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Short communication

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

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A R T I C L E I N F O

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A B S T R A C T

We report simple and low-cost setup based on a modified 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. Applications of such a setup for microcantilever-based biochemical and physical sensors and in atomic force microscopy are envisaged.

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 uneven 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 [1–3]. 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 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 denaturation of the 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 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]. A simultaneous detection and photothermal actuation of the microcantilevers using a DVD OPU has not yet been reported. Here, we

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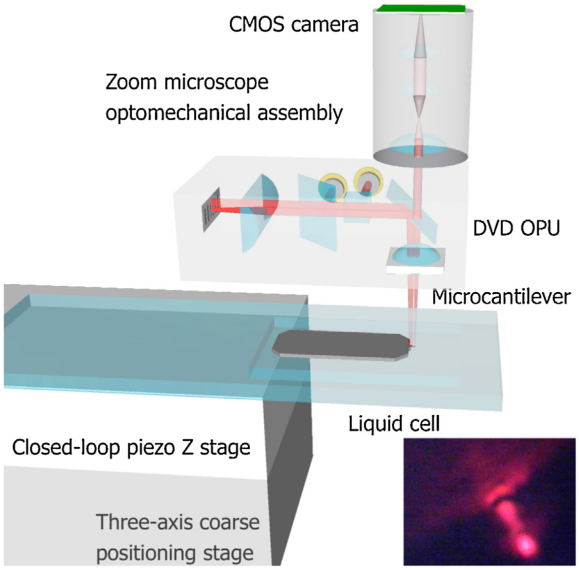

Fig. 1. Schematic representation of the experimental setup. Inset: optical microscopy image of the detection and actuation laser beams aligned on the microcantilever.

report the use of DVD OPU-based scheme 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 laser diodes with the significantly different wavelengths followed by optical filtering. To circumvent this limitation, one of the original laser diodes in the OPU (CD laser diode, 783 nm) was replaced with 650 nm laser diode in order to reduce the difference in the position of focus. Thirdly, a square waveform was used to drive the photothermal actuation laser to reduce the crosstalk between the signals from the reflected detection and photothermal actuation beams.

A schematic diagram of our experimental setup is shown in Fig. 1. Modified DVD OPU (OPU66.30, Philips) was mounted on the stand fixed to a rotation stage for adjustment of angular position of two laser 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 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 coarse positioning of the cantilever with respect to the DVD OPU. The optical microscope with zoom lens (Zeiss) was used for alignment of the laser spots on the cantilever. A photograph of the mechanical assembly is shown in Fig. 2.

Laser diode drivers were built using WLD3343 ICs (Wavelength Electronics Inc.) with manufacturer-reported bandwidth of 2 MHz. A waveform used to drive the photoactuation laser diode was supplied by lock-in amplifier (LIA) (7280, Signal Recovery) oscillator output. The DVD laser diode (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 [1–4] was used to monitor the vertical displacement of the

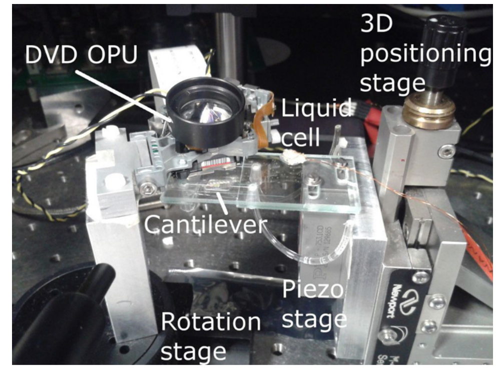

Fig. 2. Photograph of main parts of the experimental setup.

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 photothermal actuation laser diode (RLD65PZB5, Rohm) spot was positioned on the base of the cantilever by moving the laser diode holder. Owing to the difference in wavelengths of the two beams, the photothermal actuation 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 Fig. 1). On the photodetector, this beam produced a diffuse spot off the center of the photodetector, 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.

To evaluate the applicability of this detection and actuation scheme for biochemical sensing, an experiment to detect the presence of interleukin-6 (IL6) in the human blood plasma sample was devised. Cantilevers were functionalized as follows. The reflective gold coating on the cantilever was used to bind antibodies over a maximal surface, using a well- known Au-thiol chemistry. A thiolated molecule (avidin-thiol) was used, to make use of antibodies provided in a typical sandwich enzyme-linked immunosorbent assay (ELISA) kit, and to orient antibodies with their Fab arms towards the solution. Biotinylated antibodies specifically bind to avidin, neutravidin or streptavidin. These lectins, small molecules similar in molecular weight to avidin, tolerate a range of pHs including physiological. Binding of lectin to the cantilever results in a dense covering of antibodies, with a stoichiometry of 4:1.

Avidin-thiol (Protein Mods, Madison, WI, USA) was applied at 10 μg/mL and incubated for 10 min with the Au surface. Antibodies to IL6 (human IL6 ELISA Ready-Set-Go, Ebioscience) were applied at 2.5 μg/mL, and incubated with the gold surface for 30 min. Each incubation was followed by three 1-min washes with phosphate buffer solution (PBS) pH 7.4. A 10 min incubation with Magic Blocker (Candor Bioscience GmbH) to reduce the non-specific binding was intercalated between functionalization and exposure for 15 min to normal blood plasma spiked with IL6 biomarker standard. IL6 concentration was 200 pg/ml, the level correlating with the sepsis condition [11]. After the exposure to plasma, PBS was flown exhaustively through the liquid cell containing the cantilever. The cantilever amplitude-frequency sweeps were recorded in PBS both

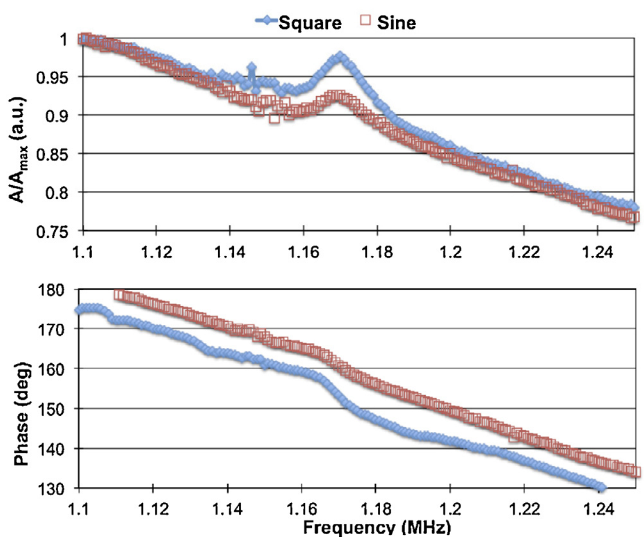

Fig. 3. Amplitude (normalized) and phase transfer functions in air obtained using photothermal actuation with sine and square waveforms (without decoupling).

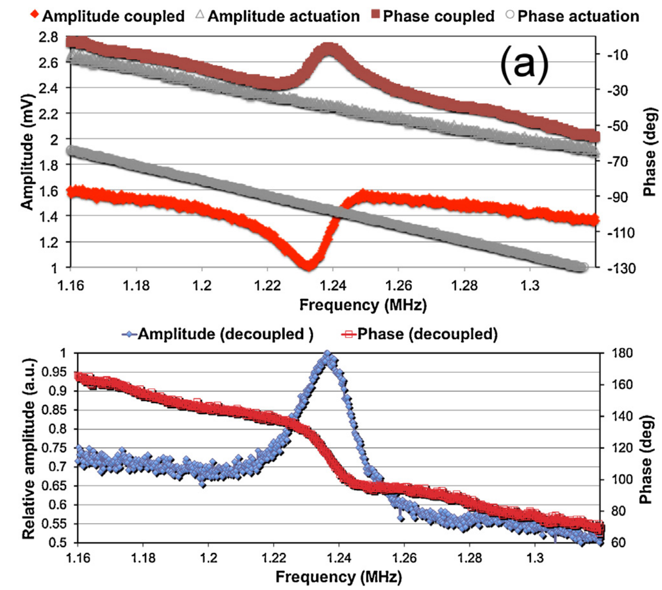

Fig. 4. Amplitude and phase transfer functions in air: (a) actuation signal (detection laser off) and coupled signal sweeps obtained using photothermal actuation; (b) partially decoupled signal sweep.

before and after exposure to IL6-spiked plasma. At all times during the functionalization and measurement procedure the cantilever was kept in solution to avoid denaturation of antibodies.

3. Results and discussion

Fig. 3 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 photothermal actuation laser diode. We found that the shape and the slope of the resonance peak obtained using the photothermal actuation is affected by the reflected photothermal actuation laser diode spot reaching the photodetector, and the transfer function of the photothermal actuation laser diode driver. Using the square waveform instead of the sine to drive the photothermal actuation laser diode 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 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 photothermal actuation laser diode driving current resulting in a distorted sine-like waveform, and it also introduces a linear slope in both amplitude and phase curves.

Additionally, as the photothermal actuation and the detection lasers 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 photodetector. 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 laser switched off and subtracting it from the coupled signal: $A_d e^{i\theta_d} = A_c e^{i\theta_c} - A_a e^{i\theta_a}$.

Fig. 4 shows graphs of amplitude and phase transfer functions of the coupled signal and the actuation signal obtained using the photothermal actuation (Fig. 3a) and the partially decoupled cantilever oscillation spectrum (Fig. 3b). Square waveform was used to drive the photothermal actuation laser. 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.

Fig. 5 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 antibodies to IL6 immersed in liquid before and after incubating it with a human blood plasma sample spiked with IL6. Both sweeps were taken in phosphate buffer saline (PBS). The data

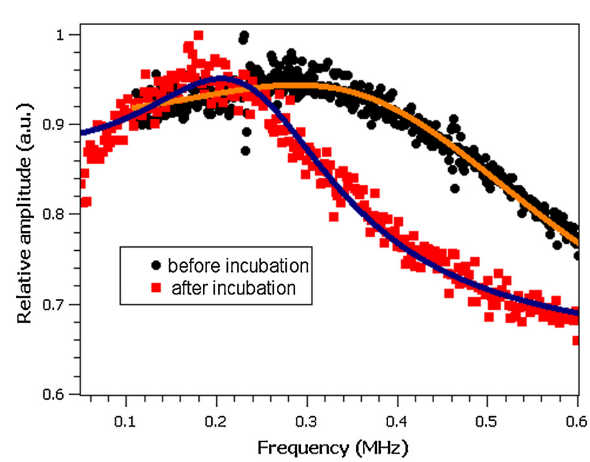

Fig. 5. Amplitude transfer functions in phosphate buffer solution obtained using photothermal actuation (after partial decoupling) before and after the incubation of the IL6-antibody-coated cantilever in human blood plasma containing the 200 pg/ml of IL6.

was fitted to the simple damped harmonic oscillator model [12] to find the resonance frequency; fits are shown by solid lines. The resonance peak of the cantilever after the incubation in the human blood plasma containing 200 pg/ml of IL6 has shifted from 463.5 kHz to 262.1 kHz which is consistent with the effect of the mass deposited on the cantilever [7].

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, as well as in the field of atomic force microscopy.

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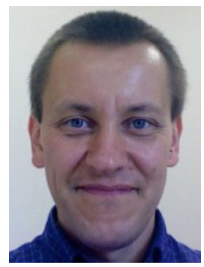
Biographies



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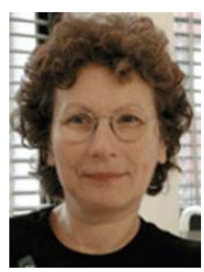

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