Monolithically integrated MEMS cantilevers with embedded waveguides for visible light beam-scanning

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Abstract

Beam-forming in the visible spectrum has important applications in, for example, fluorescence microscopy, quantum information processing, and holographic displays. For infrared light, photonic integrated circuit (PIC) beam-scanners are often optical phased arrays (OPAs) that steer a light beam using wavelength tuning and/or phase shifters. For visible light, OPAs are significantly more challenging due to the lack of wideband tunable laser sources, lower efficiency phase shifters, and need for smaller feature sizes. Here, we demonstrate side-lobe-free, wideband visible spectrum (λ = 410 – 700 nm) beam steering by electro-thermally actuated micro-cantilevers with embedded silicon nitride waveguides and grating couplers. The devices achieved a scan range of 30.6° with only 31 mW of electrical power for one-dimensional scanning and a 12°×24° field of view with 46 mW of electrical power for two-dimensional scanning. The devices were monolithically integrated in an active visible light photonic platform on 200-mm silicon wafers. Due to their scalability, ultra-compactness, and wavelength-independent scan range, these beam-scanners offer a unique approach for efficient chip-scale light projection.

Introduction

Reconfigurable optical beam patterns and optical beam scanning in the visible spectrum are essential in emerging applications such as implantable brain probes for optogenetics and fluorescence microscopy [1-7], ion/atom manipulation in quantum information processing [8,9], optical tweezers [10-13], and displays
Traditionally, optical beam scanning is achieved by discrete components, such as galvo-scanners, micro-electromechanical systems (MEMS) mirrors [20-22], or acousto-optic deflectors [23]. Recently, optical phased arrays (OPAs) using silicon (Si) photonic integrated circuit (PIC) technology have emerged as a promising solution for integrated chip-scale beam scanners. In an OPA, beam forming is controlled by a phase gradient along the steering direction [24]. Not only can PIC beam scanners minimize size and power consumption, its co-integration with other functionalities, such as photodetectors and lasers, onto a single chip can substantially simplify packaging and reduce costs [24-34]. To date, OPAs have predominantly been demonstrated in the infrared (IR) spectral region, and steering is achieved by wavelength sweeping [25,26] and/or adjusting the phase-shifters connected to the emitters [27-29]. These two mechanisms are used together for two-dimensional (2D) beam steering [30-34]. However, in the visible spectrum, OPAs are challenging to implement due to the lack of compact continuous-wave wavelength-tunable lasers and the lower efficiency of phase shifters at visible wavelengths. Furthermore, the wavelength degree of freedom cannot be used for beam scanning in applications which must use specific wavelengths, such as displays and excitation of atomic transitions. Another major obstacle to visible spectrum OPAs is that the half-wavelength pitch criterion for single-lobe emission [24] is hard to satisfy without adding significant crosstalk or reducing the minimum feature size. Recent demonstrations of visible light OPAs have used an external super-continuum source coupled with a tunable filter [35] or a rotation stage for scanning the beam in the second dimension while requiring high on-chip driving powers of 2 W [36]. These approaches are difficult to fully integrate into chip-scale systems in the foreseeable future.

Here, for the first time to our knowledge, we demonstrate visible spectrum 1D and 2D single-lobe beam scanner PICs with no wavelength tuning. The scanners consist of MEMS cantilevers with integrated silicon nitride (SiN) waveguides and grating couplers. The electrical drive power to cover the full scanning range of each axis was < 31 mW, about 2 orders of magnitude lower than previously reported visible light PIC beam scanners [36]. When resonantly driven, a scanning rate of the order of 10 kHz was achieved. In contrast to the recent Si waveguide MEMS phase-shifters and beam scanners [37, 38], our approach does not require waveguiding in Si nor electrically conductive Si. Our cantilevers are agnostic to the waveguide core material, hence applicable to SiN waveguides, which are optically transparent at visible wavelengths. By using standard fabrication processes in Si photonics foundries, our cantilever devices were monolithically integrated within a foundry-manufactured visible spectrum PIC platform on 200-mm Si (Figures 1a,b) in which other components including low-loss wideband edge couplers, high quantum efficiency waveguide photodetectors, low crosstalk junctions, and efficient thermo-optic phase shifters have been reported elsewhere [39-42]. Due to the mechanical nature of the actuation, identical steering ranges were achieved for wavelengths between 410 to 700 nm. Because our approach does not require phase shifters or wavelength tuning, excluding the laser source, our PICs possess the smallest footprint.
amongst all chip-scale beam scanners to date. These versatile MEMS cantilevers can also be easily implemented in generic silicon-on-insulator (SOI) photonic platforms with heaters, deep trenches, and an undercut step, opening new directions for compact beam-scanning PICs.

Results

Operation principle and architecture

Two types of beam scanner designs were realized: (1) a rectilinear MEMS cantilever (Figures 1c, e), which steered the output beam only in the longitudinal direction, and (2) an L-shaped singly clamped cantilever (Figures. 1d, f) capable of beam steering in both the longitudinal and transverse directions via two control voltages. In both cases, light was guided in a SiN waveguide embedded in the cantilever and terminated with an output grating coupler at the distal end. The grating coupler was 10 µm wide and 25 µm long, consisting of fully-etched 150 nm thick SiN teeth with a period of 440 nm. It had an average loss of 5.2 dB at wavelengths between 410 to 700 nm (see Supplementary Section 1 for details on the grating couplers). The simulated grating coupler emission full-width at half-maximum (FWHM) beam widths were 0.78° longitudinally and 2.2° transversely, and the measured FWHM widths were 1.4° and 3.1°, respectively. Figure 1a shows the PIC platform cross-section with the cantilever delineated. The suspended structure was formed by a deep trench SiO₂ etch followed by an isotropic Si undercut. To actuate the cantilever, we created an electro-thermal bimorph using a 2 µm-thick aluminum (Al) layer atop a 2.5 µm thick SiO₂ layer (see Supplementary Section 2 for the layer thickness design). Embedded resistive titanium nitride (TiN) strips heated the cantilever with applied voltages as shown in the circuits in Supplementary Section 3 Fig. S3. Due to the greater thermal expansion of Al compared to SiO₂, the cantilever bends downwards with increasing temperature.

Rectilinear Cantilevers

Figure 1c illustrates the schematic of the rectilinear cantilever for 1D scanning. The width of the cantilever tapered from 30 µm at the proximal end to 15 µm at the distal end. This shape strikes a balance between robustness and thermal efficiency, as a wider cantilever base is less likely to crack and has better performance under high stress, while a narrower cantilever width linearly reduces the volume to be heated, and thus higher temperatures could be reached for the same applied electrical power, $P_e$. We designed rectilinear cantilevers with four different lengths ($L_{can}$) of 300, 500, 800, and 1000 µm, with resistances of the TiN ($R_{TiN}$) heaters 430, 480, 550, and 680 Ω respectively. The choice of cantilever length is a trade-off between the steering range and actuation time constant. As will be shown, while the longest cantilever achieved the largest steering range, the shortest devices were faster due to a lower thermal time constant.
In the absence of applied electrical power, \( P_e = 0 \text{ mW} \), the cantilever bent upwards due to the initial stress between the metal and oxide, which were deposited at different temperatures. A scanning electron micrograph (SEM) of the rectilinear cantilevers captured at a 45° tilt shows this expected initial upwards bending (Figure 1e). The simulated angular steering range as a function of \( P_e \) at \( L_{\text{can}} = 500 \mu\text{m} \) is shown in Figure 2a. The top and bottom insets of Figure 2a illustrate the downwards displacement of the cantilever tip under applied power. The simulations predict an angular scan range of 17.6° and 29.5° respectively for the 500 and 1000 \( \mu\text{m} \) long cantilevers at \( P_e = 30 \text{ mW} \).

**L-Shaped Cantilevers**

Figure 1d shows a schematic of the L-shaped cantilever for 2D beam scanning. The design has two primary arms that tilt the grating coupler in the transverse direction under a control voltage \( V_\varphi \), and a secondary arm which tilts the beam in longitudinal direction with a control voltage \( V_\theta \). An SEM image of the device is shown in Figure 1f. The primary and secondary arms were 500 and 600 \( \mu\text{m} \) long, respectively, with a constant width of 20 \( \mu\text{m} \). The SiN waveguide in the cantilever had a 40 \( \mu\text{m} \) bend radius to connect the input to the grating coupler at the cantilever tip. Figures 2b and 2c show the simulated beam steering along the \( \varphi \)-axis with respect to applied power to the primary arms \( (P_{e,\varphi}) \), and along \( \theta \)-axis with respect to electrical power applied to the secondary arm \( (P_{e,\theta}) \), respectively. Thermal crosstalk between the primary and secondary arms causes a slight \( \theta \)-axis tilt under \( P_{e,\varphi} \), and vice-versa (see Supplementary Section 3), but is sufficiently small to allow for independent control of the beam direction along the two angular axes. The simulations predict a maximum beam steering of 23.7° along longitudinal direction under \( P_{e,\theta} = 20 \text{ mW} \), and 13.8° under \( P_{e,\varphi} = 20 \text{ mW} \).

**Experimental Results**

1D beam-steering with the rectilinear cantilevers

The far-field radiation pattern was captured using the setup described in the Methods Section and illustrated in Figure 3a, where the input laser light is coupled from a multi-wavelength laser source via a single-mode fiber onto the chip. Unless otherwise stated, the input polarization was set to transverse-electric (TE) mode to maximize the optical transmission of the grating coupler. The recorded far-field image of the grating output shows a divergence angle of 1.4° in the longitudinal direction (\( \theta \)) and 3.1° in the transverse direction (\( \varphi \)) at \( \lambda = 488 \text{ nm} \). As the beam steering range is independent of the laser wavelength due to the mechanical nature of the actuation, \( \lambda = 488 \text{ nm} \) was chosen as a representative wavelength for measurements unless otherwise stated. Figure 3b visualizes the extent of the steering range of the four rectilinear cantilevers, by capturing an overlay of the far-field images at 0 mW (right beams) and 20 mW (left beams) applied powers.

The measured beam steering angles as a function of the applied electrical power is shown in Figure 3c. We measured maximum beam scanning ranges of 11°, 17.6°, 22.6° and 30.1° with 30 mW applied...
electrical power respectively for 300, 500, 800, and 1000 µm long cantilevers, in good agreement with simulated values (dashed lines). This corresponds to ~ 8, 12, 16, and 21 resolvable points at λ = 488 nm, respectively for the shortest to the longest cantilevers. The power efficiency in terms of $\frac{d\theta}{dP_e}$ of the 1000 µm cantilever was 1°/mW and was lower for shorter cantilevers due to the heat sinking effect of the metal contacts, which reduced the effective temperature in the proximal end of the cantilever. The cantilevers contacting the bottom Si substrate resulted in the abrupt change of the efficiency slopes seen in Figure 3c (see Supplementary Section 3 for a detailed analysis).

The scanning rate was mainly limited by their thermal time constant. We measured the time response of the devices by applying a 10 mW pulsed signal with various duty cycles and recording the far-field pattern (see Methods Section and Supplementary Section 4). Figures 3d and 3e respectively show the measured rise and fall time responses (10% to 90%) of the 300 µm long cantilever (see Figures S4 and S5 for the time response of the other beam scanners). We measured an average response time of 1.2, 2.6, 4.1 and 4.7 ms, respectively, for the shortest to the longest cantilevers. These response times are comparable to the fastest liquid crystal switches [43]. While millisecond time responses are sufficient in some applications, such as neural stimulation, in other applications, such as LiDAR, a shorter response time is preferrable. To reach higher scanning rates, we drove the cantilevers at their resonance frequencies, beyond the electro-thermal time-constant limit (Figure 3f). The resonance frequencies of the devices were 5.7, 11.8, 24.8, and 77.4 kHz respectively for 1000, 800, 500, and 300 µm long cantilevers. At these frequencies, a maximum beam scan range of 9.8°, 11.3°, 10.4°, and 12° was achieved under 20 mW of applied electrical power, respectively.

2D beam steering with the L-shaped cantilevers
The measured angular scan ranges of the L-shaped cantilever are shown in Figures 4a and 4b, respectively in the longitudinal and transverse directions. The lengths of the primary and secondary arms were respectively 500 and 600 µm. An angular steering range of 24.0° and 12.2° was achieved under maximum applied electrical power of 23 mW respectively at θ-axis and φ-axis. To illustrate the 2D angular range of the steering in Fourier space, we applied two different signals to each set of arms. A 120 Hz sinusoidal electrical signal with a peak-to-peak voltage of 4 V and a DC offset of 2 V was applied to the secondary arm, while a 30 Hz electrical signal with a peak-to-peak voltage of 3 V and DC offset of 1.5 V was applied to the primary arms. The corresponding far-field image of the output beam captured over a 33 ms exposure time is shown in Figure 4c, covering a range of ~ 24°×12° in Fourier space.

The 10-90% rise time of the primary and the secondary arms were 4.3 and 4.7 ms, but faster beam steering is possible on resonance. Figure 4d shows the simulated first (left) and second (right) resonance modes of the L-shaped cantilevers, which were at 6.9 kHz and 14.3 kHz, respectively. At the first resonance,
both the secondary and the primary arms were in-phase, simultaneously moving upwards (or downwards) thus moving the Fourier image of the far-field beam in the negative (or positive) directions of the $\theta$- and $\phi$-axes. Experimentally, the first resonance frequency was found to be 7.6 kHz, with its far-field radiation pattern shown in Figure 4e. At the second resonance frequency, measured to be 17.4 kHz, the displacement of the primary and secondary arms had a $\pi$-phase difference, resulting in the far-field pattern in Figure 4f. To excite the resonances, a pulsed voltage with an average power of 10 mW was applied to the primary arms of the L-shaped cantilever. These resonances can be excited in linear superposition, as shown in Figure 4g.

As a proof-of-concept demonstration, we used the cantilever to project a 2D image of our department name “NINT” (Figure 4h). The applied voltages to the primary and secondary arms were controlled by a computer to steer the beam in the Fourier space in the desired directions. The images were generated without controlling the laser output power, and the pattern formation solely relied on the actuation of the beam. The refresh rate of the image was set to 30 Hz over a 33 ms exposure time. The experimental results of both types of devices are summarized in Table S1.

Finally, we characterized our beam scanner in cryogenic conditions, which are sometimes necessary for quantum and space-borne applications. The L-shaped cantilever was tested in a cryostat at temperatures as low as 10 K (see Methods and Figure S7 for details on the cryogenic unit). By reducing the temperature, the cantilever was further bent upwards due to the higher expansion coefficient of Al compared to SiO$_2$. Therefore, the initial angle of the output beam was increased in both $\theta$ and $\phi$ directions, as shown in Figure 5a, where the simulated initial angle (lines) and the measured values of the tilt (dots) are plotted. The simulated scan range of the L-shaped cantilever versus the applied electrical power in $\theta$ and $\phi$ directions are respectively shown in Figures 5b, c. The dashed line shows the simulated scan range at room temperature for comparison. The experimental results (yellow dots in Figures 5b, c) are in a good agreement with the simulated tilt of the cantilever. Due to the limited field-of-view of the cryogenic setup, the experimental observations are limited to angles less than 20°. The cantilever was driven at resonance frequency for ~7 million cycles at 10 K with no observable degradation. Thermal simulations show that the heat is localized to the cantilever device (Supplementary Section 6). The calculated half-decay length of the temperature, defined as the distance where the difference between the local temperature and the cryostat setting is 50% of the maximum, is 20 $\mu$m for 26 mW of applied power, and the temperature on the PIC drops to below 11 K within 600 $\mu$m distance from the edge of the cantilever.

**Discussion**

These reported ultra-compact, power efficient, monolithically integrated MEMS cantilevers are, to the best of our knowledge, the first side-lobe free 2D beam scanners for wavelengths spanning the visible spectrum
Our devices achieved a 2D scan range of 24°×12° with arm lengths of ~ 500 μm with only 46 mW of drive power. The beam scanning was achieved without wavelength-tuning or using phase shifters at scan rates of tens of kHz on resonance. The scanning range and power emission of the devices were unchanged after one billion cycles on resonance in ambient conditions.

In comparison with prior art, our device offers unique advantages (see Supplementary Section 7 for a comparison chart). Our approach is distinct from the photonic-MEMS phase-shifters using Si waveguides [37,38], since we do not require highly doped Si. It also achieves a single-lobe output beam without wavelength tuning, which has not yet been possible with visible spectrum OPAs [15,36,44]. The power consumption of the cantilever beam scanners was roughly 2 orders of magnitude lower than visible wavelength OPAs which required ~2 W [36]. Our beam scanners are also distinct from previous MEMS-tunable grating couplers for spectral tuning and fiber-to-chip coupling in the infrared [45-49]. First, we have achieved a larger 1D scan range (30° in 1D vs. 5.6° in [48]) and 2D scanning for the first time [49]. Second, our design displaces the entire grating emitter rather than tuning the grating period and apodization, so the emission profile minimally deteriorates during cantilever actuation. For example, in [48], due to the wide angular beam width, the number of resolvable points is only about 0.62. In contrast, the number of resolvable spots of the L-shaped cantilever here is about 66, limited by the divergence angle of the grating emission (1.4° in θ-direction and 3.1° in φ-direction).

The cantilever beam scanner performance can be improved in a few ways. Our scan range was limited by the substrate, so it can be increased by making the undercut deeper. To increase the number of resolvable spots, the divergence angle of the output beam along the propagation direction could be significantly decreased by using weaker and longer gratings (Supplementary Section 5). To reduce the power consumption, we may consider electro-static or piezoelectric actuation instead of electro-thermal actuation [50]. Improvements to the cantilever mechanical actuation or architecture may draw inspiration from the field of planar compliant mechanisms.

In summary, the electro-thermally actuated cantilevers demonstrated here open exciting avenues for photonic beam forming. The cantilever approach decouples the design of the scan range from the light emitter. Beyond grating couplers as emitters, edge couplers, sub-wavelength waveguides, OPAs, and meta-surfaces can also be considered. The deformation along the cantilever may also be exploited as a tuning method or sensor via embedded waveguide devices. The cantilever fabrication can be incorporated into any photonics platform possessing a top metal layer, dielectric clad waveguide, heater, and undercut. Taken together with their monolithic integration in a full photonic platform [39-42], our MEMS cantilever beam scanners can enable new beam forming photonic integrated circuits.
Methods

Numerical simulations

Electro-thermomechanical simulations of the MEMS structures were performed using finite element method (FEM) in COMSOL Multiphysics to find the resonance modes of the cantilevers, as well as their displacements with respect to the applied voltage, and their time response. The Young’s modulus of SiN, TiN, Al, and SiO$_2$ were assumed to be 250, 500, 70, and 73 GPa and their Poisson ratio was set to 0.23, 0.25, 0.33, and 0.17, respectively. For thermal simulations, the Si substrate and electrical pads were set to a constant temperature of 293 K. The thermal expansion coefficients of Al and SiO$_2$ were set to $23 \times 10^{-6}$ and $5.5 \times 10^{-7}$ 1/K, respectively with thermal conductivities of 238 and 1.4 W/mK. Optical simulations of the grating couplers were carried out using 3D finite difference time domain (FDTD) method in Lumerical software. The refractive indices of SiN and SiO$_2$ were assumed to be 1.81 and 1.46 at $\lambda = 532$ nm.

Device fabrication

The devices were fabricated on 200-mm diameter Si wafers at Advanced Micro Foundry (AMF) as part of our visible-light photonic integrated circuit platform. The fabrication process included steps to implement other devices in this platform. It started with ion implantation and partial etching of the Si substrate to define the photodetectors [40]. Next, an SiO$_2$ layer as the bottom cladding of the waveguides was formed using PECVD. Then a SiN layer with the targeted thickness of 150 nm was deposited atop the oxide layer in a PECVD process. The SiN waveguides were then defined by 193nm deep ultraviolet (DUV) lithography followed by a reactive ion etching (RIE) step. Additional SiO$_2$ and SiN deposition and patterning steps were performed to define a second 75 nm thick SiN waveguide layer to form low-loss bi-layer edge couplers [39]. The layers were planarized using chemical mechanical polishing. Next, a TiN layer was deposited and patterned to be used as a heater, followed by two Al layers and oxide openings for bond pads. The top Al layer thickness was 2 µm to enhance the strain and thus the initial displacement of the cantilevers. Finally, in order to suspend the MEMS structures, and also to form the SiO$_2$ bridges in our thermal phase shifters [42] a deep trench followed by undercut etching of the silicon were performed.

Room temperature measurement setup

Figure 2a shows the experimental setup for the device characterization. The setup captured the emission pattern in real and Fourier space imaging modes. The far-field output was collected by a high-numerical-aperture objective lens (with 20× magnification, NA = 0.42, and effective focal length = 10 mm) to project the far field radiation pattern into the Fourier plane, where it was captured by a CMOS camera. We utilized an uncollimated white light source to visualize the sample surface (not shown in Fig. 2a). For simultaneous
visualization of the near-field and facilitating the alignment procedure, a beam splitter diverted half of the radiated beam to a second CMOS camera. Light from a multi-wavelength laser source (Coherent OBIS Galaxy) was edge-coupled to the chip through a single mode fiber (Nufern S405-XP) with an inline polarization controller. The polarization was set to transverse-electric (TE) mode to maximize the optical transmission of the grating coupler.

**Time response measurements**

To measure the temporal response of the cantilevers, we coupled light into each device and recorded the far-field radiation under an applied periodic electrical pulse with peak power of 10 mW and varying duty cycles. In the case of a 50% duty cycle, provided that the period of the square pulse (T) was much longer than the rise/fall time of cantilever (t), the maximum displacement of the far-field beam would be equal to the results for a DC voltage (the first far-field image in Fig. S4a). By reducing the duty cycle to a level below the rise time of the device, the emitted beam trajectory became shorter, allowing us to determine the transient response of the device. Measurements of the far-field trajectories are shown in Supplementary Section 4.

**Cryogenic measurement setup**

The cryostat was taken to a vacuum at a pressure of < $10^{-4}$ mbar and the temperature was reduced by liquid Helium (He) cooling. The temperature of the cold head was controlled using a 100 W built-in heater connected to an automatic PID controller which could also set the He flow using a magnetic valve. To establish the electrical connectivity, the PIC was mounted on a custom printed circuit board (PCB) using a thermally conductive epoxy (Loctite 84-1LMIT1) and then wire bonded to a PCB (Fig. S7). The wires as well as the optical fiber were routed inside the chamber via electrical and optical high-vacuum fit-through adaptors. The optical fiber was attached on top of the PCB using a transparent optical adhesive (DYMAX OP-4-20632) and cured with UV light while being actively aligned to the input edge coupler.

**Data Availability**

The data that support the findings of this study are available from the authors on reasonable request; see author contributions for specific data sets.

**References**

1. Boyden, E. S. Optogenetics and the future of neuroscience. *Nat. Neurosci.* **18**, 1200-1201 (2015).
2. Cobar, L.F., Kashef, A., Bose, K. *et al.* Opto-electrical bimodal recording of neural activity in awake head-restrained mice. *Sci. Rep.* **12**, 736 (2022)
3. Sacher, W. D. et al. Implantable photonic neural probes for light-sheet fluorescence brain imaging. *Neurophotonics* 8, 025003 (2021).

4. Mohanty, A., Li, Q., Tadayon, M.A. et al. Reconfigurable nanophotonic silicon probes for sub-millisecond deep-brain optical stimulation. *Nat. Biomed. Eng.* 4, 223–231 (2020).

5. Moreaux, L. C. et al. Integrated neurophotonics: toward dense volumetric interrogation of brain circuit activity—at depth and in real time. *Neuron* 108, 66-92 (2020).

6. Segev, E. et al. Patterned photostimulation via visible-wavelength photonic probes for deep brain optogenetics. *Neurophotonics* 4, 011002 (2016).

7. Buzsáki, G. et al. Tools for probing local circuits: high-density silicon probes combined with optogenetics. *Neuron* 86, 92-105 (2015).

8. Mehta, K. K., Zhang, C., Malinowski, M., Nguyen, T. L., Stadler, M., & Home, J. P. Integrated optical multi-ion quantum logic. *Nature* 586, 533-537 (2020).

9. Niffenegger, R. J. et al. Integrated multi-wavelength control of an ion qubit. *Nature* 586, 538-542 (2020).

10. Yang, Y., Ren, Y., Chen, M., Arita, Y., & Rosales-Guzmán, C. Optical trapping with structured light: a review. *Adv. Photonics* 3, 034001 (2021).

11. Dienерowitz, M., Mazilu, M., Reece, P. J., Krauss, T. F., & Dholakia, K. Optical vortex trap for resonant confinement of metal nanoparticles. *Opt. Express* 16, 4991-4999 (2008).

12. Suarez, R. A. et al. Experimental optical trapping with frozen waves. *Opt. Lett.* 45, 2514-2517 (2020).

13. Rodrigo, J.A., Angulo, M. & Alieva, T. Tailored optical propulsion forces for controlled transport of resonant gold nanoparticles and associated thermal convective fluid flows. *Light Sci. Appl.* 9, 181 (2020).

14. Smalley, D. E et al. A photophoretic-trap volumetric display. *Nature* 553, 486-490 (2018).

15. Notaros, J., Raval, M., Notaros, M., and Watts, M. R. Integrated-phased-array-based visible-light near-eye holographic projector. *Conference on Lasers and Electro-Optics*, paper STu3O.4 (2019).

16. Chen, H., Weng, Y., Xu, D., Tabiryan, N. V., & Wu, S. T. Beam steering for virtual/augmented reality displays with a cycloidal diffractive waveplate. *Opt. Express* 24, 7287-7298 (2016).

17. Raval, M., Yaacobi, A., & Watts, M. R. Integrated visible light phased array system for autostereoscopic image projection. *Opt. Lett.* 43, 3678-3681 (2018).

18. Poulton, C. V. et al. Large-scale silicon nitride nanophotonic phased arrays at infrared and visible wavelengths. *Opt. Lett.* 42, 21-24 (2017).

19. Park, S. G., Hong, J. Y., Lee, C. K., Miranda, M., Kim, Y., & Lee, B. Depth-expression characteristics of multi-projection 3D display systems. *Appl. Opt.* 53, G198-G208 (2014).

20. Sun, J. et al. 3D in vivo optical coherence tomography based on a low-voltage, large-scan-range 2D MEMS mirror. *Opt. Express* 18, 12065-12075 (2010).
21. Zhang, X., Koppal, S. J., Zhang, R., Zhou, L., Butler, E., & Xie, H. Wide-angle structured light with a scanning MEMS mirror in liquid. *Opt. Express* **24**, 3479-3487 (2016).

22. Wang, D., Watkins, C., & Xie, H. MEMS mirrors for LiDAR: a review. *Micromachines* **11**, 456 (2020).

23. Yuan, Y., Yang, S., & Xing, D. Preclinical photoacoustic imaging endoscope based on acousto-optic coaxial system using ring transducer array. *Opt. Lett.* **35**, 2266-2268 (2010).

24. Heck, M. J. R. Highly integrated optical phased arrays: photonic integrated circuits for optical beam shaping and beam steering. *Nanophotonics* **6**(1): 93-107, (2017).

25. Dostart, N. et al. Serpentine optical phased arrays for scalable integrated photonic lidar beam steering. *Optica* **7**, 726-733 (2020).

26. Van Acoleyen, K., Bogaerts, W., & Baets, R. Two-dimensional dispersive off-chip beam scanner fabricated on silicon-on-insulator. *IEEE Photon. Technol. Lett.* **23**, 1270-1272 (2011).

27. Sun, J., Timurdogan, E., Yaacobi, A. et al. Large-scale nanophotonic phased array. *Nature* **493**, 195–199 (2013).

28. Fukui, T. et al. Non-redundant optical phased array. *Optica* **8**, 1350-1358 (2021).

29. Aflatouni, F., Abiri, B., Rekhi, A., & Hajimiri, A. Nanophotonic projection system. *Opt. Express* **23**, 21012-21022 (2015).

30. Miller, S. A. et al. Large-scale optical phased array using a low-power multi-pass silicon photonic platform. *Optica* **7**, 3-6 (2020).

31. Li, Y. et al. Wide-steering-angle high-resolution optical phased array. *Photonics Res.* **9**, 2511-2518 (2021).

32. Komljenovic, T., & Pintus, P. On-chip calibration and control of optical phased arrays. *Opt. Express* **26**, 3199-3210 (2018).

33. Zadka, M., Chang, Y. C., Mohanty, A., Phare, C. T., Roberts, S. P., & Lipson, M. On-chip platform for a phased array with minimal beam divergence and wide field-of-view. *Opt. Express* **26**, 2528-2534 (2018).

34. Komljenovic, T., Helkey, R., Coldren, L., & Bowers, J. E. Sparse aperiodic arrays for optical beam forming and LIDAR. *Opt. Express* **25**, 2511-2528 (2017).

35. Sun, C. et al. Parallel emitted silicon nitride nanophotonic phased arrays for two-dimensional beam steering. *Opt. Lett.* **46**, 5699-5702 (2021).

36. Shin, M. C. et al. Chip-scale blue light phased array. *Opt. Lett.* **45**, 1934-1937 (2020).

37. Wang, Y., Zhou, G., Zhang, X. et al. 2D broadband beamsteering with large-scale MEMS optical phased array. *Optica* **6**, 557-562 (2019).

38. Zhang, X., Kwon, K., Henriksson, J. et al. A large-scale microelectromechanical-systems-based silicon photonics LiDAR. *Nature* **603**, 253–258 (2022).

39. Lin, Y. et al. Low-loss broadband bi-layer edge couplers for visible light. *Opt. Express* **29**, 34565-34576 (2021).
40. Lin, Y. et al. Broadband high-efficiency SiN-on-Si waveguide photodetectors in a visible-spectrum integrated photonic platform. arXiv preprint arXiv:2203.11775 (2022).

41. Sacher, W. D. et al. Visible-light silicon nitride waveguide devices and implantable neurophotonic probes on thinned 200 mm silicon wafers. Opt. Express 27, 37400-37418 (2019).

42. Yong, Z. et al. Power-efficient silicon nitride thermo-optic phase shifters for visible light. Opt. Express 30, 7225-7237 (2022).

43. Melnyk, O. et al. Fast switching dual-frequency nematic liquid crystal tunable filters. ACS Photon. 8, 1222-1231 (2021).

44. Sacher, W. D., Chen, F. D., Moradi-Chameh, H. et al. Optical phased array neural probes for beam-steering in brain tissue. Opt. Lett. 47, 1073-1076 (2022).

45. Yu, W. et al. MEMS-based tunable grating coupler. IEEE Photon. Technol. Lett. 31, 161-164 (2019).

46. Ho, C. P. et al. Tunable grating coupler by thermal actuation and thermo-optic effect IEEE Photon. Technol. Lett. 30, 1503-1506 (2018).

47. Quack, N., et al. MEMS-enabled silicon photonic integrated devices and circuits. IEEE J. Quantum Electron. 56, 1-10 (2019).

48. Errando-Herranz, C., Le Thomas, N., & Gylfason, K. B. Low-power optical beam steering by microelectromechanical waveguide gratings. Opt. Lett. 44, 855-858 (2019).

49. Errando-Herranz, C. et al. MEMS for Photonic Integrated Circuits. IEEE J. Quantum Electron. 26, 1-16 (2019).

50. Dong, M., Clark, G., Leenheer, A.J. et al. High-speed programmable photonic circuits in a cryogenically compatible, visible–near-infrared 200 mm CMOS architecture. Nat. Photon. 16, 59–65 (2022).

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Fig. 1. **a** The cross-section schematic of the fabricated 200 mm wafer including double-layer edge couplers, visible-light photodetectors, thermal phase shifters and micro-cantilevers. The cantilever cross-section is delineated in the dashed box. **b** Photograph of the wafer and optical micrographs of the fabricated devices. **c** Schematic of the rectilinear cantilever for 1D beam scanning. An integrated SiN waveguide with an output coupling coupler, as well as a TiN heater layer are embedded in the cantilever. **d** Schematic of the L-shaped cantilever for 2D beam scanning in the longitudinal ($\theta$) and transverse ($\phi$) directions. **e** SEMs of rectilinear cantilevers (with 300, 500, 800 and 1000 $\mu$m lengths) and **f** an L-shaped cantilever. Due to film stress, the cantilevers bend upwards in the absence of applied electrical power.
Fig. 2. **a** Simulated angular scan range of the 500 µm long rectilinear cantilever vs. applied electrical power ($P_e$) to the TiN layer; insets show the simulated shape of the cantilever under 0 mW (bottom) and 10 mW (top) applied power. **b** Simulated angular scan ranges of the L-shaped cantilever along $\phi$-axis and **c** $\theta$-axis. The lengths of the primary and the secondary arms are 500 and 600 µm, respectively. The insets show the calculated displacement of the L-shaped cantilever under 10 mW (bottom) and 0 mW (top) electrical power applied to the **b** primary arm and **c** secondary arm.
Fig. 3. a Schematic of the imaging setup using a regular lens L for creating Fourier image, and a beam splitter BS for simultaneous capturing of the near- and far-field patterns, with solid lines and dashed lines showing respectively the near-field and far-field trajectories. b Measured far-field patterns of the grating output at 0 mW (right beams) and 20 mW (left beams) for the four cantilever lengths. The two outputs are overlaid on the same image by applying a 2 Hz step function and capturing the grating far-field output over a 1 second exposure. c Measured (dots) and simulated (dashed lines) beam steering versus the applied DC electrical power to the rectilinear cantilevers. d Fall time and e rise time of the 300 µm long cantilevers. f Far-field images of the rectilinear cantilevers captured at their respective resonance frequencies.
Fig. 4. a (b) Measured steering of the output beam in longitudinal (transverse) direction vs. the electrical power applied to the secondary (primary) arm. c Recorded far field pattern of the L-shaped cantilever output under a drive voltage $V_\theta = 2 \sin(2\pi f_1 t) + 1$ V, where $f_1 = 120$Hz, applied to the secondary arm, and $V_\phi = 1.5 \sin(2\pi f_2 t) + 1$ V, where $f_2 = 30$Hz applied to the primary arms. d Simulated resonance modes of the L-shaped cantilevers at the first and second resonance frequencies. Far-field images of the device recorded at the first (e) and the second (f) resonance frequencies, and superposition (g) of the two resonances. h Images produced by the L-shaped cantilever scanning our department name (“NINT”), demonstrating the potential for image projection.
Fig. 5. a Simulated (solid lines) and measured (dots) values of the initial angle shift with reference to the room temperature in longitudinal (left axis) and transversal (right) directions, without applying electrical power. b (c) Simulated and measured steering of the output beam in longitudinal (transverse) directions.
Supplementary information

1. Simulation and characterization of the grating couplers

The same 25 μm long grating coupler design was used in all the devices presented in the manuscript. The grating coupler was fabricated by fully etching the 150 nm thick SiN waveguide layer. The width of the grating coupler was 10 μm. A 200 μm long adiabatic taper with initial width of 380 nm (waveguide width) and final width of 10 μm (grating coupler width) ensured only the fundamental TE mode was launched into the grating coupler. The lengths of the teeth and grooves were both 220 nm. Figure S1a shows the simulated far-field pattern of the grating output beam at λ = 488 nm. The simulations were performed using three-dimensional FDTD in Lumerical. The far-field pattern along the longitudinal axis (cutline A in Fig. S1a) is plotted in Fig. S1b, and shows a full-width-half-maximum (FWHM) of 0.78° for the output beam. Similarly, the far-field pattern along the transverse direction (cutline B in Fig. S1a) predicts a FWHM of 2.2° as shown in Fig. S1c. As mentioned in the manuscript, the measured far-field image of the grating coupler had a FWHM of 1.4° and 3.1°, respectively in longitudinal and transverse directions. The difference between the simulation and experimental results can be attributed to fabrication variation, as the teeth width of 220 nm was close to the minimum feature size.

Fig. S1: Grating couplers performance. a Simulated far-field pattern of the grating coupler output at λ=488nm. b one-dimensional representation of the output beam along Cutline A (k_x). c One-dimensional representation of the output beam along Cutline B (k_y). d Simulated off-chip transmitted power of the grating coupler normalized to input power. e Simulated full-width-half-maximum (FWHM) of the grating coupler output. f Simulated on-chip optical power remaining at the end of grating coupler normalized to the input power. g Simulated output beam angle of the grating coupler. h Measured optical loss of the grating couplers.
Figure S1d shows the simulated optical power transmission of the grating coupler normalized to the launch power in the wavelength range between 400 and 700 nm. The peaks and valleys in the transmission spectrum of the grating are expected due to the interference between the emitted beam and the back-reflected beam from the substrate. Based on our simulations, the depth of the fluctuations can be minimized by reducing the distance between the grating coupler and the substrate. The simulated FWHM spectrum of the output beam along the propagation direction is shown in Fig. S1e, and is < 1° in the visible spectrum. The ratio of the power remaining at the end of the 25 µm long grating coupler is negligible at λ = 488 nm, as shown in Fig. S1f. The simulated wavelength dependence of the output beam angle is shown Fig. S1g, which is in a good agreement with the measured value of ~ 0.1°/nm. Finally, the measured transmission spectrum of the grating coupler is shown in Fig. S1h, which is slightly different from the simulated transmission spectrum (Fig. S1d) in terms of optical loss at a given wavelength. The discrepancy can be due to the high sensitivity of the optical transmission spectrum to the thickness of the oxide. For this measurement, we used a super-continuum laser source coupled to an external tunable optical filter with 1 nm optical bandwidth. At each wavelength, the polarization of the launch beam is set to TE in order to maximize the transmission of grating coupler.

2. Selection of layer thicknesses for Al-SiO₂ bimorph cantilever in the visible PIC platform

Generally, bending can be induced in a two-material laminate induced by a difference in their thermal expansion coefficients. Bi-material (or bimorph) cantilevers have been extensively studied in context of bi-metallic thermostats, such as the classic result of Timoshenko [S1], and more recently as MEMS actuators using a metal and Si [S2] or SiO₂ [S3-S6]. Bi-material cantilevers can be formed in silicon (Si) photonic platforms by repurposing existing process features. Si photonic platforms typically include a thick top Al layer for electrical routing and bond pads that is on top of the cladding SiO₂. As well, undercut etches removes a portion of the substrate to suspend the oxide and top metal layers. Undercut trenches are typically used for improving thermal isolation for thermo-optic phase shifters [S7] and suspended edge couplers [S8]. Bi-morph cantilevers can be formed by undercutting a cantilever shaped region with top metal covering the cantilever. Such cantilevers naturally incorporate optical design area within the cantilever, enabling novel design opportunities.

The deflection of an Al-SiO₂ bimorph cantilever with equal base and tip width follows the equation [S9]:

\[
d = \frac{cx(1+x)^2}{c^2x^4+4cx^3+6cx^2+4cx+1} \cdot \frac{3\Delta\alpha\Delta T L^2}{t_{Al} t_{SiO_2}},
\]

where \( x = \frac{t_{Al}}{t_{SiO_2}} \) is the ratio of the thicknesses of Al and SiO₂, \( c = \frac{E_{Al}}{E_{SiO_2}} \) is the ratio of the Young’s modulus, \( \Delta\alpha = \alpha_{Al} - \alpha_{SiO_2} \) is the difference of thermal expansion coefficients, \( \Delta T \) is the temperature change from
initial, and $L$ is the cantilever length. Deflection is maximized when the thickness ratio of the metal to elastic material is of a particular ratio [S9]:

$$\frac{t_{Al}}{t_{SiO_2}} = \sqrt{\frac{E_{SiO_2}}{E_{Al}}}$$

For values assumed in our numerical simulations, $E_{Al} = 70$ GPa, $E_{SiO_2} = 73$ GPa, $\frac{t_{Al}}{t_{SiO_2}} = 1.02$. In our platform, due to compromise with other features, this ratio was $\frac{t_{Al}}{t_{SiO_2}} = 0.8$. Based on the deflection equation, this non-optimal ratio is expected to decrease the maximum deflection by 1.5%. The deflection in the measured device will also be limited by the yield strength at the highest temperature reached. Alloys of Al which are CMOS compatible can be investigated to further improve reliability and range of the deflection. Beyond cantilevers, marrying advanced bimorph actuator geometries and structures such as in [S6] with integrated optics functionality may prove to be a fruitful avenue for research.

3. **Thermal simulations of the rectilinear and L-shaped cantilevers**

   3.1 Rectilinear cantilevers

   Figure S2a shows the simulated temperature along the 500 µm long rectilinear cantilever under 10 mW of applied electrical power. The average temperature of the cantilever for a given electrical power is inversely proportional to the cantilever volume. Hence, reducing the thickness and the width of the device would result in a higher power efficiency. However, a narrower width worsens the mechanical robustness of the cantilever, especially for longer devices. Moreover, the thickness of the SiO$_2$ layer was determined according to the functionality of other photonic devices in the platform such as bi-layer directional couplers. Shorter rectilinear cantilevers have a lower power efficiency due to the effective heat-sinking of the metal lines that provide the electrical connections on the clamped side of the cantilever. This is more clearly shown in Fig. S2b where the simulated temperature is plotted along the 500 µm long cantilever for different applied electrical powers.
Fig. S2: Electro-thermal simulation of the rectilinear cantilever. a Simulated temperature distribution on a 500 µm long rectilinear cantilever under applied electrical power of 10 mW. b Calculated temperature along the 500 µm long cantilever under different electrical powers.

3.2 L-shaped cantilevers

In an ideal two-dimensional beam steering system, the steering of the output beam in the longitudinal direction (θ) should be fully independent of the control voltage of the transverse direction (Vφ), and vice versa. For the L-shaped cantilever, this means that the electrical power applied to the secondary arm (Pθ) should not tilt the grating coupler in the transverse direction. However, as shown in Fig. S3a, the temperature of the secondary arm under 10 mW electrical power has a tail extending to the left-hand side primary arm, causing it to slightly bend down and resulting in a parasitic angular tilt (Δφ) in the transverse direction. The resulting Δφ is calculated and shown in Fig. S3b. Nevertheless, the angular tilt in the desired direction (as shown in Fig. 4b, c) dominates the tilt due to the thermal crosstalk between the arms, and thus the beam can still scan over a wide range (Fig. 4d) in Fourier space. As shown in Fig. S3a, the thermal crosstalk between the secondary arm and left-hand side primary arm is higher compared to the right-hand side primary arm, due to the metal connection between these two arms that facilitate electrical connection of the secondary arm. Similarly, applying electrical power to the primary arms results in a slight temperature increase in the secondary arm (Fig. S3c) and the corresponding angular tilt in the longitudinal direction (Fig. S3d).
Fig. S3: Electro-thermo-mechanical simulation of the L-shaped cantilever. a Simulated temperature overlaid on the displaced L-shaped cantilever when electrical power of $P_0 = 10$ mW is applied to the secondary arm. b Simulated angular tilt of the grating coupler in transverse direction under the electrical power applied to the secondary arm. The insets in a and b show the circuit diagrams. c Simulated temperature of the L-shaped cantilever overlaid on its displacement under electrical power of $P_0 = 10$ mW applied to the right-hand side primary arm. d Calculated $\varphi$-axis angle tilt of the grating coupler as a result of the applied voltage to the right-hand side primary arm.

4. Time response measurements

Using the procedure described in the Methods Section of the main manuscript, we measured the temporal response of several cantilevers. Fig. S4a shows a few recorded far-field trajectories of the 800 µm long rectilinear cantilevers, taken with different duty cycles. In the measurements in Fig. S4a, the time period of the signal was set to 20 ms. The measured and simulated time responses of the shortest rectilinear cantilever are shown in the main manuscript (Fig. 3b). Figures S4b, c, d show the extracted rise time and fall times of the 500 µm, 800 µm, and 1 mm long rectilinear cantilevers. In these measurements, the applied square pulse had a period of 20 ms and the duty cycle was varied between 1% to 50%. Since the temporal responses of
the devices were measured at discrete points (blue dots in Fig S4), we fit an exponential curve to the measured values (red dashed lines). The rise time (fall time) of the cantilevers were measured to be 1.01 (1.41), 2.42 (2.84), 4.14 (4.03), and 3.63 (5.72) ms respectively for 300, 500, 800, and 1000 µm long cantilevers, in good agreement with the simulated (yellow dashed lines in Fig S4) time response.

Fig. S4: Time response of the rectilinear cantilevers. a Recorded far-field images of the output of the 800 µm long rectilinear cantilever, under applied square signal with maximum power of 10 mW, period of 20 ms, and duty cycles of 50%, 35%, 19%, 13%, 9% and 3%, respectively from left to right. b, c, d Measured and simulated rise time (top) and fall time (bottom) of the 500 µm (b), 800 µm (c), and 1 mm (d) long cantilevers.

We further measured the time responses of the L-shaped cantilevers. The results are shown in Figs. S5. In this case, we separately measured the temporal response of the secondary arm (Fig. 5Sa) and the right-hand side primary arm (Fig. S5b). We measure the rise time of 4.26 and 4.65 ms and fall time of 4.87 and 5.64 ms respectively for the primary and the secondary arms.
Fig. S5: Time response of the L-shaped cantilever. Measured and simulated rise time (top) and fall time (bottom) of the secondary arm (a), and primary arm (b) of the L-shaped cantilever.

5. Improving the resolution by modifying the grating coupler design

The number of resolvable points of our devices were limited due to the short length (25 µm) of the grating couplers, which led to a relatively large divergence angle (FWHM = 1.4°). The number of resolvable points, at least in the longitudinal direction, could be significantly increased without modification of the cantilever design by increasing the grating coupler length along the cantilever and reducing the scattering strength of the grating. To quantitatively illustrate the effectiveness of this approach, based on the analytical model explained in chapter 6 of [S10], we calculated the FWHM of the output beam at λ=488 nm as a function of grating coupler length (L_{GC}) and scattering strength (α) of the gratings. The calculation results of the analytical model are shown in Fig. S6a for L_{GC} between 5 µm and 2 mm. For large values of the scattering strength (e.g., blue curve in Fig. S6a), increasing the grating length beyond the point where the light is fully coupled out does not decrease the FWHM of output beam. This is the case for single layer fully-etched grating couplers, which were used in this work. However, by using sidewall gratings, it is possible to effectively increase the grating length and reduce the FWHM. To validate the analytical method, we simulated a 100 µm long and 4 µm wide SiN grating coupler with additional 2 µm wide sidewall gratings, using the same thickness of 150 nm, using 3D FDTD simulation in Lumerical. The resulting output beam in propagation direction is shown in Fig. S6b corresponding to the green dot in Fig. S6a. Compared to the grating couplers we used (red dot in Fig 6Sa) the simulated grating coupler has a 4-fold improvement in the FWHM in the longitudinal dimension. The design flexibility of the demonstrated cantilevers allows for tuning the properties of the output beam for a certain application. For instance, since a high angular
resolution is desirable for head-mounted augmented reality displays [S11], the length of the grating can be increased to 1 mm (see Fig. S6a) to each a beam size of 0.02°.

Fig. S6: Simulated performance of the envisioned grating coupler. a Calculated full-width-half-maximum of the output beam of the grating coupler according to its length and scattering strength. The red and the green dots respectively represent the measured 25 µm long grating coupler (GC1) and the simulated and the simulated 100 µm long grating coupler (GC1) b Simulated far-field profile of the output beam at λ=488 nm for a 100 µm long grating coupler with α=0.002.

6. Cryogenic measurement setup of the L-shaped microcantilever

The characterization setup used for cryogenic measurements is shown in Fig. S7a. The cryostat had a 10 cm diameter open window at the top allowing us to view and measure the emitted beam. The optical and electrical packaging of the PIC were performed prior to the measurements as explained in the Methods section of the main manuscript. Generally, electro-thermally tuned optical devices are not tailored to perform in cryogenic conditions. For instance, the high thermal budget of the state-of-the-art SiN beam formers [36] can easily overwhelm the cooling power of the cryostat which is typically in the range of hundreds of milliwatts. However, due to the relatively small power consumption of our devices, the temperature could be reduced to 4K for an applied power of < 30 mW. We performed thermal simulations using COMSOL Multiphysics to calculate the temperature profile in the PIC under 26 mW of applied electrical power to the secondary arm of the L-shaped cantilever, while the chip is fixed on the cold head with T = 10 K. The results (Fig. S7b and S7c) show that at a distance of only ~ 600 µm from the cantilever, the temperature falls to 11 K, which is one degree above the set point of the cryostat. This suggests that our devices can be implemented on the same chip in conjunction with other electro-optical devices (such as single-
photon detectors) which require a low-temperature condition for their performance, without any significant crosstalk, provided that an adequate clearance is maintained.

![Cryogenic measurement setup](image)

**Fig. S7:** a Cryogenic measurement setup. b Simulated temperature profile in the vicinity of the L-shaped beam scanner under 26 mW applied electrical power. c Temperature along the green dashed line in b) showing the decay of the temperature.
7. Comparison with the state-of-the-art beam steering systems

The results of the rectilinear and the L-shaped cantilevers in terms of steering range, power consumption, number of resolvable spots, temporal response, and resonant frequencies are summarized in Table S1.

| Device            | Dimension | Steering range (°) | Resolvable points | Required Power (mW) | $t_{\text{rise}}$ (ms) | $t_{\text{fall}}$ (ms) | $f_{\text{res}}$ (kHz) |
|-------------------|-----------|--------------------|-------------------|---------------------|------------------------|------------------------|------------------------|
| L-shaped cantilever | 2D        | 24 × 12            | 66                | 45                  | 4.3, 4.7               | 7.6 ($f_1$)            | 7.0 ($f_2$)            |
| Rectilinear (300 µm) | 1D        | 11                 | 8                 | 30                  | 1.0                    | 1.4                    | 77.4                   |
| Rectilinear (500 µm) | 1D        | 17.6               | 12                | 30                  | 2.4                    | 2.8                    | 24.8                   |
| Rectilinear (800 µm) | 1D        | 22.6               | 16                | 30                  | 4.1                    | 4.0                    | 11.8                   |
| Rectilinear (1 mm)  | 1D        | 30.1               | 21                | 30                  | 3.6                    | 5.7                    | 5.7                    |

Table S2 presents a comparison of our beam steering device with other demonstrations in the visible spectral range. Only a few integrated beam steering devices have so far been reported. The cantilevers presented here achieve fast beam steering without wavelength sweep at a record low power consumption.

| Device            | Dim. | λ (nm) | Beam steering method | Steering range (°) | Resolvable points | Required power (mW) | Time response | $f_{\text{res}}$ (kHz) | Emitter loss | Ref. |
|-------------------|------|--------|----------------------|--------------------|-------------------|---------------------|---------------|------------------------|--------------|------|
| L-shaped cantilever | 2D   | 410 - 700 | θ: MEMS ϕ: MEMS | 24 × 12 | 66 | θ: 23 | ϕ: 23 | ~ 5 ms | 7.6 ($f_1$) | 5.2 dB | This work |
| Optical phased array | 1D   | 520 - 980 | θ: Wavelength sweep | 65 | ~ 260² | Not reported | Not reported | | | Not applicable | [S12] |
| Optical phased array | 1D   | 488    | ϕ: Thermal tuners | 50 | ~ 294² | ϕ: 2000 | Not reported | | | Not applicable | [36] |
| Optical phased array | 2D   | 650 - 980 | θ: Wavelength sweep ϕ: Thermal tuners | 44 × 13 | Not reported | θ: Not rep. | ϕ: Not rep. | | | Not applicable | [35] |

¹ Two-dimensional beam steering can be achieved at any target wavelength in this range.
² Calculated based on the reported FWHM.
³ FWHM in longitudinal direction is reported 3.4° at $\lambda = 850$ nm.
S1 Timoshenko, S. Analysis of bi-metal thermostats. *Josa* **11**, 233-255 (1925).

S2 Zhang, Y., Toda, A., Okada, H., Kobayashi, T., Itoh, T., & Maeda, R. (2012, January). New wafer-scale MEMS fabrication of 3D silicon/metal cantilever array sensor. In 2012 IEEE 25th international conference on micro electro mechanical systems (MEMS) (pp. 297-300). IEEE.

S3 Prajesh, R., Shankar, B., Jain, N., & Agarwal, A. (2014, December). A quick method to realize and characterize bimorph cantilevers. In 2014 IEEE 2nd International Conference on Emerging Electronics (ICEE) (pp. 1-3). IEEE.

S4 Wang, P., Liu, Y., Wang, D., Liu, H., Liu, W., & Xie, H. Stability study of an electrothermally-actuated MEMS mirror with Al/SiO2 bimorphs. *Micromachines* **10**, 693 (2019).

S5 Liao, W. et al. Total-Ionizing-Dose Effects on Al/SiO 2 Bimorph Electrothermal Microscanners. *IEEE Transactions on Nuclear Science* **65**, 2260-2267 (2018).

S6 Jia, K. et al. An electrothermal tip–tilt–piston micromirror based on folded dual S-shaped bimorphs. *Journal of Microelectromechanical systems*, **18**, 1004-1015 (2009).

S7 Jacques, M., Samani, A., El-Fiky, E., Patel, D., Xing, Z., & Plant, D. V. Optimization of thermo-optic phase-shifter design and mitigation of thermal crosstalk on the SOI platform. *Optics express* **27**, 10456-10471 (2019).

S8 Jia, L., Li, C., Liow, T. Y., & Lo, G. Q. Efficient suspended coupler with loss less than− 1.4 dB between Si-photonic waveguide and cleaved single mode fiber. *Journal of Lightwave Technology* **36**, 239-244 (2018).

S9 Peng, W., Xiao, Z., & Farmer, K. R. Optimization of thermally actuated bimorph cantilevers for maximum deflection. *Nanotech Proceedings* **1**, 376-379 (2003).

S10 Balanis, C. A. (2015). Antenna theory: analysis and design. John wiley & sons.

S11 Tan, G., Lee, Y. H., Zhan, T., Yang, et al. Foveated imaging for near-eye displays. *Optics express* **26**, 25076-25085 (2018).

S12 Wang, H., Chen, Z., Sun, et al. Broadband silicon nitride nanophotonic phased arrays for wide-angle beam steering. *Optics Letters* **46**, 286-289 (2021).