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Optical fibre Fizeau-based OCT

P. Casaubieilh, H. D. Ford and R. P. Tatam,

Optical Sensors Group, Centre for Photonics and Optical Engineering, School of Engineering, Cranfield University, Cranfield, Bedford, MK43 0AL, UK.
Tel (01234) 754630, e-mail r.p.tatam@cranfield.ac.uk

ABSTRACT

An optical fibre, Fizeau configuration Optical Coherence Tomography (OCT) system is presented in this paper. The interferometer is formed between the distal end of the sample-arm fibre and the sample itself. This ensures 'downlead insensitivity'; polarisation variation is not a problem, as it is in the standard Michelson configuration. Path-length matching is performed by a secondary, bulk-optic scanning Mach-Zehnder interferometer. In this paper, we demonstrate the use of an optical circulator and balanced detection to permit optimum use of the light and maximise the signal-to-noise ratio.

Keywords: Optical Coherence Tomography, Fizeau interferometer, Low coherence interferometry.

1. INTRODUCTION

Optical Coherence Tomography (OCT) is a low-coherence optical imaging technique for investigating the three-dimensional sub-surface structure of semi-transparent materials. It is based on the principles of low coherence interferometry; the sample is positioned in one arm of an interferometer illuminated by a broadband source. Light scattered from a particular depth within the sample gives rise to interference fringes only when the interferometer paths are matched to within the coherence length of the source. Refractive index (R.I.) discontinuities within the sub-surface region of the sample result in localised backscattering, producing a burst of fringes for that sample depth and allowing the R.I. structure of the sample to be mapped. One-dimensional information is obtained from a single depth, or z-scan, but this can be extended to two or three dimensions by taking z-scans over a grid of points across the sample surface.

Most reported optical fibre based OCT systems are based on the Michelson interferometer configuration, as it offers a relatively simple optical system with a minimum of optical components. It also permits implementation of different sources for comparison. It has been possible to compare, using this configuration, the influence of the wavelength on the obtained OCT image [1], and the use of a variety of optical delay line implementations.

However this configuration suffers from polarization fading and temperature sensitivity. In fact, perturbing the fibre or changing the temperature of the reference or sample arms, causes changes to occur in the interference signal. To minimize these, polarization controllers are generally used.

In this paper we demonstrate the feasibility of an OCT system based on the Fizeau configuration with a Mach-Zehnder receiving interferometer. Auto-balanced detection and an optical circulator are used to improve the SNR to approximately the same value as the standard Michelson configuration.

2. BACKGROUND

The most commonly used arrangement for an OCT system is the fibre-coupled Michelson interferometer (Figure 1). Light from a low-coherence source, often a super-luminescent diode (SLD), is amplitude-divided by a directional coupler. Half of the optical power is guided down one interferometer arm, via a focusing lens to a reference mirror. The reflected light is re-coupled into the fibre and travels back through the coupler to a detector. Light from the other fibre arm is similarly focused onto the tissue sample under investigation. At boundaries of different R.I (as in microstructures within the tissue) light is backscattered, with an intensity which is proportional to the square of the R.I. difference. The backscattered light is re-coupled into the optical fibre and mixes interferometrically on the detector with the light reflected back from the scanning mirror. Interference fringes are observed only when the optical path difference (OPD) between the mirror and a particular R.I. boundary in the sample is within the coherence length of the source. This interference signal is detected as a burst of sinusoidal fringes modulated by the coherence function envelope.

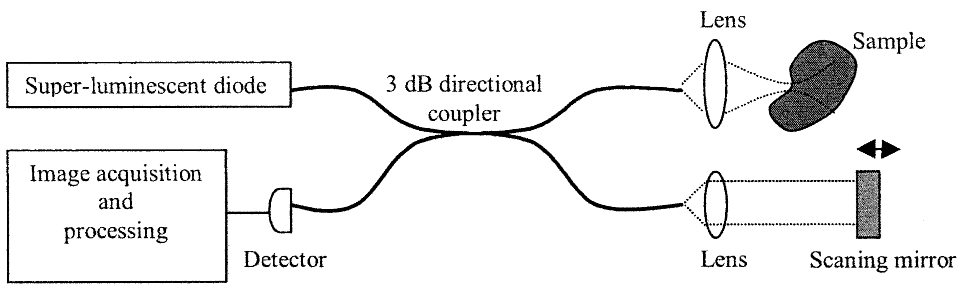

Figure 1: Fibre-coupled Michelson interferometer configuration for OCT.

To overcome the problems of polarization and temperature sensitivity, the downlead-insensitive in-fibre Fizeau configuration is investigated. Since path length matching cannot be achieved in this arrangement with the Fizeau interferometer alone, an additional processing interferometer is required. The merits and disadvantages of two alternative processing interferometers are compared.

The Fizeau-based interferometer system has been investigated previously in our group using a coupler and a Michelson interferometer receiver [2]. The general scheme is shown below in figure 2:

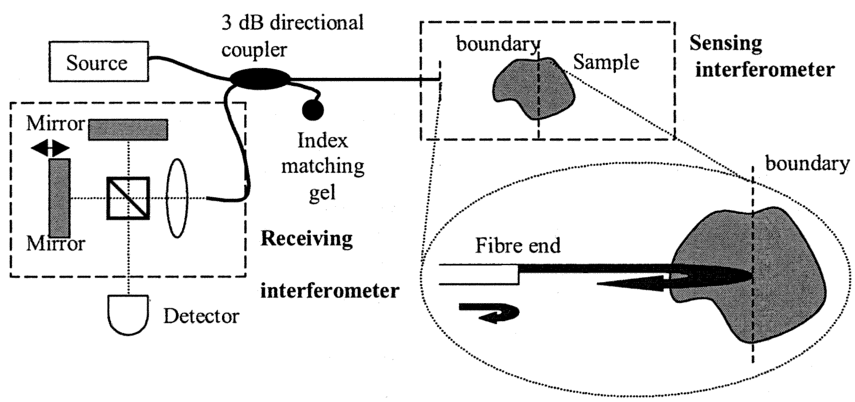

Figure 2: Fizeau interferometer configuration for OCT, based around a 3 dB directional coupler

The light from the source passes through the coupler, which has a 50% splitting ratio. The light in the sample arm undergoes two reflections: one at the end of the fibre (the reference light), and the second due to the sample (the backscattered light, depending on the optical properties of the tissue sample); the region including the end of the fibre and the sample forms the sensing interferometer. Both the reference and the backscattered light pass through the coupler to the receiving interferometer (in figure 2 a Michelson receiving interferometer is shown, but this could be a Fabry-Perot, a Mach-Zehnder or a Michelson) where for each component 2 reflections occur; then at the detector 4 electric fields are detected. Less than 25 % of the light from the source reaches the detector. Interference occurs when between the optical path differences in the sensing and receiving interferometer is within the coherence length. Therefore, this system suffers from a poor SNR, but it has the advantage of downlead insensitivity: both signal and reference beams are carried by the same fibre and therefore experience identical polarization changes and phase perturbations within the fibre coupler.

By scanning one of the mirrors in the receiving interferometer, the optical path difference (OPD) can be changed and the different layers of a sample can be addressed, when the difference between the optical OPD in the receiving interferometer and the OPD in the sensing interferometer is within the coherence length of the source. Other optical delay lines could be used for example the rapid-scanning optical delay line based on the femtosecond technique to provide quick acquisition [3].

To improve the optical efficiency [4], a circulator is used instead of the coupler to maximize the light on the sample and the detected light, as shown in figure 3:

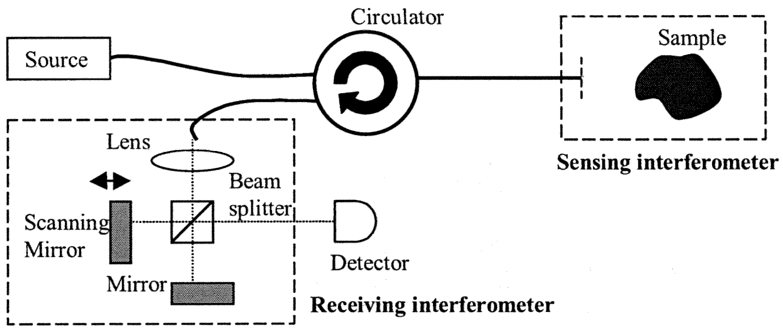

Figure 3: Fizeau configuration with a Michelson receiving interferometer

3. EXPERIMENTAL

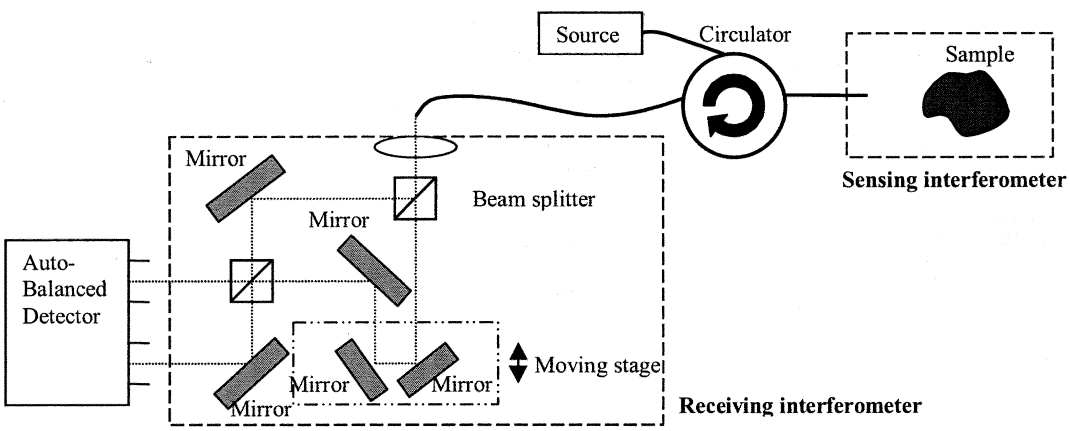

Figure 4: Fizeau configuration with a Mach-Zehnder receiving interferometer

A Fizeau-based OCT system using a circulator, balanced detection and a Mach-Zehnder receiving interferometer is shown in figure 4. The broadband source is a 2 mW super-luminescent diode (SLD) with centre wavelength 1550 nm and bandwidth 40 nm (corresponding to coherence length of 17 μm). The light from the source is coupled into port 1 of the circulator and travels round to port 2, where it is coupled out and focused into the sample, using a pair of lenses that result in a Rayleigh range of about 0.5 mm and a spot size of 30 μm. At interfaces within the sample the light is scattered and the backscattered light is re-coupled into port 2 of the circulator. From here it travels to port 3, where it is collimated and directed into the bulk-optic scanning Mach-Zehnder interferometer. Two mirrors in the Mach-Zehnder interferometer are scanned stepwise (Step size: 0.843 μm, scan speed: 0.2 mm s^{-1}) parallel to the beam axis, under the control of a Labview™ program, to achieve matching of the OPD with that of the Fizeau interferometer. The two beams from the scanning interferometer recombine on the detector, the output of which is digitised and stored in the computer subsequent to each mirror movement. By scanning transversally the probe, a B-scan imaging (2-D image) can be produced.

4. RESULTS AND DISCUSSION

This system has been tested on a sample comprised of an air gap formed between two glass slides (figure 5(a)). The image in figure 5(b) is composed from a series of one hundred z-scans, with a longitudinal step size of 0.843 μm and a lateral step size of 30 μm. The boundaries between different refractive index regions within the sample can be clearly seen in the image.

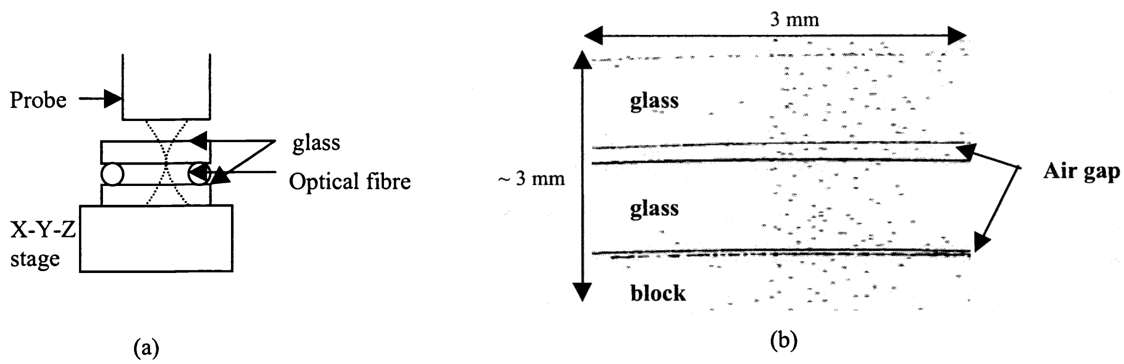

Figure 5: (a) Experimental set-up, showing position of the Rayleigh range relative to the sample and (b) 2D image formed from scans.

The results from the test presented above are encouraging preliminary results from the balanced Fizeau configuration OCT system.

Previously, despite the advantage of downlead insensitivity, the Fizeau/Michelson combination made rather inefficient use of the optical power. The optical power available at the detectors from the modified configuration is much higher, and the SNR of the Fizeau/Mach-Zehnder combination, using a circulator and balanced detection, is sufficiently high to obtain clear results from air/glass and air/anodised aluminium interfaces.

5. CONCLUSIONS

A Fizeau system using a 1550 nm source and incorporating an in-fibre optical circulator has been constructed. The system currently uses an auto-balanced detector, with frequency filtering, to improve the SNR. Preliminary two-dimensional scans demonstrate its ability to map samples. The system is currently being improved to maximise the experimental SNR.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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Casaubieilh, P.

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