Stationary Fourier Transform Spectroscopy

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ABSTRACT

We develop an interferometer for measurement of narrow atmospheric spectral lines, mainly in the infra-red. The bias and background are dominant, but irrelevant for the measurement. Hence we employ an optical band-pass filter tuned to the expected width of the spectral lines: Instead of scanning the full path delay with a single detector, we image the fringes on a two-dimensional camera. Applications are for search for life on exoplanets, and for our own atmosphere.

Keywords: Fourier Spectroscopy, Narrow line spectroscopy, Exoplanets

1. **Selective FTIR**

We develop an interferometer for measurement of narrow atmospheric spectral lines, mainly in the infra-red [1-6]. The bias and background are dominant, but irrelevant for the measurement. Hence we employ an optical band-pass filter tuned to the expected width of the spectral lines: Instead of scanning the full path delay with a single detector, we image the fringes on a two-dimensional camera [7]. Applications are for search for life on exoplanets, and for our own atmosphere.

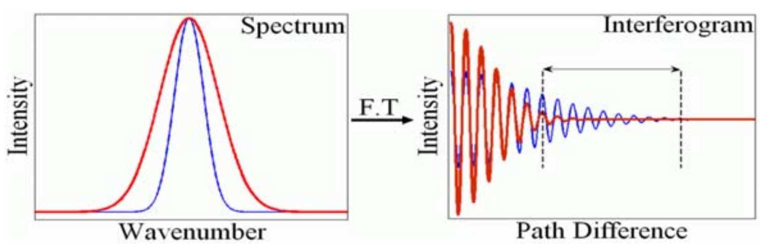

Fig. 1. Fourier band-pass filtering of the spectrum. (Left) Two spectral features with different widths. (Right) The interferograms of both spectral features with the chosen delay range bring out the sharper narrow feature, and reduce high-frequency noise.

2. **Interferometer**

We employ the Ribak-Lipson interferometer [8] operated at zero lateral shear. A telescope produces a collimated beam, which crosses two consecutive beams splitters. Four beams are formed, where each two interfere as a pair (Fig. 2). Between the beam splitters we insert a delay which varies in steps. Each step shifts the fringes on the facing camera rows, and allows for a much larger number of fringes. If the first rows measure the first hundred fringes, the following rows measure the next hundred, etc. The staggered fringes thus allow a higher spectral resolution (Fig. 3).

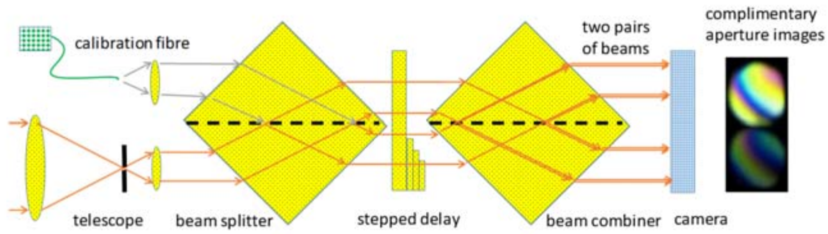

Fig. 2. The two interfering pairs of beams form fringes on the detector. Adding delays in stairs will produce many more fringes, and thus much higher spectral resolution.

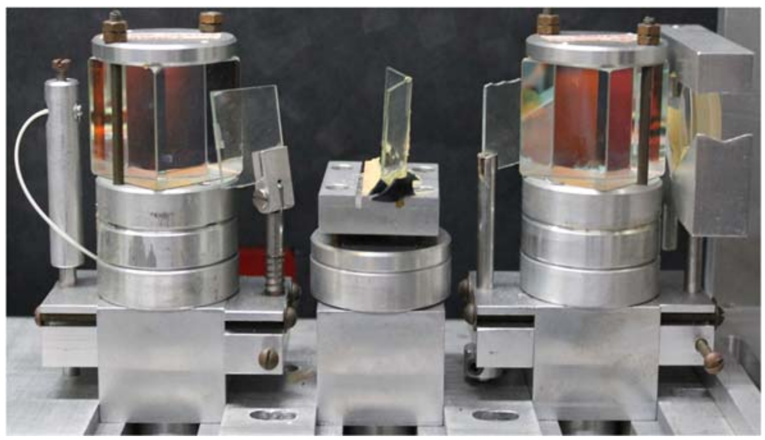
Fig. 3. Side view of the interferometer at the telescope. Thin microscope slides introduced a single delay for compensation of beam splitters path difference and misalignments [6].

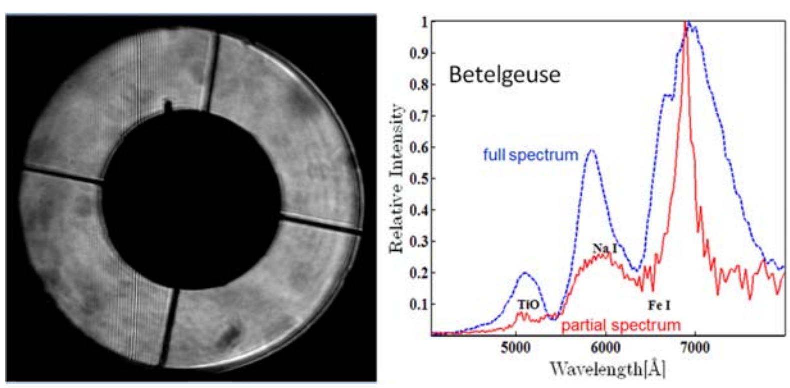

Fig. 4. (Left) Stellar fringes on 1m telescope aperture, here showing the central white-light fringe. (Right) Spectra retrieved from the entire interferogram (blue, dashed) and from the selected part of the interferogram without the central fringes (red). A significant contrast improvement is clearly seen.

3. **Experiments**

Using the Fourier spectrometer, we confirmed the ideas presented in an observatory, and showed that we can easily see fainter and narrower lines (Fig. 4). We are now modifying the device for the infra-red region for measurements of atmospheric gases. All measurements were taken without scanning, and integration times can be very long, since the zero-shear interferometer is not sensitive to turbulence at all.

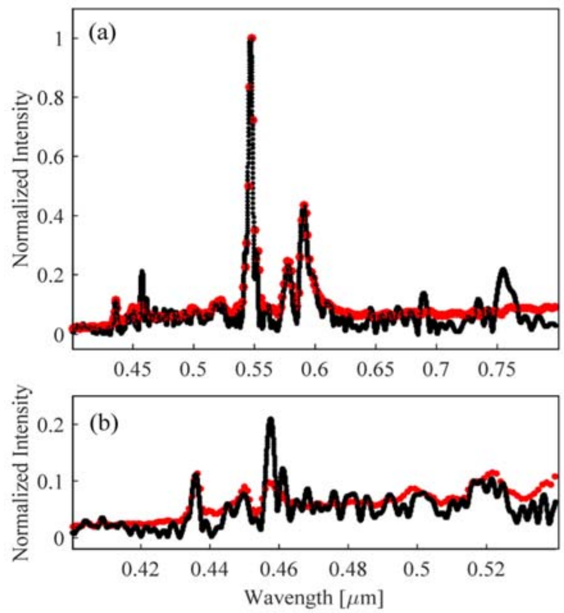

Fig. 5. (a) A metal halide lamp Fourier spectrum from a rotated (black) and vertically aligned (red) interferogram. (b) High frequency (short wavelength) part of the spectrum in (a) showing more delicate spectral features for the rotated fringes.

4. **High-pass**

Too much signal, and too high a fringe contrast at the centre of the interferogram, tax the camera dynamic range. To remove the centre, a large delay is added to one of the paths. When the camera pixel count is too small (as in the infra-red) even this single delay is insufficient. We first tilted the fringes [9], thus adding more sampling points across them (Fig. 6). We also manufactured more delays, each for a number of camera rows (Fig. 7, right, and Fig. 8).

5. **Properties**

We list below some of the advantages and disadvantages of the stationary Fourier transform spectrometer:

+ A zero-shear interferometer is not sensitive to turbulence and aberrations outside the device.

+ Two complementary outputs mean that all light is measured, and can serve to improve SNR.

+ The two outputs can be measured by two cameras of different wave lengths.

+ Fringe modulation is possible, albeit at the camera frame speed.

+ The interferometer is extremely stable and very compact, with no moving parts.

+ Wave length calibration is performed through the other input port.

- The spectral resolution drops with wider field or object jitter.
- The fixed delay needs to be custom made and calibrated.

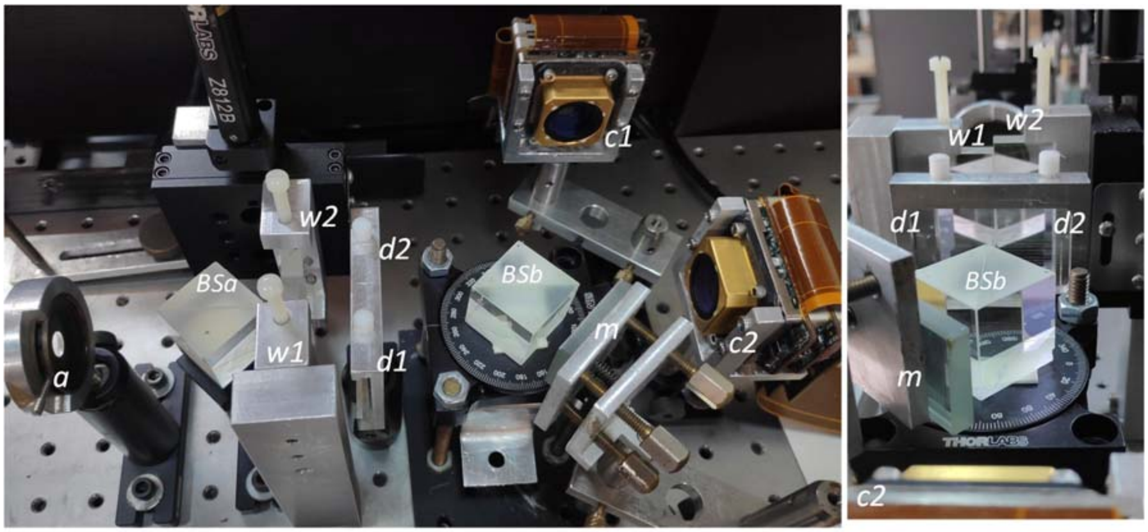

Fig. 6. Laboratory set-up, top and back views (left and right panels). From left: aperture *a*, beam splitter *BSa*, two-wedge delays *w1,w2*, flat and stair delays (*d1, d2,* only frame visible), beam splitter *BSb*, folding mirror *m* for camera *c1*, and two IR cameras *c1, c2*. Looking back into the source (right panel), the fine delay stairs can be seen on the right beam *d2*.

6. **Applications**

The interferometer was already used in stellar observations in the visible regime [6] and narrow earth's atmospheric lines in the infra-red. Further applications are for detection of narrow lines in the atmospheres of remote and solar planets (e.g. phosphine in Venus). These lines are dominant in the infra-red, while broad atomic lines in the visible regime can be blocked both by their width, and by an additional spectral filter. Radial velocity measurements of stars with exoplanets have higher sensitivity when using narrow lines.

7. **Conclusions**

In exoplanet imaging, the bright central star is occulted by a coronagraph, to allow the detection of the much fainter nearby planet. In a similar manner, but in the Fourier domain, we remove the very bright central fringes, which reduce our visibility of the pattern far from the zero-path-difference regime. This is done by adding a delay to one of the beams, so as to push the centre out of the detector area. Notice that by doing that, the noise attributed to the central signal is not removed, since it is spread evenly over the whole Fourier domain. Thus the big advantage of this optical high-pass filtering is the reduction in dynamic range required from the detector. For fast cameras, it is also possible to modulate the fringes [9] to further reduce this background.

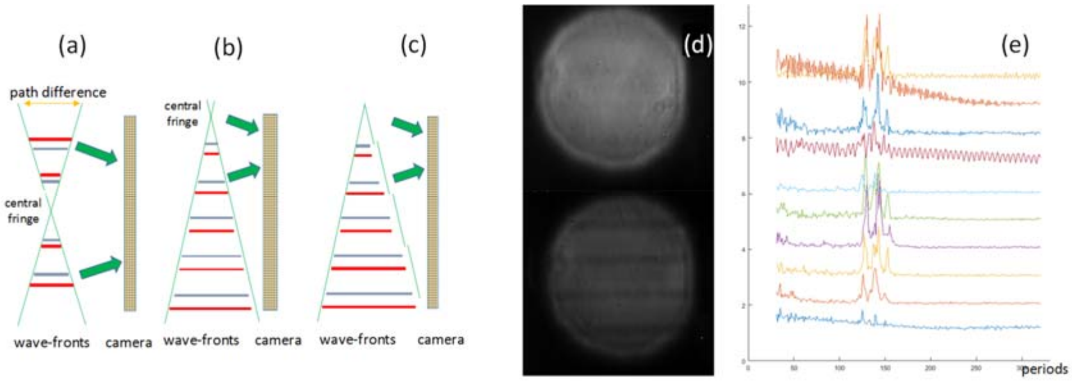

Fig. 7. (a) Two sets of colour fringes projected on the camera, the white fringe is in the centre. (b) With added delay, it is just inside the detector area. (c) One wave front has additional delays, adding more fringes and finer spectrum. (d) A xenon interferogram broken into 5 stripes (both outputs, slightly defocused) . (e) The 10 stripes are inverse-transformed individually. The Xe coherent lines show even at bottom, for the longest delays (~.8mm).

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References

[1] R J Bell, Introductory Fourier Transform Spectroscopy (Academic, 1972).

[2] P Griffiths and J A De Haseth, Fourier Transform Infrared Spectrometry, 2nd ed. (Wiley, 2007)

[3] D J Erskine, J Edelstein, M Sirk, A Vanderburg and E Wishnow, *Imaging and Applied Optics, OSA Technical Digest* paper FM2D.2 (2013)

[4] J. D. Monnier, "Optical interferometry in astronomy," *Rep. Prog. Phys.* **66**, 789–857 (2003)

[5] C Lovis, D A Fischer, Radial velocity techniques for exoplanets. In Seager, S. (ed.) Exoplanets. University of Arizona Press, 31 pp (2010)

[6] E Schwartz and S G Lipson, Spectroscopic interferometric method of revealing spectral features from extra-solar planets," in *Fourier Transform Spectroscopy*, *OSA Technical Digest,* paper JPDP4 (2011)

[7] E Schwartz, S G Lipson and E N Ribak, Improving identification of weak spectral lines in the presence of a strong continuum. *Astrophysics and Space Science* **361**, 166 (2016)

[8] E Ribak and E Leibowitz: Shearing Stellar interferometer: 1. Digital data analysis scheme. *Applied Optics* **24**, 3088 (1985); E Ribak, E Leibowitz, and E K Hege: Shearing Stellar interferometer: 2. Opto-electronic phase-locked system. *Applied Optics* **24**, 3094 (1985)

[9] E Schwartz and E N Ribak: Enhanced sampling of 2D interference patterns, *Applied Optics* **56**, 1977-81 (2017)