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White Light Extended Source Shearing Interferometer

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A grating lateral shear interferometer is described that can be used with a white light source. The use of the interferometer with certain types of extended sources is also demonstrated.

In a recent paper a simple double frequency grating shearing interferometer, similar to a Ronchi interferometer, was described for use with a quasi-monochromatic point light source.[1] An advantage of the double frequency grating interferometer over the Ronchi interferometer is that it can be made to produce any desired amount of shear and still have only two beams interfering, while the Ronchi interferometer requires that the shear is at least one-half of the pupil diameter to have two-beam interference. However, unlike a Ronchi interferometer that can use a white light source, the double frequency grating interferometer described in Ref. 1 requires a quasi-monochromatic light source. In this paper a modification is described that permits the interferometer to be used with a white light source. Also it is shown that the interferometer can be used with certain types of extended sources.

Figure 1 shows a drawing of the interferometer for the case of a point white light source. The light source is brought to focus near a diffraction grating that has two different line spacings. The grating can be produced holographically as described in Ref. 1. Since the grating has two different line spacings, it produces two diffracted cones of rays at two slightly different angles. A shearing interferogram results in the region of overlap. The angular shear $\Delta\theta$ between the two diffracted cones of rays can be approximated as $\Delta\theta = \lambda(\nu_2 - \nu_1)$, where ν_1 and ν_2 are the two spatial frequencies of the two frequency grating. It should be noted that $\Delta\theta$, the angular shear, is directly proportional to the wavelength λ. For a given optical path difference, the phase is inversely proportional to the wavelength. As will be shown below, since the shear is proportional to wavelength and the phase is inversely proportional to wavelength, for certain types of aberrations the spacing of the resulting interference fringes will be independent of wavelength. Thus the interferometer produces an interferogram whose fringe spacing is completely independent of wavelength.[2] However, this does not mean that it is truly an achromatic interferometer. For an achromatic interferometer not only must the fringe spacing be independent of wavelength, but the fringe position must also be independent of wavelength. In order to obtain a fringe position independent of wavelength a blazed achromatizing grating must be added as shown in Fig. 1. The exact position of this grating is not critical. If this second grating has a spatial frequency equal to one of the spatial frequencies of the two frequency grating, the corresponding diffraction order from the two frequency grating will be completely achromatized or put back together by the blazed grating. In practice the blazed grating should have the average spatial frequency of the two frequency grating, which means it overcorrects one of the diffracted orders and undercorrects the other diffracted order. As will now be shown, this makes the fringe position independent of wavelength.

The achromatic shearing interferometer is illustrated in more detail in Fig. 2. Using the small angle approximation the grating equation gives

$$\theta_1 - \theta = \lambda\nu_1, \tag{1}$$

$$\theta_2 - \theta = \lambda\nu_2, \tag{2}$$

$$\theta_1 - \theta_3 = \lambda(\nu_1 + \nu_2)/2, \tag{3}$$

$$\theta_2 - \theta_4 = \lambda(\nu_1 + \nu_2)/2. \tag{4}$$

Combining Eqs. (1) and (3) and (2) and (4) shows that one beams experiences an angular deviation of

$$\Delta_1 = \lambda(\nu_2 - \nu_1)/2, \tag{5}$$

while the other beam experiences an angular deviation of

$$\Delta_2 = \lambda(\nu_1 - \nu_2)/2 = -\Delta_1. \tag{6}$$

Thus, in the focal plane of lens *L1* there are two beams of light, one shifted an amount $f\Delta_1$ from the unshifted position and the other shifted an amount $-f\Delta_1$. These two shifted light beams will interfere in the region of overlap. If $\phi(x,y)$ is the OPD (optical path difference) distribution of the light that

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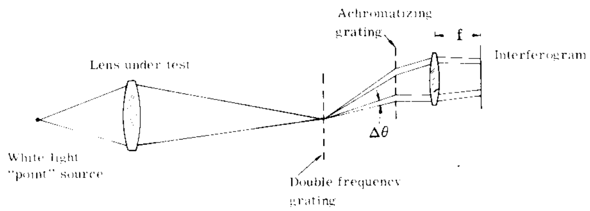

Fig. 1. Double frequency grating, white light shearing interferometer.

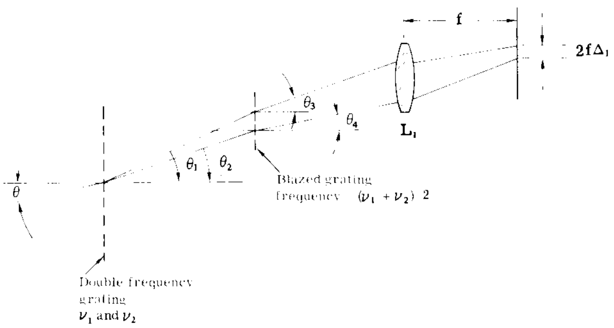

Fig. 2. Achromatic shearing interferometer.

would exist in the focal plane of the lens Ll if the gratings produced no angular deviation, the phase distribution of the two shifted beams can be written as $\phi(x - f\Delta_1, y)$ and $\phi(x + f\Delta_1, y)$. A bright fringe will be obtained in the interference pattern whenever

$$\phi(x + f\Delta_1, y) - \phi(x - f\Delta_1, y) = m\lambda, \qquad (7)$$

where m is an integer.

Equation (7) can be expanded using a Taylor expansion to yield

$$m\lambda = 2f\Delta_1\left[\phi'(x,y) + \frac{f^2\Delta_1^2}{3!}\phi'''(x,y) + \frac{f^4\Delta_1^4}{5!}\phi^{v}(x,y) + \cdots\right], \qquad (8)$$

where $\phi^n(x,y)$ is the nth derivative of $\phi(x,y)$ with respect to x.

It is interesting to look at Eq. (8) for different aberrations. If for example the only aberration is defocus, $\phi(x,y)$ is equal to $A(x^2 + y^2)$, and Eq. (8) becomes

$$m\lambda = 2f\Delta_1(2Ax), \qquad (9)$$

or

$$m = f(\nu_2 - \nu_1)(2Ax). \qquad (10)$$

Since Eq. (10) is completely independent of the wavelength, both the fringe spacing and the fringe position are completely independent of wavelength.

If the above derivation is performed for the interferometer without the achromatizing grating, the right side of Eq. (10) would have an additional term independent of x, but proportional to the wavelength. This means that without the achromatizing grating the fringe spacing is independent of wavelength, but the fringe position depends upon the wavelength.

Even though the achromatizing grating does give a large improvement, the fringe spacing and position do depend slightly upon the wavelength if higher order aberrations are present. If, for example, third order spherical aberration of the form $B(x^4 + y^4)$ is present, Eq. (8) becomes

$$m = f(\nu_2 - \nu_1)(4Bx^3 + 4Bxf^2\Delta_1^2), \qquad (11)$$

which clearly is not independent of wavelength. However, the blurring is much less than what would be obtained if the shear were not a function of the wavelength. If the shear $2f\Delta$ were independent of wavelength the equation describing the loci of fringes would be

$$m\lambda = Bf\Delta(8x^3 + 8xf^2\Delta^2). \qquad (12)$$

A measure of the fringe blurring is $dm/d\lambda$; $dm/d\lambda$ for the grating interferometer is found from Eq. (11) to be

$$dm/d\lambda = [(+8\Delta_1 fBx)/\lambda^2](2\Delta_1^2 f^2). \qquad (13)$$

While for a conventional interferometer in which the shear is independent of the wavelength $dm/d\lambda$ is found from Eq. (12) to be

$$dm/d\lambda = [(-8\Delta fBx)/\lambda^2](\Delta^2 f^2 + x^2). \qquad (14)$$

By comparing Eqs. (13) and (14) it is seen that while having a shear proportional to wavelength does not

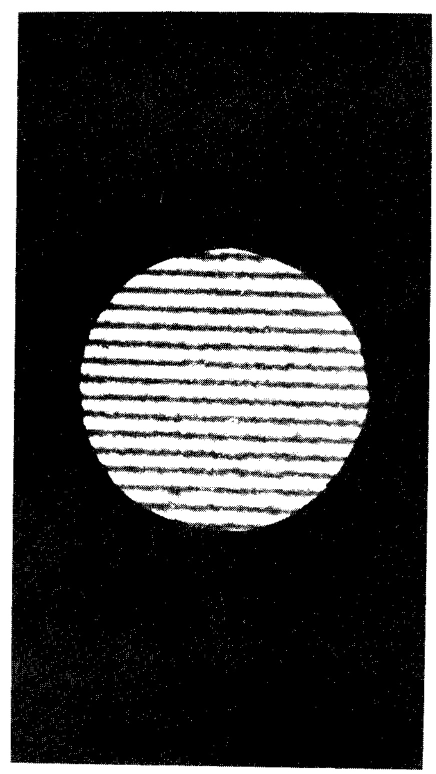

Fig. 3. Shearing interferogram of lens obtained using tungsten arc source.

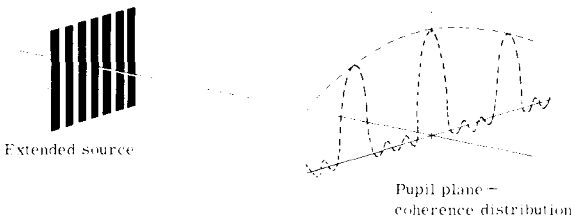

Fig. 4. Extended source and corresponding coherence distribution

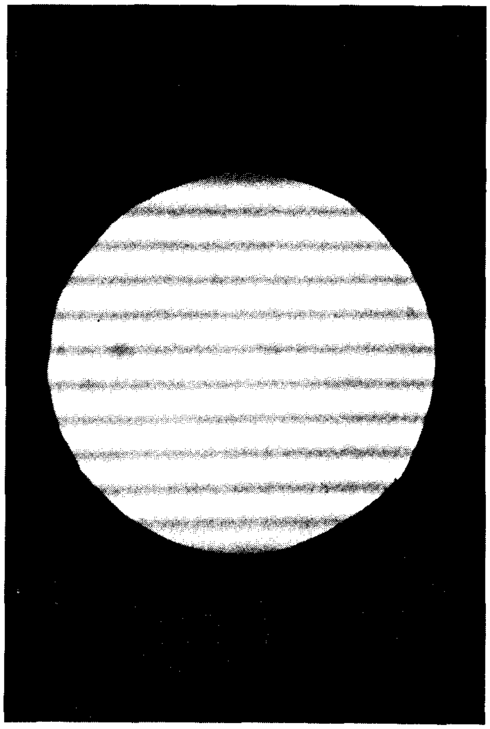

Fig. 5. Shearing interferogram of lens obtained using incandescent bulb with Ronchi ruling in front of bulb.

eliminate the fringe blurring for third order spherical aberration, it does indeed reduce the blurring. If, for example, the shear is 10% of the pupil diameter, making the shear proportional to wavelength reduces the blurring by more than a factor of 50.

The above results show that the interferometer is indeed achromatic if the only wavefront error is defocus. If higher order aberrations are present, the interferometer is not strictly achromatic. However, it is much more nearly achromatic then an interferometer that does not have shear that depends on wavelength. A potential use of this type of interferometer is in an optical system in which there is a real time correcting unit, i.e., in a system where the wavefront error is measured and corrected in real time so the end result is a null interferogram. The small amount of blurring that is obtained by using an aberrated wavefront does not limit the measuring accuracy since the blurring decreases as the measured wavefront error decreases.

Figure 3 shows an interferogram obtained using a white light tungsten arc source. The interferometer setup was the same as shown previously in Fig. 1. The spatial frequencies of the two frequency grating were 290 l/mm and 310 l/mm, and the blazed grating was the average of this, or 300 l/mm.

The interferometer can also be used with certain types of extended sources. In order to obtain good contrast fringes with a lateral shear interferometer there must be a high degree of coherence between points in the pupil separated the shear distance. By the Van Cittert-Zernike theorem the coherence function of a. source is given by the Fourier transform of the intensity distribution of the source.3 Let us consider for example an extended incoherent uniform source that emits quasi-monochromatic light. If a grating or Ronchi ruling is placed in front of the source the coherence distribution is given by the Fourier transform of the grating which is a periodic function as shown in Fig. 4.[4] It should be noted that the spectra shown does not actually exist, it simply represents the coherence distribution. Thus, if points separated by the peaks of the coherence function are interfered, good contrast fringes will be obtained. The spacing of these peaks is determined by the grating frequency and the distance between the grating and the pupil plane. If the grating frequency is selected such that the distance between the peaks is equal to the amount of shear, good contrast interference fringes will be obtained. If the light source is not quasi-monochromatic, the spectrum of the coherence function is scaled up by the wavelength. But the shear is also scaled up by the wavelength. Thus, regardless of the wavelength, if the grating placed in front of the source has the correct spacing to give good interference fringes at one wavelength, good contrast fringes will be obtained for all wavelengths.

Figure 5 shows results for testing a lens using a white light extended source. The experimental setup used was the same as shown in Fig. 1 except the light source used in this case was a regular household incandescent bulb with a Ronchi ruling placed in front of the bulb. It can be shown that since a Ronchi Ruling has a 50% duty cycle, the maximum fringe visibility, which is equal to the peak of the first diffraction order, is $2/\pi$ or about 64%.

In conclusion, the shearing interferometer described in this paper can be used with a white light source and certain types of extended sources. The fringe blurring that normally results from the use of a white light source is completely eliminated if the only wavefront aberration is defocus and is greatly reduced, although not completely eliminated, if higher order aberrations are present.

References

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