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Single lens logarithmic confocal distance measurement array

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Abstract: This article presents a method and results based on confocal microscopy for non-contact axial distance measurement from a lens to a partially reflective surface using an array of photodetectors. The ratio of the photodetector signals is independent of the surface reflectivity and light source variations over a range of distance. By using logarithmic photodetector signals the object distance is proportional to the difference between the signals. This technique potentially allows measurement of sound produced by single living cells, or the high velocity surface shape changes in the hohlraum in laser fusion experiments.

OCIS codes: (150.5670) Range finding; (180.1790) Confocal microscopy; (280.3400) Laser range finder.

References and links

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1. Introduction

Confocal microscope based optical systems are used in high speed, nanometer precision, non-contact distance measurements [1, 2] with minimal disturbance to the object being measured. The principle method is to use a lens to focus light onto an object to be measured. The reflected light from the object passes back through the lens and is focused onto a pinhole covering a photodetector. If the object is moved away from the focal point, the light incident on the pinhole will be out of focus which reduces the detected intensity. Thus the distance is found by correlating the intensity received by a photodetector behind a pinhole to the distance of the object. However, since the distance is correlated to photodetector intensity the measurement is susceptible to variations in the light source intensity or surface absorption. Here we show that an array of photodetectors can be used to reduce or eliminate the effect of intensity variations in the light source or surface reflectivity on confocal based distance measurement. By subtracting the logarithm of one photodetector signal from another, the measured distance can be made independent of the intensity as long as the detector signals have an acceptable signal to noise ratio. The conversion of the linear photodetector response curves to logarithmic simplifies division operations and is similar to the photoreceptor and neuron response curves that allow the

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perception of color in animals based on the relative photoreceptor response ratios [3,4]. Unlike interferometric or chromatic based distance measurement, there is no computational burden such as counting fringes or spectral analysis to delay the conversion of the sensor input to a distance [1]. Also, the simple elements that make up the array can be miniaturized to make photonic integrated optical circuits. Finally, the nearly diffraction limited spot size and high speed can enable a number of applications such as converting the motion of a bacteria into sound, measuring a crystal oscillator, or determining how the surface of a hohlraum deforms during laser fusion experiments.

2. Experimental setup and analysis

The experimental setup for the confocal distance measurement shown in Fig. 1 will now be described. First the 633 nm light from a 100 mW diode laser (Oclaro HL63163DG) is collimated by an aspheric lens L1. The light then passes through an anamorphic prism pair (APP1) to correct the ellipsoidal intensity distribution. The polarization of the light is controlled by a pair of Fresnel Rhombs FR1. The propagation angle and translation of the light is performed by the three folding mirrors M1-M3. The light then passes through a polarization beam splitting cube LP1 oriented to pass horizontally polarized light. The light passes through a wedged prism beam sampler BS1 to compensate for the displacement of beam sampler BS2. The beam sampler BS2 reflects a small portion of the light into a silicon photodetector PD3. The signal from PD3 is used to measure the time varying intensity of the laser light source. The light then passes through the polarization beam splitter PBS0, a 1/4 wave plate (QWP1) then a 20x objective lens L2 with a numerical aperture of 0.4 that focuses the illumination light onto the front surface of a glass slide with a surface area of approximately 5 mm^2. The numerical aperture does not necessarily affect the resolution of the axial distance measurement since it is a function of the lens aperture and focal length. The axial resolution is only affected by the focal length of the lens, and not the diameter of the aperture. The benefit of a larger diameter lens is a reduction in the cross sectional spot size in the plane perpendicular to the optical axis at the focal point. The slide fragment is attached to a PZT and stepper motor based linear actuator with a displacement range of 20 μm and 11 mm respectively.

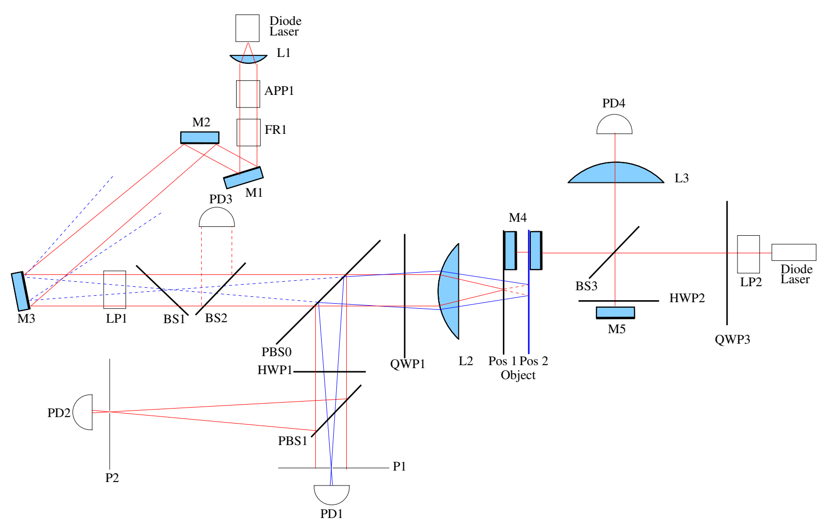

Fig. 1. The experimental setup used to capture data from an array of two photodetectors.

The photodetector signals are sampled at a rate of 20 KHz. All the signals have a voltage

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standard deviation of 1 mV. The motor position is incremented in 5 steps = 0.474 μm every 700 ms. As the glass slide moves toward the lens L2, the point where the rays of reflected light converge moves away from the opposite side of the lens L2. Since the distance to photodetector PD1 is closer to the lens L2, the light focuses on the pinhole in front of PD1 and generates the first signal peak in PD1. The intensity of light then decreases as the cone of light blocked by the pinhole. As the glass moves even closer to L2, the point where the rays of reflected light converge passes through the pinhole in front of PD2. This causes the PD2 signal to peak. Similarly the signal from PD2 decreases as the cone of light diverges as the glass plate continues to move toward the lens L2. Since the nanostepping motor and linear stage do not move in a linear fashion, a Michelson interferometer is used to verify the distance traveled by the glass sample by counting fringe crossings.

The distance between the slide and the lens L2 is changed using the microstepping motor (NSA12) and a linear stage. Some of the light incident on the glass is reflected from the glass surface back through the objective and passes through QWP1 and reflects off of PBS0. The light then passes through half wave plate HWP1 which allows controlling the ratio of light transmitted and reflected by the polarization beam splitter PBS1. The reflected light from PBS1 passes though the 300 μm pinhole P2 and is converted to an electrical signal by PD2. The light transmitted by PBS1 passes through a 200 μm pinhole P1 and is converted to an electrical signal by PD1. The pinhole diameter P2 is bigger than P1 in order to compensate for the increasing spot size as the distance from lens L2 increases. The signal from photodetectors PD1-PD3 are amplified and digitally recorded as the confocal measurement signal. The linear displacement of the glass slide is measured by counting the fringes from a Michelson interferometer due to the movement of mirror M4. The intensity fringes are converted to an electrical signal using photodetector PD4.

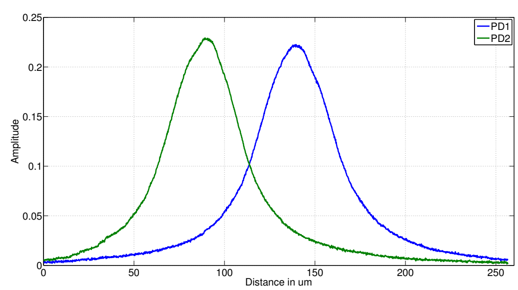

Fig. 2. The experimental data for the two photodetectors PD1 and PD2 versus axial distance from the lens L2 in micrometers. The peak for PD2 occurs to the left of the peak for PD1.

The resulting signal from PD1 and PD2 are displayed in Fig. 2. The horizontal axis represents the position of the glass relative to L2. The vertical axis represents the amplified photocurrent from the photodiodes PD1 and PD2. The response of the two photodiodes represent unique distances as measured from the lens to the glass. A three dimensional graph of the mapping between the axial distance Z to the lens L2 versus the signals received from PD1 and PD2 is shown in Fig. 3. As can be seen in the figure each point on the Z axis has a unique coordinate in the PD1 and PD2 plane. Additionally, the ratio of the signal between PD1 and PD2 can be used to uniquely determine the distance Z over the range between the peaks. The three regions with the log of the ratio between PD2 and PD1 is displayed Fig. 4. Since the derivative of PD1 is the opposite of PD2 in region B and not in the other two regions it is easy to determine if the object is in region B by moving the glass plate. The advantage of measurements in region B are that the distance measurement is tolerant of changes in the amplitude of the signal from PD1 and PD2. These amplitude changes might be caused by the light source, or the reflectivity of the surface being measured. This region can be extended by adding more sets consisting of a polarization beam splitter, pinhole, and photodetector as shown in Fig. 5. An array of N sets of polarization beam splitters, half wave plates and photodetectors with pinhole apertures can be arranged as shown in Fig. 5 to extend the distance measurement range without losing distance resolution as long as the intensity of the laser light is increased to maintain the signal to noise ratio at each photodetector.

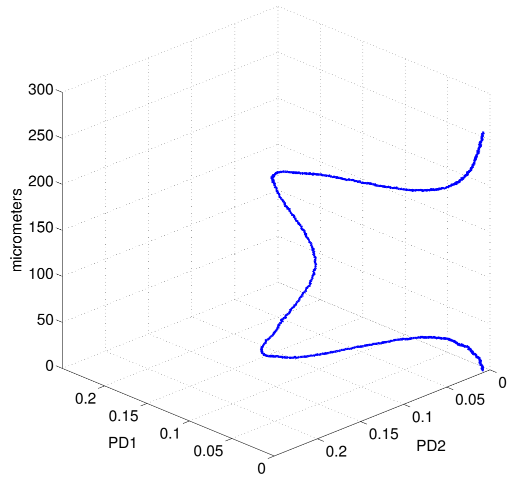

Fig. 3. Three dimensional plot of photodetector signals PD1 and PD2 in the horizontal plane versus the axial distance in micrometers along the optical axis of lens L2.

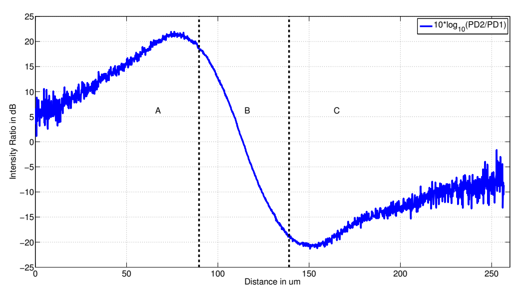

Fig. 4. Plot of the log of the ratio between the photodetectors PD2:PD1 versus axial distance. The dashed vertical lines represent the peak intensity from each photodetector as the distance to the object is changed. In region A both photodiodes intensity increase. In region B, the photodiode PD1(PD2) signal increases (decreases) as the axial distance increases. In region C both photodiode signals decrease with increasing axial distance.

3. Findings

The main findings for this work are that it is possible to make a scalable array of photodetectors to measure distance to a partially reflective surface. This method of distance measurement is non-contact and can measure the distance to objects with micrometer dimensions. With a 20x microscope objective and an array of two photodetectors the sensitivity is 0.84 dB/μm. The electronics have a noise standard deviation of 1 mV. It was also found that the ratio between two photodetectors used to measure distance is tolerant of light source amplitude and surface absorption fluctuations. This is illustrated in region B displayed in Fig. 4. The region B is bounded by the peak of photodetectors PD1 and PD2 as shown in Fig. 2. The derivative of the

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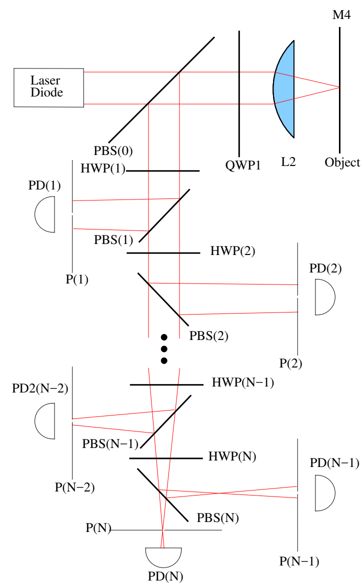

Fig. 5. The configuration for an array of N confocal photodetectors.

photodetector signal versus distance is the opposite(negative) between the two photodetectors which allows detecting a malfunction in the two photodetectors. This greatly reduces distance measurement noise that would otherwise make distance measurements unusable.

4. Conclusion

In conclusion a non-contact optical method of measuring distance with nanoprecision and tolerance to surface absorption and illumination laser amplitude fluctuations has been presented. This distance sensing method can be used to sense the motion of objects without a vibration medium since it only needs an optical path to the object to be sensed. This allows a vibrating object to be undisturbed by the measuring device or a medium. This property is useful for measuring vibrating or oscillating objects such as crystal oscillators or surface acoustic wave devices which can only function properly with minimal mechanical disturbance. A sound based measurement is affected by the attenuation of high frequency sound in air of 120 dB/m^{-1} at a frequency of 1 Mhz [5]. However the confocal distance technique uses a light based measurement which is not attenuated by air.

The measurement location on the object to be measured can be a nearly diffraction limited cross sectional area on the surface which allows nanometer resolution ultrasonic measurements of the surface of very small objects such as bacteria, or the surface of a hohlraum. The ability to electro-optically convert the motion of a surface(sound) into an electrical signal is equivalent to a microphone. So, effectively this technique gives the ability for researchers to give a microphone to a single celled organism such as a bacteria. Recent research indicate that single celled organisms use mechanical sound waves to promote growth [6]. A confocal microphone could boost research in this area to discover other reasons bacteria communicate. The phototoxic effect is reduced in living cells by using a monochromatic light because the excitation of photosensitive chemicals in cells usually requires multiple excitation wavelengths to efficiently transition to a high energy state that generates cell damaging reactive oxygen species [7].

Additionally this method can be used for low frequency measurements, unlike an etalon based optical microphone [8] which is limited to greater than 5 Hz due to the compensation needed for laser frequency drift. The ability to measure low frequency motion can allow measurement of slowly changing quantities such as barometric pressure, temperature or seismic motion. Since this method only needs logarithmic photodetector signals to determine position, the computational resources are reduced as compared with a system that keeps track of the phase over multiple sinusoidal fringe amplitudes such as a Mach-Zehnder interferometer [1].