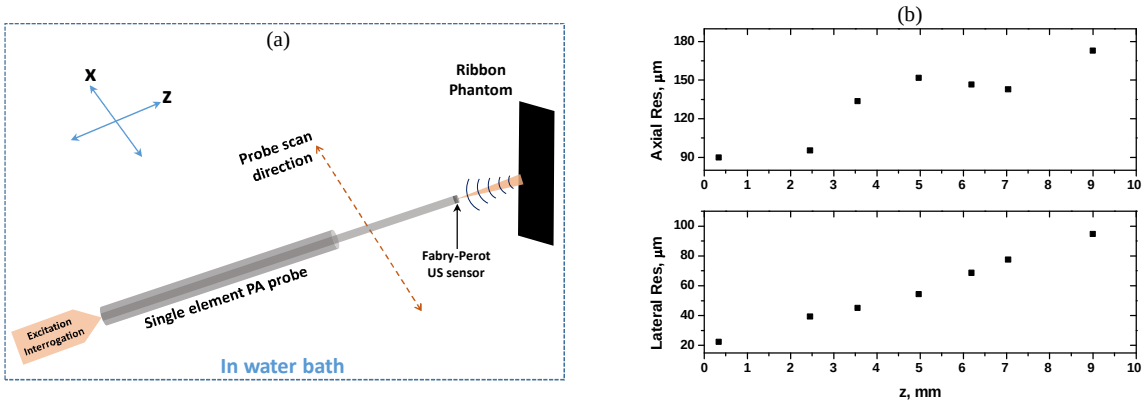

Figure 5. (a) PA Probe vs phantom orientation for spatial resolution measurements, and (b) Estimated axial *(top)* and lateral *(bottom)* resolution of the GRIN probe.

The axial resolution was estimated by taking the envelope of the PA signal generated in the ribbon. The product of the speed of sound in water and the FWHM of the envelope was then taken as an estimate of the axial resolution of the probe [4] and plotted as a function of distance in figure 5(b). This shows that it lies in the range 90 – 172 µm for distances up to 10 mm from the probe tip.

BLOOD VESSEL MIMICKING PHANTOM

To demonstrate the potential of the probe to detect blood vessels, a blood vessel mimicking phantom was fabricated. The phantom comprised a 62.5 µm ID (125 µm OD) PMMA tube filled with human blood at a haematocrit of ~ 0.6. The tube was fixed in a water bath and the probe was mounted on a linear translation stage as shown in figure 6(a). In this case the probe was translated towards the phantom and the PA signal generated from the phantom was recorded. The PA signal was recorded by the probe from distances as far as ~ 7 mm from the phantom. The PA signals recorded at z = 7.11 mm and 0.78 mm are shown figure 6 (b) & (c). The signal that appears before the arrival of the PA signal from the phantom is likely to be due to absorption of the excitation laser pulse within the FP sensing element.

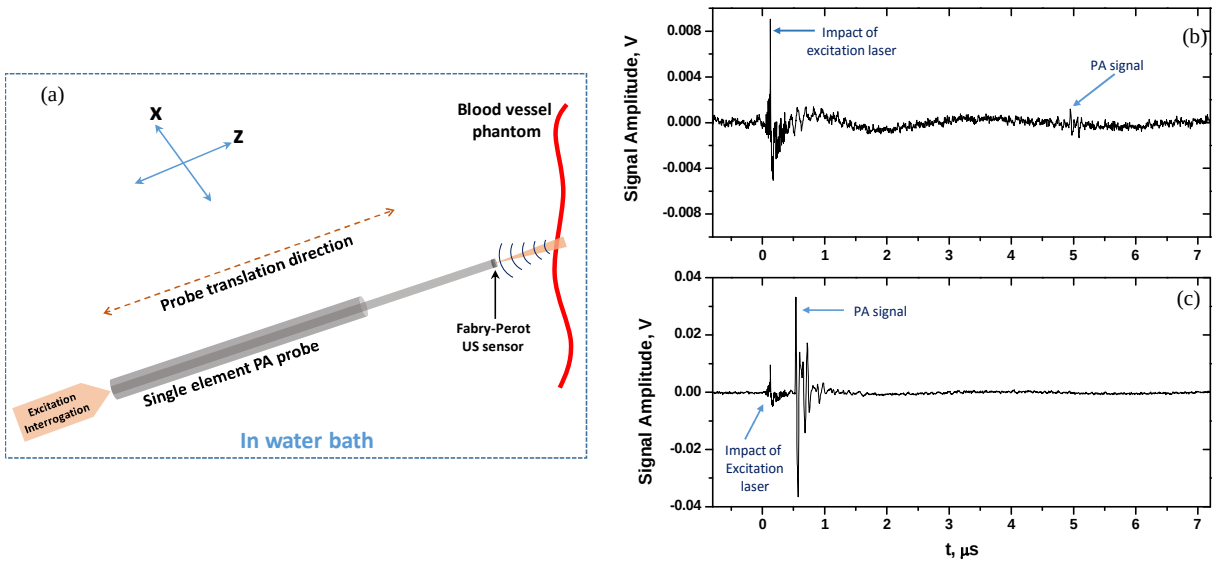

Figure 6. (a) Experimental setup for blood vessel phantom detection. (b) PA signal detected with the phantom at a distance of ~ 7 mm from the probe, and (c) PA signal detected with the phantom at a distance of ~ 0.78 mm from the probe. The impact of the excitation laser and the arrival of the PA signal are marked in both case.

CONCLUSIONS

This study has demonstrated the feasibility of a forward-viewing all-optical miniature probe that can generate and detect PA signals at the tip of a single mode optical fibre. The probe employed a novel GRIN lens based design that provides two advantages. First, it reduces the FP sensor interrogation beam walk-off enabling higher acoustic sensitivity to be achieved. Second, it confines the excitation light in order to improve lateral resolution. The ability of the probe to detect a blood vessel was demonstrated using a blood vessel mimicking phantom. The highly miniaturized nature of the probe (o.d.= 175 µm) suggests it should be possible to integrate it within medical needles for the purpose of guiding needle-based interventional procedures such as the delivery of regional anesthesia.

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