This document provides supplementary information to “2D broadband beamsteering with large-scale MEMS optical phased array,” https://doi.org/10.1364/OPTICA.6.000557. Comparison of the OPAs with those reported in the literature, the design guideline, specifications, detailed analysis of the grating-based phase shifters, the fabrication process of the MEMS grating OPA, electrical characterization, electronic driver circuit and bias optimization for OPA control, holographic pattern generation details, and descriptions of the supplementary videos are included in this document.

Section I. Comparison of OPAs in Literature and in This Work

Table S1 compares the performance of the OPA reported here with other works reported in the literature.

Liquid crystal (LC) OPAs have been developed more than two decades ago [1]. LC OPAs offer 2-D beamforming, large apertures and broad transmittance spectrum [2], [3]. However, the response time of LC OPAs is limited to milliseconds, too slow for many applications. Fast beamsteering with ferroelectric-liquid-crystal has been reported [4], but the response time is still on the order of hundreds of microseconds. Most of the reported silicon photonic OPAs are 1-D arrays. Scanning in the orthogonal axis relies on wavelength scanning [5], [6]. Some 2-D OPAs were reported, but they are limited to small arrays [7]. Waveguide-based OPAs also suffer from high optical coupling losses.

MEMS-actuated piston mirror arrays have been reported for both 1-D and 2-D OPAs [8]–[12]. Phase shift is achieved by vertical displacement of the individual mirrors. However, large displacement for long wavelength application is challenging for small MEMS mirrors due to pull-in effect, and the vertical displacement is large compared to the mirror size.

Section II. Grating Phase Shifter Characteristics

Fig. S1 shows the schematics of the grating phase shifter. The phase shift of the diffracted beam is dependent on the pitch and displacement of the grating element: $\Delta \Phi = \frac{2\pi d}{\Lambda}$, where $\Lambda$ is grating pitch and $d$ is the displacement. Maximum diffraction efficiency is achieved by designing the grating profile including depth and width. In this $xyz$ coordinate system, the grating lines are aligned parallel to the input beam.
Table S1. Comparison of the MEMS grating OPA reported here with other OPAs in the literature.

| Device type                      | 1-D or 2-D | Aperture size (mm²) | FOV | Optical efficiency | Wavelength | Beam Width | Required Voltage | Response time | Response time limit | Material                  |
|----------------------------------|------------|---------------------|-----|--------------------|------------|------------|------------------|---------------|---------------------|----------------------------|
| Liquid Crystal [1]               | 1-D        | 20 × 20             | 10⁰ | 78%                | 10.6 μm    | 0.1⁰       | <5 V            | 1 s           | Liquid crystal dynamics | LC                         |
| Liquid Crystal [2]               | 2-D        | 20 × 15             | 1.1⁰ × 1.1⁰ | 87%               | 632.5 nm, and 1550 nm | 1.32 λ diffraction limit | 0.02 s for Visible, 0.2 s for IR | Liquid crystal dynamics | LC                         |
| Liquid Crystal [3]               | Cascaded   | 1-D                 | 40 × 40 | 2.5⁰               | 1550 nm    | 0.01⁰      | 32 V             | 2 ms          | Liquid crystal dynamics | LC                         |
| Liquid Crystal [4]               | 1-D        | 9.9 × 9.9           | 0.12⁰ | 91%                | 658 nm     | 0.004⁰     | ±45 V            | <200 us       | Liquid crystal dynamics | LC                         |
| Silicon Photonics [5]            | 1-D + λ tuning | 0.194 × 0.197     | 80⁰ | 91%                | 1260 - 1360 nm | 0.14⁰       | Silicon         |                            |                            |
| Silicon Photonics [6]            | 1-D + λ tuning | 0.023 × 0.055     | 19.6⁰ × 15⁰ | 26.9% (−5.4 dB) | 1480-1580 nm | 1.2⁰ × 0.5⁰ | 2.13 V           | 48 μs         | Metal heater phase shifter | Silicon                    |
| MEMS Mirror [7]                  | 2-D        | 0.072 × 0.072      | 9.8⁰ × 9.8⁰ | 51%               | 1550 nm    | 4.6 V       | Mechanical Resonance frequency | Si, Ni & Al |                            |
| MEMS Mirror [8]                  | 1-D        | 41 × 0.15           | 4⁰ | 80%                | 350-410 nm | <10 V      | <0.2 μs          | Mechanical Resonance frequency | Si, Ni & Al |                            |
| MEMS Mirror [9]                  | 1-D        | 0.7 × 0.7           | 4⁰ × 4⁰ | 99.9%             | 1550 nm    | 0.14⁰      | <20 V            | 3.8 μs        | Mechanical Resonance frequency | Poly-silicon               |
| MEMS Mirror [10]                 | 2-D        | 0.24 × 0.24        | 2.52⁰ × 2.52⁰ | 99.9%          | 1550 nm    | <30 V      | 5.8 μs           | Mechanical Resonance frequency | Poly-silicon               |
| MEMS Mirror [11]                 | 2-D        | 9.6 × 8             | 85% | 200-900 nm         | 10 ms      | Electronic controller | Aluminu m alloy |                            |
| MEMS Mirror [12]                 | 2-D        | 2.56 × 0.64        | DUV | 2 V               | 10 μs      | Mechanical Resonance frequency | Al coated poly-silicon |                            |
| This work                        | 2-D        | 3.2 × 3.1           | 6.58⁰ × 4.44⁰ | >85%          | 1200-1700 nm | 0.042⁰ × 0.031⁰ | <12 V         | 5.7 μs        | Mechanical Resonance frequency | Poly-silicon               |

the z-axis. Let us consider a collimated light wave illuminating the grating, as shown above, with an angle of incidence $\theta$, the complex wavefield can be written as (dropping the time-dependent harmonic term $e^{i\omega t}$),

$$U_i (r) = Ae^{i(kr)} = Ae^{i(k \sin \theta - \cos \theta)}$$

(1)

Where $r$ is the position vector $r = (x,y,z)$, $A$ is the wave amplitude, and $k$ is the wave vector with amplitude equal to $k = 2\pi/\lambda$. At the grating plane $y = \theta$, the incident wavefield is,

$$U_i (x,0,z) = Ae^{i(k \sin \theta)}$$

(2)

The grating then adds its spatial modulation $g(x)$ to the incident wave. The function $g(x)$ is periodic with a period $\Delta$, which can be expanded in to a Fourier series as follows,

$$g(x) = \sum n \eta_n e^{\frac{2\pi n x}{\lambda}}$$

(3)

where the coefficients $\eta_n$ is determined by,

$$\eta_n = \frac{1}{\Delta} \int_{-\Delta}^{\Delta} g(x) e^{-\frac{2\pi nx}{\lambda}} dx$$

(4)

The outgoing light wave field at the grating plane then can be expressed as,

$$U_0 (x,0,z) = \sum n \eta_n A e^{i(k \sin \theta \sin \Delta + k \cos \theta \cos \Delta)}$$

(5)

From the angular spectrum of the wavefield point of view, the above equation represents a set of out-going plane waves from the grating, i.e. the diffracted beams. Taking the $n^{th}$ order diffracted beam from the grating shown in the figure as an example, the out-going wavefield can be written as,

$$U_0^n (r) = \eta_n A e^{i\left(\frac{k \sin \theta \sin \Delta + k \cos \theta \cos \Delta}{\lambda}\right)}$$

(6)

where $\Delta$ is the diffraction angle, which can be shown from the above equation to fulfill the condition that,

$$\sin \theta = \sin \theta + (n\lambda / \Delta)$$

(7)

Clearly, the diffraction efficiency of this order is related to $|\eta_n|^2$. Then if the grating is shifted along the x-axis with a displacement of $d$ as shown in the figure, the grating modulation function then becomes $g(x+d)$ instead. Since this shift does not change the periodicity, the Fourier expansion Eq. (3) remains the same. However, the coefficient in each order now changes to $\eta_n'$, where

$$\eta_n' = \frac{1}{\Delta} \int_{-\Delta}^{\Delta} g(x+d) e^{-\frac{2\pi nx}{\lambda}} dx = \frac{1}{\Delta} \int_{-\Delta}^{\Delta} g(x) e^{-\frac{2\pi n(x-d)}{\lambda}} dx$$

(8)
Changing variable is used in the last step of the above equation. Since, \( g(x) \) is periodic, it is obvious that,

\[
\eta' = \frac{1}{\Lambda} \int_0^\Lambda \frac{1}{\pi} \frac{dx}{g(x)} e^{\frac{2\pi n x}{\Lambda}} = \left( e^{\frac{2\pi n x}{\Lambda}} \right) \frac{1}{\pi} \int_0^\Lambda \frac{dx}{g(x)} e^{\frac{2\pi n x}{\Lambda}} dx
\]

(9)

\[
\eta' = \left( e^{\frac{2\pi n x}{\Lambda}} \right) \frac{1}{\pi} \int_0^\Lambda \frac{dx}{g(x)} e^{\frac{2\pi n x}{\Lambda}} dx + \frac{1}{\pi} \int_0^\Lambda \frac{dx}{g(x)} e^{\frac{2\pi n x}{\Lambda}} e^{\frac{2\pi n (x + \Lambda)}{\Lambda}} dx
\]

(10)

Because \( g \) is period, i.e. \( g(t + \Lambda) = g(t) \), and replacing \( t \) back to \( x \), we can obtain,

\[
\eta' = \left( e^{\frac{2\pi n x}{\Lambda}} \right) \frac{1}{\pi} \int_0^\Lambda \frac{dx}{g(x)} e^{\frac{2\pi n x}{\Lambda}} dx + \frac{1}{\pi} \int_0^\Lambda \frac{dx}{g(x)} e^{\frac{2\pi n x}{\Lambda}} e^{\frac{2\pi n (x + \Lambda)}{\Lambda}} dx
\]

(11)

Hence, a phase shift of \( \Delta \phi = 2\pi n d/\Lambda \) will be imposed on the \( n^{th} \) order diffracted beam. The \( n^{th} \) order out-going diffracted wavefield can then be written as,

\[
U_n(r) = \left( e^{\frac{2\pi n d}{\Lambda}} \right) \eta_n A e^{i(k \sin \theta \frac{2\pi n}{\Lambda} + \pi \cos \theta)}
\]

Fig. S2 shows the calculated and measured diffraction efficiency of the grating versus (a) the operating wavelength and (b) etching depth of the grating. Compared with silicon grating, Au and Al gratings exhibit larger difference between their simulation and experimental values. This is attributed to the poor step coverage of the metal coating as the Au and Al gratings are made by evaporating gold and aluminum on top of silicon grating structure.

**Section III. Device Fabrication**

Fig. S3 shows the fabrication process flow. The starting n-type single crystalline silicon wafers were pre-cleaned in piranha solution to remove any organic contaminants. Then the wafer was coated with low stress nitride (LSN) by low-pressure chemical vapor deposition (LPCVD) for electrical insulation. Trenches were patterned on LSN by deep-UV (DUV) photolithography and dry etching for interconnect wires. Those trenches were filled with doped polysilicon by LPCVD, followed by chemical mechanical polishing (CMP) to expose the un-etched LSN. Likewise, a second LSN layer was coated to cover the polysilicon interconnect wires, then patterned with via structure, etched, refilled with polysilicon, and chemical-mechanically polished to create via contact between interconnect wires and the MEMS actuators.

Fig. S2. Simulated and experimentally measured optical efficiencies of the grating versus a. wavelengths and b. grating etched depth. All data are measured with TM-polarized incident light. The colors of the curves and symbols represent data from gold (red), aluminum (blue), Si (black), respectively.
Next the MEMS layers were deposited and patterned on top of the interconnect and via layers. First, a 500 nm thick polysilicon layer layer was deposited and patterned as ground shield between the interconnects and the combdrive actuators to suppress the electrical crosstalk. Then a sacrificial oxide was deposited and planarized with CMP for a thickness of 500 nm. Polysilicon plugs are formed by a damascene process to anchor the MEMS structures on top as well as to provide electrical contacts for the actuators. The MEMS structures comprising 2-µm-thick doped polysilicon were formed by DUV lithography and deep reactive ion etching (DRIE). The resolution of our DUV stepper (ASML 5500/300) is 250 nm. This enabled us to pattern 300nm wide comb fingers with 300nm spacing.

To add gratings on top of the MEMS actuators, a 2-µm-thick high-temperature oxide (HTO) sacrificial layer was first deposited and then planarized by CMP. Next, polysilicon plugs (posts) were formed by the same damascene process as the anchors. Gratings were patterned on a 1-µm-thick polysilicon deposited on top of the posts. Finally, the MEMS structures were released in liquid HF followed by critical point drying (CPD).

**Section IV. Electrical Characteristics**

160 × 160 OPA consists of 25,600 unit cells. The schematic of the unit cell is depicted in Fig. 2 of the main text. The grating is attached to the movable comb which is suspended by a folded spring. The combdrive actuators are designed for analog operation, exploiting its large displacement without pull-in. The schematic of the actuator without bias and under maximum bias voltage for π phase shift are shown in Fig. S4a and Fig. S4b, respectively. Fig. S4c shows the measured displacement-vs-voltage curves of 12 OPA elements. The average voltage to achieve ±0.5μm displacement for ±π phase shift is 10.5 V, with a standard deviation of 0.64 V. The voltage variations are mainly due to fabrication nonuniformity. The spring constant of the folded-beam flexure design is calculated by:

\[
k = \frac{Eh b^3}{L^3}
\]
where $E$ is the Young’s modulus of polysilicon (169 GPa), $b$ is the width (300 nm), $h$ is the thickness of the spring layer (2 μm), and $L$ is the length of one spring segment (17 μm). The resonance frequency of the OPA element is

$$f = \frac{1}{2\pi} \sqrt{\frac{k}{m}},$$

where $k$ and $m$ are the spring constant and mass of the movable portion of the OPA element, respectively. With a spring constant $k = 1.86$ N/m and a mass of 4.52 ng, the calculated resonance frequency is 102.1 kHz. This agrees well with value obtained from the finite-element-method (FEM) simulation using ANSYS® software, 98.8 kHz, as shown in Fig. S5a. The frequency response is measured with a Lyncée Tec® digital holographic microscope (DHM). The resonance frequency is measured to be 55.0 kHz, as shown in Fig. S5b. This measured resonance value is 40% lower than the theoretical calculation and the numerical FEM simulated value. The difference is due to the sidewall thinning of the folded beam springs during DRIE, resulting in a lower spring constant. The measured phase difference between high- and low-frequency regions is close to 180°, as shown in the frequency response of Fig. S5b. This phase difference fits well with the theoretical phase response of a typical 2nd order harmonic oscillator.

The high resonance frequency enables a fast response time. Fig. S6 shows the measured temporal response of a MEMS OPA element for a step-function input voltage with an amplitude of $V_{pp} = 12$ V. A steady-state displacement of 0.5 μm is reached at 12 V. This displacement agrees well with the static transfer curve in Fig. S4.
The actuator is under-damped and significant ringing is observed in Fig. S6a. To suppress the ringing, we used a three-step voltage waveform as shown in Fig. S6b. A smooth step response is obtained with a rise time of 5.7 μs for π phase shift, the maximum amount needed for our bi-directional actuator. The combdrive actuator has a capacitive load. During steady state, it does not consume any power, just like complementary metal-oxide-semiconductor (CMOS) circuits. If we operate the OPA at \( f = 20 \) kHz, the dynamic power consumption is \( P_{\text{max}} = \frac{1}{2} C \cdot V_{\text{max}}^2 \cdot f = 2.7 \text{ nW} \) for each phase shifter, where \( C \) is the total capacitance of the combdrive actuator (1.89 fF) and \( V_{\text{max}} \) is the voltage required for π phase shift (12 V). The power consumption of the entire OPA with 25,600 phase shifters is 69 μW. For the entire system including drive circuits, the capacitance of the interconnect wires also needs to be considered. Even including this capacitance, the device level power consumption is still orders of magnitude lower than typical silicon photonics OPA described in [6] in Table S1.

Section V. Optical Performance Characterization

With a uniform, overfilled incident light, the diffractive aperture can be modeled as a rectangular shape aperture. With 45° diffraction angle, the effective aperture of the MEMS OPA is 2.2 × 3.2 mm². The theoretical divergence angle of the diffracted beam is thus 0.040°×0.027°. The experimental optical divergence angle of the OPA is characterized by two methods, both agree well with the theoretical value.

The first method images the output beam on an IR camera with a lens. When a monochromatic plane wave passes through a thin lens, the field at the focal plane of the lens can be modeled as the Fourier transform of the input wavefront. Fig. S7 shows the measured beam profile with 0.042°×0.031° divergence angle using a thin lens (Thorlabs AC254-150-C). The second method is to measure the beam spot size at a distance of 5m in free space propagation. The measured beam spot size is then compared with that is theoretically calculated using Fresnel simulation. Fig. S8 demonstrates the experimentally characterized beam spot profile compared with the theoretical beam profile modeled by Fresnel propagation. The broadening of the beam width is attributed to the non-uniformity of the displacements, which can be compensated by calibrating the translation of the OPA pixels.

Section VI. Electronic Control and Optimization of the OPA’s Control Voltage Array

Due to fabrication imperfections, the displacements of different
OPA pixels have a distribution under the same voltage bias, as illustrated in Fig. S4c. To compensate this non-uniformity, an optimization program was developed to fine tune the voltage applied on each specific OPA pixel. The merit function of this optimization program is to maximize the main-to-sidelobe suppression ratio (MSSR) of the diffracted beam in the desired steered direction.

In practice, the optimization program enhances the intensity of the beam in the desired direction, while suppressing the intensity level of the undesired sidelobes and background noise floor through tuning of the voltage map for the OPA. The detailed optimization flow is illustrated in Fig. S9a. First, a complete list of digital-to-analog converter (DAC) code for all starting positions derived from theoretical calculation was generated. After applying the DAC codes to the drive board and waiting for the device to stabilize, which typically takes ~100 ms, the program takes an image of the captured diffracted patterns for all possible angles on the IR camera. Then, the optimization program uses the SimpleBlobDetector® feature in OpenCV to identify non-overlapping spots in the image, and then bin the detected spots into a 2-D matrix representing all possible unique spot locations. Afterwards, the program identifies the pattern files to generate the brightest point for each spot, and uses the pattern files as the start location of each particle in the particle swarm optimization (PSO) instead of random start positions. To acquire the PSO fitness value for each optimization step, the program calculates the MSSR by summing the pixel intensity values inside and outside of the region of interest (ROI) around the spot. Fig. S9b and c illustrate the improvement of MSSR for the steered beam locating at the angle of (-1.65°, 0.42°), after the PSO treatment, the MSSR was improved from 0.54 dB to 9.66 dB.

Section VII. Hologram Generation Details

In principle, any arbitrary holographic patterns can be generated in the far field by tailoring the phase shift of all OPA elements. Fig. S10 shows the SEMs of 4 passive holographic OPAs with pitches of 3 × 3 μm, 5 × 5 μm, 10 × 10 μm, and 20 × 20 μm. At 1260 nm wavelength, these pitches lead to FOVs of 26.7°×24.8°, 15.6°×14.6°, 7.7°×7.2°, and 3.9°×3.6°. The grating periods are identical (1 μm) for all designs. During operation, the light is incident at 65° from the normal of the substrate. The phase maps of the holograms are fixed by photolithography and fabrication. Fig. S11a shows the overlay of the diffraction patterns of four static holographic OPAs with checkerboard phase patterns showing their FOVs. The pitches of the OPAs are 3, 5, 10, and 20 μm. Fig. S11b-c show the measured far-field diffraction patterns of two fabricated holographic OPAs with 320 × 320 elements and 10 μm pitch. The holograms correspond to the phase maps of a "Cal" logo and a Golden Gate Bridge picture. The images were successfully reproduced in the diffracted far-field pattern. It is worth noting that since the phase shifts of the grating OPA are independent of wavelength, the passive holographic OPAs can generate the same far-field patterns over a broad wavelength band, with only pattern

Fig. S10. SEMs of part of the 3 × 3 mm OPA system fabricated on a Silicon wafer. Different element pitches of a. 3 μm b. 5 μm c. 10 μm, and d. 20 μm are fabricated and characterized.

Fig. S11. Experimental holographic patterns from MEMS OPA. a. Far-field diffractive patterns from checkboard phase profiles with different FOVs captured with 1260 nm wavelength, corresponding to different OPA pitch designs, b. and d. The far-field diffractive pattern of the "Cal" logo and Golden Gate Bridge using 320 × 320 OPAs with 10 μm element pitch captured with 1260 nm wavelength. c. and e. The far-field diffractive patterns generated by the same samples with 1550 nm wavelength.
size change due to the wavelength dependence of FOV (shown in Fig. S11 d-e). In contrast, if the phase shifts were wavelength dependent, there would be significant side-lobe spots observable in the far-field pattern.

Section VIII. Descriptions of Supplementary Visualizations

Video 1: Dynamic movement of the MEMS grating OPA under low frequency actuation. Video captured in the experiment showing top view of a laterally moving MEMS OPA element. The time scale is 0-9 seconds. The actuation voltage is a 6Hz sinusoidal signal with Vpp = 10V.

Video 2: Sweeping of the OPA diffracted beam spot in diagonal direction. Video captured in the experiment showing the far-field of the OPA with the output beam sweeping from the upper left to the bottom right of the FOV.

Video 3: Raster scan of OPA. The video shows raster scan of the OPA diffracted beams through 17 x 9 addressable angles. Residue spots at angles other than the steering angle are due to the mismatch of the grating and the pixel pitches. They can be eliminated by making the pixel pitch an integral multiple of the grating pitch, which we have confirmed in a separate short-loop experiment.

Video 4: Steering of the OPA diffracted beam for various wavelengths. Video captured in experiment showing the far-field spots of the OPA for various optical wavelengths.

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