# Nano-opto-electro-mechanical Switches Operated at CMOSlevel Voltages

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# **Abstracts:**

Reprogrammable optical networks that operate in symbiosis with CMOS electronics are expected to trigger technological advancements such as optical neural networks. However, current electro-5 optical switching technologies fail to combine CMOS-level voltages, micrometer-scale footprints, nanosecond switching and minimal optical losses. Here, we demonstrate an approach that utilizes opto-electro-mechanical effects in micrometer-scale hybrid-photonic-plasmonic structures to provide a full switching capability under CMOS voltages and 0.1 dB optical losses. The plasmonic confinement of light to the location of mechanical actuation enables a strong opto-electromechanical effect (G<sub>EOM</sub>  $\approx$  1.25 THz/V) resulting in voltage-length-products of (27 ± 4) µm, while 10 the combination with photonics guarantees lowest optical losses ( $0.026 \pm 0.002$ ) dB/um. Furthermore, the nanometer-scale skin depth in plasmonic metals, allows reduction of the actuation to a 40 nm thin gold membrane of low mass resulting in nanosecond-scale switching. Our work demonstrates that plasmonics provides an alternative to photonics even for applications such as reprogrammable optical networks, where minimizing optical losses is of utmost most 15 importance.

**One sentence summary:** Opto-electro-mechanical effects and hybrid-photonic-plasmonic devices are combined to enable optical networks that can be switched by CMOS-level voltages.

# Main Text:

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Electrically reconfigurable photonic networks have the potential to enable technological advances in many fields such as optical neural networks used to process information with low power at the speed of light (1); optical metrology to feed multiple sensors with a single light source (2); alloptical routing to avoid the current bottleneck of optical-electrical-optical conversion (3), and integrated quantum optical circuits (4). However, to make such reconfigurable photonic networks practical, they need to be up-scaled into large circuits and co-integrated with complementary metal-oxide semiconductor (CMOS) electronics. To achieve this level of scaling and integration, the elementary electro-optical switch unit needs to feature compact footprints (~ 1  $\mu$ m<sup>2</sup>), CMOS driving voltages of ~ 1 V, fast switching (~ 1 ns), low optical losses ( $\leq 0.1$  dB) and low power consumption ( << 1 mW) (5).

Electro-optical switches typically rely on interferometric waveguide configurations to divert light to different outputs via constructive or destructive interference. This is achieved by changing the refractive index ( $\Delta n$ ) of the waveguide material. State-of-the-art networks control  $\Delta n$  by the 15 electro-thermo-optical effect (6), however, the milliwatt power consumption per switch in standby limits the scalability of this approach (7). Furthermore, all-optical (8), phase-change (9, 10), and electro-optical (11-15) switching approaches show remarkable results (e.g. compact footprint, low driving voltages, low-loss), but struggle to excel in all requirements simultaneously. For instance, under a CMOS driving voltage of 1 V, electro-optic materials currently yield  $\Delta n < 10^{-2}$ , 20 requiring device lengths of  $> 100 \,\mu\text{m}$  to achieve full switching (11, 12). Resonant approaches reduce the footprint by leveraging the high finesse of micrometer-sized cavities. Yet, the frequency tunability of lowest-loss resonators is  $\leq$  50 GHz/V, which limits the optical bandwidth of switches (16, 17). Moreover, power hungry stabilization is required since similar resonance frequency shifts occur for single Kelvin temperature fluctuations (18). 25

Opto-electro-mechanical (OEM) switches provide an alternative way to control the flow of light by mechanically changing the waveguide geometry rather than modulating the material's intrinsic refractive index (7). In this approach, waveguide motions lead to local  $\Delta n$  on the order of unity. Because of the strong  $\Delta n$ , small actuations suffice to induce large *effective* refractive index changes  $(\Delta n_{\rm eff})$ . Importantly, OEM switches consume negligible amounts of energy in stand-by, as the mechanical geometry is controlled by electrostatic forces that are not accompanied by static currents. Photonic OEM devices implemented to date are switched by actuating hundreds of nanometer scale gap between two silicon waveguides with a remote electro-mechanical driver (19-21). The photonic approach yields low optical losses (< 0.1 dB), while the large gap size requires high driving voltages (> 10 V). In contrast, the sub-wavelength confinement of light (22) in allplasmonic devices enables stronger OEM responses, which reduce the drive voltages (23). Allplasmonic switches utilize two metals to form tens of nanometer wide gaps, where light is confined and its phase is modulated by changing the width of the gap via electro-mechanical actuation (24). However, such confinement comes at the expense of metal induced optical loss (i.e. Ohmic loss ~ 1 dB/ $\mu$ m) (25), which have to date limited the realization of large-scale plasmonic switching networks.

In this paper, we introduce a hybrid-photonic-plasmonic OEM technology that benefits from a strong plasmonic OEM-effect to fully switch light with a CMOS-level voltage ( $\approx 1.4$  V) and a compact footprint ( $\approx 10 \ \mu m^2$ ). Simultaneously, the technology benefits from photonics to lower

the propagation losses (0.026 dB/ $\mu$ m ± 0.002 dB/ $\mu$ m) by two orders of magnitude compared to allplasmonic approaches. A strong OEM-effect ( $\approx 0.03 \Delta n_{eff}/V$ ) is achieved by utilizing the plasmonic confinement of light such that a nanometer mechanical movement of an ultra-thin metal membrane provides already full switching control of light. CMOS voltages suffice to induce such small actuations because the nanometer-scale structures offer strong electrostatic forces. Further, our design enables nanosecond-scale switching as the plasmonic skin-depth and strong OEM effects enable low-mass cantilevers with fast response times. Furthermore, the low propagation losses allowed us to exploit resonant nano-opto-electro-mechanical (NOEM) switching with intrinsic quality factors exceeding 3000 to enhance the efficiency such that on-off switching with 200 mV becomes feasible. The resonator's OEM tunability  $\approx 1.25$  THz/V permits switching of broadband optical passbands (> 300 GHz) overcoming the typical narrowband limitations of other low-loss ( $\leq 0.1$  dB) resonant switches.



Fig. 1 Operating principle of plasmonic NOEM networks. (A) Incident light guided in the through port is switched to a drop port if its wavelength ( $\lambda_0$ ) matches the node's resonance wavelength ( $\lambda_{res}$ ), while it bypasses otherwise. (B) Hybrid-photonic-plasmonic disc resonators (radius 2 µm) are formed by a thin gold membrane suspended above a silicon disc forming a gap ( $z_0$ ). (C) Doped silicon and gold bridges are used to apply a voltage across the gap, thus inducing an electrostatic force that bends the membrane and prevents light from coupling to the resonator. (D) Through

port spectra for various dz. Low-loss and high-contrast operation requires  $\Delta \lambda_{\text{res}}$  to be multiple of the loaded resonator's full-width-half-maximum (FWHM). (E) Calculations (26) show that  $\Delta \lambda_{\text{res}}$  increasingly exceeds the intrinsic FWHM when reducing  $z_0$ . This enables low-loss switching of broadband optical signals ( $\approx 1$  THz) despite using a resonant approach.

Fig. 1A conceptually shows two resonant plasmonic NOEM switches, as proposed in this work, that dynamically route light. The incident light of wavelength λ<sub>0</sub> is guided in the through port. The light path is determined by the individual resonance wavelength (λ<sub>res</sub>) of the switches (27, 28). In the drop-state light, excites a traveling wave resonance and is transferred to the adjacent drop port if it meets the resonance condition (λ<sub>0</sub>=λ<sub>res</sub>). In the through-state (λ<sub>0</sub>≠λ<sub>res</sub>), light continues along the waveguide and bypasses the plasmonic resonator, thereby avoiding Ohmic losses (29). The hybrid-photonic-plasmonic (HPP) resonator comprises of a thin (t ≈ 40 nm) gold foil partially suspended above a silicon disc forming an air gap (z<sub>0</sub>). The air HPP waveguide combines low-loss propagation in the silicon waveguide (26) with strong field enhancement at the metal surface in the gap (Fig. 1B). Additionally, gold and silicon form an air capacitor to actuate z<sub>0</sub> via an electrostatic force generated by an applied voltage (V<sub>drive</sub>). The gold membrane bending (dz) induces a resonance shift (Δλ<sub>res</sub>) by changing the mode index (Δn<sub>eff</sub>), see Fig. 1C.

The large tunability of the resonance wavelength is indicated in Fig. 1D, where  $\delta z$  as small as 4 nm already provide  $\Delta \lambda_{res}$  sufficiently larger than the resonance's loaded full-width-half-maximum (FWHM). This enables large extinction ratio (ER) switching between the ports. Furthermore, low-loss coupling to the drop port requires that the plasmonic loss rate in the resonator (intrinsic FWHM) is smaller than drop waveguide-resonator coupling rate (*30*). The overall switching efficiency is limited by the ratio between  $\Delta \lambda_{res}$  and the intrinsic FWHM, which are shown Fig. 1E as a function of  $z_0$ .  $\Delta \lambda_{res}$  exceeds the FWHM by more than an order of magnitude when reducing  $z_0$ . This yields a tunability of >1 THz/V (> 10 nm/V) for  $z_0 \approx 35$  nm, which in combination with the sub-nanometer intrinsic FWHM enables low-loss switching with hundreds of gigahertz optical passbands (*26*).

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This strong tuning can be understood by separating the OEM effect into its two sub-processes. First, the opto-mechanical coupling ( $G_{OM} \propto d\lambda_{res}/dz$ ) increases for decreasing gaps because of the plasmonic confinement of light to the gap (26). Thus, more light experiences the strong  $\Delta n$  between air and metals upon actuation (31). The gold's skin-depth of infrared light is  $\approx 25$  nm, thus thin and low-mass metal foils suffice as high reflectors to concentrate light in the gap. Second, the electro-mechanical coupling ( $G_{EM} = dz/dV$ ) reaches large values as the voltage, which is applied over nanometer-scaled gaps, induces strong electrostatic forces ( $\propto 1/z_0^2$ ) (26).

Furthermore, the dynamics of the NOEM switch is determined by its geometrical parameters similar to a ruler that extends beyond the edge of a table. Shorter suspensions (i.e. stiffer spring) and a lighter mass result in faster ruler oscillations ( $f_{res}$ ). In our design we make the overhang as short and thin as possible. The combination of small moving mass, large forces and small mechanical Q-factors enables nanosecond switching at CMOS driving voltages.



Fig. 2 Scanning-electron-microscopy images and measured device properties. (A) Perspective view and transmission spectrum. The small cavity volume results in a free spectral range (FSR) of 45 nm. (B) Focused-ion-beam cross section. The gold membrane and silicon discs form small air gaps ( $z_0$ ) of 35 nm or 55 nm depending on the fabrication sequence. Gap length: 600 nm. Inset: simulated optical field, which is strongest in the gap. (C) ER and loaded Qfactor versus waveguide-disc separation (w) for  $z_0 \approx 55$  nm. The ER peaks at  $\approx 200$  nm indicating critical coupling, and high  $Q_{\text{intrinsic}} \approx 7000$ ) despite the plasmonic character of the resonator. (D)  $\Delta \lambda_{\text{res}}$  and FWHM as a function of voltage for  $z_0 \approx 35$  nm. The inset illustrates complete optical switching with 200 mV difference. (C) and (D) The 95 % confidence intervals are approximately equal to the symbol size.

Fig. 2A and B show perspective and cross-section images of fabricated resonators. The drop port 10 was omitted to probe the intrinsic OEM properties of the resonators. Vertical HPP waveguide geometries were uniformly created by depositing and selectively removing a sacrificial alumina layer by wet-etching to a typical undercut value of  $\approx 1.1 \,\mu\text{m}$ . Here, atomic layer deposition provides z<sub>0</sub> with atomic level precision. The critical feature size is given by the lateral waveguidedisc separation (w) for which our low-loss design enables values > 120 nm that are easily 15 achievable with low-cost photolithography.

To extract the cavity's intrinsic Q-factor ( $\propto 1$ /FWHM), we varied w and measured the ER and loaded Q-factor (Fig. 2C). At critical coupling (30)  $Q_{\text{intrinsic}}$  equals  $2 \cdot Q_{\text{loaded}} \approx 7000$ , which translates to propagation lengths and losses of  $(395 \pm 70)$  µm and  $(0.01 \pm 0.002)$  dB/µm, respectively (26). The reason for such low plasmonic loss is multi-fold. First, Ohmic losses are proportional to the fraction of the optical mode energy penetrating the metal. This fraction drops with decreasing permittivity of the gap dielectric; air or vacuum provide a low dielectric permittivity, minimizing loss (26). Second, excess losses induced by typical adhesion layers for gold (32, 33), such as chromium or titanium, are minimized. Overall Ohmic losses are cut

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approximately in half as air exposure oxidizes the 1 nm titanium adhesion layer used here. Third, the interaction of the HPP mode and gold membrane is mostly restricted to the smooth metal surface facing the gap, reducing scattering losses compared to those of metallic horizontal waveguides (*34*).

In order to characterize the switching capability, we measured Δλ<sub>res</sub> and the loaded FWHM as a function of DC voltage (Fig. 2D). The total Δλ<sub>res</sub> is > 6 nm and equals five times the FWHM. The nonlinear red-shift is expected from electro-mechanical effects as the increasing proximity of the metal membrane increases Δn<sub>eff</sub> (26). Furthermore, the quadratic voltage dependence of the electrostatic forces allows one to enhance the voltage sensitivity of the resonance shift (Δλ<sub>res</sub>/V) to ≈ 10 nm/V (i.e. ≈1.25 THz/V) by biasing the device with 1 V (26). In comparison, other resonant switching technologies (i.e. free-carrier-dispersion or Pockels effects) feature Δλ<sub>res</sub>/V of ≤ 50 GHz/V (*11*, *16*, *17*). Furthermore, the demonstrated tuning capability enables the compensation of thermally induced Δλ<sub>res</sub> which are typically hundreds of pm/K (*16*, *29*). The large *G*<sub>OM</sub>, *G*<sub>EM</sub> and Q-factors allows to reduce the required actuation distance to a few nanometers, and correspondingly the switching time to tens of nanoseconds as shown in the following.



**Fig. 3 Time dynamics. (A)** Modulation frequency response for a sinusoidal driving signal. A fundamental mechanical Eigenfrequency at  $\approx 12$  MHz can be seen. Squeeze-film stiffening causes a roll-off in response prior to the Eigenfrequency. **(B)** Utilizing more complex driving signals (red) enable optical (blue) rise and fall times on the order of tens of nanoseconds. The optical contrast between on and off-state exceeds 90 %.

Fig. 3A shows the small signal modulation response with a  $f_{res}$  of  $\approx 12$  MHz. The small mechanical Q-factor and the roll-off in modulation at lower frequency is attributed to squeeze-film damping and stiffening; e.g. air compression increases the stiffness when increasing the frequencies and thus lowers the actuation (26). The effect becomes more dominant for smaller gaps. This low-pass characteristics can be overcome by vacuum packaging or advanced driving signals (35). Fig. 3B shows a twostep driving scheme, the applied drive voltage (I) and (III) exceeded the steady-state voltage (II) and (IV) at the start of the individual on and off switching pulses. This resulted in rise and fall times of 60 ns and 100 ns, respectively, where the difference is due to electrostatic actuation forces that are larger than the spring restoring forces. The devices have been switched with megahertz frequencies over hours (billions of switching cycles) without showing a degradation of the signal quality. We estimate an electrical power consumption of  $\approx 600$  nW and 130 aJ when switched at tens of megahertz and a peak to peak voltage of 1.4 V and 0.2 V,

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respectively (26). Further optimization promises that NOEMS can reach fall and rise times approaching the few nanosecond level, while maintaining CMOS driving voltages (26).



5 Fig. 4 Performance of 1x2 NOEMS. (A) Perspective SEM image of two NOEMS. (B) Measured power spectrum of light coupled to the through port (blue) and the drop port (red) under 0 V (solid) and 1.4 V (dashed) bias. (C) Through port (blue/circle) and drop port (red/cross) transmittance over voltage. The crosstalk is below -15 dB, while  $IL_T$  and  $IL_D$  are  $\approx 0.1$  dB and 2 dB, respectively. Low through port losses are beneficial for switching architectures such as cross-grid networks envisioned in (D). Here, light (various rainbow colors) only needs to be switched once to a drop port while propagating through a 15x15 network. The 95 % confidence interval is smaller than the symbol size.

Subsequently, we performed 1x2 switching experiments. Fig. 4A shows a colorized SEM image of the fabricated devices. The through and drop port transmission spectra are plotted in Fig. 4B. Coupling the resonator to the drop port broadens the FWHM (optical bandwidth) from  $\approx 1$  nm (125 GHz) to  $\approx 2.5$  nm (350 GHz), yielding optical broad-bandwidth operation. Still,  $\Delta\lambda_{res}$ ( $\approx 6.2$  nm) exceeds multiple FWHM. Fig. 4C shows the transmittance versus voltage. Here, 0 V and 1.4 V correspond to routing light to the drop and through ports, respectively. In both cases, cross-talk was below -15 dB and drop port losses (*IL*<sub>D</sub>) were  $\approx 2$  dB, while through port losses (*IL*<sub>T</sub>) were  $\approx 0.1$  dB. Numerical optimization may further reduce *IL*<sub>T</sub> to  $\approx 0.02$  dB and *IL*<sub>D</sub> to  $\approx 1.5$  dB (26). This loss asymmetry is ideal for future applications in NxN cross-switching grids, as envisioned in Fig. 4D. Because light experiences *IL*<sub>D</sub> only once, accumulated losses (i.e. path of the red light beam) are dominated by through port loss (i.e. overall loss  $\leq 2N \cdot IL_T + IL_D$ ) when propagating through the network. This would result in an average loss-to-port count ratio of 0.12 dB per port for an optimized 15x15 network.

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We presented devices that challenges the common presumptions that opto-electro-mechanics is a slow and bulky technology that requires high driving voltages. We demonstrated NOEM switches whose unique compactness pave the way for high-density optical switch fabrics that are directly co-integrated with CMOS driving circuits. For instance, 200 switches and their electrical drivers could be integrated on an area as small as the cross-section of a single human hair. Beyond that, the strong OEM interaction and low-loss could enable non-resonant functional units such as phaseshifters and intensity-modulators for, e.g., LiDAR applications. The performance of phase shifters is typically evaluated by the voltage-length product  $V_{\pi}L$ , which states the minimal combination of  $\pi$  phase shift voltage times device length. The HPP prototypes demonstrated here already feature combination with  $V_{\pi}L = (27 \pm 4)$  Vµm, which in low propagation losses а  $(\alpha = 0.026 \text{ dB}/\mu\text{m} \pm 0.006 \text{ dB}/\mu\text{m})$ , represents a substantial improvement over the state-of-the-art (26). The scaling law governing OEM switches predict that a further reduction of the gap size to 10 nm will enable  $V_{\pi}L < 1$  Vµm. The stronger effect permits reduction of the device length to reduce the overall device losses by a factor up to ten. These switches could form the building blocks of optical field-programmable gate arrays (OPGA) and trigger a technological revolution similar to the one enabled over the past few decades by electrical field-programmable gate arrays (FPGA).

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- Author contributions: C.H., conceived the concept and supervised the project. C.H., A.J., F.M.
   D.C. designed the switch and performed numerical optimization. C.H., A.J. and Y.F. fabricated the modulator and developed the required process technology. C.H., A.H, M.D., M.B., M.M. and V.A.A. designed and performed the experiments. All authors discussed and analyzed the data. C.H., A.J., M.M., H.J.L., V.A.A and and J.L. wrote the manuscript.

Competing interests: J.L. is involved in activities towards commercializing high-speed plasmonic
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**Data and materials availability:** All data is available in the main text or the supplementary materials.

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# Supplementary Information – Nano-opto-electro-mechanical Switches Operated at CMOSlevel voltages

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# I. Comparison State-of-the-Art

In the following, we draw a comparison between our NOEMS technology to state-of-the-art electro-optic technologies, which should feature low optical loss and low driving voltages, while maintaining the most compact footprint possible to reduce cost. In order to compare the various technologies, we visualize these figures of merit with the help of the voltage-length-loss product  $(V_{\pi}L \cdot \alpha \text{ [VdB]})$  and the voltage-length-product  $(V_{\pi}L \text{ [V}\mu\text{m]})$ . The former quantifies the trade-off between optical loss (in decibel) and driving voltage (in volts) while the latter indicates the tradeoff between device footprint (micrometer) and driving voltage (in volts). The ideal technology should feature the lowest values for both. Fig. S1 shows experimental values (dots) obtained from the following phase shifting technologies: free carrier dispersion photonic devices (blue) (1–7), Pockels effect photonic devices (red) (8–11), Pockels effect plasmonic devices (yellow) (12–15) and nano-opto-electro-mechanical photonic/plasmonic devices (purple) (16, 17).

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Fig. S1 Technology comparison in terms of  $V_{\pi}L\alpha$  and  $V_{\pi}L$  for various phase shifter technologies (free-carrierdispersion-effect in photonics (blue), Pockels effect in photonics (red), Pockels effect in plasmonics (yellow) and nano-opto-electro-mechanical effects (purple). The  $V_{\pi}L\alpha$  indicates the driving voltage to achieve a  $\pi$  phase shift and the associated propagation loss in dB. The  $V_{\pi}L\alpha$  is a figure of merit for device compactness when minimizing the operating voltages. The device in this work combines the best both of these figures of merit, enabling new fields of applications. Please note, this comparison focuses solely on phase-shifting technologies as they enable low-loss devices.

As expected, photonic Pockels technologies perform well in terms of  $V_{\pi}L\alpha$  due the low inherent losses, but require long devices as is reflected in the large  $V_{\pi}L$  values. In contrast, plasmonic Pockels devices -- with their strong electric field confinement -- improve electro-optic efficiency to allow for smaller footprints (small  $V_{\pi}L$ ) but at the expense of high propagation losses (larger  $\alpha V_{\pi}L$ ). NOEM-based implementations follow this tradeoff, but, are already among the best of their peers. The hybrid-photonic-plasmonic technology in this work pushes the frontiers of the NOEM technology to the lower-left corner of the plot, enabling the first compact and low-loss electrooptic technology that is capable of being operated with CMOS driving voltages. Optimizing this technology promises further improvements. For instance, reducing the gap to 20 nm will reduce  $V_{\pi}L$  by more than an order of magnitude approaching  $V_{\pi}L$  of voltananometer-level, while simultaneously lowering  $V_{\pi}L\alpha$  by a factor of two or more.

20 Please note that we excluded opto-electro-thermal devices because their stand-by power consumption is typically milliwatt per switch (18) and a dense integration might suffer from thermal crosstalk (19). Contrarily, the ideal power consumption of NOEMS is negligible and only nanowatt power is consumed even when switching at highest rate.

In order to compare non-resonant and resonant technologies with each other, we extracted the  $V_{\pi}L$ and the propagation loss ( $\alpha$ ) by utilizing a resonator's sensitivity ( $\Delta\lambda/V$ ), circumference ( $L = 2\pi R_{eff}$ ), group refractive index ( $n_g$ ), free spectral range (FSR) and intrinsic Q-factor. The  $V_{\pi}L$  was calculated via

$$V_{\pi}L = \frac{FSR}{2 \cdot \frac{\Delta\lambda}{V}} \cdot 2\pi R_{\text{eff}} \text{ with } V_{\pi} = \frac{\pi}{\Delta\varphi/V} = \frac{FSR}{2 \cdot \frac{\Delta\lambda}{V}}, \quad (1)$$

where  $\Delta \varphi / V$  is the per Volt induced phase shift after one circumference.

The propagation loss per length is

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$$\alpha = \frac{10 \cdot \log_{10}\left(\frac{P}{P_0}\right)}{L} \text{ with } P = P_0 \cdot \exp(-2k''L) = \exp\left(-\frac{2\pi \cdot n_g}{Q \cdot \lambda_0} \cdot L\right).$$
(2)

where k'' is the mode's imaginary part of the wave vector. Furthermore, 1/2k'' equals the propagation length of a mode. Please note, that the equation (2) is obtained by utilizing the following relations:  $\exp(-\delta t_{rt}) = \exp(-2k''L)$ , where  $\delta = \omega_{res}/Q$  is the power decay rate of the cavity and  $t_{rt}$  is the roundtrip tip time.

5 In the following we discuss the uncertainties of our measurements that influence the extracted parameters such as  $V_{\pi}L$  and  $\alpha$ . For our devices, we measured an FSR of 49 nm with an uncertainty of  $\pm$  0.3 nm for the device presented in Fig. 2D of the main manuscript. This uncertainty is defined by the laser's digital step resolution during the wavelength sweeps. A further uncertainty is given by the average circumference that light covers during one roundtrip in the HPP resonator. The HPP 10 mode is mostly confined to the inner ( $\approx$  1.5 µm) and outer ( $\approx$  2 µm) radius. This provides an upper and lower bounds for the circumference estimation ( $2\pi R_{\text{effective}} \approx 2\pi \cdot 1.75 \mu m \pm 2\pi \cdot$ 0.25 µm). We determine  $V_{\pi}L = (27 \pm 4) \mu m$  when biased with 1 V, where the upper and lower bounds are determined by the upper and lower bounds of the circumference and FSR.

The uncertainties in estimating the propagation losses are governed by the uncertainties of the quality factor and group refractive index

$$n_{\rm g} = \frac{\lambda_0^2}{FSR \cdot L} = 4.5 \pm 0.7.$$
(3)

Again, we use the upper and lower bounds of the FSR and the circumference L determined in the previous paragraph to determine the upper and lower bounds of the group refractive index. The loaded Q-factor of the device presented in Fig. 2D of the main text is  $1560 \pm 160$ , with the 95 % confidence interval statistical uncertainty determined from the fit to the data. Based on these uncertainties we estimate propagation losses of  $(0.026 \pm 0.006) \text{ dB}/\mu\text{m}$  and propagation lengths  $(178 \pm 40) \,\mu\text{m}$ . Following the same analysis for the device presented in Fig. 2C, we obtain propagation losses of  $(0.01 \pm 0.002) \,\text{dB}/\mu\text{m}$  and propagation lengths  $(395 \pm 70) \,\mu\text{m}$ .

# II. Opto-mechanical Coupling

The sensitivity of propagating light to waveguide deformations (e.g. reduction of the gap size  $z_0$ ) can be quantified by the change in the effective refractive index ( $\delta n_{eff}$ ) or the opto-mechanical coupling rate ( $G_{OM}$ ) (20)

$$G_{OM} = 2\pi \frac{df_{\rm res}}{dz_0} = -2\pi \cdot \frac{d\lambda_{\rm res}}{dz_0} \cdot \frac{c_0}{\lambda_{\rm res}^2},\tag{4}$$

where  $c_0$  is the speed of light in vacuum.  $f_{res}$  and  $\lambda_{res}$  are the resonance frequency and wavelength, respectively.  $G_{OM}$  is related to  $dn_{eff}$  by

$$G_{\rm OM} = -2\pi \cdot \frac{dn_{\rm eff}}{dz_0} \cdot \frac{f_{\rm res}}{n_{\rm eff}}$$
(5)

Fig. S2 shows both  $G_{OM}/2\pi$  and  $dn_{eff}/dz_0$  as a function of the gap distance  $(z_0)$  for a hybridphotonic-plasmonic (HPP) waveguide. The results are obtained by means of FEM simulations. Please note, we approximated the bended disc resonator by a straight rectangular waveguide for

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reason of simplicity as bending losses are negligible for discs with radius of 2  $\mu$ m (21) and the utilized actuation is negligible to the suspension length of  $\approx 1.1 \mu$ m.



**Fig. S2 Opto-mechanical coupling** ( $G_{OM}$ ) as a function of the the gap height. (A) Optical mode of an hybrid plasmonic photonic waveguide.(B) Coupling rates up to THz/nm can be achieved for the smallest gaps. Moderate gaps of 20 nm to 50 nm result in  $G_{OM}$  of hundreds of gigahertz while benefiting from Q-factors of several thousands.

The HPP waveguide's optomechanical coupling benefits from a strong plasmonic enhancement with reduced gap size and can reach values of up to 1400 GHz/nm and 250 GHz/nm for gap height of 10 nm and 30 nm, respectively. In the following, we use the perturbation theory as introduced by Johnson et al. (22) to discuss the origin of the strong coupling

$$G_{\rm OM} \propto \frac{\int dz_0(x, y) \cdot \left( \left( \varepsilon_{\rm r,air} - \varepsilon_{\rm r,obj} \right) |E_{\rm p}|^2 - \left( \frac{1}{\varepsilon_{\rm r,Air}} - \frac{1}{\varepsilon_{\rm r,obj}} \right) |D_n|^2 \right) dA}{\int (U_{\rm electic} + U_{\rm magnetic}) dV},$$
(6)

where  $U_{\text{electric}}$  and  $U_{\text{magnetic}}$  are the electrical and magnetic energy of the optical mode. The integral in the numerator defines the change in the energy of the optical mode (resonance shift) induced by an actuation  $(dz_0(x, y))$  of the object's surface (dA). The integral comprises two terms to account for the discontinuity of the boundary condition. The first accounts for the energy change experienced by the electrical field parallel  $(E_P)$  to the object/air interface, while the second accounts for the perturbation of the displacement field normal to the interface  $(D_n)$ . The following three conclusions can be drawn. First, for materials with negative permittivity, a larger  $G_{OM}$ requires that fields are strongly polarized  $(E_p \gg E_n \text{ or } E_p \ll E_n)$ , since the contributions of the parallel and perpendicular field components have opposite signs. This is the case for plasmonic waveguides at infrared wavelengths. Second, the coupling increases with the field strength at the interface. The field strength is increased in our device because the suspended gold membrane acts as a near perfect electrical mirror that confines energy to the air gap, see Figure 2B in the main manuscript. Third, a large difference in the relative permittivity of the object and air is desired to maximize the change in energy.

Our device achieves an optimum balance between low loss and high G<sub>OM</sub>. For comparison, lossy (Q<sub>intrinsic</sub> ≈ 100) metal-insulator-metal (MIM) waveguide geometries report G<sub>OM</sub> values of 2π · 2000 GHz/nm for gaps of 15 nm (23). Meanwhile, low-loss (Q<sub>intrinsic</sub> > 10000) silicon photonic crystal waveguides report values of 2π · 36 GHz/nm for gaps of 30 nm (24). These two demonstration are at the extreme of the loss versus opto-mechanical coupling spectra. Resonant switching networks require a

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$$\frac{1}{Q_{\text{loaded}}} = \frac{1}{Q_{\text{coupling,d}}} + \frac{1}{Q_{\text{coupling,t}}} + \frac{1}{Q_{\text{intrinsic}}} < 750, \tag{7}$$

to provide nanometer optical bandwidth. At the same time the drop port coupling rate should be higher than the intrinsic loss rate, to achieve acceptably low drop port loss (i.e.  $Q_{\text{coupling,d}} > Q_{\text{intrinsic}}$ . Furthermore, minimizing the crosstalk between through and drop port requires that the critical coupling condition is fulfilled

$$\frac{1}{Q_{\text{coupling,t}}} = \frac{1}{Q_{\text{coupling,d}}} + \frac{1}{Q_{\text{intrinsic}}}.$$
(8)

Fig. S3 shows the evolution of the loaded Q-factor as a function of the intrinsic Q-factor. Small intrinsic Quality factor have a strong influence while its influence strongly diminishes for  $Q_{\text{intrinsic}} > Q_{\text{coupling}}$ , see Fig. S3. Thus, the hybrid-photonic-plasmonic waveguide geometry provides a good trade-off between opto-mechanical coupling and Q-factors to enable broadband and low-loss optical switching networks.



Fig. S3 Loaded quality factor as a funciton of the intrinsic Q-factor under critical coupling. The devices presented in the main manuscript were designed for an optical bandwith of 2 nm, which is indicated here by the black dashed line. The green area highlights the typicall Q-factors achievable for different waveguide geometries and  $Q_{\text{coupling.d}} = 1500$ .

For completeness, we would like to briefly discuss the potential application for quantum optoelectro-mechanical converters (25). These ideally require a single- photon-coupling-rate ( $g_0$ ) that is larger than the square root of the product between optical ( $\gamma_{0,loaded}$ ) and mechanical ( $\gamma_{M}$ ) decay rates.  $g_0$  is given by

$$\frac{g_0}{2\pi} = \frac{G_{\rm OM}}{2\pi} \cdot z_{\rm zpf} = \frac{G_{\rm OM}}{2\pi} \cdot \sqrt{\frac{\hbar}{2m_{\rm eff}\omega_{\rm mech}}} \approx 4 \,\rm MHz \tag{9}$$

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The zero-point fluctuation 
$$(z_{zpf})$$
 of our approach is  $\approx 20$  fm based on an effective mass of  $\approx 1.8$  pg  
and a mechanical frequency of  $\approx 12$  MHz. The optical decay rate at critical coupling is  $\gamma_0 < 200 \ GHz$  for an loaded Q-factor larger than 1000. The mechanical decay rate was increased by  
squeeze film damping to a few megahertz. However, operation under vacuum and further  
optimization could lead to  $\gamma_M \sim 10$  kHz (i.e. mechanical Q-factors of 1000) (23). Thus, the ratio

between the square of the single-photon coupling rate and decay rates reaches values close to unity. Future improvements can be expected as Ohmic loss of metals are reduced at cryogenic temperature (26). Alternatively, silver could be used to replace gold to lower the optical loss further (27, 28). Normally, silver is avoided because it oxidizes in ambient atmosphere, however, we expect the devices to be vacuum sealed.

### III. Electro-mechanical Coupling

The sensitivity of the mechanical actuation with respect to an applied voltage  $(dz_0/dV)$  is quantified by the electro-mechanical coupling  $(G_{\rm EM})$  (25). In the following, we highlight laws that govern the actuation as a function of the voltage and geometrical/material properties. For a more detailed discussion, we refer the reader to (29).

We are operating the presented NOEM switches with deformations  $dz_0 < 10$  nm being a fraction of the overall gap  $z_0$ . Thus, for reason of simplicity, we approximate a constant electrostatic force density along the suspended gold foil. Stronger actuation results in a position dependent force increase, which normally results in larger displacement as discussed by Hibbeler et al. (30). The load is

$$F_{\rm EM} = \frac{dU}{dz_0} = \frac{1}{2} V_{\rm drive}^2 \cdot \frac{dC(z_0)}{dz_0},$$
 (10)

where, U is the electrical energy stored in the capacitor.  $V_{\text{drive}}$  is the applied voltage. C is the device capacitance, which is approximated by an air-filled parallel plate capacitance having a suspended surface area  $A = \pi (R^2 - (R - l)^2)$ . Therefore

$$F_{\rm EM} \approx \frac{1}{2} V_{\rm dirve}^2 \cdot \frac{\varepsilon_0 \cdot A}{z_0^2}.$$
 (11)

20 The electrostatic actuation (typically:  $F_{\rm EM} \sim 10$  nN for our geometry) induces a small deformation and is counterbalanced by an elastic restoring force, that can be model by a spring system for small actuations

$$F_{\rm restoring} = -k_{\rm spring} \cdot dz_0, \tag{12}$$

where  $k_{\text{spring}}$  is the effective spring constant of the suspends gold membrane. Please note, the restoring force is linearly proportional to the displacement as long as the induced stress is smaller than the yield point of the material (amorphous gold:  $\approx 0.2$  GPa (31); crystalline gold:  $\approx 0.8$ GPa (32)). This is the case under small actuation. The electrostatic (equation (11)) and restoring (equation (12)) force are equal in steady-state, thus yielding

$$dz_0 = \frac{A}{k_{\rm spring}} \cdot \frac{1}{2} V_{\rm drive}^2 \cdot \frac{\varepsilon_0}{z_0^2}.$$
 (13)

Thus we can estimate an upper limit of the spring constant

$$k_{\rm spring} < \frac{A}{dz_0} \cdot \frac{1}{2} V_{\rm drive}^2 \cdot \frac{\varepsilon_0}{z_0^2} \approx (15.4 \pm 7.3) \,\mathrm{N/m.}$$
 (14)

Here we utilized the  $\Delta\lambda_{\rm res}$ , measured at  $V_{\rm drive} = 0.4$  V, to transform it into a  $dz_0 \approx (0.4 \pm 0.1)$  nm with the help of the calculated  $G_{\rm OM} \approx (220 \pm 40)$  GHz/nm. Please note, that the

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uncertainties of the lower and upper values are given by the minimal and maximal measured gap heights during the characterizations of multiple devices ( $z_0 = (35 \pm 5)$  nm). As a comparison, the analytic expression for a point loaded cantilever yields (33)

$$k_{\rm spring} = E \frac{wt^3}{4l^3} \approx 10.5 \,\rm N/m,$$
 (15)

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where w is the average circumference of the suspended gold membrane. E is the Young's modulus, which is  $\approx 70$  GPa for amorphous gold (31). Please note, that the analytic expression (15) underestimates the effective spring constant compared to equation (14), as the load is applied at the tip of the cantilever, which induces a larger displacement compared to an equally distributed load.

In summary, we can draw the following conclusions for the small actuation limit ( $dz_0 < z_0$ ) from equation (3).

- i. For a constant drive voltage, the displacement is proportional to the inverse of the squared gap height. This provides a scaling path and by reducing  $z_0$  to tens of nanometers sufficient actuation can be achieved despite small CMOS level driving voltage. Furthermore, reducing the gap height not only increase  $G_{\rm EM}$  but also  $G_{\rm OM}$ .
- ii. The quadratic voltage dependency allows amplification of small signal voltage by using a bias as  $F_{\rm EM}(t) \propto (V_{\rm AC}(t) + V_{\rm DC})^2$  and  $F_{\rm EM,AC}(t) \propto (2V_{\rm DC}V_{\rm AC}(t))$ . For instance, using a bias of  $V_{\rm DC} = 1$  V effectively enhances a  $V_{\rm AC} = 200$  mV by ten-fold. This enhancement enable on- and off-resonance switching with only  $V_{\rm AC} = 200$  mV, as shown in Fig 2D.

Fig. S 4 shows the analytically calculated electro-mechanical coupling ( $G_{\text{EM}}$ ) as a function of a bias voltage ( $V_{\text{DC}}$ ) and initial gap height ( $z_0$ ) for a beam length of 1.1 µm. The values are obtained for a small AC-signal actuation around the bias ( $V_{\text{AC}} = 2\% V_{\text{DC}}$ ).



Fig. S 4 Electro-mechanical coupling rate ( $G_{EM}$ ) as a function of applied bias and initial gap height  $z_0$ .  $G_{EM}$  for a beam length of 1.1 µm.  $G_{EM}$  reaches values beyond 20 nm/V. The dark blue areas at the bottom right indicate the voltages for which an irreversible pull-in of the beam is expected. Please note, during our experiments, we observed pull-in voltages > 1.5 V for gaps of 35 nm.

The dark blue area in Fig. S 4 indicates the parameter space for which a destructive and not reversible pull-in event of the gold membrane is expected (33). The pull-in event occurs when the quadratic dependency on the gap height of  $F_{\rm EM}$  out-scales the linear dependency of  $F_{\rm restoring}$ , meaning that  $dF_{\rm EM}/dz > dF_{\rm restoring}/dz$ . Biasing the device close to the pull-in is not desired despite the increased sensitivity because:

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- i. Voltage spikes during operation can cause the irreversible pull-in event.
- ii. The system's effective spring is softened and reaches zero when the bias approaches the pull-in voltage. This ultimately reduces the switching frequencies to zero.

### IV. Switching speed and stability

The achievable switching speed ( $\propto 1/f_{res}$ ) is determined by the mechanical damping ( $\propto 1/Q$ ) and mechanical eigenfrequency of the suspended gold membrane, which can be roughly approximated by

$$f_{\rm res} \approx \frac{1}{2\pi} \sqrt{\frac{k_{\rm spring}}{m_{\rm eff}}},$$
 (16)

where,  $m_{\rm eff} \approx 1.8$  pg is the effectively oscillating mass of the gold membrane and can be approximated by  $m_{\rm eff} \approx 1/_4 \cdot A \cdot t \cdot \rho_{\rm metal}$  (29). Fig. S 5A shows the dynamic responses (actuation vs. time) to a 1 V driving signal applied at t = 0 ns for various damping coefficient under vacuum. The fastest response is observed for the underdamped case (blue), however, the mechanical ringing results in a settling time that is hundreds of nanoseconds long. The ringing can be avoided by using advanced driving schemes to increase the acceleration and deceleration, enabling a rise time of  $\approx 10$  ns (34).

Contrarily, the switching speed is reduced if the system is subject to damping and such systems behave like low-pass filters (yellow; or red) and increasing the switching speed requires a driving signal that compensates the low-pass characteristics by enhancing the energy of the signal's high frequencies components. Such an approach is shown in Figure 3B of the main manuscript.



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Fig. S 5 Dynamic properties. (A) Actuation over time for various mechancial Quality factors. Q above 0.5 corresponds to underdamped systems while values below indicate an overdamped system. Critical damping is observed for Q = 0.5. The response was obtained for a rectangular 1 V driving signal using Newton's law of motion for a 1100 nm beam that is underdamped (blue), critically damped (red) and overdamped (yellow). (B) FEM simulations of  $f_{res}$  of a gold membrane with various suspension lengths (C) Measured eye-diagram. The ring tone of 23 MHz indicates that the system is underdamped. Parameters: Rectangular driving voltage of  $V_{DC}$ =4.75 V and  $V_{AC}$ =0.5 V. for a  $z_0 = (55 \pm 5)$  nm.

In addition the resonance frequency can be increased by increasing the stiffness  $(k \propto 1/l^3)$  of the spring or by reducing the springs mass  $(m_{\text{eff}} \propto l \cdot t \cdot \rho_{\text{Au}})$ , see equation (16). Fig. S 5B shows  $f_{\text{res}}$ 

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as a function of the suspension length l for a gold thickness of 40 nm based on accurate FEM simulations. Shorter suspension result in larger eigenfrequency and the numerically calculated values (blue line) are  $\propto 1/l^2$ . Experimental values are highlighted by the green dots. For a  $(600 \pm 100)$  nm under etch, we observed a eigenfrequency of  $\approx 23$  MHz, which is clearly visible in the measured optical eye-diagram of a 1.2 Mb/s pseudo-random-bit-sequence. The visibility of the ring tone indicates that this device is underdamped ( $Q \approx 10$ ). This is in contrast to the strong damping (Q  $\approx$  1) observed for the devices having a z<sub>0</sub> of 35 nm and a suspension length of  $(1100 \pm 100)$  nm, manuscript. The difference in damping is due to squeeze film damping (35) that is more pronounced in the device with larger undercut and smaller gaps. Furthermore, the modulation response in Fig. 3A drops prior to approaching the resonance frequency. We attribute this to the elastic force contribution of the squeezed air, which in such small gaps can be on the same order as the mechanical restoring force. This may explain a large decrease in the dynamic response, due to both the increased stiffness as well as the strongly modified mode shape. For instance, the modal motion at the edge of the gold membrane will decrease more than at the points closer to the clamp.

Furthermore, optimization requires that both the eigenfrequency and the driving voltage are considered as both for instance scale with the spring constant. Thus we need to optimize

$$\frac{f_{\rm res}}{V_{\rm drive}} \propto \sqrt{\frac{\varepsilon_0}{\rho_{\rm metal} \cdot t \cdot z_0^2 \cdot dz_0}}.$$
(17)

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We increased this ratio significantly by combining narrow gaps with a thin gold membrane and a low loss resonant approach. Here, narrower gaps enable larger electrostatic driving forces while keeping the voltage low. Thinner membranes reduce the mass resulting in faster  $f_{res}$ . A higher finesse allows one to reduce the actuation needed to induce enough phase shift ( $\Delta \phi \propto G_{OM} \cdot dz_0$ ). Non-resonant structures require a phase shift of  $\pi$  to completely switch light, while resonant structures reduces the required phase shift by  $\propto 1/Finesse$ . Our low-loss resonator provides a finesse of  $\approx 21$  for a 1x2 switch and  $\approx 49$  for a 1x1 switch which is a strong improvement over allplasmonic approaches featureing Finesse of 1 to 3 (23, 36).

Furthermore, improvement of  $f_{\rm res}/V_{\rm drive}$  by a factor of 4 can be achieved by using silver ( $\rho_{\rm Ag} \approx$  $0.5 \cdot \rho_{Au}$ ) and reducing the thickness to 20 nm and the gap to 20 nm. The lower Ohmic loss in silver compared to gold (27, 28) compensates for the increased losses due to the tighter mode confinement when reducing the gap.

The device was operated for billions of switching cycles and no deformation was observed. This 30 indicates that the induced stress at the anchor point of the beam did not exceed the yield point of the material. Please, note the n-doped chip is highly doped, and thus, we do not expect any RCbandwidth limitations prior to the mechanical eigenfrequency.

#### V. **Optical Loss and Switching Network**

35 The presented hybrid-photonic-plasmonic resonator reaches opto-mechanical coupling  $> 2\pi$ . 300 GHz/nm while featuring Q-factors of several thousand as shown in Fig. S6. The measured Qfactors of the devices are highlighted by the blue crosses. Please note, we measured gap variations up to  $\pm 5$  nm in the gap height as indicated by the arrows with the help of atomic force microscopy. Q-factors of a few thousands can be achieved despite plasmonic gaps of only tens of nanometers. This corresponds to propagation length  $(L_{\rm prop})$  of a few hundreds of microns. Please note, that

cavity losses are dominated by Ohmic propagation loss because the high confinement of light minimizes the bending losses (21).



5 **Fig. S6 Calculated Quality factor (blue) and propagation length (red) of an ideal HPP waveguide geometory.** The blue crosses highlight the measured Quality factors based on our experiments and confirm that this structures is capable of achieving large Q-factors. Arrows highlight the maximal measured variations in the gap height.

The achieved propagation lengths of hundreds of micrometeres are – to the best of our knowledge record values for any plasmonic electro-optic devices (*37*). This can be understood by the low permittivity of the air gap, lowering the fraction of mode energy inside the metal. Fig. S7 shows the dependency of the propagation length for various gap filling materials.



**Fig. S7 Modeled Propagation length of various hybrid-photonic-plasmonic waveguides.** The gaps are filled with the stated materials and lowest losses are observed for air gaps. Here, OEO stands for organic-electro-optic molecules and BTO for barium titanate (*11*, *38*).

For instance, air HPP waveguides feature an order of magnitude lower loss than organic-electrooptic chromophores (OEO) HPP waveguides. This providing an advantage for our OEM HPP technology over competing plasmonic technologies to realize large-scale low-loss switching networks.

20 Designing a switching network (e.g. NxN cross-grid networks) requires consideration of the various trade-off between drop port losses, through port losses and signal bandwidth. The maximal insertion loss of a cross-grid networks is given by  $\langle 2N \cdot IL_T + IL_D$ . Small networks require balanced through port and drop port losses, while larger networks benefit from lower through port loss.

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**Fig. S8 Insertion loss (IL) of light routed to the through port (A) and drop port (B).** The white dashed lines indicate the achievable FWHMs and values larger than 2 nm are desired for 100 GHz signals.

Fig. S8 shows the calculated insertion loss for the through port (A) and drop port (B) as a function of  $Q_{intrinsic}$  and  $Q_{coupling,drop}$  (coupling loss to drop port). The calculations are based on an analytic model assuming critical coupling and negligible loss in the waveguide-cavity coupling section (39). The white dashed lines highlight the achievable FWHMs of 1x2 switch. Broadband optical responses of >2 nm are desired for broadband optical switching and thermal stability. Increasing the coupling between the drop port and cavity (i.e. reducing  $Q_{coupling,drop2}$ ) increases the through port loss ( $IL_T$ )as the second drop port acts as a further cavity loss channel. This results in an increase of  $IL_T$  from 0.025 dB to 0.2 dB for a  $Q_{Cavity} \approx 3000$ . Contrarily, increasing the coupling rate lowers the drop port loss  $IL_D$  from -1.5 dB to -0.5dB. Furthermore, stronger coupling results in a larger FWHM that requires higher driving voltages to achieve  $\Delta\lambda_{res} >$  FWHM.

 $IL_{\rm T}$  has been determined by measuring the transmission as a function of the number of resonators coupled to the bus waveguide. The results are shown in Fig. S 9 in blue, while the black dashed line represents a linear fit. From a linear fit we extract average  $IL_{\rm T}$  of  $\approx 0.1$  dB per resonator. We attribute the deviation from the optimal value of 0.025 dB to fabrication imperfections as well as pull-in of individual resonators during the critical-point-drying process.



Fig. S 9 Cut-back measurment for determing the through port loss ( $IL_T$ ). The linear fit indicates loss of  $\approx 0.1$  dB per resonator. The variance is attributed due to miss alignment and pull-in events during fabrication indicating ample room of improvement for the coming generations.

### 25 VI. Energy Estimation and Device Capacitance

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The power consumption of OEM devices is governed by the energy required to perform a switching operation and the number of operations per second. The measured static current in standby was < 1 nA (noise floor). This confirms that the static power consumption is negligible for OEM switches as their air capacitor acts as a perfect isolator.

5 The energy required to switch  $(U_{switch})$  is determined by the energy lost in the resistive elements of the circuit when loading the OEM device capacity

$$U_{\rm switch} = \frac{1}{2} C V_{\rm drive}^2.$$
 (18)

Large capacitances (*C*) or driving voltages ( $V_{drive}$ ) increase the charging time and current flow through the device circuit resistance, respectively (40). The measured device capacitance is  $\approx 6$  fF and agrees with theoretical models based on a simple plate capacitor. Thus, we estimate  $U_{switch}$  to be  $\approx 6$  fJ and  $\approx 130$  aJ for the 1x2 switch ( $V_{Drive} = 1.4$  V) and 1x1 switch ( $V_{Drive} = 0.2$  V), respectively. Please note these driving voltages result in complete switching between constructive and destructive interference (ER > 20 dB), while other works reporting attojoule switching energy are limited to ER  $\approx 3$  dB (41). Overall, the power consumption ( $U_{switch} \cdot f_{switch}$ ) of the 1x2 switch and 1x1 switch is  $\approx 600$  nW and  $\approx 12$  nW, respectively, assuming future switching frequencies of 100 MHz.

Further optimization can be achieved by reducing the device capacitance. The device's capacitance consists of two parallel capacitors. One is formed by the alumina post at the center of the disc  $(C_{\text{post}} \approx 2.4 \text{ fF})$ , while the other is formed by the air gap that encircles the alumina post  $(C_{\text{gap}} \approx 2.3 \text{ fF})$ . Locally doping the silicon below the air gap (and not under the alumina post) would omit the alumina capacitor, and thus lower the device capacitance by a factor of 2. Furthermore, the device radius can be reduced by a factor of two without diminishing device performance. This reduces *C* by an additional factor of four and could give rise to an attojoule device capacitance.

Furthermore, the small device capacitance and driving voltage enable operation powered by a single gate transistor. Please, note the energy consumption of single gate transistors ranges from a few femtojoule down to hundreds of attojoule (40). Indeed, other switching effects are faster, however, we want to emphasize here that the electrical current (I) of a low power transistor  $(I_{\text{transistor}})$  is on the order of a few microamperes. This results in a charging time  $(t_{\text{charging}} \approx C_{\text{device}}/I_{\text{Transistor}})$  of few nanoseconds to hundreds of picoseconds. And taking full advantage of fast (i.e. few picoseconds) electro-optic approaches (e.g. Pockels effect) requires multiple high power transistors operated in parallel.

#### VII. Fabrication

The devices were fabricated on two silicon-on-insulator chips (340 nm Si device layer / 2  $\mu$ m SiO<sub>2</sub> buried oxide / 725  $\mu$ m Si substrate), with one chip having an intrinsic  $\approx 10^{15}$  cm<sup>-3</sup> p-type boron doping and the other  $\approx 10^{18}$  cm<sup>-3</sup> n-type phosphorus doping. The p-doped chip was used for passive optical characterization (e.g. Q-factor dependency versus waveguide-cavity separation). The n-doped chip was used solely for active measurements and to prevent any RC-limitations. In a first step, the silicon waveguides, grating couplers, contact pads with rails and disc resonators were patterned using hydrogen silsesquioxane (HSQ) resist with electron beam lithography (EBL: 100 keV) and etched using inductively-coupled-plasma reactive-ion-etching (ICP-RIE). The waveguides were fully etched through the  $\approx 340$  nm Si layer, whereas the  $\approx 70$  nm-high Si contact

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pad and rail were partially etched using a second EBL and ICP-RIE step with AR-N as a resist. The electrical contact to the Si rail was deposited with electron-beam physical-vapor-deposition (EBPVD) of either  $\approx 80$  nm Au with  $\approx 2$  nm Ti adhesion layer for the p-doped chip or  $\approx 80$  nm Ni for the n-doped chip. Both steps used EBL with a polymethyl methacrylate (PMMA)/ methyl methacrylate (MMA) double layer resist and lift-off processes. Additionally, the Ni-Si contact was 5 annealed in a rapid thermal annealing system to form a silicide (90 s at 450°C). In a next step,  $\approx$  40 nm of Al<sub>2</sub>O<sub>x</sub> was grown over the whole chip using atomic layer deposition (ALD) to define the dielectric post height. The  $\approx$  40 nm-thin Au top disc of the resonator was deposited using the previously mentioned EBL, EBPVD and lift-off process. To contact the Au discs on top of the resonators, suspended air bridges and contact pads were built of  $\approx 500$  nm Au/  $\approx 5$  nm Ti (EBL, 10 EBPVD, lift-off), using a sacrificial spacer layer below the bridges. Finally, the discs and bridges were released by chemical wet etching of the Al<sub>2</sub>O<sub>x</sub> with phosphoric acid and subsequent critical point drying to avoid irreversible sticking of the discs. The etch duration was calibrated such that it resulted in the desired undercut beneath the Au disc (typically  $\approx 1 \,\mu$ m). The short under etch is beneficial as it reduces the upbending of the gold foil due to intrinsic stress. This normally 15 constitutes a challenge for large-scale structures.

Residual stress induced an upwards bending of  $\approx 10 \text{ nm}$  to 20 nm of the gold foil during the fabrication of the p-doped chip. The n-doped chip did not suffer from the same bending because an additional ALD layer of 5 nm SiO<sub>x</sub> was grown on top of the Au disc. This counteracted the previously induced stress of the Al<sub>2</sub>O<sub>x</sub>-Au interface at the bottom side of the Au disc. The SiO<sub>x</sub> was removed afterwards by wet etching with hydrofluoric acid. However, this adjustment limited the disc resonator yield to < 5% as the devices were more susceptible to pull-in events triggered by chip handling during fabrication. This prevented us from actively testing multiple 1x2 switches sharing the same through port waveguide. Future optimization of the fabrication process promises to overcome this issue. The cross-section shown in Fig. 2B was prepared by focused-ion-beam milling. Low ion currents were required to prevent destruction of the thin Au disc due to stress-induced bending by the gallium ions.

# VIII. Electro-optic Characterization

The optical response of the hybrid resonators was determined by utilizing cut-back measurements of similar photonic waveguide circuits that were not coupled to a resonator. The passive photonic 30 circuit elements used to couple and guide light comprised of air-cladded TM grating couplers (pitch: 680 nm / duty cycle: 0.63 / etch depth: 140 nm / efficiency per coupler: -14 dB) and photonic waveguides (width: 450 nm / height: 340 nm / propagation loss (n-doped): >1 dB/mm) of equal dimensions but without the hybrid resonators. The spectral responses were obtained by using tunable laser sources electrically connected to an optical power meter (power range 1 pW to 35 10 mW) to trigger the measurements while performing wavelength sweeps (1465 nm to 1635 nm). The optical input power to the chip was limited to  $\approx$  -0.3 mW to ensure that thermal tuning of the resonances was suppressed. Thermal tuning of the resonances could be observed for optical input power of > 10 mW for the high Q-devices (gap  $\approx 55$  nm). Typical thermal tuning of photonic and plasmonic disc and ring resonators is 200 pm/K - 300 pm/K. This is well below the voltage 40 tunability of the NOEMS switches (10 nm/V) enabling a "power-less" thermal compensation if required in future applications.

The static electro-optic characterization was performed by using the same optical setup-up in tandem with pico-probes to electrically connect the devices to a precision voltage source via the  $\approx 50 \ \mu m$  by  $\approx 50 \ \mu m$  contact pads. The ground contact was chosen to be on the top Au disc and

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the signal was applied to the bottom Si disc via the rail. The pull-in voltage was determined by increasing the applied bias voltage stepwise and measuring the optical spectrum in between steps. Upon pull-in the Ohmic loss increased by orders of magnitude. This drastically reduces the ER of the resonance because the critical coupling condition is no longer full-filled. No static current (< 1 nA) was measured prior to pull-in, confirming the low-power consumption of electro-optomechanical switches.

The dynamic electro-optic response (Fig. 3A) was characterized by using an RF-synthesizer (frequency range 9 kHz to 40 GHz;  $P_{output} \approx 60 \text{ mV}$ ) in combination with a high-speed photodiode (InGaAs  $f_{3dB} = 5$ GHz). Furthermore, an erbium-doped-fiber amplifier was used to amplify the modulated light to match the power requirements of the photo-diode. The laser wavelength was fixed to the quadrature (3dB) point of the corresponding optical resonance. The advanced driving signal (Fig. 3B) was generated with an arbitrary wave form generator (frequency range: DC to 30 MHz). All the above-mentioned experiments were performed under ambient atmosphere.

# 15 IX. Parameters

Two device generations have been fabricated. In the following we summarize the design parameters and material properties used in the calculations/simulations.

Parameters		
doping	10 <sup>15</sup> cm <sup>-3</sup> p-doped	10 <sup>18</sup> cm <sup>-3</sup> n-doped
l	≈500 nm and ≈ 1000 nm	≈1000 nm
t	≈ 40 nm	≈ 40 nm
Z <sub>0</sub>	≈ 55 nm	≈ 35 nm
R	≈ 2000 nm	≈ 2000 nm
W	≈ 50 nm-190 nm	≈ 120 nm -140 nm
h <sub>Si,Disc</sub>	≈ 340 nm	≈ 340 nm
n <sub>doping</sub>	p-type: ≈ 10 <sup>15</sup> cm <sup>-3</sup>	n-type: 5x10 <sup>18</sup> cm <sup>-3</sup>
Electrodes (Signal/Ground)	Gold/Gold	Gold/Nickel
h <sub>Si,WG</sub>	≈ 340 nm	≈ 340 nm
W <sub>Si,WG</sub>	≈ 300 nm	≈ 300 nm

Experiment

#### Simulations

$arepsilon_{ m Si}$	11.9
$\mathcal{E}_{Air}$	1
$\varepsilon_{\rm SiO_2}$	2.07

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$\mathcal{E}_{\mathrm{Au}}$	Ref. ( <i>13</i> )
$\varepsilon_{Al_2O_3}$	3.05
$E_{ m youngmodule,Au}$	70 GPa
$ ho_{ m Au}$	19000 kgm <sup>-3</sup>

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