# Optomechanically actuated slot cantilever for mass sensing.

Jesper Håkansson[1] and Dries van Thourhout[1]

[1] Photonic Research Group(INTEC), Ghent University

*NEMS cantilever systems have been pushing the sensitivity of mass, force and pressure sensing over the last decades. However conventional electrical designs for transduction and readout are lacking in bandwidth and free space optical methods are difficult to integrate because of diffraction limits. We demonstrate a broadband, all optically transduced cantilever for mass sensing using end coupled slot waveguides in the silicon platform. Simulations show a displacement responsivity of 1.4 um $^{-1}$ and many times greater forces at lower effective mass for similar designs.*

## Introduction

NEMS cantilevers are rapidly becoming more attractive as mass sensors in biological and chemical sensing. They are compatible with CMOS fabrication methods allowing dense arrays to be fabricated with small footprint and at low cost. For mass sensing applications the sensitivity of the resonance frequency to changes in mass is utilized as a sensor. Most electrical transduction methods have a limited bandwidth, a problem not found for optical methods. We suggest using end-coupled cantilevers. These have been successfully investigated before [2] [1] and to expand upon this work we suggest utilizing optomechanically transduced slot waveguides. They are an attractive choice because the sharp contrast at the air-silicon boundary enhances both optomechanical forces as well as sensitivity to displacement. Unlike cantilevers which must be bent in post processing to optimize the displacement sensitivity, slot waveguides vibrate in the plane of the substrate can be aligned for optimal sensitivity lithographically. This improves yield and repeatability. By relying on near field effects for transduction and detection we bypass diffraction limits and by not relying on interferometric schemes of detection we get a broadband device that does not need a coherent light source. Another benefit of integrated photonics is that difficulties in alignment are avoided.

## Results

Three ways to improve the mass sensitivity of the cantilever has been suggested [3] [4] ; reducing the resting mass of the cantilever, reducing the modal effective mass fraction and increasing the mechanical quality factor. Reducing the dimensions of the cantilever reduces the resting mass but how far this can be taken is limited by practical factors such as retaining a guided optical mode, fabrication limits and the sensitivity of the detection setup. For cantilevers the mass is reduced quite significantly with higher order modes, sadly the force that excites the vibrations is homogenous along the cantilever and thus only the fundamental mode will be efficiently pumped. The quality factor can be increased foremost by reducing the effects of air damping either through increasing the

resonance frequency to the GHz range or throughoperating the device in vacuum, secondly through reducing clamping losses.
A first order approximation of the frequency response to added mass can be written as [3],

$$\frac{\Delta f}{\Delta m} = -\frac{1}{2} f_n \frac{1}{m_{eff,n}} \tag{1}$$

where $f_n$ is the resonance frequency of the mechanical mode $n$ and $m_{eff,n}$ is the effective mass of the same mode $n$.
The mechanical actuation of the slot beams is achieved through the optical gradient force. The attractive force generated between the two beams in the slot by the optical field can be calculated using the response theory for optical forces [5].

$$F_q(\omega, q) = \frac{LP_{op}}{c} \frac{\partial N_{eff}}{\partial q} \tag{2}$$

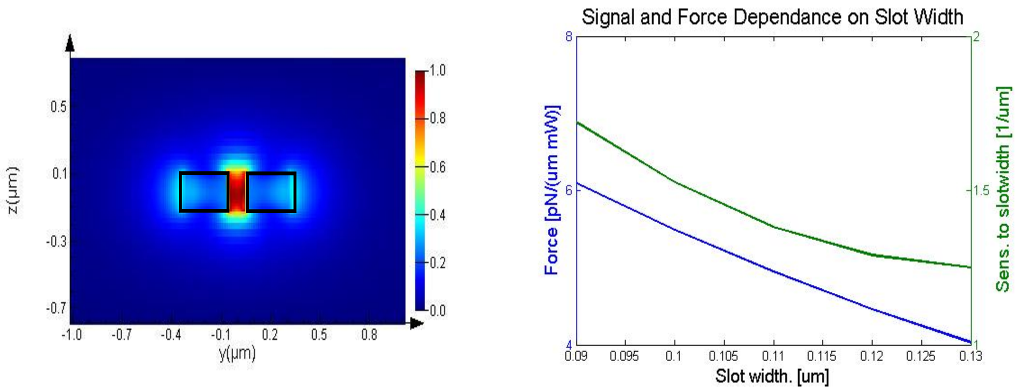
where $F_q$ is the force for a given slot width, $q$, and optical frequency, $\omega$. $L$ is the interaction length, $P_{op}$ the optical power, $c$ the speed of light and $N_{eff}$ the effective refractive index. The force increases inversely with the slot width so a slot as small as possible would be desirable but we are limited by fabrication to a slot width of 110 nm. From this and the shape of the first vibrational mode it is possible to write down the expected displacement noise at resonance,

$$D_{disp} = \frac{2\pi \cdot P_{pump} \cdot \varepsilon_{mode,n} \cdot F_q \cdot Q_{mech} \cdot L^3 \cdot \sqrt{m_{rest}}}{\beta_n^4 \cdot E \cdot I} \tag{3}$$

where $\varepsilon_{mode,n}$ is the mean normalized displacement of the vibrational mode $n$ , $P_{pump}$ the amplitude of the modulated optical power, $m_{rest}$ is the resting mass of the cantilever, $\beta_n$ the eigenvalue corresponding to the vibrational mode, $E$ the Young's modulus and $I$ the area moment of inertia. The displacement is then transduced to optical power as the slot misaligns. The displacement sensitivity,

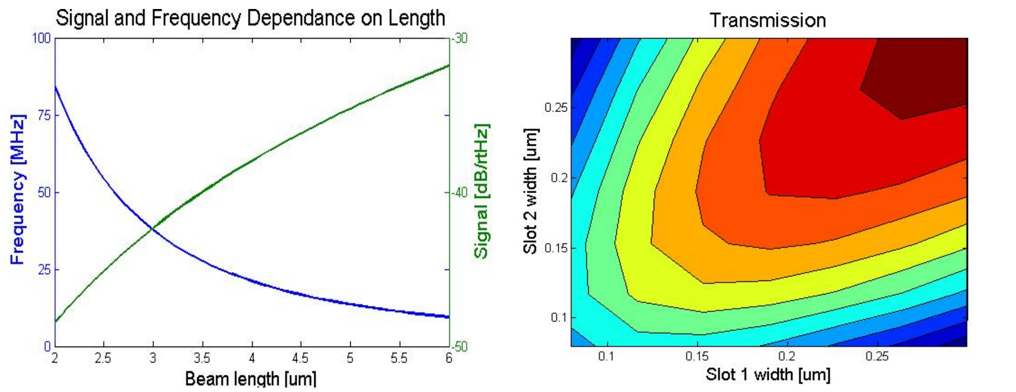
$$S_{disp} = \frac{\partial T}{\partial q} \tag{4}$$

is calculated using FDTD simulations. The results, shown in Fig. 2b, show that the sensitivity grows with the width of the opposite slot. Because a slot on oxide, when compaired to a suspended slot, have a significantly smaller cut off width for the optical mode the slot must be tapered down to a width that can support the mode, see Fig. 3b. We fabricated the cantilevers using the IMEC's standard passives line. It uses DUV-lithography on SOI, the result can be seen in Fig. 3a. The effective mass of the fundamental mechanical mode for a 3um long cantilever is 263 fg resulting in a frequency shift of 56 Hz/ag. The setup used for detection is shown in Fig. 4. By letting the pump and the probe laser propagate in different directions beat noise is avoided. Ultimately the phase of the signal relative to the pump must be measured and compared to the expected phase difference for forced oscillations to exclude other potential signal sources.



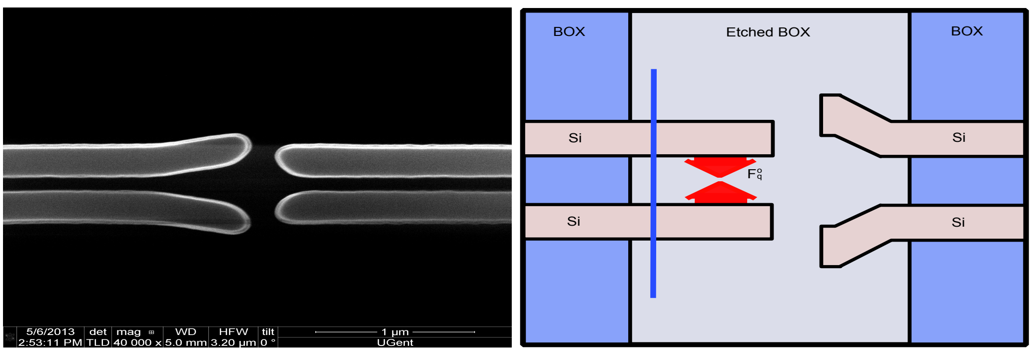

(a) (b)

Figure 1: (a) The mode of the electric field in an under etched slot waveguide. The outline of the waveguide is drawn in black. (b) The graph shows how force and responsivity depends on slot width.




(a) (b)

Figure 2: (a) How eigenfrequency and signal strengh of the 1st mechanical mode depends on length of the suspended slot. The beams of the slot are 280nm wide and the slot 110nm. $Q_m$ is assumed to be 4000 and $P_{pump}$ is 1 mW. (b) FDTD simulations of the transmission of end-coupled slot waveguides as dependent on the width of the two slots.




(a) (b)

Figure 3: (a) SEM image of the fabricated cantilevers before underetching. (b) An illustrative sketch of the cantilever design as seen with a top view. The red arrow marks the direction of the optomechanical force.

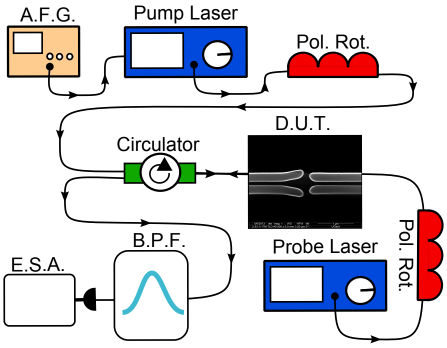



Figure 4: The pump laser is modulated through direct current modulation and excites the vibrations of the cantilever. The probe laser, passing through the cantilever in the opposite direction, is then detected by a photo diode and analyzed by the electric spectrum analyzer. To filter out any reflections of the pump beam a band pass filter is introduced between the circulator and the photodiode.

## Conclusion

We have demonstrated a broadband, all optically transduced cantilever for mass sensing using end coupled slot waveguides in the silicon platform. Simulations show a displacement responsivity of 1.4 um $^{-1}$ and many times greater forces at lower effective mass compaired to previously reported optically transduced devices [2]. As for further improvements the displacement responsivity can be effectively doubled by introducing a broadband bragg reflector after the cantilevers. Simulations show a displacement sensitivity of 40 fm/rtHz. Measurements are to follow.

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