Frequency Swept Measurements of Coherent Diffraction Patterns

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Abstract

Interference fringes arising from multiple reflections can significantly alter the diffraction patterns of diffractive optical elements. One way to reduce interference effects is by time-integrating the diffraction pattern while frequency sweeping the laser source. This method is especially useful when it is not possible to remove the cover glass from the observation camera.

The use of charge coupled device (CCD) cameras in optical systems, together with a laser light source, is widely applied to a variety of measurements. But coherent imaging can introduce severe alterations of the detected signal due to the unwanted interference of multiple reflections of the beam. These reflections that arise from various optical surfaces in the system, including the cover glass of the CCD chip, are difficult to completely eliminate. A classic solution is to use a spatially coherent broadband source.[1] An alternate approach, described in Reference 1, adds together a set of images, each formed with a different wavelength of spatially coherent narrowband light. While the emphasis of the earlier work was to reduce speckle, the procedure evidently reduces interference fringes as well (see Fig. 21.15 in Ref. 1). Today, with the availability of tunable laser diodes and CCD cameras, it appears possible to perform wavelength averaging in real-time. We will demonstrate this technique and report on the improvement in the accuracy and repeatability of the diffraction patterns produced by a set of diffractive optical elements (DOEs).

Figure 1 illustrates a typical source of interference from Fresnel reflections in a glass plate. A fringe pattern is usually observed across the plate due to (even a slight) lack of parallelism between the two surfaces. The fringe pattern can be averaged out by continuously varying, by at least 2π the phase difference between the transmitted beam and the doubly reflected beam, and integrating the intensity pattern during the sweep time. A 2π phase change is achieved with a sweep range of

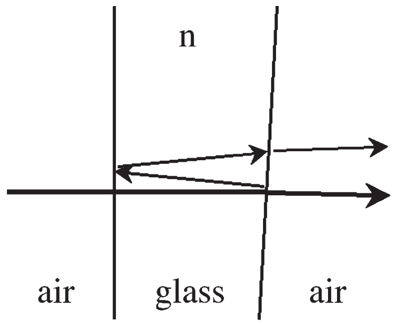

Figure 1. Multiple reflection between two interfaces.

$$\Delta\lambda = \lambda^2/2nd = (\lambda/\nu)(c/2nd) \qquad (1)$$

where λ is the source wavelength, d is the separation between the two reflecting surfaces, and n is the refractive index (which is assumed to be constant with wavelength). A wavelength change of $\Delta\lambda = 0.25$ nm will produce a 2π shift for $\lambda = 860$ nm, $n = 1.5$, and a thickness $d = 1$ mm, a typical thickness for cover glass and planar DOEs. The second equality is written in terms of the source frequency ν and the speed of light c. Writing equation 2 this way identifies the frequency change $\Delta\nu = c/2nd$ *as the free spectral range of a Fabry Perot etalon.*[2]

In a preliminary experiment, a diode laser of nominal wavelength $\lambda = 860$ nm is used. A collimated beam is passed through a 3-mm microscope slide and the 1-mm cover glass of the observation camera (a cooled CCD camera with variable time integration) and is recorded by the camera. The observed intensity distribution is shown in Figure 2a. The larger period fringes are from the microscope slide and the smaller period fringes are from the cover glass. The temperature of the laser head, and thus the frequency of the emitted light, can be controlled by an external voltage. An input voltage between 1–4 V varies the temperature between 10–40°C. By supplying a time varying voltage the temperature changes accordingly. A low frequency step function (period $T = 60$ s) as the control voltage is used. This results in a temperature change that varies linearly with time between 24°–37°. As the temperature changes the fringe pattern is observed to translate. By exposing the CCD during one period of the fringe translation the interference pattern is averaged out. In our set-up one period of fringe translation, corresponding to the desired 0.25-nm wavelength change, occurres in 3 s. The pattern resulting after a 3 s exposure is shown in Figure 2b. While the fringes are averaged out, the frequency sweep has no visible influence on the diffraction pattern from the dust particles on the glass plate.

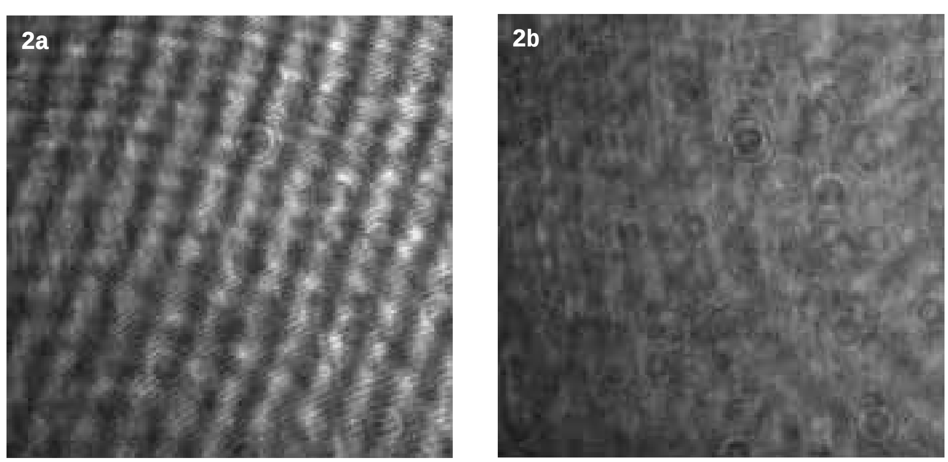

Figure 2. Image of laser illumination through a microscope slide and the cover glass of the CCD. Image (a) without and (b) with frequency sweep.

The swept frequency method is used to characterize a set of identically designed diffractive optical elements. These devices, when illuminated with collimated light, are designed to produce 64 spots of nearly equal intensity in the Fourier plane. The uniformity (defined as the standard deviation of the intensity of the spots) of the designed spot array, is calculated to be 7%. The DOEs are 300 3 300 pixel phase elements with each pixel set to one of eight possible phase levels. Four of the seven DOEs are anti-reflection coated on the backside of the glass substrate. In our measurements the DOE is illuminated with a collimated beam and the diffracted light is focused with a lens onto the CCD camera. The diffraction pattern is recorded on the CCD camera with and without frequency sweeping. With no frequency sweeping an average uniformity of 12.1% with a standard deviation of 1.5% is measured. There is no appreciable difference between measurements of antireflection and non-antireflection coated devices. This indicates that the disturbing reflections mainly originate from the cover glass of the CCD camera. With frequency sweeping the average measured uniformity of the seven devices is reduced to 7.9% with a standard deviation of 0.8%. The swept frequency method improves the repeatability of the uniformity measurement. In addition, the results compare more favorably with the theoretical levels. Other measurements including signal-to-peak background ratio and diffraction efficiency compare well with theory, though these measurements are not as sensitive to reflections as is uniformity.

The method is valid as long as the sweep range $\Delta\lambda$ does not introduce severe wavelength dispersion of the diffraction pattern. This is true as long as

$$\Delta\lambda/\lambda << w/f \qquad (2)$$

where f is the highest spatial frequency of interest in the diffraction pattern and w is the resolvable width of the optical system. For example, the diffraction pattern of an optical system that has a circular aperture is an Airy pattern of angular width $\theta_w = \tan^{-1}(w/z) \approx 1.22\lambda/l$ where l is the diameter of the aperture and z is the distance from the aperture. For the measured diffractive optic reported above the aperture is 4 mm and $\theta_w = 0.015°$. Furthermore, through numerical integration of the Airy intensity pattern over the sweep range $\Delta\lambda = 0.25$ nm the wavelength dispersion introduces less than 5% reduction in intensity for angles less than 26.9°. In the measurements reported, dispersion is negligible since the highest frequency spot from the array generator is at an angle of 0.85°.

In conclusion, the method of time averaging while frequency sweeping the source can be used to suppress interference fringes arising from multiple reflections. This method can more accurately measure the performance of diffractive optical elements. It is worth noting that by sweeping a laser in under 1/30 s it would be possible to eliminate multiple reflections as observed on a live video camera. This speed was not possible with temperature tuning, nor was it possible to tune the laser over an adequately large range by adjusting the laser current. However, we have reviewed the specifications for several commercially available, external cavity laser diodes, and find that with the fastest sweep rates (6–10 nm/s) fringe suppression can be observed with a live video camera.

Acknowledgments

The diffractive optical elements were fabricated by Honeywell as part of the DARPA diffractive optical element foundry run. This study was sponsored by NASA cooperative agreement NCC5-222 and ONR grant N00014-96-1-1296.

References

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