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Externally Dispersed Interferometry for Low Photon Noise High Resolution Broadband Spectroscopy

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Abstract: An externally dispersed interferometer (EDI) is a hybrid instrument combining the compactness and beamshape insensitivity of a FTS with the low photon noise of a grating spectrograph. A broadband Moiré effect heterodynes high detail spectral information to low spatial frequencies resolved by the grating spectrograph. This resolution boosting effect is demonstrated on the solar spectrum.

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

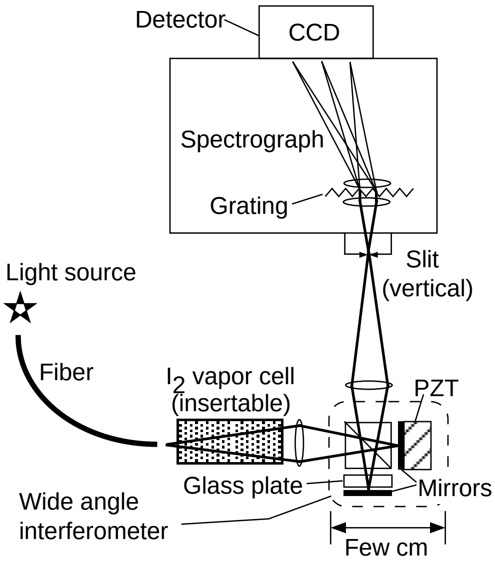

Fig. 1. Schematic of the EDI. Wide-angle interferometer[1] with 11 mm fixed delay created by glass plate imprints fringes on beam at spectrograph slit, creating a fringing spectrum at CCD. PZT transducer dithers interferometer delay in 3 or 4 steps of $\lambda/3$ or $\lambda/4$ to isolate fringing from nonfringing spectral components. Optional iodine cell imprints reference spectrum.

1 Apparatus

Figure 1 shows the schematic of the 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. 2a) detected by a CCD. One of the interferometer mirrors is mounted on a PZT transducer which dithers the interferometer delay in 3 or 4 steps of $\lambda/3$ or $\lambda/4$. This allows isolating the fringing from nonfringing spectral components.

The nonzero (typically 1 to 3 cm) interferometer delay τ is not scanned, but is semifixed. It produces a normalized sinusoidal transmission spectrum

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

The phase ϕ_y describes the detailed value of τ about its default value. In the simplest mode of taking data the interferometer mirrors are slightly misaligned so that ϕ_y varies transversely (y) to the dispersion axis (ν).

This allows recording all phases simultaneously in a single exposure without piston phase stepping. (However piston phase stepping is usually used as well, to improve rejection of fixed pattern noise).

When the interferometer mirrors are aligned so that the spatial fringe expands beyond the spectrograph slit size, then ϕ_y is y-independent. This mode allows use of beams too small to splay the phase spatially. For example, the EDI has been used to produce fringing spectra[2] from the Lick Obs. echelle grating spectrograph, which already uses both spatial dimensions on the CCD as dispersion axes. The uniform phase mode also makes 1d imaging EDI spectrographs feasible.

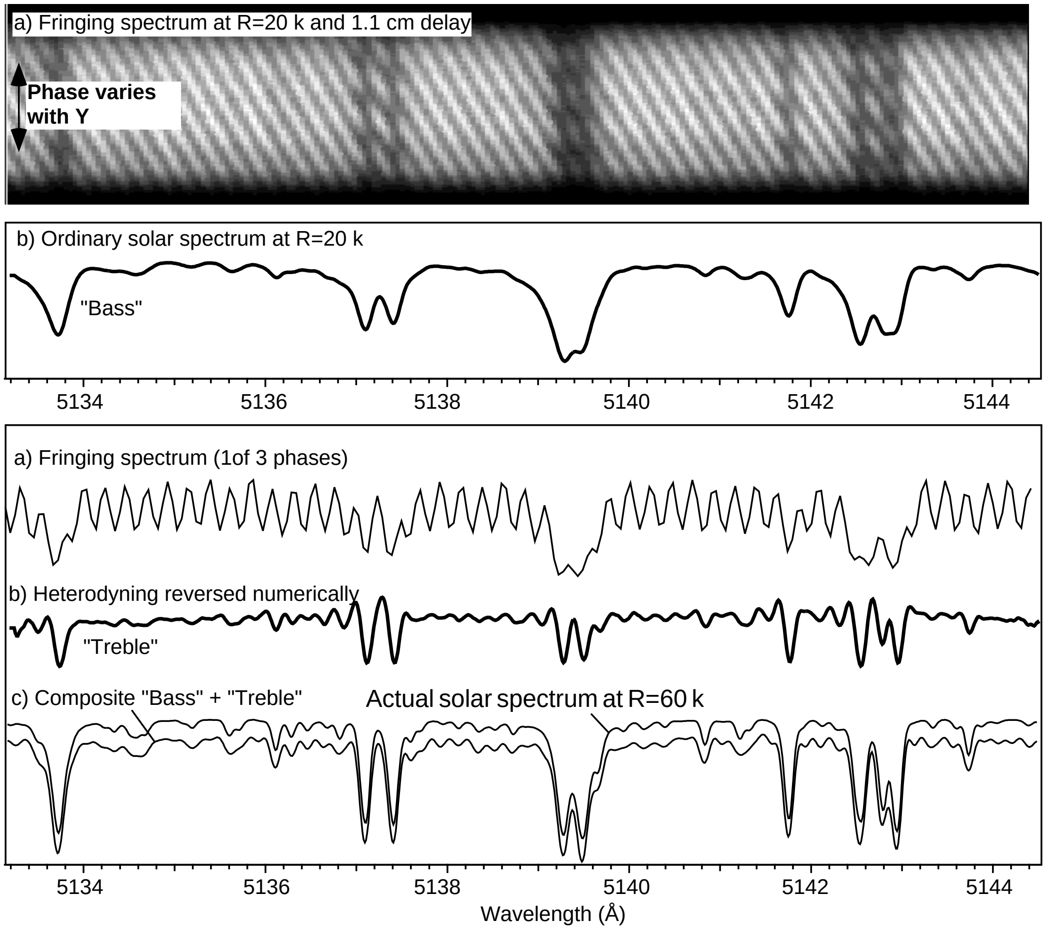

Fig. 2. Demonstration of resolution boosting on a R=20 k linear grating spectrograph and the solar spectrum. a) The fringing spectrum obtained with a fixed 11 mm delay interferometer in series with the spectrograph. The interferometer phase varies linearly along slit height. Only a subset of full wavelength range is shown. b) The ordinary spectrum ("bass" signal) obtained when the intensity data is averaged along each y-column, destroying fringes. c) A line-out of a) at fixed y along dispersion axis. Three or more such lineouts are needed to isolate the fringing from nonfringing components. d) The heterodyning that occurs optically is reversed numerically to form the "treble" signal. e) Composite (lower) of bass and treble signals, after minor equalization to smooth instrument response using iodine calibration spectra. Comparison to Kitt Peak/NOAO FTS solar spectrum (upper) artificially blurred to R=60 k shows excellent agreement. Data taken June 16, 1998 at LLNL by Erskine with the first EDI prototype.

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 $\mathbf{W}(\nu)$. Hence the EDI records a vector spectrum rather than a conventional scalar spectrum $S(\nu)$. Under a Doppler shift the vector spectrum rotates (and twists slightly). By measuring the rotation relative to that of the a reference spectrum (such provided by the insertable iodine vapor cell) the EDI has been used to measure 1 m/s scale Doppler velocities of starlight and sunlight[3, 4, 5, 6, 7]. (The detail value of the interferometer delay drops out). However, in this report we are interested in the ability of the EDI to reconstruct the high resolution shape of the input spectrum beyond what the grating can resolve by itself. This involves measuring the ν-dependence of $\mathbf{W}(\nu)$ instead of its bulk rotation.

2.1 *Reversal of Heterodyning*

The sinusoidal transmission $T(\nu)$ of the interferometer multiplied against the input spectrum creates up and down shifted heterodyned components. These are also called Moiré patterns. High spectral detail information, having high spatial frequencies (ρ) on the CCD, are beaten to low spatial frequencies by the amount $\Delta\rho = \tau$. Since the Moiré pattern is measured at several values of ϕ_y, the full information content (expressed as a complex wave $\mathbf{W}(\nu)$) is determined. Hence there is no ambiguity in the heterodyned signal for original ρ's slightly larger or smaller than τ.

The down shifted Moiré component survives the blurring of the spectrograph slit and carriers information about the high spatial frequencies of the input spectrum. The heterodyning that occurs optically can be reversed numerically to reconstruct the high details of the original spectrum. The ordinary spectrum (providing low spatial frequency information) is simultaneously obtained from the same data by averaging along y-pixels, destroying the fringes. When the ordinary and heterodyned information are combined, the composite spectrum has an effective resolution ($R = \nu/\Delta\nu$) several times greater than the grating used alone, while still having the light gathering benefit of the original large slit width. This is demonstrated on the solar spectrum in Fig. 2, where a 20 k resolution linear grating spectrograph (Jobin-Yvon 640) is effectively boosted to near 60 k.

A dispersive spectrograph has superior photon signal to noise ratio to a FTS, and hence are favored by visible light astronomers. The EDI can approach the photon limited performance of a dispersive spectrograph, and even exceed it for high ρ features, but with several times smaller instrument size for the same effective resolution. This produces dramatic cost and weight reductions compared to a purely dispersive instrument. While at the same time the EDI shares the superior (to the grating) beam profile insensitivity typical of interferometers.

This concept can be extended to N multiple fixed delays distributed in value, e.g. τ =1, 2 and 3 cm, sharing the same external spectrograph. This further increases the spectral resolution, while decreasing the photon signal to noise ratio by $1/\sqrt{N}$. In the limit $N \to \infty$ the EDI approaches the same regime as the classic FTS.

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