A review and analysis of Fourier transform spectroscopy in the soft X-ray region: advancing historical designs with modern technology

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ABSTRACT

We are developing a Fourier transform spectrometer to enable fast high-resolution spectroscopy (>100,000 at rates close to 1 Hz) in the soft X-ray regime. We review three existing approaches to split and delay the beam that have been proposed and discuss how they are suitable for soft x-ray applications. We present preliminary results in the visible range for an approach based on a polka-dot like beamsplitter to assess requirements in terms of instrument stability and performance. We find that with appropriate metrology, this approach could be used for soft x-ray applications.

1. INTRODUCTION

One of the most effective techniques for investigating phenomena at extremely small scales is spectroscopy. Soft X-rays, with wavelengths below about 10 nanometers (corresponding to photon energies of roughly 100 eV), carry sufficient energy to excite core-level electrons from atoms. These core-level transitions occur at unique energies for each element, producing sharp absorption edges that serve as elemental fingerprints. Moreover, the precise energy and shape of these absorption features are influenced by the local chemical environment, including bonding configurations, oxidation states, and electronic structure.

Grating-based spectrometers have a resolution limited by the periodicity and density of their gratings. Fabricating highly periodic, nanoscale gratings presents a substantial technical bottleneck. Even small deviations in spacing or alignment at this scale significantly reduce a grating spectrometer's ability to resolve fine spectral features. In addition, high-resolution grating spectrometers in the soft X-ray regime tend to have low diffraction efficiencies (generally much less than 10%[1]) and often require long detector arm lengths[2]—in excess of 10 m —which can create significant integration challenges in laboratory or synchrotron facilities.

Fourier transform spectrometers (FTSs) are widely used in the visible and infrared regimes due to their high resolution, broadband operation, high light efficiency, and compact form factor. They are also employed at synchrotron light sources for techniques such as nano-FTIR.[3] However, in the soft X-ray regime, the development of FTSs has been relatively slow due to three main technical challenges.

First, there is a lack of suitable beamsplitters: most beamsplitters operate in transmission, but absorption lengths in the soft X-ray regime are on the order of micrometers, making this approach impractical. Second, the required optical quality is extremely high, with tolerances often at the nanometer scale. Third, the scanning mechanism and mechanical stability of the apparatus must be maintained to within a fraction of the wavelength, necessitating very precise feedback and a tightly controlled environment.

In this paper, we review various Fourier transform spectrometer designs and present experiments in the visible-light regime to better understand the implementation details and technical challenges relevant to soft X-ray measurements.

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Advances in X-Ray/EUV Sources, Optics, and Components XX, edited by Ali M. Khounsary, Hidekazu Mimura, Proc. of SPIE Vol. 13620, 136200Q · 2025 Published by SPIE
0277-786X · doi: 10.1117/12.3064137

2. FOURIER TRANSFORM SPECTROSCOPY

Fourier Transform Spectroscopy[4] works by splitting an incoming beam into two paths, introducing a controllable optical path difference (OPD) between them, and then recombining the beams to produce interference between the reference arm and the delayed arm (Figure 1). By varying the delay and measuring the resulting interference pattern on a detector, an interferogram is recorded. Applying a Fourier transform to this interferogram directly yields the spectral distribution of the input beam.

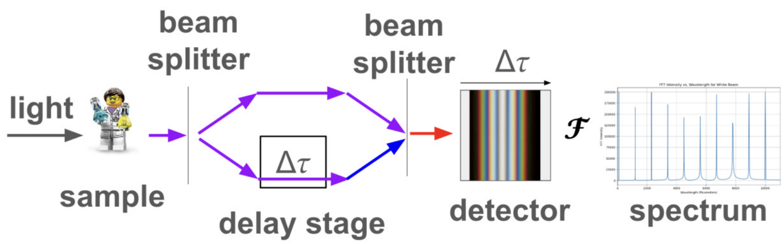

Figure 1. Principle of operation of a Fourier Transform interferometer

2.1 Amplitude division

The archetype of the Fourier Transform Spectrometer is the Michelson interferometer (Figure 2.) While this configuration is not available for soft x-ray application due to the lack of transmission beamsplitters, it is conceptually interesting as it provides insights on implementation challenges, in terms of step size, sensitivity to vibrations, and noise.

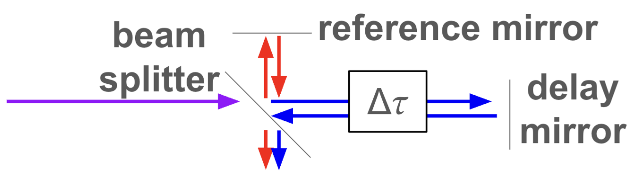

Figure 2. Amplitude division interferometer (Michelson-type)

We built a setup (Figure 3, left) using a 50:50 beamsplitter, a precision linear stage (Physik Instrumente P-629.1CD, 1.3 mm travel range with 3 nm resolution) and a CMOS camera (Basler a2A1920-51gmBAS), and controlled the experiment with a custom python script.

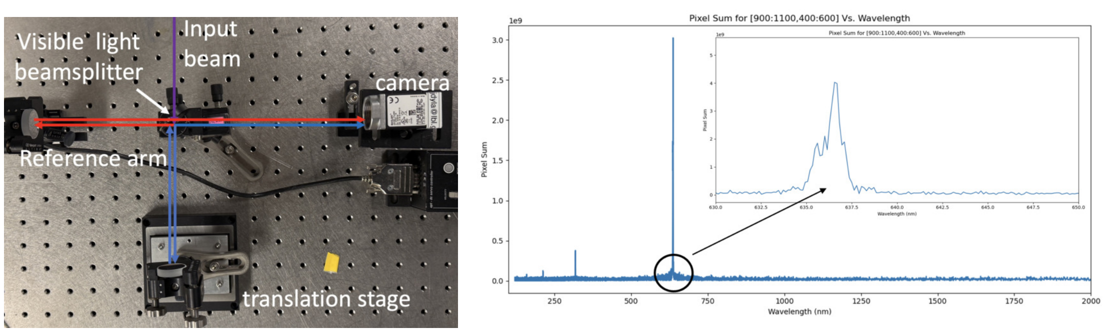

Figure 3. Amplitude division Fourier Transform interferometer (Michelson-type). Left: picture of the setup; Right: Spectrum of the source (a HeNe laser) after taking the Fourier transform of the interferogram (inset: detail around 630 nm)

We first used a Helium Neon laser (single wavelength at 632.8 nm) and we collected images for 20 nm translation stage steps over 1 mm, extracted a 1D interferogram by the intensity from a central region of the image of 200 × 200 px and we computed the spectrogram by taking the Fourier transform of the interferogram (Figure 3, right.) The system has a theoretical resolution near the central wavelength of about 2,000 owing to the scanning range, although we observe a 3 nm broad peak near the laser line that is likely due to position jitter and noise in the measurements. The spectrum shows some aliasing or harmonics due to jitter at half the wavelength due.

We used a collimated white LED lamp to determine the position of equal path length between the two arms and collected data over 100 μm. The interferogram (Figure 4, left) shows a relatively limited support (20 μm) indicative of the short temporal coherence of the source, and some echo-like features that are caused by the finite thickness of the beamsplitter.

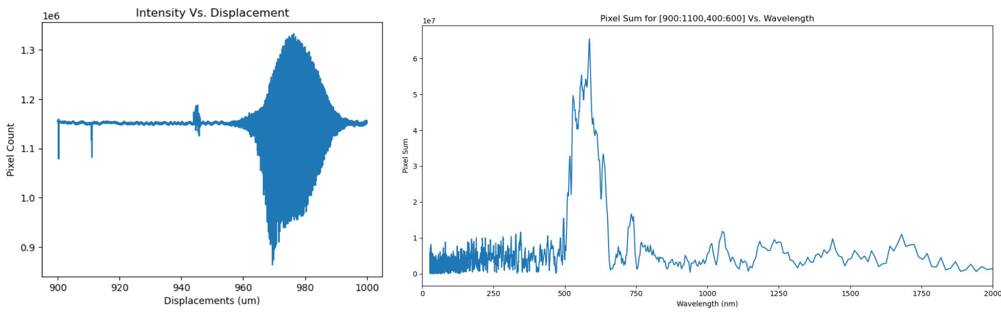

Figure 4. White light interference in the visible range with an amplitude division Fourier Transform Spectrometer. Left: Interferogram; Right: Spectrogram

The spectrogram (Figure 4, right) shows the relatively wide spectrum of the source, together with features caused by noise and jitter and the absence of signal filtering.

2.2 Wavefront division

Fourier transform spectrometers based on wavefront division division avoid beamsplitters by splitting a spatially coherent beam into two upon reflection on two different mirrors, and introducing a small tilt between the mirrors so that the beams overlap at a downstream plane and produce interference. (Figure 5.) By varying the relative longitudinal positions of the two mirrors, we can collect an interferogram. The mirrors are generally roof mirrors retroreflectors so that there is no beam relative walk-off when the scanning mirror is translated.

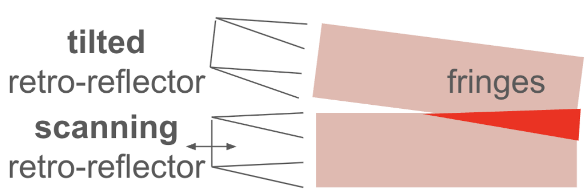

Figure 5. Wavefront division interferometer

They have been demonstrated in the VUV regime with 1,000,000 resolving power down to 40 nm wavelength (corresponding to 30 eV photon energy.[5]) Due to the low reflectivity of mirrors above 30 eV, the configuration using retroreflectors is not suitable for use in the soft x-ray regime, though variants using grazing reflection can be devised.[6]

We built a setup working in the visible range using roof mirrors (Figure 6.) For the source, we used a HeNe laser and we spatially filtered it with a microscope objective and a 5μm pinhole, and collimated it using a lens. The other components are similar to the previous experiment with amplitude division.

We collected data by acquiring camera frames while varying the delay line by 20 nm over a 1 mm range (Figure 7.) The 1D interferogram was built by extracting a single pixel at the center of the camera. The spectrum is obtained by taking the Fourier transform of the interferogram.

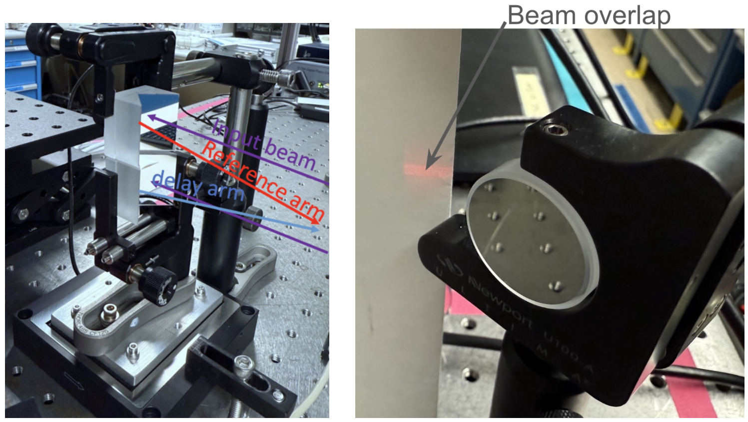

Figure 6. Wavefront division Fourier Transform Interferometer in the visible range. Left: picture of the double roof-mirror retroflector with a relative angle between them. Right: picture of the two beam overlapping after reflection

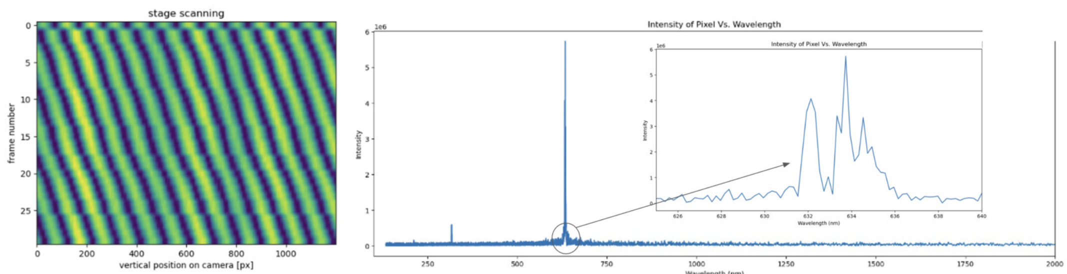

Figure 7. Experiment with a wavefront division Fourier Transform Interferometer in the visible range. Left: synthetic data taken by extracting one line of the each acquired frame for each linear stage delay. Right: spectrogram of a He-Ne laser

Since the interference only occur in one dimension, we can extract a single line from each frame for each delay, we can use the redundancy in the date estimate of the jitter (Figure 7, left) and potentially correct it in post-processing.

2.3 Hybrid beamsplitter and FTXR

The concept of semi-transmissive membranes (Figure 8, left), where a reflective thin membrane is perforated to allow half the beam intensity to pass through (functionally similar to polka-dot beamsplitters), can be used in the soft x-ray regime to split the beam[7] and build a Mach-Zehnder-type Fourier Transform spectrometer.[8] However, strict flatness requirements on the membrane (so as not to introduce wavefront errors that would muddle the interferences), and complex opto-mechanics have long limited progress.

Recent nanofabrication advances have enabled patterned membranes made on low-stress silicon nitride (Figure 8, right), with sub-nm figure error over several millimeters and can operate at grazing angle. They act as wavefront "mixers": they functionally act as amplitude division beamsplitters but rely on wavefront division through diffraction effects (we term them "hybrid")

Our project builds on the Fourier Transform X-Ray in Reflection (FTXR) interferometer originally developed at NASA JPL[9] (Figure 9, right). In this setup, two beamsplitters are on a fixed frame to split and recombine the beam. Both arms are at 10° relative to the central axis, and a set of mirror pairs on a movable platform allows to vary the delay between the two arms (Figure 9, left.) The movable platform is on flexure to increase stiffness and stability, and the whole assembly is made out of invar to reduce sensitivity to thermal drift.

We performed the alignment of the device using a laser diode The movable platform was translated using a picomotor (Newport, < 30nm minimum incremental motion) and we scanned the stage using single steps while monitoring the position using a fiber laser interferometer (SmarAct Picoscale.) For each position we collected a frame on a CMOS camera, and we used the central pixel to form the 1D interferogram. Because of the

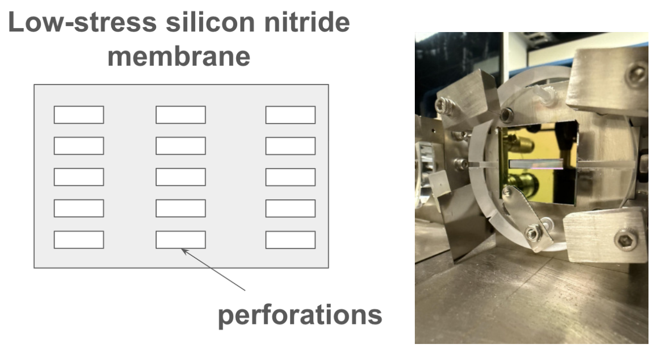

Figure 8. Wavefront mixer for x-ray beamsplitting. Wavefront mixers are polka-dot-style beamsplitters operating in grazing incidence, with perforations on a low-stress silicon nitride membrane

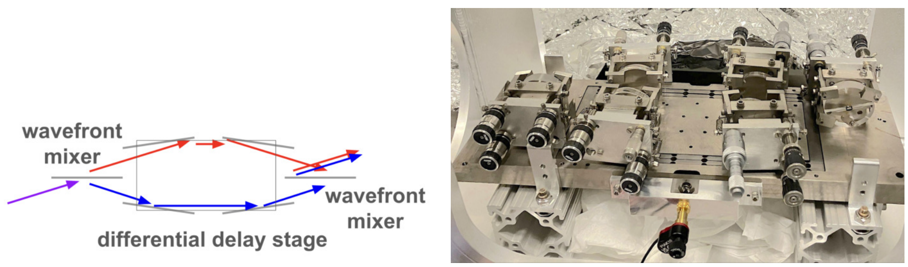

Figure 9. Fourier Transform X-Ray in reflection (FTXR). Left: principle of operation; Right: picture of the JPL FTXR.

vibrations in out experimental environment, the interferogram shows non-monotonic data collection (Figure 10, left) By performing an ensemble average of ten points, we smoothed out the jitter and were able to get an initial spectrogram (Figure 10, right.)

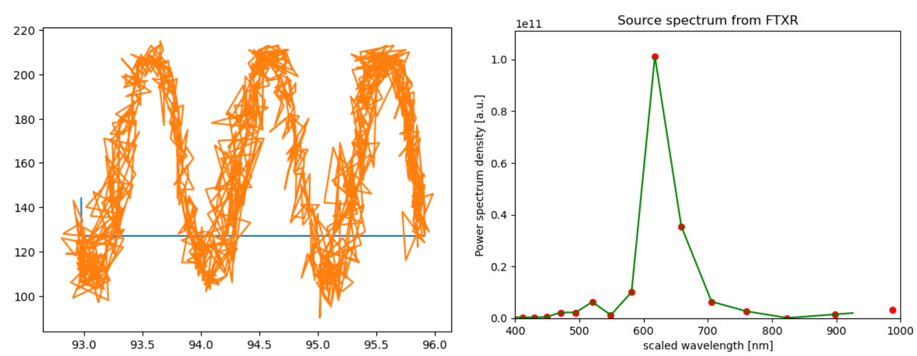

Figure 10. Measurements with the Fourier Transform X-ray Interferometer in the visible range (source: red diode.) Left: data acquired with a laser interferometer (the constellation of points Right: Detail of the resulting spectrogram showing

We are currently assessing the stability of the stage, in terms of vibration and drift (Figure 10)

3. CONCLUSION AND FUTURE DIRECTIONS

Our work shows that piezo motor–driven stages could potentially achieve nanometer-scale stability, providing the precision required for high-resolution Fourier transform spectroscopy in the soft X-ray range. Simulations and visible-light experiments have validated the instrument design and control methods. Future work will focus on testing the apparatus in the soft X-ray regime. To mitigate vibrations in the current noisy environment, we plan to enhance damping via specialized mounts and real-time error correction. We also plan on exploring wavefront division at grazing incidence, to take advantage of fully coherent beams provided by 4th generation synchrotron light source.

ACKNOWLEDGMENTS

This work was supported by the Director, Office of Science, Office of Basic Energy Sciences of the U.S. Department of Energy, under Contract No. DE-AC02-05CH11231.

Andrew Lindburg and Antoine Islegen-Wojdyla are supported by an Early Career Award in the X-ray Instrumentation Program, in the Science User Facility Division of the Office of Basic Energy Sciences of the U.S. Department of Energy, under Contract No. DE-AC02-05CH11231.

REFERENCES

[1] Voronov, D. L., Park, S., Gullikson, E. M., Salmassi, F., and Padmore, H. A., "6000 lines/mm blazed grating for a high-resolution x-ray spectrometer," *Optics Express* **30**, 28783 (8 2022).

[2] Jarrige, I., Bisogni, V., Zhu, Y., Leonhardt, W., and Dvorak, J., "Paving the way to ultra-high-resolution resonant inelastic x-ray scattering with the six beamline at nsls-ii," *Synchrotron Radiation News* **31**, 7–13 (3 2018).

[3] Bechtel, H. A., Muller, E. A., Olmon, R. L., Martin, M. C., and Raschke, M. B., "Ultrabroadband infrared nanospectroscopic imaging," *Proceedings of the National Academy of Sciences of the United States of America* **111**, 7191–7196 (5 2014).

[4] Bell, R. J., [*Introductory Fourier Transform Spectroscopy*], Academic Press, New York (1972).

[5] de Oliveira, N., Roudjane, M., Joyeux, D., Phalippou, D., Rodier, J.-C., and Nahon, L., "High-resolution broad-bandwidth fourier-transform absorption spectroscopy in the vuv range down to 40 nm," *Nature Photonics* **5**, 149–153 (3 2011).

[6] de Oliveira, N., Joyeux, D., Phalippou, D., Rodier, J. C., Polack, F., Vervloet, M., and Nahon, L., "A fourier transform spectrometer without a beam splitter for the vacuum ultraviolet range: From the optical design to the first uv spectrum," *Review of Scientific Instruments* **80** (4 2009).

[7] Howells, M., Frank, K., Hussain, Z., Moler, E., Reich, T., Möller, D., and Shirley, D., "Toward a soft x-ray fourier-transform spectrometer," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **347**, 182–191 (8 1994).

[8] Moler, E., Hussain, Z., Duarte, R., and Howells, M., "Design and performance of a soft x-ray interferometer for ultra-high resolution fourier transform spectroscopy," *Journal of Electron Spectroscopy and Related Phenomena* **80**, 309–312 (1996). Proceedings of the 11th International Conference on Vacuum Ultraviolet Radiation Physics.

[9] Wilcox, J., White, V., Shcheglov, K., and Kowalczyk, R., "Beam splitting mirrors for miniature fourier transform soft x-ray (ftxr) interferometer," in [*Advances in X-Ray/EUV Optics and Components V*], Khounsary, A. M., Morawe, C., and Goto, S., eds., **7802**, 780206 (8 2010).