Reconfigurable Metamaterials

electro-optical applications and beyond

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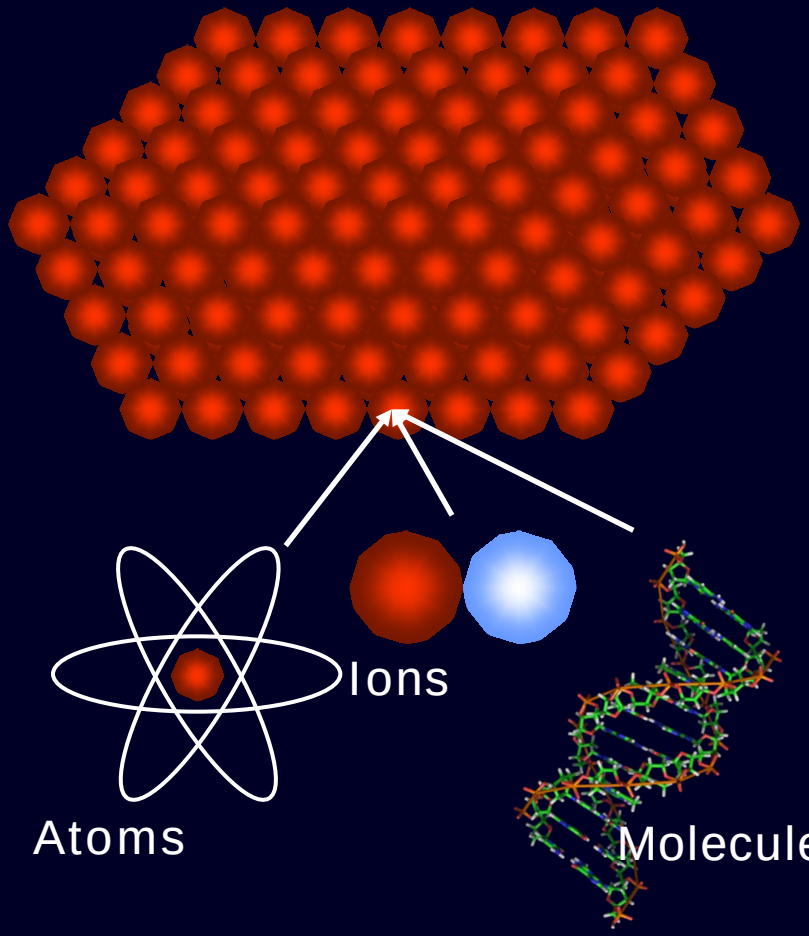
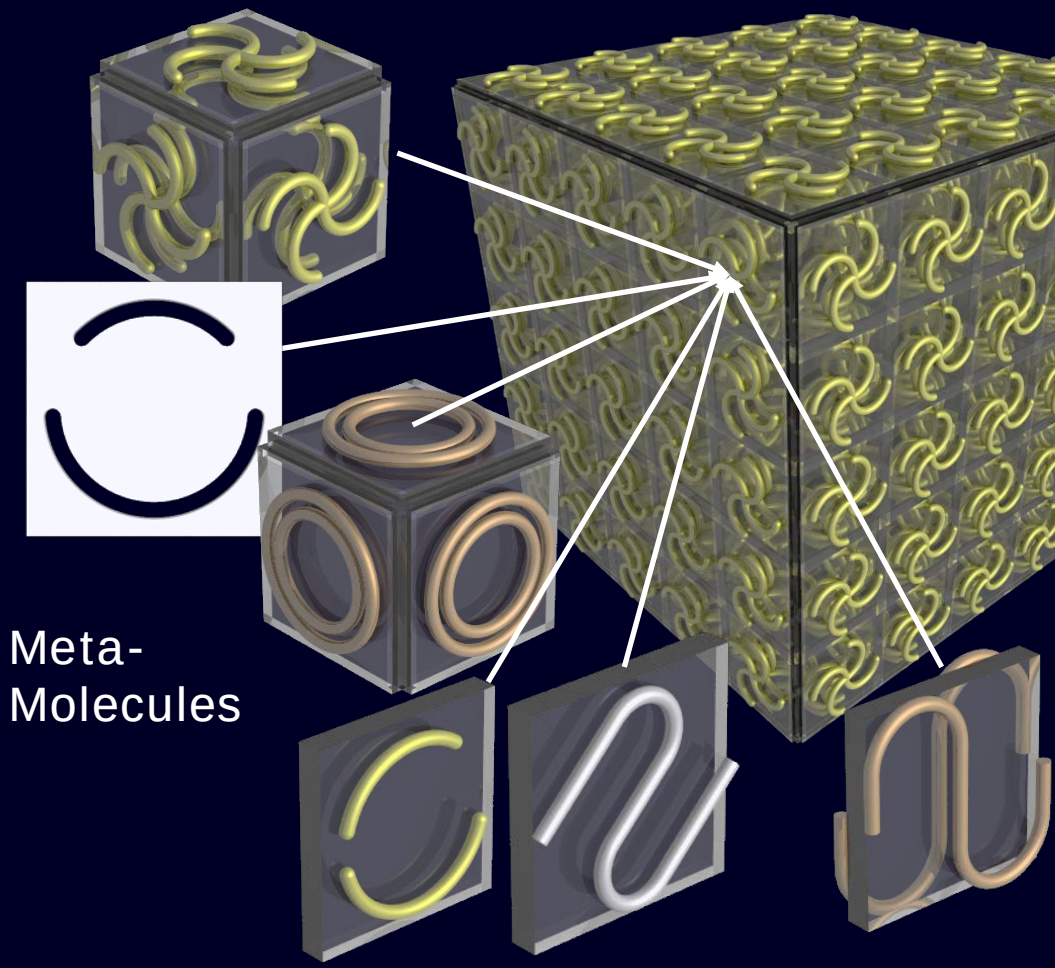
Photonic Metamaterials: Technologies and Application Opportunities, 11am, 13 Sep 2012, Southampton, UK

Natural Materials vs. Metamaterials



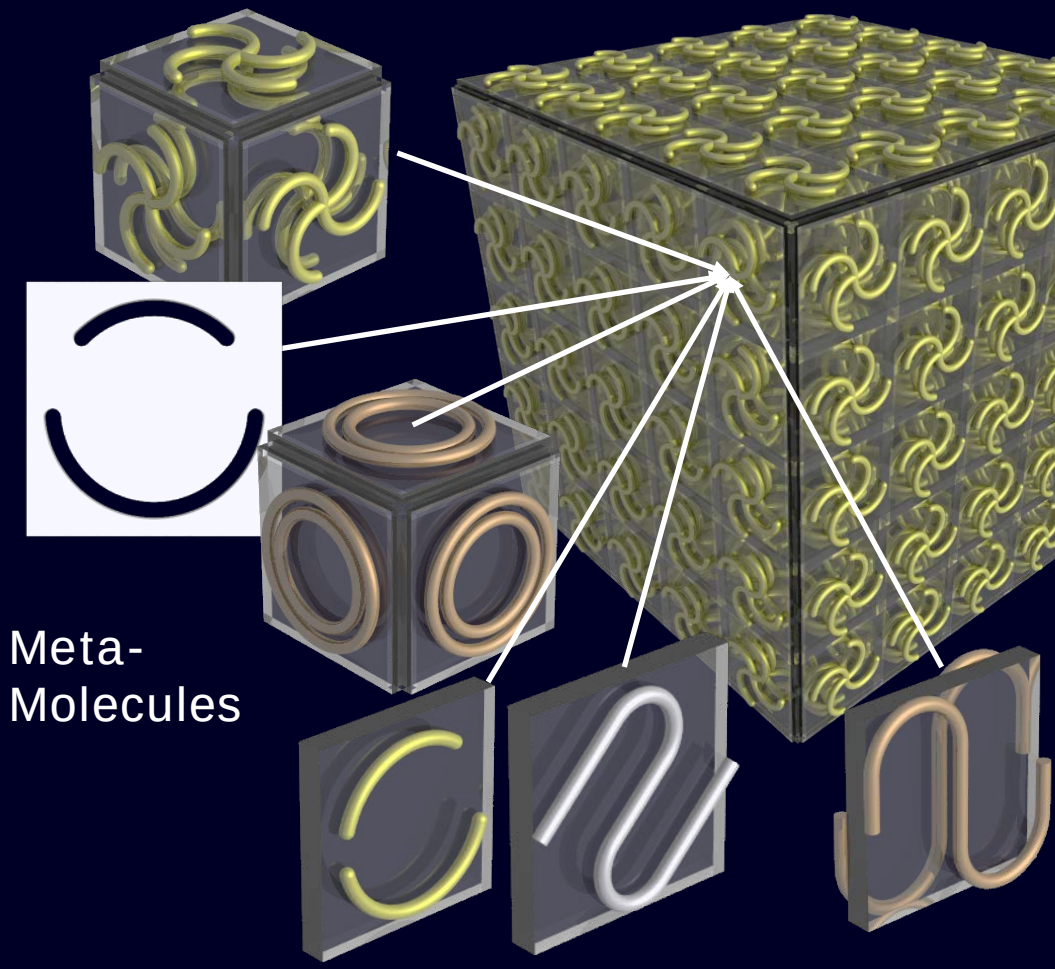
DNA image taken
from Wikipedia



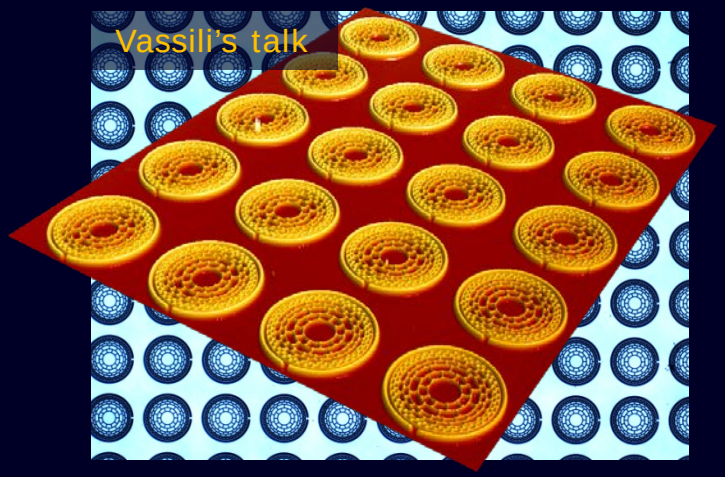
Metamaterials are artificial materials structured on the sub-wavelength scale

Metamaterials

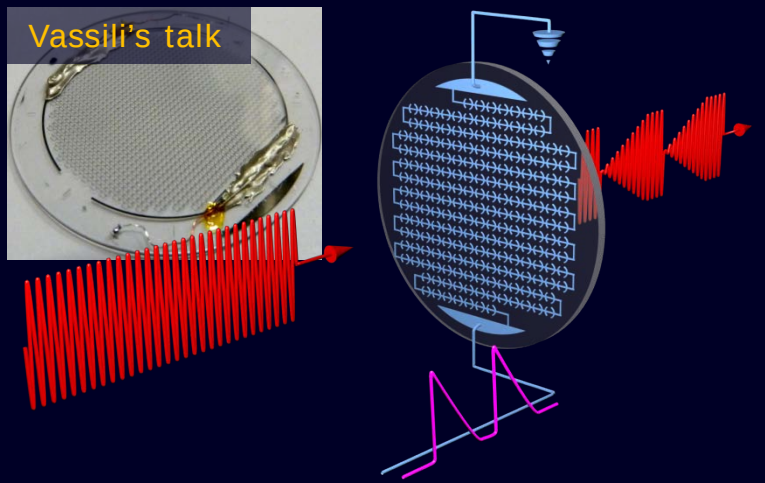
- Metamaterials are artificial materials periodically structured on **sub-wavelength** scale
- No diffraction
- Properties arise from geometry of meta-molecules
  - Huge playground of shapes and symmetries
- Metamaterial properties usually not found in constituent materials



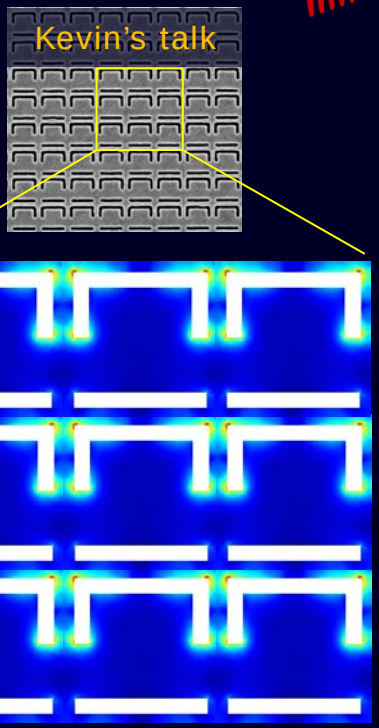
Tunable / Switchable Metamaterials



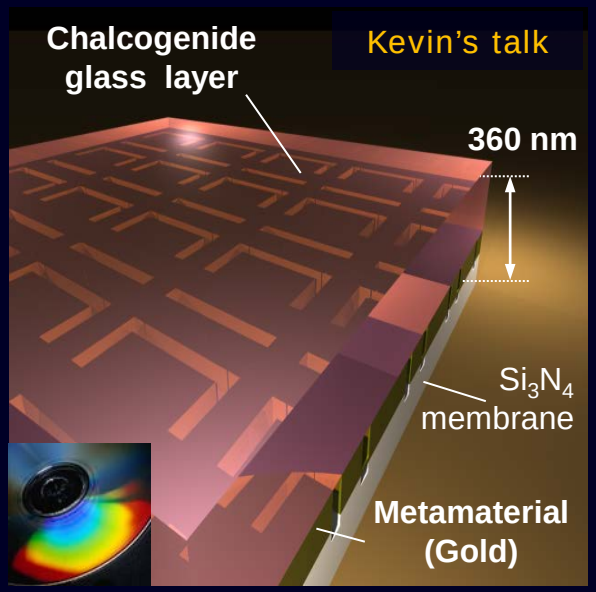
Quantum Flux Exclusion,
[*Scientific Reports* **2**, 450 (2012)]



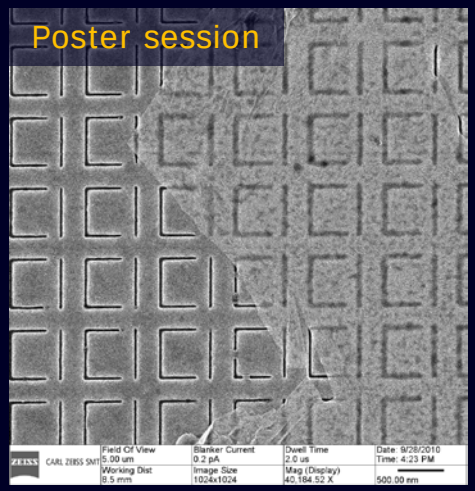
Superconducting EO modulator,
Southampton



Ultrafast nonlinear metals,
[*Adv. Mater.* **23**, 5540 (2011)]

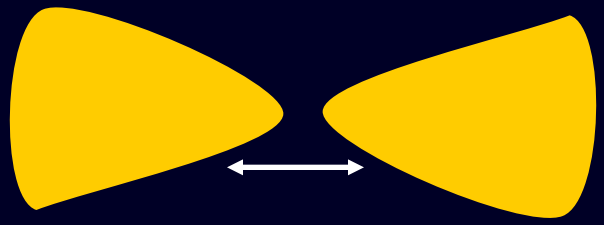


Switchable metamaterial (ChG),
[*Phys. Status Solidi-RRL* **4**, 274 (2010)]

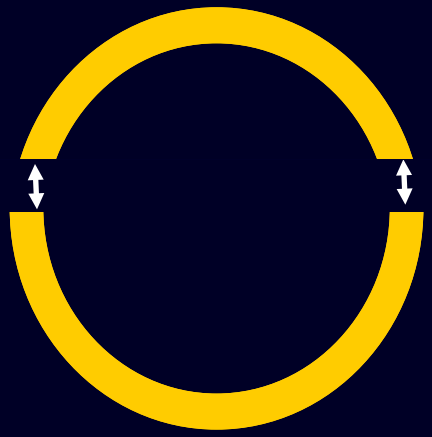


Graphene,
[*Opt. Express* **18**, 8353 (2010)]

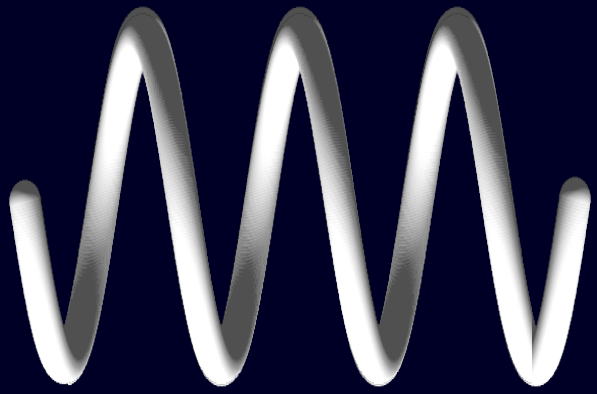
Reconfigurable Metamaterials



Tunable nanoantenna



Tunable split-ring



Tunable chirality

Challenge

Nanometre scale synchronized control of >10^3 meta-molecules

Nanoscale Advantages

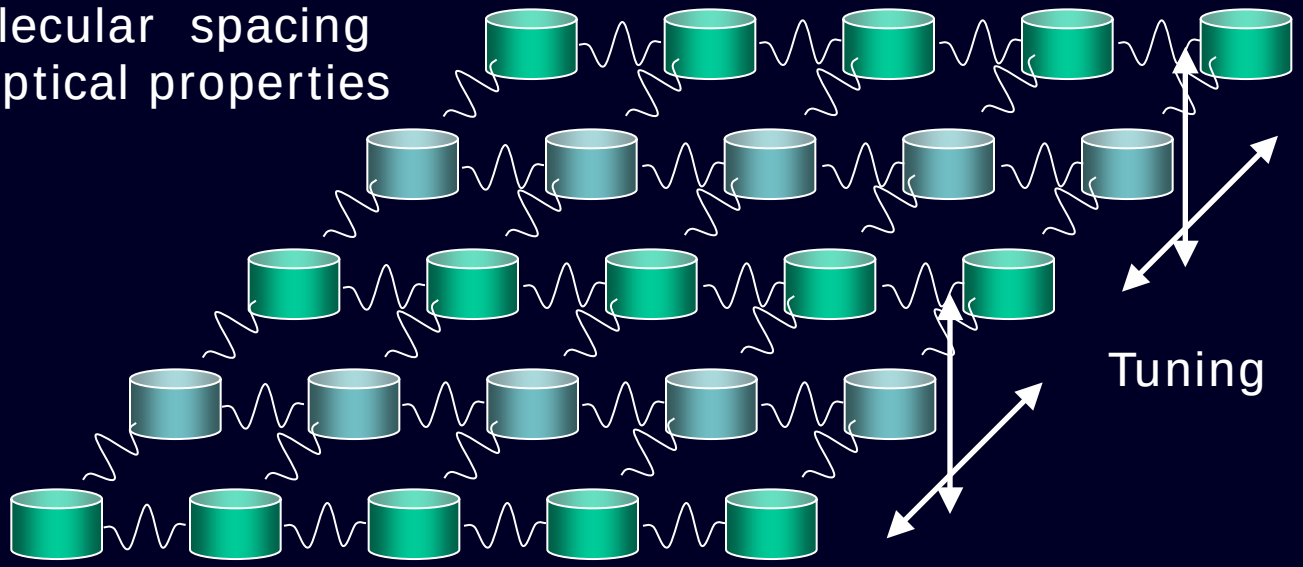
Changing balance of forces

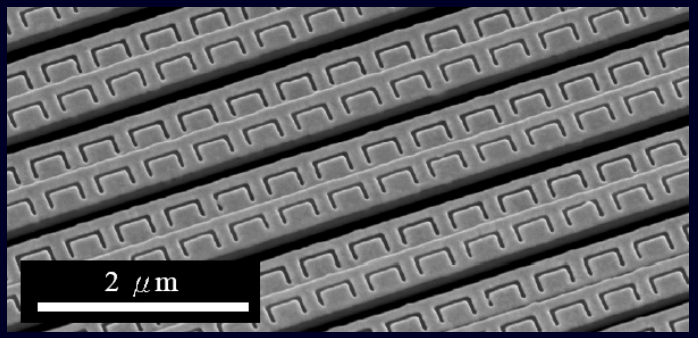
- Electrostatic force ~ 1/d
- Elastic force ~ d
- Mass ~ d^3

High resonance frequencies

From controlling meta-molecules to controlling arrays

Meta-molecular spacing controls optical properties



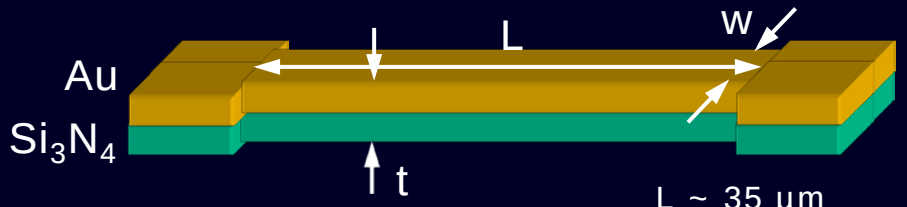


A reconfigurable bridge...

Weight ~ 20 pg

Resonance freq. ~ 1 MHz

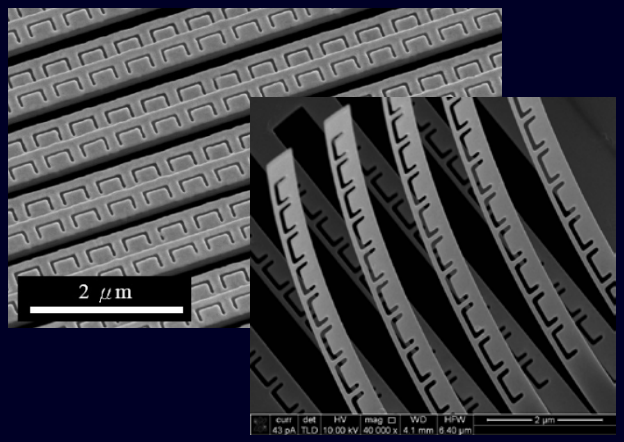
Meta-molecules supported by an array of reconfigurable bridges



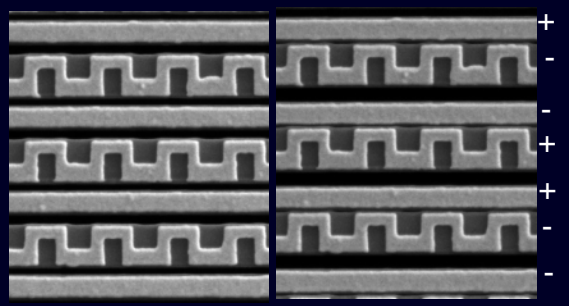
L ~ 35 μm
w ~ 500 nm
t ~ 100 nm

Reconfigurable Metamaterials controlled by…

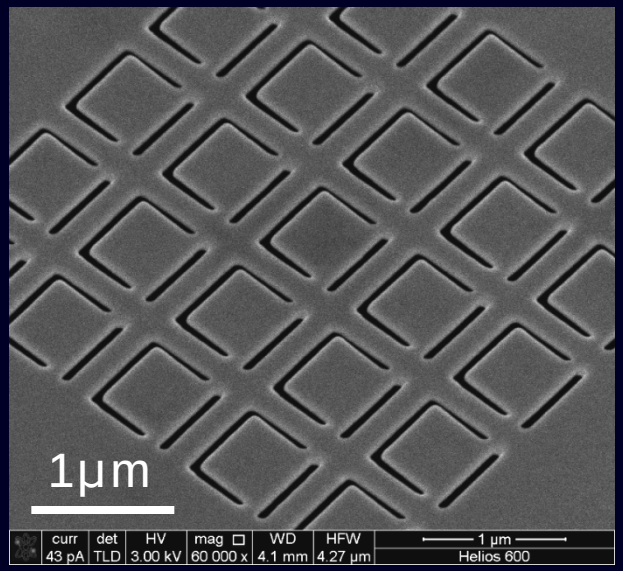
Temperature

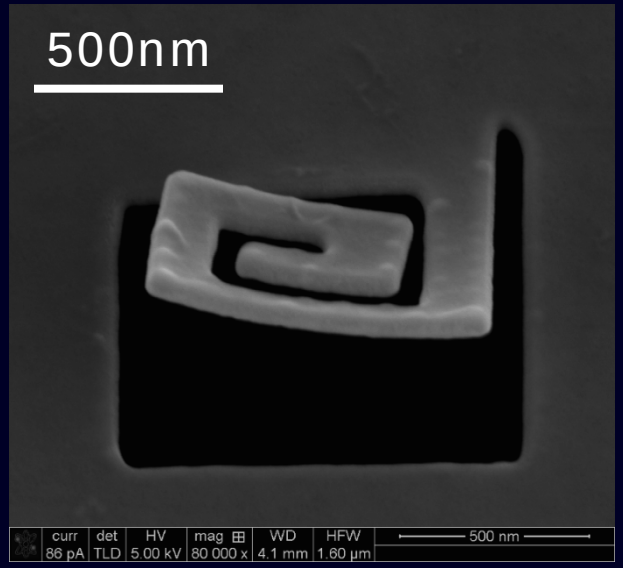


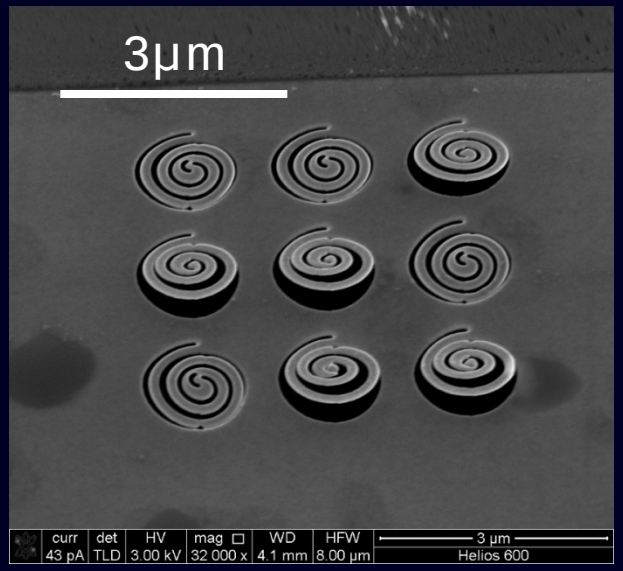
Voltages



Towards Nano Reconfigurable Metamaterials

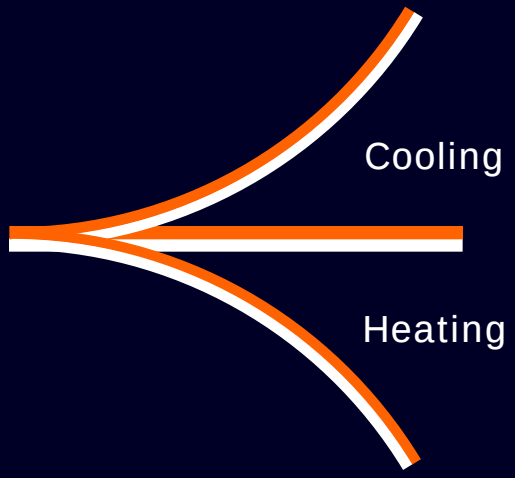






Bimorph:

A bilayer of two materials with different thermal expansion coefficients will bend upon temperature change.

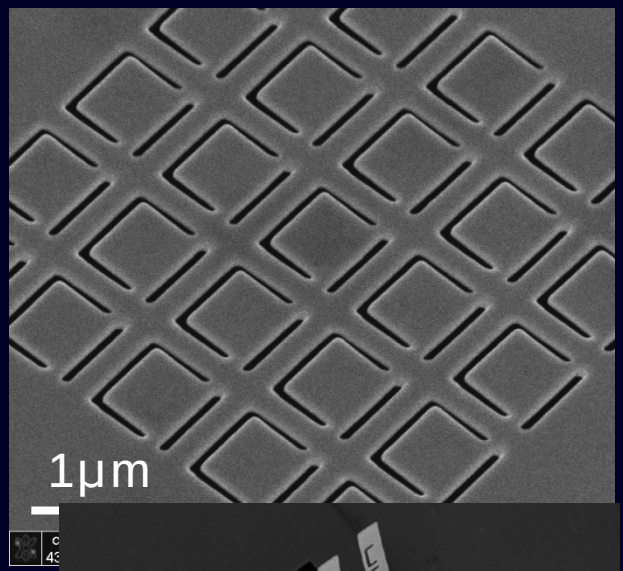


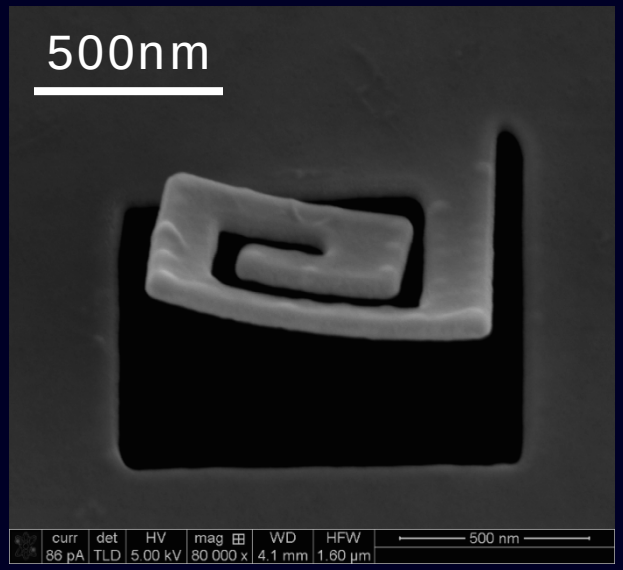
Bending proportional to

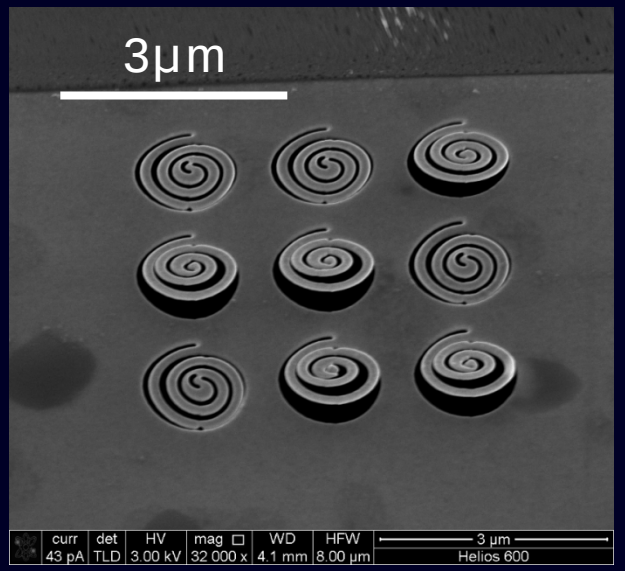
- Temperature change
- Thermal expansion difference
- Length/thickness

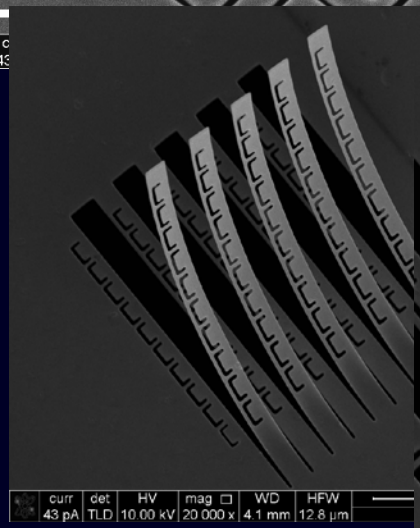
Large tuning requires long, thin structures
L/t ~ 100

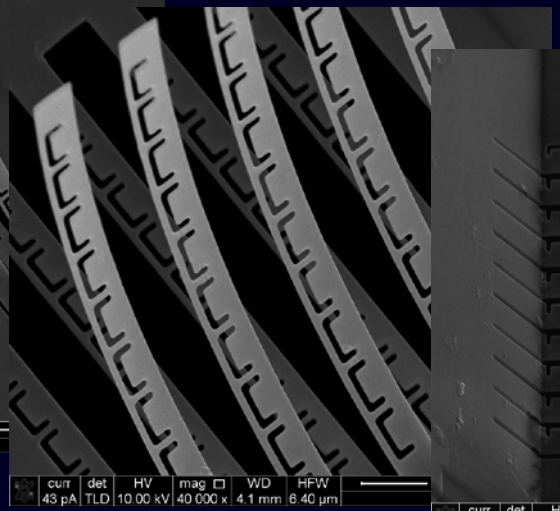
Towards Nano Reconfigurable Metamaterials

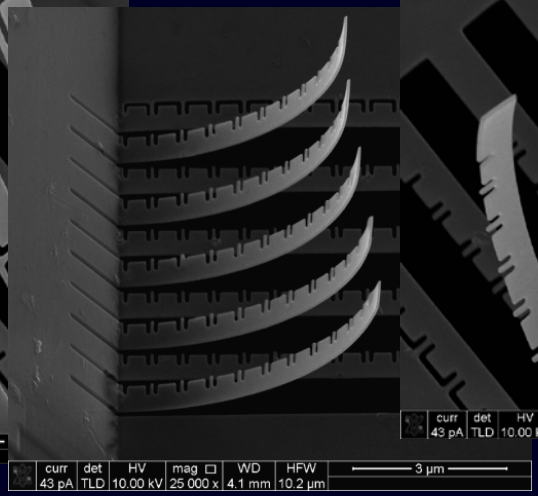


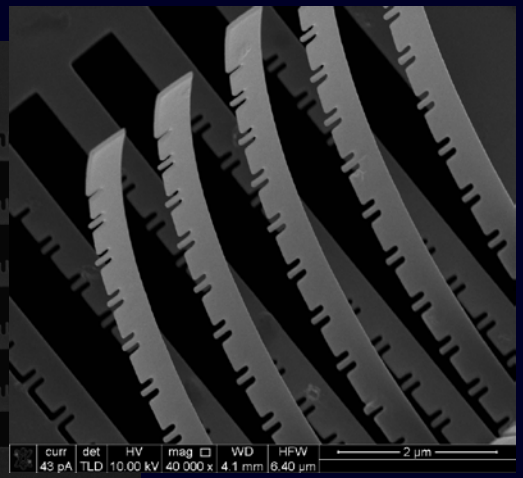




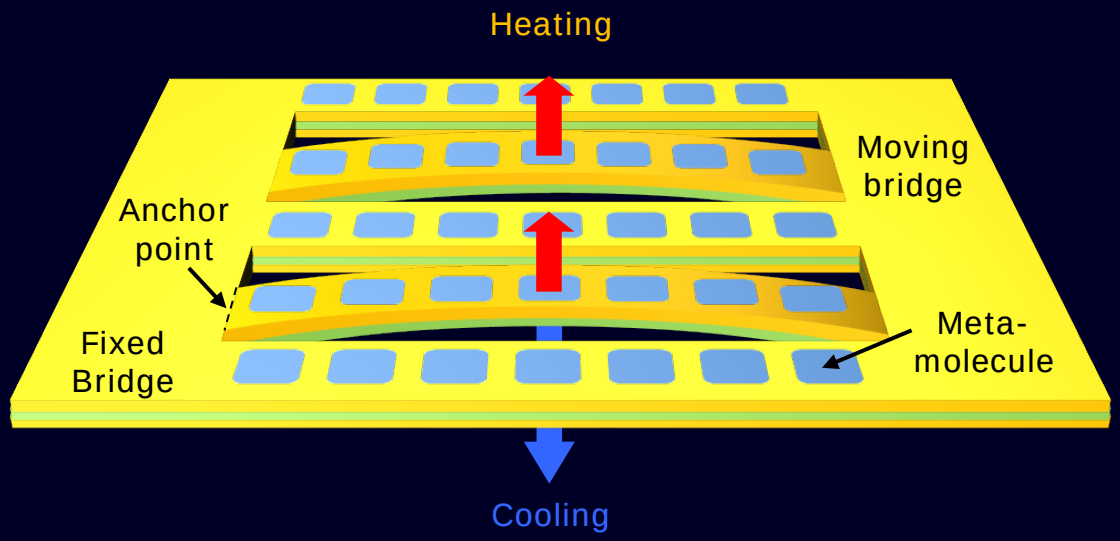


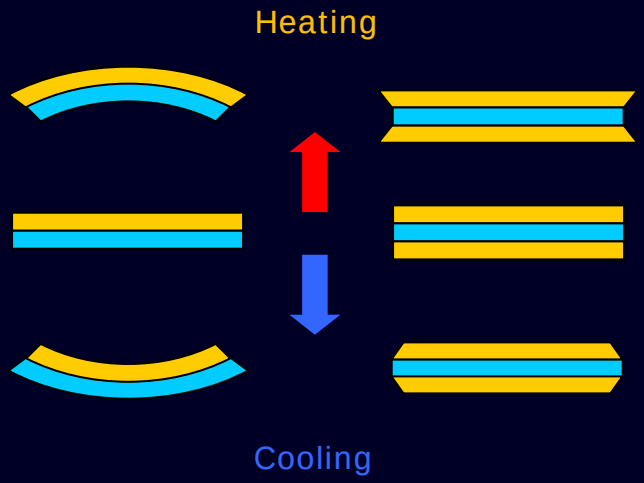






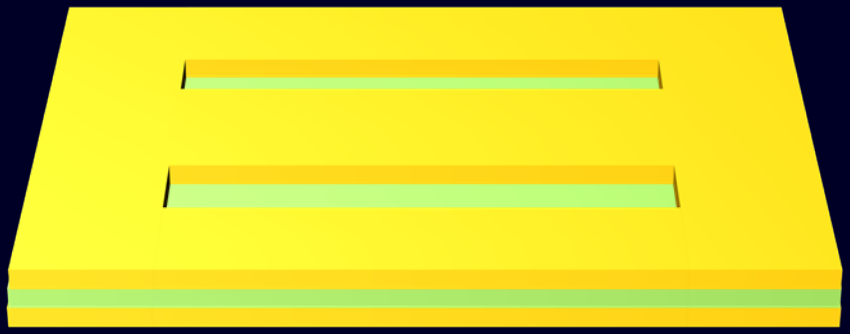
Temperature-Controlled RPMs: Concept



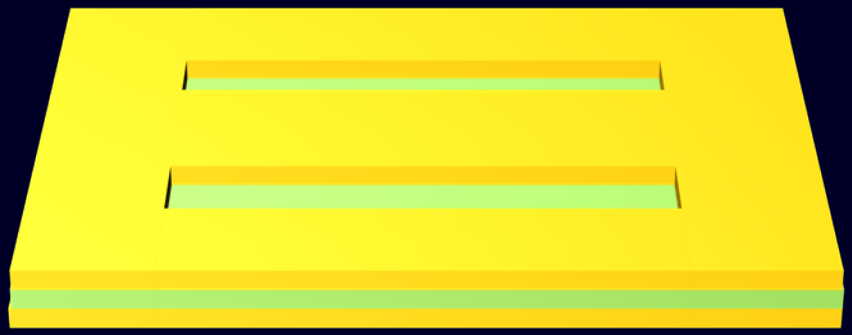


Temperature-Controlled RPM: Fabrication

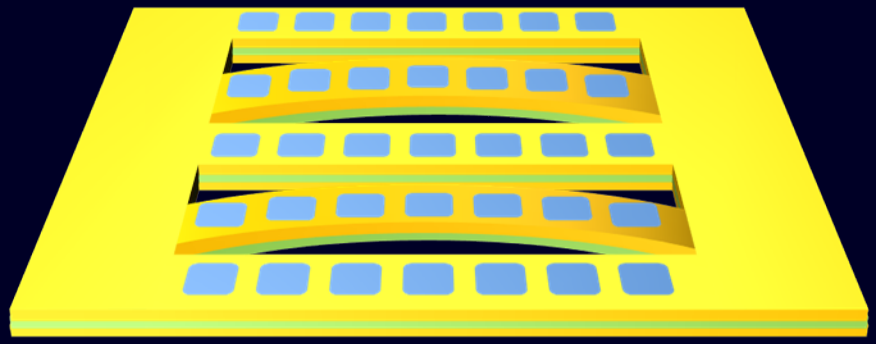
Au on both sides of Si_3N_4 membrane



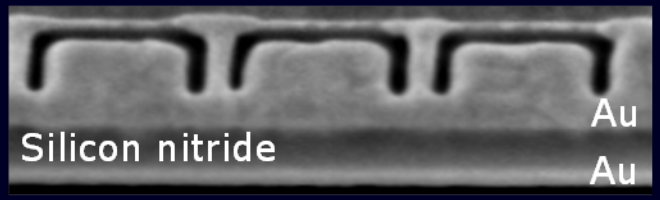
Flip Sample



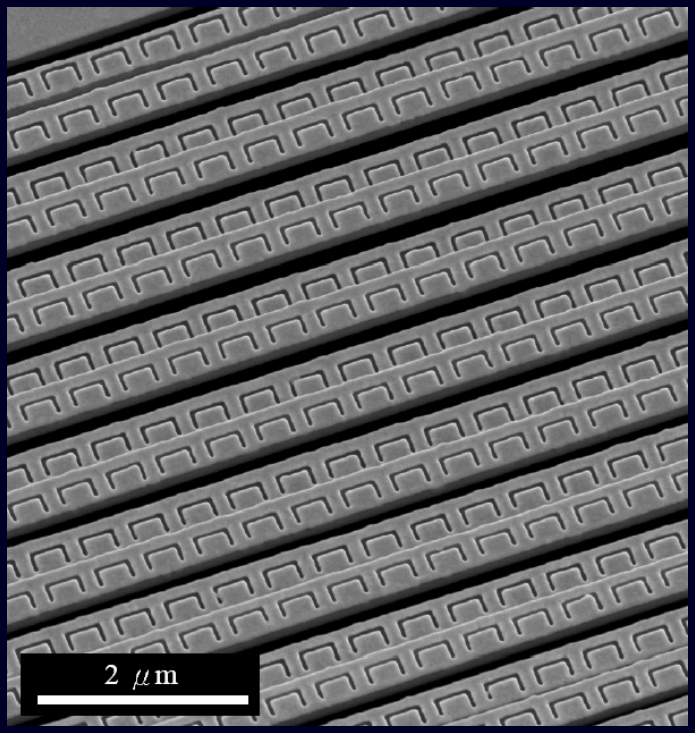
Alternating Gold slits removed by FIB

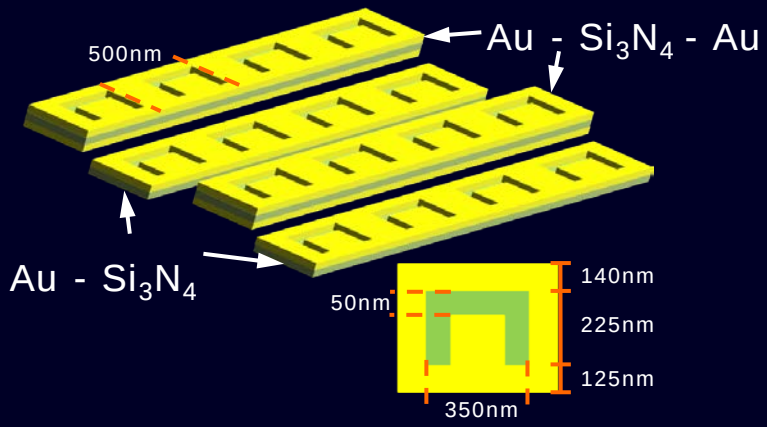


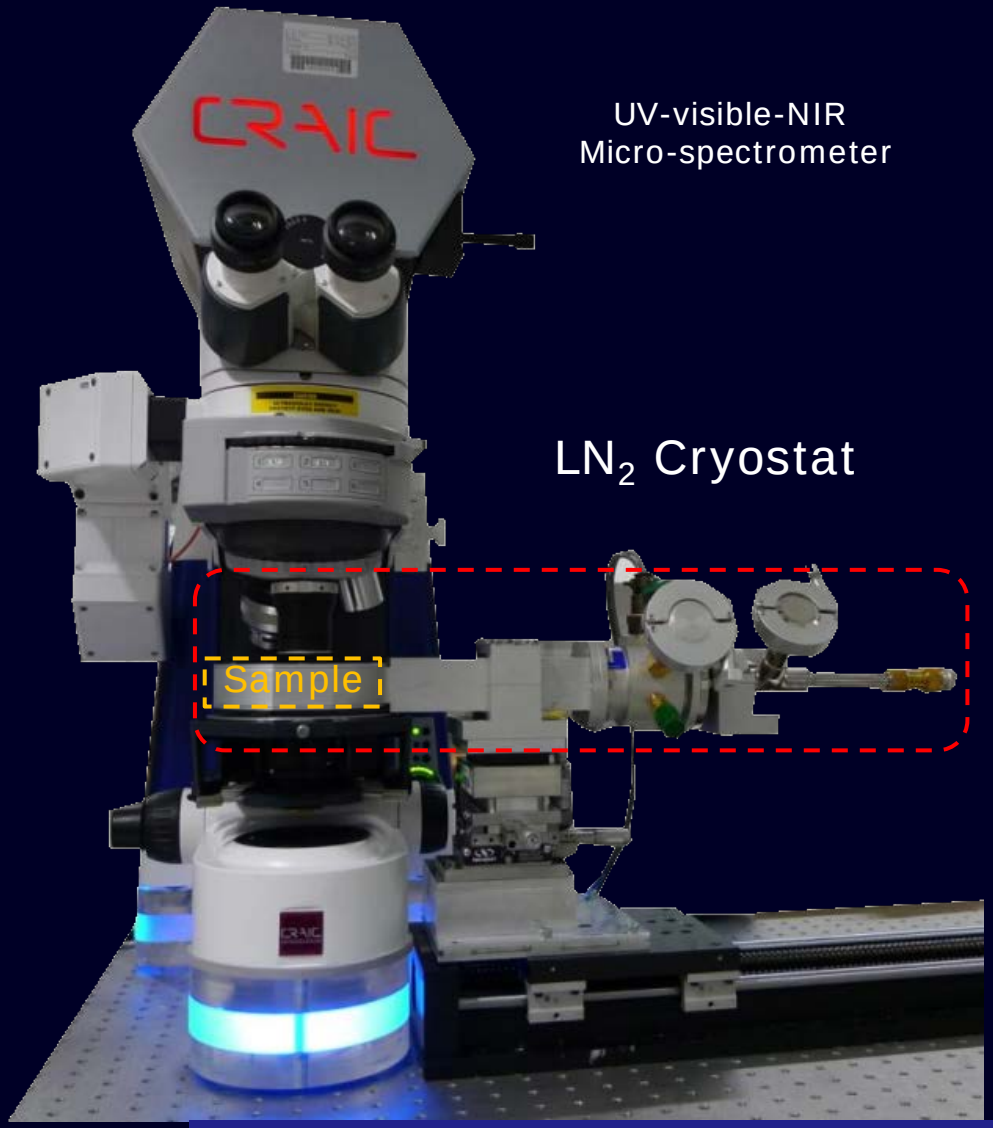
Meta-molecules patterning by FIB
Bridges cut through



Temperature-Controlled RPM: Optical Characterization

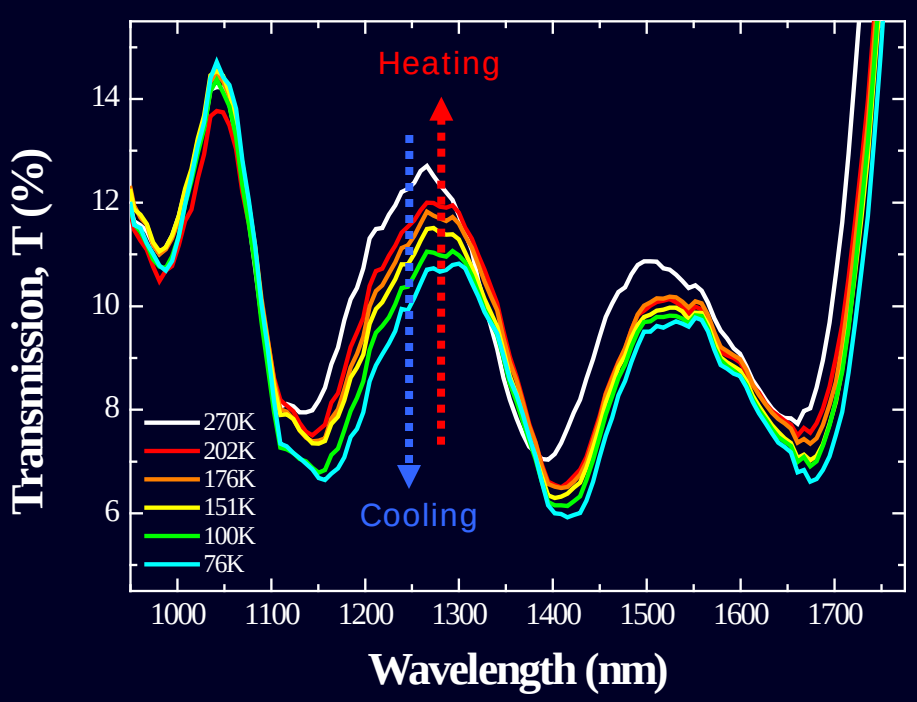


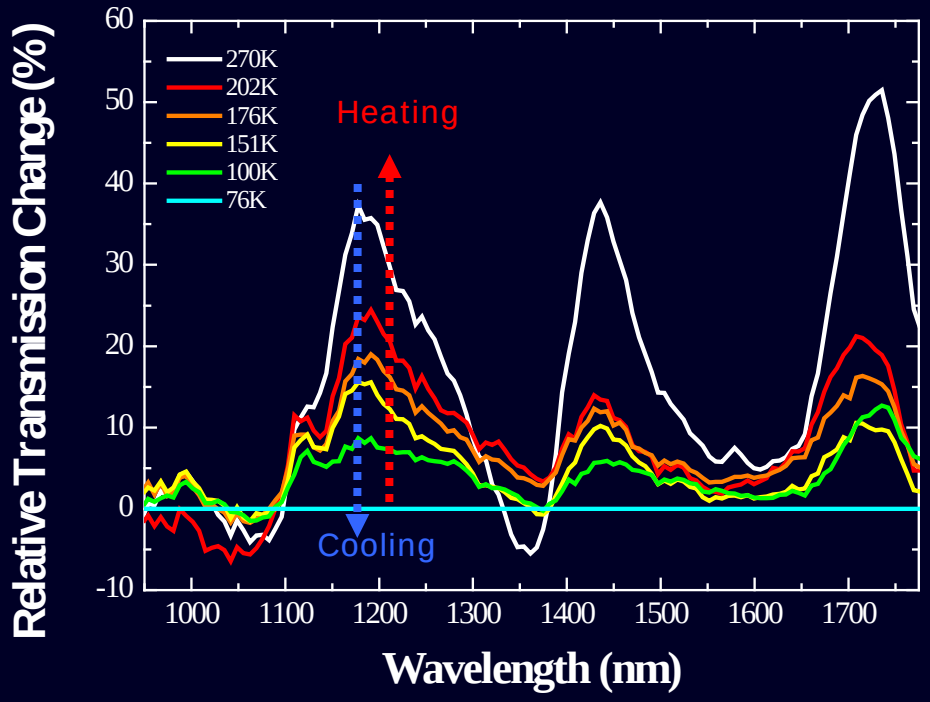




J. Y. Ou, E. Plum, L. Jiang, and N. I. Zheludev, *Nano Letters* **11**(5), 2142 (2011)

Temperature-Controlled RPM: Performance



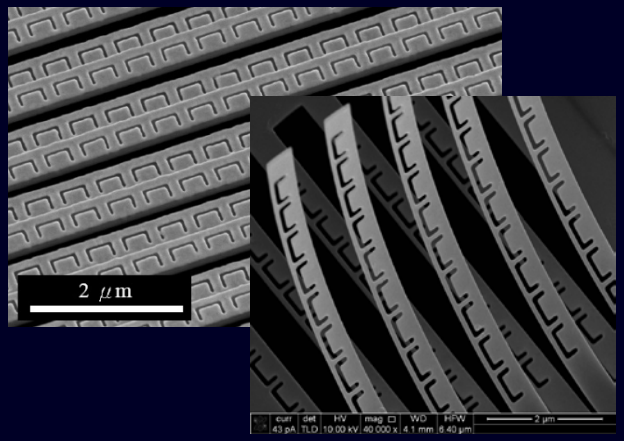


Reversible continuous tuning by cooling/heating
Relative changes in transmission up to **50%**

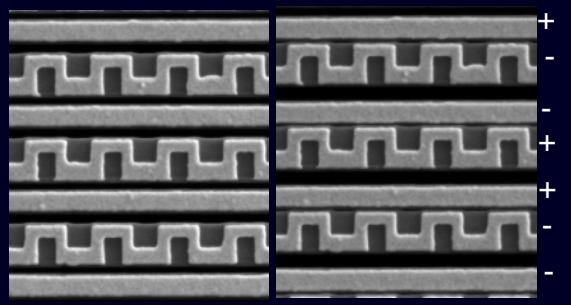
J. Y. Ou, E. Plum, L. Jiang, and N. I. Zheludev,
Nano Letters **11**(5), 2142 (2011)

Reconfigurable Metamaterials controlled by…

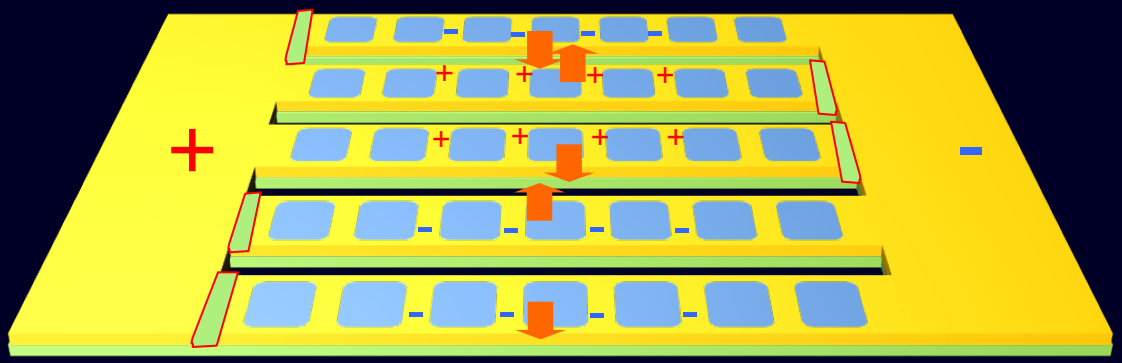
Temperature



Voltages



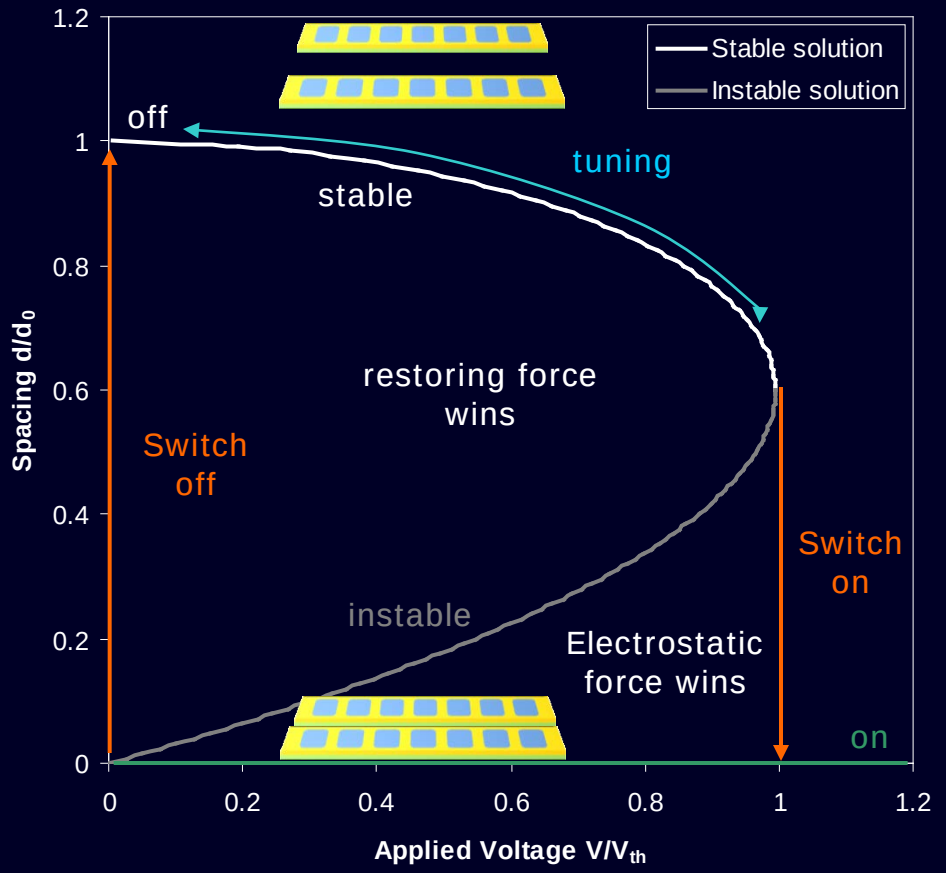
Electrostatically Controlled RPM: Concept



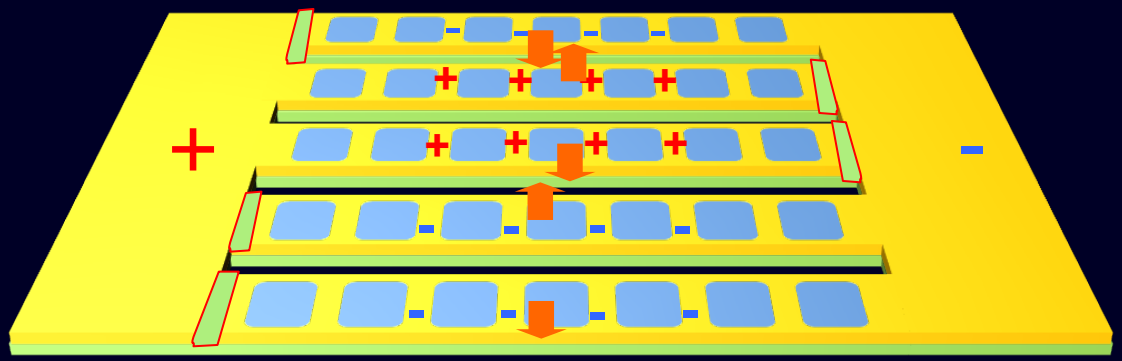
- V ~ 1V
- d ~ 100nm
- E ~ 10 MV/m

Electrostatic Control of Spacing

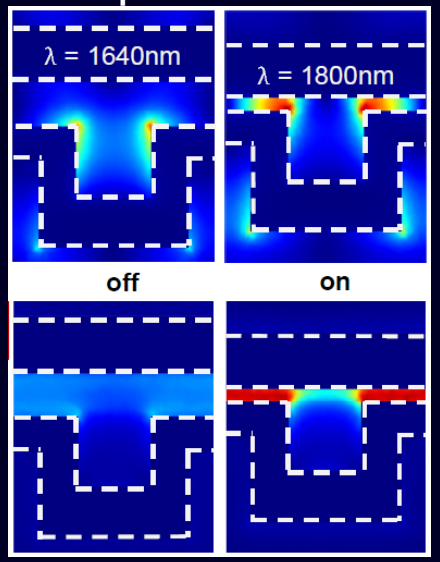
- Equilibrium
  - Restoring force
  - Electrostatic force
- Electrostatic
  - Tuning
  - Switching (on/off)
  - Memory (low holding voltage)



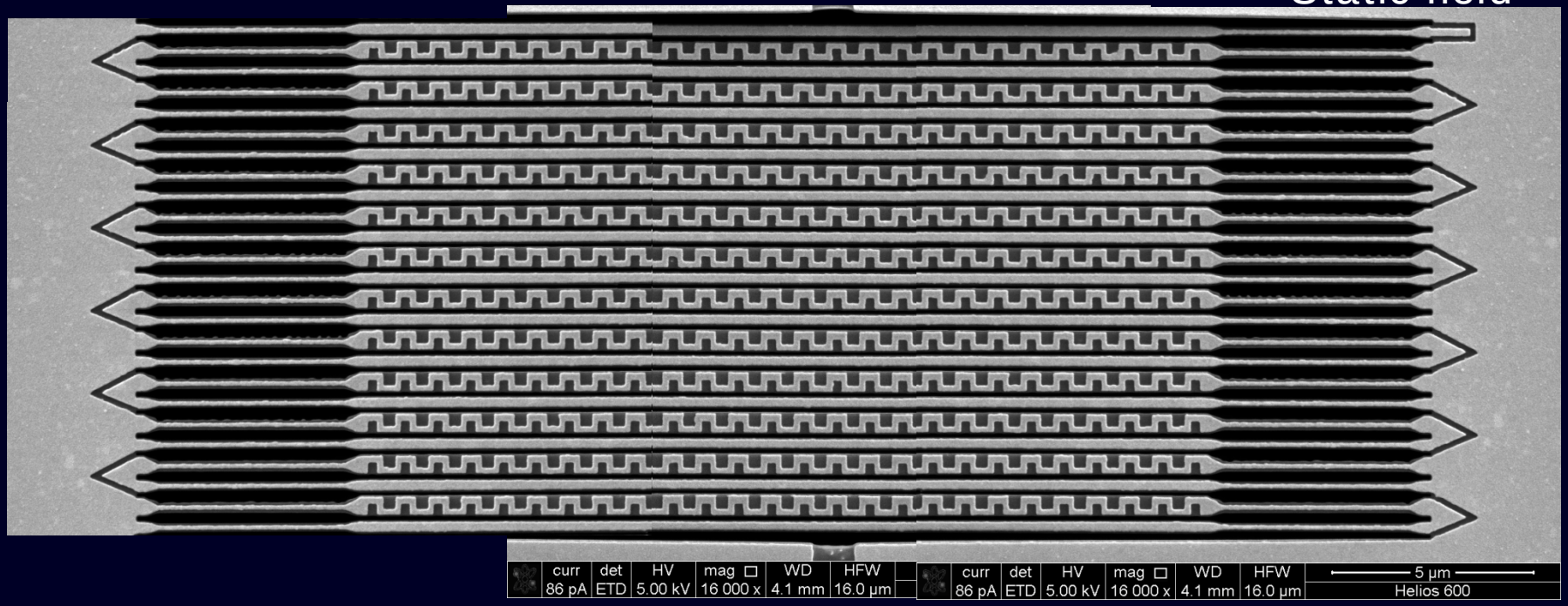
Electrostatically controlled RPM



Optical field

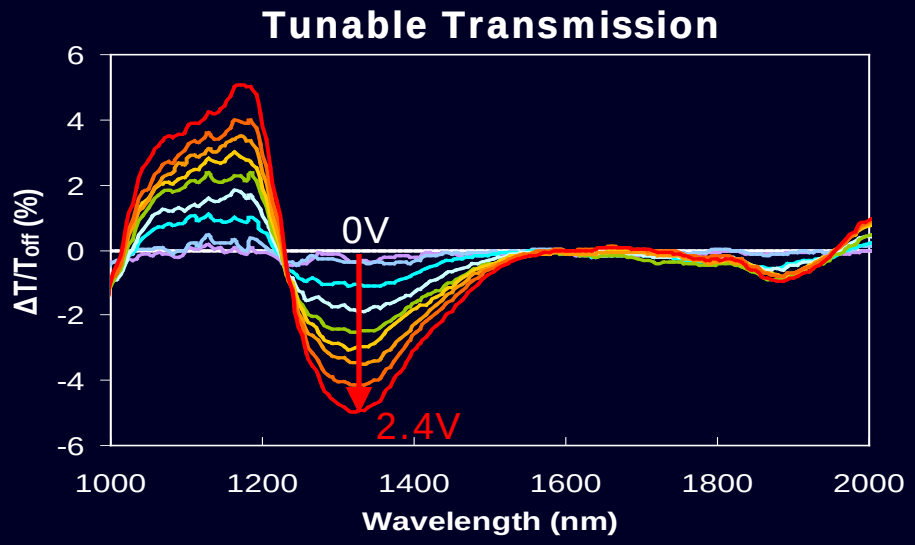


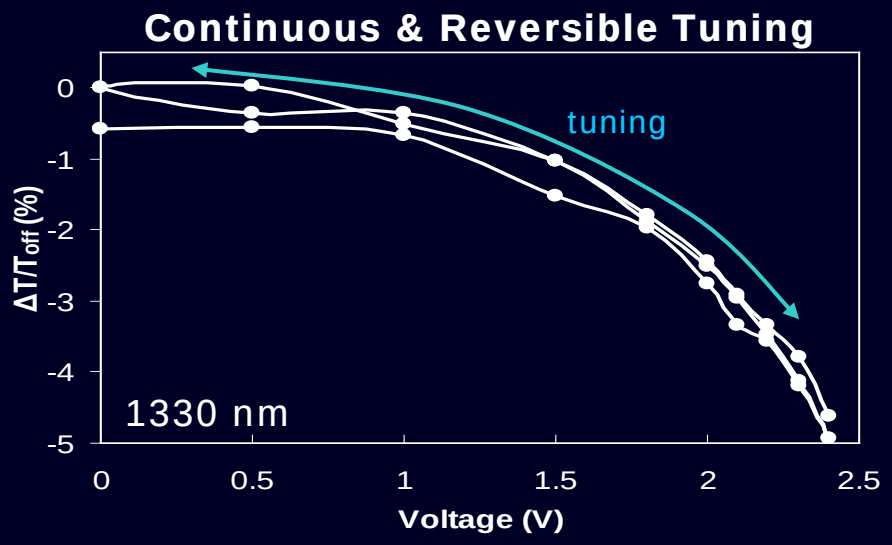
Static field

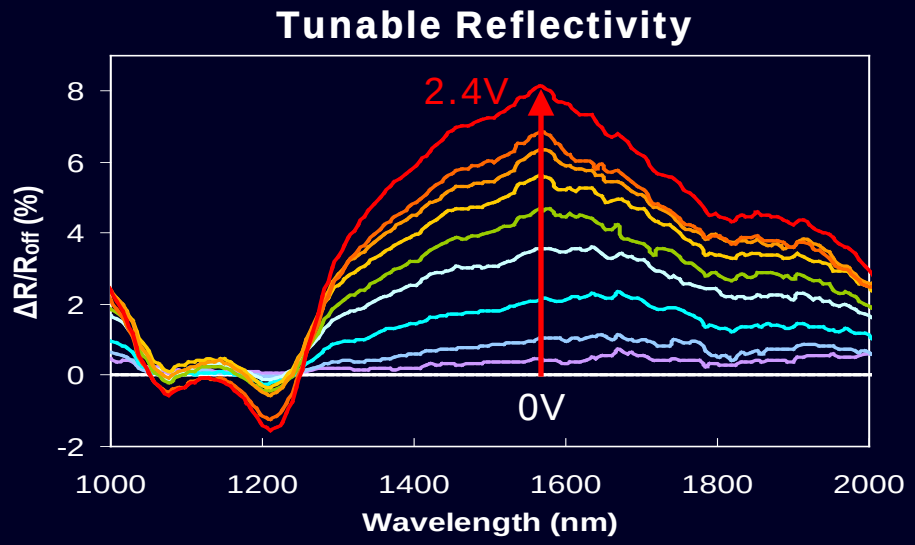


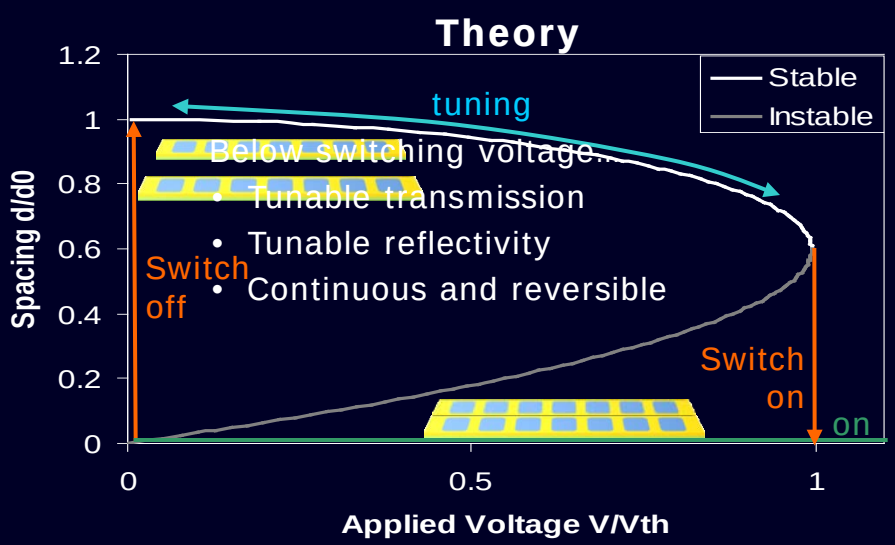
J. Y. Ou, E. Plum, J. Zhang, and N. I. Zheludev, *Nat. Nanotechnology*, under review

Electrostatically Controlled RPM: Tuning









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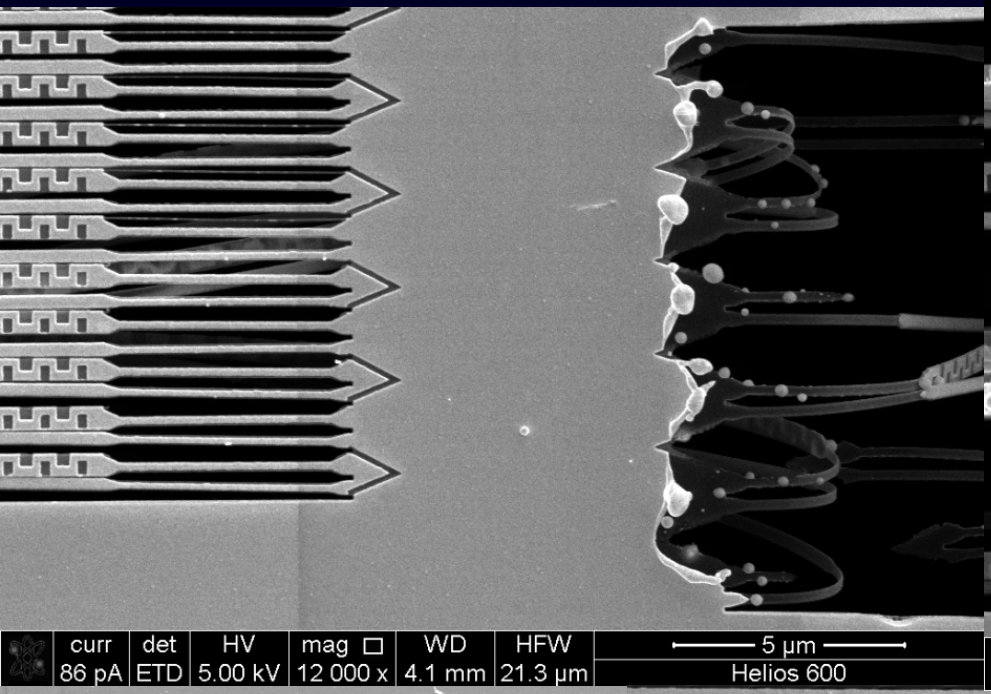
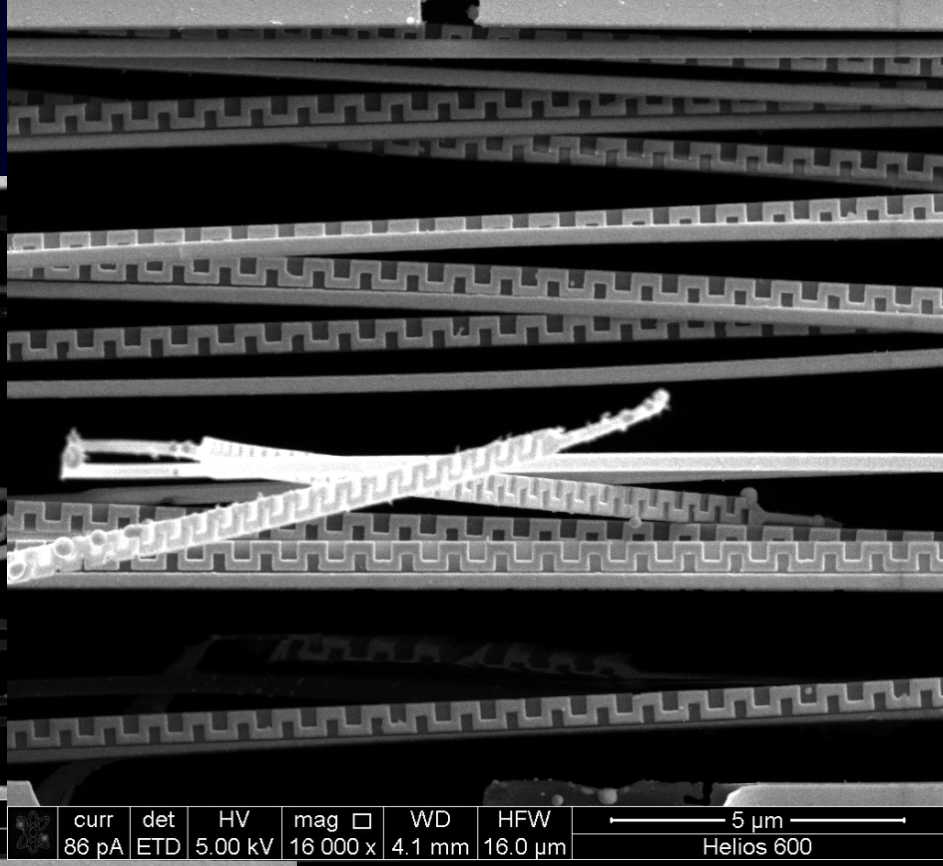
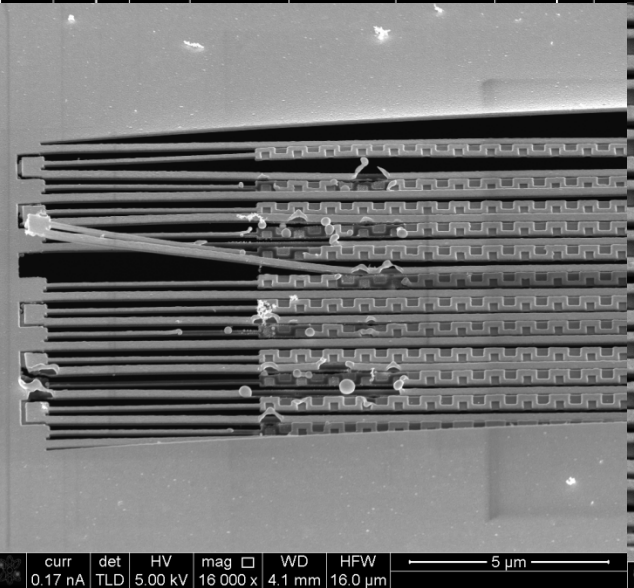
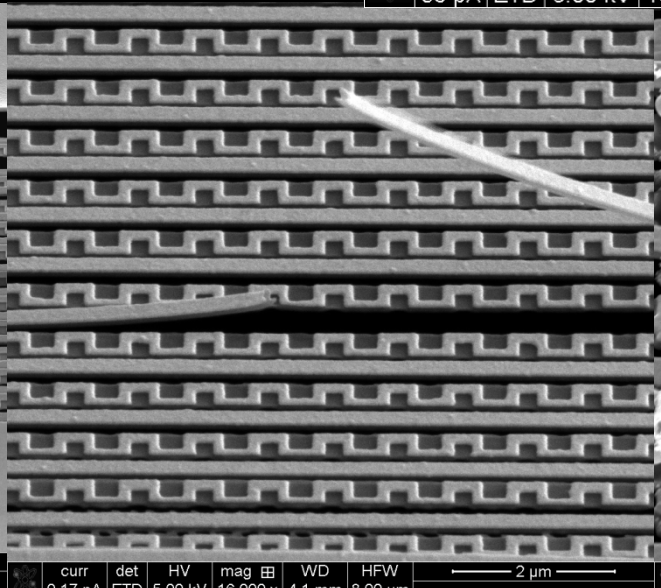
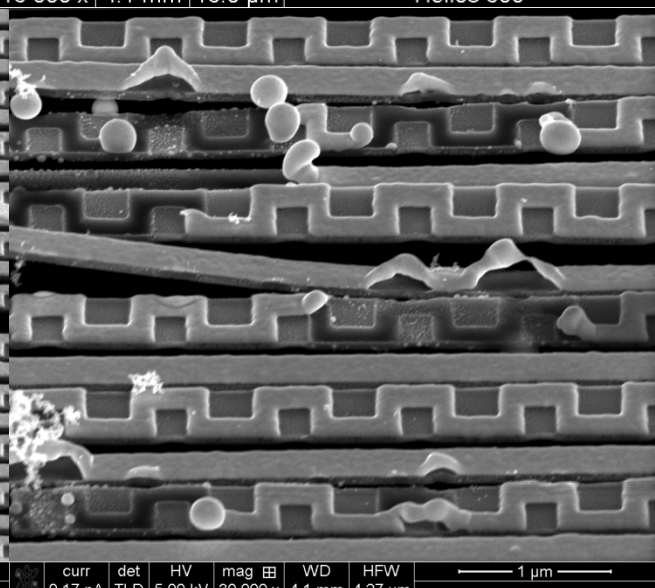
Beautiful Accidents



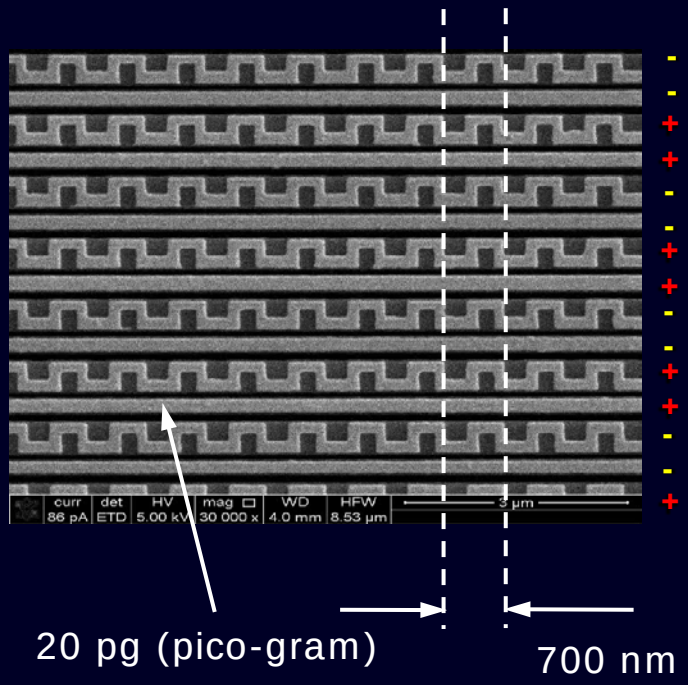


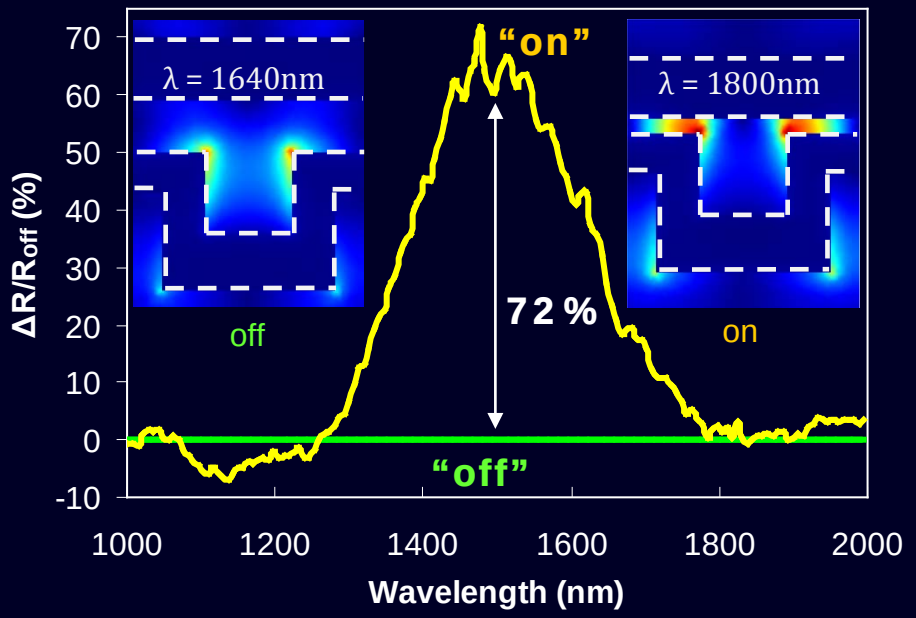


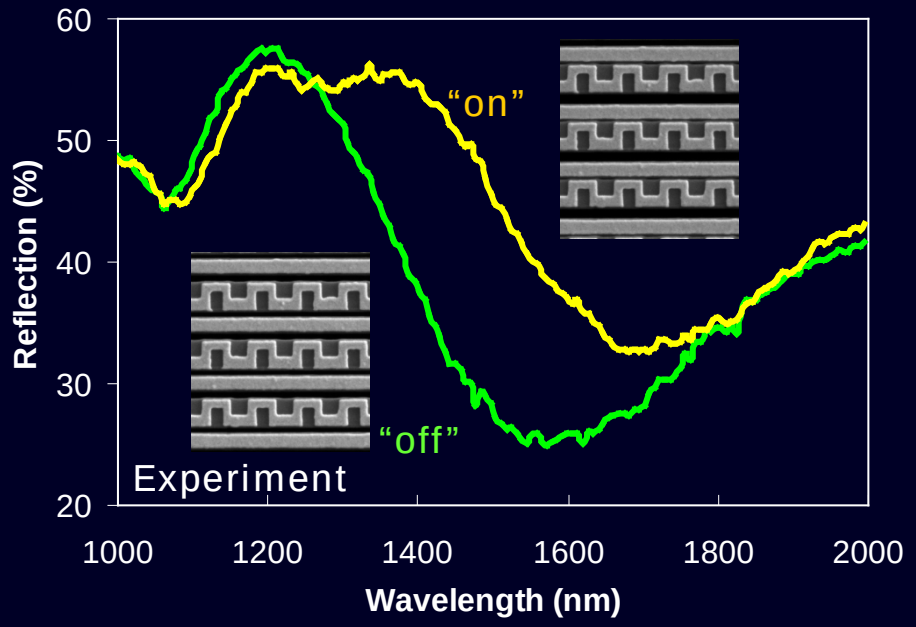




High-Contrast Electrooptical Switch

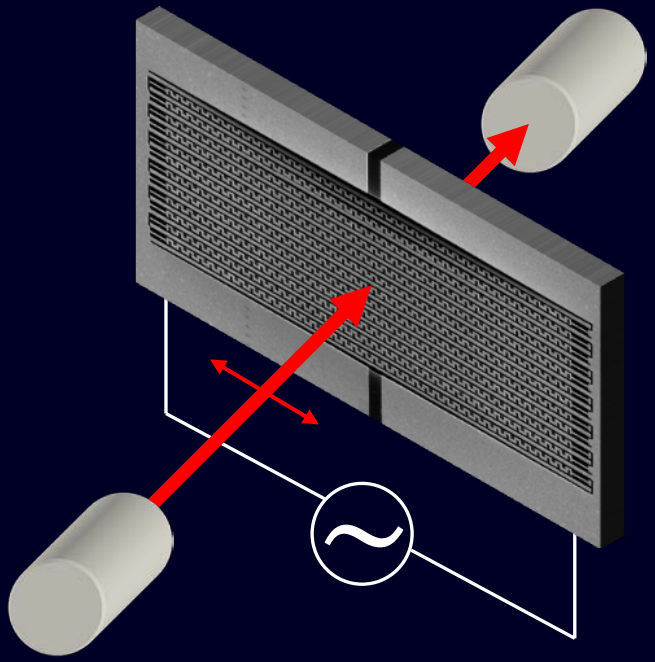


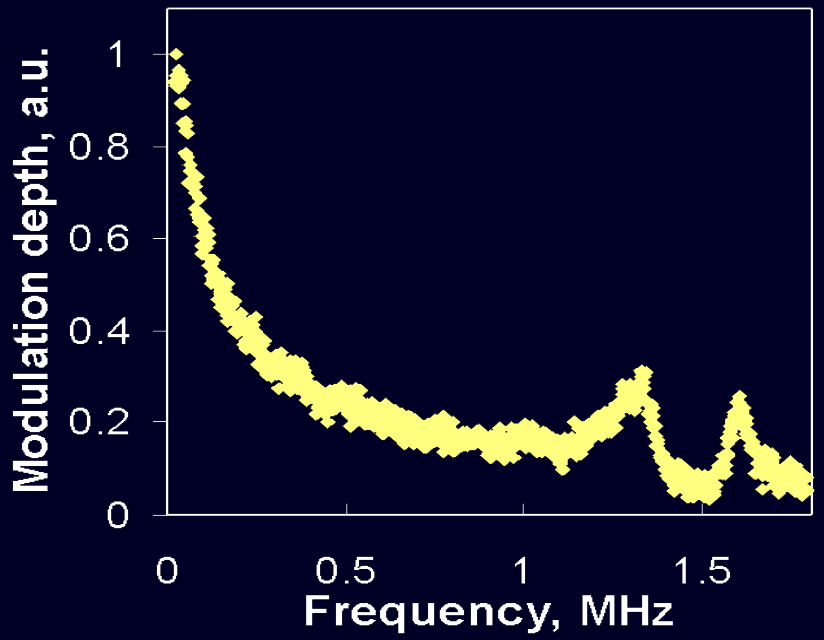




J. Y. Ou, E. Plum, J. Zhang, and N. I. Zheludev, *Nat. Nanotechnology*, under review

Fast Electrooptical Modulator

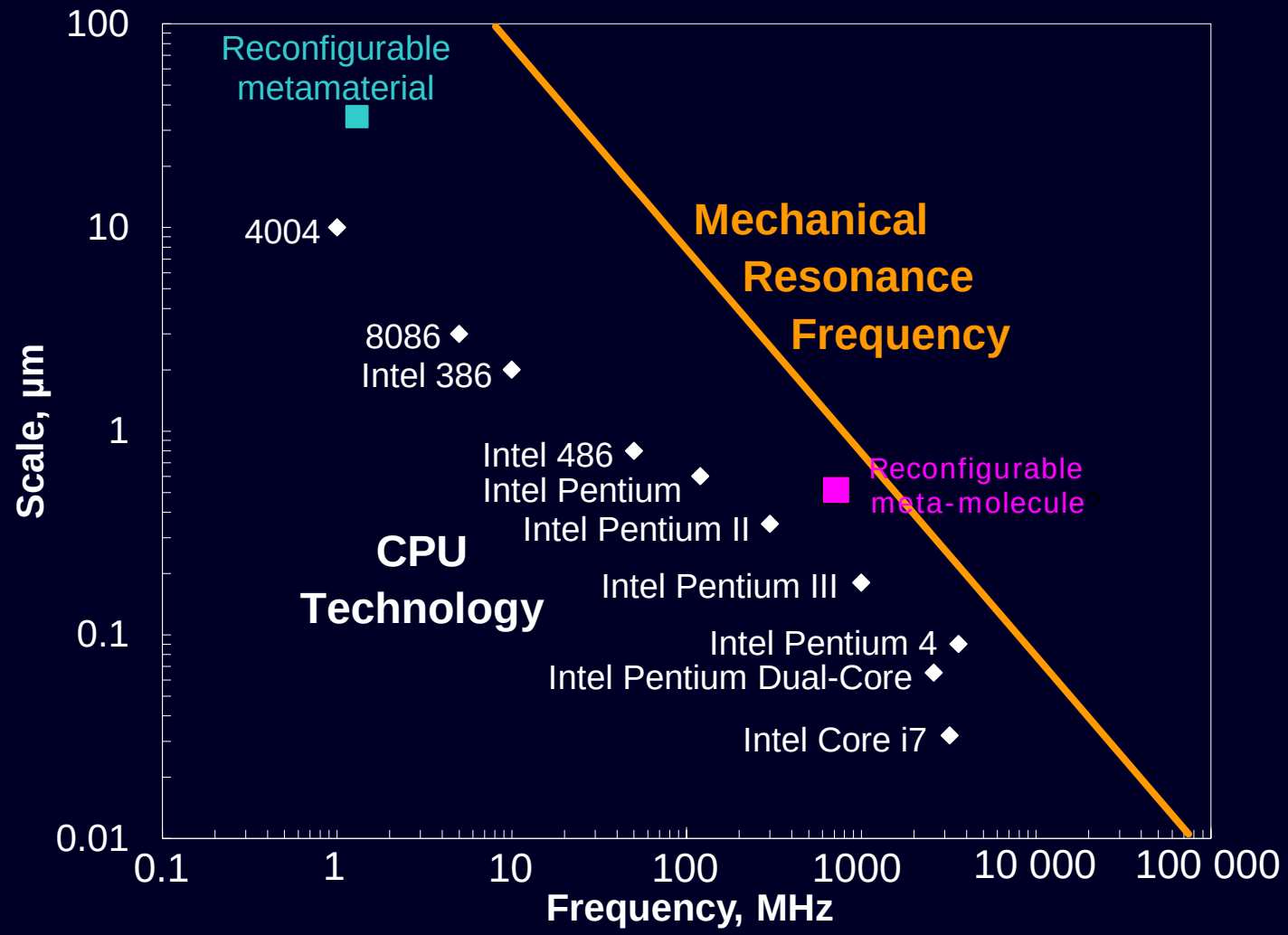




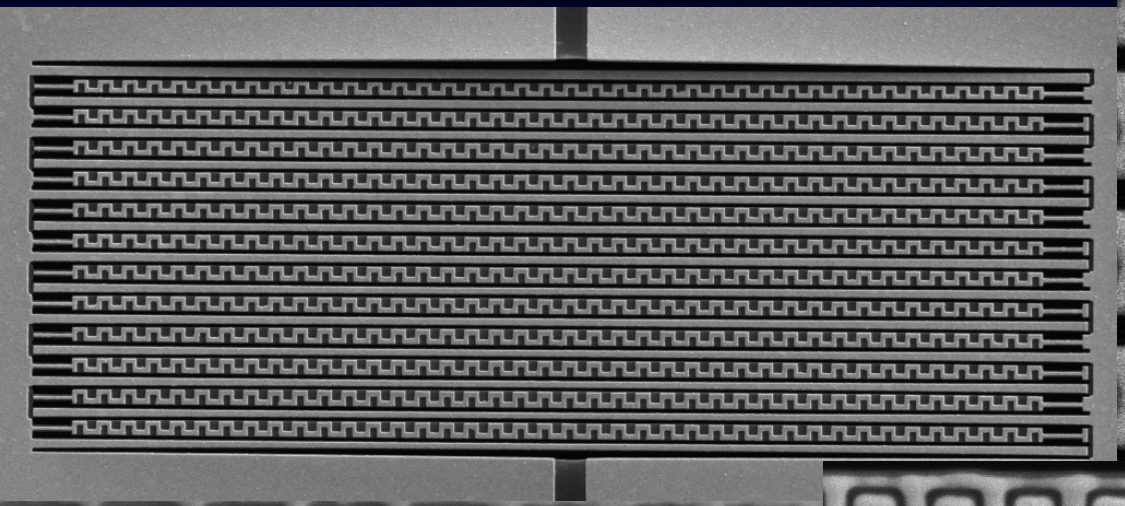
- Sub-wavelength thickness
- No need for polarizers
- MHz bandwidth
- 10 μW power consumption
- ~ 200 fJ switching energy
- Effective electro-optic coefficient ~ 10^{-5} m/V
  5 orders of magnitude higher than in $LiNbO_3$

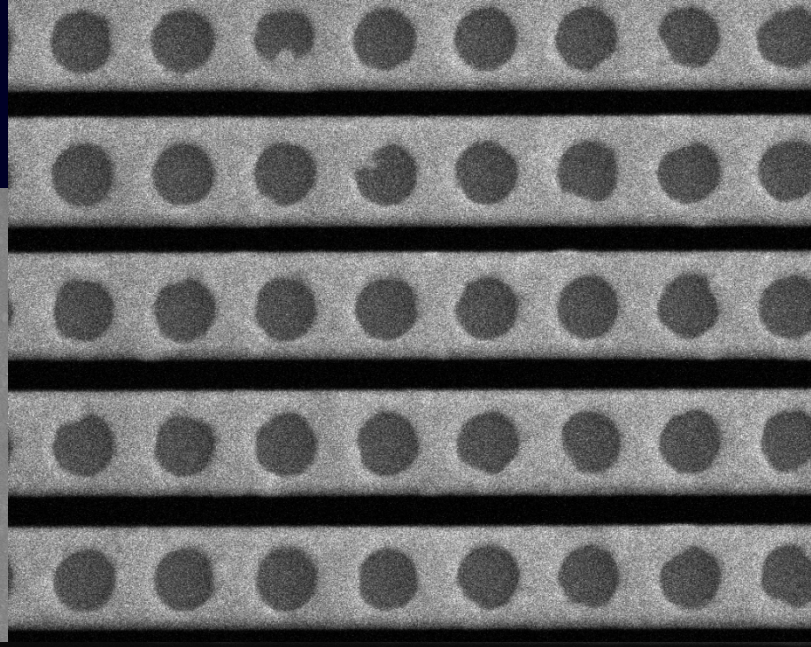
J. Y. Ou, E. Plum, J. Zhang, and N. I. Zheludev, *Nat. Nanotech.*, under review

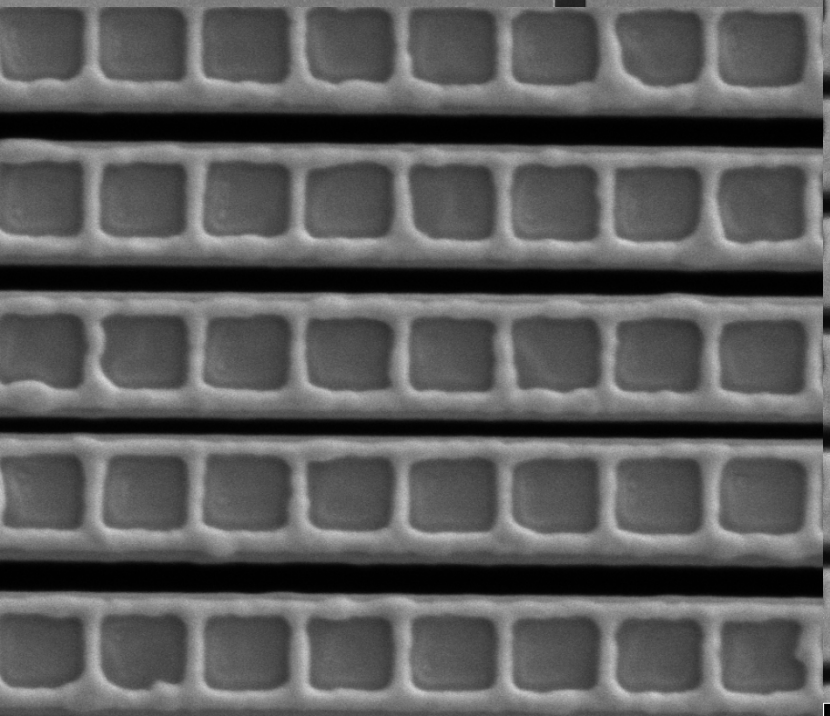
Nanoelectronics vs Nanomechanics

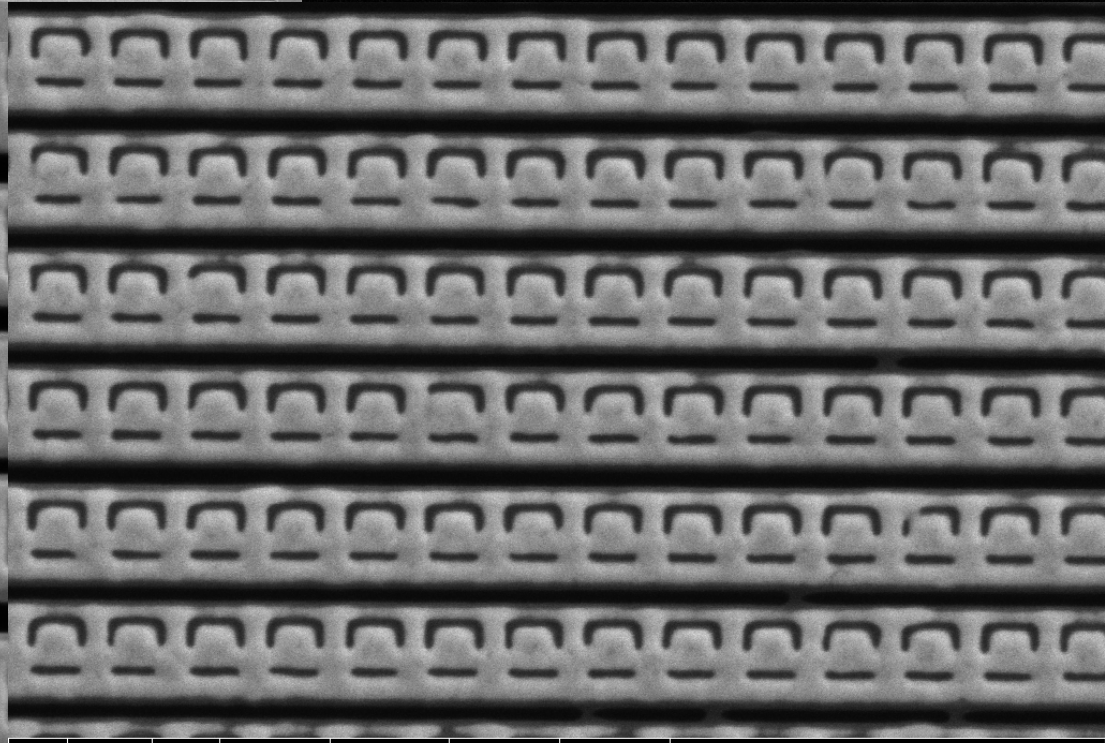


Various Designs





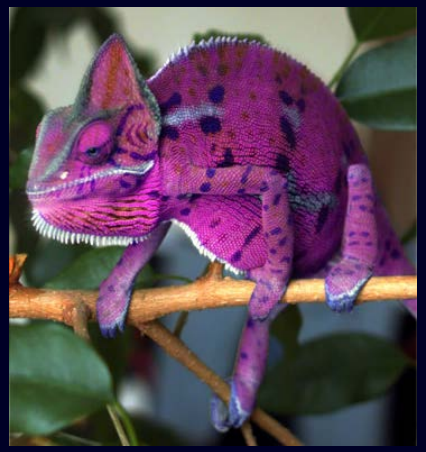




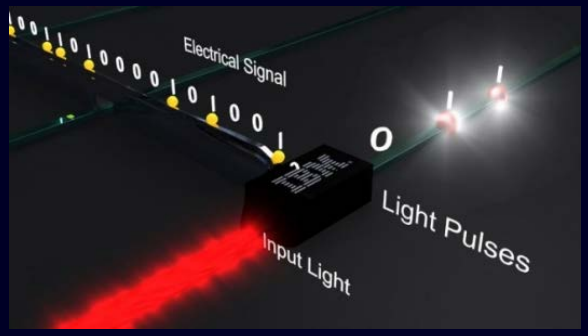
curr 43 pA | det ETD | HV 5.00 kV | mag 40 000 x | WD 4.0 mm | HFW 3.20 µm | 1 µm | Helios 600

curr 86 pA | det ETD | HV 5.00 kV | mag 40 000 x | WD 4.0 mm | HFW 3.20 µm | 1 µm

Potential Applications



Colour-changing surfaces



Electro-optical switches and modulators

Switchable cloaks and programmable transformation optics metamaterials

Tunable spectral filters

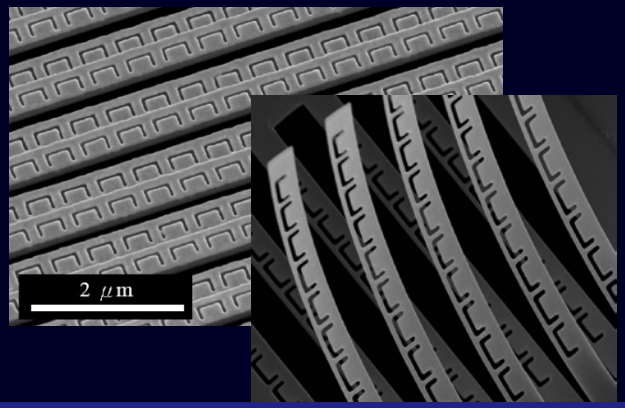
Giant electro-optical effects

Reconfigurable Photonic Metamaterials

... provide a flexible platform for tuning and switching metamaterial optical properties !

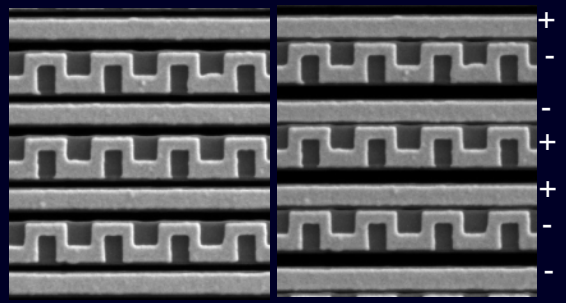
- MHz modulation bandwidth
- High contrast tuning & switching
- Sub-pJ switching energy
- High throughput fabrication possible via nanoimprint
- Many potential applications

Temperature-control



J. Y. Ou, E. Plum, L. Jiang, and N. I. Zheludev, *Nano Letters* **11**(5), 2142 (2011)

Electrical control



J. Y. Ou, E. Plum, J. Zhang, and N. I. Zheludev, *Nat. Nanotechnology*, under review

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J. Y. Ou, J. Valente, J. Zhang, N. I. Zheludev

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