Instantaneous phase-shift, point-diffraction interferometer.

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Abstract: We demonstrate an instantaneous phase-shift, point diffraction interferometer that achieves high accuracy and is capable of measuring a single pulse of light at NA greater than 0.8.

Introduction

Wavefront measurement is important in the manufacture of individual optical components and for the optimization of sub-assemblies in optical data storage. The trend towards short-wavelength, high numerical-aperture pickup systems predicates the need for active optical alignment during final assembly. Thus, a real-time measurement system capable of operation at blue wavelengths and at high numerical aperture is of significant utility for the fabrication and test of next generation of optical data storage devices.

Point diffraction interferometry is a simple, self-referencing configuration to measure the wavefront quality of low temporal coherence optical beams.[1] Significant research has been devoted to adapting phase-shift interferometric techniques to common path interferometry to enable high precision wavefront measurements. Several methods have been proposed and have demonstrated accuracies better than one fortieth of a wave.[2,3] These systems all involve a relatively slow temporal phase-shifting process that is incompatible with measuring single, short pulses of light and are sensitive to mechanical vibration. In addition, the retardation and splitting elements are optically thick and add aberration to the measurement, which must be subtracted through calibration. Finally, these techniques have been restricted to low numerical aperture beams because of feature size limitations in the point diffraction device.

In this paper we present a method that accomplishes high-resolution phase-shift interferometry with a self-referencing point diffraction plate where all the phase-shifted data is acquired simultaneously.[4] This has the advantage of allowing the measurement of single optical pulses, which can freeze out vibrations and capture transient events.

Background

Common-path interferometry that takes advantage of a so-called point-diffracting element is a simple, well-known configuration for measuring the quality of an optical wavefront. It was first described nearly 70 years ago by Linnik[1] where a point diffraction element is placed at the focus of an optical beam. The point diffraction element is an optically thin disk approximately ½ the Airy spot diameter, equal to $(1.22\lambda)/NA$, where λ is the optical wavelength and NA is the numerical aperture of the incident wavefront. The disk modulates amplitude and/or phase of the transmitted beam relative to the surrounding area. The point diffraction element can be regarded as generating a synthetic reference beam in addition to transmitting the original wavefront. The basic concept of the point diffraction interferometer is shown in Figure 1.

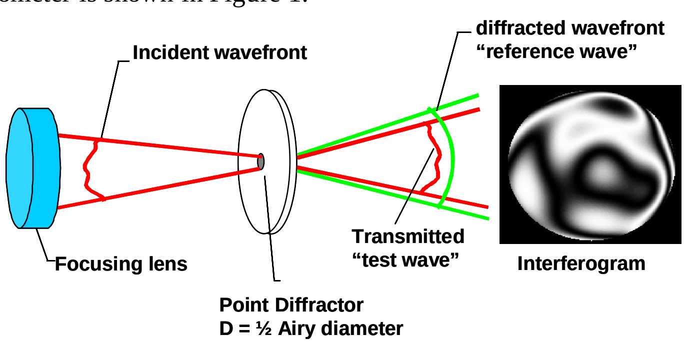

Figure 1. Basic layout of the point diffraction interferometer.

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Early common-path designs produced only a single optical interference pattern, which made it difficult to obtain quantitative information about the wavefront under test. Recently, significant research has been devoted to adapting phase-shifting interferometric techniques to common-path interferometry in order to improve the precision of wavefront measurements.

Providing more than one value of phase shift between the object beam (also referred to as the test beam) and the reference beam has proven to be difficult in a common-path design. Several methods have been implemented, however, using some form of temporal phase shifting (wherein the phase shift between the reference and test waves is introduced sequentially.) For example, a tunable liquid crystal waveplate was combined with a microsphere point diffractor[2] and waveplates with point diffraction holes were combined with rotating polarizers to affect temporal phase-shifting.[5,6] The prior art also describes using point-diffraction interferometers that have non-common paths.[3]

These methods demonstrated a high degree of accuracy (better than one fortieth of a wavelength). Yet, they are restricted to slow-numerical-aperture beams because of the limited feature size of the phase-plate. In addition, the optical thickness of the retardation and splitting elements adds aberrations that must be subtracted through calibration in order to obtain accurate measurements. Also, the temporal nature of phase-shifting techniques requires a high degree of mechanical stability of the pinhole and the interferometer with respect to the test beam during the entire acquisition time (typically, 3 to 7 video frames), thus rendering the technique particularly sensitive to vibrations.

Optical Configuration

The measurement technique combines two innovative ideas: an ultra-thin polarization point diffraction plate (PDP) coupled with an optical configuration for producing four phase-shifted interferograms on a single CCD sensor.[7] The polarization PDP utilizes a finite-aperture conducting grid structure. The plate generates a synthetic reference beam that is orthogonally polarized to the transmitted test beam. The plate has very high polarization contrast (>500:1), works over an extremely broad angular range, and is only 100 nanometers thick. The unique features of the polarizing element make the technique amenable to measuring strongly convergent light from high numerical aperture optics without the need to use a point reference source to calibrate the system. The overall design of the system is shown in Figure 2.

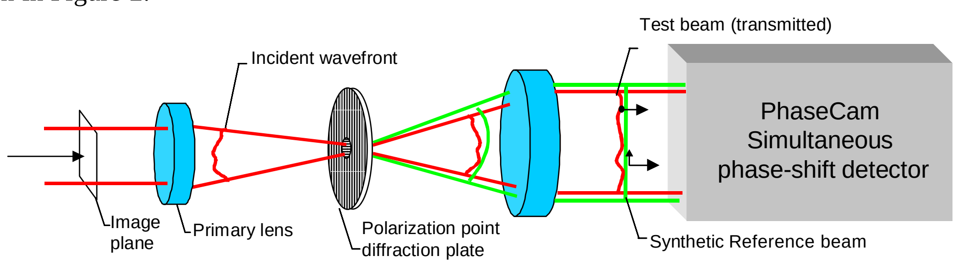

Figure 2. Combination of the polarization point diffraction plate with th e PhaseCam single camera, simultaneous phase-shift detector.

Simultaneous phase-shift configuration

The rapid phase measurement is accomplished with a spatial phase-shift detector where four phase-shifted interferograms are simultaneously generated on a single detector array.[8] The optical layout of the simultaneous phase-shift detector, which is sold under the trade name of PhaseCam™, is shown in Figure 3. The imaging section splits the combined beams into four replicas and images the entrance pupil onto the detector. The four image replicas are transmitted through a polarization phase-mask, made from a combination of waveplates and polarizers, which is located just in front of the detector array. In this case, the detector array is a conventional CCD array having a resolution of 1000 x 1000 pixels. Each sub-image is approximately 500 x 500 pixels. Systems utilizing 4 million-pixel arrays, which have a sub-image size of 1000 x 1000, have also been demonstrated.

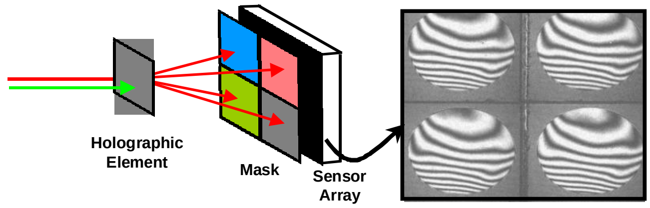

Figure 3. Layout of the simultaneous phase-shift interferometer (PhaseCam^{TM}).

Because the four-interferograms are detected at identically the same time, high accuracy measurements can be made in the presence of significant vibration. With a 1 mW laser and a 1M pixel CCD the electronic integration time is on the order of 30 microseconds.

The wavefront phase can be calculated from

$$\Phi_{x,y}(t) = \mathrm{atan}\left(\frac{A_{x,y}(t) - C_{x,y}(t)}{D_{x,y}(t) - B_{x,y}(t)}\right) \qquad (1.)$$

where A, B, C and D are the intensities measured in each of the four sub-images and correspond to the relative phase-shifts of 0, 180, 90 and 270, respectively. The arctangent function results in a modelo 2π phase encoding, which must be removed by phase unwrapping techniques. We have previously demonstrated repeatability and accuracy better than 0.001 waves rms and 0.002 waves rms, respectively, by averaging 16 single measurements.

Polarization Point Diffraction Plate

The purpose of the polarizing point diffraction plate (PDP) is to produce a synthetic reference wave that is orthogonally polarized with respect to the undiffracted transmitted wavefront. In principle any thin polarizer properly patterned could be used for this purpose. Ideally the polarizer material should be very thin, less than the quantity $1.5\lambda/(NA)^2$, to avoid volume diffraction effects, and should accommodate a wide input angle. It has been demonstrated that long conducting strips with periods much less than the wavelength of light can be used as efficient polarizing elements[9]. These arrays efficiently transmit light with polarization orthogonal to the strip direction while reflecting light with a collinear polarization. The planar nature of such a conducting strip structure permits using it as a polarizer over an extremely wide angle of incidence and over a broad range of wavelengths (provided that the array period remains much less than the wavelength). Jensen and Nordin have shown that sub-wavelength wire-grid arrays can provide a high degree of polarization extinction even when the length of the wire structure is only on the order of half a wavelength.[10] Here we propose and demonstrate several types of polarization diffraction plates based on finite aperture conducting wiregrids.

Figure 2 shows two possible configurations for the polarizing point diffraction plate. Configuration A consists of a uniform grid and a small central region that is clear. This first design is relatively easy to produce by first starting with a uniform grid and selectively removing material. In practice this can be accomplished using focused ion beam milling. While straightforward to manufacture, this type of PDP does not ensure orthogonal polarization between the reference and test beams and therefore, requires careful adjustment of linear input polarization to achieve optimal phase contrast.[11]

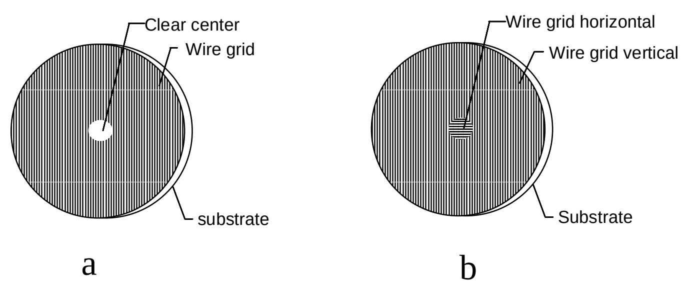

Figure 3. Three different point diffraction plates: a) simple grid with transmitting region and b) crossed grid structure.

Configuration B contains a polarizing element oriented perpendicular to the outside region. In the case of using wiregrid polarizers the two orientations can be accomplished through photolithographic techniques. Configuration B will work with virtually any input polarization, including circular. The angular alignment of the plate relative to the input polarization can be used to optimize the contrast ratio over a range of input aberrations.

Figure 4 shows an image of the central region of a PDP of the type shown in configuration A, fabricated using focused ion beam milling on a commercial wiregrid polarizer. Both the wiregrids and the transparent central diffracting spot are clearly visible. The diffracting region shows good circularity.

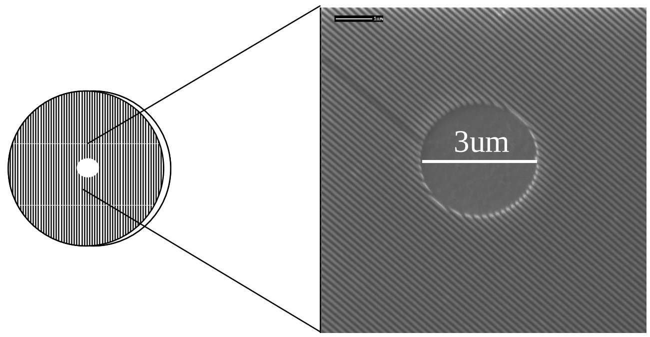

Figure 4. FIB image of a 3 micron hole produced in uniform wiregrid material.

The orientation of the PDP in the test system determines the role of the substrate in the measurement. If PDP is oriented so that the incident wavefront first passes through the substrate, the aberrations of the substrate will be added to the test but not the reference beam. Conversely, if oriented in the opposite direction

Modeling

We constructed a model to examine the performance of the PDP in more detail. We examined the fidelity of the synthetic reference beam in both amplitude and phase as a function of the pinhole diameter, using a approach similar to others.[10] Because we are performing phase-shifting the amplitude roll-off at the edge of the beam does not introduce an error in the measurement, although it does change the fringe contrast across the pupil. The phase non-uniformity will, however, introduce an error. The phase error in the synthetic reference beam is heavily dependent on the aberration in the incident wavefront. To simulate a real-world case we modeled 12 waves of spherical aberration and plotted the PV and rms wavefront error as a function of pinhole diameter in Figure 5. The error remains very low, below 1/100 waves, for pinhole diameters below 0.7 Airy width. Thus, a nominal choice of 0.5 Airy width provides very good accuracy while still permitting some variation in the actual NA of the beam.

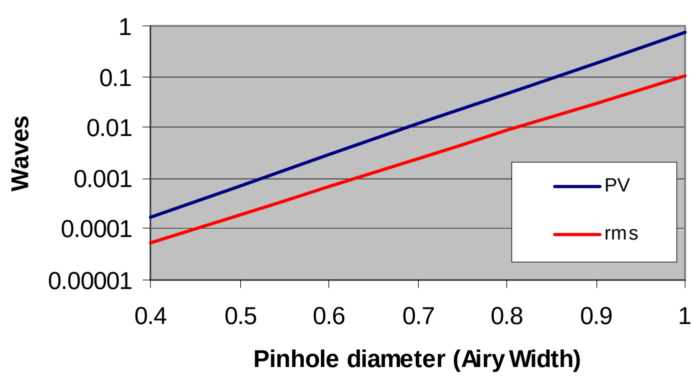

Figure 5. Calculated wavefront error of synthetic reference wave as a function of pinhole diameter (relative to Airy width of focused beam).

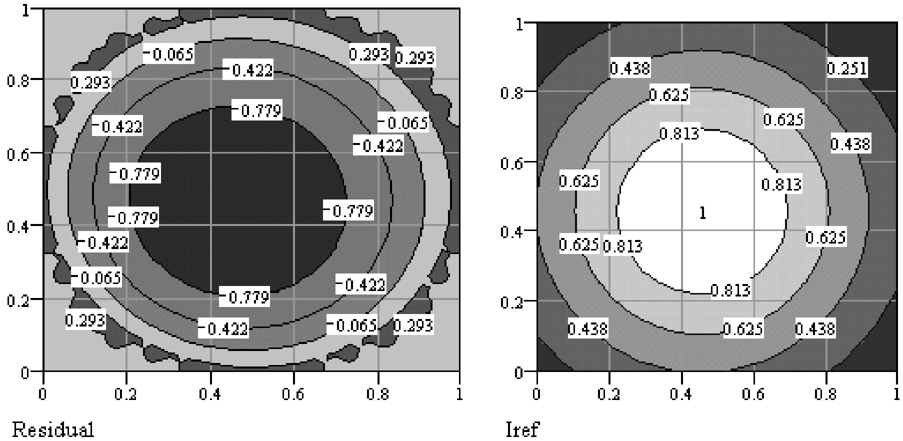

Figure 6. Calculated spatial profile of synthetic reference beam phase and amplitude for point diffraction spot having a diameter of 0.5 Airy width. Units of reference phase are 10^{-3} waves and reference intensity, Iref, are normalized to the peak intensity.

Another important parameter in modeling performance is to consider the fringe contrast of the interferometer. As the beam becomes aberrated, less energy is intercepted by the pinhole and thus the power in the synthetic reference beam decreases. One advantage of our PDP configuration is that varying the input polarization state can control the power in the reference beam. Figure 7 shows the ratio of synthetic reference beam energy to transmitted object beam as a function of input polarization state. The input state can be controlled either by rotating the PDP axially, or by introducing a linear polarizer in the input channel. With moderate amounts of aberration in the input beam , approximately 4 waves distributed over spherical, coma and astigmatism, the fraction of light incident on the pinhole can vary over a range of about 200:1.[12] Thus, the PDP measurement system and be easily adjusted for optimal fringe contrast over a wide range on operating conditions. In practice, the range is limited by the finite extinction ratio of the polarizer.

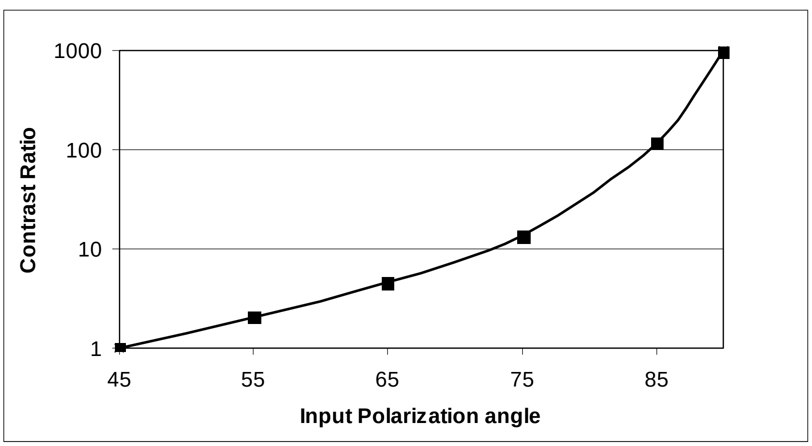

Figure 7. Calculated contrast ratio (synthetic reference to transmitted object) as a function of input polarization angle. Calculation is for an un-aberrated test beam.

Experimental Results

To demonstrate the applicability of the this technique for the testing of optical data storage components we constructed a PDP as shown in Figure 3 (configuration A) and used it to test a lens with NA=0.8 as shown in Figure 8. Figure 8 also shows an SEM photograph of the wiregrid and pinhole region. For this test, the point diffraction element was located on the backside of the substrate. The substrate thickness was selected to approximately match the coverglass compensation design of the lens. The measured interferograms, wrapped phase, and unwrapped phase maps are shown in Figure 9. We intentionally introduced defocus into the measurement system to demonstrate the ability to obtain high contrast phase-shifted fringes over a wide operating range. A 36 term Zernike fit was used to fit the measured data and remove focus. The result shows 1.9 waves of residual aberration after focus is removed.

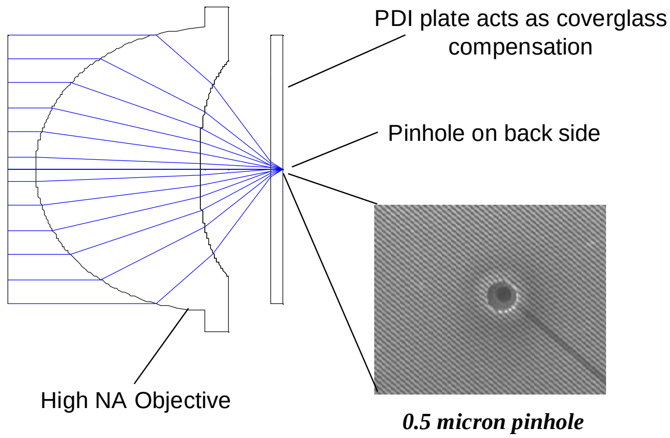

Figure 8. Test setup for measuring a high numerical objective lens.

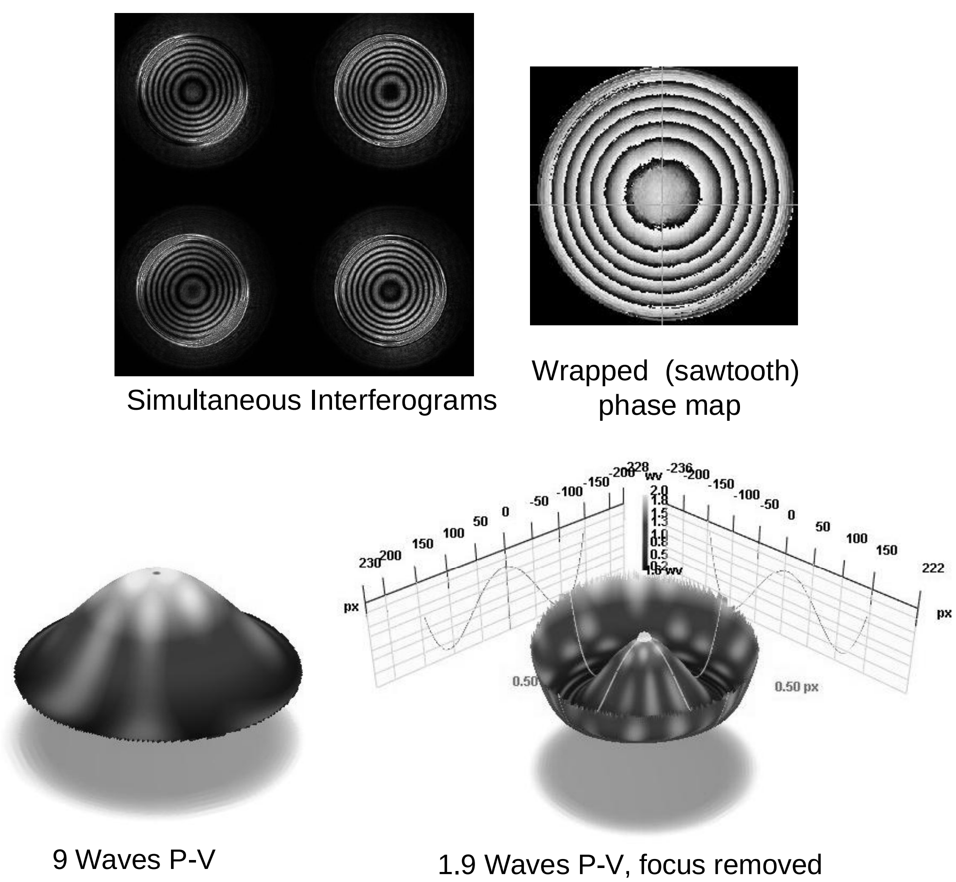

Figure 9. Measurement results for an NA 0.8 lens. Significant defocus was intentionally introduced to demonstrate the dynamic range of the measurement.

The dynamic nature of the measurement was demonstrated by introducing a refractive index gradient from an air jet in the collimated region of the beam before an objective. Figure 10 shows the experimental arrangement used. The objective lens had a focal length of 100mm and was selected to produce an optimal spot size with a 7.5 mm beam and a 10 micron PDP. Figure 11 shows the data measured with the system. The camera integration time was 30 microseconds. The four phase-shifted interferograms were processed to produce a phasemap that was a measure of the air density integrated along the optical path length.

The transient measurement demonstrates a capability that cannot be achieved with conventional phase-shifting point-diffraction interferometers. This capability has several advantages for the testing of optical data storage components. First, it achieves a high degree of vibration immunity, making it possible to test in high vibration areas. Secondly, it make it possible measure wavefronts from short pulses of light such as a write laser where aberrations may fluctuate from shot to shot.

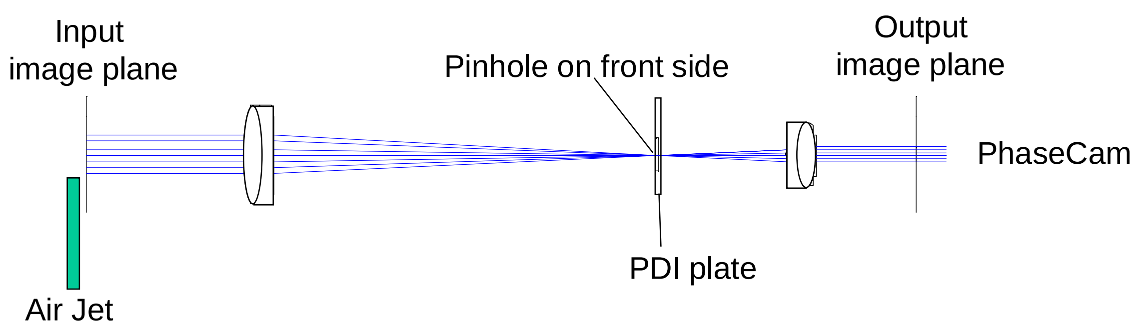

Figure 10. Experimental arrangement for measuring dynamic events.

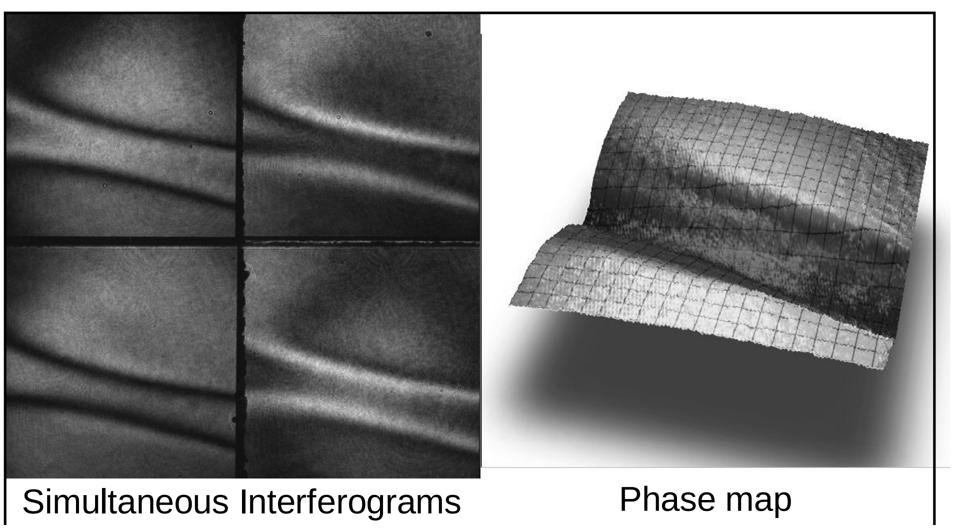

Figure 11. Measurements of transient air flow in the test setup of Figure 10.

Conclusion

We have demonstrated the operation of a new type of point diffraction interferometer that accomplishes high-speed measurement of optical wavefronts. Data is acquired in a single camera frame, making the system suitable for measuring pulsed laser sources such as the write source in DVD and CD writers. The thin dimension of the point diffraction plate coupled with the polarizer's ability to achieve high contrast over a wide-angle make the technique suitable for measuring high numerical aperture components. In addition, the polarizer has good contrast at wavelengths as small as 400nm, so the system is suitable for Blue Ray applications. The unique nature of the PDP plate eliminates the need for a point reference source to calibrate the system.

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