A benchtop tool micromechanical

A compact tool, based on a magnetomotive transduction technique at room temperature and pressure, was developed for the characterization of the dynamic properties of micromechanical systems. Using a permanent magnet that generates up to 2.5 Tesla in an adjustable gap, mechanical resonances at megahertz frequencies can be measured. The driving force is strong enough to drive microresonators into nonlinearity, and to detect microresonators vibrating in liquids.

• ***Warner Venstra*** •

For several decades, lithographic processes originally developed for the integrated circuits industry have been used to fabricate tiny mechanical structures. Commercial applications of these micro-electromechanical systems include accelerometers, as shown in Figure 1, force and pressure sensors, switches and motion detectors. Mechanical systems with micro- and nanometer dimensions are extremely responsive and this has led to new instruments that enable, for example, mass sensing on the scale of single atoms, manipulation of individual atoms on a surface, and detection of displacements in the femtometer range.

Author

Warner Venstra, Ph.D., is a researcher at the Kavli Institute of Nanoscience in the Faculty of Applied Sciences, Delft University of Technology. After receiving his M.Sc. in Mechanical Engineering, he worked on the development of the first generation of DVD video recorders at Philips Components in Eindhoven, the Netherlands. He returned to university for a Ph.D. project on micromachining techniques with applications in DNA-sensors. His current research focuses on nonlinearities in nanomechanical structures, and low-power nanomechanical computing.

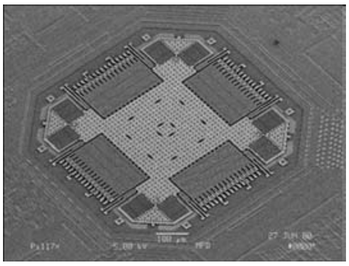


Figure 1. MEMS accelerometer commercialized by Analog Devices in airbags and game consoles.

The principle of mechanical sensing often involves determination of a mechanical resonance frequency, which is affected by the quantity that has to be measured. In Figure 2, the resonance frequency of the V-shaped beam changes as a result of mass adsorbed on its surface. As with electronics, lithographically produced micro- and nanomechanical systems can be integrated on a large scale, and this will enable new applications such as high-speed imaging and manipulation of surfaces on atomic scale by

for characterizing systems

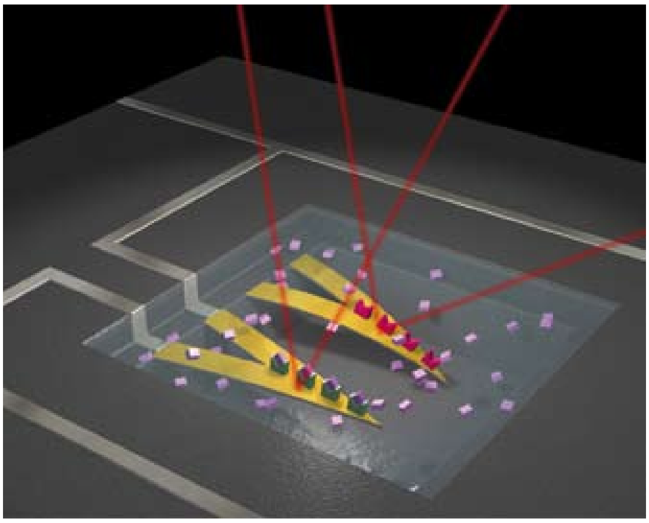


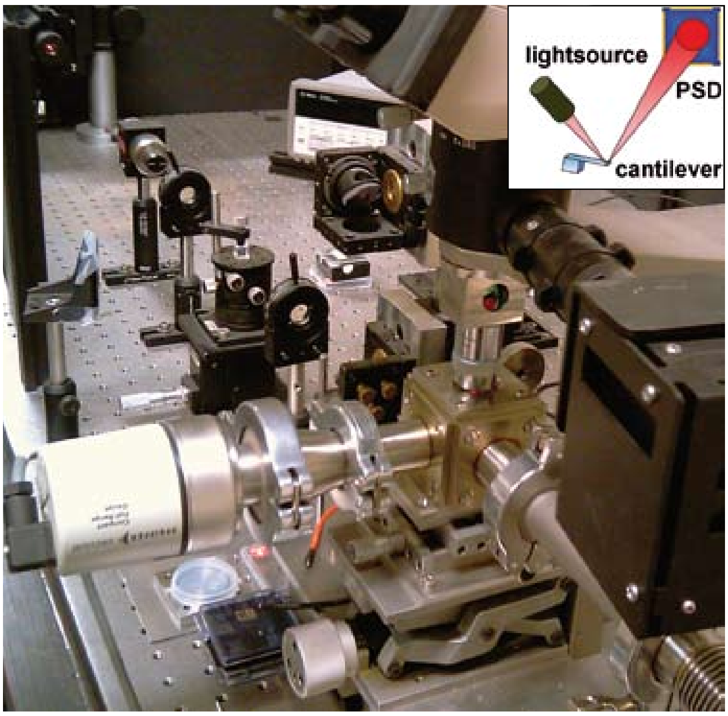
Figure 2. Microresonators for biomolecule sensing.

scanning probes, mechanical memories and logic, and sensor arrays for the simultaneous detection of multiple chemical compounds. Most of these devices operate at atmospheric pressure, in air or in water. Characterization of the dynamical properties in these environments is essential for their development.

Characterization

Optical techniques are often used to characterize the dynamical properties of micro- and nanomechanical systems. Commercial tools are available, such as the laser vibrometer shown in Figure 3a, which detects the Doppler shift of an optical beam reflected from the vibrating micromechanical device. Another popular method is the optical deflection technique. An optical beam is reflected off the vibrating structure and captured on a position sensitive detector (PSD). This scheme, shown in Figure 3b, is often applied in scanning probe microscopes.

(a) Commercial laser Doppler interferometer.



(b) Optical deflection setup for characterization in vacuum, air and water.

Figure 3. Optical tools for the dynamic characterization of micromechanical systems.

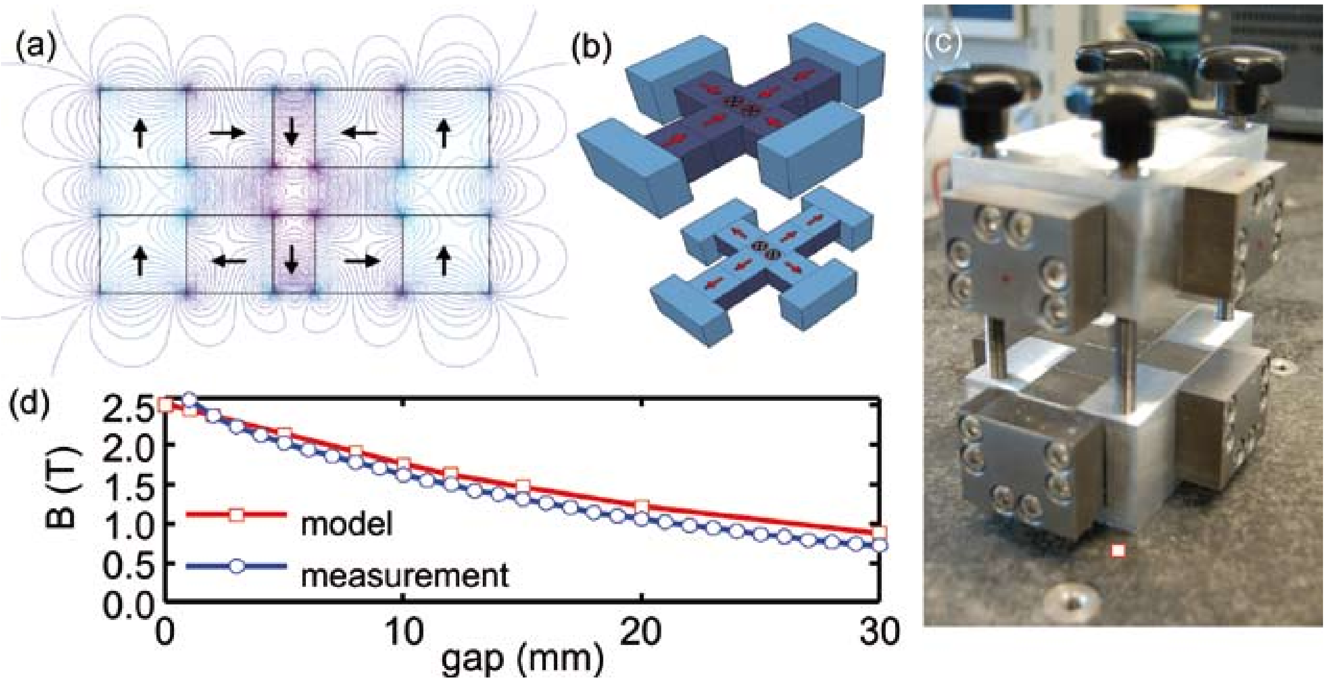


Figure 4. Development of a 2.5 Tesla permanent magnet.
(a) Magnetic field of a Halbach array, calculated by finite element analysis. The arrows indicate the polarization of the magnets.
(b) Implemented magnet arrangement.
(c) The resulting magnet; the gap can be adjusted by four screws.
(d) Measurement of the magnetic field as a function of the gap.

Optical techniques are straightforward to implement, but they have several drawbacks. The minimum dimension of the devices that can be characterized is limited by diffraction. The structure should also be accessible by the optical beam. The optical axis should be aligned with the displacements to be detected. This is not the case for a range of micromechanical devices, such as the electrostatic actuator shown in Figure 1, which are designed to move in the plane of the wafer. Although microscopic imaging under stroboscopic illumination can be used to visualize these lateral movements, the resolution of such measurements is limited. Optical techniques are also inadequate to measure the response of multiple devices simultaneously. Positioning multiple optical beams and capturing the reflections on one or more detectors is a complicated task.

Many of the limitations connected with optical techniques can be overcome by a technique based on electromagnetic induction. This magnetomotive technique can be used to simultaneously drive and detect conducting micromechanical structures.

Magnetomotive drive and detection

To drive the resonator, an alternating current I is applied in the presence of a static magnetic field B. A Lorentz force ($F = B \times I$ per unit length) is acting on the resonator and causes a displacement. Movement of the resonator changes the flux Φ through the current loop, and this generates an electromotive force (EMF) equal to $E = -d\Phi/dt$, proportional to the velocity of the resonator. When the frequency of the driving current matches the mechanical resonance frequency, the displacements are amplified and the induced voltage peaks. A mechanical resonance can thus be detected by measuring the generated EMF as a function of the frequency of the driving current.

In micro- and nanomechanical systems, the displacements and the corresponding flux changes are very small. Moreover, the driving currents are limited as the devices easily heat up and resistances are relatively high. However, the extremely low mass results in very high resonance frequencies, and as a result the magnetomotive transduction technique scales favourably when shrinking the device dimensions. It appears that the technique is particularly well-suited for the characterization of micro- and nanomechanical structures.

A quadratic relation exists between the generated EMF and the applied magnetic field, and to detect resonators with lengths in the micrometer range one needs a high magnetic field. Fields that are strong enough can be generated by cooling a Niobium-Titanium coil to below the critical temperature, usually at 4 K, the temperature of liquid

Helium. Once the coil is superconducting, a large current can circulate without dissipation. Magnetic fields over 15 T can be generated in this way, which is more than ten times the remanence of today's strongest permanent magnets. Although these cryogenic systems have been used to explore the dynamics of nanomechanical resonators [1], they are expensive and take great effort to operate and maintain. This makes them impractical for routine characterization purposes.

A 2.5 Tesla permanent magnet

The remanence of state-of-the-art Neodymium permanent magnets is approximately 1.5 T, but the field rapidly diminishes when the magnetic circuit includes an air gap. To obtain a strong field inside a gap which is large enough to accommodate a variety of experiments, the magnetic flux can be concentrated by using a special arrangement of piece-wise rotated magnets, known as a Halbach array [2]. Several implementations of such a magnet array were simulated using a two-dimensionsal finite element analysis. Figure 4a shows a simulation of a Halbach array. The field is maximum in the center of the air gap, and rapidly diminishes outside the magnet. Figure 4b shows the implemented magnet arrangement, slightly different from the Halbach configuration to facilitate the assembly procedure. Each magnet pole is constructed from six 1 $inch^3$ NdFeB cube magnets and two 1 x ¼ x ¼ $inch^3$ rods. The magnets are forced in an aluminum holder by following a special procedure, invented to withstand the huge repulsive forces. Figure 4c shows the realized magnet. The gap distance can be adjusted by four screws, rotating on pivots formed by silicon nitride bearing balls.

Figure 4d shows the magnetic field measured as a function of the gap distance. Also shown is a 2D simulation for this composition of magnets. For a large gap, the simulated field is slightly higher than in the experiment. This is due to fringe fields at the magnet boundaries; these boundaries are absent in the 2D model. For a small gap, the simulation underestimates the field and here the effect of the side magnets is prominent. The measured field in a 6 mm gap is 2 T, and when the gap is a millimeter, still enough to accommodate a silicon wafer, the magnetic field exceeds 2.5 T. For a gap of 6 mm, the field was measured as a function of the position. In a volume of 6 x 6 x 6 mm^3 around the center of the magnet the field varies less than 5%. The devices to be characterized can be placed anywhere within this relatively large volume. In contrast to optical systems, alignment of the sample is not critical.

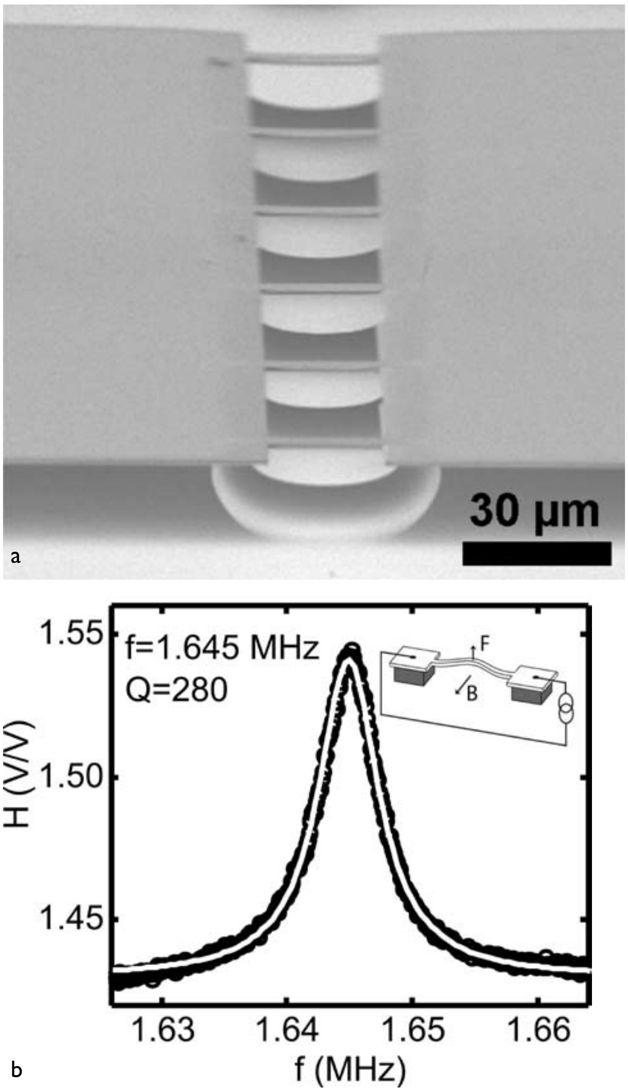


Figure 5. Resonator fabrication and characterization.
(a) Clamped-clamped resonators fabricated from a silicon nitride film by electron beam lithography. (b) Frequency response of one of the resonators at room temperature and atmospheric pressure.

Detection of mechanical resonances

The magnetomotive setup was used to characterize various types of microresonators, including crystalline silicon beams and silicon nitride beams and strings. Depending on the flexural rigidity and the residual tension, the resonator behaviour is governed by beam equations or a wave equation. The resonators shown in Figure 5a were fabricated from a 200 nm thick film of silicon nitride with a residual stress of several tens of MPa, and the behaviour is near the cross-over between a beam and string. A thin layer of gold was evaporated on top of the resonators to create a conductive path.

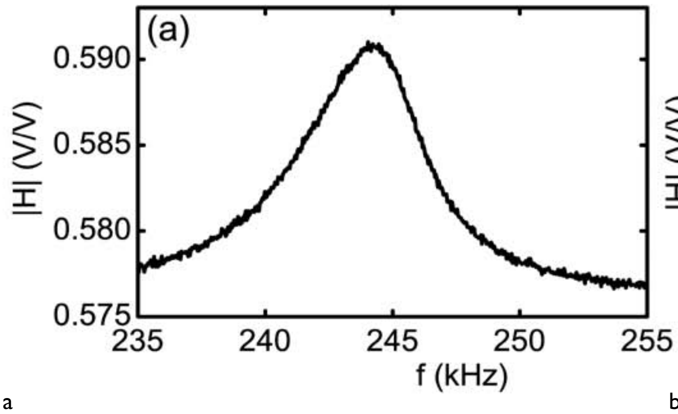
Figure 5b shows the frequency response of one of the resonators, measured with the magnetomotive technique at room temperature and atmospheric pressure. The mechanical resonance frequency is 1.645 MHz. Another important parameter, which represents the amount of damping, is the width of the resonance peak. A narrow peak means low damping, and a large displacement amplitude at resonance. It allows accurate determination of the resonance frequency. The damping can be quantified by the quality factor (Q-factor), defined as the energy stored in the resonator divided by the energy loss per movement cycle. It is related to the velocity dependent damping force by $Q = 1/(2\gamma)$. In addition to the viscous drag, the resonator is damped by the current passing through the detector circuit. To minimize this current, the EMF is measured using a high-impedance input amplifier. For the present resonator, the Q-factor is around 280, limited by the viscous drag from the ambient air molecules at atmospheric pressure.

Multiple resonators

Unlike optical techniques, the magnetomotive method is suitable for the simultaneous detection of multiple resonators. To characterize an array of resonators, all the elements are connected in series and driven by a single frequency sweep. This results in a response with multiple peaks, each peak representing a resonator. When the separation between the resonance frequencies in the frequency spectrum is less than the width of the resonance peak, individual resonators can not be resolved. This situation easily occurs in viscous environments, such as air and liquids, where the damping is high. As an example, Figure 6a shows the response of a series circuit of four resonators with nearly identical resonance frequencies. The responses add up and form a single peak, and no discrimination can be made between the resonators. Damping thus limits the number of resonant sensors that can be used simultaneously in a given frequency band.

This problem can be circumvented by making use of the nonlinear properties of the mechanical resonator [3]. When the driving force on a clamped-clamped resonator is large, the resonator behavior qualitatively alters, and the frequency response strongly deviates from the damped-driven harmonic oscillator. At large vibration amplitude the beam stretches significantly, and in addition to the flexural rigidity now the *axial* rigidity starts to play a role as well. This effect inserts a cubic stiffness term in the equation of motion, and the frequency becomes amplitude-dependent.

In the case of a clamped-clamped resonator, such as shown in Figure 5, the resonance frequency is pulled to a higher value. At sufficiently large amplitudes, typically in the order of the resonator thickness, the resonator amplitude can become bistable. Instantaneous transitions between high and low vibration amplitude can then occur, and the frequency response curve is hysteretic. The forces developed in the magnetomotive setup are large enough to access this interesting regime.



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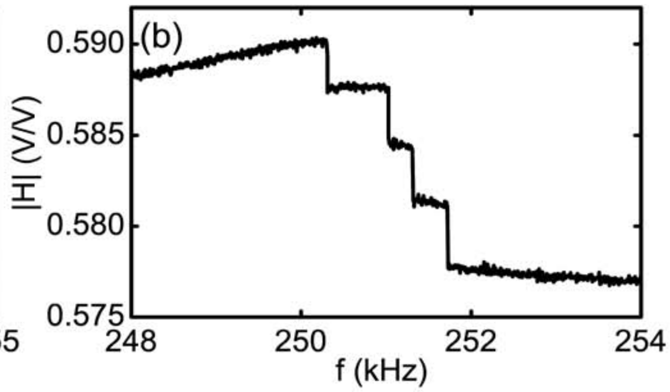

b

Figure 6. Simultaneous detection of multiple resonators.
(a) Collective linear response of four nearly identical resonators.
(b) When strongly driven, the resonators can be discriminated by making use of their nonlinear properties.

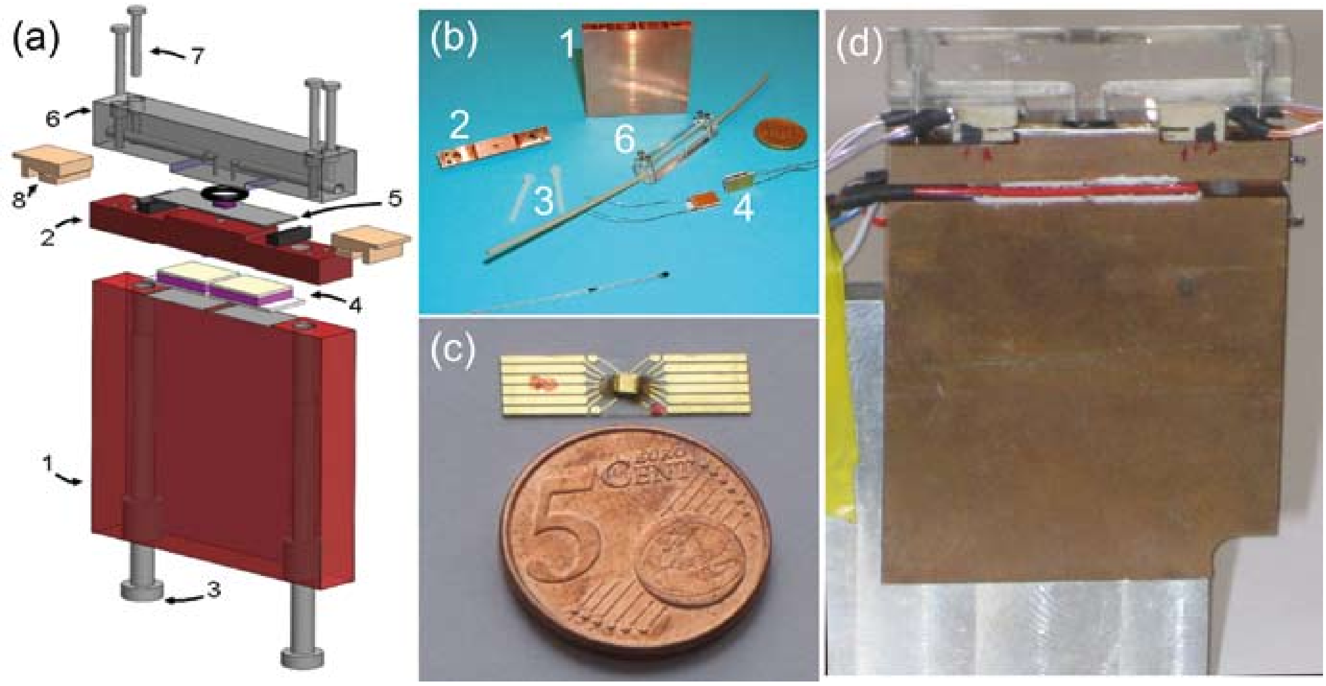

Figure 7. Construction of a flow cell.
(a) Exploded view of the flow cell.
(b) Collection of fabricated parts.
(c) Resonator chip bonded on carrier glass plate.
(d) The resulting flow cell.

The sudden jumps in the vibration amplitude can be used to discriminate resonators that could not be resolved in the linear regime of Figure 6a. This is shown in Figure 6b, which represents the same four resonators but with the drive strength increased up to the point where the resonators become bistable. In this regime, individual transitions are clearly visible for each of the four resonators. Adding or releasing mass at the surface of one of the resonators induces in a shift of the transition correspondig to that resonator, whereas the location of the other transitions remains unaffected. This principle allows the simultaneous operating of multiple resonant sensors in environments with high damping.

Flow cell

Sensing applications related to biology require operation of the microresonators in water, and to investigate the dynamic behaviour of immersed resonators, a flow cell was developed. To maximize the magnetic field, the height of the cell should be minimized. The sample is mounted upright to detect the flexural modes, using both the magnetomotive technique and a reference optical deflection technique.

Figure 7a shows the flow cell design. A heat sink (1) is connected to a sample holder (2) by isolating screws (3). Peltier elements (4) acting as heat pumps are placed in between. The sample is bonded on a carrier glass plate (5), an O-ring is placed, and a transparent cover (6) equipped with fluid in- and outlets is mounted (7). The transparent cover gives optical access to the resonators. Figure 7b shows an overview of the fabricated parts. Electrical contacts are made by two connectors (8) clamped on the carrier plate. Figure 7c shows a carrier plate, fabricated by photolithographic patterning of a gold-coated glass wafer. The sample containing the resonators is bonded on top. Figure 7d shows the flow cell that was realized. The building height is 6 mm, it contains a volume of 3 microliters, and using the Peltier elements the temperature can be stabilized to within a few mK.

Detection in liquids

With this setup, the heavily damped motion of clamped-clamped micromechanical resonators in water was detected [4]. For this experiment, 200 μm long string resonators were used. The fundamental resonance mode was first measured in air at $f_{1,air}$ = 213 kHz with a Q-factor of $Q_{1,air}$ = 50. The flow cell was then filled with water, and the measurements were repeated using the magnetomotive detector and an optical deflection technique as a reference.

Figure 8 shows the responses of the immersed resonator, as obtained by both detectors. The resonance frequency and Q-factor were $f_{1,water}$ = 53 kHz and $Q_{1,water}$ = 2. The magnetomotively detected resonance was confirmed by the optical measurement. The observed shifts in resonance frequency and Q-factor are the result of mass added by a water layer moving together with the resonator, and the

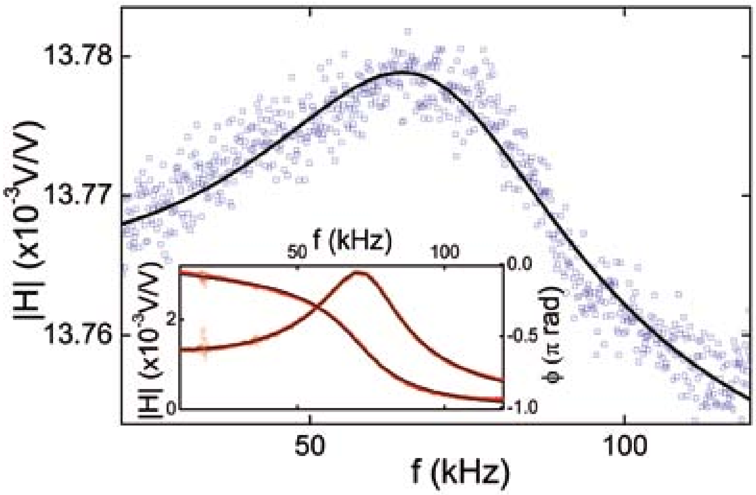

Figure 8. Magnetomotive detection of a micromechanical resonator in water. The upper inset shows the resonator, the lower inset shows the control measurement by an optical deflection technique. The solid lines represent damped-driven harmonic oscillator fits.

friction associated with the viscosity of the water. A theory was developed that quantitatively describes these effects for clamped-clamped resonators in water for arbitrary mode number [4]. Both the theory and the experimental data obtained for the fundamental and higher modes indicate that the Q-factor of immersed resonators increases with the mode number. This suggests that higher modes are less susceptible to viscous drag, and more suitable for resonant sensing in liquids.

Conclusion

An instrument was developed for the characterization of the dynamic properties of micromechanical systems. The tool uses a magnetomotive transduction technique, operating at room-temperature and atmospheric pressure. A permanent magnet was constructed that generates up to 2.5 Tesla in an adjustable gap. Mechanical resonances at megahertz frequencies can be measured, and the driving force is strong enough to drive microresonators into nonlinearity. The tool was equipped with a flow cell to allow the characterization of micromechanical systems in liquids.

The instrument has a number of advantages over optical techniques. The dimensions of the devices to be characterized are not limited by diffraction, no optical access is required, and there is no need for a separate actuator to drive the device. The magnetomotive technique allows multiple devices to be detected simultaneously, while the positioning of the samples is not critical. An alignment microscope is not needed, which this makes the tool compact and inexpensive. These features make the apparatus very convenient for fast and routine characterization of micromechanics.

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