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A prism-based non-linear optical readout method for MEMS cantilever arrays

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ABSTRACT

This paper demonstrates the use of a single right-angle prism for the optical readout of micro-electro-mechanical systems (MEMS) cantilever arrays. The non-linear reflectivity arisen from the internal reflection at the right-angle prism's hypotenuse plane enables the measurement of cantilever deflections. The cantilever arrays used in the experiments are made of electroplated nickel structures and actuated at resonance by an external electro-coil. A laser beam illuminates multiple cantilevers, and then it is partially reflected by the prism. The prism reflectivity changes with the cantilever deflection and modulates the laser intensity at the photodetector. The detection sensitivity of the optical readout system is determined by the initial angle of incidence at the prism's hypotenuse plane, numerical aperture of the illumination system and the polarization of the laser beam. In this paper, we showed both theoretically and experimentally that self-sustained oscillations of two MEMS cantilevers with simple rectangular geometry is achievable using only one actuator and one photodetector. The gain saturation mechanism for the oscillators was provided by the optical non-linearity in the prism readout, which eliminates the requirement for separate sensing electronics for each cantilever. Based on our analytical and experimental data, we found that the prism incident angle around 41.2° is desirable in the closed-loop system due to high responsivity. Finally, we demonstrated simultaneous self-sustained oscillations of two cantilevers in closed-loop with resonant frequencies in the range 25–30 kHz. It was shown that multiple oscillations are obtainable if the cantilever resonant frequencies are separated from each other by at least 3 dB bandwidth.

1. Introduction

Various optical methods have been used for measuring the deflections of the cantilevers in atomic force microscopy (AFM) [1,2] and cantilever based chemical/biological sensors [3,4]. Optical readout has important advantages such as simplicity, reliability and ability to measure deflection without electrical connections to the cantilevers. Beam deflection [1,3] and interferometry [5,6] are the most common forms of optical methods.

Optical beam deflection method measures the deflection of the cantilever by reflecting a focused laser beam from the cantilever. The angular deflection of the cantilever changes the angular direction of the reflected laser beam. The change in the position of the laser spot due to this angular change can be detected via position sensitive detectors [1,2]. Alternatively, spatial filtering at Fourier plane by using a knife edge filter can be employed to measure the deflection of the cantilever while monitoring the intensity fluctuations using a photodetector [7]. Yet another alternative is interferometry, where the laser beam reflected from a cantilever beam is interfered with a reference beam. The interference signal is measured using a photodetector to find the phase difference and hence the deflection of the cantilever [8].

Prism-based approach has also been used for angle measurement in the past. The direction of an optical beam reflected from a moving surface can directly be measured by internally reflecting the beam near the critical angle using a single prism [9,10]. This technique offers high sensitivity in angle measurements [11]. It was shown that, the prism-based approach, which is based on the internal reflection, offers better sensitivity in practice for compact sensor applications compared to the conventional bi-cell or optical beam deflection approach [12]. In our recent work, prism based method was used in MEMS thermal sensing applications [13]. The

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sensitivity of the thermal sensors was improved with the proposed prism-based approach compared to the conventional knife-edge method.

To our knowledge, this method has not been used for measuring MEMS cantilever oscillator arrays. In this paper, we demonstrate an optical readout method for MEMS cantilever arrays based on this internal-reflection method. In a chemical/biological sensor, the tilt angle of a cantilever changes when it is exposed to a sensor input. A right angle prism was utilized to convert this tilt angle change to a reflectance change at the prism's glass-air interface near critical angle. Hence, we used a TM polarized wave, which has higher responsivity due to the steep portion of the reflectivity curve with respect to the incoming wave's incident angle, as compared to TE polarized or unpolarized wave [10].

This unique optical method has several benefits such as making the optical readout setup simpler and more compact by directly measuring the angular change. Moreover, this non-linear optical method can have a significant effect on enabling the self-sustained oscillation (SSO) operation of MEMS cantilever arrays in a closed-loop system. In an SSO system that uses a cantilever as the mechanical structure, the oscillation frequency locks to the resonant frequency of the cantilever with the help of a feedback loop that contains a saturation mechanism [14]. The main advantages of this closed-loop operation are the simplicity of the electronics [15], the possibility to parallelize the system easily [15] and the opportunity for larger measurement bandwidths [16] compared to the open-loop techniques. The feedback loop, which consists of a differentiator and an amplifier, is typically very simple for the fundamental mode oscillation where the system output is delayed, amplified and fed back to the cantilever for the excitation at resonance [17]. Therefore, the closed-loop operation does not require time-consuming frequency sweep and it can provide larger measurement bandwidths, which enable measurement of rapidly changing nanoscale mass distributions using a cantilever oscillator [18].

The SSO of a single cantilever can simply be achieved by using a nonlinear element (a variable limiter) in the electronics [19,20]. However, it is not possible to sustain multiple oscillations from an array of cantilevers with a common electrical saturation block [21] with this approach. In addition, dense MEMS/NEMS arrays with large number of elements cannot be interfaced easily to the separate actuation and readout electronics because of increased number of connections and large electronics. Therefore, oscillator arrays that share a common actuator and common electronics are desirable for multi-channel sensor applications. Mechanical or optical saturation mechanisms can simply provide the required separate saturation mechanism in order to achieve this multi-channel oscillation operation [21]. Chen et al. presented a mechanical nonlinearity related to the intrinsic nonlinear dynamics of the mechanical oscillator to sustain oscillations [22]. Although mechanical nonlinearity is suitable for sustaining oscillations in an array using a single feedback loop, the designated mechanical nonlinearity was demonstrated for a single oscillator [22]. In addition, the displacement is often needed to be increased excessively for the MEMS cantilever case to enable mechanical saturation; and this may impose limitations for the cantilever geometry and may require electronics with high dynamic range. Nevertheless, optical non-linearity offers the required separate saturation mechanisms of each oscillator with a simple architecture to achieve multiple oscillations from multiple cantilevers in a closed loop system [15,21].

In our previous work, we demonstrated parallel operation of MEMS cantilevers with embedded diffraction gratings for multiple oscillations, which can enable multi-channel sensor applications [21]. However, a large diffraction grating at the tip of the cantilever complicates the cantilever design and decreases the quality factor of the MEMS cantilever [21] due to squeezed film damping between the cantilever and the reference surface. Consequently, we propose a prism-based optical readout method based on internal reflection, which provides the required optical non-linearity for rectangular shaped simple cantilever geometry. In this method, the total-internal reflection at the glass-air interface of a prism acts as a separate saturation mechanism for each cantilever, which supports the system to limit the diverging oscillations within a single feedback loop. Besides the significance in providing the separate saturation mechanism for enabling the multiple oscillations in a closed-loop system, the prism-based non-linear optical readout method has the potential for being used with smaller size (e.g., nano-cantilevers) cantilevers.

It is noteworthy to mention that, non-uniformity in the arrays can be a problem for this internal reflection method, as it is a problem for the previously mentioned conventional optical readout methods. Since each cantilever may have different initial tilt angles in a non-uniform array, they will have different sensitivity levels. This non-uniformity can considerably be overcome by fine-tuning the tilt angle of the prism, and the gain of the feedback loop to an optimal point regarding the selected cantilevers in the array.

The structure of the paper is as follows: Section II consists of two subsections, where we describe the proposed single prism-based optical readout method, and present the simulation results. Section III presents the experimental results. Finally, conclusion summarizes our findings.

2. Prism-based optical readout method

In this work, prism-based optical readout is used for both the open-loop (frequency sweeping) and closed-loop (obtaining SSOs) operation of the MEMS cantilevers. A right-angle prism is used in order to directly convert the change in the tilt angle of the MEMS cantilevers to the change in the optical power at the detector plane. Prism's hypotenuse plane is used for the internal-reflection near the critical angle by means of the refractive index difference between the N-BK7 glass ($n = 1.5168$) and air ($n = 1$). This hypotenuse plane acts as an optical sensor that transforms the change in the incident angle to a change in the reflectivity for the glass-air interface and thus, optical intensity measured at the detector. The direct measurement of this angular change makes this method simple and convenient for MEMS cantilevers. In order to obtain a better responsivity, a TM polarized wave is used for illumination, for which the reflectivity vs. the incident angle of the incoming wave function has a higher slope. The prism-based optical readout method will be explained for open-loop and the closed-loop case in separate subsections.

2.1. Open-loop operation

In the open-loop operation, an AC signal generator is used in order to sweep the frequency in a pre-defined range to track the resonance of the MEMS cantilevers. Fig. 1a shows the proposed prism-based optical readout setup for open-loop operation. A TM polarized red laser beam ($\lambda = 633$ nm) is focused onto a single cantilever that is placed on top of a coil. The numerical aperture (NA) of the illumination optics, which composed of a magnifier system and a focusing lens, is selected to maximize the responsivity. The reflected light from the single cantilever is directed to the right angle prism by using a beam splitter. Then the light is refracted through the prism, which has a refractive index of $n = 1.5168$, and propagated towards the hypotenuse plane of the prism. The beam is exposed to an internal reflection due to the refractive index difference of the glass-air interface before captured on a PD with a lens.