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Multiple-Delay Externally Dispersed Interferometry

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Abstract: An externally dispersed interferometer (EDI) is the series combination of a fixed delay interferometer (Michelson) with an external dispersive spectrograph. Its performance combines the compactness and beamshape insensitivity of a FTS with the order of magnitude or more lower photon noise of a grating spectrograph relative to the FTS. A broadband moiré effect heterodynes high detail spectral information to low spatial frequencies resolved by the grating spectrograph. The iodine spectrum was measured while stepping the Michelson delay in a few large increments, to 4.6 cm maximum delay. The reconstructed spectrum has a Gaussian spectral resolution approximately 6 times greater than the grating spectrograph used without the interferometer.

OCIS codes: (300.6300) Spectroscopy, Fourier Transform; (300.6310) Spectroscopy, Heterodyne

1 Apparatus

Figure 1 shows the schematic of the externally dispersed interferometer (EDI), which is the series combination of an undispersed fixed-delay interferometer and an external grating spectrograph. Fringes formed at the interferometer are relayed to the slit plane by a lens. When dispersed by the grating spectrograph, this forms a fringing spectrum (Fig. 2) detected by a CCD. The interferometer delay τ is not scanned in small steps as in a Fourier Transform spectrometer, but moved in a few large jumps. The interferometer has a normalized sinusoidal transmission spectrum

$$T(\nu, y) = 1 + \cos(2\pi\tau\nu + \phi_y). \quad (1)$$

Usually the interferometer mirrors are tilted so that the phase ϕ_y varies transversely (y) to the dispersion axis (ν). This records all phases simultaneously in a single exposure. (Piston phase stepping is often used as well, to improve rejection of fixed pattern noise).

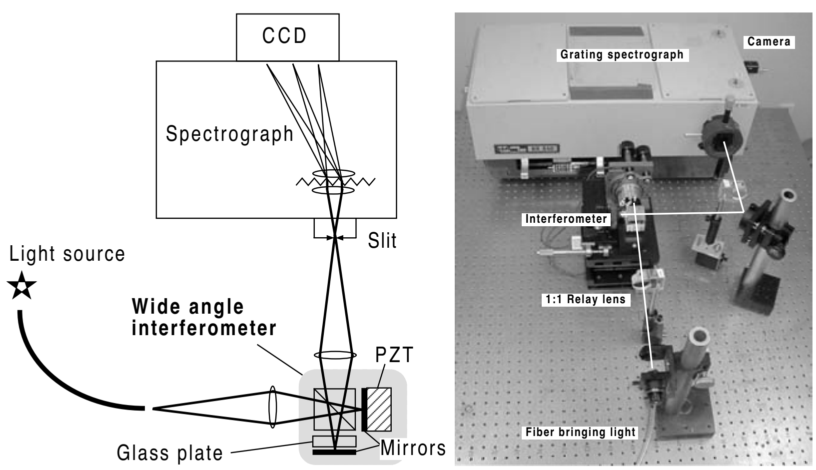

Fig. 1. Schematic and photograph of EDI apparatus used to demonstrate ∼6× resolution boosting. Light enters Michelson interferometer via fiber. The fiber end is imaged to the interferometer mirror plane, which in turn is imaged to the Jobin-Yvon 640 spectrograph slit plane. A glass etalon next to one of the interferometer mirrors contributes to the delay value, and provides angular independence to the delay so that wide fibers can be used. Data was taken sequentially with a series of etalon thicknesses. A single delay can produce a resolution boost of ∼2.5×. Multiple delays allows much larger boosts, proportional to the longest delay used.

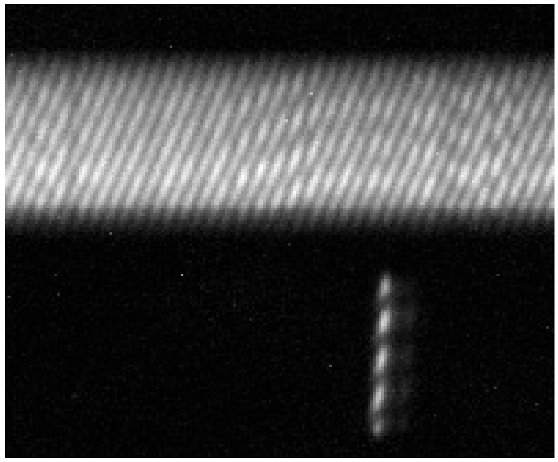

Fig. 2. Raw CCD data for delay glass thickness of 1/4 inch (τ=1.1 cm) showing fringing spectra of iodine (top) and 546 nm Hg lamp line recorded through the same interferometer. (Only 200 of 2500 horizontal pixels shown.) Vertical lines are iodine absorption features. Tilted lines are sinusoidal interferometer transmission comb, whose phase varies vertically. Interaction between the two creates moiré patterns such as the arc-like shapes. Different interferometer delays produce different patterns.

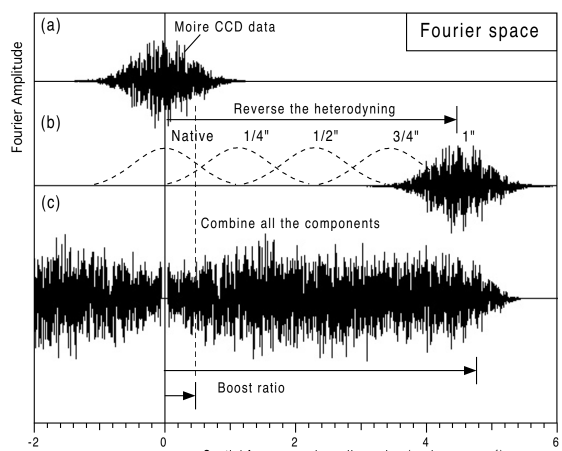

Fig. 3. Steps in reconstructing a spectrum to higher resolution, illustrated in spatial frequency space, ρ. Note that ρ units of cycles per cm^{-1} are same as delay, i.e. cm. (a) The raw data recorded on CCD has a range of spatial frequencies limited by blurring of grating spectrograph. The ordinary spectrum is removed leaving the moiré (fringing) component. (b) The spatial frequency of the data is shifted to its original higher spatial frequency by amount τ, the interferometer delay. (c) Results from different delays are concatenated together to form a composite result. Taking the real part of this effectively copies the positive to negative branch. The composite result has a spatial frequency range that is much wider than the grating alone (dashed peak "Native"). Hence the spectral resolution has been boosted by a significant factor.

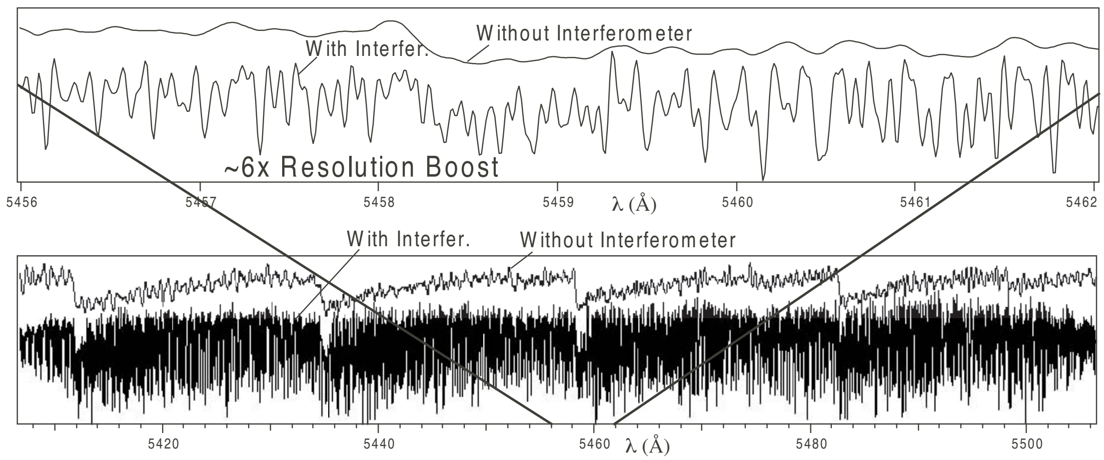

Fig. 4. Laboratory EDI demonstration of a $\sim$6$\times$ resolution boosting effect measuring the iodine spectrum. Top curves in both panels are the grating spectrograph without interferometer. The fine iodine lines cannot be seen. The bottom curves use the interferometer and reconstruct the spectrum from the moiré patterns. The fine lines are now easily seen. The native $\sim$25,000 grating resolution was effectively boosted to $\sim$147,000 Gaussian resolution. The bandwidth is the same as the native bandwidth of the grating spectrograph, in this case $\sim$100 Å.

2 Data Analysis

For each frequency (ν) channel in the CCD data, the phase and amplitude of the fringe transverse to the dispersion direction is measured and represented by the angle and magnitude of a complex value $\mathbf{W}(\nu)$. Under a Doppler shift this vector spectrum rotates. By measuring the ν-averaged rotation relative to an iodine reference spectrum the EDI has measured 1 m/s scale Doppler velocities of starlight and sunlight[1, 2, 3, 4] and has detected an exoplanet[5]. However, here we are interested in the spectrographic ability. This involves analyzing the ν-dependence of $\mathbf{W}(\nu)$.

The sinusoidal transmission $T(\nu)$ of the interferometer multiplied against the input spectrum creates a heterodyned beat component, also called a moiré pattern. High spatial frequency (ρ) spectral features are lowered by $\Delta\rho = \tau$. This moiré component survives the blurring of the spectrograph slit to carry information about narrow spectral features that are unresolved by the spectrograph used alone. We numerically reverse the heterodyning that occurs optically to reconstruct the narrow details of the original spectrum. Previously we have demonstrated $\sim$2.5$\times$ boosting using a single delay[6, 7]. Here we demonstrate $\sim$6$\times$ boosting using several delays and compositing the results (Figure 3) for each ρ-range they sense. Figure 4 shows the reconstructed iodine spectrum having much greater resolution, and yet the same bandwidth, as the grating spectrograph used alone. Further details are described elsewhere[8].

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