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High-Resolution Laser-Vibrometer Microscopy

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Abstract:
Precise high-frequency electronics, as for example in smart phones, require advanced filters based on micro- or even nanoelectromechanical (MEM or NEM) resonators. MEM or NEM resonators excite high resonance frequencies in the GHz range at complex 3D-modes. The vibration transfer characteristic, the mode shapes, and the energy flow of acoustic waves are important to understand electrical transfer characteristic and damping influences. Heterodyne Interferometer Microscopes are an excellent widely used tool for out-of-plane vibrations. However, frequency range and vibration amplitude resolution need to be improved. The current bandwidth is limited to approximately 600 MHz for direct demodulation of the carrier detector signal and vibration-amplitude resolution is limited to 10-30 fm/√Hz. The spatial resolution is limited to the interferometer wavelength. In this paper, we present the current limit of available systems and discuss technical solutions to breach the limits.

Key words: Laser-Doppler vibrometry, microscopy, high-frequency vibrations, MEM resonators, nanoscopy.

Introduction

Heterodyne interferometry combines with confocal microscopy to a powerful laser-vibrometer microscope [1]. Recently, this technique has been advanced to a completely three-dimensional-vibration measuring system [2] by employing the direction-dependent Doppler effect. A heterodyne interferometric system up to 1.2 GHz presented in [3] assures not only high vibration-amplitude resolution but also very good accuracy due to a well-analyzed uncertainty budget [4]. A vibration-amplitude resolution without averaging in the order of 10-30 fm/√Hz is the state-of-the-art. Digitization noise limits the maximum resolution for highly reflective surfaces. The detector signal of the system discussed in [3] would provide a shot-noise limited resolution in the order of 1-3 fm/√Hz. Lateral resolution is limited by the laser focus diameter of the measuring beam. The vibration must be uniform within the beam diameter otherwise three-wave-mixing effects falsify the measurement result dramatically. We can assume that the tiniest laser focus of nowadays solutions is in the order of the laser wavelength of approximately 500 nm.

However, higher resolutions are required to advance the technology to higher frequency ranges above 1.2 GHz. Higher frequencies lead to higher required power levels to excite a certain vibration amplitude. For example, an oscillator with a peak-to-peak displacement amplitude of 100 nm at 1 kHz would have an amplitude of just 10 fm at a vibration with equal velocity amplitude at 10 GHz. The resolution of the measuring system should be substantially better, desirably in the attometer/√Hz regime. A transversal soundwave in silicon has a speed of sound of 5843 m/s corresponding to a wavelength of 584 nm at 10 GHz. Taking into account that the amplitude should be measured in an uniformly vibrating area a lateral resolution in the range below 100 nm should be realized.

In this paper, we discuss the recently achieved research results to improve the vibration-amplitude and the lateral resolution of laser-vibrometer microscopes. The displacement resolution of any displacement sensor depends on its noise and its signal sensitivity to displacement. The smallest displacement amplitude that exceeds the noise in 1 Hz bandwidth defines the resolution. Therefore, only two ways exist to advance the resolution: (1) decreasing noise and (2) increasing the signal sensitivity to displacement. Since the noise is already shot-noise-limited, we can gain lower noise levels only with squeezed-light techniques [5]. Such photon states can only be generated with nonlinear expensive optical elements and degrade rapidly with light losses. Unfortunately, realistic reflectivity of a measurement surface always results in substantial degradation of squeezed-light states. It seems to be more feasible to aim for higher displacement sensitivity. Multiple-reflection interferometry provides such higher sensitivity as the field of cavity optomechanics demonstrates [6]. A first realization of this idea [7] demonstrates already resolutions below the shot-noise limit of the conventional system.

In order to achieve lateral resolutions beyond the classical diffraction limit we have identified amplitude absorbance modulation [8] as a suitable technique to generate a dynamic pinhole on a surface covered with a thin (<< 1 µm) photochromic layer. This technique has been explored for lithography [9] and transmitted-light microscopy [10] so far. We have theoretically investigated the application of this technique to reflected-light microscopy [11]. To achieve these results we have advanced existing simulation models by adding the influence of the reflected light in rate equations and by estimating diffraction losses roughly. We expect that an improvement of a factor of 10 for the lateral resolution is feasible in respect to our simulations. We also discuss these results in this paper.

Open-Optical-Resonator Interferometer

A mirror integrated into the microscope objective at a surface where no refraction appears makes possible multiple reflections of the measurement beam between specimen surface and the additional integrated mirror surface. Fig. 1 shows the schematic of the open-optical-resonator (OOR) setup.

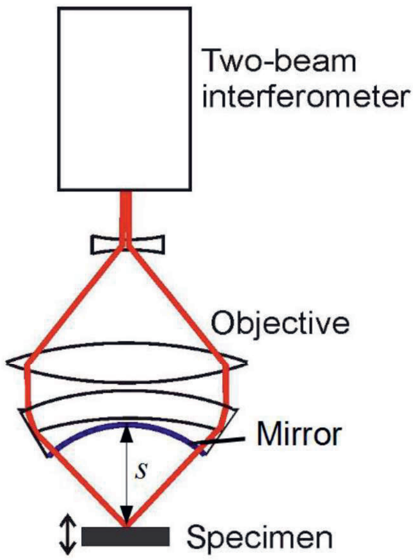

Figure 1: Schematic of the microscope objective with mirror to increase the displacement sensitivity.

In [7] we have shown recently by experimental results that we can achieve resolutions on a reflective surface below the shot-noise limit and we have demonstrated theoretic results, which predict resolutions below 1 fm/√Hz for a carefully adapted microscope-mirror reflectivity.

Assuming small displacements $\Delta s(t)$ (<< 1 nm) as well as an adjustment of the resonator on the maximum transmission where the phase deviation is maximal and by referencing to the sensitivity of the two-beam interferometer $\phi_{2BI} = \frac{4\pi}{\lambda}\Delta s(t)$, with wavelength λ, phase response

$$\phi_R = G_S \cdot \phi_{2BI} = G_S \frac{4\pi\Delta s}{\lambda} \qquad (1)$$

yields with the sensitivity amplification

$$G_S = \frac{\sqrt{R_s}\,(1-R_r)}{\left(\sqrt{R_r} + \sqrt{R_r R_s} - \left(R_r\sqrt{R_s} + \sqrt{R_s}\right)\right)} \qquad (2)$$

for the phase of the reflected light that can be evaluated with a standard heterodyne interferometer and laser-Doppler vibrometer phase decoders. Obviously, the reflectivity of the OOR in respect to the specimen reflectivity has a critical influence. The phase gain G_S at the operation point where the distance is a multiple of the wavelength is not defined for reference mirror reflectance and sample reflectance $R_r = R_s$. The phase has a point of discontinuity at this point, which leads to an undefined sensitivity gain at this condition. Our simulations show [7] that a high gain >> 100 is possible.

Unfortunately, the reflected light power is minimal at the maximum sensitivity gain because the optical resonator is light-transmissive at the working point. This results in a light attenuation gain

$$G_L = \frac{1 + R_r/R_s - 2\sqrt{R_r/R_s}\cos\delta}{1 + R_r R_s - 2\sqrt{R_r R_s}\cos\delta} \quad , \qquad (3)$$

where the phase of the light returning from the resonator is $\delta = \phi_{2BI}$. Thus, careful selection of the parameters is necessary to achieve a resolution improvement.

The resolution of the OORI is derived in reference [7]

$$\Delta s_{OORM} = \frac{\lambda}{2\pi\varepsilon\, G_S}\sqrt{\frac{h\nu B\left(G_L P_m + P_I\right)}{\eta G_L P_m P_I}} \,. \qquad (4)$$

The resolution gain G_R results from equation (4) and the resolution of the two-beam interferometer

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$$\Delta s = \frac{\lambda}{2\pi\varepsilon}\sqrt{\frac{h\nu B(P_m + P_I)}{\eta P_m P_I}} \text{ to}$$

$$G_R = \frac{\Delta s}{\Delta s_{OORM}} = G_S\sqrt{\frac{G_L(P_m + P_I)}{(G_L P_m + P_I)}} \quad . \qquad (5)$$

Here, P_m is the reflected light power at the sample and P_I is the power of the reference beam of the interferometer

Many micro- and nanosystems are made of silicon. 532 nm has been identified as well-suited wavelength for a heterodyne-interferometric microscope because a small laser focus is possible as well as shot-noise-limited detection. Therefore, Fig. 2 demonstrates the situation for silicon with a reflectivity of 0.38 at 532 nm.

Even on plain silicon, the OOR technique can improve the resolution by a factor of more than 1.8. Considering a specimen with a reflectivity of $R_{Sample} = 0.95$ investigated with an OOR reflectivity of $R_{OORM} = 0.98$ the achievable resolution would result in respect to equation (10) to 76.6 attometer per square-root-Hertz. Thus, attometer resolution is possible with our approach for highly reflecting surfaces. However, even for silicon with $R_{Sample} = 0.38$ it would be possible with an OOR reflectivity of $R_{OORM} = 0.4$ to achieve with P_I = 10 mW reference power and P_0 = 5 mW measurement light power to achieve 823 attometer per square-root-Hertz resolution. Fig. 3 shows the single-shot measurement of the piezo-actuator vibration at 50 kHz.

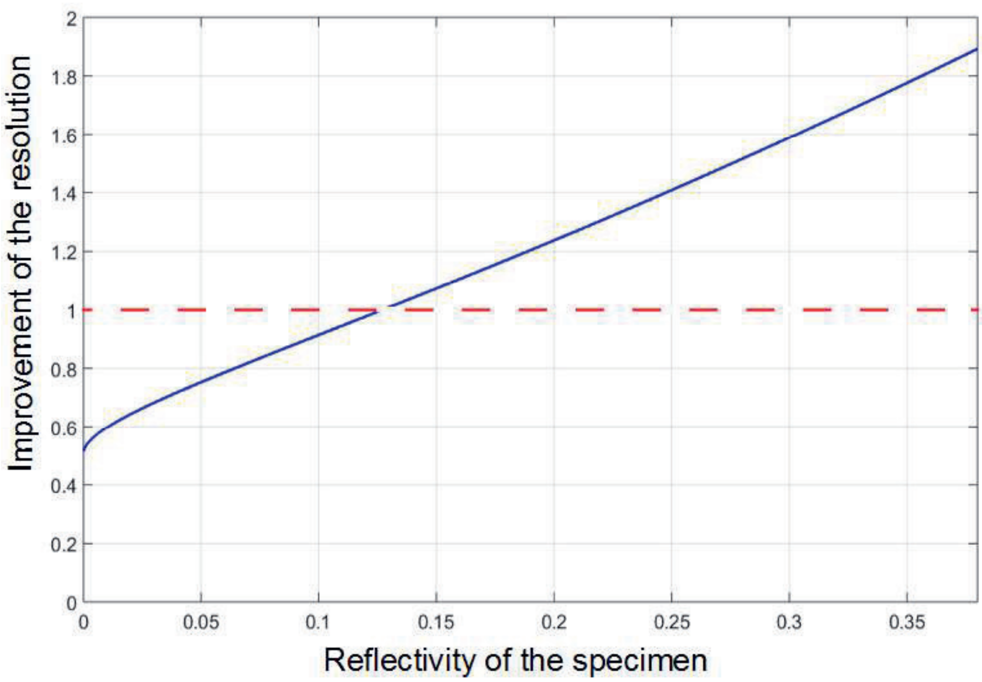

Figure 2: Resolution improvement of an OOR reflectivity of 0.4, which is slightly higher than the reflectivity of silicon (0.38) for 532 nm wavelength. A red line marks the threshold for resolution improvement.

The gray bars show the spectrum for a measurement with a conventional microscope objective. The noise level is too high to allow measuring the piezo-vibration amplitude without averaging. The measurement with OOR objective was calibrated and corrected in respect to the reference measurement. The noise level achieved with the OOR objective is at 56 fm for 250 Hz (corresponding to 3.5 fm/√Hz) without averaging (black bars). Thus, a resolution gain of $G_R = 10$ was achieved for this measurement. The level of the measurement performed with the OOR objective is below the quantum shot noise level of the conventional microscope-objective measurement for 100 µW measurement-light power and a green line marks the shot-noise-level at 67 fm (4.2 fm/√Hz). In this case, 20 complex averages of the spectrum decreases the noise level to 780 attometer for 1 Hz resolution bandwidth.

Thus, attometer resolution is feasible for reasonable measurement conditions.

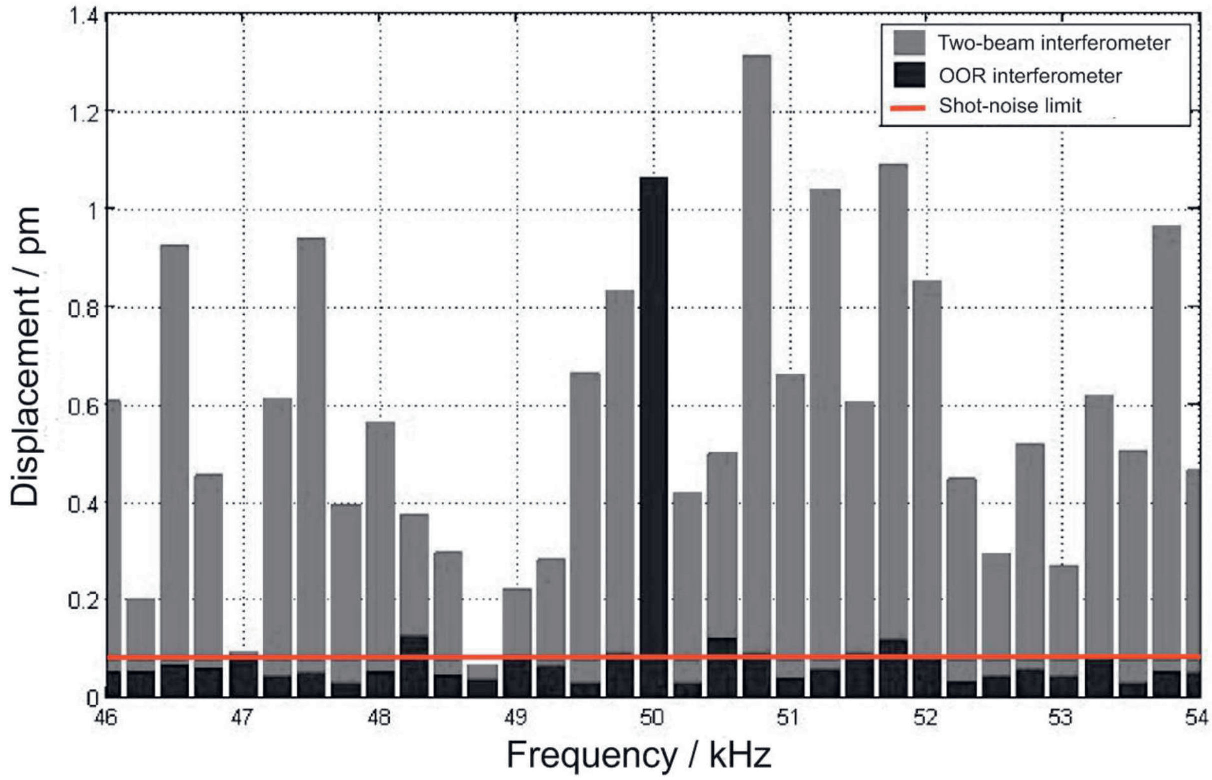

Figure 3: Comparison of the displacement spectrum for the reference measurement with approximately 1 pm amplitude at 50 kHz at RBW = 250 Hz. First we measured the vibration of the piezo specimen wit a conventional microscope objective without averaging (red bars). The noise level is too high to allow measuring the piezo-vibration amplitude. The measurement with OOR objective was calibrated and corrected in respect to the reference measurement. The noise level achieved with the OOR objective is at 56 fm (corresponds to 3.5 fm/$\sqrt{\mathrm{Hz}}$) without averaging. The level is below the quantum shot noise level of the conventional- microscope-objective measurement marked by a red line.

Nanoscopy with Absorbance Modulation

Absorbance Modulation has been introduced to improve the resolution of lithography beyond the diffraction limit and the application to transmission-light microscopy has been explored by simulations and experiments [8][9][10]. The detection of vibrations on microstructures requires reflected light microscopy in combination with interferometric evaluation of the measurement light. In order to explore theoretically the requirements for reflected-light nanoscopy with absorbance modulation we have advanced existing simulation models by adding the influence of the reflected light in rate equations of a photochromic layer [11]. This polymer layer endowed with photochromic molecules covers the surface of the measurement object.

The incorporated bistable photochromic molecules provide a saturable optical transition, which allows to reversibly modulating the absorbance spectrum of these special molecules between two states by irradiation at two different wavelengths [12]. In analogy to STED microscopy, one wavelength switches the photochromic layer to an opaque state providing only a single local zero where the absorbance properties remain transparent. Thus, this technique creates optically a scanning sub-wavelength aperture directly on the surface of the specimen.

For the generation of an annular sub-wavelength aperture a doughnut-shaped laser spot at the wavelength λ_1 (“activating beam”) is employed to switch the photochromic layer to an opaque state for the measuring wavelength λ_2 (Fig. 4 (a)). In the center of this irradiation pattern, the process generates the necessary transparent local zero. The focused, diffraction-limited “measurement beam” at the wavelength λ_2 (Fig. 4 (b)) is absorbed anywhere but in the transparent zero and, in turn, reduces the absorbance in the photochromic layer dependent on the local irradiation. The simultaneous irradiation with both wavelengths, thus, initiates a dynamic process in the photochromic layer until reaching an equilibrium where the effective spot at the measuring wavelength is beyond the diffraction limit (Fig. 4 (c)).

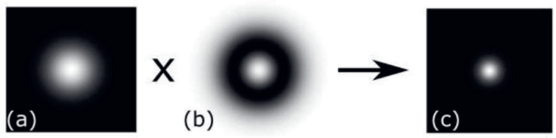

Figure 4: Light intensity distribution of the diffraction limited measuring spot (a), opaque light-induced, doughnut-shaped aperture (b), and effective measuring spot (c) beyond the diffraction limit.

For modelling bistable photochromic molecules, a rate-equation approach is convenient. Concentration change $\partial c_A / \partial t$ of photochromic molecules in the transparent state A (for λ_2) can be expressed as

$$\frac{\partial}{\partial t}c_A \approx -\varphi_{\lambda 1}^{\leftrightarrow}\cdot\sigma_{A\to B}^{\lambda 1}\cdot c_A + \varphi_{\lambda 2}^{\leftrightarrow}\cdot\sigma_{B\to A}^{\lambda 2}\cdot c_B \quad , \qquad (6)$$

where $\varphi_{\lambda}^{\leftrightarrow}$ are the bidirectional photon current densities at the different wavelengths and $\sigma_{X\to Y}^{\lambda}$ is the cross section for the transition between the two states X and Y. With idealizations the rate of the concentration of molecules in the opaque state B is

$$\frac{\partial}{\partial t}c_B = -\frac{\partial}{\partial t}c_A \quad . \qquad (7)$$

For minor concentrations with thin layers an analytical solution for this differential equation can be found [13]. However, the necessary high absorption for the application to interferometric evaluations requires a different model and a different mathematic approach. Here, the photon current densities strongly change during the penetration of the layer and, thus, there is only a numeric solution for this dynamic process. For the application with high numerical apertures, a thin photochromic layer is essential due to short depths of focus.

The simulations with this model enable us to evaluate of both temporal and spatial properties with deliberate irradiation patterns at both wavelengths under variation of design parameters of the photochromic layer. The main design parameters are the layer thickness, photochromic concentration, spectral properties of the utilized photochromic molecule and the irradiation patterns.

The results show a strong dependency of the achieved improvement of the lateral resolution on the power ratio of the incorporated beams. Transmission models take this dependency already into account. Since our model includes the reflection on the surface and the back-propagation from the specimen to the objective, this dependency on the power ratio is further increased.

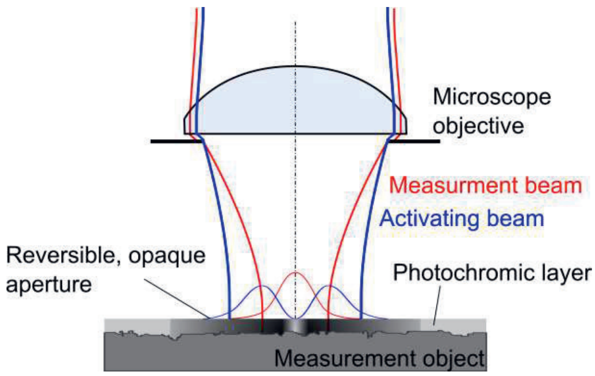

Figure 5: Side view of the intensity distribution of the photochromic layer on the measurement object for the generation of a reversible, opaque aperture.

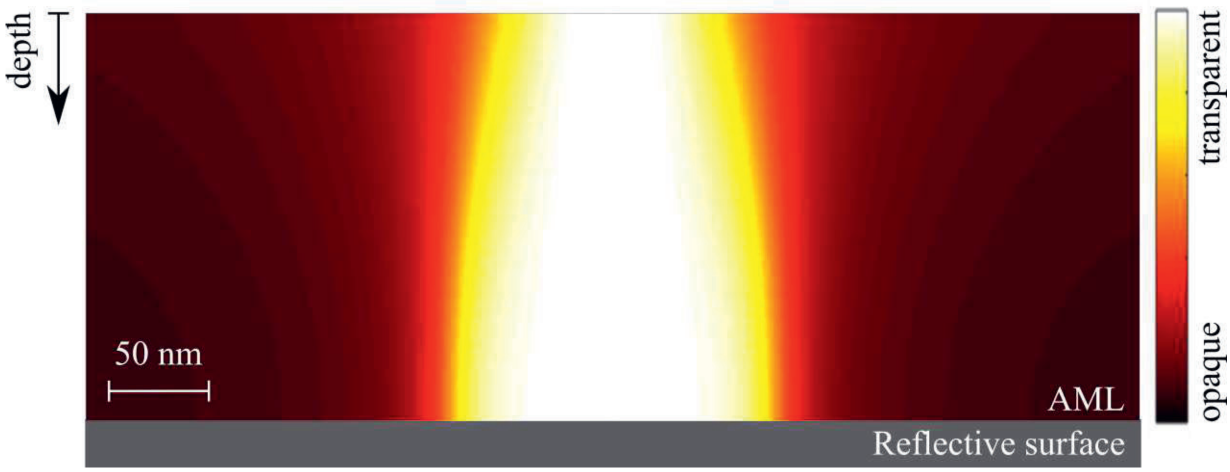

Figure 6: Exemplary crossection throught the absorbance modulation layer (AML) showing the absorbance distribution at the measurement wavelength over the layer depth in equilibrium.

We have simulated with our model the beam absorbance through a photochromic layer of 200 nm with a high concentration of a Diarylethen derivate whose properties are published in [13]. Under the irradiation with a doughnut-shaped activating spot at 325 nm and a diffraction-limited measurement spot at 632 nm with emission power in the mW regime the simulations show a capability of improving the lateral resolution to a tenth of the diffraction limit. Especially in the central zero the reflectivity of the surface influences the width of the sub-wavelength aperture.

The inevitable intensity losses of >98 % cause low measurement intensities. However, the light losses seem to be acceptable, especially for interferometric measurement methods where coherent amplification ensures high sensitivity. Additional losses will occur due to diffraction at the subwavelength-aperture [14] resulting in light fractions, which propagate in absorptive region of the optical created pinhole. These diffraction losses are subject to our further research.

Conclusion

Reference [7] proves that it is possible to magnify the sensitivity and to improve the resolution of a two-beam interferometer by employing an OOR lens. We have discussed the theory for the OOR interferometer in this paper. The phase gain and the resolution improvement have been verified by experiments. Noise levels below the quantum limit of the two-beam interferometer are possible. Experiments demonstrate attometer resolution with 20 averages for 1 Hz resolution bandwidth. In addition, our theoretical findings show that attometer vibration-amplitude resolution per √Hz is achievable if the alignment is perfect and the interferometric detection is quantum limited. The most important future goal is the experimental demonstration of attometer resolution per √Hz without averaging on a vibrating microstructure. In addition, we will explore the stabilization of the operation point with a robust electronic control loop.

We have also summarized our theoretic work on lateral resolution improvement by reflectance absorbance modulation. Our findings predict a lateral resolution improvement by a factor of 10 facing absorption of 98%. In our future work, we will focus on the additional diffraction losses to design a nanoscopic measurement system.

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