Three-dimensional imaging by sub-Nyquist sampling of white-light interferograms

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We demonstrate a simple way of increasing the data acquisition and processing speed in a scanning white-light interferometer for surface topography measurement. The method consists of undersampling interference data and processing the resultant sub-Nyquist interferograms in the frequency domain to create complete three-dimensional images. Experimental results on a 20-μm step height standard show a measurement repeatability of 10 nm.

The ideal way to analyze complex interference data electronically is to acquire a high density of data points per interference fringe to capture all the detail of the interference signal. There are, however, practical limits to the amount of data that can be stored, processed, and displayed. This is particularly true of scanning white-light interferometry (SWLI) for surface topography measurement. These instruments use broadband sources together with mechanical translation of the object or reference surface to measure large discontinuous surface features. Typically, a SWLI instrument acquires three to five intensity values per interference fringe per pixel and must process millions of data values to generate a single three-dimensional image. The volume of data involved means that 25 μm of depth range can require several minutes just for data acquisition.

We have found that for many cases of interest it is possible to reduce dramatically the amount of storage and processing required for three-dimensional SWLI by acquiring data at widely spaced depth intervals, equivalent to less than one data point per fringe per pixel. Although the appearance of such undersampled interferograms is strongly distorted, data processing in the frequency domain still permits accurate unambiguous measurement of surface topography. The reduced data-storage requirement also permits separate acquisition and processing steps instead of having to acquire and process data simultaneously. In this Letter we describe the basic principles of the technique and report some preliminary results.

Figure 1 shows a standard interference microscope modified for SWLI. A piezoelectric actuator (PZT) is used to translate the object in a direction parallel to the optical axis of the interferometer over an interval of several tens of micrometers. The resulting interference pattern for a single pixel resembles the data simulation shown in Fig. 2(a). The traditional way of measuring surface topography with such a system is to calculate the fringe contrast as a function of scan position and then relate the point of maximum contrast to a surface height for each pixel in the image.[1,2] There are several ways to calculate the fringe contrast for this purpose, including measuring the maximum and minimum intensity values, by standard phase-shift interferometry formulas[3,4] or digital filtering.[5,6] These fringe-contrast techniques have in common a high density of image frames over the range of PZT translation.

An alternative to measurement of the fringe contrast in SWLI is to transform the interference data into the frequency domain by Fourier analysis and then determine relative surface height by calculation of the rate of change of interferometric phase with wave number. This technique has become widespread in the characterization of one-

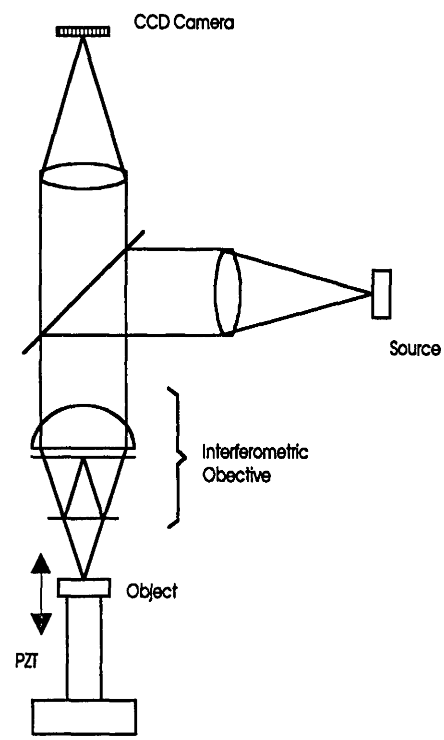

Fig. 1. Scanning white-light interferometer. The PZT translates the object in a direction perpendicular to the optical axis of the objective while intensity images are recorded with the detector array. These images are processed in the spatial frequency domain to generate a three-dimensional representation of the surface topography.

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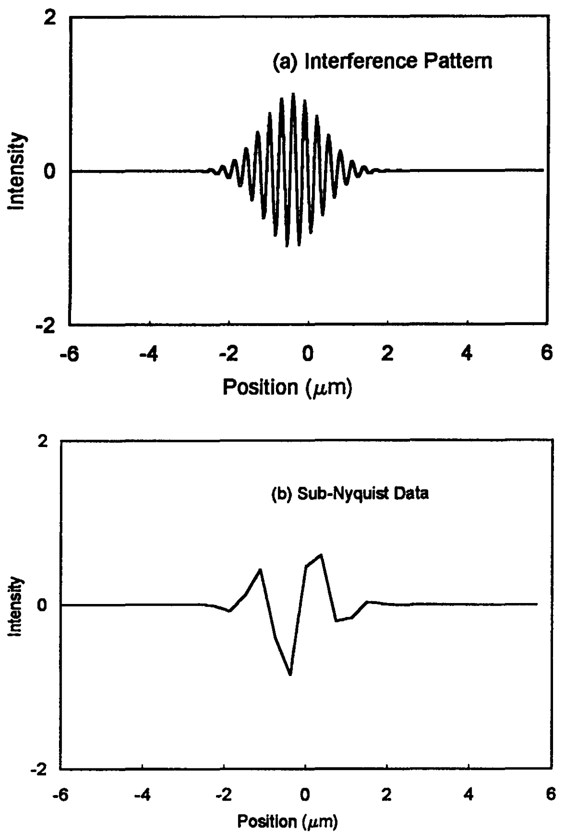

Fig. 2. Simulated interference data. (a) Dense sampling correctly represents the complete interference pattern. (b) Sub-Nyquist sampling (1 point every $5\pi/2$) results in a severely distorted data set that is still useful for three-dimensional imaging if correctly processed.

dimensional waveguides, which are so dispersive that measurements based on fringe contrast alone are inadequate.[7] Although this technique has previously been restricted to these special one-dimensional problems, there are many advantages to frequency-domain analysis for three-dimensional imaging.

The fundamental physical concept of frequency-domain processing of interferograms is that a complex broadband interference pattern may be considered the incoherent superposition of several simple single-frequency interference patterns. Each of these single-frequency patterns may be represented by the simple formula

$$I = 1 + \cos(\phi), \qquad (1)$$

where

$$\phi = kZ. \qquad (2)$$

Here k is the angular wave number and the distance Z is the phase-velocity optical path difference in the interferometer. For simplicity we assume a perfectly compensated and intensity-balanced interferometer. From Eq. (2) it is clear that

$$Z = \mathrm{d}\phi/\mathrm{d}k. \qquad (3)$$

Thus one way to measure distances is to calculate the rate of change of phase with spatial frequency. To calculate this rate of change, we need phase values ϕ over a range Δk of frequencies centered around a mean frequency k_0. This is exactly what the Fourier-transformed white-light interferogram provides.

Spatial frequency-domain analysis has the interesting characteristic that data sampled at less than the Nyquist frequency (two data points per fringe) is still useful, provided that care is taken to avoid segmenting and overlapping the frequency bandwidth.[8] For example, if data are acquired at phase intervals of $5\pi/2$, as shown in Fig. 2(b), the mean frequency k_0' of the undersampled data is five times lower than that of the actual interference pattern, but the bandwidth Δk and the rate of change $\mathrm{d}\phi/\mathrm{d}k$ are exactly the same. The phase ϕ_0' at k_0' is also the same as the phase ϕ_0. These characteristics are evident in Fig. 3, which shows the Fourier-transformed data separated into a modulus [Fig. 3(a)] and a phase [Fig. 3(b)].

A simple linear fit to the phase data in Fig. 3(b) provides the rate of change $\mathrm{d}\phi/\mathrm{d}k$ and the mean phase ϕ_0'. This information can be used to calculate the distance in either one of two ways. The rate of change of phase can be used alone to calculate distance with Eq. (3). Alternatively, this preliminary calculation can be used to remove the 2π ambiguity in the mean phase ϕ_0', which may then be used in an inverted form of Eq. (2) for high-precision measurements.

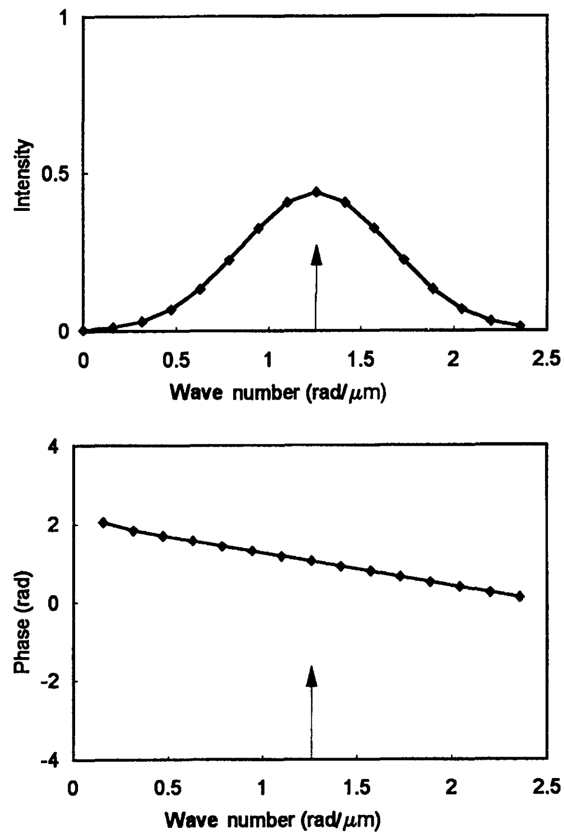

Fig. 3. Fourier transform of the sub-Nyquist data shown in Fig. 2(b). The arrow indicates the mean or peak wave number, which is much smaller than the actual mean wave number of the interference pattern because of undersampling. The phase information in (b) is used to calculate local surface height.

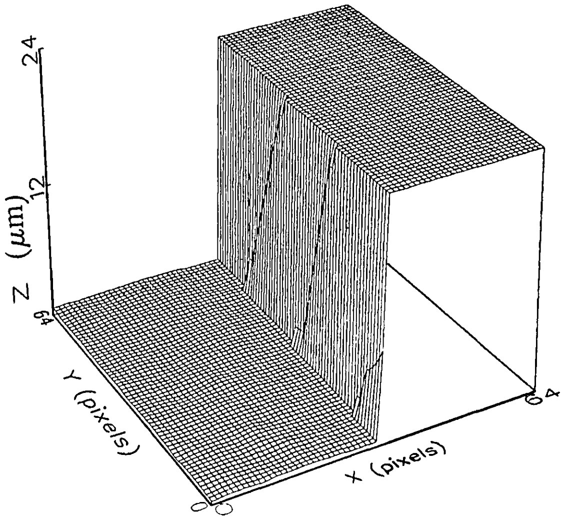

Fig. 4. Three-dimensional profile of a 20-μm standard step height obtained from sub-Nyquist white-light interferograms. The repeatability of the measurement is 10 nm.

Figure 3 shows how sub-Nyquist sampling can be applied advantageously to the analysis of surface features. The apparatus shown schematically in Fig. 1 was used to profile a 20-μm standard step height with sub-Nyquist data sampling. The experiment was performed on a standard Nikon microscope with an incandescent light source and a 10× Mireau interference objective. A 64 × 64 CCD camera captured the resultant images. The PZT stage translated the object over a range of 24 μm, during which 64 frames of intensity data were acquired and stored in a personal computer. The three-dimensional representation shown in Fig. 3 was then constructed by applying Eqs. (2) and (3) to the Fourier-transformed interferograms. The instrument accurately determined the step height with a repeatability of 10 nm.

The surprising conclusion is therefore that even highly corrupted data such as those shown in Fig. 2(b) can provide accurate results provided that the data are processed in the spatial frequency domain. Indeed it is hard to see how useful information could be obtained any other way, because it would be difficult to extract a fringe-contrast envelope from Fig. 2(b) as required for the more familiar methods of SWLI. The principal disadvantage with use of undersampled data is of course a reduced signal-to-noise ratio not only because fewer data are acquired but also because of aliasing of noise at higher frequencies than the sample rate. However, this reduction in signal-to-noise ratio may in many circumstances be offset by the ability to average several scans during a shorter period and with less computer storage than is required by conventional methods. The rapid scans also reduce the sensitivity of the instrument to certain environmental effects, such as mechanical drift due to temperature and vibration.

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