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Parallel optical readout of cantilever arrays in dynamic mode

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Abstract
Parallel frequency readout of an array of cantilevers is demonstrated using optical beam deflection with a single laser–diode pair. Multi-frequency addressing makes the individual nanomechanical response of each cantilever distinguishable within the received signal. Addressing is accomplished by exciting the array with the sum of all cantilever resonant frequencies. This technique requires considerably less hardware compared to other parallel optical readout techniques. Readout is demonstrated in beam deflection mode and interference mode. Many cantilevers can be readout in parallel, limited by the oscillators' quality factor and available bandwidth. The proposed technique facilitates parallelism in applications at the nano-scale, including probe-based data storage and biological sensing.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Arrays of microcantilevers are fast and highly sensitive sensors having enormous potential in a variety of applications, among which are probe-based data storage [1, 2], biochemical analysis and gas detection [3]. Optical illumination of cantilever arrays can provide an accurate, reliable and non-invasive readout. Previous work has shown sequential optical readout [4, 5] by illuminating only one cantilever at each instance of time. Parallel readout requiring one detector for each cantilever in the array and a considerably more complex cantilever design has also been demonstrated [6]. Others have detected the multi-frequency response of a cantilever array [7], but neither a selective shift of a cantilever resonance frequency was measured, nor the absence of cross-talk between cantilevers. Here we present a technique for the optical readout of resonance frequency shifts of individual cantilevers within an array using a single laser–diode pair, see figure 1 for a schematic overview. The readout technique is demonstrated using cantilever torque magnetometry [8] to create resonance frequency shifts.

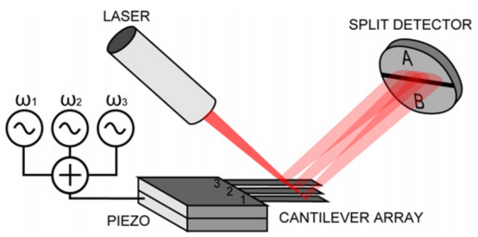

Figure 1. Schematic depiction of the technique for parallel readout of cantilever arrays.

2. Experimental details

The cantilever arrays are fabricated from one large cantilever that is about 40 μm in width and 320 μm in length. First, a 600 nm thick magnetic layer (CoNi 80/20) is deposited by e-beam evaporation. The deposition is done on one side of the cantilever to create the final array with one magnetic cantilever (see figure 2). Only one cantilever is made magnetic to be able to identify possible mechanical coupling between the cantilevers. Next, we use a focused ion beam (FIB) to machine the cantilever into three cantilevers of slightly different lengths

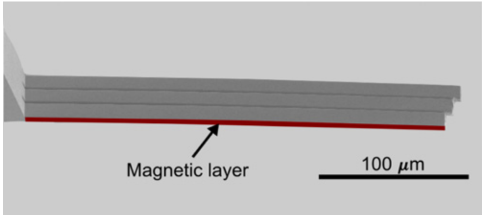

Figure 2. SEM image of a cantilever array consisting of three cantilevers each with a slightly different length. The array is machined by FIB out of a large, single cantilever.

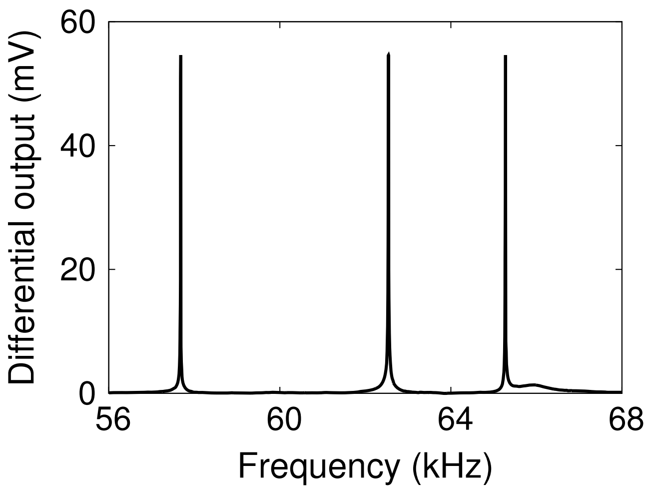

Figure 3. Frequency spectrum of a cantilever array with three cantilevers of slightly different lengths. The three peaks are well separated in frequency space.

(roughly 5 μm). The natural resonance frequency of a cantilever is inversely proportional to the cantilever length squared. The varying length yields a different resonance frequency for each cantilever and allows multi-frequency addressing. The resonance frequency shift of the magnetic cantilever due to an applied field can now be distinguished from the detector signal by locking on the corresponding frequency. The cantilever we use is a CantiClever [9] for its rectangular cross-section. The selection of the CantiClever is mainly intended to obtain three cantilevers with the same inertial moment such that the resonance frequency of each cantilever only varies due to the length difference.

The experimental setup is a standard optical lever setup where a laser spot of approximately 60 μm in size is focused on the free ends of all three cantilevers. A HeNe laser (1 mW, $\lambda = 632.8$ nm) is used as illumination source. The reflected light is collected on a split-photodiode (OptoDiode ODD-3W-2). The cantilever array is piezoelectrically actuated, and in order to increase the quality factor it is placed in a vacuum environment (10^{-2} mbar). The frequency response of the cantilever array as measured by a lock-in amplifier is displayed in figure 3. The total duration of the frequency sweep is 31 s. The measurement shows that the resonance of each individual cantilever is well separated from the others.

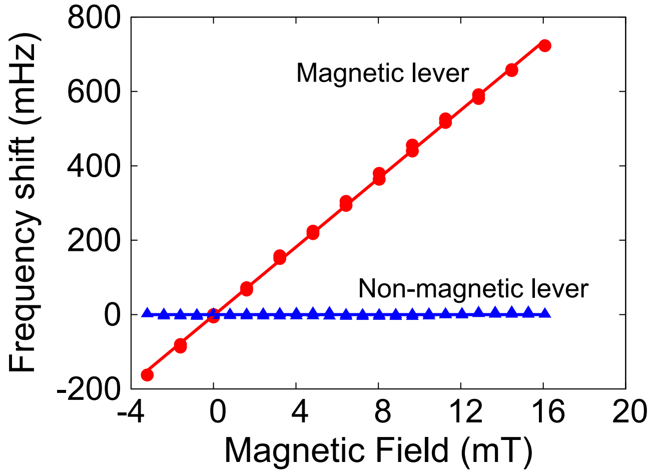

Figure 4. Measured frequency shift versus the externally applied magnetic field. The magnetic field is increased in steps and subsequently decreased. A linear regression fit is made to our data. The magnetic cantilever shows a sensitivity of 46 mHz mT^{-1}. The neighboring, non-magnetic cantilever has a maximum shift of 6 mHz not showing any relation to the applied field.

3. Results

3.1. Beam deflection

Figure 4 shows the field dependent measurement of the resonance frequencies of the magnetic cantilever and the non-magnetic neighboring cantilever. The orientation of the field is along the length direction of the cantilever, where the positive direction is from the base to the free end. The strength of the magnetic field is varied in steps and after each step a PID controller acquires the new value for the resonance frequency by keeping the phase difference between the driving voltage and the cantilever oscillation constant. A clear linear response (46 mHz mT^{-1}) of the resonant frequency of the magnetic cantilever to the applied field is observed. The resonance of the neighboring cantilever is not affected by the applied field showing a maximum variance of 6 mHz without any relation to the applied field, indicating that mechanical cross-talk is undetectable.

3.2. Interferometric readout

In addition to the beam deflection method used above, we also demonstrated interferometric readout. In our experiment the 12 μm wide cantilevers are closely spaced at an inter-cantilever distance of 1 μm giving rise to a diffraction pattern on the detector side (figure 5). We can therefore use the cantilever array as an optical grating, in contrast with previous demonstrations of interferometric readout where a grating has been fabricated within a single cantilever [10, 6]. Since the Fresnel numbers are smaller than one, the diffracted intensity profile can be adequately described by Fraunhofer diffraction. The laser spot covers the free ends of the cantilevers completely in the width direction, but in the length direction of the cantilever the spot size (d) is smaller than the cantilever length. The cantilever operates in the first vibration

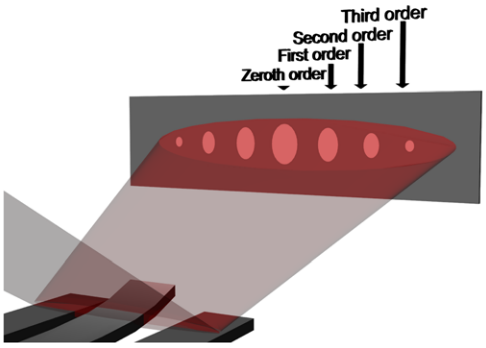

Figure 5. Schematic drawing of coherent laser light reflected off the back of a cantilever array, which functions as a reflection grating, creating a diffraction pattern in the detector plane.

mode and for simplicity we make a linear approximation to the cantilever bending profile over the range of the spot. The cantilever angle with the horizontal is θ_n and we define the downward shift of the cantilever tip end as δ_n, where n represents the nth cantilever in the array, with $n \in \{-1, 0, 1\}$. The intensity $I(x, y)$ of the reflected light can be described as the sum of the contributions of all three cantilevers

$$I(x, y) \propto \mathrm{sinc}^2\left(\frac{qw}{2}\right)\left|\sum_{n=-1}^{1} \mathrm{sinc}\left(\frac{d}{2}(m + k\theta_n)\right)\mathrm{e}^{-\mathrm{i}\phi_n}\right|^2 \quad (1)$$

where w is the cantilever width, $q = kx/R$ and $m = ky/R$, with R the distance from the cantilever array to the detector. The phase ϕ_n is equal to $(2k\delta_n - nqp)$, with p the cantilever period. The origin of the (x, y) coordinate system is centered on the detector.

The light intensity $I(x, y)$ as calculated according to equation (1) is shown in figure 6. The left plot shows the intensity on the detector side when all three cantilevers are in the equilibrium position. The right plot is calculated for a $\lambda/6$ deflection of the tip end of the center cantilever, showing the decrease in the zeroth order peak together with an increase in the first order peaks. To illustrate the consequence of interference we again aimed only the zeroth order mode of the reflected laser light on the split-photodiode, the first order modes fall outside the detector area. Now the vibration amplitude of the center cantilever is increased. Figure 7 displays a high-accuracy frequency sweep showing the resonance peak of one cantilever within the array. The array that is used in this experiment is similar to the one shown in figure 2, however the values of the resonance frequencies are slightly different. The measurement is performed using the differential output of the split-photodiode. At increased cantilever amplitude the intensity of the light decreases, leading to maximum light extinction at $\lambda/4$ deflection. The resulting indented resonance peak of figure 7 follows from the behavior of a split-photodiode detector, which is sensitive to both translation of the laser spot as well as to a change in the intensity. The intensity modulation of the light occurs twice every oscillation period of the cantilever and can thus be measured at twice the cantilever oscillation frequency. To demonstrate the interferometric readout a similar three-cantilever array with one magnetic cantilever is used. Instead

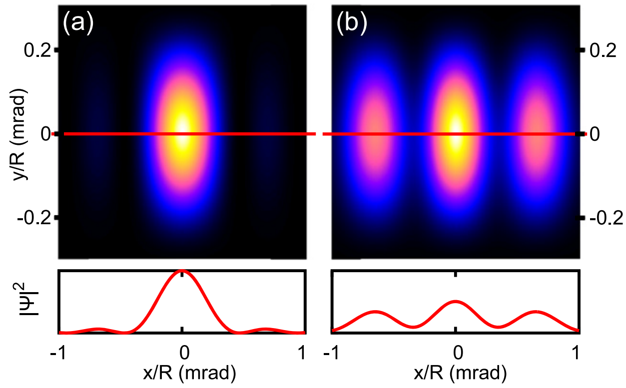

Figure 6. Calculated intensity of light reflected from a three-cantilever array. (a) Reflection of the array with all cantilevers in the equilibrium position. (b) Intensity plot when the center cantilever is deflected downwards over $\lambda/6$. The resulting translation in the negative y-direction of the zeroth order intensity peak is hardly visible on this scale.

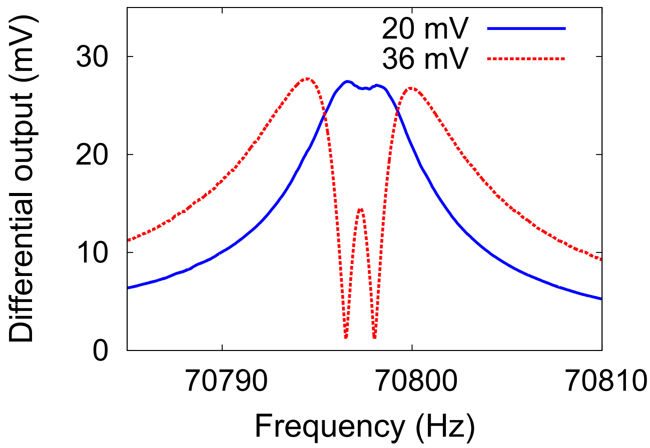

Figure 7. Measurement of a cantilever resonance curve that starts to show indents due to destructive interference when the deflection amplitude is increased, displayed for two different actuation voltages.

of subtracting the signals from both diodes now a sum amplifier is used. The inset of figure 8 shows the frequency response of the cantilever array measured at twice the excitation frequency of the array. The frequency band is limited to the resonance peak of the magnetic cantilever. Next a magnetic field is applied and the resonance frequency shift as a function of applied magnetic field is obtained (figure 8). The single photodiode instead of the split-photodiode measures only the intensity modulation and no laser spot displacements. Consequently the alignment of the laser spot on the detector is much less demanding than in the case of a split-photodiode.

4. Conclusion

The two demonstrated readout techniques require the same hardware and can therefore be interchangeably used. Readout of the beam deflection by a split-photodiode is preferred if a cantilever array has a large pitch such that it can no longer

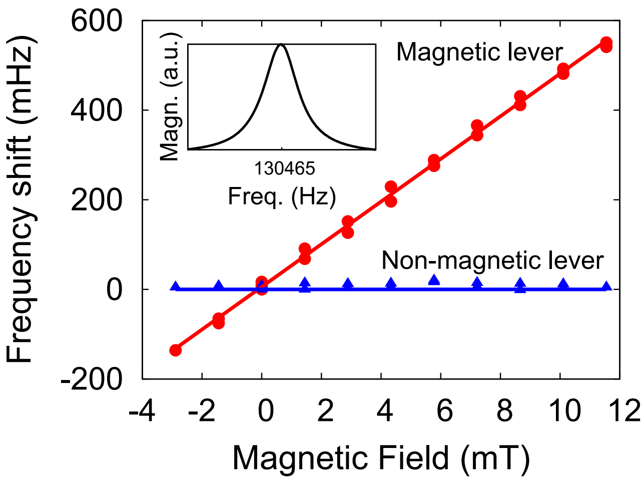

Figure 8. Measurement of the resonance frequency of a magnetic cantilever and its non-magnetic neighbor in an array using the intensity change in the laser spot. The magnetic cantilever shows a sensitivity of 48 mHz mT^{-1}. The inset shows a typical frequency sweep of the same cantilever. The FWHM is 6.5 Hz. Notice that the measurement frequency (on the x-axis) is exactly twice the oscillation frequency of the cantilever.

be treated as a grating. We foresee that sizable arrays pose a challenge in the focusing of all reflected laser spots on a split-photodiode. A cylindrical or line shaped laser spot is useful to improve the uniformity of laser light distribution over the complete array. Compared with conventional parallel readout of cantilever arrays where laser sources have to match the periodicity of the cantilever array, the flexibility for deviations in geometry of cantilever arrays is now strongly increased. The interferometric readout method offers the advantage of the usage of a single photodiode, which eases the alignment of the laser spot. Interferometry does require the deflection amplitude of each individual cantilever to stay below $\lambda/4$.

In conclusion, two optical readout techniques have been developed for the parallel readout of cantilever arrays in dynamic mode. The well-known optical lever technique is extended to arrays without any modification to the detection hardware while maintaining the high throughput. Addressing each cantilever at its own resonance frequency is the key in distinguishing the response of each individual cantilever. The interferometric detection functions likewise, however it requires only a single photodiode instead of a split-photodiode by exploiting the inherent destructive interference effects occurring when light is reflected from closely spaced cantilevers. Both techniques have been demonstrated showing accurate measurements of a single cantilever within the array that changes its resonance frequency. Mechanical coupling effects were not observed within the measurement precision ($<$10 mHz).

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