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In-plane photonic transduction of silicon-on-insulator microcantilevers

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Abstract: We demonstrate an in-plane photonic transduction method for microcantilevers, which have been widely investigated for sensor applications. In our approach the microcantilever is etched to form a single mode rib waveguide. Light propagates down the microcantilever and crosses a small gap at the free end of the microcantilever, some of which is captured by an asymmetrical multimode waveguide that terminates in a Y-branch. The Y-branch outputs are used to form a differential signal that is monotonically dependent on microcantilever deflection. The measured differential signal matches simulation when microcantilever rotation is properly accounted for. The measured differential signal sensitivity is 1.4×10^-4 nm^-1 and the minimum detectable deflection is 0.35 nm.

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1. Introduction

Microcantilevers as nanomechanical sensing devices [1,2] have been investigated for biological [2-9], chemical [1,10-12], and environmental [13] sensing applications due to their high sensitivity, selectivity, and label-free operation. To utilize microcantilevers for sensing, a chemo- or bio-selective layer is coated on the surface of each microcantilever beam. When target molecules are adsorbed on the selective layer, typically either a change in mass is measured by determining the shift in microcantilever resonance frequency or a change in surface stress is determined by measuring deflection of the beam [14]. Measurement of resonance frequency shifts tend to be done in vapor or vacuum ambient, while deflection measurement is particularly suited to liquid environments. The sensitivity of microcantilever-based sensors is affected by the readout method chosen to determine changes in microcantilever properties. Moreover, the readout method influences the number of microcantilevers that can be simultaneously measured in an array. Typical readout methods include laser beam reflection [3-5,10] and piezoresistive [6-9,13,15], piezoelectric [11,16], and capacitive [17,18] approaches. Reflection of a laser beam from the end of a microcantilever and measurement with a position-sensitive photodetector are well-known in atomic force microscopy (AFM). Although this optical readout method can have subangstrom resolution, it is typically limited in the number of microcantilevers that can be simultaneously measured. Alternatively, piezoresistive and piezoelectric approaches are adaptable to batch microfabrication techniques such that large numbers of microcantilevers can be fabricated on a single chip, but these methods tend to suffer from electrical and system noise, which influence detection sensitivity. In the capacitive approach changes in capacitance between a microcantilever and an adjacent surface are measured. While this approach can be very sensitive in some implementations, its use is difficult for situations in which the...
dielectric constant of the medium between the surfaces varies, such as is the case for many biosensing scenarios.

In this paper we propose an alternate readout method wherein the microcantilever forms a single mode waveguide in which light propagates down the length of the microcantilever, crosses a small gap (300 nm in our case), and is captured in an asymmetric multimode waveguide section that terminates in a Y-branch. By forming a differential signal with the outputs of the Y-branch, a monotonic dependence of the differential signal on microcantilever deflection can be realized. In Section 2 we describe our design for silicon-on-insulator microcantilevers and compare it to other photonic microcantilever concepts. Fabrication and measurement of microcantilevers for experimental demonstration of this technique are discussed in Sections 3 and 4, followed by an analysis of the experimental data in Section 5. We show that the observed measurement sensitivity of the differential signal is $1.35 \times 10^{-4} \text{nm}^{-1}$, which is at least two orders of magnitude greater than piezoresistive transduction techniques and comparable to other optical transduction methods. While beyond the scope of this paper, our motivation for investigating this photonic transduction approach is its suitability for large-scale microcantilever arrays [19-21] using our recently demonstrated compact waveguide splitter networks [22].

2. Photonic waveguide microcantilever design

A number of groups have proposed measuring microcantilever properties by turning the microcantilever into a waveguide and capturing light with a static single mode waveguide that is fixed across a small gap from the free end of the microcantilever [23-25]. To illustrate the advantages and disadvantages inherent in this approach, consider the photonic microcantilever geometry in Fig. 1(a) in which a silicon microcantilever is etched to form a single mode rib waveguide [26]. The waveguide cross section is shown in Fig. 1(b) and supports a single transverse electric (TE) mode (i.e., electric field polarized in the plane of the silicon layer) at a wavelength of 1550 nm. The optical power captured in the static waveguide is shown in Fig. 1(c) as a function of vertical deflection of the photonic microcantilever. (All simulations presented in this paper are performed with FIMMWAVE/PROP by Photon Design.) Note that near zero deflection there is very little change in the output power since the slope in this region is small. Hence this approach suffers from lack of sensitivity in the middle of the measurement range. If, however, one could bias the operating point to a deflection of, say, 0.2 μm, and operate in a range of approximately ±0.15 μm around this deflection, then this approach offers the advantage of use of simple waveguides.

![Fig. 1](image)

Fig. 1. (a). Schematic layout of photonic microcantilever with single mode receiver waveguide. (b). Waveguide cross section. (c). Simulation result for the normalized power in the output waveguide as a function of microcantilever deflection.
To eliminate the above problem and operate over a deflection range of ±0.5 μm, we have proposed a new in-plane photonic waveguide microcantilever transduction mechanism [19-21] based on an asymmetric multimode static receiver waveguide. Figure 2(a) shows a schematic diagram of the microcantilever and waveguide geometry. The receiver waveguide consists of a 3.0 μm wide etched rib in the silicon layer and a 0.1 μm thick amorphous silicon strip loading that is 1.5 μm wide and is placed over half of the etched rib. This asymmetric multimode section supports two TE waveguide modes and terminates in a Y-branch 1×2 optical power splitter. The optical power in each output, P₁ and P₂, as a function of microcantilever deflection is shown in Fig 2(b) for a 100 μm long asymmetric multimode receiver waveguide. Note that the individual output power profiles are each Gaussian-like similar to what is observed for a single mode receiver waveguide as shown in Fig 1(c). However, there is a small offset (Δ) between the peaks of P₁ and P₂ in Fig. 2(b). This is significant because it results in the differential signal, η, defined as

\[ η = \frac{P₂ - P₁}{P₂ + P₁} \]

Fig. 2. (a). Schematic 3-D layout of a photonic microcantilever with asymmetric multimode receiver waveguide. (b). Simulation results for output power as a function of microcantilever deflection. (c). Differential signal.
being a monotonic function of deflection as shown in Fig. 2(c), and therefore the full measurement range is available. For \( \pm 0.5 \ \mu m \) deflection, the contrast, \( \kappa \), of the differential signal (i.e., difference between the differential signal values at the endpoints of the measurement range, -0.5 \( \mu m \) and 0.5 \( \mu m \)) is 0.23.

![Diagram](image)

Fig. 3. (a). Schematic layout of a test structure with photonic microcantilever having two single mode waveguides. The lower waveguide is for reference purposes only. SEM images of (b) a waveguide microcantilever fabricated on a SOI wafer and (c) close up of the microcantilever, strip-loaded multimode receiving waveguide, and 300 nm gap between them.

3. Microcantilever design and fabrication

To experimentally validate our readout method, we fabricated 1 cm\(^2\) silicon-on-insulator (SOI) chips with eight copies of the waveguide and microcantilever layout shown in Fig. 3(a). Each microcantilever is 100 \( \mu m \) long and 35 \( \mu m \) wide, and has two waveguides that are simultaneously illuminated from a single input waveguide. The upper waveguide sources light into our differential splitter structure while the lower one is used with a static single mode receiver waveguide to allow determination of zero deflection for the microcantilever. Fabrication starts with a 100 mm SOI wafer that has a 0.75 \( \mu m \) single crystal silicon layer and a 3 \( \mu m \) buried oxide layer. Waveguides and cantilevers are defined in separate photolithography steps in a contact mask aligner, each of which is followed by a silicon etch in an inductively coupled plasma reactive ion etcher (ICP RIE) (Surface Technology Systems). Next, the wafer is diced into discrete die. An individual die is further processed by patterning a 300 nm gap at the end of each microcantilever to form its free end. This is done by electron-beam-lithography (EBL) with a Nanometer Pattern Generation System (JC Nabiity NPGS) and field emission environmental scanning electron microscope (FEI/Philips XL30 ESEM-FEG) using alignment marks that are patterned in the same step as the waveguides.
After anisotropic etching of the gap and stripping of the e-beam resist, a further EBL step is done to define the strip loading on the multimode waveguide, followed by sputtering of amorphous silicon and lift-off. Etching in hydrofluoric (HF) acid followed by critical point drying (Tousimis Autosamdri 815B) is used to remove the buried oxide and release the microcantilevers. Figure 3(b) shows a fabricated photonic microcantilever after the release process. A close-up of the gap region is shown in Fig. 3(c) in which placement of the strip loading can be clearly seen.

![Probe tip](image)

Fig. 3. (a) Schematic of the experimental set-up using thermally treated SU-8 to bend the cantilever beam up. (b) SEM image of a cantilever beam bent up by a stressed SU-8 patch. (c) CCD camera image during an experiment to demonstrate the photonic waveguide microcantilever transduction mechanism.

4. Experimental measurement

To measure the differential signal as a function of microcantilever deflection, we pattern an SU-8 polymer layer on the top of the microcantilever and heat treat it to deflect the microcantilever due to the compressive stress induced by thermally driven epoxy cross-linking. As shown in Fig. 4(a), a sharp probe tip located on the end of a piezoactuator (Physik Instrumente, Germany) makes physical contact with the microcantilever such that vertical displacement of the microcantilever tip can be accurately controlled by pushing down on the microcantilever. Figure 4(b) shows an SEM image of a microcantilever bent up by a stressed SU-8 film. The amount of the initial deflection is controlled by the temperature at which the film is cured. In our samples this is typically 6-10 μm. A top-view microscope image of a probe tip pushing down a microcantilever is shown in Fig. 4(c).

Light from a fiber-coupled super luminescent light emitting diode (SLD) at a center wavelength of 1550 nm is amplified by an erbium-doped fiber amplifier (EDFA) and propagated through a polarization controller paddle to create TE polarized light at the end of the fiber. The TE polarized light is then butt-coupled to the chip. An optical fiber array block
is used to simultaneously collect the three optical output powers (P₁, P₂, and Pₚₑᵣᶠ) which are directed to individual photodetectors (PDA10CS, Thorlabs) that are sampled at 5 kHz by a computer-controlled data acquisition card (NI BNC-2110, National Instruments). The total piezoactuator scan distance for a measurement is 3 μm with a step increment of 50 nm. At each position, 100 data points are recorded and averaged.

Figure 5(a) shows the measured optical power for the three outputs as a function of piezoactuator position. The position of the peak of P₁ is coincident with that of Pₚₑᵣᶠ, and P₂ has an offset as expected. To determine the actual deflection of the microcantilever, the piezoactuator position is converted to microcantilever position based on the contact point of the probe tip and knowing that the peak of Pₚₑᵣᶠ occurs at zero deflection. The result is shown in Fig. 5(b) in which P₁ and P₂ are plotted as a function of microcantilever deflection. Gaussian curve fits are also shown.

![Fig. 5. (a). Measured output power as a function of piezoactuator position. (b) P₁ and P₂ as a function of deflection of the microcantilever converted from the piezoactuator position.](image)

5. Analysis and discussion

There are a number of differences between the experimental measurement in Fig. 5(b) and the initial simulation result in Fig. 2(b). For example, the ratio of the peak value of P₁ to P₂, P₁/P₂, in Fig. 2(b) is approximately 0.16/0.72 = 0.22, whereas it is (6.0 μW)/(0.58 μW) = 10 for the experimental data. Note that there are a number of possible causes for this difference. These include quality of the polished output facet and the concomitant effect on coupling efficiency into the two output fibers, different defects in the waveguides between the Y-branch and the output facet, and the fact that the fibers in the fiber block have a 1 μm center-to-center spacing tolerance that affects the individual fiber coupling efficiency.

There is another difference between measurement and simulation that is more significant. In Fig. 2(a) the position of the peak of P₁ relative to the peak of P₂, Δ, is 0.035 μm, whereas it is -0.045 μm for the experimental data. Note that the sign as well as the magnitude of the offset is different. Through a combination of experimental investigation and simulation, it is clear that the difference is due to a rotation of the microcantilever about its long axis which is caused by the probe tip contacting the cantilever at a position off of the centerline of the microcantilever. As the probe tip pushes down on the microcantilever, it causes a rotation of the cantilever as well as a deflection if the probe tip is off-center. Referring to Figs. 3 and 6(a), the sense of rotation is counterclockwise (ccw) if the probe tip touches above the microcantilever center line (i.e., positive x-axis in Fig. 6(a)) and clockwise (cw) if it is below the center line.

In our experimental setup it is not possible to reliably place the probe tip directly on the microcantilever center line. We therefore infer the rotation from experimental measurement and compare with simulation for that inferred rotation. Figure 6(b) shows the predicted offset (left axis) as a function of microcantilever rotation. Note that the offset is positive for microcantilever rotations greater than -1.5°, and negative for rotations less than -1.5°. The
horizontal blue dashed line indicates the experimentally measured offset of -0.45 μm and the vertical blue dashed line shows that this corresponds to a microcantilever rotation of -3.3° (i.e., 3.3° ccw around the z-axis).

Fig. 6. (a). Definition of counter-clockwise (ccw) and clockwise (cw) rotation, (b) Offset and contrast as a function of rotation angle of the microcantilever about the z-axis.

Figure 7 shows simulation results for $P_1$ and $P_2$ for the case of 3.3° ccw microcantilever rotation. Now the offset of $P_1$ and $P_2$ of course matches experiment, but the peak $P_1$ to peak $P_2$ ratio, $P_1/P_2$, is still different (0.44). It turns out that the differential signal is dependent on this ratio, as illustrated in Fig. 8, which is obtained by scaling $P_1$ relative to $P_2$ and forming the differential signal. Note that for $P_1/P_2$ ratios of order 1, the differential signal curves are quite similar (i.e., have nearly the same slope and therefore nearly the same contrast) and differ mainly in their average value. However, when the ratio significantly differs from 1 (such as the case of $P_1/P_2 = 10$) the slope and hence the contrast becomes smaller. Figure 9 shows the differential signal from simulation for $P_1/P_2 = 10$ and the measured differential signal. There is good agreement between measurement and simulation, indicating that the differential signal behaves as predicted and hence we can expect the differential signal for an unrotated microcantilever to exhibit characteristics similar to Fig. 2(c).
We turn now to a discussion of microcantilever measurement sensitivity, which can be calculated as [27]

\[
S = \Delta \eta \frac{1}{\eta_0 \Delta z}
\]

where \(\Delta \eta\) is the differential signal variation over some deflection range \(\Delta z\), and \(\eta_0\) is the differential signal for zero deflection. From the initial simulation (Fig. 2), we calculate a sensitivity of \(3.6 \times 10^{-4}\) nm\(^{-1}\). The observed deflection sensitivity from Fig. 9 is \(1.4 \times 10^{-4}\) nm\(^{-1}\), which is smaller than predicted by simulation primarily because of the reduced contrast attributable to the large \(P_1/P_2\) ratio. Note, however, that the observed deflection sensitivity is...
still at least two orders of magnitude greater than piezoresistive transduction techniques [27-30] and comparable to other optical transduction methods [31,32].

Another way to characterize the performance of the microcantilever sensor is the minimum detectable deflection (MDD) [29,32] which is defined as the deflection that corresponds to a signal-to-noise ratio equal to unity. The MDD is calculated as,

\[ MDD = \frac{\delta \eta}{m} \]  (3)

where \( m \) is the slope of the differential signal and \( \delta \eta \) is the differential signal noise, which in turn can be expressed as

\[ \delta \eta = \frac{2 \sqrt{(\delta P_1 \cdot P_2)^2 + (\delta P_2 \cdot P_1)^2}}{(P_1 + P_2)^2} \]  (4)

where \( P_1 \) and \( P_2 \) are the power of the two output signals, and \( \delta P_1 \) and \( \delta P_2 \) are their noises, respectively, for a given bandwidth. The powers and noises are determined empirically from the noise floors of measured signal spectra.

We determined the differential signal noise for a low-noise version of our data acquisition system (PDA10CS detectors, Thorlabs, and NI PCO-6052E data acquisition board, National Instruments) in which \( \delta P_1 \) and \( \delta P_2 \) are measured to be 0.12 nW and 0.14 nW, respectively, for a bandwidth of 250 Hz. The measured \( P_1 \) and \( P_2 \) from Fig. 5(a) are 6 \( \mu \)W and 0.58 \( \mu \)W. These measurements give a \( \delta \eta \) calculated by Eq. (4) of 0.023\times10^{-3}. Using Eq. (3) and a differential signal slope of 0.11 \( \mu \)m^{-1} from Fig. 6 gives an MDD of 0.35 nm, which is limited by broadband noise on each output signal. This broadband noise does not appear to be shot-noise dominated as has previously been assumed [32], but is instead a power independent background noise from the detectors and preamplifiers, indicating that it is either thermal or dark current shot-noise. Improving the detectors and electronics to reach the shot noise limit would improve the MDD by nearly an order of magnitude to 0.054 nm, which is comparable to the best performance offered by laser reflection transduction.

6. Conclusion

We have designed and demonstrated an in-plane photonic transduction method for microcantilevers that maintains signal sensitivity over the full measurable microcantilever deflection range. The microcantilever is etched to create a single mode rib waveguide and light from the end of the microcantilever is captured by an asymmetric multimode waveguide with a Y-branch splitter. The differential signal formed with the two Y-branch outputs is monotonically dependent on microcantilever deflection. Fabrication and measurement of a test microcantilever shows good agreement between simulation and measurement when microcantilever rotation and \( P_1/P_2 \) ratio are taken into account, thereby validating the in-plane photonic transduction method. The measured differential signal sensitivity is 1.4\times10^{-4} \( \mu \)m^{-1} and the minimum detectable deflection is 0.35 nm.

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