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Single Optical Fibre Ultrasound Transducer for Rotational Imaging

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ABSTRACT

All-optical ultrasound imaging has emerged as paradigm that is well-suited to highly miniaturized applications. With this technique, ultrasound is both generated and received using light, allowing the use of optical fibres for device fabrication. Ultrasound generation typically requires multimode light delivery to provide the pulse energies needed for high pressure generation. Whilst ultrasound reception typically requires single mode light delivery to provide high sensitivity. This means that devices have typically comprised two optical fibres, one multimode for ultrasound generation and one single mode for ultrasound reception. Recently, we demonstrated an all-optical ultrasound imaging device based on a single dual-clad optical fibre. In this work, we build on our previous study and demonstrate rotational imaging with this device. Two copper wire phantoms were imaged, and the wire were well-resolved, demonstrating a signal-to-noise >20 dB. The presented device and system are well-suited for use in minimally invasive and intravascular imaging applications and future work will focus on translating the device.

Keywords: Optical ultrasound, laser generated ultrasound, intravascular ultrasound, optical fibres, imaging devices

1. INTRODUCTION

All-optical ultrasound (OpUS), an imaging paradigm that uses light to both generate and receive ultrasound, has emerged as a technology well-suited to minimally invasive surgical applications. With this technique, ultrasound is generated via the photoacoustic effect when pulsed or modulated laser light is incident on an optical absorbing coating [1]. This leads to a transient heat rise and corresponding pressure rise which propagates as an ultrasound wave. Ultrasound reception can then be achieved via interferometry, using devices which include microring resonators [2.3] and Fabry-Pérot cavities [4,5]. By fabricating these coatings and interferometers on the tips of optical fibres, highly miniaturized imaging devices can be fabricated. These devices, which typically comprise two optical fibres, one for generation and one for reception, are well-suited to integration into medical devices, such as catheters and needles [6,7].

Previous studies have demonstrated a range of OpUS imaging paradigms with these devices, which include 2D and 3D B-mode imaging [5,8], M-mode imaging [6,9,10] and rotational imaging [11]. In our recent study, we pioneered the use of a single optical fibre with dual cladding to provide light for both ultrasound generation and reception, thereby removing the requirement for two separate optical fibres [12]. This study demonstrated a fast-linear pull-back scheme to provide a synthetic imaging aperture; imaging of a tungsten wire phantom and *ex vivo* swine aorta was carried out. In this work, we build on this previous device, integrating a fibre optic rotary junction (FORJ) to allow for continuous rotational imaging.

2. METHODOLOGY

In this study, we developed a rotational imaging platform for a single optical fibre OpUS device and demonstrated rotation imaging of a wire phantom. For this, a single dual-clad optical fibre OpUS imaging device, previously described [12], was connected to an imaging console [12] via a custom FORJ (Princetel, USA) (Figure 1). Briefly, the console comprised a pulsed Q-switched Nd:YAG laser (SPOT-10-500-1064, Elforlight, UK) with pulse width 2 ns, wavelength 1064 nm and pulse energy 20 µJ, for ultrasound generation. A continuous wave tunable laser (Tunics T100S-HP CL, Yenista Optics, France) with wavelength range 1500-1600 nm was used for ultrasound reception and coupled to the OpUS device via a circulator and dual-clad fibre coupler. Light from the plano-concave microresonator on the OpUS device was monitored using a custom photodiode which split the signal into low and high frequency components.

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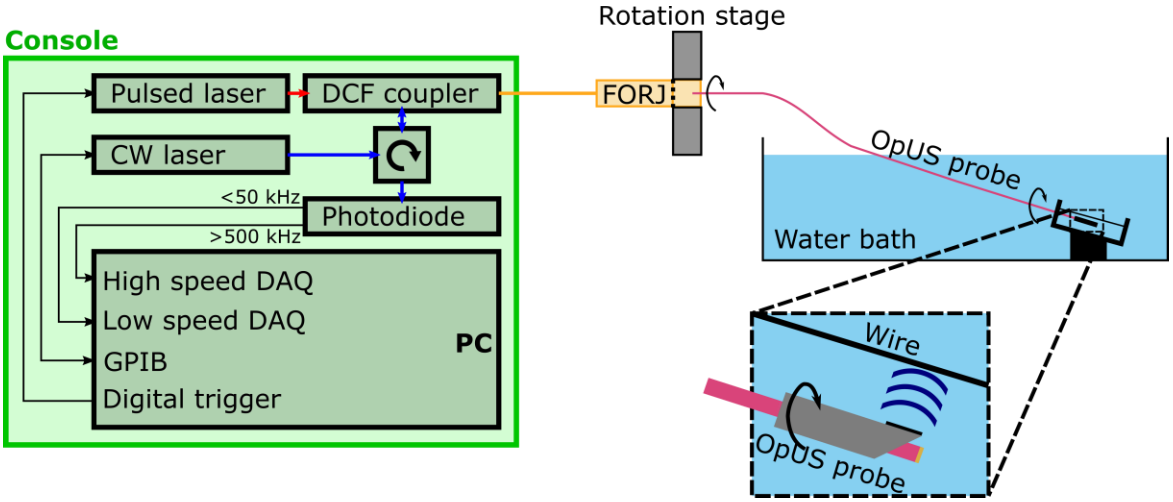

Figure 1. Schematic of the experimental setup used for rotational OpUS imaging with the single fibre OpUS transducer. Console with the pulsed laser for ultrasound excitation, CW laser for ultrasound reception, circulator, dual clad fibre (DCF) coupler, photodiode and PC for control shown (left). The probe is connected to the fibre optic rotary junction (FORJ) which is mounted in a rotation stage. Close-up schematic of the distal tip of the imaging probe with wire phantom shown (bottom right).

To provide rotation for imaging, the rotor of the FORJ and the proximal end of the OpUS device were mounted on a motorized rotation stage (PRM1/MZ8, Thorlabs, UK). Imaging was carried out by rotating the device at a constant rate of 25°/s and image A-lines were acquired at a rate of 25 Hz. This gave an A-line separation of 1° and a total of 360 A-lines per complete rotation. During imaging, the acquired OpUS image was displayed in real-time on a custom LabVIEW script and the acquired data was saved for offline processing. Two imaging phantoms were used. The first comprised two 0.4 mm diameter copper wires mounted on a plastic frame at an approximate depth of 1.5 mm. The second comprised a single 0.2 mm copper wire at a depth of 2.5 mm from the OpUS device. Images of the phantoms were acquired and displayed.

3. RESULTS

Rotational OpUS images of two different copper wire phantoms were acquired (Figure 2). In both images there was crosstalk, resulting from ultrasound signals transmitted directly from the transmitter to the receiver, which was visible as concentric rings at the centre of the image. With both phantoms, the wires were visualized and appeared as extended points in the images. For the phantom comprising two 0.4 mm copper wires, the wires had a signal-to-noise ratio of *ca.* 23 dB. The lateral extent of the wires was *ca.* 21° and the axial extent was *ca.* 0.11 mm. For the phantom comprising a single 0.2 mm copper wire, the wire had a lower signal-to-noise ratio of *ca.* 10 dB. The lateral extent was 27° and the axial extent was *ca.* 0.1 mm.

4. DISCUSSION AND CONCLUSIONS

In this work we build on a previous single optical fibre OpUS device, demonstrating rotational OpUS imaging. The device was connected to a custom FORJ and mounted on a rotational translation stage. Images of two copper wire phantoms were acquired, and for both phantoms the wires were well visualized. The signal-to-noise ratio was greater for the phantom with the larger wires positioned at shallower depths. This is expected due to the greater reflected ultrasound signal from the larger wire diameter, and the lower depth-dependent signal loss. The axial extent was similar for both phantoms, with values *ca.* 0.11 mm. This signal was likely generated only from the top of the copper wires due to their high acoustic impedance mismatch with water; as a result, both wires acted as point sources and yielded similar axial extents despite their different diameters.

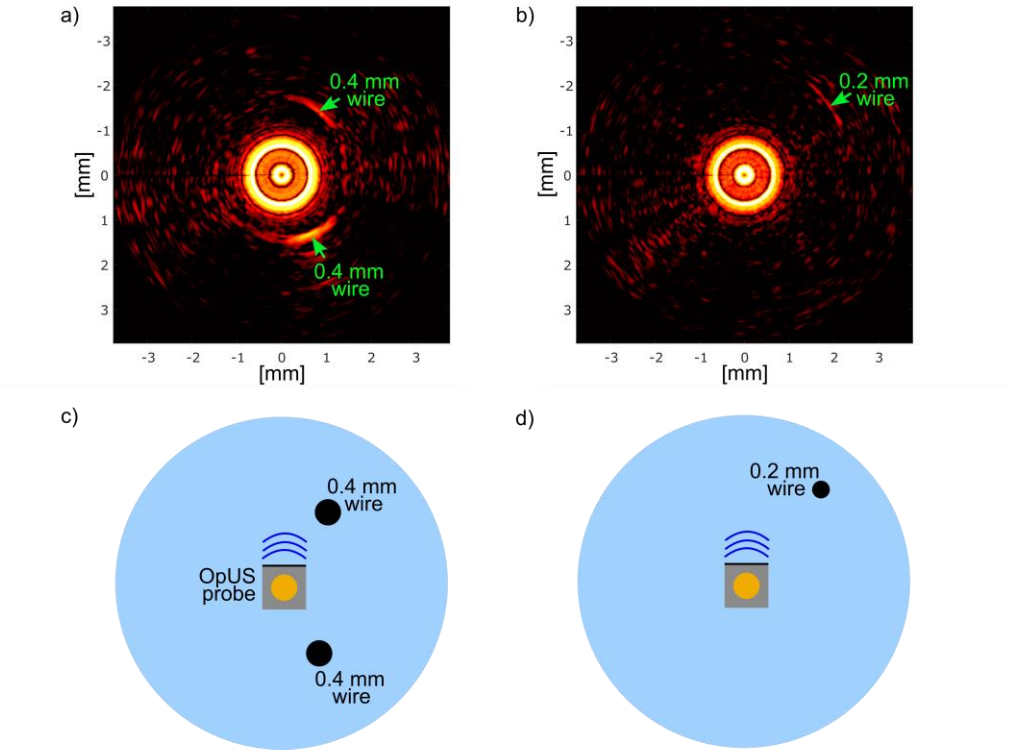

Figure 2. a), b) Rotational OpUS images of two copper wire phantoms (dynamic range 30 dB); a) a phantom with two 0.4 mm copper wires, b) a second phantom with one 0.2 mm copper wire. c), d) Corresponding schematics showing the OpUS probe in the centre and the locations of the copper wires.

This work represents the first steps towards rotational OpUS imaging with a single optical fibre. The imaging targets used in this study were wire phantoms. However, they set the stage for *ex vivo* animal tissue images that could be performed with rotation within the confines of a thin device with an ultrasonically-transparent window for imaging. Additionally, the rotation rate in this study was limited by the rotation speed of the motorized stage used. To acquire video rate images at > 5 Hz, a faster rotation rate is needed. This should be possible by replacing the motorized stage with one capable of higher translation rates. A linear pull-back would provide 3D helical imaging, analogously with optical coherence tomography (OCT). It is expected that these single optical fibre OpUS devices will find broad application in intravascular imaging and other minimally invasive procedures.

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