A Non-contact measurement technique to measure micro surface stress and obtain deformation profiles of the order of 1nm in Micro-cantilever based structures by single image Optical Diffraction method

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Abstract

A new method based on analysis of a single diffraction pattern is proposed to measure deflections in micro-cantilever (MC) based sensor probes, achieving typical deflection resolutions of **1nm** and surface stress changes of **50µN/m.** The proposed method employs a double MC structure where the deflection of one of the micro-cantilevers relative to the other due to surface stress changes results in a linear shift of intensity maxima of the Fraunhofer diffraction pattern of the transilluminated MC. Measurement of such shifts in the intensity maxima of a particular order along the length of the structure can be done to an accuracy of **0.01mm** leading to the proposed sensitivity of deflection measurement in a typical microcantilever. This method can overcome the fundamental measurement sensitivity limit set by diffraction and pointing stability of laser beam in the widely used Optical Beam Deflection method (OBDM).

Micro-cantilever based sensors, Surface Stress, Optical Diffraction

1. Introduction

Micro-cantilever based sensor probes translate molecular recognition events into a nanomechanical response by the use of microcantilever (MC) structures [1]. Recent developments by Calleja et al.[2], show application of SU-8 polymer based low noise microcantilevers, where, single layer molecular-interaction-induced surface stress changes of the order of ~**1 – 10 mN/m,** have been ascertained by measuring nano-deflections of the structures involved using the popular Optical Beam Deflection method (OBDM) [3,4]. OBDM involves reflection of a focused laser beam from the active MC surface onto a Position Sensitive Detector (PSD), where, deflections in the microstructure, move the reflected laser beam across the detector, a distance proportional to the deflection. The authors envisaged to achieve surface stress resolutions of the order of **50µN/m** with reduced thickness structures of the same material for biosensing applications [2]. Scaling down of dimensions increases the mechanical response sensitivity of the microcantilever structures due to their increasing surface-to-volume ratio [5].

However, diffraction of interrogating laser beams at micro-dimensioned structures limits the measurement sensitivity of AFM or MC based sensor probes by OBDM [6]. Also, the pointing stability of the laser beam is degraded by the downscaling[3] of cantilever dimensions owing to reduction in effective reflective area. Detailed analysis of OBDM by

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Putman et al. had assumed the diameter of the focused beam to be less than the microstructure length, ensuring complete reflection by the cantilever surface [6]. In addition, the sensitivity of OBDM is a function of illumination position of the laser spot along the length of the cantilever, the maximum being at the free end of the microstructure. At the free end, there is significant loss in the reflected intensity onto the PSD due to losses of part of beam to freespace beyond the structure tip. Hence the illumination positioning becomes a compromise between measured sensitivity and reflected signal intensity onto the PSD [7]. Modeling of molecular recognition induced mechanical deformation profiles in MC based biosensors by OBDM involves multiple measurements of deformation at all cross-sections along the length.

To account for the limits set by diffraction and pointing stability, a new optical diffraction-based measurement technique is proposed employing a double MC structure, which utilizes the pattern obtained by diffraction of an incident planar wavefront at the microstructure as a signature for the MC deflections. Analysis of obtained diffraction pattern can give 2D uniform deformation profiles of microstructures from a single CCD image, unlike OBDM.

2. Method

A double MC structure with dimensions of **100 x 20 x 1**(L x W x H) microns each and with a gap of 1µm between the two, as shown in Fig. 1, is proposed, where, one of the micro-beams (gray) act as a fixed reference with respect to the other active micro-beam (skin), that can respond to molecular recognition induced surface stress changes. Deformations of the order of **1nm** at free end of such a MC gives surface stress resolutions of the order of **50µN/m.**

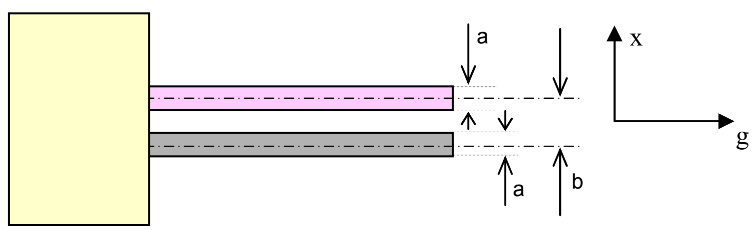

Fig. 1. Double MC structure cross sectional view, a=1µm, b=2µm

The microstructure profile across the thickness dimension will act as a double-slit aperture mask to an incident planar wavefront as shown in Fig. 2 below. Here we neglect the cantilever tip shorter edge diffraction effect, since it does not affect the proposed measurement technique. Diffraction at the microstructures will give Fraunhofer diffraction pattern as shown in Fig. 3 below, on a screen placed at an appreciable distance D behind the structure following the condition that Fresnel number F<<1, where F is given by

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

a is the characteristic size of the aperture, *D* is the distance of the screen from the aperture and λ is the incident wavelength.

Obtained intensity pattern will be uniform along the length of the microstructure unlike that in OBD method [7], since it depends only on the structure dimensions and its distance to the screen.

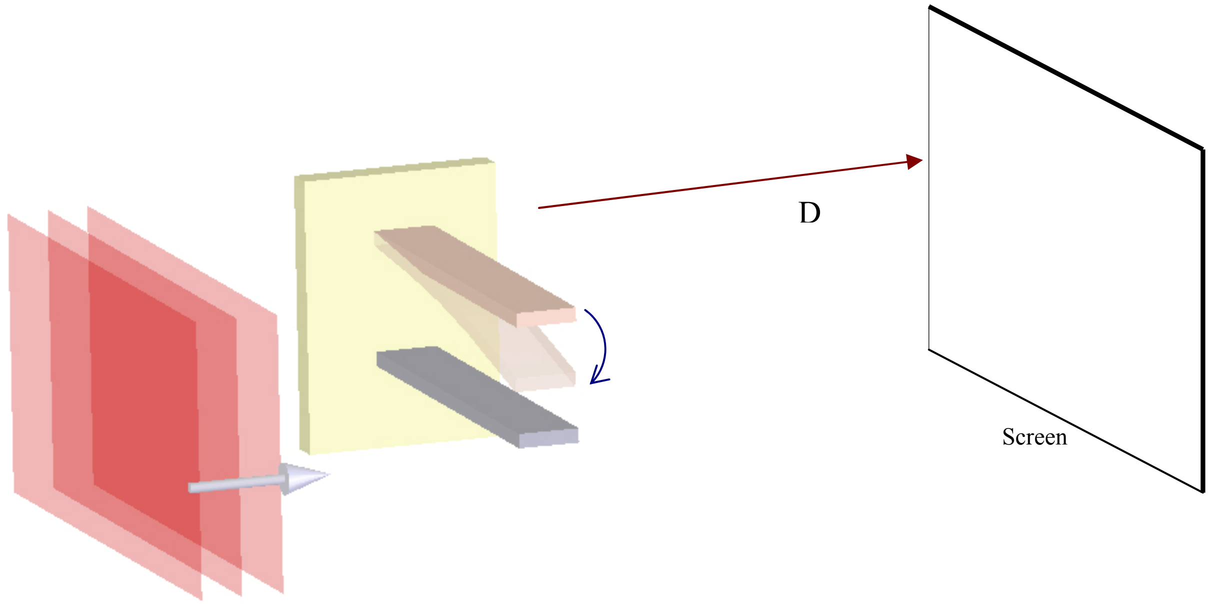

Fig. 2. Optical diffraction-based experimental setup to obtain Fraunhofer diffraction pattern from the double MC structure

The intensity pattern across any cross section of the obtained diffraction pattern corresponding to the cross section of the microstructure along the length is shown in Fig. 4.

Spatial extent of intensity maximas of the diffraction pattern acts as a signature for the cantilever separations. Relative change in gap owing to the deflection of one of the micro-cantilevers because of surface stress changes, results in spatial shift of intensity maximas.

Fig. 3 Simulated Fraunhofer diffraction pattern at the double MC structure

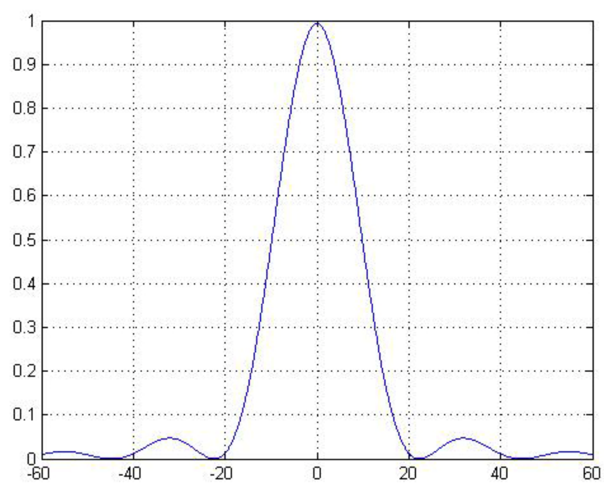

Fig. 4 Intensity pattern at any cross section along the length of the obtained diffraction pattern

2. Theoretical Formulation

The input source function of the periodic double MC structure as shown in Fig. 1, is given by

$$g(x) = 1 - \prod\left[\frac{x - b/2}{a}\right] - \prod\left[\frac{x + b/2}{a}\right] \qquad (2)$$

where $\prod$ is a rectangular slit function, *a* is the width of each structure and *b* is the distance between the two structures as shown in Fig. 1.

Now, if light passes through two slits of width *a* separated by a distance *b*, then the Fraunhofer diffraction intensity pattern at the screen is the same as single slit pattern but modulated by the interference caused by two slits and is given by

$$I(f) = I_0\left[Sinc\left(\frac{\pi a}{\lambda D} f\right)\right]^2 Cos^2\left(\frac{\pi b}{\lambda D} f\right) \qquad (3)$$

where I_0 is the unperturbed intensity, *D* is the distance of the screen from the slits and *f* is the spatial frequency

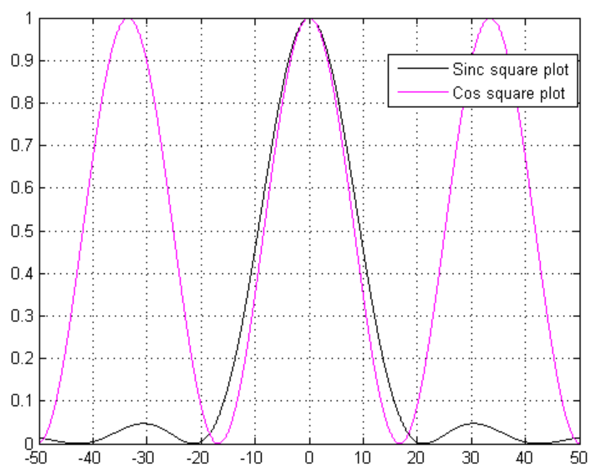

Fig. 5 Plot of $Sinc^2$ & Cos^2 functions of I(f)

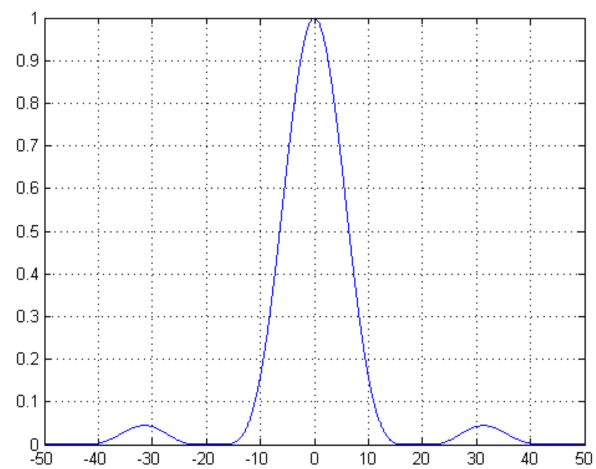

Fig. 6 Plot of final Intensity pattern [I(f)] with $I_0 = 1$.

The equivalent intensity pattern due to our proposed double MC structure following equation (2) is given by

$$I_s(f) = \delta(f) - I(f) \qquad (4)$$

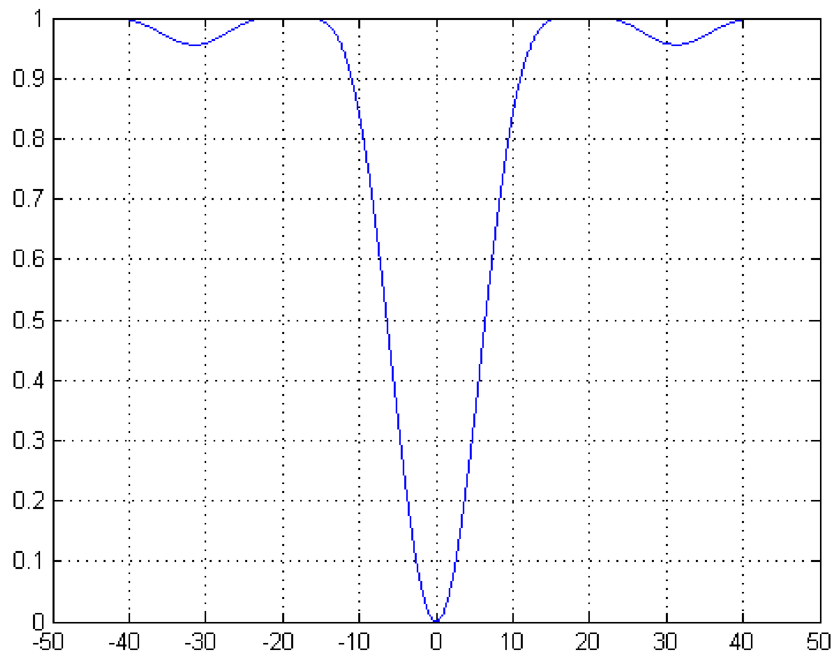

Fig. 7 Plot of Intensity pattern [$I_s(f)$]

Maxima intensities occur when argument of the cosine function in equation (3) equals a multiple of π.

$$\frac{\pi b}{\lambda D} f = m\pi \quad [m=0, \pm 1, \pm 2, \pm 3] \tag{5}$$

The distance between the central maxima and the first order maxima of the Fraunhofer diffraction pattern following equation (3) is,

$$f_1 = s_0 = \frac{\lambda D}{b} \tag{6}$$

where, λ is the wavelength of light used, *D* is the distance of the microstructure and the screen, *b* is the gap between the two structures.

The spatial shift in $\boldsymbol{\delta s_0}$ due to **1nm** variation in b is of the order of **0.0167mm** (according to calculations) when the distance between the structure and the screen is 10cm and wavelength is 670nm. Measurement of such shifts in the intensity maxima of a particular order, along the length of the structure can be determined from a single image of the obtained diffraction pattern after deformation by comparing the same with the image of the diffraction pattern of the non-deformed structure.

3. Simulation and Results

Simulation was done using MATLAB to obtain the Fraunhofer diffraction pattern of the proposed double MC structure for various screen distances and output screen dimensions with equal lengthwise change in MC separation. Simulation involves diffraction pattern generation using Fresnel Cosine and Fresnel Sine integrals.

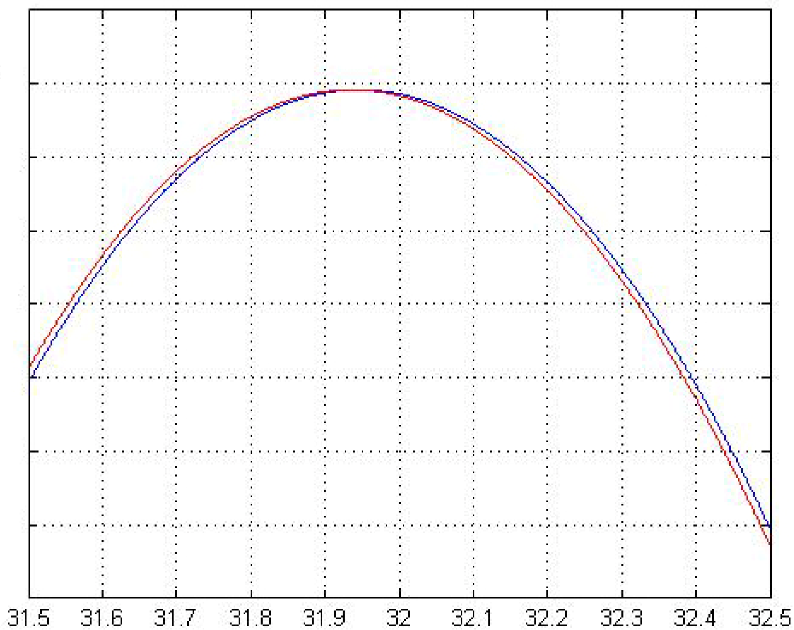

Fig. 8. Simulated relative shift of 1st order intensity maxima due to 1nm deflection at any cross section.

Table 1. Simulation results, where, a is the cantilever thickness, d is the gap between the two structures, λ is the wavelength of light used, D is the distance to the screen and MC separation change is 1nm.

a, d=b/2, λ, D	**s_0 (mm)**	**s_0^+ (mm)**	**s_0^- (mm)**	**δs_0^+ (mm)**	**δs_0^- (mm)**	**Output screen dimension (cm)**
1µm,1µm 670nm, 10cm	31.9484025	31.9384030	31.9584020	0.0099995	0.0099995	121

4. Conclusions

The measurement of first order intensity maxima shifts of the order of ~ **0.01mm** can give deflection measurement resolutions of the order of **1nm** in typical microstructure based static biosensor probes, achieving surface stress resolution of the order of ~**50µN/m** by the proposed method. Scanning and analysis of proper exposed CCD image along each pixel gives the deformations at any cross section along the length thus eliminating the need for multiple measurements as in OBDM. The proposed method overcomes the inherent limitation posed by diffraction in the Optical Beam Deflection method since it uses the diffraction at the microstructure as a signature for the deflection measurement. Obtained results can assist complete modeling of MC sensor profiles due to micro surface stress changes and can also be extended to profile deflections due to various loading techniques.

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