Optical Phased Array Using Single Crystalline Silicon High-Contrast-Gratings for Beamsteering

Byung-Wook Yoo*[a], Trevor Chan[b], Mischa Megens[a], Tianbo Sun[a], Weijian Yang[a], Yi Rao[a], David A. Horsley[b], Connie J. Chang-Hasnain[a], Ming C. Wu[a]
[a]Dept. of Electrical Engineering and Computer Sciences, University of California Berkeley, Berkeley, CA, USA 94720
[b]Dept. of Mechanical and Aerospace Engineering, University of California Davis, Davis, CA, USA 95616

ABSTRACT

We present a single crystalline silicon optical phased array using high-contrast-gratings (HCG) for fast two dimensional beamforming and beamsteering at 0.5 MHz. Since there are various applications for beamforming and beamsteering such as 3D imaging, optical communications, and light detection and ranging (LIDAR), it is great interest to develop ultrafast optical phased arrays. However, the beamsteering speed of optical phased arrays using liquid crystal and electro-wetting are typically limited to tens of milliseconds. Optical phased arrays using micro-electro-mechanical systems (MEMS) technologies can operate in the submegahertz range, but generally require metal coatings. The metal coating unfortunately cause bending of mirrors due to thermally induced stress.
The novel MEMS-based optical phased array presented here consists of electrostatically driven 8 × 8 HCG pixels fabricated on a silicon-on-insulator (SOI) wafer. The HCG mirror is designed to have 99.9% reflectivity at 1550 nm wavelength without any reflective coating. The size of the HCG mirror is 20 × 20 μm^2 and the mass is only 140 pg, much lighter than traditional MEMS mirrors. Our 8 × 8 optical phased array has a total field of view of ±10° × 10° and a beam width of 2°. The maximum phase shift regarding the actuation gap defined by a 2 μm buried oxide layer of a SOI wafer is 1.7π at 20 V.

Keywords: single crystalline silicon (SCS), high-contrast-gratings (HCG), beamsteering, optical phased array, micro-electro-mechanical systems (MEMS), silicon-on-insulator (SOI), mirror, response time

1. INTRODUCTION

Optical phased arrays have a wide variety of applications in imaging, free space communication, laser radar, and ranging and proximity detection [1]. Conventional optical phased array technology is mainly based on liquid crystals. Though many liquid-crystal optical phased arrays have been demonstrated, their operation speeds are slow because it takes tens of milliseconds for an electric field to reorient the molecules of the liquid crystal [2]. Another approach is based on micro-electro-mechanical systems (MEMS) micromirror arrays [3]. Typical MEMS micromirrors are coated with metal to increase their reflectivity. However, the thermally induced bi-layer stress often cause mirror to warp, affecting the optical performance. The residue absorption in the metal also limits the maximum optical power before catastrophic damage. Alternatively, high performance multi-layer mirror such as distributed Bragg reflector (DBR) can be used, at the expense of heavier mirror and therefore lower resonance frequency.
Here, we demonstrate a MEMS optical phased array incorporating single crystalline silicon (SCS) high-contrast-gratings (HCG) fabricated on silicon-on-insulator (SOI) wafers. The HCG consists of a thin layer (450 nm) of single crystalline silicon with sub-wavelength-scale grating. The mass of a 20 μm × 20 μm HCG mirror is only 140 pg, which is 85× lighter than DBRs with comparable reflectivity. The ultra-lightweight mirror is key to fast response time (2μs). Since the mirror consists of a single material, it is expected to operate at high optical power without damage or warping due to thermal expansion coefficient mismatch.

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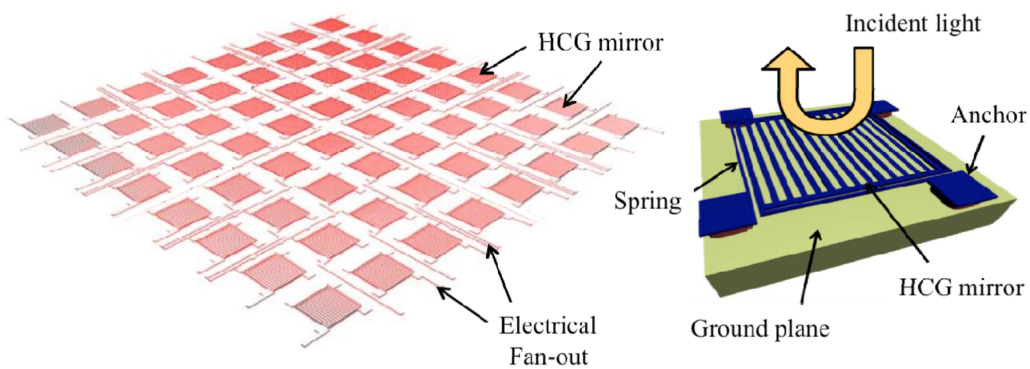
2. DESIGN

2.1 Design of MEMS HCGs

The layout of optical phased array with MEMS HCG mirrors is shown in Figure 1 (a). The size of the array is 8 × 8. The pitch of the HCG mirror is 35 μm; the maximum beamsteering angle is designed to be ±1.32° at 1550 nm wavelength. The beam width of 0.26° is determined by the area of the array. The spacing between HCG mirrors is 15 μm. Each mirror is directly connected to a wirebonding pad. Figure 1 (b) is the schematic view of a SCS HCG mirror. Each mirror is directly connected to a wirebonding pad. Figure 1 (b) is the schematic view of a SCS HCG mirror. The 20 × 20 μm^2 HCG mirror is suspended by four mechanical springs. The design parameters are shown in Table 1. When an electric field is applied between a HCG mirror and its ground plane, the HCG mirror is pulled downward and creates a phase shift. Phase shifted reflection from 64 HCG mirrors interfere each other in the far field, generating beamsteering. Spring stiffness and mirror mass determine the resonant frequency. The designed response time is 2 μs, which is faster than any liquid crystal optical phased array in the literature.



(a) (b)

Figure 1. (a) Layout of the 8×8 HCG array. (b) Schematic of the HCG mirror pixel.

Table 1. Design parameters of the HCG optical phased array

Parameter		Value
HCG mirror	pixel area	20 × 20 μm^2
	thickness	450 nm
	grating width	670 nm
	grating period	1380 nm
	weight	140 pg
Mechanical spring	thickness	450 nm
	width	350 nm
	length	18 μm
Mirror pitch		35 μm
Array size		8×8
Maximum beamsteering angle		±1.32° × 1.32°
Beam width		0.26°
Response time		2 μs

2.2 Benefits of HCG as a mirror

Figure 2 shows the benefits of SCS HCG mirrors compared with distributed Bragg reflectors (DBR). Only one thin layer of HCG can achieve the same reflectivity as a 40-pair DBR (>99.5%), across a much larger bandwidth [4]. The mass of the HCG mirror is 85× times lighter than the DBR mirror as can be seen in Figure 2 (a). The peak reflectivity of the HCG is still the same as that of the DBR at 1550 nm, for beamsteering. Figure 2 (b) depicts the reflectivity spectra of HCG (red line) and DBR (blue line), obtained by a Rigorous Coupled Wave Analysis (RCWA) method based on a single-layered silicon HCG and a DBR having 40 pairs of TiO_2/SiO_2. The reflectivity spectra show that the reflectivity of the HCG can be maintained over a broad wavelength range of $\Delta\lambda/\lambda$~30%, as reported in [4]. Such enormous weight reduction with high reflectivity along the broad bandwidth has proven very beneficial for tunable VCSELs [4] in terms of fast response time and we successfully applied it to our MEMS mirror design for optical phased array [5].

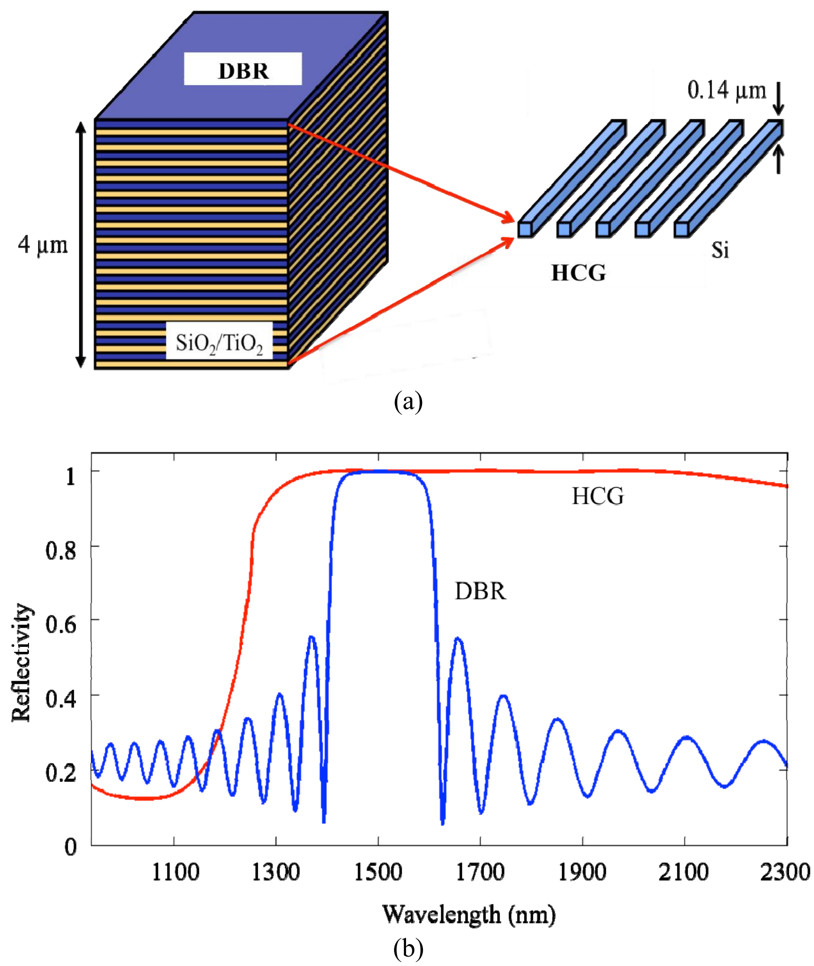


Figure 2. Lightweight HCGs show very high reflectivity along a broad bandwidth, wider than distributed Bragg reflectors (DBR). (a) HCG is lighter than DBR by 85 times for the same reflectivity of 99.5%. (b) HCG is highly reflective at the broad wavelength range compared to DBR.

3. FABRICATION

Optical phased arrays are fabricated on a SOI wafer. The device layer of the SOI wafer is heavily doped in a furnace in order to provide low resistivity. Figure 3 shows the fabrication process of the HCG phased array. The one-mask process results in high yield and low cost. First, a deep ultraviolet (DUV) stepper (ASML300) is used to pattern HCG mirrors on the SOI wafer (Figure 3 (a)). Dry etching of the SCS device layer follows (Figure 3 (b)). The buried oxide layer is partially etched to alleviate the need of large anchors for the release process (Figure 3 (c)). An oxygen plasma step removes the photoresist used as the etch mask, and the mirrors are released using vaporized hydrofluoric (HF) acid. Here, care should be taken not to release the anchors (Figure 3 (d)).

Figure 4 shows the scanning electron microscope (SEM) images of a fabricated HCG mirror. In Figure 4 (a), the released HCG is captured. The HCG is tethered by mechanical springs without any residual stress thanks to the benefit of SCS and a single material mirror. The oxide anchors underneath SCS layer visible because the thickness of the HCG is only 450 nm. The electrical bias lines are also patterned on the same SCS layer. The actuation gap is 2 μm, defined by the thickness of the buried oxide layer. Figure 4 (b) shows the magnified view of HCG bars, springs and the anchor in Figure 4 (a).

The released MEMS die is mounted on a chip carrier, as shown in Figure 5. Standard gold wirebonding is used to address individual mirrors. The packed die is used for various tests such as resonant frequency, vertical displacement, and interferometric phase shift measurements.

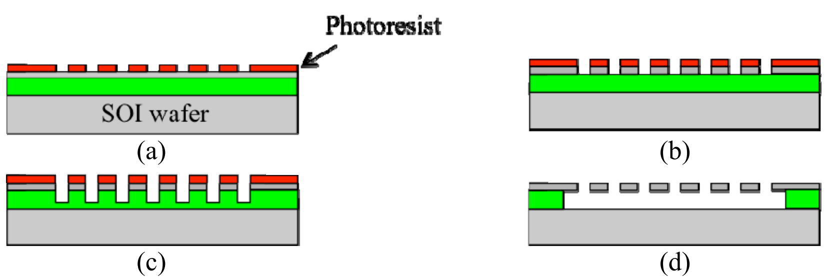


Figure 3. The fabrication process for HCG optical phased array. Only one photomask is needed. (a) Lithographic step using deep ultraviolet (DUV) stepper. (b) Dry etching of SCS HCG mirrors. (c) Partial dry etching of buried oxide layer to facilitate release etching. (d) Release of HCG mirrors using vaporized hydrofluoric (HF) acid.

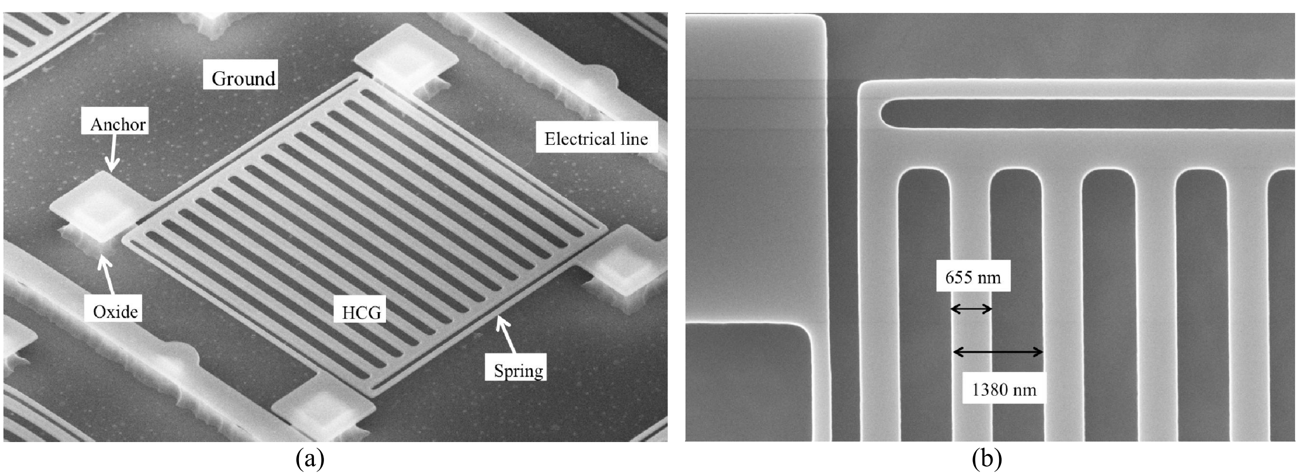
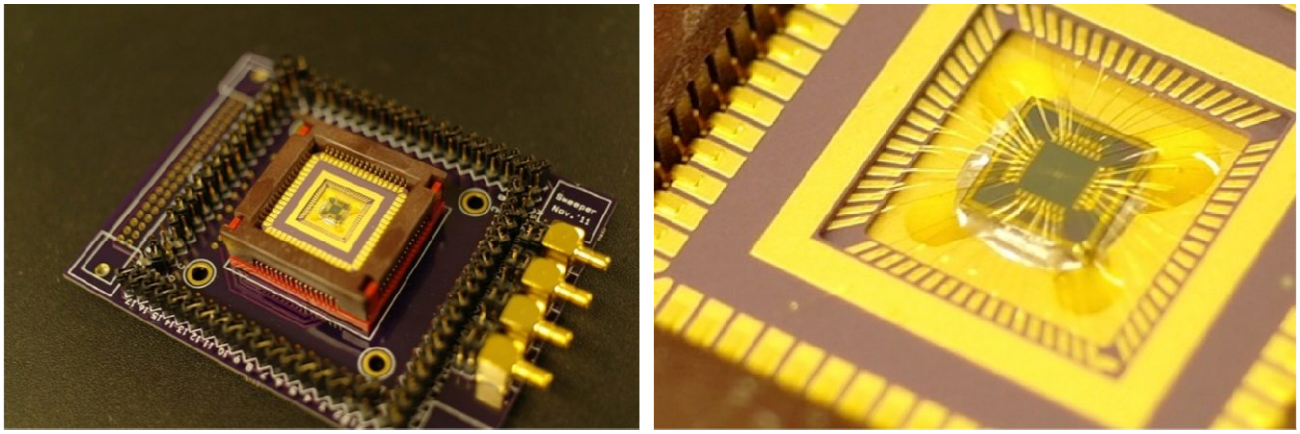


Figure 4. SEM images of the fabricated HCG mirror. (a) Released HCG mirror supported by four springs and anchors. (b) Fabricated HCG bars with period and width of 1380 nm and 655 nm, respectively.

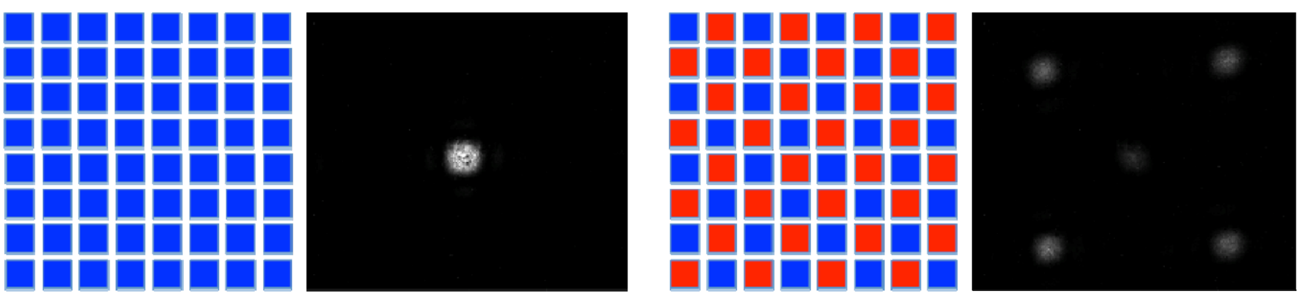


(a) (b)

Figure 5. (a) Optical micrograph of the MEMS optical phased array mounted on a chip carrier, chip socket, and circuit board. (b) Close-up view of the packaged die with 64 gold wirebonds.

4. MEASUREMENT

Two dimensional beamsteering is realized using the packaged HCG optical phased array die. A stroboscopic interferometry setup described in [6] is employed to simultaneously measure the phase shifts of all mirrors. Figure 6 (a) depicts the phase map of the unbiased phased array. Figure 6 (b) shows the measured far-field pattern with a very strong zero-th order beam. Figure 6 (c) represents the phased array with a diagonal phase gradient, corresponding to the maximum steerable angle. Figure 6 (d) shows the experimentally measured far-field pattern with four first-order diffraction spots. The $\pm 10° \times 10°$ measured at four corners are the maximum achievable angles with a 4*f* optical imaging system. The zero-th order beam here is strongly reduced. Further suppression of the zero-th order beam can be achieved by increasing the fill-factor of optical phased arrays. This can be realized by further reducing the sizes of the anchor pads and employing buried electrical lines. This can be achieved by employing additional photomasks and different anchor materials (e.g., silicon nitride). Through-silicon vias (TSVs) can also be used to address the high fill-factor optical phased array.



(a) (b) (c) (d)

Figure 6. Beamsteering measurement results. (a) Phase map of unbiased phased array (blue: zero phase shift) and (b) the corresponding beamsteering pattern. (c) Phase map of binary checkerboard pattern (blue: zero phase shift, red: π phase shift) and (d) the corresponding far-field.

5. CONCLUSIONS

The 8×8 single crystalline silicon (SCS) optical phased array has been developed by combining ultra-lightweight high-contrast-gratings (HCG) mirrors and micro-electro-mechanical systems (MEMS) actuators. The HCG mirror is designed to have 99.9% reflectivity at a wavelength of 1550 nm. With a weight of only 140 pg for the $20 \times 20\ \mu m^2$ HCG mirror, the response time of a HCG from the applied electrostatic force is measured to be just a few microseconds. The optical phased array has a total field of view of ±10° × 10° and a beam width of 2° with a 4*f* optical imaging system. The maximum phase shift of this device is 1.7π at 20 V. Thanks to the use of a single material mirror, this fast HCG optical phased array can be potentially used for high power applications.

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