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The Potential of Optical Coherence Tomography for Geometric Analysis and Refractive Index Measurement of Three Dimensional Structures

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Abstract

In this article recent quantitative image processing developments for optical coherence tomography are discussed. Example images of complex structures requiring accurate geometric interpretation are presented and a technique is introduced for separating geometric dimensional and refractive index data. Our method is demonstrated for a simple one layer sample and issues surrounding the measurement are discussed, including the extension to multiple layers and 3D structures.

Introduction

Optical coherence tomography (OCT) [1] is a versatile imaging technique, capable of non-invasively obtaining cross-sectional images of turbid samples. Multiple adjacent cross-sectional images can be used to re-construct a three dimensional representation of the sample [2].

The technique itself is based on low coherence Michelson interferometry used for the short-range detection of faults in optical telecoms systems and photonic components [3]. It has been used almost exclusively for medical (notably ophthalmic) imaging for some years, however recently it has been demonstrated as a measurement solution in other areas, such as the paper industry [4], characterisation of polymer composites[5] and non-invasive monitoring of tissue scaffolds [6]. As a direct consequence of the wide application of OCT technology, we investigate the processing of OCT data to provide reliable quantitative results. Work of this nature is well supported in the literature with the measurement requirements being reviewed in Ref. [7].

Some of the key parameters of interest are the depth resolved scattering co-efficient, geometric structural dimensions, three dimensional refractive index distributions and local dispersion. A number of models exist for analysing the optical scattering co-efficient of samples. Recently interest has turned towards separating the geometric dimensional data and sample refractive indices from OCT interferometric scans. In this area the work of Bruno and Chaubell [8] is notable, with the introduction of a solver for the OCT inverse backscattering problem. Numerical dispersion compensation in OCT has been formerly demonstrated, however, thus far dispersion measurement has only been clearly demonstrated using the distinctly non-classical two-photon interference of quantum OCT [9].

In the present article, we investigate the potential of Fourier Domain OCT (FD-OCT) for the measurement of refractive index variations that lead directly to an accurate geometric description of the sample.

Fourier Domain OCT Theory

The FD-OCT interference signal $I(\omega)$ corresponding to a single depth (axial) scan, can be described by the following equation:

$$I(\omega) = T_r T_s S(\omega) \left\{ R_r + 2\sqrt{R_r} \Re \left[H(\omega) e^{-i\varphi(\Delta z)} \right] + |H(\omega)|^2 \right\}$$

where the subscripts r and s indicates the reference and sample arms of the Michelson interferometer configuration respectively. The source spectrum $S(\omega)$ is given as a function of angular frequency ω as is the sample response function $H(\omega)$. R_r is the reference mirror reflectivity, here taken to be unity and the beam-splitter transmittivity for each arm is given by T . The phase term $\varphi(\Delta z)$ is used to account for the reference mirror position offset Δz and is given by,

$$\varphi(\Delta z) = 2\omega \frac{n_{air}}{c} \Delta z.$$

The refractive index of air is given by n_{air} and the speed of light by c .

From the above equations, using a suitable sample response function, the FD-OCT signal can be modelled. Therefore, the following question arises – can the detected spectral interference be used to determine the properties of the response function H ? This inverse problem has recently been investigated for time-domain OCT by Bruno and Chaubell [8] with promising results. In our work we have used a simple summation model for H to determine the refractive index and geometric thickness of a single layer using the measured spectrogram. The summation model is expressed as

$$H(\omega) = \sum_{j=1}^N r_j \exp \left\{ i 2 \frac{\omega}{c} \sum_{m=1}^j (n_m z_m) \right\}$$

for a sample consisting of N layers, each of refractive index n_m and thickness z_m . The reflectance at each interface is given by the Fresnel coefficient

$$r_j = \frac{n_{j+1} - n_j}{n_{j+1} + n_j}$$

Experimental Arrangement

Our FD-OCT system operates in the near infra-red, using an optical spectrum analyser (OSA) for the spectral data acquisition. For this work an erbium doped fibre (EDF) amplified spontaneous emission (ASE) source was used with a centre wavelength of 1565 nm. A schematic of the experimental arrangement is shown below in figure 1.

A single pure silica glass slide was then used as a sample to obtain spectral interference. The interference arises from light reflected from the front and back surfaces of the sample

combining with the light reflected from the reference mirror at the OSA. Such reflections can be modelled simplistically using the summation model mentioned earlier, that neglects contributions from multiple internal reflections.

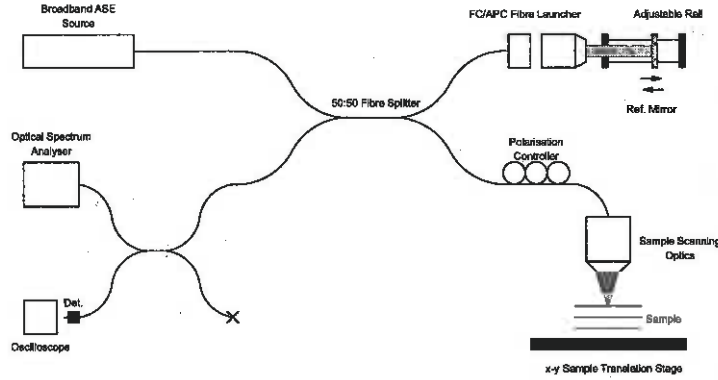


Figure 1. NPL FD-OCT setup

To remove the self-coherence terms two axial scans are subtracted, one having a half wavelength phase shift relative to the other. The resulting spectrum is then de-convolved from the source spectrum, multiplied by a cosine windowing function and finally amplitude normalised. This procedure enables us to directly compare our modelled spectral interference pattern with that measured.

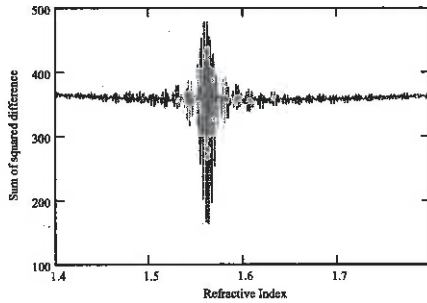


Figure 2a. Finely sampled squared difference between measurement and model for constant geometric thickness. Used to determine layer optical thickness.

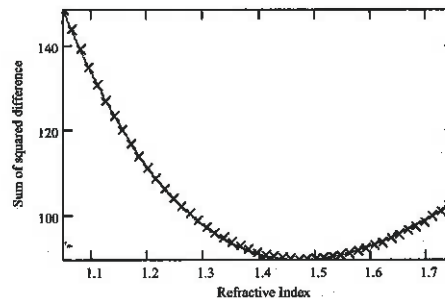


Figure 2b. Minimisation of sum of squared differences for constant optical thickness. A polynomial (line) is fitted to the measured data (points).

Extraction of Layer Parameters

Since the spectral interference is by nature sinusoidal, non-linear least squares fitting routines based upon Newton methods tend to converge to local minima, rather than the global minimum for the model. This results in incorrect parameter estimation, unless an excellent starting guess is provided. Techniques based on Prony's method have been demonstrated for robust frequency estimation in measured sinusoidal signals [10]. Such approaches may provide an efficient method for fitting to the experimental data. However, in the present study we have used a more rigorous and computationally expensive method to study the

topology of the minimisation surface as the layer refractive index and geometric thickness are varied in the model.

Inspection of the minimisation surface reveals many local minima, however, the global minimum is evident as the lowest point on the surface, representing the best fit of the experimental data to the model. As a result we are able to extract both the layer refractive index and geometric thickness at which the global minimum occurs.

In practice, a coarsely sampled minimisation surface is used to select a single thickness and refractive index range over which to finely sample and therefore determine the layer optical thickness, figure 2a. The sum of the squared differences is computed for a range of refractive index and thickness values, holding the measured optical thickness constant. The minimum of the resulting curve is then an estimate of the global minimum, and hence yields the layer parameters. Here the minimum is determined by differentiation of a third order polynomial fitted to the data, figure 2b.

By repeating this technique for multiple refractive index and thickness parameter pairs it would be possible to accurately determine the properties of a multi-layer structure.

Conclusions

We have demonstrated that the refractive index and geometric thickness of a single layer can be accurately determined by spectral analysis of the Fourier domain optical coherence tomography interference. Although the method used here is computationally expensive, our results indicate that it should be possible to implement faster minimisation algorithms tailored to this particular problem.

Since the method requires no extra measurements, it can be applied to data after collection. Importantly, our results demonstrate a potential route for the realisation of traceable three-dimensional measurement by OCT.

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