Optical Phased Array Using High-Contrast Grating All-Pass Filters for Fast Beam Steering

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ABSTRACT

A novel 8x8 optical phased array based on high-contrast grating (HCG) all-pass filters (APFs) is experimentally demonstrated with high speed beam steering. Highly efficient phase tuning is achieved by micro-electro-mechanical actuation of the HCG to tune the cavity length of the APFs. Using APF phase-shifters allows a large phase shift with an actuation range of only tens of nanometers. The ultrathin HCG further ensures a high tuning speed (0.626 MHz). Both one-dimensional and two-dimensional HCGs are demonstrated as the actuation mirrors of the APF arrays with high beam steering performance.

Keywords: Beam steering, optical phased arrays, micro-electro-mechanical structures, gratings, subwavelength, high contrast gratings, high contrast metamaterials

1. INTRODUCTION

Optical phased arrays have enabled free-space beam steering for a wide range of applications, such as imaging, display and sensing. A chip-scale and high-speed optical phased array is of particular desire. It matches the high-integration-density, small-footprint, low-power-consumption and high-speed requirement of advanced applications such as optical circuit switching, light detection and ranging (LIDAR) etc. Several phase tuning mechanisms have been demonstrated for optical phased arrays, such as electro-mechanical[1], and thermo-optic effect[2]. Most of them are relatively low speed at a few kHz to tens of kHz. Electro-optic phasing tuning on arrayed waveguides can be fast[3]; however for two dimensional beam steering, a tunable laser with high tuning speed is required, which largely increases the complexity of the whole system.

In this paper, we demonstrate a novel 8x8 optical phased array based on high-contrast grating all-pass filters with high speed micro-electro-mechanical actuation. Each array element is an all-pass filter (APF) with a high-contrast grating (HCG)[4-9] as a reflective top reflector and a distributed Bragg reflector (DBR) as the bottom reflector. The all-pass filter is essentially an asymmetric Fabry-Perot (FP) etalon with carefully designed reflectivity of the top and bottom mirror. By actuating the HCG to tune the length of the etalon across its FP resonance, the reflection phase of the surface normal incident light experiences a continuous phase change approaching 2π, while the reflection beam power can maintain nearly the same with the incident light. The APF enables a high efficiency phase tuning with small actuation distance of the HCG. Beam steering is experimentally demonstrated by creating a near-field reflection phase pattern with different applied voltages on individual pixels.

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The high-contrast grating (HCG) is a single layer of periodic subwavelength grating composed of a high-refractive-index material (e.g. Si or III-V semiconductors) surrounded entirely by low-index materials (e.g. air or SiO_2)[4-9], shown schematically in Fig. 1 (for one-dimensional HCG). The HCG has been demonstrated as an ultra broadband high reflection mirror (R>0.99, $\Delta\lambda/\lambda$>30%)[5] and implemented as a top mirror of the vertical-cavity surface-emitting laser (VCSEL)[6-9]. By actuating the HCG, the lasing wavelength can be tuned. Thanks to the ultrasmall thickness of the HCG, the tuning speed can be very fast[8]. The same principle applies to the APF, where 0.626 MHz mechanical resonance frequency is demonstrated here. Both one-dimensional (bars) and two-dimensional (grids) HCGs are designed and fabricated. The symmetric design of the two-dimensional HCG overcomes the polarization sensitivity of the one-dimensional HCG. Furthermore, it can be actuated more uniformly, especially at high frequency. We believe that by an optimization of the micro-electro-mechanical structures (MEMS), bandwidth > 1 MHz can be achieved for the beam steering.

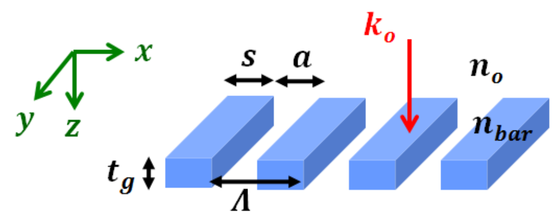

Figure 1. Schematic of a one-dimensional HCG. The grating comprises a periodic dielectric bars with high refractive index n_{bar} surrounded entirely by low-index materials n_0. The plane wave is incident from the top at surface normal incidence. Λ, HCG period; s, bar width; a, air gap width; t_g, HCG thickness. The duty cycle η is defined as a/Λ.

2. HIGH-CONTRAST GRATING ALL-PASS FILTER

Figure 2 shows the schematic of an individual pixel of the optical phased array. The device is fabricated on a GaAs epitaxial wafer. The HCG is defined by electron beam lithography, and followed by a reactive ion etch on a p-doped $Al_{0.6}Ga_{0.4}As$ epitaxial layer, which is on top of an intrinsic sacrificial layer and 22 pairs of GaAs/$Al_{0.9}Ga_{0.1}As$ n-doped DBR. The sacrificial layer is subsequently etched to form a FP cavity with the suspended HCG as top mirror and DBR as bottom mirror. To form the all-pass filter, the reflectivity of the DBR is designed to be >99% and the HCG ~ 90%. We first design and fabricate the one-dimensional HCG. The HCG period, bar width and thickness is designed to be 1150 nm, 700 nm and 450 nm respectively. The incident light polarization is TE, i.e. electrical field along the HCG bars. The static cavity length is 700 nm; with the reflection phase response of the designed HCG, this corresponds to the cavity resonance wavelength of ~ 1550 nm. Each HCG mirror is 20 µm by 20 µm in size, and 8x8 individual pixels form the whole optical phased array, with the pitch ~33.5 µm. Each pixel is electrically addressable through the metal fanned-out lines. Figure 3 shows the scanning electron microscope (SEM) image of the fabricated device.

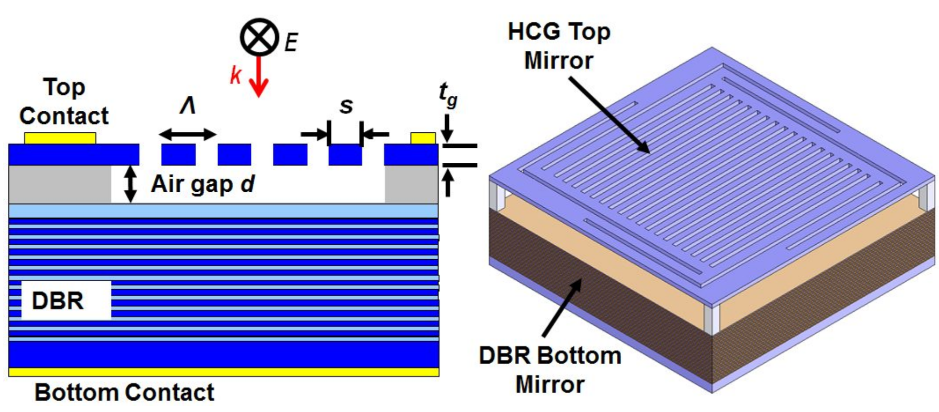

Figure 2. Schematic of an individual pixel of the optical phased array (with one-dimensional HCG). The $Al_{0.6}Ga_{0.4}As$ HCG and 22 pairs of GaAs/$Al_{0.9}Ga_{0.1}As$ DBR serve as the top and bottom reflector of the Fabry-Perot etalon. The incident light is surface normal to the etalon, and polarized parallel to the grating bar. Λ, HCG period; s, grating bar width; t_g, HCG thickness; d , air gap between HCG and DBR.

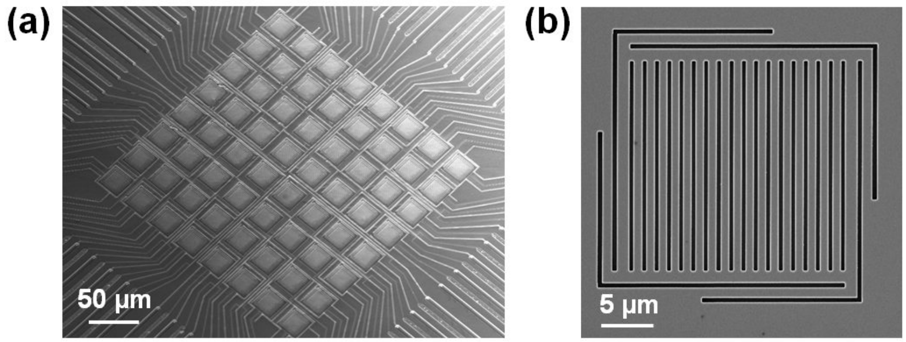

Figure 3. (a) SEM image of an 8x8 optical phased array. Each pixel is an HCG-APF, which can be individually electrically addressed by the fanned-out metal contacts. The pitch of the HCG mirror is ~33.5 µm. (b) Zoom-in view of the HCG mirror in a single pixel. The HCG mirror size (without the MEMS) is 20 µm by 20 µm.

The HCG can be actuated by applying a reversed electrical bias between the p-doped HCG and n-doped DBR. This changes the cavity length and thus the reflection phase of the incident light. Figure 4 shows the reflection phase of a single pixel versus applied voltage, measured by a Michelson interferometer. A total phase change of ~1.7 π is achieved within 10V actuation voltage range at a wavelength of 1556 nm. The actual displacement of the HCG can be measured by the applied voltage dependence reflection spectrum of the APF, where the reflection dip indicates the resonance wavelength of the APF and thus the cavity length. For this 1.7 π phase change, the HCG displacement is 16 nm. This demonstrates the high phase tuning efficiency of the APF. The reflectivity of the HCG and DBR is extracted from the reflection spectrum measurement, and they are used to simulate the reflection phase in Figure 4, which matches well with the experimental measured values. The HCG reflectivity is higher than the design value due to an inadvertent inaccuracy in electron beam lithography and etching process.

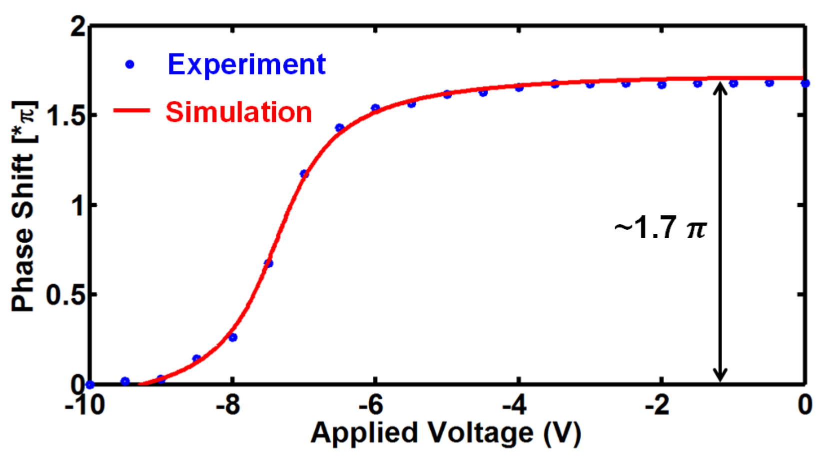

Figure 4. Reflection phase shift versus applied voltage on a single HCG-APF of the phased array. ~1.7 π phase shift is achieved within 10V actuation voltage range at a wavelength of 1556 nm; this corresponds to a displacement of 16 nm of the HCG. This APF design enables a small actuation distance for a large phase change. The experimental data (blue dots) are well matched with the simulation results (red curve).

3. BEAM STEERING EXPERIMENT

Beam steering in far-field is achieved by creating the desired near-field phase front of the reflection beam on the whole 8x8 phased array. By controlling the applied voltage on each individual pixel of the HCG-APF array, the near-field phase pattern can be generated. Figure 5 shows various near-field phase patterns on the phased array, and the corresponding measured far field pattern. The strong zeroth order beam is due to the relatively low filling factor of the phased array (~36%). Quite a large portion of light gets directly reflected from the background without phase shift, contributing to the zeroth order beam. With this consideration and the near-field phase patterns, Fourier optics is applied to calculate the far-field patterns, also shown in Fig. 5, which are in good agreement with the simulation.

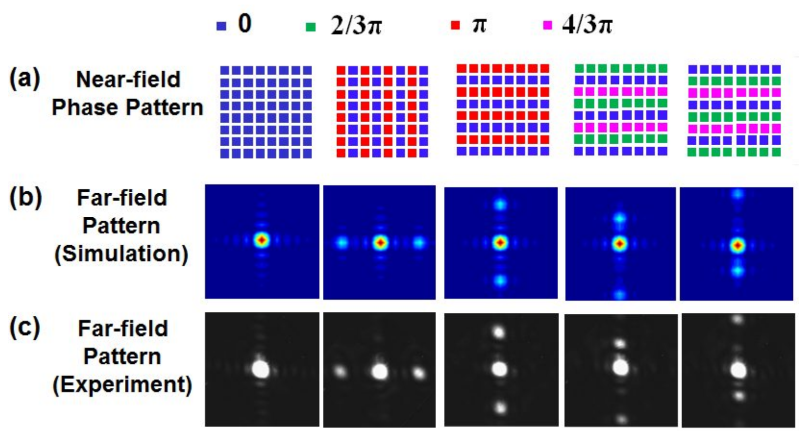

Figure 5. Beam steering experiment. (a) Near-field phase pattern created by the HCG-APF optical phased array. (b) The corresponding far-field pattern calculated by Fourier optics. (c) Experimentally measured far-field pattern, in good agreement with the calculation. The strong zeroth order beam is due to the relatively low filling factor of the phased array (~36%). The light that does not hit on the HCG-APF gets directly reflected without phase shift, contributing to the zeroth order beam.

4. DISCUSSION

To suppress the zeroth order beam, a high-filling factor phased array is designed by grouping four pixels together without isolation trenches in between. Furthermore, two dimensional HCG is designed and fabricated. The symmetric HCG can overcome the polarization sensitivity of the one-dimensional HCG. The two-dimensional HCG grid can also be actuated more uniformly, especially at high frequency. Figure 6 shows the SEM image of an individual pixel. The HCG mirror size is 20 μm by 20 μm, and the filling factor is ~47%.

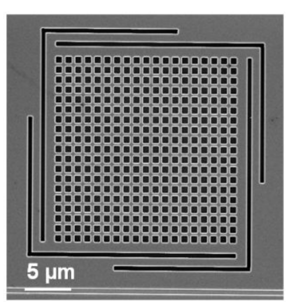

Figure 6. SEM image of a two-dimensional HCG mirror for an HCG-AFP. The HCG mirror size (without MEMS) is 20 μm by 20 μm.

Beam steering is experimentally demonstrated with the two-dimensional HCG-AFP. Thanks to the high filling factor, more power is obtained with the steered beam. To further optimize the beam steering performance, a mircolens array can be placed in front of the phased array, which can focus the input beam onto the HCG mirror of each pixel. This effectively increases the filling factor to 100%, and will ultimately suppress the zeroth order beam.

Since it only requires a very small actuation distance of the HCG to create the near-field phase pattern, the beam steering bandwidth can be estimated by the mechanical resonance frequency f_r of the HCG actuation. Laser Doppler velocimetry is used to measure the mechanical frequency response of the MEMS, and f_r is measured to be ~0.626 MHz for the two-dimensional HCG-APF. Such a high mechanical resonance frequency is attributed to the light weight of the HCG. We believe that bandwidth in excess of 1 MHz can be achieved by the optimization of the MEMS design.

5. SUMMARY

In summary, a novel 8x8 optical phased array using HCG-APF is experimentally demonstrated for beam steering. The all-pass filter design enables a highly efficient phase tuning (16 nm HCG displacement for 1.7 π phase shift), and the light weight of the HCG facilitates the fast tuning speed (~0.626 MHz). Both one-dimensional HCG and two-dimensional HCG are demonstrated as the top mirror for the APF. Beam steering is achieved by creating the desired near-field phase pattern on the HCG-APF array. Beam steering performance can be optimized by increasing the filling factor. We believe that by integrating a microlens array in front of the phased array, the effective filling factor can increase to 100%, leading to a greatly improved beam steering efficiency.

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