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Computational Three-dimensional Imaging with Near Infrared Synchrotron Beam Using Fresnel Zone Apertures Fabricated on Barium Fluoride Windows Using Femtosecond Laser Ablation

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ABSTRACT

The near infrared (NIR) part of the infrared synchrotron beam is usually discarded to improve the signal to noise ratio of spectral imaging at the Australian Synchrotron. In this study, NIR synchrotron beam has been extracted and used for three-dimensional (3D) imaging. A Fresnel zone aperture (FZA) was fabricated on barium fluoride windows using femtosecond ablation. The 3D point spread functions (PSFs) were recorded using the FZA mounted between the pinhole and the image sensor. An object is then placed within the boundaries of the PSF library and an object intensity distribution was recorded. Computational reconstruction methods were applied to reconstruct the object information.
Keywords: Synchrotron; near infrared beam; holography; incoherent optics; chemical imaging; computational imaging; 3D imaging.

1. INTRODUCTION

Fourier transform infrared (FTIR) spectroscopy is a widely used technique to understand the chemical composition of biochemical samples [1]. In many studies, obtaining the absorption spectrum at a point is sufficient. However, when there is a spatial variation of the chemical composition, it is necessary to record the spectrum at all the points. In such cases, the data structure can be organized in two ways: spectral variation with respect to location and 2D images with respect to wavelength. Most of the commercial FTIR systems cannot record spectral images and the IR beam is weak. The researches that require the above two can be carried out at the IR beamline of the Australian Synchrotron [2]. The IR microscope (IRM) at the Australian Synchrotron is equipped with two types of IR detectors namely single pixel mercury-cadmium-telluride (MCT) detector and a focal plane array (FPA) detector with 64×64 pixels both cooled by liquid nitrogen. In the case of small objects, a high temporal resolution can be obtained using the FPA detector at the expense of a low imaging resolution (64×64). But for large objects and when a high imaging resolution is needed, the single pixel MCT detector is used with a pixel-by-pixel scanning of the sample stage. But in this case, the high imaging resolution is obtained at the expense of low temporal resolution. In the recent years, there have been many advanced studies carried out at the IRM of the Australian synchrotron [3-6]. In [5,6], novel computational imaging techniques have been implemented at the IRM system to achieve 3D imaging of samples from a single camera shot. However, the above studies were carried out using the FPA resulting in a low imaging resolution. The IR beam extracted from the Synchrotron has a broad spectrum. But, the presence of near IR wavelengths contributed to the increase in noise during spectral imaging and therefore they are filtered out before interaction with the sample. While the detectors available in mid-IR region have low a resolution, many accessible commercial cameras are sensitive to NIR wavelengths. In this study, the usually discarded synchrotron NIR beam was extracted and used for computational imaging using a NIR sensitive camera.

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2. METHODS

The optical configuration of the IRM system at the Australian Synchrotron and the newly attached synchrotron NIR computational imaging module is shown in Figure 1. The synchrotron IR beam as seen in Figure 1 has an unusual fork-shaped beam profile which is tightly focused using Cassegrain or Schwarzschild objective lenses to a point and used for imaging. The low wavelength filter used in the system was removed and it was utilized for computational imaging using a Fresnel zone plate (FZP). The indirect imaging process consists of three steps. In the first step, the point spread function (PSF) was recorded using the FZP and an object O was placed at the same location as the PSF and the object intensity I_O given as O⊗PSF was recorded in the next step, where '⊗' is a 2D convolutional operator. The image of the object was reconstructed by processing I_O with the PSF which is achieved using a non-linear reconstruction (NLR) given as $I_R = \mathcal{F}^{-1}\left\{\left|\widetilde{PSF}\right|^{\alpha}\exp\left[j\cdot\arg\left(\widetilde{PSF}\right)\right]\left|\tilde{I}_O\right|^{\beta}\exp[-j\cdot\arg(\tilde{I}_O)]\right\}$, where α and β are tuned until an optimal reconstruction defined by the lowest entropy is obtained, where $\mathcal{F}^{-1}$ is the inverse Fourier transform and $\tilde{I}$ is the Fourier transform of I [7].

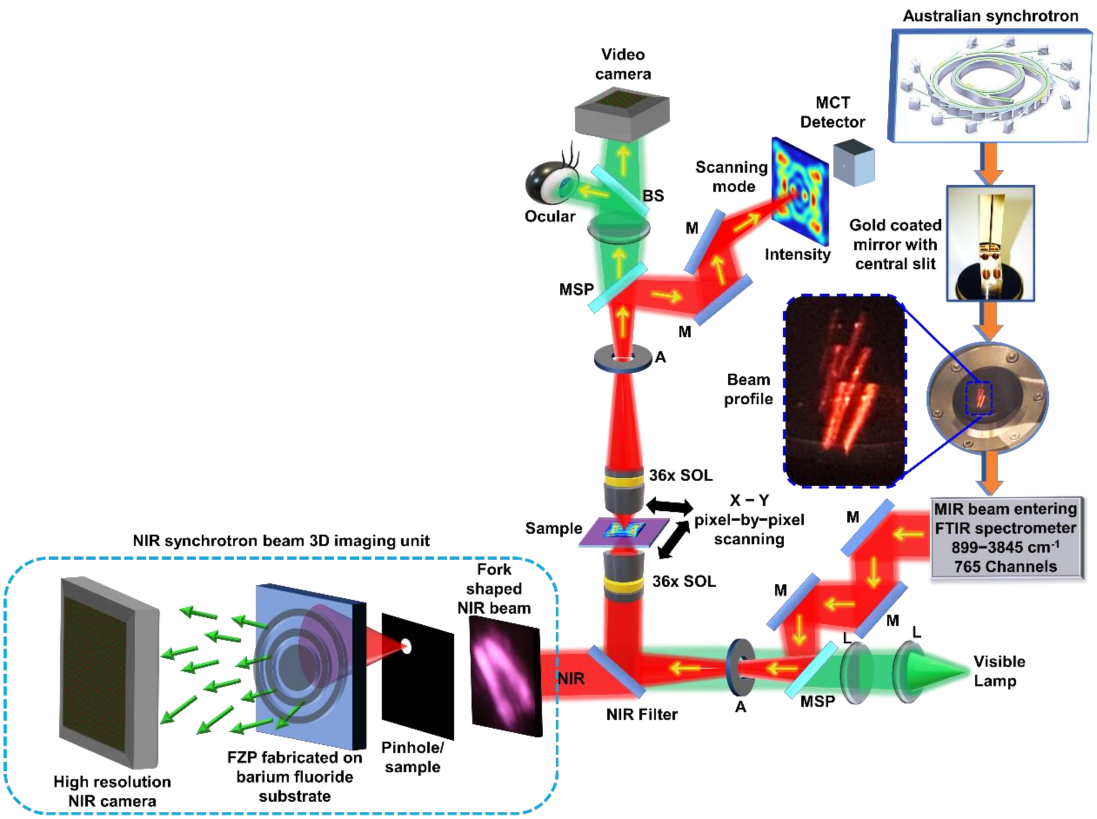

Figure 1. Schematic of the Australian synchrotron's IRM system and the newly attached synchrotron NIR computational imaging module shown within dotted line. BS – beam splitter, M – mirror, L – lens, MSP – motorized sliding plate, A – aperture, MIR – mid infrared. The synchrotron-IR beam is extracted using the gold coated mirror with central slit, and enters the FTIR spectrometer, which is subsequently coupled into the IR/VISIBLE transmission microscope.

An FZP with a diameter of 20 mm was fabricated on barium fluoride substrate using femtosecond ablation using Pharos laser (Light Conversion, Lithuania) operating at 200 kHz repetition rate, λ = 1030 nm wavelength, 2.5W average power, 230 fs pulse duration and 5× magnification, NA = 0.14 numerical aperture Mitutoyo Plan Apo NIR infinity corrected objective. The image of the fabricated device is shown in Figure 2(a). The experimental set up built in the IRM system of the Australian Synchrotron is shown in Figure 2(b). A pinhole with a diameter of 100 µm was used for the study. An NIR sensitive camera was used for recording the diffraction patterns. The images of the recorded PSFs and object intensity patterns obtained for a cross shaped object for three distances namely 60 mm, 120 mm and 190 mm are shown in Figure 3. The reconstruction results from NLR are shown in Figure 3. The fork shaped intensity distribution caused a non-uniform intensity distribution on the object plane resulting in a distorted reconstruction.

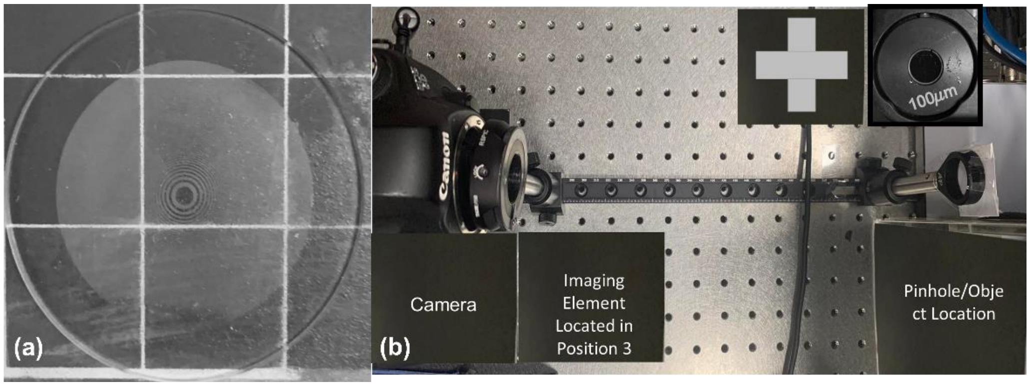

Figure 2 (a) Image of the FZP fabricated on barium fluoride substrate using femtosecond ablation. (b) Photograph of the experimental set up built in the IRM system.

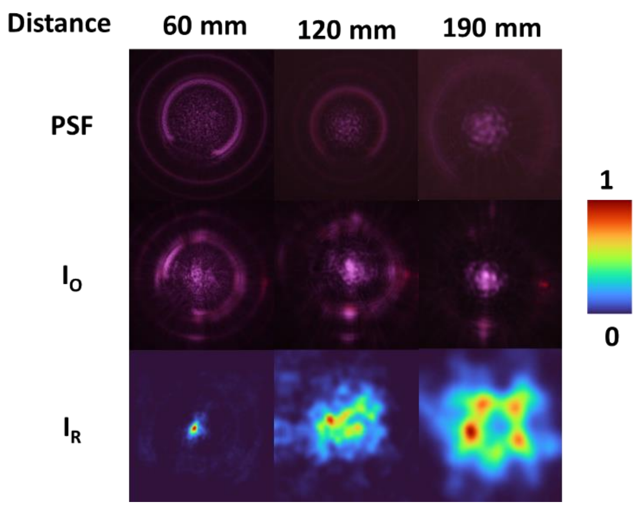

Figure 3 Images of PSFs, I_Os and reconstructions I_Rs for distances 60 mm, 120 mm and 190 mm.

3. CONCLUSION AND FUTURE PERSPECTIVES

A single shot, 3D imaging technique was attempted using the NIR synchrotron beam at the Australian Synchrotron in a similar fashion as phase imaging [8-10]. However, the peculiar beam shape affected the imaging process. Further studies are needed in order to optimize the experiment and achieve single shot 3D imaging using the NIR synchrotron beam.

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