Optically Modulated Laser Ultrasound using a Fibre-Based Side-Looking Source

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1. Fibre-based laser ultrasound

Recent advances in **fibre-based all-optical ultrasound** imaging have resulted in forward-looking imaging probes that yield high quality images of *ex vivo* tissue [1]. Due to its small diameter (<0.5 mm), such a probe is ideally suited to interventional biomedical applications, and the low sensitivity of optical fibres to electromagnetic interference allows for long cable leads and concurrent use of different imaging modalities. In this work, a **side-viewing probe** is presented to be used in, for example, intravascular ultrasound. In order to maximise the acoustic signal-to-noise ratio (SNR), this probe is **illuminated with modulated rather than pulsed laser light**.

2. Side-looking ultrasound fibre probe

A multimode optical fibre (core/cladding diameter: 200/220 µm) was modified and coated to obtain a source generating an acoustic field perpendicular to the fibre axis. Ultrasound was generated through illumination of a *ca.* 1 µm thick coating consisting of **functionalised multi-walled carbon nanotubes** covered by a 20 µm thick layer of **PDMS** [2]. Acoustic pulse-echo signals were recorded using an omni-directional detector consisting of a **Fabry-Pérot etalon** built onto a second fibre [3]. A **synthetic aperture** was mechanically scanned to image a phantom consisting of two layers of parallel wires spaced approximately 1 mm apart (Fig. 1).

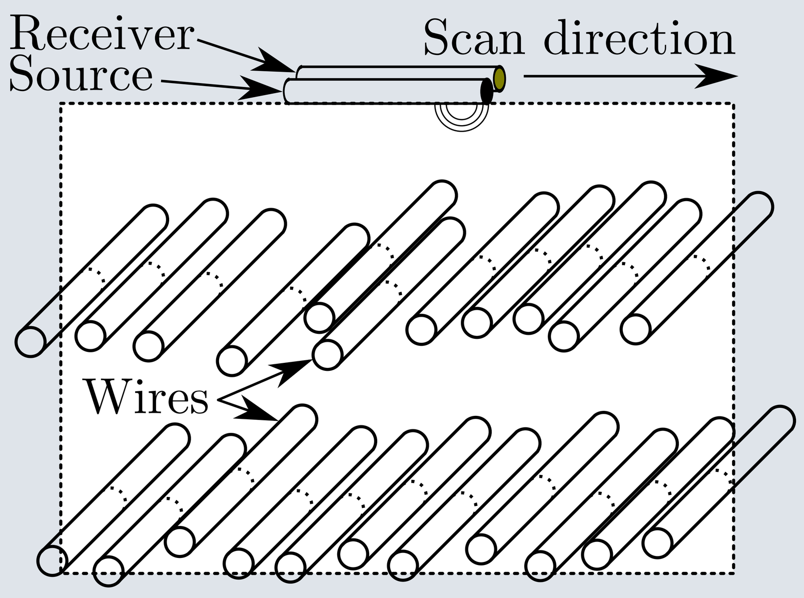

Fig. 1 - Schematic of the wire phantom and scan geometry

3. Modulated optical excitation

In conventional laser ultrasound, light pulses of nanosecond duration are used that can generate ultrasound with large bandwidths (> 100 MHz). However, in practice **typically much narrower bandwidths are observed** due to source and detector non-idealities and attenuation, and a significant **part of the optical energy is lost** [4]. In addition, the damage threshold of the optically absorbing coating typically limits the optical fluence. This damage threshold was avoided by using a temporally modulated laser diode and compensating for its lower peak power by emitting **temporally extended optical modulations**. The large bandwidth of the laser diode (> 200 MHz) allowed for **accurate control over the spectral content** of the emitted ultrasound.

Scan parameters: mechanical: 400 steps of 25 µm; Optical: 4 µs chirps, 750 Hz, 1.5 µJ/chirp; Acquisition: 750 averages, +40 dB amplification; pulse compression: matched-filter cross-correlation
Excitation laser: Lumics LU1064M450-1006N10A + Picolas BFS-VRM-03-HP; Interrogation laser: Yenista TUNICS T100S-HP; Translation stages: Thorlabs MTS50-Z8; Preamplifier: Femto DHPVA-200; DAQ: Spectrum M4i.4420-x8

4. Results

Transmitting linear chirps with different bandwidths revealed (Fig. 2) that the **detected pulse-echo signals were limited to a bandwidth** between 1.5 and 15 MHz. Consequently, limiting the chirp to this bandwidth significantly increased the SNR in phantom images (Fig. 3) while maintaining the resolution.

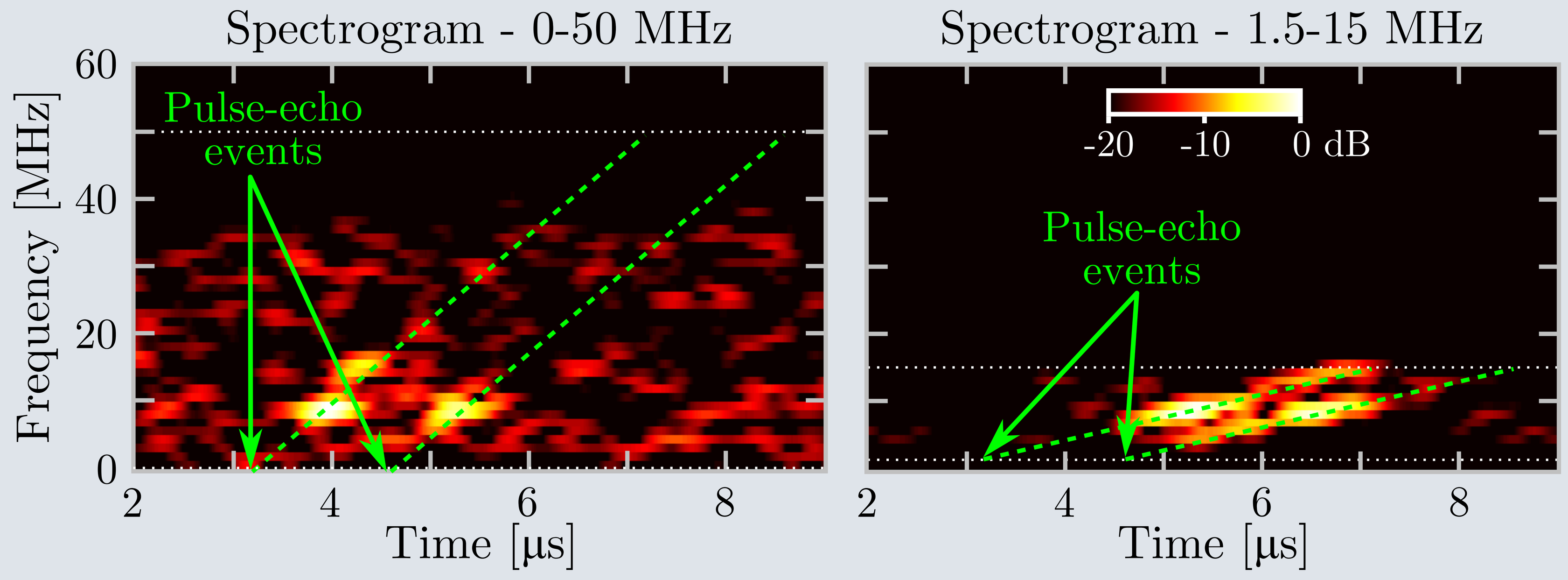

Fig. 2 - Spectrograms of pulse-echo signals obtained using linear chirps with bandwidths between 0-50 MHz (left) and 1.5-15 MHz (right). Two separate reflection events can be observed.

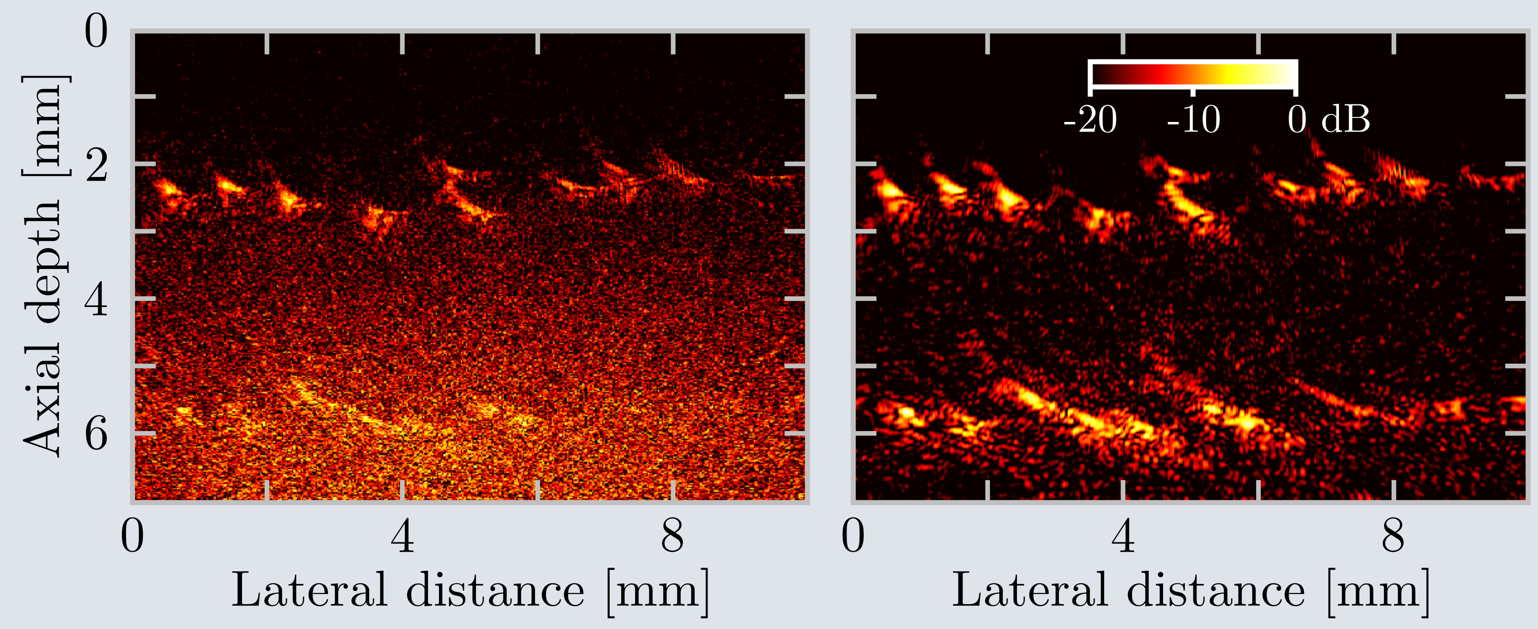

Fig. 3 - Images obtained of the wire phantom after pulse compression of linear chirps with bandwidths between 0-50 MHz (left) and 1.5-15 MHz (right).

5. Conclusions

By limiting the spectral content of the optical excitations to the detected acoustic bandwidth, **the SNR of images obtained with a side-viewing fibre-based laser ultrasound probe was significantly increased without sacrificing resolution**. In addition, by transmitting temporally extended optical modulations, more optical energy can be transmitted without exceeding the material damage thresholds. These findings are readily extended to other imaging modalities such as **photoacoustic imaging**, where the spectral content of the detected signals is not known *a priori*, or to **contrast enhanced ultrasound** imaging, where tuning the excitation to microbubble resonance will strongly increase image contrast. In addition, by varying the optical modulation **the same probe could be used for imaging modalities requiring wide, narrow, or intermediate bandwidths**.

References
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This work was supported by ERC Starting Grant 310970 MOPHIM, and by an Innovative Engineering for Health award by the Wellcome Trust [WT101957] & the EPSRC [NS/A000027/1].