USING DIFFRACTION TO DETECT DEFLECTION OF THE CANTILEVERS IN AN ARRAY

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Abstract — **We present an optical technique to detect cantilever deflection of an array using Fraunhofer diffraction patterns. Application areas include probe-based data storage. Intensity profiles of different cantilever arrays are captured on a CCD camera and compared with our model. These measurements are in excellent agreement with the Fraunhofer theory, less than 3% deviation is found. Each cantilever can either be deflected by a fixed amount or undeflected. Based on noise measurements on our setup and intensity patterns simulations, we predict that this method allows the measurement of $1\,\mathrm{nm}$ deflections in an array of six cantilevers with an SNR of 35dB.**

Keywords — **Cantilever array, diffraction, optical readout, probe storage**

I – Introduction

Cantilever arrays are used in many applications like probe-based data storage [1], probe based nano-lithography and nano-manufacturing. In many cases feedback of the cantilever position is needed. A common way to achieve this is by integrating a sensor on every cantilever like piezoelectric [2], thermal [3] and magnetoresistive. These techniques present complexity of fabrication and constrains on the cantilever design. Optical readout on the other hand is separated from the array, does not put any constrains on the fabrication and cantilever design, and is simple to incorporate.

Sensing of cantilever deflection using diffraction patterns was first introduced by [4], by fabricating a grating inside a cantilever which creates a diffraction pattern. Later, this technique is extended to parallel operation and capturing on separate detectors [5]. We present a new scheme where the cantilevers themselves form an optical grating so that the state of deflection of each cantilever within the array determines the diffraction pattern, as is shown in figure 1. We consider the situations where the cantilevers can only be in two states: undeflected or deflected by a fixed amount.

Detection of the diffraction patterns can be performed by comparing measured patterns with calculated patterns stored in a look-up table. This is, however, not the most efficient way. In [6], fast, low complexity detection algorithms are presented to retrieve the state of the cantilevers from the measured intensity profiles. In this paper we focus on the experimental verification and quantification of the change in the diffraction patterns.
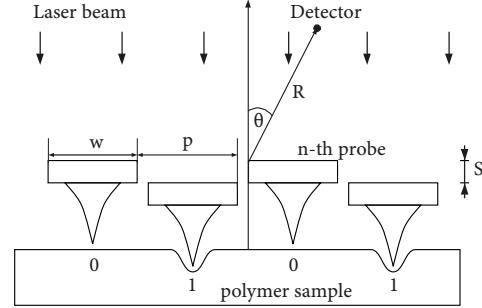

Figure 1: *Schematic of the optical readout using Fraunhofer diffraction patterns. A line shaped laser beam illuminates the array. The reflected light from the cantilevers will give rise to a diffraction pattern which is captured by a CCD camera. Small deflections of the cantilevers will result in different intensity patterns.*

II – Theory

When coherent laser light is focused on the array, the phase of the reflected light waves depends on the amount the cantilevers are deflected. This change in phase results in a different interference on the screen thus changing the intensity pattern. To be in the Fraunhofer region it must hold: $F \ll 1$, where F is [7]:

$$F = \frac{a^2}{R\lambda} \qquad (1)$$

where a is the radius of the aperture, λ the wavelength and R the distance between the array and the camera. Because the thickness of the line shaped beam incident on the array is much smaller than the length of the cantilevers, we consider the one dimensional Fraunhofer integral. The equation of the intensity profile on the camera is then given by:

$$I(x) = I(0)\, sinc^2\left(\frac{qw}{2}\right) \left| \sum_{n=0}^{N-1} e^{-i(2ks+qnp)} \right|^2 \qquad (2)$$

where $I(0)$ is the irradiance at the center of the screen with no cantilever deflected, s the deflection, k the wavenumber, w the cantilevers width, p the cantilevers period, n the cantilever index and $q = \frac{kx}{R}$ with R being be the distance between the array and the screen where the diffraction pattern is measured while x represents the coordinate on the screen.

A. A figure of merit for diffraction patterns

In order to quantitatively evaluate the difference between two intensity patterns, a figure of merit is proposed based on the area between two intensity profiles,

$$\Delta I_{\text{P}} = \sqrt{\frac{\int_{\text{profile}} [I_{\text{P1}}(\theta) - I_{\text{P2}}(\theta)]^2 \, d\theta}{\int_{\text{profile}} I_{\text{P1}}(\theta)^2 d\theta}} 100\% \quad (3)$$

where I_{P1} and I_{P2} are the two intensity profiles to be compared.

III – Experimental

A schematic of the setup is shown in figure 3. The spot from a laser diode with a wavelength of 635 nm and 3 mW power is expanded five times using a beam expander. This expanded beam is then passed through a rectangular shaped aperture of 15 mm width and 10 mm height. The resultant beam is focused on the array by a cylindrical lens with a focal length of 200 mm. This way all cantilevers are illuminated by a line-shaped coherent beam of 15 mm wide and 80 μm thick. Because the laser spot is not exactly at the tip end of the cantilever, the measured deflection is smaller than the deflection at the tip.

The diffraction pattern created by the reflected light from the array is reflected by a second prism onto another cylindrical lens with a focal length of 60 mm and rotated 90° with respect to the first lens. The diffraction pattern is then projected onto a CCD camera positioned in the back focal plane of the second lens. By placing the image plane in the back focal plane of the lens, the Fraunhofer diffraction pattern can be observed independently of the distance between the array and the lens: the image plane is placed effectively at infinity [8]. Using a lens has several advantages: the size of the diffraction pattern can be tuned with the focal length of the lens and also the optical path can be shortened using a lens with a shorter focal length. The camera has a resolution of 2048x1536 pixels and a pixel size of 5 μm.

The cantilever array is mounted on two slip-stick motors on top of each other: one allows the adjustment of the roll-angle of the array and the other allows the course positioning in the z-direction (normal to the sample surface).

Measurements were performed with arrays without tips as these are easier to fabricate. Because this method is based on the phase shift introduced by the difference in height of the reflective surface of the cantilevers, it is very important that the cantilevers thickness be as uniform as possible and that their surface be as coplanar as possible. The cantilevers are etched out of the device layer of a SOI wafer, which therefore determines the uniformity of the reflecting surface height of the cantilevers. The fabrication process is similar to that described in [9], with exclusion of the steps that define the tips. A SEM photo of an array with four cantilevers, 14 μm wide, 250 μm long and 3 μm thick, is shown in figure 2.

In order to deflect certain cantilevers in an array, a medium was fabricated consisting of a silicon wafer
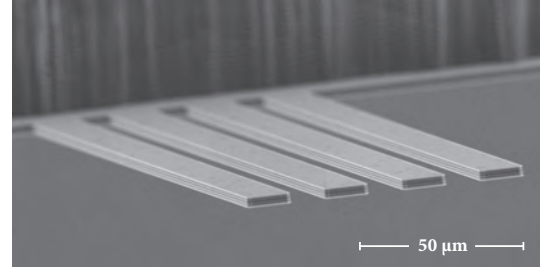

Figure 2: *Scanning electron micrograph of an array with four cantilevers* 15 μm *wide and a pitch of* 25 μm *used to measure the patterns shown in figure 4, 7 and 6*
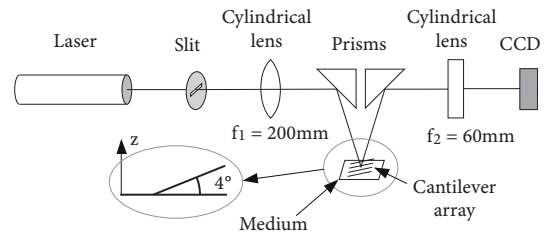

Figure 3: *Schematic of the setup used to measure diffraction patterns. An expanded laser beam is first passed through a rectangular shaped aperture and then focused by a cylindrical lens on the array. The second cylindrical lens projects the diffraction pattern on a CCD camera.*

with etched pits of varying size in order to match the cantilevers width and pitch. The medium is mounted on a *xyz* stage used for fine positioning. By moving the medium in the *z*-direction, certain cantilevers are deflected when they touch the medium, while others fall into the pits, thus remaining undeflected.

A. Analyzing CCD images

In the recorded CCD images the angle of diffraction, which is approximately equal to x/R (with x and R being defined in equation 2), is oriented horizontally. The captured images are averaged over 200 lines in the vertical direction in order to minimize the influence of dust and particles. After this averaging, low pass filtering is performed to remove high spatial-frequency noise. All the post-processing of the images is done in MatLab software.

IV – Results

A. Diffraction patterns with no cantilever deflection

Our first experiment was performed in order to check the accuracy of our model. To avoid aberrations, the second lens in the optical path ($f_2 = 60$ mm) was removed. The CCD camera was placed at a distance of 70 mm from the array. An array with five cantilevers was used having a width of 14 μm and a pitch of 20 μm. The array is not in contact with the medium underneath so that all cantilevers are undeflected. The measured in-
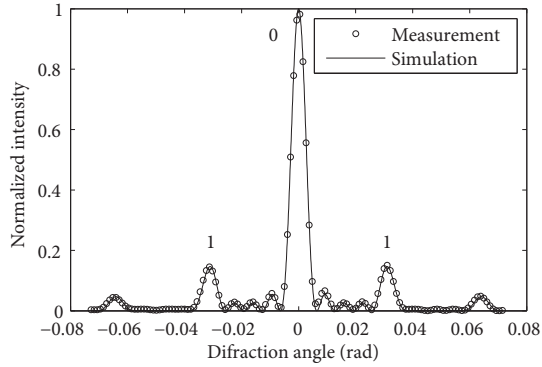
Figure 4: *Calculated and measured intensity profile of the diffraction pattern created by an array of five undeflected cantilevers. The numbers near the maxima indicate the zeroth- and first-order maxima. The ΔI_P between theory and measurement, as defined in equation 3 is 3%.*
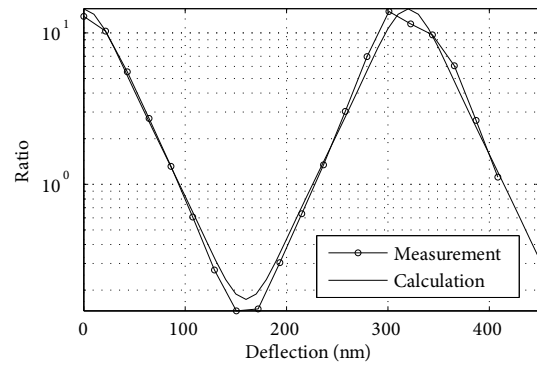

Figure 5: *The ratio of the amplitudes of the zeroth mode maximum to the first mode maxima as function of deflection for an array of N = 3 with the two side cantilevers bended. The measurements are in good agreement with the model.*

tensity profile and calculated are shown in figure 4. The error of fit according to equation 3 is smaller than 3%, showing the measurements are in excellent agreement with theory.

B. Introducing cantilever deflection

In the next set of experiments we introduce cantilever deflection. Here we use an array of three cantilevers 30 μm wide and a pitch of 40 μm where the outer two cantilevers are deflected by the same amount. With increasing deflection, the zeroth-order maximum decreases while the first-order maxima increase (figure 4). The ratio of the zeroth-order and first-order maxima is used as a measure of cantilever deflection. Figure 5 shows the calculated and measured ratio as a function of deflection. These measurements are in good agreement with theory for deflections up to 440 nm. Furthermore, figure 5 shows that the sensitivity of this technique changes based on the deflection point around which the cantilevers are operating. Maximum sensitivity is achieved when the cantilevers are operating around a deflection bias of 30 nm and lowest sensitivity when operating around 159 nm (1/4 λ).

C. Offset in deflections

We illustrate the effect of biasing using an array of four cantilevers having a width of 14 μm and a pitch of 25 μm. The outer right cantilever is deflected in steps of 50 nm. The deflection at the center of the spot is calculated to be 23 nm. For this array and deflected cantilever, we calculated the most sensitive biasing point to be 1/4 λ. First we measure two intensity profiles with 22 nm biasing. These two profiles for $h = 22$ nm and $h = 45$ nm are shown in figure 6. The calculated ΔI_P for this pair is found to be 17.6%. Next, we measure another pair with 136 nm biasing: $h = 136$ nm and $h = 159$ nm. These two patterns are shown in figure 7. ΔI_P in this case is calculated to be 32.2%. This is a
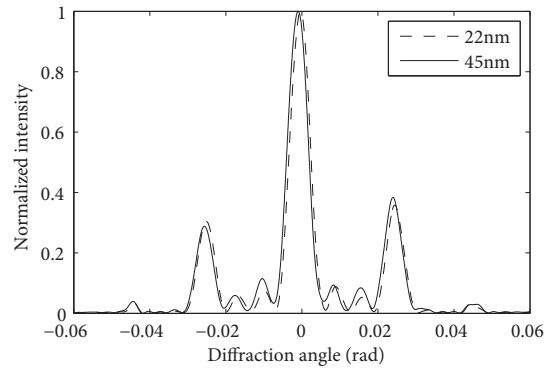

Figure 6: *Two normalized diffraction intensity profiles created by an array of four cantilevers with its outright cantilever bent at 22 nm and 45 nm. The ΔI_P as defined in equation 3 for this pair is 17.6%.*

factor 1.83 better compared to the case where 22 nm biasing was used.

D. Noise measurement

In order to give a quantitative evaluation of the capability of this technique, noise measurements were performed on an array with six cantilevers, 19 μm wide and 30 μm pitch. A hundred patterns were measured with one second interval and 9 ms exposure time giving a bandwidth of 111.1 Hz. The patterns were corrected for drift. Noise amplitude for each measurement was calculated using equation 3 with I_{P1} being the measured intensity profile and I_{P2} the calculated profile. The standard deviation of $\Delta I_P(n)$ is a measure for the noise level.

The signal amplitude of the same array is calculated with the outer right cantilever deflected at 159 nm and 160 nm. We use equation 3 with I_{P1} and I_{P2} being the simulated intensity profiles of the two deflections. Together with the noise level calculated above, this leads to an SNR of 35 dB.
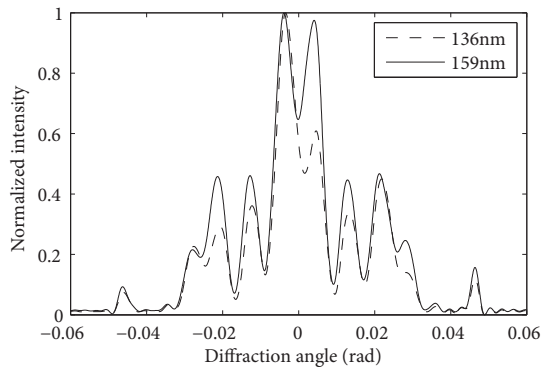
Figure 7: *Two normalized diffraction intensity profiles created by an array of four cantilevers with its outer right cantilevers bent at* 136 nm *and* 159 nm. *The* ΔI_P *as defined in equation 3 for this pair is 32.2%.*

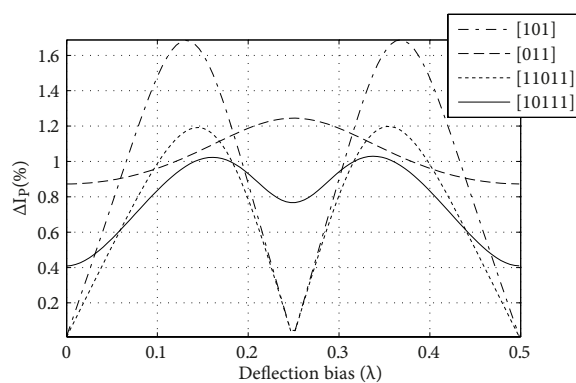Figure 8: *Simulated* ΔI_P *for* 1 nm *deflection at different offsets for different cantilever arrays. "1" and "0" represent undeflected and deflected cantilevers respectively. Sensitivity differs per array and per set of deflected cantilevers.*

V – Discussion

Measurements show that diffraction patterns are very sensitive to cantilever deflection. Sensitivity can be increased by biasing the cantilevers at a certain deflection. The simulations in figure 8 show that the exact amount of bias for optimal performance differs per array and also per set of cantilevers that are deflected. Instead of a CCD camera, a photodiode array could be used to increase bandwidth and resolution resulting in faster and more accurate measurements.

We expect thermal noise to be negligible compared to shot noise, especially with increasing laser power. Moreover, when used in information storage, the cantilevers will be supported by the sample where the data is stored, further reducing thermal noise.

VI – Conclusion

In this work we show that parallel optical readout of cantilever arrays can be achieved by analyzing the diffraction patterns created by such arrays when illuminated by a line shaped laser beam. The diffraction pattern obeys the one-dimensional Fraunhofer theory.

Noise measurements on our setup and intensity profile simulations predict that a 1 nm deflection of individual cantilevers can be detected with a SNR of 35 dB, in a bandwidth of 111 Hz.

Sensitivity can be improved by biasing the cantilevers deflection. The exact amount of bias for optimal performance differs per array and also per set of cantilevers that are deflected. For an array of four cantilevers, with the outer right cantilever deflected, we measured a signal improvement of a factor 1.83 when the cantilever is biased by 136 nm.

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