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*Published in:*
Optics Express

*DOI:*
10.1364/OE.21.016901

*Published: 01/01/2013*

*Document Version*
Publisher's PDF, also known as Version of record

*Please cite the original version:*
Shavrin, I., Lipiäinen, L., Kokkonen, K., Novotny, S., Kaivola, M., & Ludvigsen, H. (2013). Stroboscopic white-light interferometry of vibrating microstructures. *Optics Express, 21*(14), 16901-16907. https://doi.org/10.1364/OE.21.016901
Stroboscopic white-light interferometry of vibrating microstructures

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Abstract: We describe a LED-based stroboscopic white-light interferometer and a data analysis method that allow mapping out-of-plane surface vibration fields in electrically excited microstructures with sub-nm amplitude resolution for vibration frequencies ranging up to tens of MHz. The data analysis, which is performed entirely in the frequency domain, makes use of the high resolution available in the measured interferometric phase data. For demonstration, we image the surface vibration fields in a square-plate silicon MEMS resonator for three vibration modes ranging in frequency between 3 and 14 MHz. The minimum detectable vibration amplitude in this case was less than 100 pm.

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OCIS codes: (110.0110) Imaging systems; (110.3175) Interferometric imaging; (120.0120) Instrumentation, measurement, and metrology; (240.6648) Surface dynamics; (180.3170) Interference microscopy.

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1. Introduction

Optical probing techniques have manifested their strength in direct, non-contact measurements of vibration fields in a wide variety of sample types [1–7]. Scanning laser interferometry [8–10], which can detect vibration amplitudes down to the (sub)picometer range, has dominated the characterization of high-frequency electromechanical devices, for which the typical maximum amplitudes are below 1 nm and the operation frequencies can extend up to several GHz.

The development of silicon-based MEMS resonators with their typical operation frequencies ranging from sub-kHz to several tens of MHz and with their maximum out-of-plane vibration amplitudes as high as hundreds of nm has raised an interest in utilizing stroboscopic white-light interferometry for device characterization [11, 12]. Even though the strongest vibrations may have those rather high amplitudes, often weak effects such as spurious resonances or energy leakage from a resonator are of particular interest. Therefore, a sub-nm detection limit combined with a large dynamic range is desired to provide an in-depth characterization of surface vibrations in such devices.

Stroboscopic imaging with short enough light pulses can be used to effectively "freeze" the vibrational motion by synchronizing the illumination pulses to the electrical excitation of the device, thus enabling the use of static optical probing techniques [12, 13]. By repeating the measurement for different phase delays between the sample driving and the light pulses, accurate information of the periodic vibrational motion can be obtained.

White-light interferometry (WLI) provides today a widely used optical method for non-contact 3D probing of static surface features with high resolution over a large dynamic range. In contrast to laser interferometry, it makes use of a broad spectrum of the light source. The limited coherence length of the light results in a spatially localized interference pattern, which can
be used for unambiguous mapping of the surface topography. The broader the light spectrum, the more localized is the fringe pattern. This approach for advancing stroboscopic vibration analysis has recently been suggested by using special light sources with increased emission bandwidth [14, 15].

The resolution of the surface profiling can, however, be further improved by combining the fringe envelope location measurement with phase detection of the interferometric signal [16]. This phase-shifting white-light interferometry (PSWLI) enables one to detect sub-nanometer surface height features over a large dynamic range [16–19]. While broadening the spectrum of the light source does improve the position determination of the fringe envelope, it will decrease the resolution obtainable from the interferometric phase information [18]. High-resolution PSWLI will therefore require a proper balance of the spectral properties of the light source. Even a simple LED source can actually give a close match to this.

In this paper, we present a stroboscopic PSWLI setup together with an enhanced data-analysis method capable of measuring absolute amplitude and phase fields of out-of-plane surface vibrations with a minimum detectable amplitude of less than 100 pm. To demonstrate the performance of the setup, we measured the surface vibration fields in a square-plate silicon MEMS resonator [20, 21] for three different vibration modes with the maximum amplitudes ranging from 40 nm down to 300 pm and resonance frequencies from 3 to 14 MHz. These results push the performance of stroboscopic PSWLI vibration analysis to new limits: Unambiguous height determination can now be obtained with an amplitude resolution comparable to that obtained by full-field laser interferometry [22] and approaches that of scanning laser interferometry [6, 9, 10]. The upper frequency is currently limited to tens of MHz by the width of the light pulse only.

2. Experimental setup

The measurement setup is based on a Michelson-type PSWLI with stroboscopic, LED-based polychromatic illumination. The collimated light from the LED is split into a reference and sample arm of the interferometer by a non-polarizing beam splitter cube. The beams reflected back from the sample and the reference mirror (optical grade quartz wafer) are combined with the beam splitter, and the resulting interference pattern is imaged on a digital camera, see the illustration in Fig. 1.

To vary the optical path length difference (OPLD) between the two arms of the interferometer, the sample position along the optical z-axis is scanned in steps of about 40 nm with a piezoelectric translator.

For stroboscopic illumination, a pulse generator together with custom-built electronics is used to drive a green LED to produce optical pulses with their duration down to 8 ns FWHM. The spectral width of the LED is 35 nm around the central wavelength of 510 nm, as shown in Fig. 1(a). The vibrating sample is electrically driven with a sinusoidal excitation by a function generator and the stroboscopic illumination is synchronized to this.

By tuning the phase delay $\delta$ between the sample’s electrical excitation and the stroboscopic illumination, the instantaneous sample deformation can be studied throughout the complete vibration cycle (see measured signals at 3 MHz in Fig. 1(b)). The setup is computer-controlled and the resulting interference pattern is recorded by the camera at each z-scan step, for each of the $\delta$ values as illustrated in Fig. 1 and Fig. 2(a). In this way the data set contains information of the sample topography, but also of the sample surface deformation at a chosen number of phase points over the complete vibration cycle.
Fig. 1. Schematic presentation of the experimental setup, with the insets showing (a) the measured source spectrum and (b) the optical pulses (green line) tuned to phase $\delta$ with respect to the sample excitation waveform (blue line). A collimated LED beam is split into the sample and reference beams of a Michelson interferometer by a non-polarizing beam splitter. The returning beams are combined and imaged onto a camera (The Imaging Source DMK 21BU04) equipped with a lens for microscopic imaging (Volpi AS11/50).

3. Data analysis

The light intensity recorded at each camera pixel for a selected phase point $I_{xy}$ as a function of $z$ is that of a typical white-light interferogram (see Fig. 2(b)) with the peak contrast corresponding to zero OPLD. By analyzing the interferograms at each camera pixel, the instantaneous sample surface height-map can be constructed.

There are several analysis methods developed for PSWLI, of which we have implemented the frequency domain analysis (FDA) approach described in [16, 19]. In this method, the analysis is performed entirely in the frequency domain, where finding the peak-location of the fringe envelope of the interferogram is replaced by a phase-slope analysis, see Figs. 2(b)-2(d). The FDA takes advantage of the fringe localization to avoid ambiguity problems, and at the same time provides the high resolution for the height-map measurement available in the phase data [19]. Furthermore, as is characteristic to FDA, all measured data points of the fringe pattern contribute to the final result. In contrast to the methods based on finding the peak of the fringe envelope, which assume a particular functional form, the FDA is not sensitive to the envelope shape, and hence to the spectrum of the light source [16]. Therefore, the analysis method is tolerant to differences in the reflectivities of the different materials on the sample surface.

In the research of electromechanical components, weak effects such as energy leakage from a resonator and unwanted parasitic vibration modes are often of particular interest. Typically this information cannot be effectively visualized by presenting an instantaneous 3D view of the deformed sample on a linear scale. Instead, amplitude and phase maps of the vibration are desired. Here we show that this information can be readily obtained in an elegant and straightforward way by applying an additional Fourier transform to the set of measured height maps. Presented in a logarithmic scale, the acquired amplitude map allows one to visualize the
Fig. 2. Schematic presentation of the FDA approach for processing stroboscopic PSWLI data and illustration of the vibration analysis concept. (a) During the measurement, a stack of images is acquired as a function of the varied OPLD (z-scan). For each OPLD value, an image is recorded for each driving phase delay value \( \delta \). When examining the light intensity data from a particular camera pixel through the stack, \( I_{xy}(\delta) \), (b) a typical WLI interferogram with localized fringes is observed. (c) Applying a Fourier transform (FT) to the interferogram, the spectral amplitude content \( A(k) \) of this signal peaks at the spatial frequency \( k_0 \), in the vicinity of which the spectral phase \( \Phi(k) \) is linear. (d) The FDA analysis utilizes the spectral phase linearity to obtain a high-resolution height map for each measured driving phase value \( \delta \) (covering exactly one vibration period). (e) The surface deformation at a single spatial point as a function of \( \delta \), \( h_{xy}(\delta) \), is a sinusoid with a DC-offset \( \sigma_{xy} \). (f) Applying a second Fourier transform, independently for each spatial point on the set of height maps, yields the sample surface topography \( \sigma_{xy} \) and both the absolute amplitude \( A_{xy} \) and phase \( \theta_{xy} \) of the surface vibration.

entire dynamic range of the measurement and, together with the phase data, enable an in-depth study of weak effects in the presence of high amplitudes. Furthermore, the amplitude and phase data can be combined to calculate a 3D representation at an arbitrary vibration phase value, as well as to produce an animation of the surface vibration.

When stepping the phase delay, the height variation observed at a single surface point as a function of \( \delta \) is described by a sinusoidal motion with amplitude \( A_{xy} \) and phase \( \theta_{xy} \) around the z-offset \( \sigma_{xy} \), which corresponds to the sample surface topography, as illustrated in Fig. 2(e). When the instantaneous surface deformation is measured at phase values spanning exactly one period of the surface vibration, \( A_{xy} \) and \( \theta_{xy} \) are found from the first bin of the discrete Fourier transform, while \( \sigma_{xy} \) is obtained from the zeroth bin (see Fig. 2(f)). The vibration analysis requires a minimum of three \((N = 3)\) phase values with equal step sizes \( \Delta\delta = 2\pi/N \), while a higher number of \( N \) will improve the resolution.

4. Experimental results

The performance of the interferometer setup and the data analysis method are demonstrated by studying the vibration fields in a piezo-electrically actuated square-plate silicon MEMS resonator [20, 21]. The sample was designed and manufactured by VTT Technical Research Centre of Finland, Micronova, see Figs. 3(b) and 3(c). It has the primary square-extensional
Fig. 3. A set of measured vibration amplitude (first row) and phase (second row) data for the 3.37 MHz, 7.18 MHz and 13.72 MHz vibration modes. The vibration amplitude and phase data for the 3.37 MHz mode are shown also for the reduced input drive powers of $P_0 - 20$ dB and $P_0 - 40$ dB. At the nominal input drive power ($P_0$), the amplitude data feature more than 40 dB of dynamic range, and the nodal line of the vibration mode is seen as a thin and deep minimum, with the corresponding phase data showing a sharp transition. Decreasing the input drive power, and hence the vibration amplitude, serves to illustrate that the setup is capable of resolving vibration modes with a maximum amplitude of less than 300 pm, and features a minimum detectable amplitude limit of less than 100 pm. The amplitude and phase data can also be combined to create a 3D view of the instantaneous surface deformation at an arbitrary phase of the vibration (a,d,e), also demonstrated by animating the surface vibration (Media 1, Media 2, Media 3). The extremes of the colormaps for the 3D views correspond to the limits shown on each of the z-axes in (a,d,e). A schematic view (b) and photograph (c) of the square-plate silicon MEMS resonator is also included.

In-plane vibration mode at 15.3 MHz, but in addition to that it also features several out-of-plane modes. Since the resonator is designed to operate in vacuum, a small vacuum chamber with an optical window was constructed to allow for the interferometric characterization of the vibration fields without performance degradation caused by air damping.

In the measurement, the OPLD was scanned in 300 steps over a z-range of approximately 12 μm. At each z-scan-step, the phase delay $\delta$ between the electrical excitation and the illumination pulses was varied in 18 steps to record the instantaneous surface deformation over the complete vibration cycle.

We measured the surface deformation of the out-of-plane vibration mode at $f = 3.37$ MHz at a nominal driving power of $P_0 = -27$ dBm (50 Ω system), and with two reduced power levels of $P_0 - 20$ dB and $P_0 - 40$ dB in order to show the noise floor of the measurement, and thus to quantify the minimum detectable amplitude limit. The results for the extracted amplitude and phase maps as well as the constructed instantaneous 3D view (at $P_0$) are shown in Fig. 3. By analyzing the nodal line of the amplitude field at $P_0$ and the $P_0 - 40$ dB amplitude data, we estimate the minimum detectable surface vibration amplitude to be less than 100 pm, a result
that outperforms the current state-of-the-art stroboscopic WLI [12, 23, 24].

The achieved amplitude detection limit enabled us to characterize the higher frequency vibration modes of the sample at 7.18 MHz and 13.72 MHz with maximum amplitudes of \(\sim 2\) nm and \(\sim 300\) pm, respectively. As is often the case, the maximum amplitude decreases with an increase in frequency. The measured amplitude and phase maps together with an instantaneous 3D view of the deformation are shown in Fig. 3 (the two right-most columns). The reader should also refer to the animations of the instantaneous 3D views in Figs. 3(a) (Media 1), 3(d) (Media 2) and 3(e) (Media 3).

5. Conclusions

We have presented a stroboscopic phase-shifting white-light interferometer and a data analysis method for the study of surface vibration fields in electromechanical components, such as MEMS resonators. The data were analyzed in the frequency domain combining the benefits of the fringe localization in low-coherence interferometry and the high resolution of the phase-shifting techniques. This allowed avoiding phase ambiguity, and resulted in a set of high-resolution instantaneous height maps of the periodically vibrating surface for a given number of phase delay values throughout the vibration cycle. An additional Fourier transform was then applied to the set of height maps to yield detailed amplitude and phase data of the surface vibration. The performance of the system was demonstrated by measuring the vibration fields in a piezoelectrically actuated square-plate silicon MEMS resonator with maximum vibration amplitudes ranging from 40 nm down to 300 pm and with resonance frequencies extending from 3 to 14 MHz. In fact, the vibration fields in the sample at the highest frequency are only detectable due to a minimum detectable amplitude of less than 100 pm. All these results were obtained without any spatial filtering. The achieved performance level shows the promise for stroboscopic phase-shifting white-light interferometry to become an attractive method for studying high-frequency, small-amplitude vibrations in electromechanical devices.

Acknowledgments

This work has been financially supported by the Academy of Finland as part of the “Photonics and Modern Imaging Techniques” research programme (Project 134857). IS thanks the Graduate School of Modern Optics and Photonics and LL acknowledges Finnish Cultural Foundation for scholarship. The authors thank VTT Technical Research Centre of Finland for collaboration and providing the sample.