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Beyond Fourier Transform Imaging: Subsurface imaging of Agate with Complex Leader-Follower Full-Field OCT

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ABSTRACT

This study explores the application of Complex Leader-Follower Swept-Source Optical Coherence Tomography (CLF-FF-SS-OCT) for the internal structure inspection of an Agate sample, a microcrystalline quartz with characteristic internal impurities and multilayered structure. The source utilized in this setup is a commercial tunable laser with a tuning range of 120 nm centered at 1580 nm, which ensures a high penetration depth in SiO₂-based materials such as quartz. The study compares image reconstruction via Fast Fourier Transform (FFT) and CLF protocols. The system successfully revealed the internal structure of the stone with a penetration depth of more than 1 mm.

Keywords: Swept source, Optical Coherence Tomography, Full-field, Complex Leader-Follower Interferometry, Agate.

INTRODUCTION

According to the International Mineralogical Association, more than 5000 minerals are known today [1]. Their identification and study traditionally involves imaging techniques, such as assessing surface lustre and colour as well as destructive methodologies. These include testing cleavage and fracture, measuring hardness, performing streak tests, or conducting acid reactions. In these examinations, the mineral under study is typically broken, scratched, or powdered. These invasive diagnostic methods are not always the best choice, especially in cases where the sample is rare, valuable or part of a fragile and irreplaceable context. This is particularly important in archaeological studies, jewellery or for samples returned from space missions. For such scenarios non-destructive testing techniques are essential [2].

The most common techniques of non-destructive testing in geology are Raman spectroscopy, X-ray tomography and scanning electron microscopy (SEM) [3, 4, 5]. These techniques allow a precise mineral identification and rock characterisation without creating any damage to the studied sample. Another less common but promising method is Optical Coherence Tomography (OCT). This technology is capable of non-invasively probing and visualizing the sub-surface microstructure of geological materials with micron-scale resolution. Unlike techniques requiring vacuum environments or are limited to surface-only data, OCT enables visualization of cross sectional features like mineral grains and pores under the surface of minerals and rocks. OCT has already demonstrated its potential in the non-destructive analysis of cultural heritage objects and geological materials [6]. For instance, it was successfully employed in the examination and identification of jade material [7], in the sub-surface investigation of ancient faience objects [8] and to characterise the microporosity and grain boundaries in sedimentary rocks [9].

Agate stones are a variety of chalcedony, a microcrystalline form of silica (SiO₂), characterised by its micro-banded structure formed over millions of years, serving as a geological record of hydrothermal processes. Despite their prevalence in jewellery and industry, the internal characterisation of agate presents a significant health challenge due to the toxicity of its dust [10]. Using OCT to study these stones not only eliminates the hazards but also allows for the preservation of the sample.

This study aims to identify the internal structure of naturally polished agate stones via Fast Fourier Transform (FFT) and Complex-Leader-Follower Interferometry (CLFI) in a full-field (FF) – swept source (SS)-OCT system operating in the 1550 nm band. This spectral range is particularly advantageous due to the stone composition and morphology, allowing for a deeper sub-surface visualisation. By combining this specialized spectral range with advanced computational analysis, this work provides a non-destructive method for high-resolution morphological assessment of geological specimens.

METHODOLOGY AND SETUP

The FF-SS-OCT is based on a Michelson interferometer configuration (Fig. 1). The light source is a tunable laser (Toptica DLC Pro, 1510-1630 nm) delivering 15 mW. This specific model is designed for high spectral purity and narrow linewidth rather than high-speed swept-source operation. Consequently, a step-and-capture protocol was adopted to ensure stable, mode-hop-free tuning at each wavelength step. The collimated beam (1.21 mm waist diameter) passes through lens L1 ($f_1 = 40$ mm) towards a 50/50 beam splitter (BS). The light is split into a reference arm and a sample arm, where identical lenses L2 and L3 ($f_2 = f_3 = 40$ mm) provide flood illumination to the reference mirror (RM) and the agate stone (OBJ), respectively. The reflected light is recombined in the BS and passes through L4 ($f_4 = 150$ mm) before arriving at the NIR camera. A neutral density filter (NDF) is placed in the reference arm to balance the light intensity between the two arms.

The interference patterns were recorded using an InGaAs camera (*Bobcat 320 TEO & WL series*, 320x256 pixels). Frames were acquired at discrete 0.2 nm wavelength increments for the full bandwidth of the source; this specific step size was chosen to balance axial range and acquisition time.

Volumetric reconstruction was performed using two methodologies: a standard Fast Fourier Transform for a rapid preliminary verification, and a Complex Leader Follower Interferometry (CLFI) algorithm. As described in the foundational work of Rivet et al. [11], the CLFI method has two phases: Leader, which is the calibration stage, where the source non-linearity and system dispersion functions ($g(k)$ and $h(k)$, respectively) are determined, by locating a mirror at different optical path difference in the object arm, to create an arbitrary number of masks; and Follower, which is the imaging stage, where the sample data set is collected and then correlated with the masks created in the calibration stage to reconstruct the sample volume.

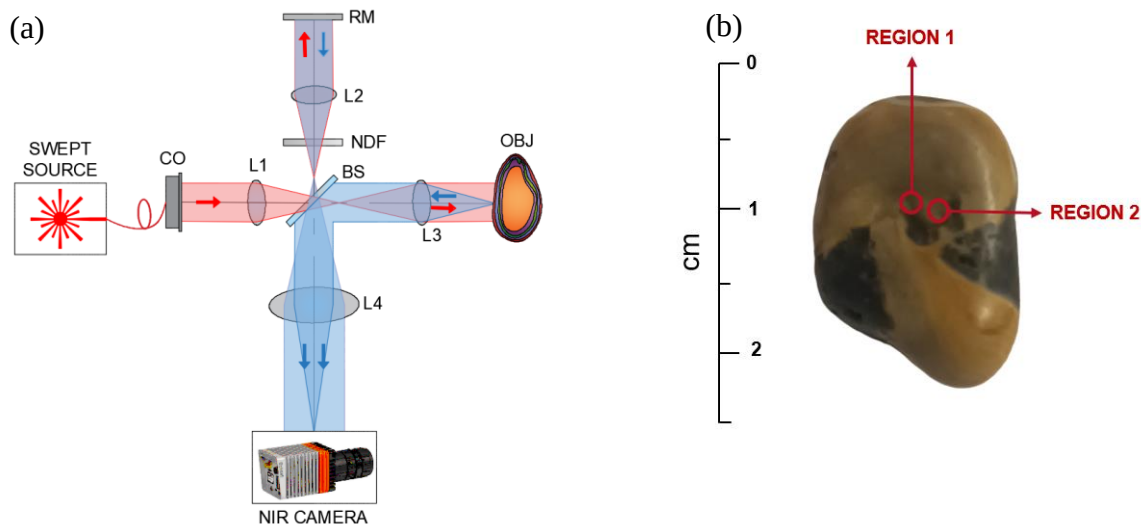


Figure 1 (a) Schematic representation of a SS-FF-OCT system. CO: collimator, BS: beam splitter, L1=L2=L3: plano-convex lens ($f = 40$ mm). L4: plano-convex lens ($f = 150$ mm), NDF: neutral density filter, OBJ: object under study, RM: reference mirror. (b) Sample of agate stone with scale and two regions of study.

RESULTS

The internal morphology of the agate sample was investigated in two regions, as indicated in Figure 1 (b). The calibration was implemented with 250 masks over a 3 mm range, yielding to an axial sampling interval of 12 μm .

Figure 2 presents the reconstruction of Region 1, where the beam focus was set on the stone's surface. The *en face* view of Fig. 2 (a) serves as spatial reference to indicate the coordinates of the cross-sectional B-scans (red lines). In the XZ (d)-(e) and YZ (b)-(c), the surface is clearly resolved by both reconstruction methods, where CLFI algorithm (Fig. 2b, d) produces a sharper surface profile than FFT (Fig. 2c,e). In this area no further layers have been found.

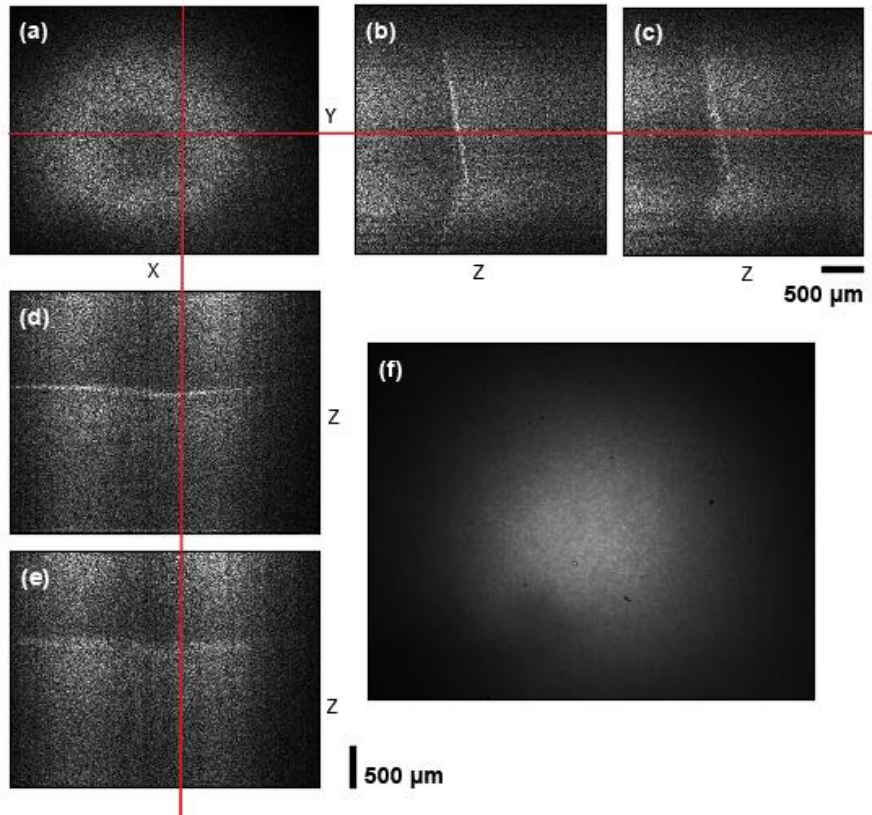


Figure 2. Region 1: (a) *En face*, (b) CLFI B-scan (YZ plane), (c) FFT B-scan (YZ plane), (d) CLFI B-scan (XZ plane), (e) FFT B-scan (XZ plane), (f) Camera image taken with a broadband source.

In Figure 3, the focal plane was shifted toward the interior of the stone to enhance subsurface visualisation of Region 2. The resulting B-scans, both for the YZ plane (Fig. 3(b)-(c)) and the XZ plane (Fig. 3(d)-(e)) reveal a complex arrangement of internal bands, with approximately five layers visible to the naked eye.

The internal structures exhibit notable variations in width and morphology. While the upper interfaces remain relatively flat, the deeper layers in YZ plane show a slight change in their slope, whereas in the XZ plane they exhibit a curved shape. Figures 3 (f) and 3 (g) show the A-scans extracted from the the XZ and YZ coordinates of these B-scans to provide a more detailed analysis of the data. In these profiles the distances between the main peaks vary between 4 and 26 pixels. Considering the axial sampling and a refractive index of the sample $n \approx 1.536$, these intervals correspond to physical thicknesses of 31 to 204 μm .

In these A-scans, the signal attenuates in depth. Specifically, in Fig. 3 (g), both FFT (red line) and CLFI reconstruction (black line) drop to around 50% around pixel 80, this demonstrates that the system effectively resolves subsurface structural information beyond 1 mm depth. Particularly, Fig. 3 (f) shows sharper peaks for CLF than for FFT, proving the superiority of OCT in terms of depth resolution.

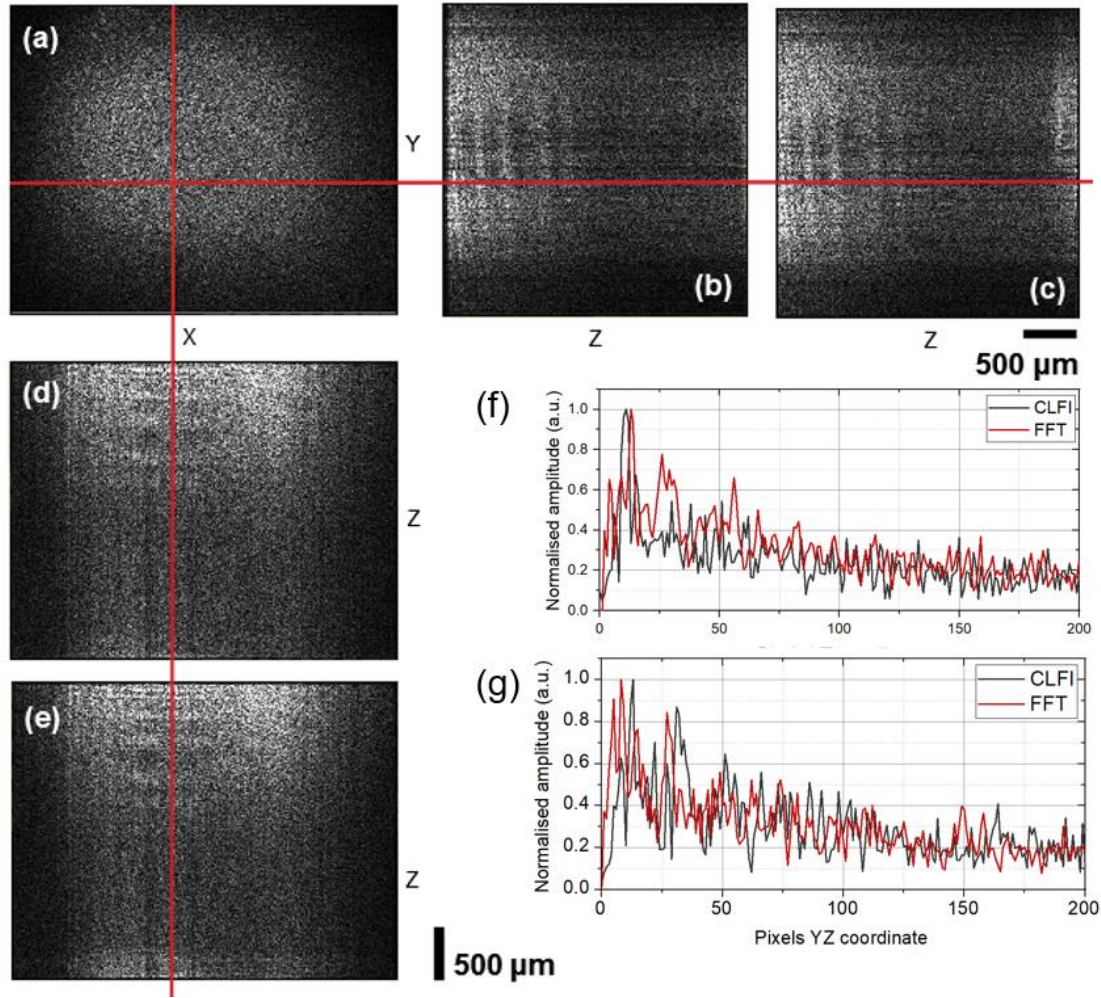


Figure 3. Region 2: (a) *En face*, (b) CLFI B-scan (YZ plane), (c) FFT B-scan (YZ plane), (d) CLFI B-scan (XZ plane), (e) FFT B-scan (XZ plane), (f) A-Scan of XZ coordinate for CLFI processing method (black) and FFT method (red). (g) A-Scan of YZ coordinate for CLFI processing method (black) and FFT method (red).

CONCLUSION

This work demonstrates the effectiveness of a 1550 nm FF-SS-OCT system combined with Complex Leader-Follower Interferometry (CLFI) for the non-destructive internal inspection of agate stones. The use of a specialized NIR spectral range allowed for significant penetration into the SiO₂ matrix, reaching an optical depth beyond 1 mm. The comparative analysis proves that the CLFI algorithm provides high resolution profiles as good as the FFT. The system successfully identified a complex multilayered structure with thicknesses as fine as 31 μm, proving to be a valuable tool for geological characterization and the preservation of valuable archaeological or mineralogical specimens without the risks associated with invasive testing.

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