Grated Waveguide Optical Cavity as a Compact Sensor for Sub-nanometre Cantilever Deflections

L.J. Kauppinen, H.J.W.M. Hoekstra, M. Dijkstra, R.M. de Ridder and G.J.M. Krijnen

MESA$^+$ Research Institute for Nanotechnology, University of Twente,
7500 AE Enschede, The Netherlands

L.J.Kauppinen@utwente.nl

Abstract. **We propose a novel and highly sensitive integrated read-out scheme, capable of detecting sub-nanometre deflections of a cantilever in close proximity to a grated waveguide structure. We discuss modelling results for an SiO_2 cantilever to be integrated with an optical cavity defined by a grated Si_3N_4 waveguide.**

1. Introduction

Microcantilever-based sensors can be used to detect molecular adsorption, which causes changes in the surface stress [1], leading to deflection of the cantilever. Often, an optical beam deflection method is used to measure the cantilever deflection [2]. Although the method is simple and accurate, it is bulky, and therefore dense and compact integration of cantilever sensors is not possible with this method.

Different designs for integrated optical read-out of microcantilever deflection have been proposed and demonstrated e.g. [3] and [4]. Based on our simulations we propose a compact, novel and highly sensitive integrated read-out scheme to detect small deflections of a cantilever in close proximity to a grated waveguide (GWG) structure.

2. Device structure and principle of operation

We consider a grating defined in a shallow ridge silicon nitride (Si_3N_4) waveguide (WG), as shown in the inset of Fig. 1. The grating can be realized e.g. with laser interference lithography [5]. A very compact and stable sensor element can be realized by monolithically integrating a microcantilever structure with the GWG, using conventional layer deposition and sacrificial layer etching techniques. The cantilever core material can be silicon dioxide (SiO_2) or Si_3N_4.

The device can be functionalized by depositing a sensitive layer on top of the cantilever, e.g. palladium (Pd) for hydrogen (H_2) sensing. Absorption of H_2 into Pd will cause the cantilever to bend [6]. This bending of the cantilever can then be optically detected

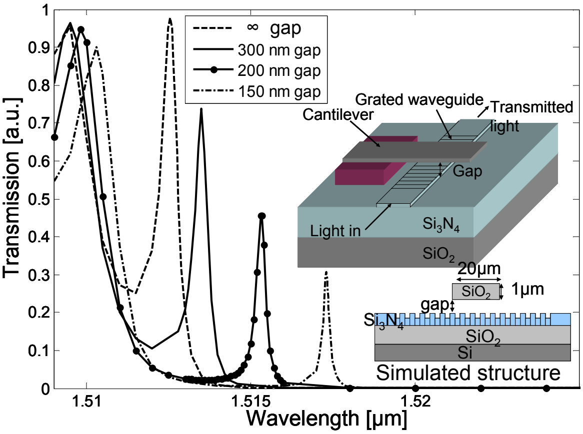

Fig. 1. Simulated transmission spectra of a 200-period grating, with the cantilever position as parameter, using a 2D bidirectional eigenmode propagation method [8]. Insets: device structure and its 2D model.

by exploiting the properties of the GWG.

The presence of a dielectric object, in this case a cantilever, in the evanescent-field region of the GWG may lead to the occurrence of propagating modes for wavelengths inside the stop band of the grating, and so to resonances (defect modes) inside the stop band, as shown in Fig. 1. As the cantilever approaches the grating, the first near band-edge resonance peak is pulled inside the stop band and its spectral width decreases. This effect can be used for the detection of cantilever displacements.

3. One-dimensional modelling

The optical deflection sensitivity (*dT/dgap*) depends strongly on the maximum slope of the transmission peak of the mode that the cantilever pulls into the stop band. Because of noise considerations, the sensitivity depends on the peak amplitude as well. Sensitivity is dependent on width, thickness and initial gap of the cantilever. To analyze the effect of cantilever width on the slope of the transmission peak, 1D calculations were performed applying the transfer matrix method to the cantilever-loaded grating structure. The cantilever-induced effective-index change was calculated with a 2D mode solver, and the obtained values were used in the 1D calculations. The modelled 1D grating is composed of layers arranged as HLHL…H'L'H'L'…HLHL, where H and L represent high- and low-index layers, respectively, and H' and L' are the corresponding indices in the cantilever induced defect region. The period of the modelled grating is 490 nm and the refractive indices of the layers H and L are 1.5928 and 1.53211, respectively. The proximity of the cantilever increases the indices below it by ~0.5%. A cantilever induced defect region width of 20 to 30 periods in a 100-period grating produces the steepest slope, as shown in Fig. 2. The slope also depends strongly on the grating length. Using the same method as above, the slope was calculated as a function of grating length. Two cases were studied: (a) the cantilever width is fixed at 20 periods, and (b) the relative cantilever width is constant, in this case at 20% of the total grating length. Doubling the grating length provides more than one order of magnitude slope improvement, as shown in Fig. 3. A large spectral slope means a high quality factor *Q* of the defect mode. However, the 1D method does not account for scattering loss that is often high for a high Q resonance [7].

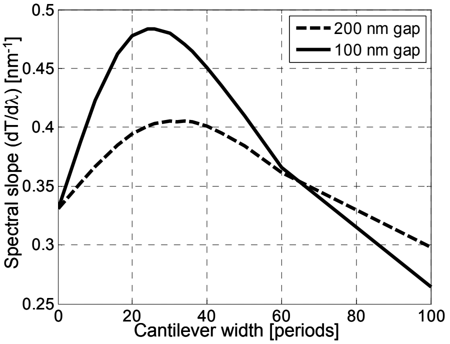

Fig. 2. Spectral slope of defect-mode transmission peak in a 100-period grating versus of cantilever width.

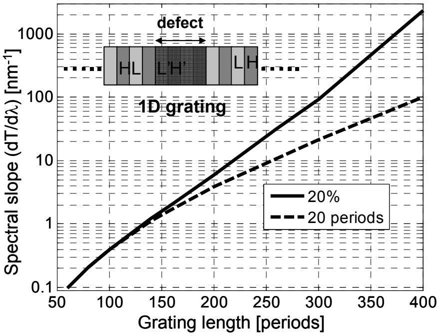

Fig. 3. Spectral slope versus grating length. Dashed line: constant 20 periods defect length; solid line: constant relative defect length (20%). Inset: simulated 1D structure with induced defect region.

4. Two-dimensional modelling

A 2D bidirectional eigenmode propagation (BEP) method [8] was applied to the model shown in Fig. 4, to analyze the effect of cantilever thickness on the deflection sensitivity. The defect-mode spectra corresponding to various cantilever thicknesses are shown in Fig. 5. Thinner cantilevers induce defect modes closer to the stop band edge and with higher transmittance than thicker ones. The difference in slope is small and thus the difference in deflection sensitivity comes mainly from the spectral shift. Since the defect modes of the thicker cantilevers are deeper in the stop band, they experience a larger spectral shift when the gap decreases from infinity to 200 nm. This suggests that the optical sensitivity is higher for the thicker cantilevers at this gap range (∞ to 200 nm).

The optical deflection sensitivity of the grating was calculated with two different cantilever thicknesses, 200 nm and 1 µm. Figure 6 shows the transmitted power versus the cantilever deflection for 2 different initial gaps, 200 nm and 300 nm. The wavelength is fixed at the resonance peak of the corresponding defect mode at each initial gap. Figure 6 shows that the sensitivity at an initial 300 nm gap is higher for the thick cantilever, although the difference is not large. However, at 200 nm gap the thin cantilever is preferred due to a higher transmission power and a slightly higher sensitivity.

The theoretical deflection sensitivity can be estimated from the graphs in Fig. 6. The sensitivity slope of the 200 nm thick cantilever at 200 nm initial gap is 0.058/nm. By assuming that the noise level allows power detection at an accuracy of 10^{-2} (e.g. transmission unit is in µW and noise level is <10 nW), the deflection can be detected with a resolution of 0.17 nm. Higher sensitivity is possible, e.g. with a longer grating, provided that the losses remain low.

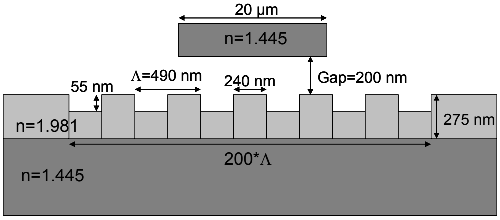

Fig. 4. 2D cross-sectional model of the device used in simulations.

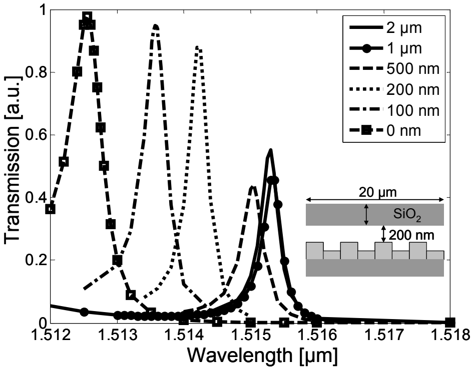

Fig. 5. Defect mode positions obtained with different cantilever thicknesses. Thinner cantilevers induce defect modes that are closer to the stop band edge.

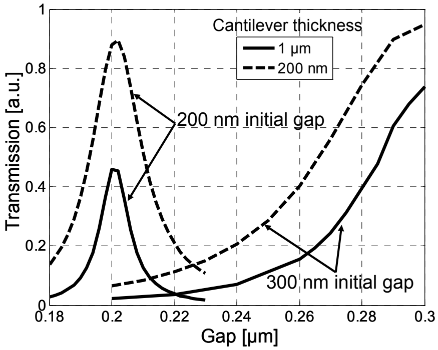

Fig. 6. Simulated transmitted power versus cantilever deflection, calculated for 2 cantilever thicknesses and 2 fixed wavelengths corresponding to resonances at 200 and 300 nm initial gap values.

The choice of cantilever thickness should be carefully considered to obtain maximum sensitivity and stable operation. Thinner cantilevers are more sensitive to mechanical bending that arises from differential surface stress, as follows from Stoney's model [2], $\Delta z = 3\,\Delta\sigma\, L^2(1-\nu)/(Et^2)$, where Δz is the tip displacement of a cantilever having length L, thickness t, Poisson's ratio ν and Young's modulus E, and $\Delta\sigma$ is the differential surface stress. However, the thermal and mechanical stability of thin cantilevers is low due to this high sensitivity. Also, if a thin cantilever is coated with a metal layer, the evanescent field of the WG may reach the metal layer through the thin silicon dioxide layer, increasing optical loss. Partial metal coating can be used to avoid such a loss, but at the expense of smaller sensitive area and therefore smaller surface stress.

From the fabrication point of view, it is convenient to have the initial gap between the WG and the cantilever as large as possible. For the considered WG design, the maximum gap for getting an optical response on downward deflection is around 400 nm. For this initial gap there is not a large difference in optical sensitivity between thin (200 nm) and thick (1 µm) cantilevers.

For maximum sensitivity, a thin cantilever with a small initial gap should be selected, whereas a safer design calls for a thick cantilever with a large initial gap.

6. Conclusions

Based on our simulations we have shown that GWG can be used to sense deflections of micromechanical cantilevers at sub-nanometre resolution. The presented read-out scheme is a good candidate to enable dense integration of cantilever sensors, providing an accurate and stable optical position detection.

Acknowledgement

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