High resolution Fourier domain Optical Coherence Tomography at 2 microns for painted objects

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ABSTRACT

Optical Coherence Tomography has been successfully applied to the non-invasive imaging of subsurface microstructure of a variety of materials from biological tissues to painted objects of art. One of the limitations of the technique is the low depth of penetration due to the strong scattering and absorption in the material. Previous studies found that for paint materials, the optimum window for large depth of penetration is around 2.2 microns. This is also true for many other materials with low water content. We have previously demonstrated OCT systems in this wavelength regime for imaging with improved depth of penetration. In this paper, we present an improved 2 micron high resolution Fourier domain OCT system using a broadband supercontinuum source. The system achieved a depth resolution of 9 microns in air (or 6 microns in paint or any polymer).

Keywords: Optical Coherence Tomography, interferometry, multiple scattering, supercontinuum laser source, infrared lasers, pigments

1. INTRODUCTION

Optical Coherence Tomography (OCT) is by now a well-established technique in biomedical imaging. In recent years, its applications in art conservation, history and archaeology along with other non-biomedical fields that require non-invasive imaging have been expanding[1,2]. However, one of the limitations of OCT is the probing depth for materials that are either highly absorbing or highly scattering. It is known that for most materials, the optical scattering coefficient decreases with increasing wavelength in the visible and near infrared. A recent systematic survey of paint transparency found that the optimum spectral window for OCT imaging of paint is around 2.2 microns[3]. However, since most biomedical materials contain water which absorbs strongly around 2 microns, OCTs were not built at this wavelength. The situation is different in non-biomedical applications such as the non-invasive imaging of paintings where the materials have low water content. As proof of concept we first developed a time domain OCT with an amplified spontaneous emission (ASE) source developed in-house[4,5]. While it demonstrated the improved depth of penetration, the bandwidth of the ASE source was still too narrow to give the high resolution required to resolve most paint layers. In addition, the time domain OCT was slow and therefore it was time consuming to image an area large enough for the study of underdrawings. Subsequently, we developed a Fourier domain OCT using an in-house built supercontinuum source with 220 nm bandwidth centered at 1960 nm[6]. In this paper, we demonstrate an improved Fourier domain OCT in the 2 μm wavelength regime that allows fast, efficient capturing of 3D image cubes at a high axial resolution of 6 μm in paint.

2. SYSTEM SETUP AND CHARACTERISTICS

2.1 Broadband supercontinuum source at 2 microns

An in-house built high power pulsed source was constructed using a thulium doped fiber and a single mode 1565 nm fiber laser source as the pump. The Q-switched source operates at a peak wavelength of 1850 nm with a FWHM bandwidth of 24 nm. The single mode output from the pulsed source was used as a seed for supercontinuum generation using a 5 m length small core germanium doped highly non-linear fiber (Fig. 1). The pulse repetition rate can be tuned between 10 kHz and 200 kHz. The bandwidth of the source increases with decreased repetition rate. At a repetition rate of 50 kHz, the average power is 1.2 W with a pulse duration of ~100 ns. The supercontinuum source has a spectral power density > 0.5 mW/nm over the wavelength range of ~1800 – 2200 nm. The light was then passed through a thulium doped fiber to remove the pump emission by filtering out light shorter than 1850 nm. The *rms* pulse to pulse energy variation per 1.4 nm wavelength bin over the spectral band of 1850 – 2200 nm was found to be ~1-2%. The *rms* pulse to pulse total intensity (sum over the spectral band) variation is ~0.2%. Details of the supercontinuum source can be found in Cheung et al. (2015)[6].

2.2 Fourier domain OCT setup

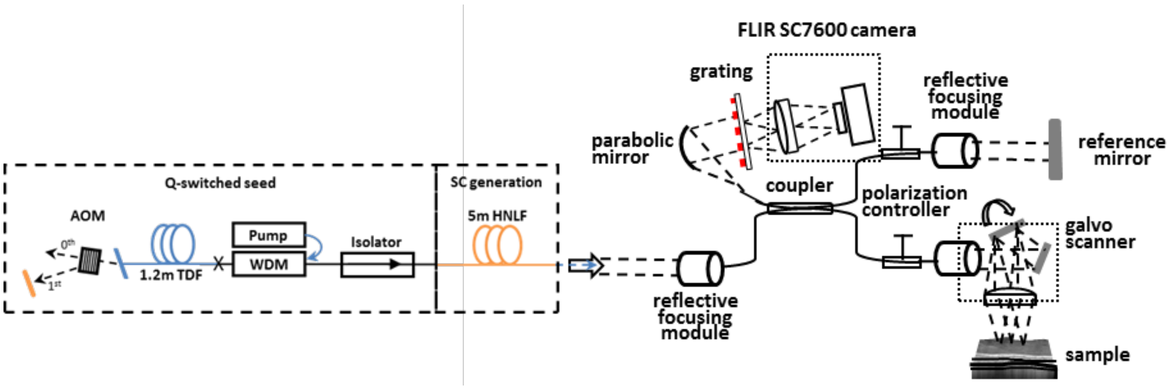


Figure 1. Schematics of the supercontinuum source and the Fourier Domain OCT setup.

The OCT has a classic spectral domain setup where light from the supercontinuum source is coupled into a 2 micron fiber connected to a fiber coupler which directs light into 2 arms, one to a reference mirror and another to the sample; the light reflected back from both arms is then directed through the fiber coupler to a reflective collimator and projected onto a 300 l/mm transmission grating and the dispersed light is then received by the FLIR SC7600 camera which records the interference fringes. The FLIR SC7600 camera with its broadband lens is sensitive to the wavelength range between 1.5 and 5 microns. A short pass filter is used to block out the unwanted thermal emission beyond 2.6 microns. A minimum region of interest comprised of 4 rows of 640 pixels can be selected for the collection of the spectrum at a speed of 2500 Hz. The SC source was operated at a repetition rate of 50 kHz.

2.3 Characteristics of the 2 micron FDOCT

The source spectrum spans over the wavelength range from ~1800-2250 nm on the detector of the spectrometer, giving an axial resolution of ~9 microns in air (with Hann windowing applied) or 6 microns in paint assuming a refractive index of 1.5 (Fig. 2). The transverse resolution is measured to be 17 microns.

To estimate the sensitivity of the OCT system, the reference and sample arms were adjusted to have equal power (~2 mW incident light on the sample) for optimum visibility. The peak signal was at 106 dB for a thick glass slide at the focus of the objective and the noise floor of 33 dB was estimated with the sample removed. Since glass reflects 4% at normal incidence, this means the noise floor is 87 dB below a 100% reflective sample. The noise level with no sample under the objective can be reduced to 10 dB with 400-500 averages as shown in Fig. 3a, giving an ultimate sensitivity of 110 dB. The noise reduction as a function of averages follows the shot noise behavior. Similarly, Fig. 3b shows that the signal-to-noise increases with the number of pulses used for imaging as expected from shot noise behavior. The system is therefore shot noise dominated.

The spectral resolution of the spectrometer limits the sensitivity at large depth since the fringe rate increases with large optical path length difference and therefore the finite spectral resolution will eventually wash-out the fringes. In addition, the objective lens will also limit the sensitivity to a depth range corresponding to its depth of focus. Figure 4 shows the signal to noise ratio as a function of depth measured by moving the sample away from the objective lens. The initial increase in sensitivity with depth is due to both the position of focus of the objective (at 200 microns in depth) and the general decrease in noise as a function of depth.

It is important to note that most of the paint layers of interest have thicknesses up to 100-200 microns. The system is more than adequate for this purpose. The point of long wavelength OCT is to improve the penetration depth in materials that are highly opaque at shorter wavelength due to either high scattering or high absorption properties.

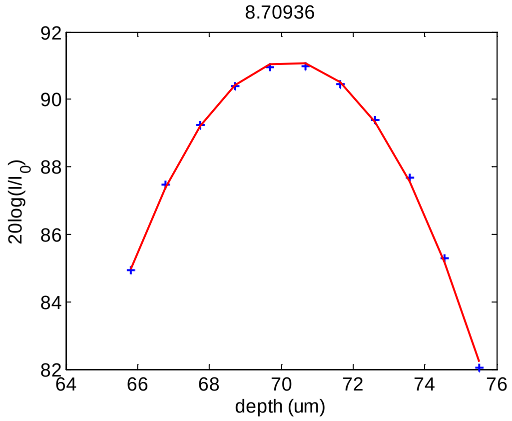


Figure 2. The OCT axial PSF measured with a glass microscope slide (blue crosses) fitted by a Gaussian (red curve) of FWHM 8.7 microns.

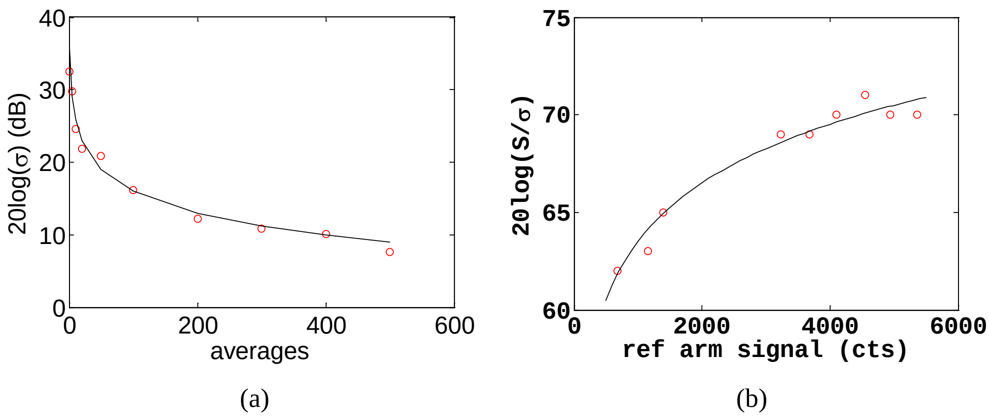


Figure 3. a) Noise (in dB scale) estimated between 190-270 μm in depth (using the signal from the reference arm alone) as a function of the number of averages. b) Signal to noise ratio as a function of the reference arm signal (proportional to the number of pulses) for a glass microscope slide. The black curves represents the expected shot noise behavior (Poison noise).

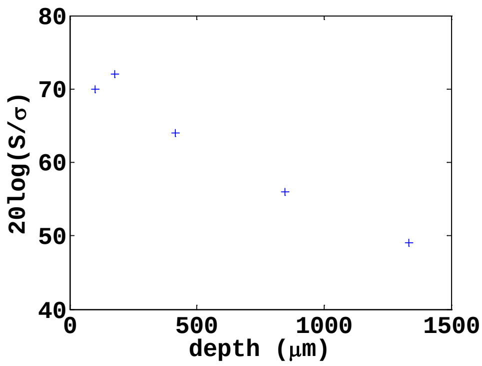
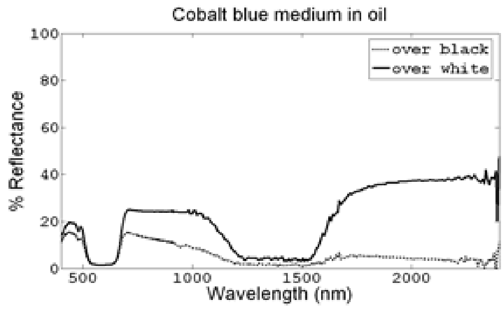


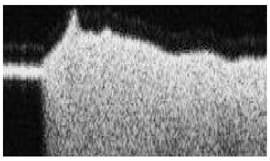
Figure 4. Signal to noise ratio as a function of depth including the effect of spectral resolution and depth of focus of the objective lens; the objective is focused at 200 μm in depth.

3. APPLICATIONS

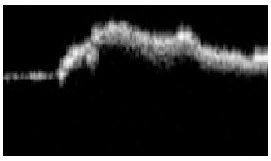
(a)



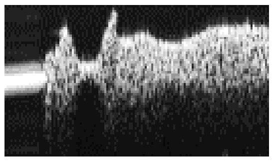
(b)



(c)



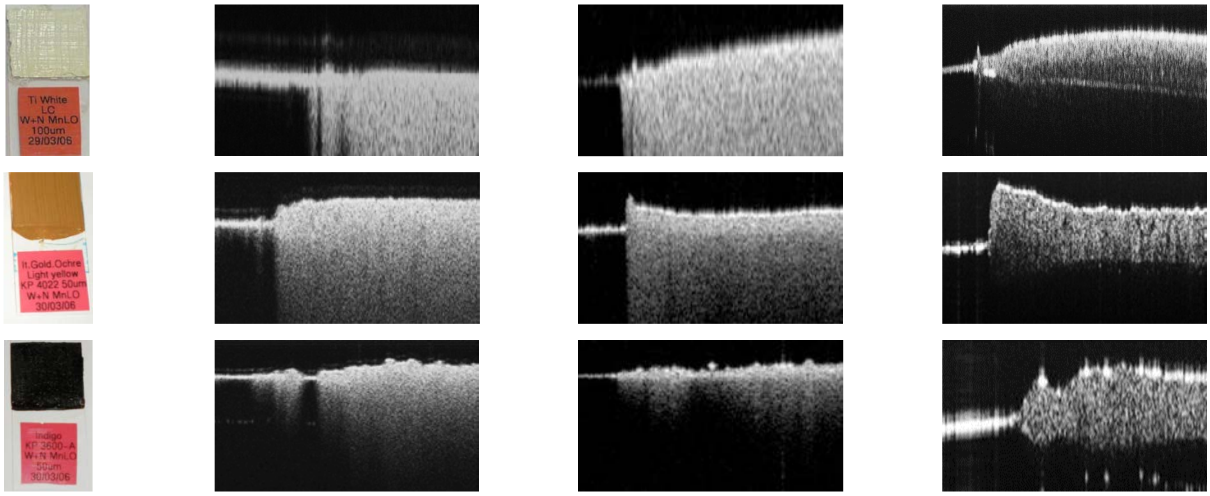
(d)



(e)

Figure 5. a) A paint sample of Cobalt blue pigment in oil painted on a glass microscope slide; b) reflectance spectra of the paint sample measured over a white background and a black background showing the paint to be moderately high in scattering coefficient at 930 nm, highly absorbing at 1300 nm and relatively transparent at 2000 nm; Cross-section images of the paint on glass taken with a 930 nm OCT (c) , a 1300nm OCT (d) and the 1960 nm OCT (e).

To verify the improvements in depth of penetration achieved using the 2 micron FDOCT, a survey of paint samples consisting of historical artists' pigments was conducted. Figure 5 shows an example of a paint sample (cobalt blue in linseed oil) that is opaque because it is moderately high scattering around 930 nm and highly absorbing around 1300 nm. The paint is transparent at 1960 nm and the paint/glass interface can be clearly observed in the 1960 nm OCT image. Similarly, Fig. 6 shows that multiple scattering masks the paint layers in titanium white (TiO_2), Italian golden ochre and indigo at 930 and 1300 nm but at 1960nmsingle scattering dominates and the paint layers are transparent.



(a) (b) (c) (d)

Figure 6. a) A paint sample of titanium white, yellow ochre and indigo in oil painted on a glass microscope slide; b) Cross-section images of the paint on glass taken with a 930 nm OCT , c) a 1300nm OCT and d) the 1960 nm OCT.

4. CONCLUSIONS

A high resolution Fourier domain OCT at 1960 nm is demonstrated to have an axial resolution of ~9 μm in air (or ~ 6 μm in paint) using an in-house built supercontinuum source with >200 nm bandwidth. The OCT operates at a speed of 2.5 kHz per A-Scan (depth profile). Typical paint samples used in historical paintings were imaged and the OCT penetration depth in these materials was found to be greatly improved. Long wavelength OCT can also be used in other highly scattering materials that have low water content.

ACKNOWLEDGMENTS

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