Ulinas, A., Picco, L. M., Berry, M., Hörber, J. K. H., & Miles, M. J. (2016). Detection and photothermal actuation of microcantilever oscillations in air and liquid using a modified DVD optical pickup. *Sensors and Actuators A: Physical*, *248*, 6-9. https://doi.org/10.1016/j.sna.2016.07.007

Detection and photothermal actuation of microcantilever oscillations in air and liquid using a modified DVD optical pickup

Artūras Ulčinas[a,*], Loren M. Picco[b], Monica Berry[b], J. K. Heinrich Hörber[b], Mervyn J. Miles[b]

[a] *Department of Nanoengineering, Center for Physical Sciences and Technology, Savanorių 231, 02300 Vilnius, Lithuania*
[b] *H. H. Wills Physics Laboratory, University of Bristol, Bristol BS8 1TL, UK*

Abstract

We report simple and low-cost setup based on a modifiied DVD optical pickup unit for detection and photothermal actuation of microcantilever oscillations. Small rectangular cantilevers (length 7 μm , width 3 μm and thickness 100 nm) were successfully actuated and detected in both air and liquid environments. Application of such a setup for microcantilever-based biochemical sensors is envisaged.

Keywords: `micromechanical sensors`, photothermal actuation, optical pickup

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1. Introduction

Microfabricated cantilever beams are extensively used as sensing elements in various fields of science and technology. Examples include force transducers in atomic force microscopy (AFM) or mass transducers in bio- and chemical sensors or micro- and nanoelectromechanical systems. Sensing usually is achieved by detecting a change in static deflection or dynamic oscillation parameters of the microcantilever induced by the interaction force, deposited mass or eneven stresses between the two faces of the cantilever. Numerous techniques have been developed to register this change, including the optical beam deflection detection method commonly used in AFM, laser interferometry and capacitance measurements. As an alternative, optical pickup units (OPU) of compact disc (CD) and digital versatile disk (DVD) drives have been employed for detection of the microcantilever displacement [1, 2, 3]. This approach is particularly attractive because of their low-cost, off-the-shelf availability and small form-factor. As reported in [4], the astigmatic detection system common to most CD and DVD

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[*] Corresponding author
Email address: `ulcinas@ftmc.lt` (Artūras Ulčinas)

Preprint submitted to Sensors and Actuators A: Physical *October 7, 2015*

OPUs allows to register both linear displacement of the microcantilever with sub-nm resolution as well as two-dimensional angular displacements. Applications of such transducers as the basis of AFM instruments [5] as well as in scalable biomolecular sensing systems [6] are under investigation.

Further advantages of the DVD OPU are small (close to diffraction limit) spot size of the laser, availability of two slots for laser diodes with almost identical beam paths, and high bandwidth of the photodetector and preamplifier (hundreds of MHz). Combination of these factors makes a DVD OPU an attractive candidate as a detection system for use with small microcantilevers (length and width in the order of microns) in dynamic mode, where the resonant frequency shift of the beam due to the added mass is detected. Small cantilevers are expected to afford higher sensitivity due to their lower mass leading to the relative increase of added/sensor mass ratio [7]. Of special interest is the possibility to perform such experiments directly in fluid without intermediate drying step which may lead to the denaturation of functional and analyte molecules and uncertain amount of residual water on the cantilever.. This is complicated due to the high viscous damping these cantilevers are experiencing which in turn requires significant excitation energy. In the most common mode of mechanical excitation (shaking the holder), numerous mechanical resonances of the system (known as the "forest of peaks") are excited, which are related to coupling among the cantilever, the fluid and the mechanical assembly [8]. One of the most successful approaches which allows elimination of this problem is a photothermal actuation where the cantilever bending is actuated by the local heating of the cantilever base and is due to the difference of thermal expansion coefficients between the materials of the cantilever and the coating used to increase the reflectivity of its surface [9, 10]. Here, we report how after a simple modification of DVD OPU it was successfully used for detection and independent photothermal actuation (PA) of small microcantilevers.

2. Experimental

The following modifications of commercial DVD OPU were essential in achieving simultaneous detection and actuation: firstly, two independent laser diode drivers (LDDs) to power the laser diodes (LDs) were implemented. Secondly, because the lens in the OPU is not chromatically corrected, it does not permit the use of the LDs with the significantly different wavelengths followed by optical filtering. To circumvent this limitation, one of the original LDs in the OPU (CD LD, 783 nm) was replaced with 650 nm LD in order to reduce the difference in the position of focus between the two LDs. Thirdly, a square waveform was used to drive the PA LD to reduce the crosstalk between the signals from the reflected detection and PA beams.

A schematic diagram of our experimental setup is shown in Figure 1. Modified DVD OPU (OPU66.30, Philips) was mounted on the stand fixed to a rotation stage for adjustment of angular position of two LD spots with respect to the cantilever beam axis. The cantilever chip was mounted in a liquid cell made by cutting a chamber and inlet-outlet channels into the glass slide by gluing to

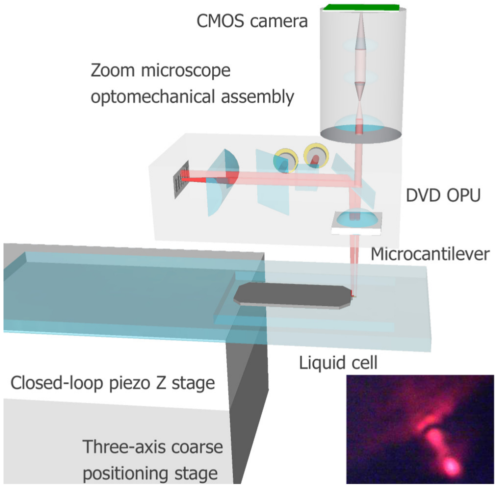

Figure 1: Schematic representation of the experimental setup. Inset: optical microscopy image of the detection and actuation laser beams aligned on the microcantilever.

the bottom of the chamber using UV-curable optical adhesive. The liquid cell was then sealed by gluing a glass coverslip on the top of the chamber using the same adhesive. It was finally mounted on the closed-loop single axis translation stage (P-753.1CD, Physik Instrumente) attached to the three-axis translation stage for course positioning of the cantilever with respect to the DVD OPU. The optical microscope with zoom lens (Zeiss) was used for alignment of the LD spots on the cantilever.

LDDs were built using WLD3343 ICs (Wavelength Electronics Inc.) with manufacturer-reported bandwidth of 2 MHz. A waveform used to drive the PA LD was supplied by lock-in amplifier (LIA) (7280, Signal Recovery) oscillator output. The DVD LD (658 nm) was focused on the free end of the cantilever for detection of the cantilever oscillations. The focusing error electrical signal derived from astigmatic detection system of the DVD OPU as described in the literature [1, 2, 3, 4] was used to monitor the vertical displacement of the microcantilevers. Detection sensitivity in the linear range was calibrated for every experiment by vertically moving the cantilever using the closed-loop piezostage. Typical detection sensitivity in our experiments was 1 mV/nm. The PA LD (RLD65PZB5, Rohm) spot was positioned on the base of the cantilever by moving the LD holder. Owing to the difference in wavelengths of the two beams, the PA beam was focused slightly above the cantilever plane, resulting in broader spot of approximately 6 μm diameter at the plane of the cantilever base (inset in Figure 1). On the photodetector, this beam produced a diffuse spot off the center of the PD, thus reducing the resulting undesirable electrical signal. The cantilever vertical displacement amplitude and phase frequency sweeps were taken using the LIA and recorded using the custom data acquisition and control software designed in LabVIEW (National Instruments).

Tipless cantilevers marketed as "special development" and made from undisclosed "quartz-like" material with manufacturer-reported values of length 7 μm, width 3 μm, thickness 0.1 μm and resonant frequency in air 1.5 MHz (SD-USC-TL-1.5, Nanosensors) were used in our experiments. These dimensions are at least an order of magnitude smaller than the cantilevers conventionally used for AFM or nanomechanical biochemical sensor applications. Cantilevers had 20 nm Au coating on the detector side.

3. Results and discussion

Figure 2 shows the amplitude (normalized) and phase transfer functions obtained using photothermal excitation with sine and square (50% duty cycle) waveforms of the same amplitude used to drive the PA LD. We found that the shape and the slope of the resonance peak obtained using the PA is affected by the reflected PA LD spot reaching the PD, and the transfer function of the PA LDD. Using the square waveform instead of the sine to drive the PA LD allowed to reduce the effect of the coupling between the actuation and detection beams, in particular at frequencies below 1 MHz. We think that this reduction is related to the fact that the the high frequencies forming the step contribute to the thermal expansion of the gold film, with the resonance frequency only present in the much smaller amount than if the actuation used a sine waveform at the resonance frequency. At the same time, the cantilever acts as a mechanical filter with displacement following the transfer function of the cantilever. At frequencies above 1 MHz, the LDD transfer function begins to affect the PA LD driving current resulting in a distorted sine-like waveform, and it also introduces a linear slope in both amplitude and phase curves.

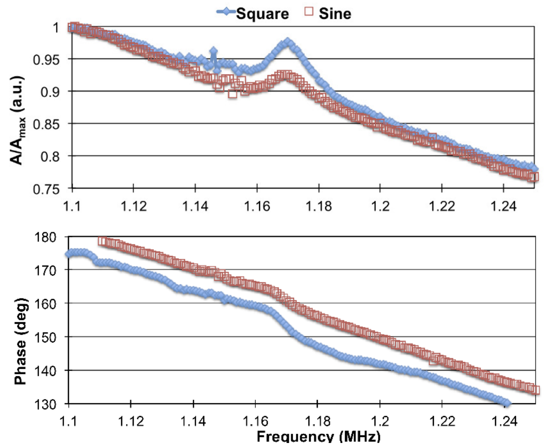

Figure 2: Amplitude (normalized) and phase transfer functions in air obtained using photothermal actuation with sine and square waveforms (without decoupling).

Additionally, as the PA and the detection LDs have different wavelengths, no optical interference is taking place, and the resulting signal is the superposition of the detection and the actuation signals generated by the PD. These signals for a given actuation frequency w can be represented by vectors (phasors): $A_c e^{iwt} e^{i\theta_c} = A_a e^{iwt} e^{i\theta_a} + A_d e^{iwt} e^{i\theta_d}$, where A_c, A_a and A_d denote the amplitudes of the coupled, actuation and detection signals, respectively, and θ symbols denote respective phase angles. Thus, the detection signal can be partially decoupled from the actuation signal by recording the amplitude and phase frequency sweeps with detection LD switched off and subtracting it from the coupled signal: $A_d e^{i\theta_d} = A_c e^{i\theta_c} - A_a e^{i\theta_a}$.

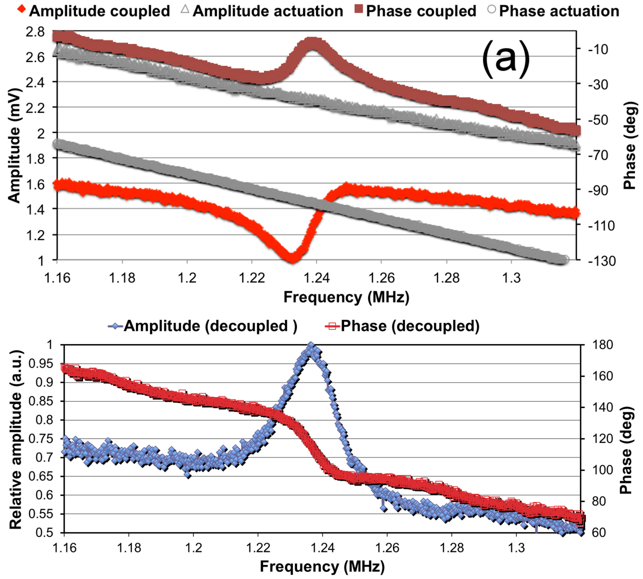

Figure 3: Amplitude and phase transfer functions in air: (a) actuation signal (detection LD off) and coupled signal sweeps obtained using phothermal actuation; (b) partially decoupled signal sweep.

Figure 3 shows graphs of amplitude and phase transfer functions of the coupled signal and the actuation signal obtained using the PA (Figure 3a) and the partially decoupled cantilever oscillation spectrum (Figure 3b). Square waveform was used to drive the PA LD. It can be seen that in this case, actuation signal amplitude was significantly higher than detection signal amplitude. This leads to the phase and amplitude information further away from the resonance being lost, which is manifested by the reduced phase shift range and the high amplitude background. However, the decoupling allows to recover the amplitude and phase information at the cantilever resonance. Mechanical actuation at this frequency even in air introduces additional peaks due to the electro-mechanical resonances of the dither piezo and mechanical assembly (data not shown). Photothermal actuation, on the other hand, provides significantly reduced noise and linear phase response.

Figure 4 illustrates the applicability of the method to actuate and detect the small cantilevers immersed in liquid. It shows the graphs of the amplitude transfer functions obtained for the cantilever coated with antibody proteins immersed in liquid before and after incubating it in a solution containing the antigene protein. Both sweeps were taken in phosphate buffer saline (PBS). The data was fitted to the simple damped harmonic oscillator model [11] to find the resonance frequency; fits are shown by solid lines. The resonance peak of the cantilever after the incubation in the antigene protein containing solution has shifted from 463.5 kHz to 262.1 kHz which is consistent with the effect of the mass deposited on the cantilever [7].

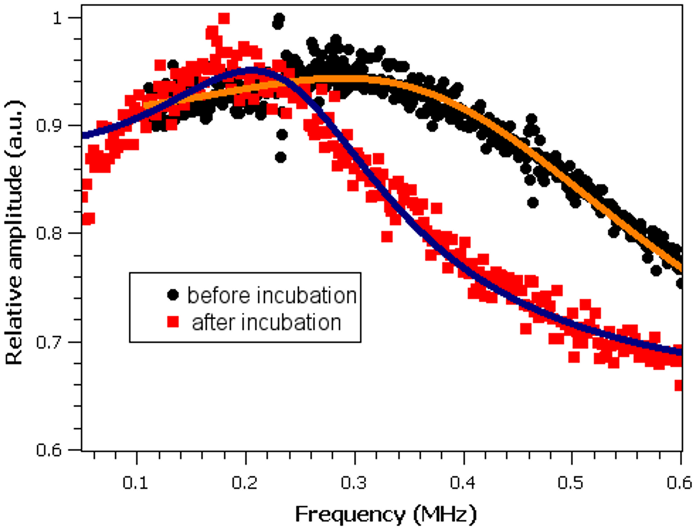

Figure 4: Amplitude transfer functions in PBS obtained using photothermal actuation (after partial decoupling) before and after the incubation of the antibody-coated cantilever in solution containing the antigene protein.

4. Conclusions

In summary, we present a simple and cost-effective method for simultaneous detection and photothermal actuation of microcantilever oscillations which uses a modified DVD optical pickup head. By virtue of the small laser beam spot size, this detection system is particularly well suited for microcantilevers with small dimensions. We envisage an application of this method in scalable multicantilever-based detection systems operating in air and liquid environments for rapid identification and quantification of bio-chemical substances.

Acknowledgments

The authors would like to thank Robert Harniman, Oliver Payton and David Smith for useful discussions, and John Rowden for fabrication of the liquid cells. This research was supported by the Severnside Alliance for Translational Research grant. MJM acknowledges a Royal Society Wolfson Merit Award. A. U. acknowledges support from Research Council of Lithuania under the grant agreement MIP-053/2014.

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