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Imaging of in- and out-of-plane vibrations in micromechanical resonator

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Vibrations in a micromechanical 13.1 MHz bulk acoustic mode silicon resonator have been imaged with a scanning Michelson laser interferometer. A novel detection scheme utilising the Michelson interferometer is developed, which enables imaging the in-plane vibrations in addition to the out-of-plane component. The novel imaging technique is demonstrated by measuring the vibrations of the extensional and Lamé modes in a square plate resonator.

Introduction: Recently increasing interest has been devoted to microelectromechanical systems (MEMS) in various applications [1–3]. The characterisation of vibration modes within MEMS devices is important to validate their design, operation and performance. Optical probing is a powerful tool for the task since the vibrations can be studied directly without perturbing the operation of the device. One can measure the frequency response of the micromechanical resonator from a single point using, for example, a Michelson interferometer [4], or map the entire out-of-plane vibration field from ultrasonic transducers using scanning interferometers [5, 6]. Also, the vibration mode shapes of cantilever microbeams and micromachined membranes have been measured using an interferometric microscope with stroboscopic illumination [7]. Full three-dimensional motion characterisation of MEMS devices has been reported by Rembe and Muller [8]. Their measurement system employs stroboscopic imaging, interferometry and digital image processing, and it is capable of measuring the out-of-plane deflections together with the in-plane rigid-body motions of the microstructures. Also, commercial full 3-D motion probes, based on video microscopy with stroboscopic illumination, have been on the market, but they typically operate only at frequencies below 10 MHz.

In this Letter, we report a simple modification to a Michelson interferometer enabling one to measure both the in- and out-of-plane vibrations in a micromechanical resonator. The advantage of the setup is that no heavy image processing tools are needed, and furthermore, measurements up to the gigahertz range are possible.

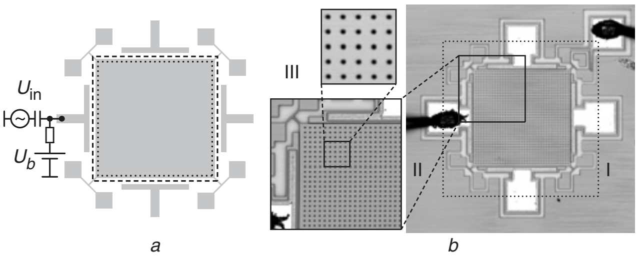

Fig. 1 *Micromechanical plate resonator*

a Schematic drawing of micromechanical resonator and driving electronics
Dotted and dashed lines illustrate the expanded and contracted phase of main vibration mode (square-extensional mode)
b Light-reflection images of resonator showing different scanning areas I, II and III
White areas represent aluminium and grey areas silicon. Detailed view of resonator plate (scan area III) shows grid of holes with diameter of 2 μm and period of 8 μm for sacrificial oxide release etch

Measurement method: The resonator plate vibrations have been visualised employing our scanning laser interferometer, which detects the out-of-plane vibrations and provides a linear response [9]. However, absolute vibration amplitude and phase are not obtained. The lateral vibration components are imaged by measuring the intensity modulation of the laser beam reflected from the resonator chip at the edges of the release etch holes shown in Fig. 1*b*. In practice, this is achieved by blocking the reference beam of the interferometer. Therefore, only the probe beam reflected from the sample surface propagates to the detector, where its intensity modulation is recorded at the sample excitation frequency. Hence a vectorial detection of the in-plane vibration components can be accomplished. To create a microscope-like image of the scanning area (hereafter called light-reflection image), the mean intensity of the laser beam reflected from the MEMS resonator is recorded at each scanning point in addition to the relative vibration amplitudes. The area shown in the light-reflection image corresponds one-to-one with the area shown in the amplitude data image.

Sample: The sample studied is a micromechanical resonator described in detail in [3]. It is an attractive alternative for the quartz reference oscillator in portable applications because of its compact size, low power consumption and integrability with integrated circuit (IC) electronics. The MEMS resonator, shown in Fig. 1, consists of a plate released from the silicon substrate and supported at the corners. The dimensions of the resonator plate are $320 \times 320 \times 10\ \mu m^3$. The device has been fabricated using deep reactive ion etching on a silicon-on-insulator (SOI) wafer. For the sacrificial oxide release etch, a 39×39 grid of holes (diameter 2 μm) has been etched to the silicon plate, see Fig. 1*b*.

The main vibration mode, the square-extensional (SE) mode, can be characterised as a two-dimensional plate expansion preserving its original square shape, see Fig. 1*a*. With single-electrode drive, the test resonator exhibits also the Lamé mode in which the edges of the square plate bend in antiphase preserving the volume of the plate [3]. In both cases, the motion is mainly in-plane. However, the resonator also vibrates perpendicular to the surface of the plate owing to the Poisson ratio for the silicon crystal. The resonance frequencies of the Lamé and SE modes are 12.15 and 13.12 MHz, respectively.

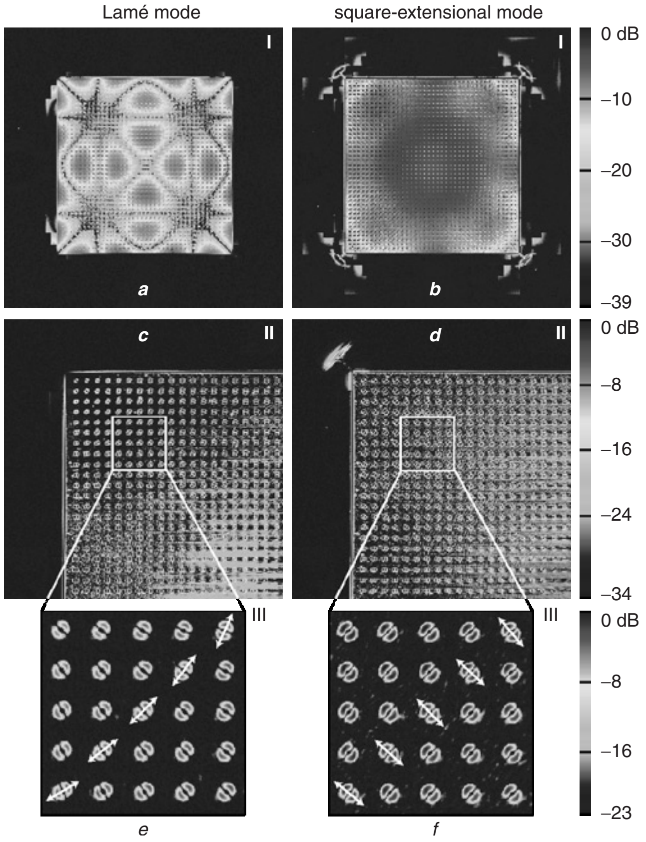

Fig. 2 *Measured vibration components*

a–b Relative amplitude of vertical vibration component in resonator. Vertical component of Lamé and the SE modes are obscured by parasitic modes
c–f Displacement vector field of in-plane vibrations in resonator. Colour of spots indicates relative vibration amplitude. Direction of in-plane vibrations is given by angle of each pair of spots, which is shown by schematic arrows drawn through maxima values of spots around each etch hole. Reference amplitude, 0 dB, and colour scaling has been selected separately for scan areas I, II and III

Results: The measured out-of-plane component of the vibration fields is shown in Figs. 2*a* and *b* for the frequencies of the Lamé and SE modes, respectively. Parasitic modes vibrating in the out-of-plane direction are dominating over the small out-of-plane component of the Lamé or SE mode. The measured in-plane component of the vibration fields at discrete points, i.e. on top of each etch hole, is shown in Figs. 2*c–f*. The coloured spots indicate the relative amplitude and direction of the in-plane vibrations at the edges of the release etch holes. The schematic arrows drawn in the detailed scans, Figs. 2*e* and *f*, show the direction of the vibrations for the Lamé and the SE modes. The location of the scanned areas I, II and III may be seen in Fig. 1*b*. The driving power is 0 dBm for the scans performed in the areas I and II, and −10 dBm for the scan made on area III. The scanning parameters for each scanned area are enumerated in Table 1. All the scans were performed at ambient pressure with a bias voltage of 60 V.

Table 1: Scanning parameters for MEMS test resonator

Parameter	Area I	Area II	Area III
Scan points	257 × 257	320 × 320	182 × 182
Scan step, μm	1.98	0.66	0.22
Scan area, μm^2	509 × 509	211 × 211	40 × 40

Conclusions: Vibrations in a micromechanical silicon resonator have been imaged using a scanning laser interferometer. A novel detection scheme for our probe is discovered, enabling the imaging of in-plane vibrations in addition to the out-of-plane component. Therefore, we have been able to measure the in-plane and out-of-plane vibration components of the RF MEMS resonator at the resonance frequencies of the Lamé and square-extensional modes. Such laser-probe measurements directly aid the research and development of high performance, high Q-value RF MEMS resonators.

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