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Non-Imaging Speckle Interferometry for High Speed Nanometer-Scale Position Detection

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We experimentally demonstrate a non-imaging approach to displacement measurement for complex scattering materials. By spatially controlling the wave front of the light that incidents on the material we concentrate the scattered light in a focus on a designated position. This wave front acts as an unique optical fingerprint that enables precise position detection of the illuminated material by simply measuring the intensity in the focus. By combining two optical fingerprints we demonstrate position detection along one dimension with a displacement resolution of 2.1 nm. As our approach does not require an image of the scattered field, it is possible to employ fast non-imaging detectors to enable high-speed position detection of scattering materials.
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Light is an ideal tool to perform contact free, non-destructive, and high-precision metrology. [1] For this reason optical positioning techniques have proven themselves indispensable in various branches of science and many important industrial processes, including the fabrication of semi-conductor-based circuits with features on the nanometer regime. Fast feedback is essential in these high-precision positioning systems as high frequency vibrational motion limits the level of precision that these techniques offer.

In smooth reflecting systems, laser interferometry [2] combined with high speed detectors offers precise displacement measurements with a large bandwidth. For disordered, rough, or complex surfaces, where conventional laser interferometry is not applicable, several speckle based metrology techniques such as speckle photography [3,4] and speckle interferometry [5–8] were developed in the late 1960s and 1970s. [9] These techniques spatially image speckle patterns to offer versatile measurements of material parameters such as strain, displacement, and rotation. [10] However, the necessary spatial information limits the attainable bandwidth because these techniques require imaging detectors, which are orders of magnitude slower than non-imaging detectors such as fast photodiodes, which can have GHz bandwidth.

Recent developments in optics [11–14] enabled control of the propagation of scattered light. These techniques, which are conceptually related to phase conjugation [15, 16] and time reversal [17], manipulate the wave front of the incident light using spatial light modulators [18] in order to steer the scattered light, for example, in a spatial and/or temporal focus at any desired position [11,19–22].

In this Letter we describe and experimentally demonstrate a non-imaging approach to displacement measurement for complex scattering materials. We concentrate the light that is scattered from the material in a sharp focus by spatially shaping the wave front of the incident light. In a complex system lacking translational invariance, this wave front acts as an unique optical fingerprint of the illuminated part of the sample. Any displacement between the fingerprint and the system reduces their overlap, thereby inevitably decreasing the intensity in the constructed focus. This dependence opens the possibility to use such optical fingerprints for position detection of the illuminated sample at resolutions in the order of nanometers. As spatial information of the scattered field is no longer required, this method furthermore enables the use of fast detectors.

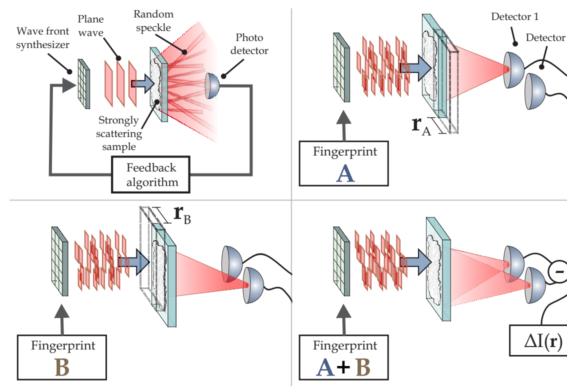

Fig. 1. Method to detect sample displacements. Light modulated by a wave front synthesizer incidents on a scattering sample. A detector coupled to the wave front synthesizer monitors the scattered light. Two optical fingerprints are generated for two sample positions. Each of the fingerprints redirects the scattered light onto one of the detectors. The sample position $\mathbf{r}$ is then determined by illuminating the sample with a superposition of the two fingerprints and monitoring the intensity difference ΔI between the two detectors. While this figure shows a horizontal displacement, the method is more generally valid and works in all directions.

In Fig. 1 we have depicted our method to detect sample displacements. With a wave front synthesizer we spatially control the phase of a light beam. A detector behind a scattering sample combined with a feedback based algorithm finds the optical fingerprint that focusses the transmitted light onto the detector. [23] We use this system to find the fingerprints A and B corresponding to two different sample positions; $\mathbf{r}_A$ and $\mathbf{r}_B$. In our current setup, this process takes several minutes. However, very recently it has be shown [14, 24] that such fingerprints can be found well within a second. Fingerprint A focusses the light onto the first detector when the sample is positioned at $\mathbf{r}_A$, while fingerprint B is constructed to concentrate the light onto the second detector when the sample is at $\mathbf{r}_B$. When we now position the sample in between $\mathbf{r}_A$ and $\mathbf{r}_B$ while illuminating it with a superposition of fingerprints A and B, the sample position can be interpolated from the intensity difference of the two detectors. This method can be easily extended to detect displacements in multiple directions by generating multiple optical fingerprints at different sample positions.

The sensitivity of this detection method and the corresponding smallest measurable displacement $\delta\mathbf{r}$ are determined by way the intensities I_A and I_B in the two foci change under a sample displacement. When the sample is illuminated by an optical fingerprint, the focus intensity I_0 as function of the sample displacement $\Delta\mathbf{r} \equiv \mathbf{r} - \mathbf{r}_0$ from its original position $\mathbf{r}_0$

$$I_0(\Delta\mathbf{r}) = \eta\langle I_{\mathrm{bg}}\rangle\langle|\gamma(\Delta\mathbf{r})|^2\rangle, \quad (1)$$

where $\langle\cdot\rangle$ denotes ensemble averaging over disorder. The enhancement factor η is defined as the ratio between the intensity $I(0)$ and the ensemble averaged background intensity $\langle I_{\mathrm{bg}}\rangle$. This enhancement depends linearly on the number of degrees of freedom in the wave front. [11] The value of $\langle|\gamma(\Delta\mathbf{r})|^2\rangle$ accounts for the loss in overlap between the sample and the optical fingerprint under sample displacement.

When the range of complexity in the sample is on a subwavelength scale, the overlap of the optical fingerprint with the sample depends solely on the illumination optics. In our experiment the pixels of the wave front synthesizer are projected onto the back aperture of an infinity corrected microscope objective. In this geometry, we calculated the overlap for an in-plane displacement to yield

$$\langle|\gamma(\Delta\mathbf{r})|^2\rangle = \left[\frac{2J_1(k_{\max}|\Delta\mathbf{r}|)}{k_{\max}|\Delta\mathbf{r}|}\right]^2, \quad (2)$$

where the maximum contributing transversal wave vector $k_{\max}$ is determined by the numerical aperture NA of the microscope objective, $k_{\max} = 2\pi\mathrm{NA}/\lambda$. This overlap only equals unity for $\Delta\mathbf{r} = 0$ and becomes smaller for any nonzero displacement.

The highest sensitivity of the systems is found by maximizing the gradient ∇ of the difference intensity $\Delta I \equiv \Delta I_B - \Delta I_A$. Using Eq. 1 and Eq. 2 we find that maximum value of this gradient lies exactly in between $\mathbf{r}_A$ and $\mathbf{r}_B$ when their distance is set to $|\mathbf{r}_A - \mathbf{r}_B|_{\mathrm{opt}} = 2.976/k_{\max}$. For these conditions the resulting optimal sensitivity S_{opt} is

$$S_{\mathrm{opt}} \equiv \max\left[\nabla(\Delta I)\right] = \frac{5.8\mathrm{NA}\eta}{\lambda}\langle I_{\mathrm{bg}}\rangle, \quad (3)$$

By changing the enhancement η, the wavelength λ, and the NA of the optics it is possible to tune the sensitivity over a wide range.

To test our position detection method we employ a spatial light modulator (SLM) from Holoeye (LC-R 2500) that allows us to spatially modulate the phase of a beam from a continuous wave laser (Coherent Compass M315-100, $\lambda = 532$ nm). The spatially modulated beam is then imaged onto the back aperture of a microscope objective (NA $= 0.95$). In the focal plane of the microscope objective we have placed a strongly scattering sample on top of a high precision positioning xyz-stage (Physik Instrumente P-611.3S NanoCube). The sample is composed of zinc oxide powder on top of a glass cover slide. At the back of the sample we collect the transmitted light and image the far field onto a CCD camera (Dolphin F-145B). Because our method does not need a spatially imaging detector, the camera can be replaced with two photo diodes to maximize bandwidth.

The optimal distance between optimization positions $\mathbf{r}_A$ and $\mathbf{r}_B$ is calculated to be 252 nm for this system. Without loss of generality, we consider only translations in the x-direction. We define the original sample position as $x_0 = 0$ nm. The sample is translated towards $x_A = -126$ nm. A feedback based algorithm finds the optical fingerprint for which the scattered light is focussed on the left side of the camera. Then we position the sample at $x_B = +126$ nm and repeat the procedure to create a focus on the right side of the camera. The two fingerprints are superimposed on the SLM. When we move the sample back to the original position x_0, the two spots become visible on the camera.

In Fig. 2 the intensity in the two spots as a function of the sample displacement $\Delta x \equiv x - x_0$ is plotted together with camera images for three different values of Δx. The two lines denote the intensity behavior predicted by Eq. 1 and Eq. 2 without free parameters. Starting from $\Delta x = 0$ where the intensity in both spots is equal, I_A and I_B change differently under sample displacement. Moving the sample in the positive x-direction results in a decreasing I_A while I_B increases for $\Delta x < x_B$. The experimental data is in good agreement with theory although the measured intensity dependence is slightly wider. This small deviation is likely to be caused by a non-ideal transfer function of the optics, which cannot be compensated for by wave front corrections.

To find the position of the sample from the measured data we look at the difference intensity between the two spots, which is plotted in Fig. 3. For $x_A > \Delta x > x_B$ (gray area) the function is bijective resulting in a unique mapping between the difference signal and the sample

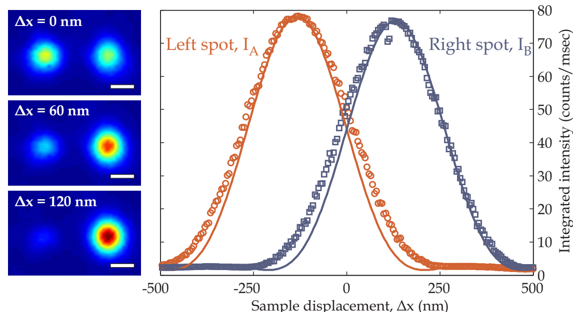

Fig. 2. Spot intensities as function of the sample displacement. On the left there are three camera images for different values of the sample displacement Δx. As Δx increases the intensity I_A in the left spot decreases while the intensity I_B in the right spot increases. The scale bars denote 1 mm. The graph on the right shows the measured spot intensities (circles I_A, squares I_B) as function of the sample displacement. The solid lines denote the theoretical expected behavior.

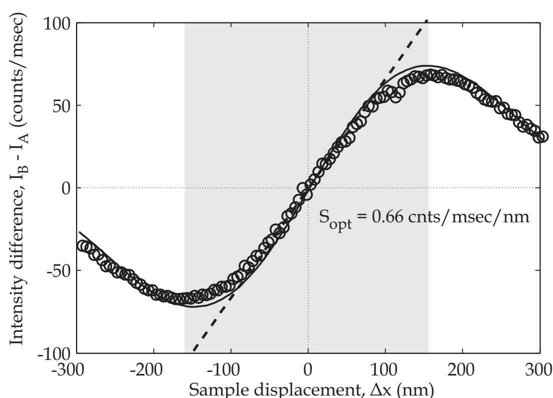

Fig. 3. Intensity difference $I_B - I_A$ as function of the sample displacement Δx. The circles denote the measured intensity difference, while the solid line represents the theoretical intensity difference. Within the gray area the function is bijective. The dotted line is a linear fit to the data points close to $\Delta x = 0$. From the fit we find that the slope equals $S_{\text{opt}} = 0.66$ counts/msec/nm.

position. Over a large distance, the function is linear and only close to the displacements $\Delta x = x_A$ and $\Delta x = x_B$ the function starts to curve. The highest sensitivity is found at $\Delta x = 0$ where the slope has a maximum value of $S_{\text{opt}} = 0.66$ counts/msec/nm, close to the theoretical limit for this system of 0.80 counts/msec/nm that we calculated using Eq. 3. The noise level in our setup is found to be 1.42 counts/msec, so that the achievable displacement resolution is 2.1 nm. We know that part of the noise may infact be signal, i.e., fluctuations of the actual sample position. The achieved resolution compares favorably with state of the art techniques [25]. A higher resolution is possible by increasing the signal-to-noise ratio in the system by, e.g., increasing the intensity enhancement η in the spots.

Instead of measuring the scattered light in transmission, one could also choose to work in reflection. Furthermore, by employing more than two detectors and generating multiple optical fingerprints, the method can be expanded in a straightforward way to simultaneously detect displacements in multiple directions. Similarly, the optical fingerprints can also be configured to detect other sample movements, such as rotations. This flexibility makes our technique very suitable for high speed and high precision position monitoring of complex scattering structures.

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