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# Thermomechanical behavior of a bimaterial microchannel cantilever subjected to periodic IR radiation

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ABSTRACT

Here we report the thermomechanical response of a bimaterial microchannel cantilever (BMC) subjected to periodic heating by IR radiation. A detailed theoretical and experimental study was performed considering the BMC as a thermal sensor. Experiments were conducted to find out the thermal sensitivity and power sensitivity of various BMC designs. The thermal sensitivity of the BMC was found by monitoring the response of the BMC to external heating while the power sensitivity was measured by observing its behavior to varying incident IR power. We report a minimum measurement of 60 μW of power, an energy resolution of ∼ 240 nJ and a temperature resolution of 4 mK using the BMC. The optimum BMC design was chosen to demonstrate a spectroscopy application to detect a minimum of 1.15 ng of ethanol in ethanol-water binary mixture. The purpose of this paper is to add molecular selectivity to the ultra-sensitive, novel design of microchannel cantilevers using photothermal spectroscopy techniques for biosensing applications.



## 1. Introduction

Microfabricated resonant beams have been extensively investigated as excellent gravimetric sensors for the detection of small quantities of basic ingredients of explosive chemicals [1], explosive materials [2], pathogens and for label- free detection of biomolecules [3,4], reaching single proton level mass resolution [5]. Though these resonators are highly successful in the detection of analytes in gaseous environments, they have received less attention in the detection of analytes in the presence of liquid. When a resonator is operated in a liquid environment, the frequency resolution and mass sensitivity are greatly affected due to damping and viscous drag effects inherent to such a system [6]. Recently, attempts have been made to weigh particles in a solution by designing an innovative resonator platform in which the liquid has been confined inside the resonator, while leaving the exterior to the gaseous environment or vacuum [7,8]. These so-called microchannel cantilevers have attracted wide attention because of their ability to measure the mass of a single bacterial cell and a nanoparticle in the solution [9], with a mass resolution of several attograms ($10^{-21}$ kg) [10]. The effective use of these microchannel cantilevers in the detection of biomolecules heavily depends on developing chemo-selective interfaces inside the microchannel using surface functionalization protocols [11]. Even though many functionalization protocols were developed for biosensing applications to bind to one particular analyte, the functionalized surface does not always guarantee 100% specificity to the targeted analyte. This is mainly because of the weak intermolecular interactions involved; especially in the functionalization process that are based on hydrogen bonding. Moreover, the efficiency of surface functionalization depends on the immobilization protocol and prior surface quality, the efficiency becomes even worse in the case of the detection of analyte in a mixture thus leading to unacceptable levels of false positives. In reality, these functionalization protocols are not only cumbersome but also add complexity and, in most instances, pose a threat to damage the device [12]. Recently, photothermal spectroscopy techniques have been investigated to address selectivity issues to overcome the difficulties associated with the surface functionalization [13,14]. Spectroscopy techniques are based on the unique molecular vibrational transitions in the mid-IR, or “molecular fingerprint”, region where many molecules display characteristic peaks free from overtones, making them highly selective. Photothermal cantilever deflection spectroscopy (PCDS) combines the high thermal sensitivity of a bimaterial microcantilever with highly selective mid-IR spectroscopy. PCDS techniques were demonstrated to provide the molecular signature

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**Table 1**
Design specifications of the BMC designs in chip-A and chip-B.

| Parameter | Length (μm) | Width (μm) | Thickness t2 (nm) | Metal thickness t1 (nm) | Channel height (μm) | Channel width (μm) | Channel volume (pL) | Spring constant (N/m) |
|---|---|---|---|---|---|---|---|---|
| Chip-A | 600 | 76 | 1000 | 500 | 3 | 32 | 115.2 | 0.020 |
| Chip-B | 500 | 44 | 1000 | 650 | 3 | 16 | 48 | 0.208 |

**Table 2**
Summary of figures of merit of the BMC. The bold-faced font indicates the desired parameters for an ideal thermal sensor.

| Figure of merit | Definition | **Formula** | **Chip-A** | **Chip-B** |
|---|---|---|---|---|
| **Responsivity R (nm/mW)** | Quasi-static tip displacement per incident radiative power | $\frac{1}{P_\lambda}\frac{dz}{dx}$ | **7.4** | 5.1 |
| **Incident flux sensitivity $S_{IF}$, (10$\hat{}$-5) nm μm$^2$/mW)** | Tip displacement per incident radiative power, per illuminated cantilever area | $\frac{R}{A_{cant}}$ | 16.22 | **23.18** |
| **Noise equivalent power NEP, (μW)** | The limit on incident power that can be measured by the cantilever | $\frac{\sigma(\Delta z)}{R}$ | 202 | **60** |
| **Noise equivalent flux NEF, (10$\hat{}$-3) μW/μm$^2$)** | The incident radiative flux that produces a signal to noise ratio of one | $\frac{NEP}{A_{cant}}$ | 4.42 | **2.72** |
| **Detectivity (μm/μW)** | | $\sqrt{A_{cant}/NEP}$ | **1.05** | 2.47 |

from trace quantities of analytes on the sensor surface [15,16]. In a similar way, the photothermal nanomechanical IR spectrum of 5 wt% of ampicillin in a solution has been demonstrated using microchannel cantilevers [17]. This kind of research paves the way for the future biomolecule sensing in the presence of a liquid without chemical functionalization. Photothermal techniques study the photo-induced change in the thermal state of a material; therefore, the resonator under study should be considered as a thermal sensor and should possess high thermal sensitivity in order to respond to small temperature variations. Temperature sensitivity was introduced by depositing a metal layer of optimized thickness to the backside of the microchannel cantilever, effectively rendering it as a bimaterial microchannel cantilever (BMC). Due to the bimorph effect, the BMCs (with pico liter volume capacity) are very sensitive to temperature. In order to further extend the applications of these microchannel cantilevers as thermal sensors, we need to understand the thermomechanical behavior of these cantilevers, when subjected to thermal pulses. So far, extensive investigation on the optimization and performance of micro- optomechanical thermal sensors, based on bimaterial microcantilevers has been reported [18–22], but there is a lack of relevant information on the thermomechanical characterization of microchannel cantilevers.

In this paper, we have measured the thermomechanical response of two different BMC designs through periodic heating by IR radiation and we have also measured the response of the BMC to external heating. A detailed experimental analysis is presented to determine the minimum detectable photon radiation and minimum temperature detectable by the BMC. We also present methods for optimizing the sensor performance and explore the limits of sensor resolution based on fundamental noise calculations as presented in Table 2 of figures of merit. In this context, the figures of merit are the generalized benchmark values of a thermomechanical sensor that reflect the performance of the sensor on a standard scale. Finally we have implemented our parameter optimization method for the optimum BMC to determine the lowest detectable concentration of ethanol in a water-ethanol binary mixture using the PCDS technique.

## 2. Experimental

### 2.1. Materials and methods

A U-shaped microfluidic channel was fabricated on the top of a plain microcantilever. Both structures were fabricated using a low-pressure chemical vapor deposited (LPCVD) silicon rich nitride (SRN) material. The fabrication was done by employing bulk micromachining techniques using polysilicon as a sacrificial material. Required metal deposition was carried out using a thermal evaporator (Cressington, Ted Pella, Inc). Two BMC designs were investigated to determine the optimum design parameters. The schematic of the top view and the SEM cross section view of the BMC are shown in Fig. 1(a) and (b) respectively. The design parameters and dimensions of the BMC are presented in Table 1. The critical differences between the two designsare the microchannel dimensions and the channel volume. Complete details on the fabrication of the device and the set up to load liquid sample can be found elsewhere [23]. A quantum cascade laser (QCL) operating in the mid-IR range (6–13 μm) (Daylight Solutions, MIRCat), at 100 kHz repetition rate with 5% duty cycle was chosen as the IR source. The IR laser pulses from the QCL were modulated to an optimized count using a function generator (DS345 Stanford Research Systems, USA) and radiated upon the BMC. The static deflection of the BMC was measured using an optical lever method by employing a photosensitive detector (PSD) (SPC-PSD from SiTeck S2-0171). In order to record the deflection of the BMC, the amplitude signals from the PSD were sent to a lock-in amplifier (SR 850 Stanford Research Systems, USA). Deflection amplitude of the BMC to external temperature variation was measured by a data acquisition system (NI DAQ 2120) together with a temperature controller (Global lab PX9). The noise spectrum and resonance frequencies of the BMC were measured using a spectrum analyzer (Stanford Research Systems, Sunnyvale, CA).

### 2.2. Theory

Static bending of the BMC, due to a stress generated from a temperature induced thermal expansion mismatch between the layers, is calculated based on simple beam theory. It is assumed that the changes in the elastic module of the materials involved are negligible for small temperature changes involved in the current experiments. Though the BMC has a hollow channel on the top of the microcantilever, which affects heat transfer to and from the cantilever, the basic bimorph behavior was not greatly affected. Hence, the BMC was approximated to have two layers: one is the metal layer (subscript 1) and other is SRN (subscript 2).

The deflection of the BMC for a rectangular cantilever of length $l$, width $w$, and thickness $t$ is governed by the following equation [18]:

$$\frac{d^2z}{dx^2} = 6(\alpha_1 - \alpha_2)\left(\frac{t_1 + t_2}{t_2{}^2K}\right)[T(x) - T_0] \quad (1)$$