Transform spectrometer based on measuring periodicity of Talbot self-images

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We demonstrate a spectrometer based on measuring the periodicity of Talbot self-images. The system contains a tilted absorption grating imaged onto a CCD camera and has no moving parts.

There is a need for compact, inexpensive, nanometer - resolution spectrometers. Such spectrometers are ideally suited for hand-held spectral imaging and sensing systems. With previous knowledge of the spectral signature of chemicals or objects such spectrometers can be used to sense, monitor, and process the spectral content of images. MEMS technology has enabled many types of small spectrometers, including Fabry-Perot interferometers,[1] grating-based spectrometers,[2] Michelson Fourier-transform spectrometers,[3] and standing wave spectrometers.[4] Here we demonstrate a novel spectrometer based on measuring the periodicity of Talbot self-images. The spectrometer has no moving parts yet appears to have the same fundamental throughput and multiplexing advantages as other transform spectrometers.

The spectrometer is based on the Talbot effect first observed by H.F. Talbot in 1836[5]. When a periodic object such as a grating is illuminated with spatially coherent light, a series of self-images of the grating are produced behind it due to Fresnel diffraction. Self-images appear at distances $2n\Lambda^2/\lambda$, where n is an integer, Λ is the grating period and λ is the wavelength of light. Interleaved with the self-images are their opposites: light and dark regions of the light field pattern are reversed, appearing at distances of $(2n+1)\Lambda^2/\lambda$. Because the spacing of Talbot self-images is proportional to optical frequency, illumination by multiple frequencies at the same time leads to beat patterns in the intensity of the image– which can be transformed to decode the spectral information.

To measure the periodicity of Talbot images without moving the detector through image planes, a grating was rotated about an axis perpendicular to the grating lines, as shown in Figure 1. The edge of the grating closest to the CCD defines the object plane that is imaged onto the CCD through a lens. If the distance from the grating to the object plane is a Talbot multiple, i.e. if $z = 2n\Lambda^2/\lambda$, then there is a true image on the CCD. If the distance is a Talbot reverse image multiple i.e., $z = (2n+1)\Lambda^2/\lambda$, then a reversed image appears on the CCD. By feeding the output of the CCD into an oscilloscope and taking the Fourier transform of one row of the CCD array the periodicity of the Talbot planes can be measured, thus determining the spectrum.

In the optical set-up shown in Figure 1, green (543nm) and red (633nm) HeNe lasers are co-linearly combined with a beam splitter. An absorption grating, rotated at an angle of $\theta=57^o$ is used to generate the Talbot self-images. A 40mm focal length lens is used to image the closest edge of the grating onto a CCD camera of width 6.55mm and height 4.87mm. The grating is magnified ~4.6 times. The full-width-half-maximum (FWHM) of the red laser spot was 2.0 mm with a power of 345μW. The green laser had a FWHM of 1.5 mm and a power of 312 μW. The grating is rotationally aligned so that its horizontal lines are parallel to the horizontal line scan of the CCD camera. The CCD camera has a neutral density filter in front of it that attenuates 99.1 % of the light.

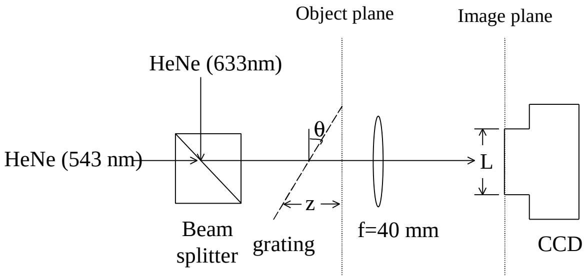
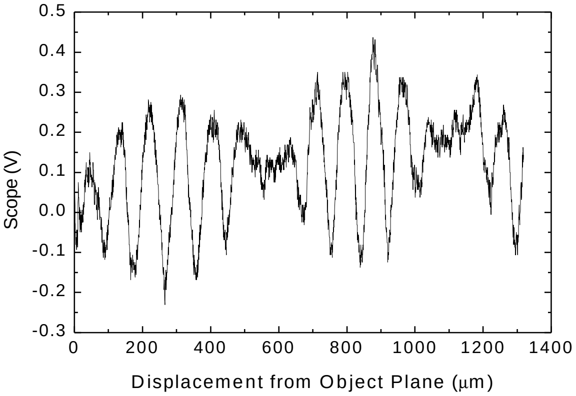


Figure 1-Optical set-up. The two HeNe laser beams are combined with a beam splitter and are made co-linear with each other. The light then passes through a tilted grating and is imaged with a 40 mm focal length lens onto a CCD camera.

The only non-standard component used in this experiment was the absorption grating. It was fabricated by evaporating 1000 Å of aluminum onto a 4” diameter quartz wafer. The wafer was then patterned with alternating lines and spaces of equal width $\Lambda/2$ where $\Lambda=5$ μm. The aluminum was then etched away, leaving the grating pattern. The total area of the grating was 6mm by 6mm.

To demonstrate this system as a spectrometer, the intensity profile was read horizontally across 512 pixels of the CCD and Fourier transformed. The untransformed intensity for both red and green light simultaneously is shown in Figure 2(a). The Fourier Transform (FT) of the red data, the green data and the data when both lasers are on is shown in Figure 2(b). For the case when both lasers are on, the FT plot shows two clearly resolved peaks that correlate well with the peaks from only the red or green laser. This demonstrates the utility of this set-up for spectrometry. Using the wavelength for red light (633nm) for calibration, the green (543nm) peak is expected to have a Talbot period of 92.1 μm. Instead a Talbot period of 93.2 μm was measured, limiting the accuracy of the current set-up to 6.5nm. We believe this error in accuracy is associated with a rotational misalignment between the grating lines and the CCD camera's pixels.

(a)



(b)

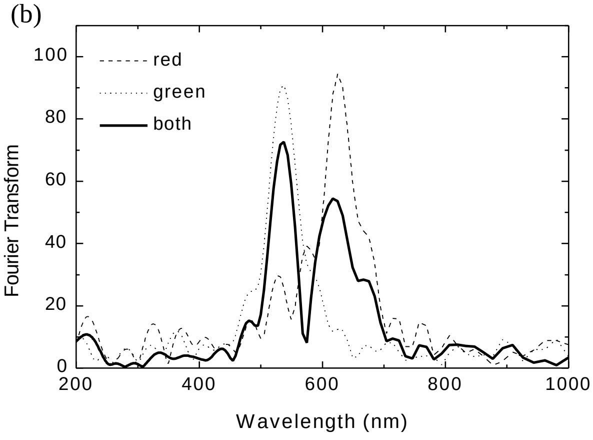


Figure 2-(a) The output of one row of the CCD camera with both the red and green lasers shining into the spectrometer simultaneously. (b) The Fourier transform of the red, green and both lasers. The frequency axis was converted to the corresponding wavelength.

The method of determining resolution for this spectrometer is similar to that for any other transform spectrometer. The conservative criterion for minimum resolution is having one more period at λ_1 than at λ_2. The number of planes seen by the CCD depends on the tilt of the grating (θ), the wavelength of light (λ), the period of the grating (Λ), the magnification (M) of the lens, beam size (W) and the size of the CCD (L) according to the following equation:

$$\#\text{ of Talbot planes} = \frac{lL\sin q}{2M\Lambda^2} \qquad (1)$$

The above equation is valid if Talbot self-images exist from the object plane to the grating for region that is imaged onto the CCD. This criterion is

$$\frac{W}{2}\left[\left(\frac{\Lambda}{l}\right)^2 - 1\right] \geq \frac{L\sin q}{M} \qquad (2)$$

The resolution criterion implies

$$\Delta l = \frac{2M\Lambda^2}{L\sin q} \qquad (3)$$

For our given grating, magnification, and rotation the best resolution is 42 nm. The resolution of this spectrometer increases quadratically with decreasing grating pitch; thus by using a smaller grating the resolution will improve.

In conclusion, we have demonstrated a transform spectrometer based on measuring the location of Talbot self-image planes. The spectrometer's spectral range is dependent only on the CCD camera's response curve. This spectrometer accuracy is limited by the rotational alignment and the resolution is presently limited by our grating size. Future improvements include integration of the grating, lens and CCD and a smaller grating pitch

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