Infrared point-diffraction interferometer

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A point-diffraction interferometer (PDI) for use in the infrared is discussed. It is shown that the PDI is simple and easy to use and also yields fringes of constant optical path difference similar to those obtained with a Twyman–Green interferometer. The fabrication of the PDI is described, and typical results obtained using the interferometer at a wavelength of 10.6 μm are shown.

Introduction

The point-diffraction interferometer (PDI) is a simple common-path interferometer capable of measuring optical-path differences (OPD) directly. This interferometer, first described by Smartt in 1972,[1,2] has since become available commercially for use in the visible spectrum. Currently activity in laser-fusion and high-energy-laser systems has stimulated interest in extending PDI principles to the infrared. Thus an infrared point-diffraction interferometer has been developed that provides a simple, stable, self-referencing wavefront sensor requiring no high-quality optical components.

Description

The point-diffraction interferometer is basically a two-beam interferometer in which a reference beam is generated by the diffraction from a small pinhole in a semitransparent coating. The operation of the interferometer is depicted in Fig. 1. Lens L1 is tested in the collimated light from a laser source, in this case a CO_2 laser. The PDI is placed at the focus of lens L1 with the pinhole positioned so that it is coincident with some portion of the aberrated point-spread function of lens L1. The light that is transmitted through the pinhole (which in size is some small fraction of the theoretical unaberrated point-spread function of lens L1) diffracts out to become the reference wave. In the limit of a point, the reference becomes a perfect spherical wave. The light surrounding the pinhole is attenuated but otherwise is transmitted unaffected through the semitransparent coating. The function of this coating is to match amplitudes of the transmitted wave with the reference wave so that the contrast of the resulting interference fringes will be high. The reference-wave amplitude depends on how much light from the point-spread function falls on the pinhole, and this depends on the specific aberration and what part of the point spread function is coincident with the pinhole. Lens L2 is used to reimage the pupil, which contains the aberration and the resulting interference pattern, onto a pyroelectric vidicon (PEV), yielding a video signal that is displayed on a standard video monitor. Tilt and defocus can be introduced in the interference pattern by laterally and longitudinally displacing the PDI.

Analysis

Fourier theory can be used to find the resultant optical amplitude in the image plane of lens L2 due to the effects of the PDI. In this image plane one observes the convolution of the complex amplitude distribution due to the aberrated test lens L1 with the Fourier transform of the amplitude transmittance of the PDI. The complex amplitude of the test lens L1 is written as

$$u(x,y) = \mathrm{cyl}\left[\frac{(x^2+y^2)^{1/2}}{D}\right]\exp[(i2\pi/\lambda)W(x,y)],$$

where D is the diameter of lens L1 and $W(x,y)$ is the OPD of the aberrated wavefront. The amplitude transmittance of the PDI can be written as

$$t(x',y') = \tau_b + (1-\tau_b) \times \mathrm{cyl}\left\{\frac{[(x'-x_0)^2+(y'-y_0)^2]^{1/2}}{d}\right\},$$

which represents a partially transmitting plane of am-

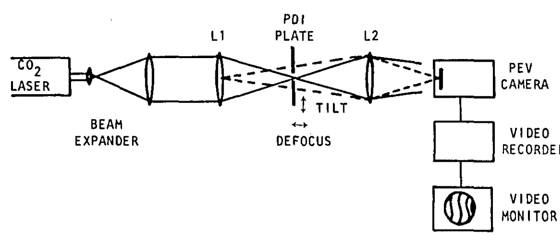

Fig. 1. Infrared point-diffraction interferometer.

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plitude transmittance, τ_b, with a totally transparent circular pinhole of diameter d shifted from the origin.

Assuming unit magnification, and neglecting an unimportant quadratic phase factor across the image, the complex amplitude in the image plane is given by

$$u'(x,y) = \tau_b \operatorname{cyl}\left[\frac{(x^2+y^2)^{1/2}}{D}\right]\exp[(i2\pi/\lambda)\, W(x,y)]$$

$$+ (1-\tau_b)\frac{\pi}{4}\frac{d^2}{\lambda f}\exp[-i2\pi x_0 x/\lambda f)]\exp[(-i2\pi y_0 y)/\lambda f]$$

$$\times \frac{2J_1[(\pi d/\lambda f)(x^2+y^2)^{1/2}]}{(\pi d/\lambda f)(x^2+y^2)^{1/2}}$$

$$* \operatorname{cyl}\left[\frac{(x^2+y^2)^{1/2}}{D}\right]\exp[(i2\pi/\lambda)\, W(x,y)],$$

where J_1 is the first-order Bessel function. The asterisk denotes convolution.

The resultant interference is thus due to the combination of an attenuated version of the original aberrated wavefront and a reference wavefront due to the convolution of the aberrated wavefront with the Fourier transform of the pinhole aperture. Therefore, as the pinhole size decreases, there will be less variation in phase of this reference wave, since the term $[2J_1(\beta r)/\beta r]$ varies little across the image of the pupil cyl(r/D). Note also that a displacement of the PDI from the optic axis (origin) produces a linear tilt in the reference wave. To change focus, a longitudinal displacement along the optic axis will add a quadratic-phase term to the aberration term $(2\pi/\lambda)W(x,y)$. Thus, as long as the PDI pinhole is sufficiently small, a PDI and a Twyman–Green interferometer produce the same type of interferogram.

Infrared PDI

The infrared PDI was made primarily for use with CO_2 laser sources, although the basic principles can be applied at any wavelength. A thin silicon wafer, 25 mm in diameter, was used as a substrate. Pinholes can be made in the semitransparent coating of the PDI by placing spherical microballoons[3] on the substrate and then overcoating. A tiny cactus needle was found to be a convenient tool for placing the individual microballoons on the silicon. After the thin, semitransparent coating (in this case, gold) is deposited, the microballoons are removed by an air jet, thus leaving a pinhole in the coating. This completes the construction of this simple interferometer.

Once a transparent substrate and coating material are selected, the PDI is then completely specified by its pinhole diameter and the transmittance of the coating.

Mounting the PDI in an x,y,z translation mount facilitates alignment tremendously. The common-path nature of the PDI allows it to be used without care for vibration isolation.

To obtain a good approximation to a reference wave, the pinhole diameter of the PDI should be less than half of the Airy-disk diameter produced by an unaberrated optic. Thus, to test optics with f numbers at wavelength λ (measured in micrometers), the pinhole diameter should be no greater than $1.22\lambda\ f\#\,(\mu m)$.

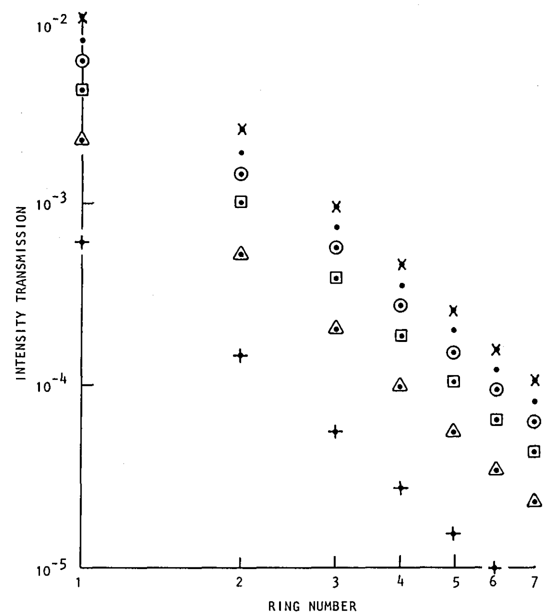
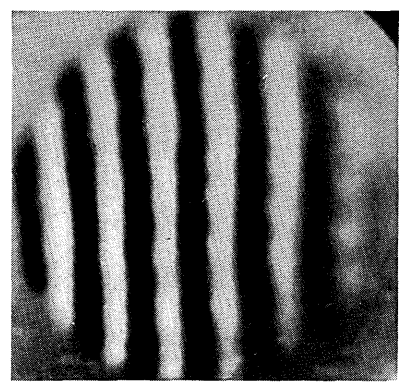
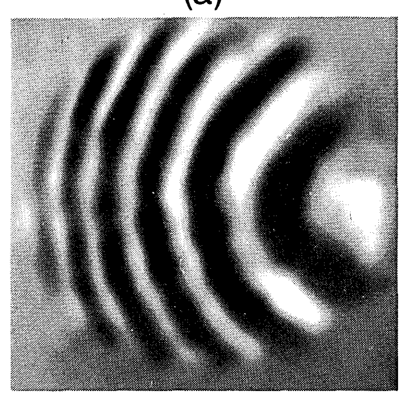


Fig. 2. Transmission of semitransparent coating versus PDI position to achieve unity contrast for unaberrated wavefront. Pinhole diameter in Airy disk units: + = 0.1, ⟁ = 0.2, ⊡ = 0.3, ⊙ = 0.4, · = 0.5, × = 0.6.



(a)



(b)

Fig. 3. Infrared PDI interferogram obtained testing $f/6$ lens: (a) tilt fringes produced by lateral displacement of PDI pinhole from optic axis; (b) tilt and defocus fringes produced by lateral and longitudinal displacement of PDI from paraxial focus.

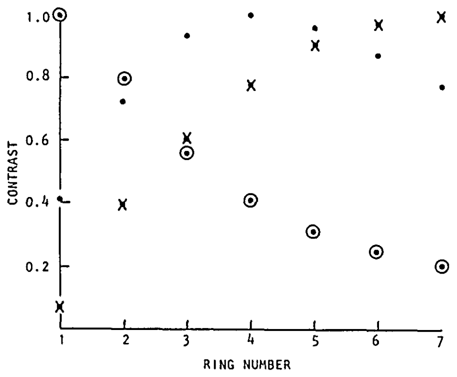


Fig. 4. Fringe contrast versus PDI position for unaberrated wavefront. Results for the PDI coating transmission optimized for three different pinhole positions are illustrated. Pinhole diameter in Airy disk units: ⊙ = 0.4, · = 0.5, × = 0.6.

The diameter of the pinhole (along with its position with respect to the point-spread function) will determine the amount of attenuation produced by the semitransparent coating. Therefore, for any given coating and pinhole diameter, the contrast of the interference fringes will vary with type and amount of aberrations, as well as with the amount of tilt. Figure 2 shows the required intensity transmission for the semitransparent coating to achieve contrast of unity for an unaberrated point-spread function versus position of the PDI pinhole for various pinhole diameters. For a circular pupil, the amount of tilt across the interferogram is equal to 1.22λ times the ring number at which the PDI is positioned. As can be seen from these data, the larger the tilt introduced, in general, the greater the attenuation and thus the greater the light loss.

Testing with the Infrared PDI

The compactness of the PDI lends itself to easy placement, requiring only a system that produces a point focus. Large-aperture telescopes or beam divergers can be tested by using the PDI at the point image.

Shown in Fig. 3 are sample interferograms of an $f/6$ lens being tested. A CO_2 laser was used, and the photograph was taken from a TV image produced by a pyroelectric vidicon. The infrared PDI used had a pinhole of approximately 65-μm diameter and a gold, semitransparent coating that had a transmittance of 2×10^{-3}. The thickness of the gold coating was 200 Å. Contrast variations due to changes in tilt vary for any given semitransparent coating. As shown in Fig. 4, contrast variations are not extreme over a range of approximately 7λ. Note that this variation will change with aberration. The major advantage of the inexpensive simplicity of the infrared PDI is, however, offset by the large cost of the infrared viewing system, the pyroelectric vidicon. This disadvantage does not exist for a visible PDI interferometer.

Conclusions

The infrared point-diffraction interferometer is simple both to use and to construct. As a common-path self-referencing interferometer, it is insensitive to vibration and can be easily placed in any optical system that produces a point image. The disadvantage of requiring an expensive pyroelectric vidicon to image the interference fringes is, however, equally applicable to any infrared interferometer.

References

1. R. N. Smartt and J. Strong, J. Opt. Soc. Am. **62**, 737 (1972).
2. R. N. Smartt and W. H. Steel, Japan J. Appl. Phys., Suppl. 14-1 **14**, 351 (1975).
3. Microballoons are hollow glass or resin spheres available from the 3M Corporation.