Holographic Spectroscopy for Single Shot Electron Bunch Diagnostics

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Outline

• Coherent radiation and the electron bunch shape
• Basics of holographic Fourier transform spectroscopy
• Holographic FTS for THz region
• First results obtained at Jlab
• Electro-optic detection with optical Fourier transform
• Conclusions
Coherent emission of a distant bunch

Electron bunch

Detector

Total intensity of the bunch radiation

\[ I_{tot}(\omega) = I(\omega)[N + N(N - 1)F(\omega)] \]

Electron bunch form-factor

\[ F(\omega) = \left| \int_0^\infty dz S(z) e^{i(\omega/c)z} \right|^2 \]
Phase problem in the bunch shape determination

Defining the phase and the form-factor amplitude

\[ \hat{S}(\omega) \equiv \int_0^\infty d\zeta S(\zeta) e^{i(\omega/c)\zeta} \equiv \rho(\omega)e^{i\psi(\omega)}, F(\omega) = \hat{S}(\omega)\hat{S}^*(\omega) = \rho^2(\omega) \]

Analogy with earlier analyses in optics and spectroscopy

\[ \ln \hat{S}(\omega) = \ln \rho(\omega) + i\psi(\omega) \]

But there are complications

\[ \psi(\omega) = \psi_m(\omega) + \psi_{\text{Blaschke}}(\omega) = -\frac{2\omega}{\pi} \text{P}\int_0^\infty dx \frac{\ln \rho(x)}{x^2 - \omega^2} + \sum_j \text{arg} \left( \frac{\omega - \hat{\omega}_j}{\omega - \hat{\omega}_j^*} \right) \]

If both phase and form-factor are found so is the bunch shape

\[ S(z) = \frac{1}{\pi c} \int_0^\infty d\omega \rho(\omega) \left[ \psi(\omega) - \frac{\omega z}{c} \right] \]
Fourier transform spectroscopy for form-factor determination

Broad band advantage

Mirror 1 - fixed

D

D – x/2

Mirror 2 - movable

x/2

Parabolic mirror

Source

Fellgett advantage

Jacquinot advantage

Detector

Parabolic mirror
Double-sided interferogram

\[ I(x) = \frac{1}{2} \int_{0}^{\infty} d\omega B(\omega) + \frac{1}{2} \int_{0}^{\infty} d\omega B(\omega) \cos \left( \frac{\omega}{c} x \right) \]
Properties of ideal HFTS

No shearing

Sheared by $\delta$

$$I_0(r', \omega)$$

$$I(r') = \frac{1}{2} \int_0^\infty d\omega I_0(r', \omega) \left( 1 + \cos \frac{\omega \delta}{c f} \right) B(\omega)$$

No restriction on the object size – ultimate throughput!

No need for large elements in the array
Imaging modifications of HFTS

Sheared images

Sheared collimated beams

Interference pattern

Image modulated by the same interference pattern

Given not very large angle $\alpha$ and sufficiently large source both imaging and spectral information are available.
Parameters of HFTS

High frequency limit in wavenumbers

\[ \sigma_{\text{max}} = \frac{1}{4h \sin \frac{\alpha}{2}} \approx \frac{1}{2h \alpha} \approx \frac{f}{2h \delta} \]

Resolving power

\[ R \equiv \frac{\sigma_{\text{max}}}{\delta \sigma} = N/1.2 \]

Spectral resolution

\[ \delta \sigma = \frac{0.6f}{Nh \delta} = \frac{0.6F}{\delta} \]
Asymmetric Sagnac interferometer

Shearing interferometer produces two mutually coherent virtual sources.

Fourier optics converges parallel rays to the same element on the detector array.
Shearing parameter $d$ determines the distance between virtual sources.

Fourier optics transforms the angular distribution of the radiation into the spatial distribution in the detector plane.
Aberrations in HFTS

Aberrations can be minimized by dividing Fourier optics
Optimization of the interferometer

Tilt interferometer has higher symmetry and thus smaller aberrations
HFTS with tilt interferometer has the throughput identical to the scanning FTS but less than with the shear interferometer.
Optical layout of the THz interferometer

Fore-optics accepts a collimated beam and is based on a off-axis parabolic mirror.

A wire grid beamsplitter sends two polarizations along different paths.

Two out-of-plane 30° off-axis parabolic mirrors collimate the beams and recombine them at the array detector.

Second wire grid polarizer at 45° is used in front of the detector.

Tilt interferometer is realized using standard optical components.

Several folding mirrors are used for more compact design.
Ray tracing analysis of THz HFTS

Interference pattern calculated with a ray tracing software confirms that aberrations are sufficiently compensated.
Field aberrations in the THz interferometer

Both in plane and out of plane field angles produce the same shift in the observed frequency as expected. The shift is the same in absolute value but opposite in sign compared to the scanning Michelson interferometer FTS.
Effects of vignetting on performance of THz HFTS

Ray tracing performed with the ZEMAX EE software in the non-sequential mode.

Vignetting results in decreasing contrast and degraded spectral resolution.

Aberrations are not of primary concern.

Acceptance angles: horizontal - 70 mrad, vertical - 100 mrad.
Experiments were conducted in the atmosphere and only few water lines were expected below 40 cm$^{-1}$
Coherent synchrotron radiation measurements at JLab

ERL parameters:
current - 1 mA
charge - 100 pC
frequency - 9.36 MHz
energy - 114.65 MeV

Detuning of the bunch energy by changing the gradient field in the RF cavities varied the electron bunch length

The stronger and broader spectra are observed for shorter bunches
Non-uniform sensitivity of Pyrocam array

Three measurements were performed

1. THz HFTS with Pyrocam array
2. Scanning Michelson FTS with the Pyrocam signal integrated for all pixels
3. Scanning Michelson FTS with the Golay cell

Dips in the spectra are due to the Pyrocam array non-uniform sensitivity
To test the spectral performance of the THz HFTS the transmission spectrum of the silicon wafer was measured both with the THz HFTS and with the scanning lamellar FTS.

The fit of the lamellar data with the two pass channel spectrum demonstrated accurate frequency values.

But the THz HFTS frequencies are shifted.
Frequency deviations can be explained by the presence of two different scaling factors in the interference pattern.

The fit of the THz HFTS data using this model confirms this idea.

The source of the additional scaling factor is most likely the birefringence of the lithium tantalate crystal used in the array pixels.
Electro-optic detection of the THz interference

Existing THz arrays do not have enough sensitivity and are not optimized for spectral measurements.

The way out is to use electro-optic detection:

1. EO effect is very fast
2. No pixel size restriction on the spectral width
3. Great flexibility and expandability of the method
Optical Fourier transformation of the THz interference pattern

Optical Fourier transform advantages

1. Signal is concentrated in the 1D pattern increasing the signal-to-noise ratio
2. No signal in the absence of the THz radiation - no need to use ultrafast laser pulses
3. Rejection of the non-informative DC component - decreased background
Schematic of the THz HFTS with optical Fourier transformation

1. Pulsed laser
2. Beam expander
3. Polarizer
4. EO crystal
5. Analyzer
6. Fourier transform lens
7. Aperture
8. Magnifying lens
9. CCD camera

The instrument is a self contained unit without external synchronized lasers
Design of the THz HFTS with optical Fourier transformation

By using folding mirrors the instrument fits on a 12’ X 36’ optical board
The Fourier transform lens is mounted on the XY stage in order to align the DC component outside of the aperture.
EO detection tests with ultrafast laser pulses

THz radiation produced with the ultrafast laser pulses is too weak to test the instrument.
Possible materials for broad band EO detection

\[ \lambda = 785 \text{ nm} \]
\[ \Lambda = 300 \mu \text{m} \]
\[ r - \text{electrooptic coefficient (} r_{411} \text{ and } r_{33} \text{ for lithium thantalate)} \]
\[ L - \text{coherence length} \]
\[ - \text{merit function} \]

Very high phonon frequencies of silicon carbide make it promising material
If the radiation pulse can be related to the bunch length it can be used to characterize the bunch shape without any external lasers.
Preliminary results confirm the idea. It might be possible to combine with the THz interferometer and realize the instrument capable to measure the bunch asymmetry using the THz analog of the FROG.
Conclusions and outlook

- Holographic FTS for THz region is developed.

- First results show insufficient performance of existing THz arrays.

- Electro-optic detection scheme is developed and realized using optical Fourier transformation.

- High intensity source of THz radiation is needed to test the instrument.

- Combination of the incoherent and coherent radiation crosscorrelation with the HFTS can result in the asymmetry measurement of the bunch.