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A Micro-Photonic Stationary Optical Delay Line for Fibre Optic Time Domain OCT

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Abstract - We present results for the characterisation of a Micro-Photonic stationary optical delay line. The delay line is intended to generate true time delays for a fibre optic based optical coherence tomography system.

Introduction

Optical Coherence Tomography (OCT) is an interferometric technique that uses the auto-modulation effect of broad-band (low coherent) Near InfraRed (NIR) light to present a reflection intensity map of a tissue's cross section. OCT can be used to a depth of up to 3 mm, with 5-10 um axial resolution [1].

In conventional time-domain Optical Coherence Tomography (OCT), a reference Optical Delay Line (ODL) is required. Typically, the ODL uses the physical movement of a mirror to scan the required depth range, which is equal to the penetration depth of the beam into the test sample. This motion can result in instrument degradation. Stationary ODL (SODLs) overcome this issue by having no moving parts. Non-mechanical, low-cost, controllable, long-range and long-life ODLs represent significant value to TD OCT. SODLs also have the potential to be more affordable, due to negligible maintenance and the use of solid state components. SODL could also enable OCT instruments to be more compact, and hence, more portable.

Fibre Optic OCT System

Fibre optic time-domain OCT systems [2], which make use of micro-photonics as a stationary ODL, have previously been proposed [3]-[5]. These systems make use of an in-fibre interferometer, which can be either a Michelson or a Mach-Zehnder interferometer. The Micro-Photonic SODL can be based on either reflective phase-modulating or transmissive intensity-modulating, Spatial Light Modulators (SLM). The Micro-Photonic SODL presented in this paper is based on a transmissive SLM.

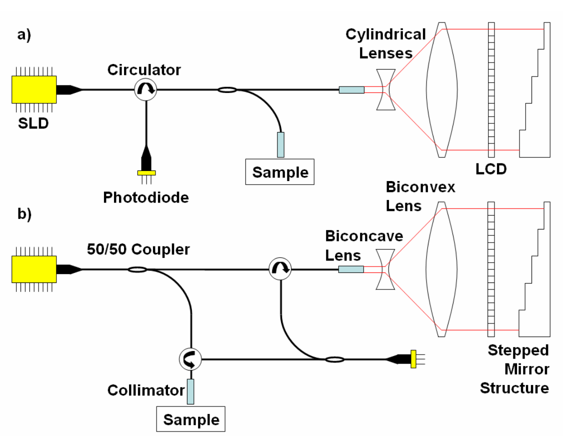

Fig. 1. Fibre optic OCT using a Michelson interferometer (a), and a Mach-Zehnder interferometer (b), with the SMS based SODL.

The optical fibre interferometer for the OCT system can utilise existing fibre technologies in the 1300nm or 1550nm range [6]. The typical light source for fibre based OCT is a Super Luminescent Diode (SLD). Other optical fibre communications components will also be utilised, specifically, optical fibre circulators, optical fibre couplers/splitters, and optical fibre collimators.

Figure 1 (a) shows the proposed OCT system based on optical fibre Michelson interferometer, using the Micro-Photonic SODL. Figure 1 (b) shows the OCT system based on the optical fibre Mach-Zehnder interferometer, again using the Micro-Photonic SODL.

In the Micro-Photonic SODL, a collimator is used to expand the light from the optical fibre. The light is then expanded in one dimension via planar optics, that is, a cylindrical lens based telescope, using both a concave and convex lens. The expanded beam is them passed through the SLM, specifically a liquid crystal light valve used as an optical switching array. Light is then reflected back through the system from the micro-photonic structure. The micro-photonic structure is a one dimensional array of staggered mirror steps, called a Stepped Mirror Structure (SMS). The system enables the selection of discrete optical delay lengths. A similar mirror array has previously been proposed for use with a SODL, based on Acousto-Optic (AO) deflection [7]-[9]. Here the proposed array was made up of a small number of macro-mirrors, with phase-modulators, to give a quasi-continuous delay length.

The ODL based on the SMS, is capable of depth hoping and multicasting. That is, switching between delay lengths, without having to scan through an

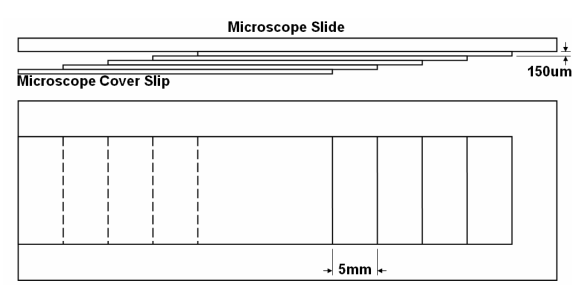

Fig. 2. Schematic of the SMS, showing the top and front view.

intermediate length, and selecting multiple lengths simultaneously. Neither of these features is possible with a standard moving mirror, or AO deflection.

Micro-Photonic Delay Line

The SMS consists of six steps, each approximately 150 um high, and 5mm wide. The fabrication of the SMS has previously been discussed [4]. Figure 2 shows the details of the SMS used in the characterisation experiments.

A change in notch frequency from an in-fibre Mach Zehnder filter was used to gauge the average step height. This method gives a direct correlation to the practical application of the structure. For a given path length difference, the possible notch frequencies obtainable are given by the notch frequency equation,

$$f = \frac{(2m+1)}{2\Delta t}, \tag{1}$$

where m is the order number. Rearranging for the time difference (Δt), and converting to a path length difference (ΔL) gives,

$$\Delta L = \frac{(2m+1)c}{2nf}. \tag{2}$$

The difference is step height can then be determined by taking the difference between two delay lengths for the measured notch frequencies for consecutive steps.

The experimental setup for mounting and aligning the SMS is show in figure 3. Preliminary results using the Mach-Zehnder filter [4] suggested a value slightly higher then 150 um. To ensure the system was aligned, and most importantly, the direction of translation was perpendicular to the optical axis, and iris and IR-VIS target were used before (and after) the alignment stage.

The optical circuit for the Mach-Zehnder filter is shown in figure 4. To ensure the arm lengths of the interferometer were even, special care was taken to measure the lengths of fibre involved. The reference arm was made slightly longer than the tunable arm (with the SMS). This then enabled the arms to be balanced to give the first notch (*m=1*) at a high frequency.

Notch frequencies were measured for 5 steps (the limit of travel of the stage used). The average step height and standard error using the Mach-Zehnder filter was (150+/-20) um. This compares very well with measurements made with a pair of Mitutoyo dial

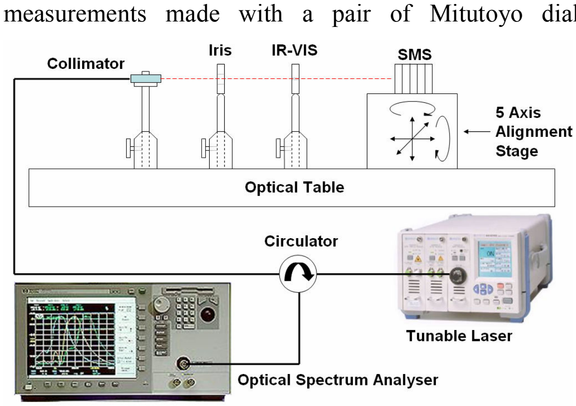

Fig. 3. Experimental setup for mounting and aligning the SMS.

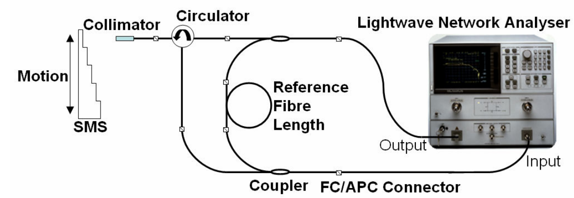

Fig. 4. Optical circuit for measuring the notch frequency of the Mach-Zehnder filter.

callipers. The average step height measured with the callipers was 150 um, with a 10 um precision.

Future Work

Work currently being undertaken involves the fabrication of smaller micro-SMS. Wet etching and dry etching of silicon is being compared to fabricate a mirror array with 5 to 10 micrometers high steps. This distance corresponds to the axial resolution limit of OCT. Hence, even though the SMS gives a discrete array of delay length, being at the axial limit means the discrete nature is of no consequence. The final structure is intended to have 320 steps, giving a total delay length in the order of 1.5 to 3 mm. This corresponds to the number of pixels in the liquid crystal light valve, and the distance is on the order of the penetration depth of OCT.

With the fabrication of the final micro-SMS, future work will then look at the implementation of the SLM; that is, the liquid crystal light valve. This will remove the requirement to translate the SMS sideways, as done in these preliminary experiments.

The final stage of the project will investigate the alignment tolerance of the system. That is, the amount of optical loss associated with angular deviation between the mirror facets and the optical axis. This has been identified as a possible issue. However, the use of a lens system with an appropriate numerical aperture should result in little optical loss, and only a variation in the effective step height.

Conclusions

In conclusion, we have presented results for the characterisation and use of a Micro-Photonic SODL for the generation of true time delays. The SODL is a micro-SMS. The use of the SMS as a reference ODL in a fibre optic OCT system has also been presented.

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