Nanobenders: efficient piezoelectric actuators for widely tunable nanophotonics at CMOS-level voltages

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Abstract: We introduce a compact (⇠10 µm²) piezoelectric actuator, and use it to tune the optical resonance wavelength of a lithium niobate photonic crystal cavity by ⇠ 5 nm/V. The tuning range is 1520-1560 nm with 4 V.

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Integrated optical components that are actively controllable are needed for applications in optical computing, communication and imaging. Nano-opto-electro-mechanical (NOEM) devices have been used for this purpose to realize switches, tunable couplers and electro-optomechanical tuning [1]. These have traditionally used electrostatics as the main actuation mechanism which comes with trade-offs between tunability, tuning range and footprint. Using piezoelectricity could allow us to bypass these trade-offs. However, state of the art piezoelectric NOEMs do not reach tuning above a few tens of pm/V [2]. Lithium niobate (LN) is a great piezoelectric material and has excellent optical properties. In the past few years, there has been ever increasing work done in the thin-film LN material platform for applications ranging from microwave optomechanical transduction [3], ultra-low power modulation [4] to nonlinear nanophotonic circuits [5].

Here, we increase the best piezoelectric NOEM tuning by two orders of magnitude by using a non-uniform electric field to generate bending with a single LN and an aluminum electrode layer. Fig. 1a shows the working principle of this actuator, called nanobender. It is composed of a suspended Y-cut LN beam with 450 nm width. On top, a pair of electrodes runs parallel to the length of the beam. The electric field $E_Y$ in the beam leads to strain...
$S_{xx} = d_{21}E_Y$ parallel to the beam, where $d_{21}$ is a transverse piezoelectric coefficient. Because $E_Y$ is non-uniform along $Z$, the strain changes sign along the width of the beam. This results in bending of the beam. The magnitude of the displacement $\Delta$ at the tip is approximated by $[6]: \Delta \approx \frac{1}{2}d_{21} \cdot \partial Z / \partial E_Y \cdot E^2 \approx \langle 0.01 \text{nm/V} \rangle \cdot \frac{E^2}{L^2} U$, where $L$ is the length of the nanobender, $w$ its width and $U$ the voltage.

We use the nanobenders to tune the optical resonance wavelength of a “zipper” optomechanical cavity [7]. The optical mode is confined in a narrow gap (Fig. 1b), making it very sensitive to gap size changes. By adding four $L = 15 \mu m$ nanobenders to the ends of the zipper cavity (Fig. 1c and d), we are able to change the gap size by applying a voltage to the nanobenders. We measure the optical reflection spectrum (Fig. 1e) of two modes $O_1$ and $O_2$ of the bender-zipper cavity. The fundamental optical mode has a quality factor $Q \sim 10^k$, limited by thermal-mechanical linewidth broadening. As we increase the voltage, the wavelength of the bender-zipper cavity shifts by $\alpha \equiv \Delta \lambda / \Delta U \approx 5 \text{ nm/V}$ around 0 V. The tuning coefficient $\alpha$ depends on voltage because when the gap decreases, the optical mode becomes more sensitive to displacement, effectively changing the optomechanical coupling. The modes of a control cavity lacking nanobenders do not tune with voltage.

Furthermore, we report tuning coefficients as a function of nanobender length $L$ for more than 40 bender-zipper cavities (Fig. 1f). All these devices have an initial gap size 200 nm, measured on a scanning electron micrograph (SEM). These measurements agree relatively well with simulations. The way nanobenders are attached to the zipper cavity plays an important role. We observe a significant decrease in tuning when a narrow tether is used to attach the nanobenders to the zipper cavity. Additionally, we measure the fundamental mechanical resonance frequency of the bender-zipper cavity to be $\sim 1 \text{ MHz}$. When further increasing the voltage, the gap closes and the two halves of the bender-zipper cavity touch (Fig. 1g). The wavelength stops tuning when further increasing the voltage. We decrease the wavelength and notice that the detaching voltage is lower than the contact voltage due to van der Waals forces resulting in a hysteresis loop. This process is repeatable and here we show the measurements of nine successive contact and detach cycles. The total tuning range amounts to almost 70 nm, using only CMOS-level voltages. From a SEM, we infer a displacement of $\sim 25 \text{ nm/V}$ from each pair of nanobinders.

To conclude, we used nanobenders to tune optical modes of a LN zipper cavity over the whole telecom C-band using less than 4 V. We also show that large displacements leading to sticking gives rise to a reversible hysteresis loop, allowing use as an optically accessed memory. The actuation mechanism is applicable to most piezoelectric materials with a non-vanishing transverse piezoelectric coefficient. We expect that the nanobenders can find application as optical phase shifters, tunable optical couplers, micromirrors, and many more applications. Our approach shows piezoelectric NOEMs that exceed the performance of electrostatic realizations in tuning range, footprint, tuning coefficient and speed.

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