High speed optical phased array using high contrast grating all-pass filters

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Abstract: We report a high speed 8x8 optical phased array using tunable 1550 nm all-pass filters with ultrathin high contrast gratings (HCGs) as the microelectromechanical-actuated top reflectors. The all-pass filter design enables a highly efficient phase tuning (1.7 π) with a small actuation voltage (10 V) and actuation displacement of the HCG (50 nm). The microelectromechanical HCG structure facilitates a high phase tuning speed >0.5 MHz. Beam steering is experimentally demonstrated with the optical phased array.

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References and links
1. Introduction

Optical phased arrays have enabled free-space beam steering for a wide range of applications, such as imaging, display, chemical-bio sensing, precision targeting, surveillance, etc. A high-speed, chip-scale optical phased array is of particular desire. It fits in the advanced applications such as optical circuit switching, light detection and ranging (LIDAR) etc, where high operation speed, low power consumption, high integration density, and small footprint are desirable. The central element of the phased array is the individual phase tuner. The phase tuner can either actively emit light with different phase, or passively transmit or reflect incoming light while modifying its transmission phase or reflection phase. Several phase tuning mechanisms have been demonstrated for optical phased arrays, such as using electro-mechanical [1, 2], electro-optic [3–6], and thermo-optic [7, 8] effect. The liquid crystal represents the most mature technology; however its response time is very slow, typically in the order of hundreds of Hz to tens of kHz [3–5]. Thermo-optic is slow in response as well. Electro-mechanical (i.e. MEMS) based phase tuner can be fast, but the MEMS structure is usually sophisticated in design and fabrication [1, 2]. High speed phase tuning has been reported in dielectric waveguide array using electro-optics effect [6]; however the waveguide is arranged in one dimension, and thus only one dimensional beam steering can be realized.

In this paper, we demonstrate a high speed novel 8x8 optical phased array based on high contrast grating all-pass filters with low voltage microelectromechanical actuation. Each array element is an all-pass filter (APF) at 1550 nm with a high contrast grating (HCG) [9, 10] as a reflective top reflector and a distributed Bragg reflector (DBR) as the bottom reflector. The incident light comes at surface normal to the APF; the phase of the reflective light can be tuned efficiently with a small actuation distance of the HCG. A phase shift as large as 1.7 \( \pi \) is experimentally demonstrated within 50 nm displacement of the HCG and 10 V actuation voltage, in a speed as high as 0.5 MHz. Beam steering is demonstrated by creating a near-field reflection phase pattern with different actuation voltages on individual pixels.

2. High contrast grating all-pass filter

The high-contrast grating (HCG) is a single layer of subwavelength grating composed of a high-refractive-index material (e.g. Si or III-V semiconductors) surrounded by low-index materials (e.g. air or SiO2) [9, 10]. The HCG can be designed as a very broadband high reflection mirror (R>0.99, \( \Delta \lambda / \lambda >30\% \)) [9]. It has been implemented as a reflector in vertical-cavity surface-emitting lasers (VCSELs) [11–14] and hollow-core waveguides [15]. HCG has also been used as a piston mirror for optical phased arrays [16], where the phase of the
reflection beam on the HCG can be tuned linearly with the displacement of the HCG. While this approach is simple and straightforward, a long HCG actuation distance is required for a $2\pi$ phase shift, trading off actuation voltage for high speed operation. To overcome this disadvantage, here we construct an all-pass filter using a top HCG and bottom DBR, with carefully designed reflectivity. Optical all-pass filters have been studied before [17–19], and MEMS tunable all-pass filter has been reported for applications as dispersion compensators [19], with a silicon nitride membrane as the front reflector [19]. By replacing the uniform membrane with HCG, one gains the flexibility in controlling the mirror reflectivity and thus the cavity quality factor. By actuating the HCG to tune the length of the etalon across its Fabry-Perot (FP) resonance, the reflection phase of the surface normal incident light experiences a continuous phase change approaching $2\pi$, while the reflection beam power can maintain nearly the same with the incident light. The resonance effect greatly enhances the phase tuning efficiency, i.e. a small HCG displacement for a large phase shift. High speed and low actuation voltage can be achieved at the same time.

Figure 1 shows the schematic of the APF. 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 GaAs and 22 pairs of GaAs/Al$_{0.9}$Ga$_{0.1}$As n-doped DBR. The sacrificial layer is subsequently selectively etched to form a FP cavity with the suspended HCG as a top mirror and DBR as a bottom mirror. To form the all-pass filter, the reflectivity of the DBR is designed to be $>0.9975$ and the HCG $\sim0.9$. 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 $\sim1550$ nm. Each HCG mirror is 20 $\mu$m by 20 $\mu$m in size, and 8x8 individual pixels form the whole optical phased array, with the pitch $\sim33.5$ $\mu$m. The pixels are isolated from each other by deep trenches, and they are individually electrically addressable through the metal fanned-out lines. Figure 2 shows the scanning electron microscope (SEM) image of the fabricated device.

Fig. 1. Schematic of an individual pixel of the optical phased array. 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 in parallel to the grating bar. $\Lambda$, HCG period; $s$, grating bar width; $t_g$, HCG thickness; $d$, air gap between HCG and DBR. We design $\Lambda = 1150$ nm, $s = 700$ nm, $t_g = 450$ nm, and $d = 700$ nm.

Fig. 2. (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 $\sim33.5$ $\mu$m. (b) Zoom-in view of the HCG mirror in a single pixel. The HCG mirror size (without the MEMS) is 20 $\mu$m by 20 $\mu$m.
2.1 Small actuation distance for large phase shift

The HCG can be actuated by applying a reverse electrical bias on the p-n junction between the HCG and DBR. This changes the cavity length and thus the reflection phase of the incident light. Figure 3(a) shows the reflection spectrum of a single HCG APF of the array, for different reversed bias. As the reversed bias increases, the cavity length decreases, resulting in a blue-shift of the resonance wavelength. The measured reflection spectrum is fitted with the standard FP etalon reflection formulation, and the top mirror and bottom mirror’s reflectivity is extracted. The reflectivity of the bottom DBR is extracted to be 0.9965 ± 0.0012, and the reflectivity of the top HCG increases from 0.955 to 0.976 as the wavelength decreases. The HCG reflectivity is higher than the designed value due to an inadvertent inaccuracy in electron beam lithography and etching process.

The reflection phase of an individual etalon versus applied voltages is then characterized by a Michelson interferometer. The result is shown in Fig. 3(b). A total phase change of ~1.7 π is achieved within 10 V actuation voltage range at a wavelength of 1550 nm. The actual displacement of the HCG can be extracted from Fig. 3(a) and the cavity design. For this 1.7 π phase change, the HCG displacement is 50 nm. This demonstrates the high phase tuning efficiency of the APF. The reflectivity of the DBR and HCG can be extracted from this phase measurement by a curve fitting. They are extracted to be 0.9977 and 0.935 respectively, in a reasonably good match with the value extracted from the reflection spectrum measurement.

![Fig. 3. (a) Reflection spectrum of an HCG-APF with different actuation voltages. As the reversed bias voltage increases, the cavity length decreases, resulting in a blue-shift of the resonance wavelength. (b) Reflection phase shift versus applied voltage on a single HCG-APF of the phased array. ~1.7 π phase shift is achieved within 10 V actuation voltage range at a wavelength of 1550 nm; this corresponds to a displacement of ~50 nm of the HCG. The measured results are curve fitted to extract the reflectivity of the DBR and HCG.](image)

2.2 High speed phase tuning

The MEMS HCG is designed to have a high mechanical resonance frequency to facilitate a fast phase tuning. Two different methods are used to characterize the mechanical resonance frequency. The first one is the laser Doppler velocimetry (LDV). A white-noise electrical signal is used to actuate the HCG. A laser is incident onto the HCG, and the Doppler shift of the reflection beam is recorded with respect to time, followed by a Fourier transform to reveal the information in the frequency domain, shown in Fig. 4(a). The mechanical resonance frequency $f_r$ is 0.53 MHz. Alternatively, a step voltage is applied to actuate the HCG mirror, and time resolved phase measurement can be used to extract the mechanical resonance frequency. This time resolved phase trace is shown in Fig. 4(b). The applied voltage changes from 6 V to 7 V at $t = 13.7 \mu s$ and back to 6 V at $t = 33.8 \mu s$. A damped second harmonic oscillator model is used to analyze the ringing trace. The damped mechanical resonance frequency is extracted to be 0.52 MHz, in good agreement with the LDV measurement.
Fig. 4. (a) Laser Doppler velocimetry measurement to characterize the mechanical resonance frequency of the HCG MEMS mirror. (b) Time resolved phase measurement of the HCG APF with a step voltage actuation signal. The blue dots are recorded in the experiment, and red traces are the simulated fitting curve from the second harmonic oscillator model.

In Fig. 4(b), ringing in the phase response is seen. This is not ideal in the practical system. To reduce the ringing, one can break the single voltage step into two steps, i.e. using input shaping technique [20–22]. Instead of changing directly from 6 V to 7 V in the above example, we first change the voltage from 6 V to 6.5 V, hold it for 1 μs, and then change from 6.5 V to 7 V. The same applies for the case when the voltage changes from 7 V to 6 V. The 1 μs corresponds to about half of the ringing period, and thus the individual ringing from these two separate steps would have destructive interference, leading to an overall reduced ringing. The comparison between the single step and two step voltage control is shown in Fig. 5. The phase settles down much quicker when the two-step voltage control is used.

Fig. 5. Comparison of the ringing between a single step and two step voltage control. In the two step voltage control case, the time interval between the two different steps is 1 μs, corresponding to half of the ringing period. The individual ringing from these two separate steps would have destructive interference, leading to an overall reduced ringing.

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. The beam steering experiment setup is similar to that described in [22]. The maximum steering angle is achieved when the phase is alternative between the pixels. This is also defined as half the total field of view (TFOV). Since the pitch of the pixel of the 8x8 array is 33.5 μm, the TFOV is 2.65°, for the operation wavelength of 1550 nm. To increase this, a two-lens system is used to magnify the beam steering angle. This angular magnification ratio is set to be 3.45 in the current experiment, and thus the TFOV is 9.14°.

Figures 6(a) and 6(c) shows various near-field phase patterns on the phased array, and the corresponding measured far field pattern. Both symmetric (column 2–5) and asymmetric (column 6–7) beam steering are performed. The TFOV is shown as the box in dashed line in Fig. 6(c). 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 reflected from the background with a fixed
phase shift, contributing strongly to the zeroth order beam. The ratio between the total power of the steered beams and that of the zeroth order beam is measured to be ~0.5 in the best case. With the consideration of the filling factor, Fourier optics is applied to calculate the far-field patterns, shown in Fig. 6(b). The measured value of the full width beam divergence at the half power point (FWHM) is ~1°. This FWHM is determined by the total size of the array, calculated to be 0.33°, and magnified to be 1.14° by the lens. The experiment is in reasonably good agreement with the calculation results.

![Fig. 6. 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 reasonably good agreement with the calculation. The strong zeroth order beam is due to the relatively low filling factor (~36%). The light that does not hit on the HCG-APF gets reflected with a fixed phase shift, contributing strongly to the zeroth order beam. The field of view of the image windows is 13° x 13°. The box in dashed line in (c) indicates the TFOV of the phased array (9.14° x 9.14°).]

4. Discussion

In the previous sections, we present the HCG all-pass filter, and its application in optical phased array for fast beam steering. While we demonstrate its high-speed and low-voltage operation, there is much room to improve the overall performance of the all-pass filter array. Here we discuss the strategies.

First of all, while the all-pass filter serves as a phase shifter for the incident beam, it also changes the power of the reflection beam, as seen in Fig. 3(a). This is not desirable. To improve this, one can increase the reflectivity of the bottom DBR, by increasing the number of pairs; and meanwhile slightly decrease the reflectivity of the top HCG. Both approaches reduce the reflection loss at the resonance.

Secondly, due to the large number of pixel, there can appear some non-uniformity among the array pixels–more specifically, the non-uniformity in the phase tuning curve shown in Fig. 3(b). In the beam steering experiment, the deviation of the phase from its desired value in each pixel effectively scatters the light into the background and thus reduces the beam steering efficiency. To overcome this problem, one can actively monitor the phase and apply a feedback loop for the phase control on each individual pixel [22].

Thirdly, both the TFOV and the divergence angle of the reflective beam from the phased array are important figure of merits. Their ratio determines the total number of resolvable spots across the TFOV in one dimension. This number is 8 in the device discussed above. The TFOV can be increased by reducing the pixel size; and the beam divergence angle can be decreased by scaling up the pixel numbers. Together, this will boost up the number of resolvable spots in TFOV.

Fourthly, the zeroth order beam appears to be quite strong in Fig. 6. To suppress it, one can increase the filling factor of the phased array. To demonstrate this, we design a high-filling factor array by grouping four pixels together without isolation trenches in between. Furthermore, two dimensional HCG [23, 24] 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. Figure 7(a) shows the SEM image of the two-dimensional HCG mirror for the HCG-AFP array. The HCG mirror size is 20 μm by 20 μm, and the filling factor is ~47%. Beam steering is experimentally demonstrated with the two-dimensional HCG-AFP, shown in Fig. 7(b). Compared to device used for Fig. 6, more power is being beam steered in this case. The ratio between the total power of the steered beams and that of the zeroth order beam is ~1.2. The increased power in the steered beam is also attributed to the improved pixel uniformity of the array.

To further optimize the beam steering performance, a micro-lens 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.

5. Summary

In summary, a novel 8x8 optical phased array using HCG-APF is experimentally demonstrated for beam steering. The key advantage of using HCG APF is its high efficient phase tuning, i.e. small HCG MEMS mirror displacement (~50 nm) for large phase change (~1.7 π), and small voltage actuation (10 V) for fast beam steering (>0.5 MHz). The property of the HCG APF is also temperature independence, since the main cavity is made up of air. 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 reflectivity of the bottom DBR, scaling up the pixel number while reducing the individual pixel size, as well as 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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