

Ultra-high resolution Fourier domain optical coherence tomography for resolving thin layers in painted works of art

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ABSTRACT

While OCT has been applied to the non-invasive examination of the stratigraphy of paint layers in recent years, it has been recognized that the resolutions of commercially available OCT cannot compete in depth resolution with conventional microscopic examination of cross-sections of paint samples. It is necessary to achieve resolutions better than 3 microns to resolve the thinnest layers of paint and varnish. In this paper, we demonstrate a Fourier domain ultra-high resolution OCT at 810nm with depth resolution of 1.8 μm in air (or 1.2 μm in varnish or paint).

Keywords: Optical Coherence Tomography, Fourier domain, ultra-high resolution, micron-scale

1. INTRODUCTION

Scientific instruments for use in the area of art history, conservation, archaeology and heritage science have been developing rapidly. Examination of works of art is essential for conservation, preservation and understanding of material change and Optical Coherence Tomography (OCT) has proved invaluable in this field.

Optical Coherence Tomography (OCT) is a non-invasive, non-contact 3D imaging technique that uses the coherent properties of broad band light sources, making the technique a very useful diagnostic tool for visualization of subsurface microstructure. OCT has found applications in the examination of jade, ceramics, ancient glass, enamel, parchment and faience [1, 2, 3, 4]. It has also been used for dynamic monitoring of the wetting and drying of different varnishes, varnish removal using solvents, real time laser ablation of varnish layers and tracking of canvas deformation due to environmental changes [1, 2, 5]. Besides the visualization of the stratigraphy of paint and varnish layers, application of OCT to paintings has shown to be the most sensitive technique for revealing preparatory drawings beneath paint layers owing to its high dynamic range and depth selection capabilities [2, 6].

However, the depth resolution of OCTs used in these applications still cannot match those of microscopic examination of sampled paint cross-sections. It is known that some varnish and paint layers can be as thin as ~ 3 microns. The depth resolution of commercial OCT systems is rarely better than $6\mu\text{m}$ in air. A depth resolution of $<3\mu\text{m}$ is needed to resolve the thinnest varnish and paint layers. Since the depth resolution of OCT is proportional to the source bandwidth, ultra wide bandwidth light allows a greater depth resolution to be achieved.

While full field time domain OCT in the visible part of the spectrum can reach depth resolutions of $\sim 1\mu\text{m}$ [7, 8], they have very limited depth penetration as most paints are opaque in the visible range. Such instruments will be restricted to examining mostly the top varnish layers. In addition, time domain instruments are less sensitive than Fourier domain instruments.

Taking advantage of the established development of supercontinuum generated light (NKT SuperK Versa), a broadband continuous spectra of light with FWHM bandwidth of 180nm is used in a spectral domain OCT system to achieve a high depth resolution imaging.

2. INSTRUMENT SETUP

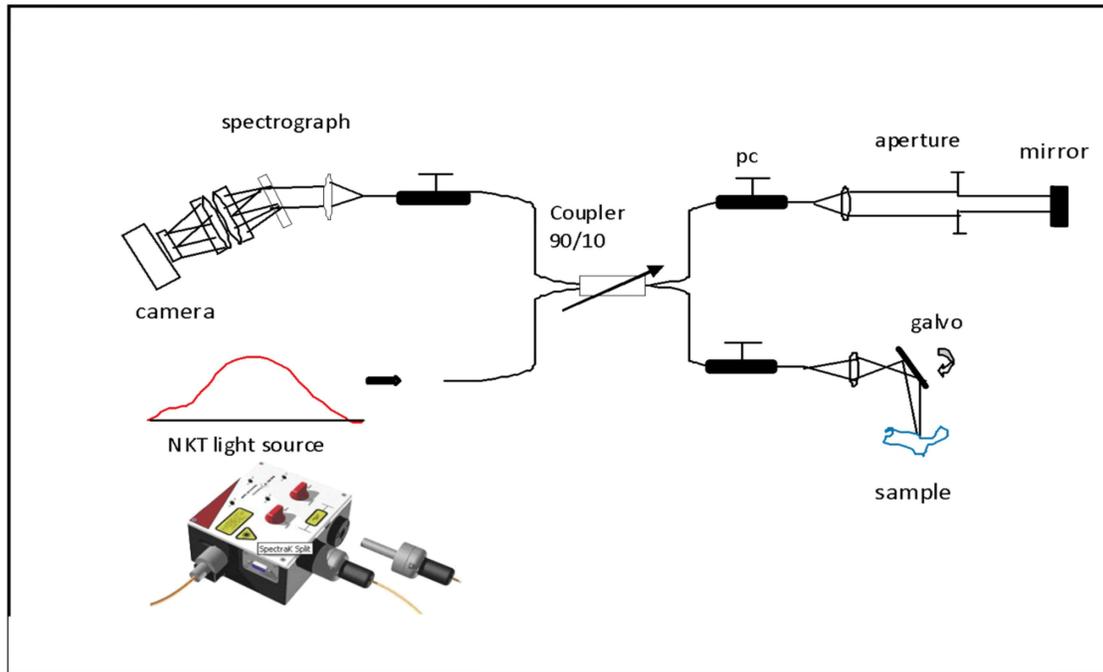


Figure 1. Experimental setup of the ultra-high resolution 810nm spectral domain OCT using the NKT SuperK Versa supercontinuum light source with a 1200 l/mm grating, a 4096 pixels linear CCD detector array.

Figure 1 shows the instrument setup. The broadband light is coupled into the input arm of a 2x2 fibre coupler with a cut-off wavelength below 600nm. One of the output arms is used to illuminate a probe with galvo scanning mirrors which scans and collect light from the sample. The returned light from the sample recombines with the reflected light from the reference mirror and the signal is captured in the spectrograph. The light is dispersed by a transmission grating (Wasatch) 1200 lines/mm and captured on a line CCD camera (E2V) with 4096 pixels (pixel size 10x10 μ m) using a ZEISS 85mm focal length camera lens. The whole system is controlled by a personal computer.

The NKT SuperK Versa source spectrum in the 600nm-1000nm wavelength region is captured by the spectrograph (central wavelength of 810nm, FWHM 180nm). Using such a broadband source presents many challenges in the design and in the availability of the optical components. The main challenge is to maintain a broadband while making sure a small focused spot is maintained over the entire length of the linear detector (4cm length) thus ensuring a reasonable depth range (>1mm). The optical components, the CCD detector all contributes to the shaping of the spectrum of the injected light.

The system is wavelength calibrated using ~20 known arc lines from Neon and Xenon lamps (Ocean Optics). The spectra are then resampled to uniform k-spacing, continuum subtracted and tapered with a Hann window before Fourier transforming to obtain the depth profiles and cross-section images

3. RESULTS

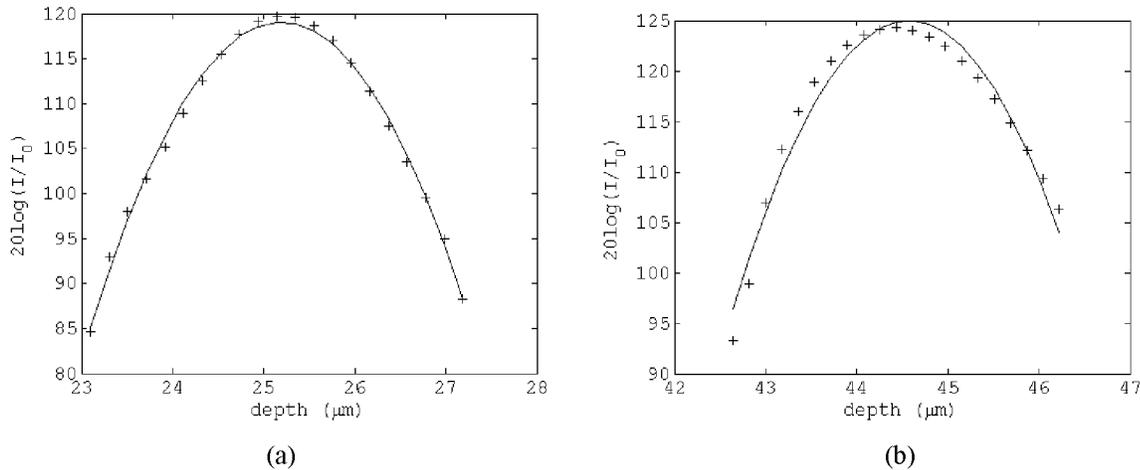


Figure 2 a) Simulated depth profile of the OCT using a measured NKT source spectrum and the CCD detector spectral response. The simulated spectrum is then processed in the same way as the actual measured data; b) The measured depth profile of a flat glass slide was found to have a FWHM depth resolution of $\sim 1.8\mu\text{m}$ in air consistent with the simulated value of $1.8\mu\text{m}$. The red curves are Gaussian fits to the profiles.

The resolution of the system was measured with a glass microscope slide and found to be $\sim 1.8\mu\text{m}$ in air without any tapering of the spectrum (Fig. 2b), or $\sim 2.2\mu\text{m}$ in air if tapered with a Hann window. This is found to be consistent with the theoretically expected resolution taking into account the CCD detector spectral response as well as the actual measured source spectrum (Fig. 2a).

Figure 3 shows cross-section images of a layer of Regalrez varnish on ground glass obtained with the 810nm ultra-high resolution (UHR) OCT and a 930nm OCT at a lower resolution ($6.5\mu\text{m}$ axial resolution).

Figure 4 shows the cross-section image of a madder lake paint in egg tempera obtained with the UHR OCT compared with a lower resolution OCT. The UHR OCT image shows clearly the scattering centers in the paint. The higher resolution also meant that the diffuse multi-scattering features in the low resolution images are not picked up.

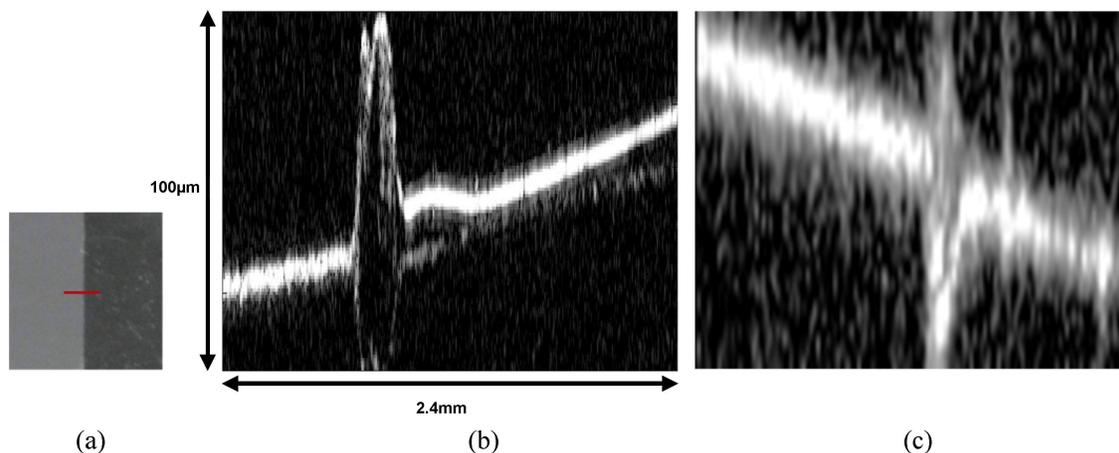


Figure 3: a) A thin layer of Regalvez varnish on ground glass (left side of image is unvarnished surface); b) cross-section image using the ultra-high resolution OCT at 810nm along the red line segment shown in a); c) with a FD-OCT at 930nm (depth resolution $\sim 6.5\mu\text{m}$) at a similar region. The two images are on the same scale in both dimensions (2.4mm wide and 0.1mm depth).

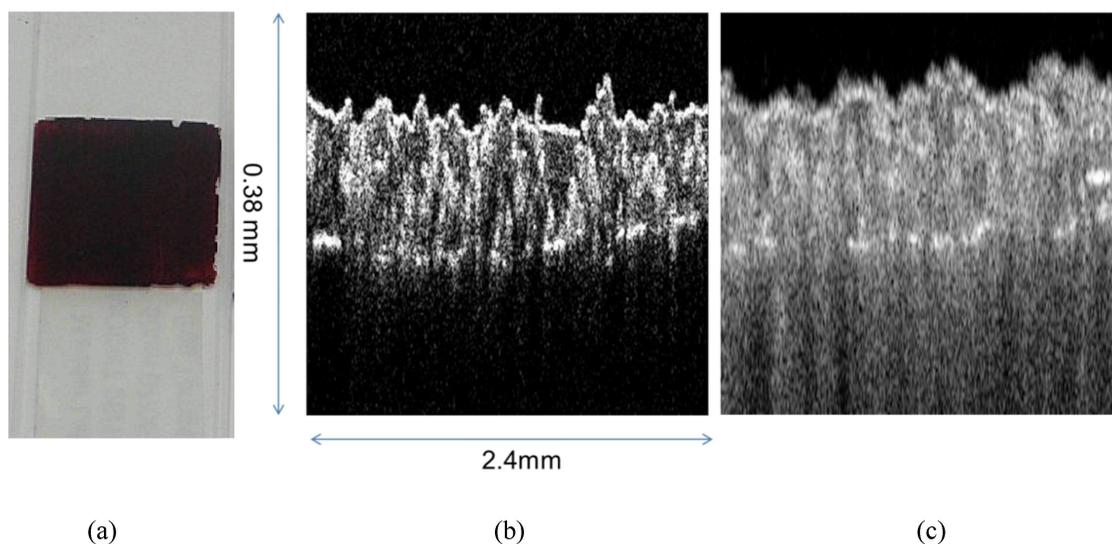


Figure 4: a) Madder lake in egg tempera painted on a glass microscope slide; b) cross-section image with the ultra-high resolution OCT at 810nm and c) cross-section image with an OCT at 930nm (depth resolution $\sim 6.5\mu\text{m}$) at a similar region. The two images are on the same scale in both dimensions.

4. CONCLUSION

By using a supercontinuum source, we have developed an ultra-high resolution spectral domain OCT at $\sim 810\text{nm}$ for high depth resolution imaging of varnish and paint layers. The theoretical depth resolution of $1.8\mu\text{m}$ (in air) is achieved and it is shown to be able to resolve thin varnish and paint layers.

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