

# Introducing the PICOSCALE Vibrometer



SmarAct GmbH

## Abstract

Vibrations plays a key role in the performance of high-precision mechanical components as well as micro-electro-mechanical systems (MEMS). With the **PICOSCALE Vibrometer**, SmarAct provides a simple solution for the dynamic characterization of a variety of samples. This application note explains the key features of the system and presents examples of measurements.

## 1. INTRODUCTION

Commonly, the impact of vibrations in micro-mechanical systems is to be minimized to maintain precision and to avoid mechanical fatigue which can lead to a failure of the system. *A contrario*, devices like sensors and loudspeakers rely on vibrations for their function. Here, it is important to have a well-defined response in the desired frequency range.

Laser interferometry and vibrometry are widely accepted methods for contactless modal analysis. The resolution for out-of-plane vibrations (along the viewing direction) can reach sub-pm levels. With the help of microscope objectives, high imaging resolution can be achieved at the same time.

To investigate vibrations at different locations on microscopic samples, conventional vibrometers often employ galvanometer mirrors to scan the laser beam with a wavelength in the visible range through a microscope objective. Although this approach provides high lateral resolution, the size of the image will be limited, because the field of view of microscope objec-

tives scales with the reciprocal of the resolution. As a result, samples of several millimeters in size cannot be imaged at once at high resolution.

Further demand for vibration measurement methods combined with high imaging resolution comes from the rapidly growing market for MEMS. Here, an additional challenge is that MEMS are often packaged and thus not optically accessible.

To address the aforementioned points, SmarAct has developed the **PICOSCALE Vibrometer** (Figure 1), an instrument that provides megapixel imaging with micrometer resolution while performing vibration measurements at each pixel of the image. A novel infrared (IR) objective with integrated Michelson interferometer is combined with SmarAct's proven high-resolution positioning technology such that the field of view is only limited by the range of the positioners. This approach makes the **PICOSCALE Vibrometer** the ideal instrument for the modal analysis of a wide variety of devices with sizes that range from a few  $\mu\text{m}$  to multiple cm, including MEMS within IR-transparent packaging.



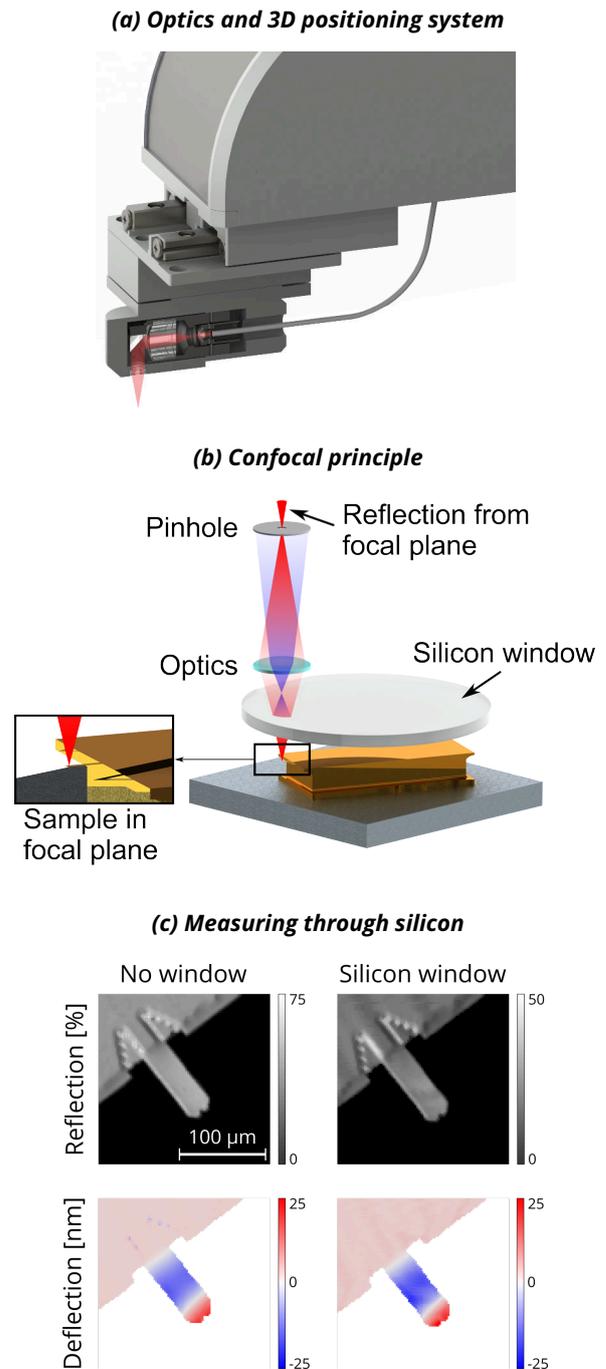
**Figure 1.** The **PICOSCALE Vibrometer** consists of a controller, a three-axis positioner that holds the microscope objective, a shaker stage to mechanically actuate the sample and software to control the measurements and to analyze the results.

## 2. WORKING PRINCIPLE

**Scanning with the microscope objective.** The objective is mounted under a three-axis positioning system (Figure 2a). The standard positioners provide a 30 nm repetitive accuracy at a traveling range of 20 mm resulting in a field of view which is much larger than that what could be achieved by galvanometer scanning mirrors. The objective combines a miniature Michelson interferometer with high-resolution imaging optics and is coupled with a single-mode optical fiber to the controller unit which contains the laser source and photo-detector. Because the interferometer and the microscope share the same optical path, the system is very compact and a separate microscope system is not necessary. The lateral imaging resolution depends on the selected objective and can be as high as 2  $\mu\text{m}$ .

**Confocal IR microscopy.** In confocal microscopy only light that is reflected from the focal plane will be detected while all other light will be blocked by the pinhole (Figure 2b). In the **PICOSCALE Vibrometer** the single-mode optical fiber acts as pinhole. Only light that can enter the optical fiber will reach the photo-detector within the controller unit. The confocal principle and its advantages such as the ability to look through partially reflective layers are discussed in a dedicated application note which can be found at the SmarAct website. Because the used laser source has a wavelength of 1550 nm it becomes possible to look through materials that are non-transparent for visible light such as silicon (Figure 2c). This is in particular relevant for MEMS and a case study on a motion sensor packaged in silicon is presented in a separate application note (SmarAct website).

**Vibration measurement.** Vibrations of the sample can be either induced mechanically with the piezo-based shaker stage that is included in the **PICOSCALE Vibrometer** or with an electrical signal. At each pixel of the image vibrations are measured by interferometry. To this end, the objective hosts a Michelson interferometer. A beam splitter divides the laser light into a reference beam which is terminated by a fixed mirror and a measurement beam that is focused on the sample. The reflected beams interfere at the beam splitter and the interference signal is directed (through the optical fiber) to a photo-detector. When the sample is displaced along the optical axis, the optical path of the measurement beam changes which results in a change in interference from which the displacement is calculated. The thus obtained displacements are intrinsically calibrated through the wavelength-stabilized laser source. Vibrations can be either analyzed by plotting the displacement data in the frequency domain or by using the integrated digital lock-in amplifier. The latter allows live imaging of complex bending modes without the need for post-processing steps.



**Figure 2.** **a)** The objective, mounted on a positioning system, can be raster scanned over the sample. Light from a 1550 nm laser source is fed into the objective through a single mode fiber and focused on the sample (the integrated Michelson interferometer is not shown). **b)** Light that is reflected from the focus follows exactly the same path back (shown in red) and can re-enter the optical fiber aperture which is visualized here as a pinhole. Light reflected from other planes (shown in blue) is blocked by the pinhole and will remain largely invisible in the measurements. **c)** Microscopy images (top) and vibration images (bottom) of a micro-cantilever driven at 95 kHz using the **PICOSCALE Vibrometer** shaker stage. Even the presence of a 0.5 mm-thick silicon window does not affect the measurement.

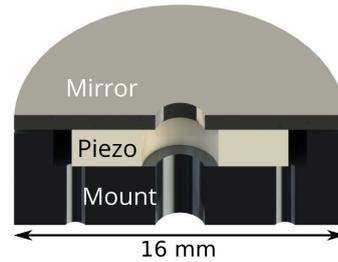
### 3. APPLICATION EXAMPLE: TESTING AN ACTUATED MIRROR

Laser systems can be actively stabilized against phase and frequency fluctuations by actuated mirrors. In its simplest form such an actuator consists of a piezoelectric element with an attached mirror off which the laser beam is reflected. By adjusting the optical path length with the piezoelectric element, the frequency and phase of the laser beam changes, which can be used to implement a feedback loop for an active stabilization. However, the bandwidth of the feedback loop will be limited by mechanical resonances of the actuated mirror which can be as low as a few hundred Hertz. To improve the performance of active stabilization systems, the actuated mirror would ideally have a flat mechanical response over a wide frequency range.

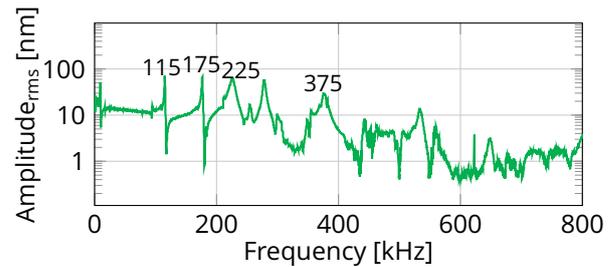
Here we show that novel designs can be rapidly tested with the **PICOSCALE Vibrometer**. The investigated actuated mirror (Figure 3a) consists of a titanium mount, a piezoelectric ring stack and a mirror with aperture. The excitation of the actuator is performed using the integrated signal generator of the **PICOSCALE Vibrometer**. To measure the response of the system, first the measurement laser is positioned at an arbitrary location on the mirror to record displacements while varying the excitation frequency with a 1 second chirp. The resulting amplitude spectrum is obtained by a Fourier transformation of the displacement data. The peaks in Figure 3b represent the actuator's natural resonances but their mode remains unclear at this point. To perform a full nodal analysis the actuator is excited at a peak of interest while imaging the vibrations of the whole structure. Figure 3c shows the bending modes at the selected peaks in the spectrum. Such measurements of the bending modes of the mirror are also important to predict the distortion of the wavefront of the reflected laser beam.

To test if the vibrations originate from the piezoelectric ring stack itself, the mirror was removed and measurements were repeated onto the bare ring stack. Despite the poor reflectivity the vibrations can still be measured, Figure 3d reveals a flatter spectrum with fewer and less pronounced peaks. The corresponding vibrational modes shown in Figure 3e are also less complex than the ones from the whole structure suggesting that the mirror itself has a strong influence on the mechanical performance due to its mass and shape.

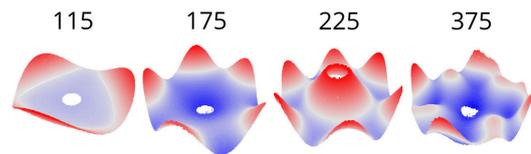
(a) Cross-section of an actuated mirror



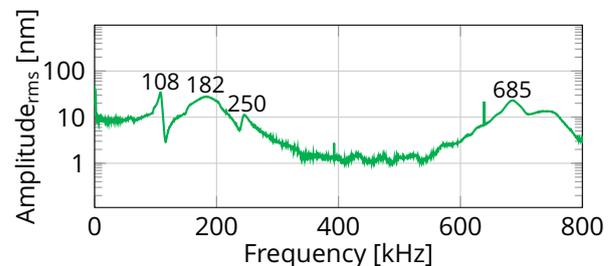
(b) Mirror: amplitude spectrum



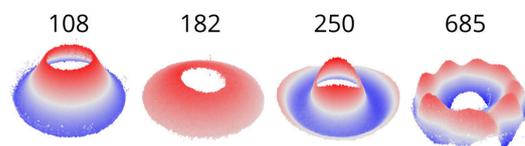
(c) Mirror: vibrational modes



(d) Piezo: amplitude spectrum



(e) Piezo: vibrational modes



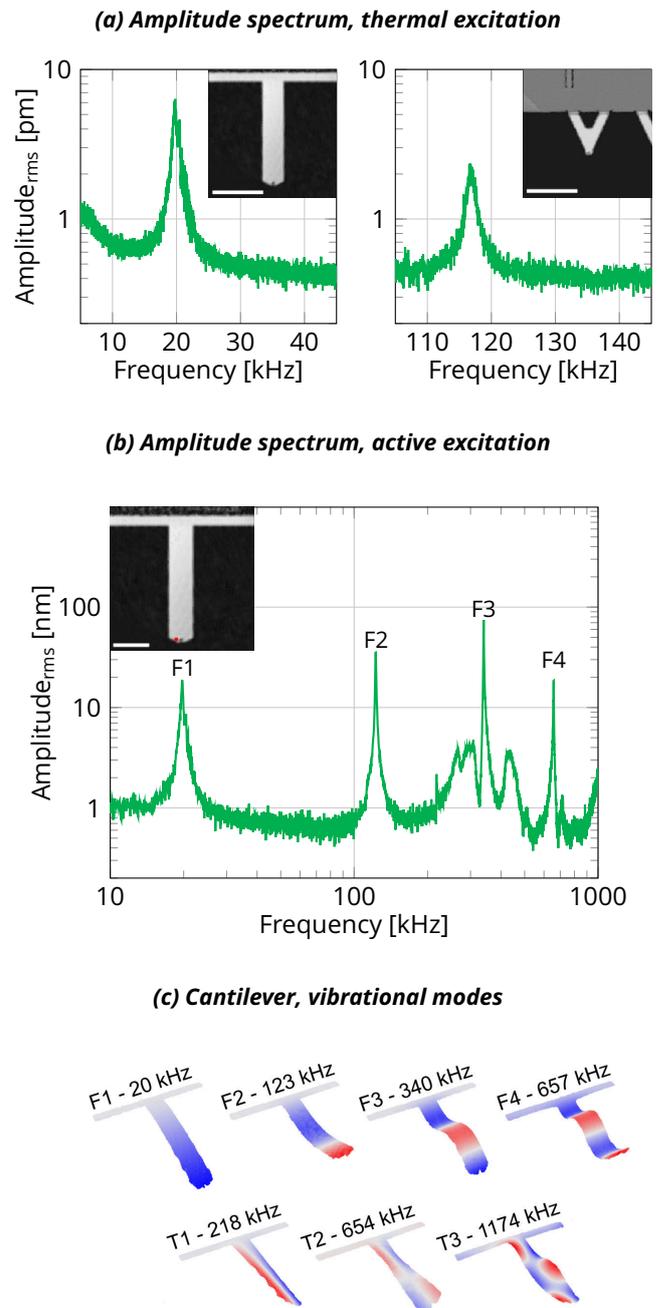
**Figure 3.** (a) A piezoelectric ring stack is sandwiched between a mirror and a titanium mount. (b) and (d) show the amplitude spectra recorded on the mirror and piezoelectric ring stack, respectively. (c) and (e) show the corresponding vibrational modes (the shown displacements are tens of nm)

#### 4. APPLICATION EXAMPLE: CHARACTERIZING MICRO-CANTILEVERS

Atomic force microscopy (AFM) has become an indispensable tool for the characterization of surface properties, such as topography, stiffness or conductance. In AFM, the surface is probed with a sharp tip that is mounted at the end of a flexible micro-cantilever. The mechanical properties of this cantilever directly affects the measurement results and often a calibration is required for the correct interpretation of the data. For example, to measure the stiffness of a surface, the stiffness of the cantilever needs to be known. Although multiple methods exist to calibrate the spring constant of a micro-cantilever most of them require physical contact with the cantilever which is potentially damaging for the fragile tip.

With the **PICOSCALE Vibrometer**, a full mechanical characterization of micro-cantilevers can be performed. Thanks to the sub-pm noise floor, even minute vibrations that originate from the thermal energy present in the system can be accurately quantified. This allows for a calibration of the cantilever spring constant based on the equipartition theorem. More details about this approach are presented in a dedicated application note which can be found at the SmarAct website. Figure 4a show the thermal vibration measurements of two cantilevers with different spring constants. Their amplitude spectra were recorded without actively exciting the cantilevers. Nevertheless, well-defined resonance peaks could be measured where the stiffer cantilever has a higher resonance frequency and a lower vibration amplitude.

Understanding the dynamic response of the cantilever is important when the AFM is operated in dynamic imaging or spectroscopy modes. The different bending modes can be actively excited using the shaker stage of the **PICOSCALE Vibrometer**. Figure 4b shows multiple resonance peaks, each corresponding to a specific bending mode of the cantilever (because of the active excitation, the amplitudes are much higher than in Figure 4a). To identify the vibrational modes the actuator is excited at the peak of interest while imaging the vibrations of the whole cantilever. Figure 4c shows the first four flexural bending modes as well as the first three torsional modes.



**Figure 4.** (a) Measurements of the thermal vibrations of two cantilevers with different geometries (insets, scale bars: 100  $\mu\text{m}$ ). The left cantilever has a spring constant of 0.05 N/m and the right a spring constant of 0.6 N/m. Vibrations were measured at the free ends of the respective cantilevers. The FFT graph shows their resonance peaks with an amplitude of just a few pm. (b) An FFT of the recorded displacements while exciting the cantilever, the multiple resonance peaks suggest different bending modes. The inset microscopy image shows the measurement position on the cantilever (red dot, scale bar: 60  $\mu\text{m}$ ). (c) The 3D renderings show the corresponding flexural bending modes at the indicated frequencies (F1 to F4). In addition, the first three torsional modes are shown. The latter frequencies were obtained by measuring the cantilever displacements at the side of the cantilever (not shown).

## Sales partner / Contacts

### Germany

**SmarAct GmbH**

Schuetten-Lanz-Strasse 9  
26135 Oldenburg  
Germany

T: +49 441 - 800 879 0  
Email: info-de@smaract.com  
www.smaract.com

### France

**SmarAct GmbH**

Schuetten-Lanz-Strasse 9  
26135 Oldenburg  
Germany

T: +49 441 - 800 879 956  
Email: info-fr@smaract.com  
www.smaract.com

### USA

**SmarAct Inc.**

2140 Shattuck Ave. Suite 1103  
Berkeley, CA 94704  
United States of America

T: +1 415 - 766 9006  
Email: info-us@smaract.com  
www.smaract.com

### China

**Dynasense Photonics**

6 Taiping Street  
Xi Cheng District,  
Beijing, China

T: +86 10 - 835 038 53  
Email: info@dyna-sense.com  
www.dyna-sense.com

**Natsu Precision Tech**

Room 515, Floor 5, Building 7,  
No.18 East Qinghe Anning  
Zhuang Road,  
Haidian District  
Beijing, China

T: +86 18 - 616 715 058  
Email: chenye@nano-stage.com  
www.nano-stage.com

**Shanghai Kingway Optech Co.Ltd**

Room 1212, T1 Building  
Zhonggong Global Creative Center  
Lane 166, Yuhong Road  
Minhang District  
Shanghai, China

Tel: +86 21 - 548 469 66  
Email: sales@kingway-optech.com  
www.kingway-optech.com

### Japan

**Physix Technology Inc.**

Ichikawa-Business-Plaza  
4-2-5 Minami-yawata,  
Ichikawa-shi  
272-0023 Chiba  
Japan

T/F: +81 47 - 370 86 00  
Email: info-jp@smaract.com  
www.physix-tech.com

### South Korea

**SEUM Tronics**

# 801, 1, Gasan digital 1-ro  
Geumcheon-gu  
Seoul, 08594,  
Korea

T: +82 2 - 868 10 02  
Email: info-kr@smaract.com  
www.seumtronics.com

### Israel

**Trico Israel Ltd.**

P.O.Box 6172  
46150 Herzeliya  
Israel

T: +972 9 - 950 60 74  
Email: info-il@smaract.com  
www.trico.co.il