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.

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.[5] 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 1.

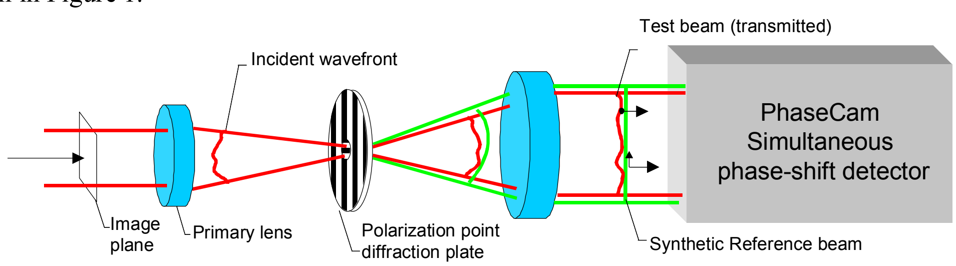

Figure 1. Combination of the polarization point diffraction plate with the PhaseCam single camera, simultaneous phase-shift detector.

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.[6] The optical layout of the simultaneous phase-shift detector, which is sold under the trade name of PhaseCam™, is shown in Figure 2. 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.

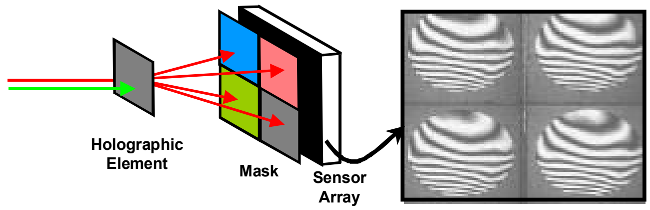

Figure 2. Layout of the simultaneous phase-shift interferometer (PhaseCam™).

Because the four-interferograms are detected at identically the same time, high accuracy measurements can be made in the presence of significant vibration in the test arm. 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.

Point Diffraction Plate

Long conducting strips with periods much less than the wavelength of light can be used as efficient polarizing elements[7]. 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 has 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.[8] Here we propose and demonstrate several types of polarization diffraction plates based on finite aperture conducting wiregrids. Figure 2 shows several of the possible configurations.

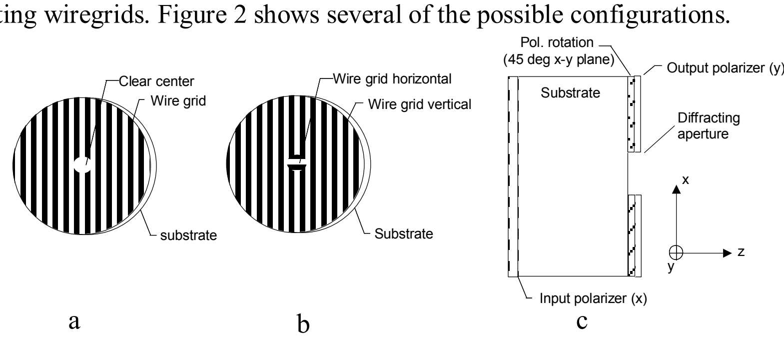

Figure 3. Three different point diffraction plates: a) simple grid with transmitting region, b) crossed grid structure, c) multi-layer structure.

Configuration A consists of a small hole in a uniform grid that is relatively easy to produce but requires careful adjustment of linear input polarization.[9] Configuration B will work with any input polarization but contrast depends on the orientation. Configuration C has optimized contrast for all types of input polarizations, but requires deposition of several layers.

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 4. Figure 4 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 match the coverglass compensation design of the lens. The interferograms and unwrapped phase measurement are also shown in Figure 4. 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 the objective. The transient measurement demonstrates a capability that cannot be achieved with conventional phase-shifting point-diffraction interferometers.

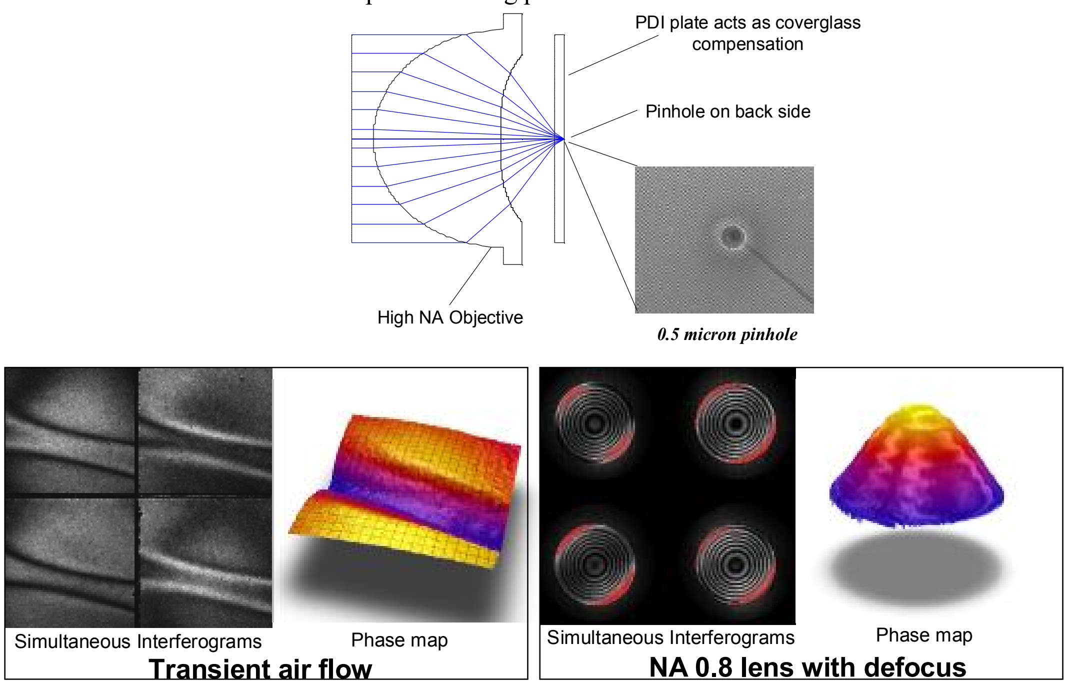

Figure 4. Test configuration for high numerical aperture objective and measurement results.

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[7] see, for example, U.S. Patent No. 6,108,131

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