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Considerations for the deployment of extended-range Fourier domain optical coherence tomography

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Abstract

Fourier-Domain Optical Coherence Tomography (FD-OCT) is a measurement technique that allows the visualisation of scatterers within the body of an optically compliant sample. Widely established for applications in biomedical imaging, the non-invasive assessment of sub-surface structures that OCT enables has resulted in an increasing number of industrial measurement applications over recent years. In FD-OCT, broadband light scattered from within a sample under test is combined with reference light to generate a spectral interferogram. Subsequent analysis of the spatial frequencies contained within the generated interferogram allow the location of both individual and multiple scatterers to be determined. In conventional OCT, the light is focussed into the sample using a spherical lens, which is also used to gather the scattered light. By deploying an axicon lens instead, the imaging performance is modified in a manner that allow scatterers over a greater range of depth along the optical axis to contribute to the signal generated. This can remove the need to scan the sample along the optical axis, leading an increase in measurement rates and more flexible deployment and integration opportunities for in/on-line measurement scenarios. While the presence of the axicon does affect both the illumination of the sample and the collection of the light, here we demonstrate that the interpretation of the signal generated remains substantially the same. However, we also show that there is an introduction of non-linearity into the relationship between spatial frequency and scatterer location, as well as some additional spatial frequencies that result in peak-spreading. We explore how this affects working range and how detection elements of the system need to be deployed. All these aspects need specific consideration if the performance of extended-range FD-OCT systems based on axicons is to be fully optimised for metrology applications.

In-process measurement, interferometry, metrology, optical

1. Introduction

Optical Coherence Tomography (OCT) is a measurement technique that allows the characterisation of optically compliant (transparent) materials, identifying the location where light was scattered from in order to build up a picture of the three-dimensional structure. While initially finding widespread use in biological applications [1,2], the ability to non-destructively detect and characterise buried features/defects, in both biomedical applications [3] and in non-biological samples such as ceramics [4] and polymers [5], has meant that interest in manufacturing has grown in recent years. Traditional OCT systems, of the form illustrated in fig 1(a), can only identify scatterers in a small region of space in a single acquisition, meaning that the measurement region within the sample needs to be scanned in order to build up a complete picture, slowing down the measurement and limiting the applications that it is suitable for. The reason for this limitation is the small region of the sample that is illuminated at any one time. Lateral scanning is typically implemented rapidly through the use of 2 axis galvanometer-based beam scanning. However, scanning along the optical (depth) axis is rather slow due to the requirement to acquire multiple lateral scans in a stepwise fashion which requires mechanical translation. While the lateral resolution of the system is directly related to the lateral extent of the illuminated region, the resolution along the optical axis is determined interferometrically and so is unaffected by the depth of the sample that is illuminated.

When a collimated beam is used to focus the illuminating light into the sample using a traditional spherical lens, good lateral resolution can be achieved, however the depth of the sample that is strongly illuminated is correspondingly limited. If the light is focussed into sample using an axicon, as illustrated in fig. 1(b), a far greater depth of the sample can be strongly illuminated without increasing the lateral region illuminated [6]. While this overcomes the limitation on the range of the sample along the optical axis that can be captured in a single measurement acquisition, the use of the axicon strongly affects the way the scattered light is collected and delivered to the spectrometer. We are, however, unaware of a full description of how light passes through the system to the scatterer and then back to the detector. To address this we present our initial work on analysing the signal formation for extended-range OCT based on axicon illumination.

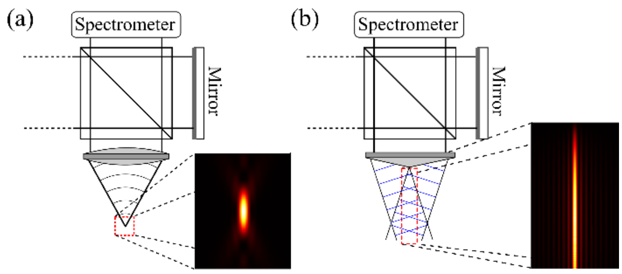

Figure 1. *A schematic of an OCT system utilising a spherical lens (part a), and with an axicon (part b). An example of the illuminated region in the object space is shown in the inset.*

2. Modified OCT system

In the following, we model light passing through the axicon into the object space to determine the phase of the incident light at a set of locations where a point scatterer is placed. The light from this scatterer is considered to spread out radially with the same phase as the light incident on it. The light is then propagated back through the axicon to the point where a detector is considered to be located where it is combined with light from the reference arm.

This calculation is carried out for a range of wavelengths with a variation in the intensity of the signal with respect to wavelength being seen that relates to the location of the scatterer. Currently the variation in intensity across the aperture is not accounted for, only the change in phase, which is most relevant for interferometric detection.

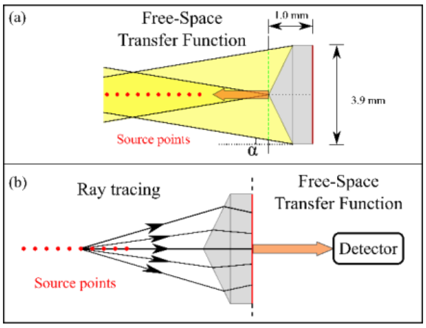

Figure 2. *An illustration of how the signal is generated. (a) The field just after the axicon is propagated to the location of the scatterer using a free-space transfer function.(b) Ray tracing is used to determine the phase on a plane at the base of the axicon due to the scattered field (marked in red), before the field is propagated to the location of the detector again using a free-space transfer function.*

The process described above is illustrated in fig 2. The light in the object space is calculated by taking the field of the form

$$E = E_0 \exp\left(-k\sqrt{x^2+y^2}\sin\alpha + \phi_1\{k\}\right) \qquad (1)$$

On the plane parallel to the base of the axicon, and that passes through the apex (marked by the green line in fig 2(a)). Here *k* is the wavenumber, α is the angle a ray parallel to the optical axis would be rotated by, in this case 9.2 degrees, and $\phi_1\{k\}$ is the phase the light accumulates passing along a straight line from the base of the axicon to the apex, a distance of 1 mm. The refractive index of the axicon is 1.45, and the base has a radius of 1.95 mm. A reduced aperture on this plane after the axicon, corresponding to the green line in fig 2(a), is calculated from the axicon base radius and the convergence of the beam. The field is propagated from the plane after the axicon to the location of the scatterer using a free-space transfer function [7], decomposing the field into an angular spectrum before propagating to the correct plane and reconstructing the field. This calculation is carried out for 10 scatterer locations, placed equidistantly between 1 mm to 10 mm after the apex of the axicon, and for 1000 wavelengths of light whose wavenumbers vary linearly between those of light with a wavelength between 820 nm and 830 nm. On each plane, the field is recorded on an array of 9801 by 9801 points extending from -2mm to 2 mm in the x and y directions. Once the phase of the incident light at each wavelength has been found, rays are traced from each scatterer location to the set of points at the base of the axicon with the same x & y locations used in the arrays previously. The optical path length of the ray is used to determine the phase of the field at the base of the axicon, however the magnitude of the field is assumed to be 1, except at points where two rays may make it to the same point (close to the centre of the axicon where rays from either side of the centre meet) where the magnitude and phase is given by the summation of the two waves with unit magnitude and with the phase corresponding to each ray. This field is once again decomposed into an angular spectrum before being propagated to the location of the detector. It is combined with a reference field $E = E_1\exp(-ikz_{detec})$, where z_{detec} is the distance from the base of the axicon to the detector (15 mm). The intensity at each wavelength is calculated from the combined electric fields of the light from the scatterer and the reference arm before it is Fourier transformed. As in the case where a conventional spherical lens is used, a peak is observed for each scatterer whose wavelength related to its location. Fig. 3(a) shows the results for each scatterer position; the base of each peak is broader and noisier than for the case where a spherical lens is used.

Figure 3(b) shows the location of the peak for each of the source positions 2 mm to 10 mm, with the scatterer at 1 mm being excluded as no clear peak is present. It can be seen that even in this modified system, the change in the peak location with position of the scatterer is close to linear, but there is some deviation. Additionally, there is some broadening of the peak, due to the off-axis paths that the rays take. However, in the specific context of the analysed system, the small angles and large distance to the detector reduces that to some degree in this instance. Modulations in the intensity in the signal produced in the space around the detector will lead to more noise on the signal, as seen.

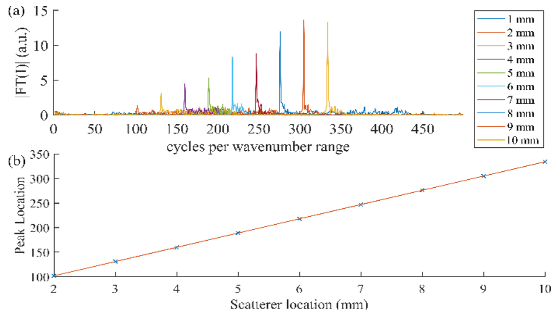

Figure 3. *(a) The magnitude of the Fourier Transformed intensity signal generated for 10 different scatterer positions. (b) shows the peak locations in (a) (blue crosses) with a linear best fit line (red).*

3. Summary and Conclusions

We have presented a model of the entire signal generation steps in an OCT system utilising an axicon. This describes not only the form of the light produced in the object space, but also how the scattered light is collected and passed to the spectrometer. This differs from the case where a spherical lens is used, producing a slightly broadened peak in the Fourier transform of the signal recorded for a scatterer at each location, but a close to linear relation between the peak in the Fourier transform of the signal and scatterer position is still obtained.

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