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# Double Frequency Grating Lateral Shear Interferometer

J. C. Wyant

A simple grating lateral shear interferometer is described that can be made to give simultaneously two interferograms having shear in two orthogonal directions. The shear for the two orthogonal directions is produced in one plane by one double frequency crossed diffraction grating that can easily be produced holographically. Translating the grating sideways causes the irradiance of the interferogram to vary sinusoidally with time enabling the interferometer to be used with real-time heterodyne phase detection.

## Introduction

In this paper a simple and stable lateral shear interferometer is described that can be used for either visual or electronic heterodyne real-time phase measurements. The interferometer is basically a grating interferometer and is similar to a Ronchi interferometer.[1-4] Like the Ronchi interferometer, the interferometer described in this paper accomplishes the shear with a single component and thus it is virtually impossible to have misalignment. However, this interferometer has three advantages over a Ronchi-type interferometer. First, in a Ronchi test unless the shear is at least one half the pupil diameter, more than two beams are being interfered. The interferometer described in this paper can be made to produce any desired amount of shear and still have only two-beam interference. Also, with this interferometer the two interfering beams always have the same intensity and thus very good contrast fringes can be obtained. Another advantage that this interferometer has over more conventional lateral shear interferometers is that it is very easy to obtain shear in two orthogonal directions simultaneously without using a beam splitter, and the problem of obtaining the same Gaussian reference spherical wavefront for the two shearing interferograms is automatically eliminated. Since a shearing interferometer gives wavefront slope information only in the direction of shear, a lateral shear interferometer must produce shear in two orthogonal directions if it is used to test nonrotationally symmetric wavefronts.[5,6]

The author is with Itek Corporation, Optical Systems Division, Lexington, Massachusetts 02173.
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## Description of Interferometer

The double frequency grating lateral shear interferometer for obtaining shear in one direction is shown in Fig. 1. A diffraction grating having two different line spacings is placed near the focus of the wavefront being tested. The grating produces two diffracted cones of rays at two slightly different angles. The diffraction angle is chosen large enough to keep the zero-order undiffracted rays separate from the first-order diffracted rays. If a wavefront having an f number $f_{n.o.}$ is tested, the condition for no overlap of the zeroth and first-diffracted orders is found from the grating equation to be

$$\nu_1 > 1/\lambda f_{\text{n.o.}} \qquad (1)$$

where $\lambda$ is the wavelength of the light and $\nu_1$ is the lower spatial frequency of the two-frequency grating.

A lens is placed after the grating to form an image of the exit pupil of the system under test. Since the grating produces two diffracted cones of rays at two slightly different angles, the lens will produce two laterally displaced images of the exit pupil. A shearing interferogram will thus result in the region of overlap. A shearing interferogram would of course result even if the imaging lens were not used; however, without the imaging lens, the interferogram gives the wavefront at a plane other than the exit pupil of the system under test. Regardless of whether an imaging lens is used or not, the amount of shear is determined by the difference between the two spatial frequencies making up the two-frequency diffraction grating. If $\nu_1$ and $\nu_2$ are the two spatial frequencies of the two-frequency grating, the grating equation shows that the angular shear $\Delta\theta$ can be approximated as

$$\Delta\Theta = \lambda(\nu_2 - \nu_1) \qquad (2)$$

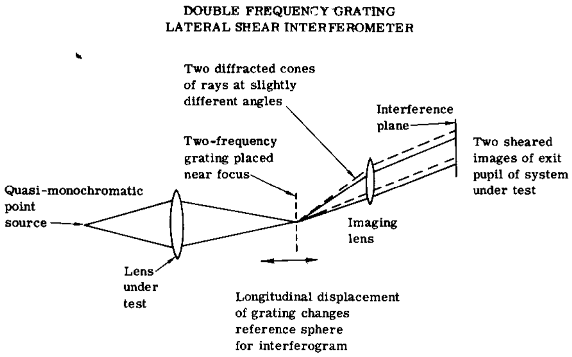



Fig. 1. Double frequency grating lateral shear interferometer.

Longitudinal displacement of the grating changes the Gaussian reference sphere for the interferogram, just as for a Ronchi test. This will be illustrated later in the experimental results.

When high spatial frequency diffraction gratings are used, the image of the exit pupil of the optical system is distorted. Generally this distortion causes no problem; however, if desired, the distortion can be corrected by putting a second grating having a spatial frequency equal to the average spatial frequency of the two-frequency grating into the diffracted beam. This grating can be a blazed grating, which can give a diffraction efficiency of 70% or more.

In practice, the two grating frequencies can be produced holographically on a single photographic plate. That is, a recording is made of the interference of two plane waves interfering at an angle $\theta$, and then a second exposure is made with the two plane waves interfering at a slightly different angle. Often it is easier to keep the angle between the two plane waves constant and to rotate the photographic plate between exposures about an axis that lies in the plane of the plate and parallel to the interference fringes to change the grating frequency. Using this technique, it is very easy to make a set of holograms giving various amounts of shear.

Shearing in only one direction gives wavefront information in only one direction. Thus to obtain all the wavefront information the wavefront should be sheared in two orthogonal directions. This can be accomplished in practice by placing four gratings on a single bleached hologram: two sets of lines in two orthogonal directions. That is, two holographic exposures are made as described above; then the photographic plate is rotated 90 degrees and the exposures are repeated. By using the bleaching technique shown in Table I and developed by Paul Remijan of Itek (present address: Institute of Optics, University of Rochester, Rochester, N.Y.), it was possible to obtain about 15% of the incident light in each of the two shearing patterns and still have low noise. This means that approximately 30% of the incident light is used.

A very good feature of this shearing interferometer is that it can be used with heterodyne real-time phase detection.7 Heterodyne phase detection is a very precise electronic method for determining phase differences $\phi(x, y)$ between two interfering wavefronts. The method can be used if the irradiance of the interference pattern can be made to vary sinusoidally with time. If the irradiance of the fringe pattern can be written as $a + b \sin[\omega t + \phi(x, y)]$, the phase differences $\phi(x, y)$ can be measured by determining electronically the time t at which $\sin[\omega t + \phi(x, y)]$ passes through zero for different points in the fringe pattern. In this shearing interferometer the irradiance of the interferogram is made to vary sinusoidally with time by translating the grating sideways. It can be shown that a moving grating causes a Doppler shift in the diffracted light, just as scattered light from a moving target is frequency-shifted.8 If v is the component of the translational velocity of the grating perpendicular to the grating lines and $\nu_1$ and $\nu_2$ are the two spatial frequencies of the double frequency grating, one first-order diffracted beam is frequency-shifted an amount $v\,\nu_1$ and the other is frequency-shifted an amount $v\,\nu_2$. Therefore, the difference in optical frequencies $\omega$ of the two first-order diffracted beams is given by

$$\omega = 2\pi v(\nu_2 - \nu_1). \qquad (3)$$

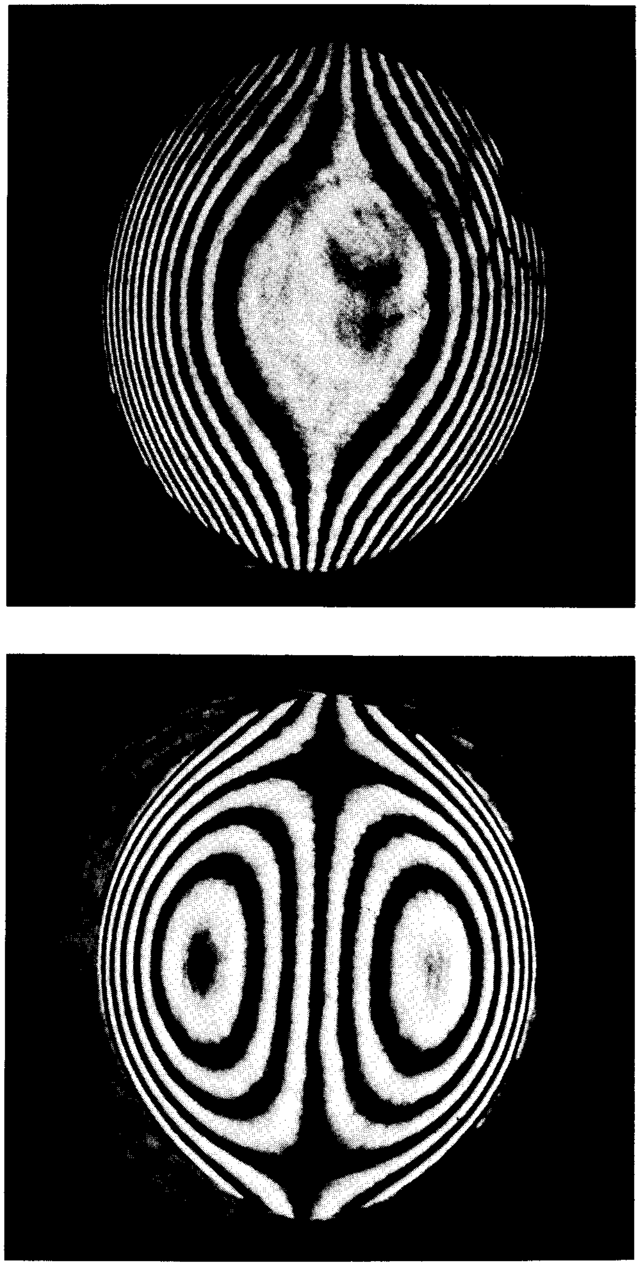
Since the two interfering wavefronts differ in optical frequency by an amount $\omega$, the irradiance of the resulting lateral shear interferogram will vary sinusoidally with time at an angular frequency $\omega$ and heterodyne phase detection can be used.

### Experimental Results

Figure 2 shows two interferograms obtained using the double frequency diffraction grating interferometer to test a lens having spherical aberration. As can be seen, the interferograms have very good contrast. The grating was moved longitudinally between the taking of the two interferograms, as shown in Fig. 1, to change the Gaussian reference sphere for the two interferograms. For Fig. 2(a) the grating was placed near the paraxial focus of the lens, while for Fig. 2(b) the grating was placed near the marginal focus.

**Table I. Bleaching Procedure Used to Make Holographic Diffraction Grating Interferometer**

| | |
|---|---|
| Develop | 30 sec in HRP (1:1 concentration) to average density 1 |
| Wash stop | 30 sec in 21.1°C water |
| Fix without hardener | 1 min |
| Wash | 1 min |
| Bleach | EB-2 until nearly transparent |
| Wash | 1 min |
| Yankee instant film dryer and conditioner | 30 sec |
| Air dry | 5 min |



(b)

Fig. 2. Interferograms obtained using double frequency diffraction interferometer.

Figure 3 shows interferograms obtained using a two frequency crossed grating. As can be seen, two interferograms are obtained for shear in the x direction and two are obtained for shear in the y direction. The undiffracted beam is shown in the center of the pattern. These interferograms illustrate the necessity for obtaining shear in two orthogonal directions when rotationally nonsymmetric wavefronts are tested.

## Summary and Conclusions

The double frequency diffraction grating lateral shear interferometer described in this paper is a very simple and stable device having a minimum of components. The interferometer can be used for either visual or electronic phase measurements. It provides a very convenient way of obtaining shear in two orthogonal directions. Although it was originally intended for use in a heterodyne phase measurement interferometer, it has found many other applications. For example, it can be used to find the focus of a lens. When the grating is placed at the focus of an aberration-free lens, one fringe will cover the pupil. The focus of the different zones of a lens having spherical aberration can also be found, as well as the sagittal and tangential focus of an astigmatic lens. The grating interferometer should provide the basis for a very good OTF measuring instrument.[9-11] Likewise, it could be used to determine index gradients of any medium through which light is passed, for example, gases or liquids.12 If the two frequency crossed grating is placed on a vibrating table, the direction and magnitude of the vibration can be determined. Without a doubt the reader can think of many other applications.

The author would like to thank P. Remijan for making the holographic diffraction gratings and R. Berggren for the encouragement to do this work.

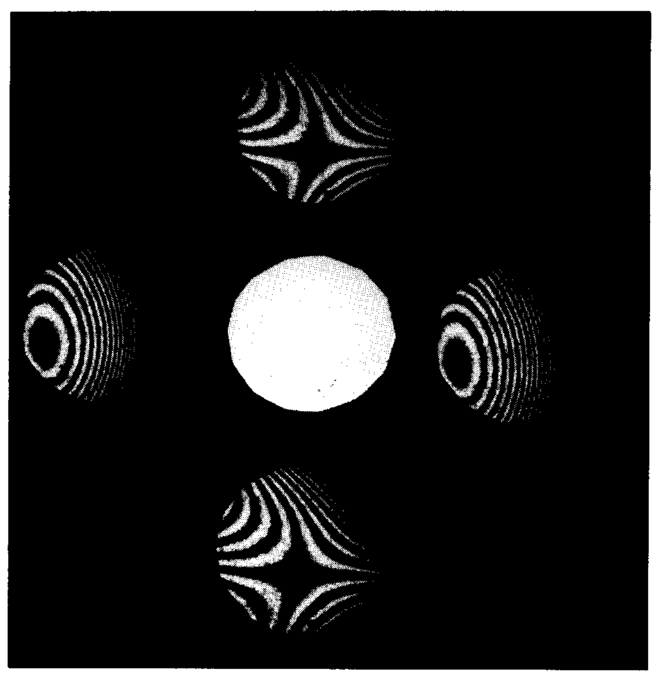


Fig. 3. Interferogram obtained using double frequency crossed grating interferometer.

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