Long-wavelength laser diode interferometer for surface flatness measurement

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Modern phase-shifting interferometers grew out of a traditional need for high-precision evaluation of polished optical components. The technology is very mature now, enough so that it is reasonable to look for other applications of these instruments. Some important industrial applications have been found, particularly in the data storage industry. However, there are still many applications where the speed and high accuracy of phase-shifting interferometry would be very desirable, but the surface-finish requirements to generate visible-wavelength interference fringes are impractical.

One way to increase the range of surface finishes compatible with interferometric analysis is to increase the source wavelength. The most common wavelength for commercial interferometers is 0.63µm, at the edge of the visible range. A few Nd:YAG interferometers are available commercially at 1.06µm, although even this wavelength is insufficient for many surfaces, and the radiation is not eye safe. Another option is a CO_2 interferometer[1] running at 10.6µm, but these machines tend to be expensive, difficult to use, and inaccurate.

Improvements in the reliability and affordability of 1.55-µm wavelength distributed-feedback laser diodes has opened up a new wavelength region for interferometric metrology.[2] The 2.5X increase in wavelength when compared to HeNe-based interferometers is sufficient a variety of important parts ordinarily considered too rough or distorted for visible-wavelength interferometry. A comparison in fringe contrast as a function of surface roughness is shown Fig.1 for 0.63- and 1.55-µm wavelengths.

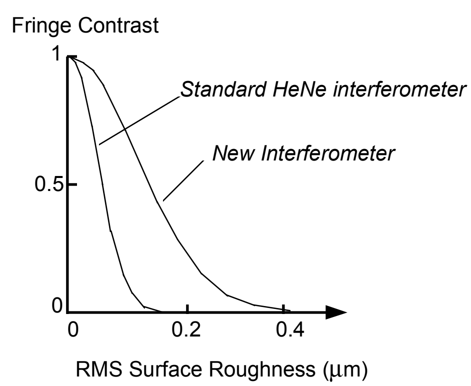
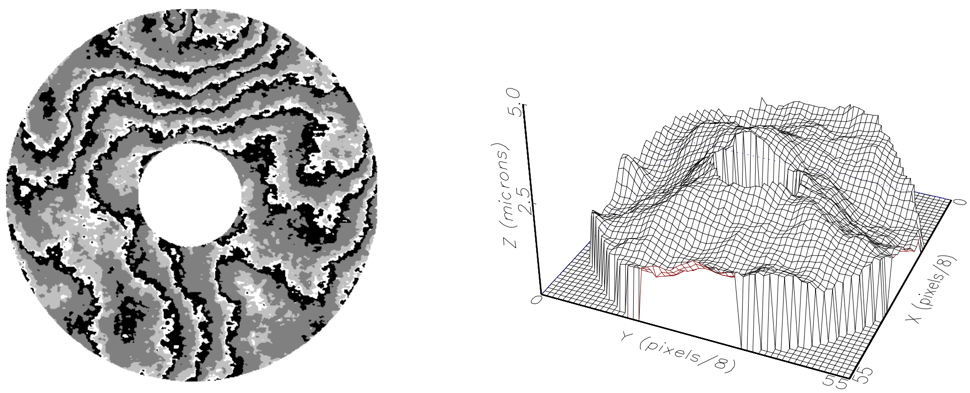


Figure 1. Improvement in fringe contrast with the 1.55µm interferometer.

A specific example of improved capability at near-infrared wavelengths is shown in Fig.2. On the left we see the wrapped phase map generated by phase-shift interferometry at 1.55μm for an aluminum part having a surface roughness of 0.25μm RMS. This is far too rough for visible wavelengths, and a conventional HeNe interferometer does not produce recognizable fringes for this part. The right-hand side of the figure shows the corresponding surface profile produced by analysis of the phase data.



Wrapped phase map *Surface height map*

Figure 2. Wire-brush finished aluminum disk (90-mm diameter).

Another example of a rough part is shown in Fig.3. The 1.55μm wavelength is just long enough to accommodate fine-ground surfaces, making it possible to test optical components before final polishing. We have tested a large number of samples for various applications, including automotive parts, air brakes, disk-drive components, and ceramics.

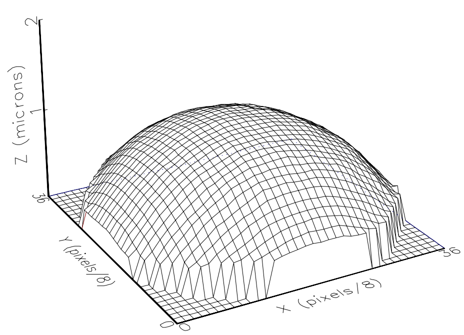


Figure 3. Height map for a 75-mm diameter ground glass surface (5-μm grit).

Although the near-infrared technology is much more affordable than it used to be, high-performance laser diodes and detectors are still more costly than HeNe lasers and visible-wavelength cameras. In order to make the near-infrared wavelength region accessible to potential users, we have greatly simplified the opto-mechanical design of the interferometer to reduce the overall cost of the instrument.

Our experimental laser-diode interferometer uses the off-axis Fizeau geometry shown schematically in Figure 4. An off-axis arrangement was chosen to avoid problems with optical feedback to the laser diode. Other advantages to this geometry include the elimination of the expensive beam splitter prism and quarter-wave plate combination characteristic of most Fizeau interferometers, and the reduction in the number of parts contributing to spurious reflections and scattering. To further simplify the optical design, spatial filtering and beam-shaping optics for the laser have been left out. Instead, we use the natural divergence of the beam emitted from a single-mode fiber for illumination. The long f-ratio imposed by the rate of beam divergence permits the use of a very simple collimator optic consisting of a single f12 plano-convex lens oriented so that the plano side doubles as a the reference surface. The camera is an IR vidicon with 600-line resolution. The 5mW laser power is completely eye safe, since the cornea is opaque to 1.55-μm radiation.

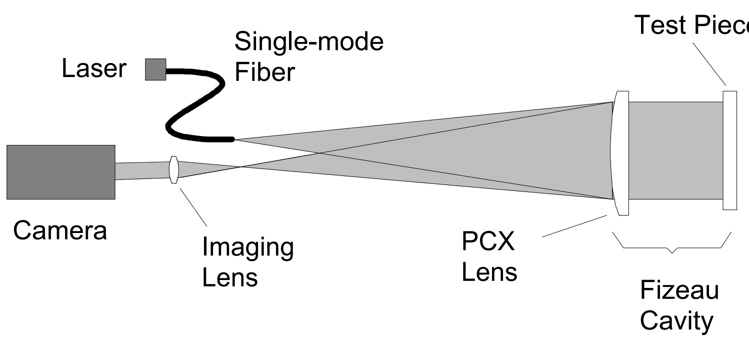


Figure 4. Near-infrared laser diode interferometer for flat surface testing.

A useful characteristic of laser diodes is that the emission wavelength can be modified very easily by adjusting the pump current. Wavelength tuning is an effective way of performing phase shifting without the need for large and expensive piezo stages.[3,4,5] We acquire a succession of intensity images at equidistant phases shifts, then calculate the phase at each pixel in the image.[6] The resulting phase maps are post-processed to generate three-dimensional images (Figs.(2)&(3)).

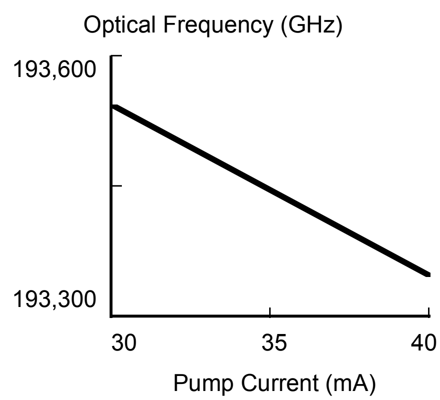


Figure 5. Tunability of laser diodes.

One concern when using laser diodes for phase shifting is the repeatability and linearity of the wavelength tuning. To reduce these concerns, we have developed a new phase-shift algorithm that is relatively insensitive to first- and second-order variations in the tuning curve shown in Fig.(5). We acquire seven intensity measurements per pixel during the wavelength ramp. The measurements correspond to integrated intensities given by

$$g_j = A \cdot \left(1 + V \cdot \cos\left(\theta + (j - 3)\alpha \right) \right), \text{ (1.)}$$

where V is the fringe visibility, A is an overall constant, $\alpha = \pi/2$ and $j = 0 \ldots 6$. The new seven-frame algorithm is

$$\varphi = \tan^{-1}(T) \quad \text{(2.)}$$

where

$$T = \frac{7 \cdot (g_2 - g_4) - (g_0 - g_6)}{-4 \cdot (g_1 + g_5) + 8 \cdot g_3}. \text{ (3.)}$$

Fig.6 is illustrates the low sensitivity to errors in the phase ramp of the new seven-frame measurement procedure.

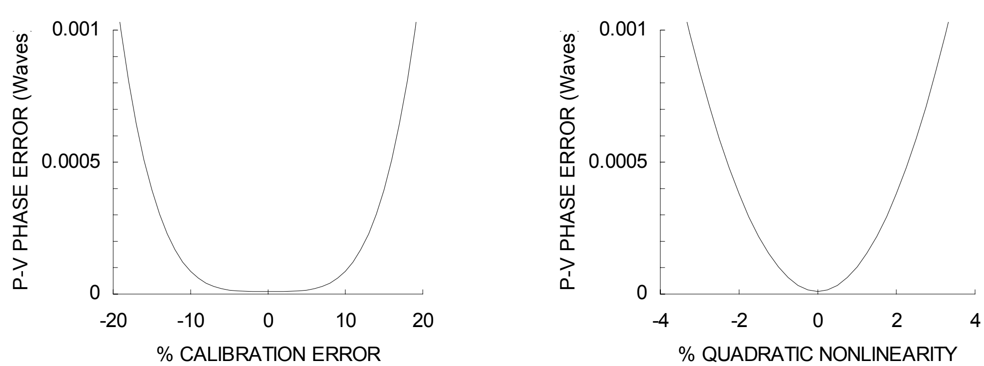


Figure 6. Performance of interferometer in the presence of first- and second-order distortions in the phase shift (left and right, respectively). The high accuracy of the laser diode interferometer is due in part to the relative insensitivity of the seven-frame measurement procedure to distorted phase shifts.

The RMS repeatability (i.e. instrument precision) for the laser diode interferometer has been determined by taking a series of profile measurements, subtracting them, and calculating the RMS values for the difference maps. There is no averaging of multiple data sets, since we do not expect that this would be the normal mode of operation. The instrument precision of the new laser diode interferometer without averaging is $\lambda/250$. This ratio is comparable to that of conventional HeNe-based instruments, indicating that there is no loss in relative precision when using wavelength tuning as compared to mechanical phase shifting.

These experiments show that wavelength-tunable, near-infrared laser diodes can significantly enlarge the range of applications for phase-shifting interferometry while maintaining high precision. For machining and optical production applications requiring high accuracy with improved tolerance for surface roughness and departure, the 1.55μm laser-diode interferometer is a practical alternative to conventional optical testing equipment.

References

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