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Transparent media thickness measurement employing low-coherence interferometry and a multi-element array

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ABSTRACT

In this communication, we present a method to measure the thickness of transparent media employing a low coherence interferometer and a multi-element array as a photo-detector. The multi-element array employed is part of a consumer-grade digital camera ($< 0.5\,$k\$). A two-beam interferometer is created by inserting the slab of a transparent material half-way through into the measurement beam. The method is evaluated on a thin microscope cover slip and on a thicker microscope glass slide.

Keywords: optical coherence tomography, non destructive testing, low coherence interferometry, low resource settings

1. INTRODUCTION

Low coherence interferometry can be used to measure thicknesses of transparent media (or their refraction indices, if their thicknesses are known) with resolutions of tens of microns, and within a range of millimetres. One implementation[1,2] involves a spectrometer and a simple two-beam interferometer, created by inserting the transparent slab being measured halfway through the measurement beam - a portion of the beam profile travels through the transparent slab and the rest through free space, creating an optical path difference between the two portions of the beam. A different configuration is presented here, where the two beams are combined (and light allowed to interfere) by being launched into a single optical fiber and where the spectrum reading is obtained via swept source interferometry, combined with a multi-element detector array (from a commercial-grade digital camera).

2. EXPERIMENTAL SETUP

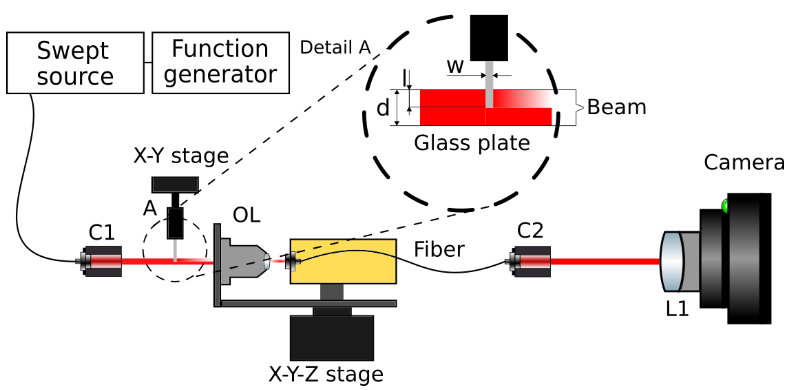

Figure 1. Schematic diagram of the experimental set-up used. C1-C2: fiber collimators; OL: objective lens for coupling light into the fiber; L1: imaging lens for the camera ($f = 20\,$mm). Inset A: detail of the transparent slab of thickness w inserted a distance l into the beam of diameter d.

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The experimental configuration is shown in Fig. 1. A swept source (Superlum Broadsweeper 840) emitting light with a central wavelength $\lambda_0 = 834.5\,\text{nm}$ and a tuning range of $\Delta\lambda \approx 50\,\text{nm}$ is used as the illumination source. Its output is collimated to form a beam of approximately 3 mm width. Half of the beam is intercepted by the slab whose thickness w is being measured; this slab can be a cover glass or a microscope slide, introduced from below or above the beam (detail A in Fig. 1). In this way, a simple two-beam interferometer configuration is created. The resulting beam is then coupled into an optical fiber, which is ultimately directed towards a digital camera via a collimator C2 and a lens L1.

The digital camera used in the system is a Nikon J5 with a $13.2 \times 8.8\,\text{mm}^2$ CMOS image sensor, with a resolution of 5586×3724 px, allowing the measurement to be made as an average over 23.01 million A-scans. This camera offers several modes of operation. By comparing these modes, we have concluded that the best signal-to-noise ratio (SNR) is achieved when the ISO sensitivity is set to 200 and the shutter speed to 1/200. In our experimental set-up, for performing the spectrum read-outs we captured video footage using the full manual shooting HD mode with a frame resolution of 1280×720 px and 30 fps.

To cover an axial range extending over 1 mm, at least 300 spectral points are targeted, given the broad tuning bandwidth of the source. This implies the same number of 300 frames. At 30 fps, this yields a total sweep time of 10s. The sweeping was driven by an external function generator (Stanford Research Systems, model DS345), with a sweep rate of 0.100 Hz.

Due to the lack of synchronization between camera and source, we collected more than one full spectral sweep in a 20s-long video file. This file was then loaded into the PC via the mass storage facility of the camera, converted into an image stack using a custom-made MATLAB script, and finally processed in a custom-made LabVIEW program to obtain the A-scans by a Fourier transform applied to the electrical signal derived from the channeled spectra. This LabVIEW program allowed the user to specify a region of interest (ROI) of arbitrary size within the video frame. The points within the ROI were averaged together prior to the Fourier transform, effectively altering the sensor area digitally.

3. RESULTS

The optical path imbalance in the interferometer (OPD), is given by the relation

$$\text{OPD} = w(n - n_a), \tag{1}$$

where w is the thickness of the transparent medium, n and n_a are refractive index of the transparent medium and air, respectively.

To obtain a strong interferometric signal, both beams should exhibit similar strength, hence the edge of the slab of transparent medium should be placed in the middle of the beam, with $l = d/2$. It is expected however that depending on the opacity of the material that the maximum signal may not be obtained when the edge is exactly in the centre of the beam. We have studied the evolution of the A-scan peak amplitude with the position of the microscope slide, with the results shown in the plot in Fig. 2.

The full width at half maximum of the trace in Fig. 2 should yield a measure of the width of the collimated beam. The value measured (approximately 1.2 mm) is far from our original beam estimation, probably due to imperfections in the edge of the slab of glass, and also given that the beam profile is Gaussian, therefore this measurement might be biased by the main lobe of the profile.

Prior to setting up the experimental set-up shown in Fig. 1, we have calibrated the swept-source interferometry conversion between OPD and channeled spectrum density by implementing a Michelson interferometer. This has determined an axial range of 1.875 mm over 150 OPD points. With this knowledge, it is possible to infer the thickness of the slab of transparent medium from the position of the A-scan peak with an accuracy of $12.5\,\mu\text{m}$.

Using a microscope cover glass (nominal thickness ~ 0.2 mm) and a microscope glass slide (nominal thickness ~ 1 mm) as samples, peaks were obtained at positions 9 and 42 along the 150 divisions of OPD. Considering an index of refraction of the material ~ 1.5, these give a thickness of $225\,\mu\text{m}$ for the cover glass and $1.050\,\mu\text{m}$ for the microscope glass slide.

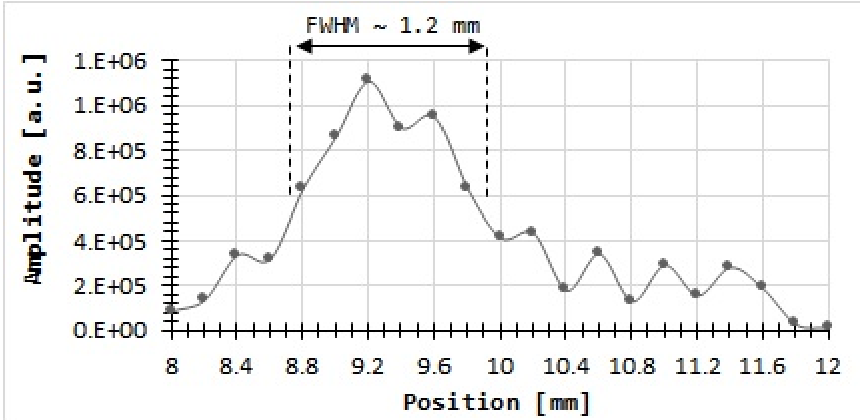

Figure 2. A-scan peak amplitude with the position of the microscope slide (inserted into the beam path)

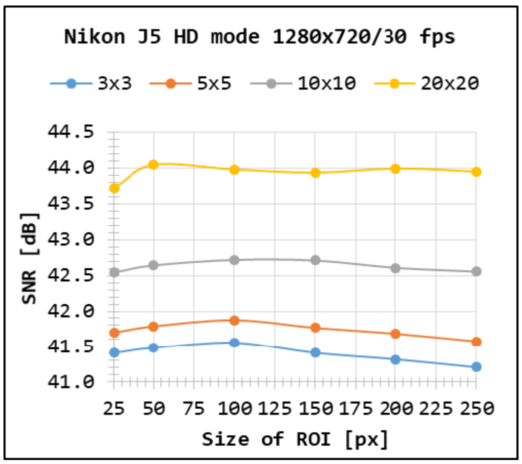

Figure 3. SNR results for the microscope cover, for several ROI and kernel sizes.

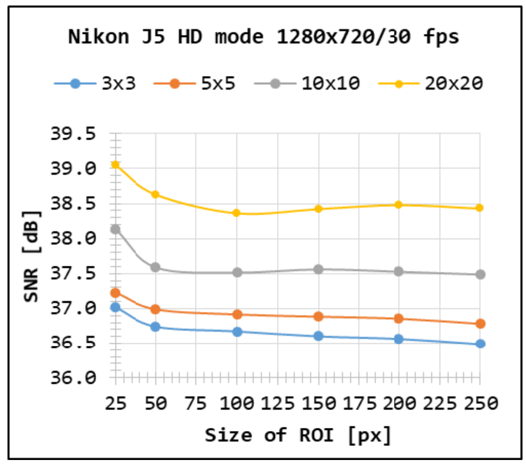

Figure 4. SNR results for the microscope glass slide, for several ROI and kernel sizes.

To evaluate the advantages of using a multi-element array detector over a single photo-detector, we performed a series of measurements using several ROI sizes in the LabVIEW program. The ROI size ranged from 25×25 px to 250×250 px. In addition to varying the ROI size, we have also assessed the effect of local averaging of the channeled spectra within the ROI, employing a selectable kernel size which ranged from 3×3 to 20×20 pixels. The impact of these parameters on the signal-to-noise ratio can be observed in the plots in Figures 3 and 4 for the microscope cover glass and the microscope glass slide, respectively.

4. DISCUSSION AND CONCLUSIONS

In this summary, we described a technique for thickness measurements of slabs of transparent material, employing low-coherence interferometry and a multi-element array. This arrangement uses a commercial-grade CMOS digital camera.

In addition to devising the optimum location of the beam profile which maximizes the measurement SNR, Fig. 2 can also be used to estimate the effective beam diameter leaving collimator C1. By taking advantage of the multi-element array of detectors, we established that increasing the size of the ROI leads to a decrease of the SNR. We believe this may be caused by the ROI covering more than just the main lobe of the Gaussian beam, incorporating regions with lower signal in the overall average. We have also found that larger kernel sizes increase the SNR which was expected.

In conclusion, with the system presented here, we have shown that an inexpensive commercial-grade digital camera can be used as a multi-array detector for measuring thicknesses of transparent materials when paired with a slow tuning swept source. This study can have far-reaching implications for low resource settings OCT, by pairing the same commercial-grade camera with a swept-source.

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