Chip-Scale Optical Phased Arrays with Ta Nanostructures

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***Abstract*—We present results on the design and simulation of optical phased arrays made with Si waveguides and Ta scattering elements. We show that multi-element apertures offer advantages in varying the output power level and beam shape, and then demonstrate narrow beams that can be steered by ~20° with thermo-optic tuning.**

Keywords—optical phased array, LIDAR, silicon photonics, beam steering

I. INTRODUCTION

Optical phased arrays (OPAs) have received much attention in recent years as a solution for scanning an optical beam [1-6], with possible applications in LIDAR, freespace optical communications, and stand-off optical sensing. As compared to traditional mechanical beam scanners, OPAs offer advantages in manufacturing, size, speed, and durability. Creating the array presents difficult technical challenges, requiring dense, low-loss optical routing, an ability to manipulate phase, and an efficient output coupler element. Here, we present OPAs created using optimized Ta nanostructures to scatter the light outward from Si waveguides. The devices are fabricated using Sandia's silicon photonics platform and are fully CMOS compatible [7]. This work advances our earlier work [6] and demonstrates scanning of narrower beams across wider angles and utilizing more devices.

II. DESIGN

Beams are synthesized by separately analyzing contributions from the array factor pattern AF and element pattern. These two parts can guide us to a design specifically tailored to a particular array. For instance, we can apodize the coupling strength of the grating elements to reduce sidelobe levels in the beam or optimize the element pattern to either support wide angle steering or reduce unwanted grating lobes.

OPAs rely on the same physical mechanisms that drive traditional RF phased arrays. Coherent electromagnetic waves are emitted from a set of radiating elements. Interference from these waves produces nulls and maxima in the radiating pattern to form a distinct pattern. By setting the phase between each element we can cause the beam to point in a different direction. The array factor AF contribution to the beam is given by [8]

$$AF = \sin\left(\frac{N\psi}{2}\right) / \sin\left(\frac{\psi}{2}\right),$$
$$\psi = \beta d \cos(\theta) + \alpha$$

where α is the inter-element phase, d is the physical separation between elements, β is $2\pi/\lambda$ (λ is the wavelength of light), N is the number of elements and θ is the beam angle. The AF equation predicts that we can achieve a narrower beam width for larger arrays (total length of Nd) and wider spacing between grating lobes for smaller d, eventually reaching single-lobed operation for an array pitch less than $\lambda/2$.

The challenge of making an OPA is scaling the phased array building blocks down to optical wavelength dimensions. Silicon photonics is a natural choice for this task, as it is built on low-loss, high-index-contrast waveguides that can route light through dense networks and manipulate optical phase with thermal and electronic means. An OPA uses all these functions and then sends the light off-chip across a distributed aperture. Output coupling of light in an integrated photonic device has traditionally been accomplished by patterning a grating element directly into the Si waveguide. In our approach, however, we pattern a secondary metal layer that controllably interacts with the waveguides, to create an optimized nanostructure to scatter the light outwards. This alternative approach is motivated by the large index contrast between metals and Si and the wide flexibility it offers for design optimization. We use Ta as the structural material, as it is CMOS compatible, can withstand high-temperature processing, and has lower optical loss than other refractory metals.

We distribute light to the emitter elements using a series feed layout, where all elements are tied to a single bus waveguide and spaced by a distance d. We inject light at one end of the waveguide, and a fraction is scattered outwards each time it encounters an emitter element. As light propagates from one element to the next it picks up phase α which depends on the

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wavelength of light, modal index, and the physical distance between feeds. The phase is varied by heating the waveguide to change the modal index through the thermo-optic effect. Because this is a relatively small change in index, we need a large propagation distance to get a large phase change, and so we introduce serpentine bends between each element (see Fig. 1(a)). This multiplies the phase tuning effect while still allowing for a closely spaced array. Finally, we insert resistive heaters and electrically connect them in parallel so that when a single electrical signal is applied, a uniform phase shift is introduced between each element, allowing us to steer the beam with a simple control scheme [6].

The period of a serpentine array feed is defined by a pair of waveguide bends that create an "S" shape, and we'd normally expect this value to set the pitch of the OPA. We circumvent this restriction and place emitters at each half-period so that the OPA pitch is half that of the waveguide feed and so increase the angular spacing of the beam pattern. Emitters will be fed alternately with upward and downward travelling waves, which could introduce problems in the beam pattern. Thus, this setup is only allowed if each element's beam pattern is identical and symmetric about the surface normal. Asymmetry in the element pattern leads to unwanted grating lobes that begin to reappear in the beam as the OPA pitch is effectively increased to the waveguide pitch.

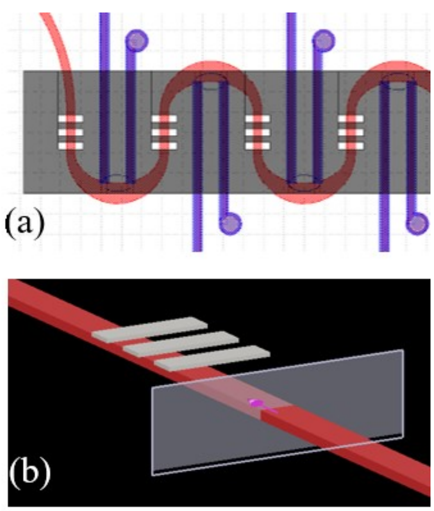

Fig. 1 (a) Image capture from the mask layout file of a meandering 1D array with a triple-aperture grating. (b) Simulation setup showing a waveguide with a triple-bar grating.

Having defined the feed architecture, we need to identify the optimum emitter element for this OPA. Two classes of emitters are studied for this role: single apertures and multi-element structures. In each case, we vary the transverse and longitudinal dimensions of each shape and the distance from the antenna to the waveguide to control the coupling strength and beam characteristics. The performance is evaluated by measuring the far field projections and recording the total upwards radiated power. Our goal is to create a beam that supports wide-angle steering, so we look for designs that produce an isotropic radiation pattern in the region above the nanoantenna. Moreover, we seek designs that change their scattering amplitude by changing the dimensions of the structure, while still maintaining the same basic beam shape, as this will aid in analytic approaches to beam synthesis.

We find that a single aperture offers little control over the amplitude, and the light power tends to be concentrated off-normal (following the same direction as the propagating mode). The optimum nanostructure is a short array of uniform rectangular apertures in a sheet of Ta. The variation of power for different designs is shown in Fig. 2(a). We find that by varying pitch and duty cycle of the apertures we can continuously vary the total upwards power by a factor of nearly 17×. If we further allow the grating count to be 2, 3 or 4 teeth, we can increase this factor to nearly 36×. By carefully balancing these parameters, we can ensure the peak emission is normal to the surface and suitable for the serpentine feed. The far field images in Fig. 2(b,c) come from apertures with 35% and 55% duty cycles and 400-nm spacing between waveguide and Ta layer. Although their total power varies by a factor of 2.7×, we see that the emission patterns are quite similar. Finally, we also consider a complementary structure of isolated Ta rectangles (Fig 1(b)). The advantage of this design is that it minimizes optical losses due to absorption in the metallic layer, but the disadvantage is the design space is rather limited; we can vary the grating pitch to affect the output power but must maintain a 50% duty cycle to keep the beam pointed vertically.

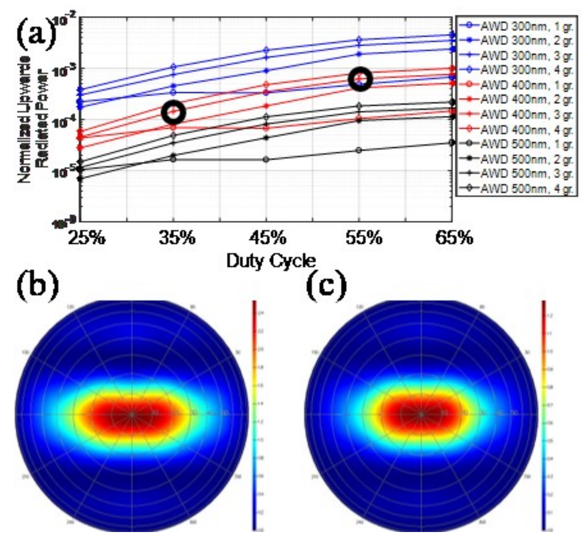

Fig. 2 Simulation results showing (a) upwards power versus aperture size for different numbers of apertures and aperture-waveguide distance, and (b, c) far field projections for the parameters indicated in (a). Duty cycle is defined as the ratio of the width of the aperture to the pitch.

The optimized scattering elements are integrated onto the serpentine waveguide feed (Fig. 1(a)). The elliptical emission pattern is well-suited to produce the desired beam because the phased array orientation is perpendicular to the emitter element array, so the two work together to narrow the beam in two dimensions. Moreover, the large divergence of the element pattern ensures that the beam can steer across the entire field of view with little fading.

III. Results and Discussion

Test structures were created to examine the variation of the scattering strength for the double-bar elements. A cascade of 2×1 splitters evenly distributes the light from a single input to different test devices with different pitch and duty cycle. A summary of the results is shown in Fig. 3. It is seen that decreasing the duty cycle increases the output intensity of each element. The curves show functionality with Λ and suggest we could use this type of output element to shape the emitted beam.

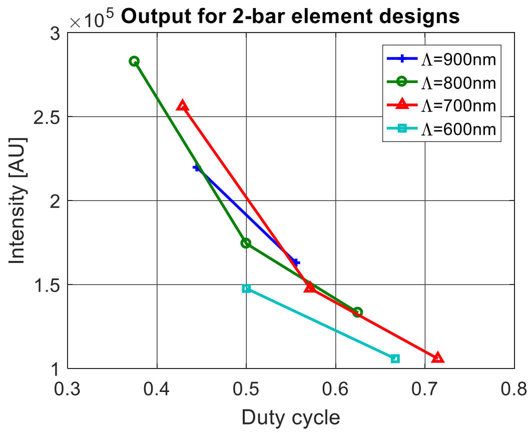

Fig. 3 Measured integrated intensity for different dimensions of double-bar type scattering elements. Duty cycle is defined as the ratio of the width of the Ta bar to the grating pitch Λ.

The experimental near field image of the device in Fig. 1(a) is presented in Fig. 4(a, b), showing the expected exponential decay of the light caused by scattering from each element and optical loss. The far field image (Fig. 4(c)) shows narrow beams of light at -7° and 13°, which represent the main beam and a grating lobe. Each beam has a FWHM of about 0.5°, which closely agrees with analytic solutions of the array factor [7] with an exponentially decaying excitation level. Midway between the bright lobes, we see smaller beams (-8 dBpp), which is where we'd expect to find grating lobes in an array with twice the pitch. Their presence points to an imperfect match between adjacent devices, but this can be counteracted by changing the excitation wavelength from 1550 nm to 1500 nm.

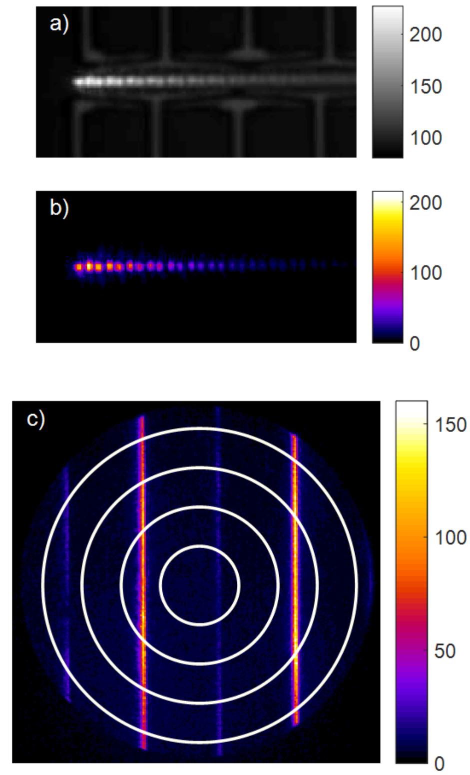

Fig. 4 Near field images of an OPA with triple-aperture elements, fed by a meandering waveguide with bends of R=2.5um (pitch = 4.6μm), a) with and b) without illumination, and c) emitted beam at λ=1550 nm and no electrical bias. Contours are drawn every 5°.

Electronic beam steering of a similar array is shown in Fig. 5, where we apply a voltage signal to a serpentine feed (2μm pitch) with triple-bar scattering elements. Increasing the bias from 0V to 7V steers the beam from -8° to 9°, indicating an inter-element phase shift of 0.8π radians. The beam width varies with bias level, which points to a dephasing in the array. For instance, unequal current injection would mean unequal thermo-optic tuning in each heater, or else heat spreading may lead to an unequal temperature distribution across the array. The first problem could be addressed by using more electrical contacts to control the array. In this case, there were two electrical inputs for 60 heaters. This lets us control the OPA without extra electronic packaging and to understand the operation of ganged control of an array. The second problem could be addressed by using dummy heaters near the array to create a uniform temperature profile.

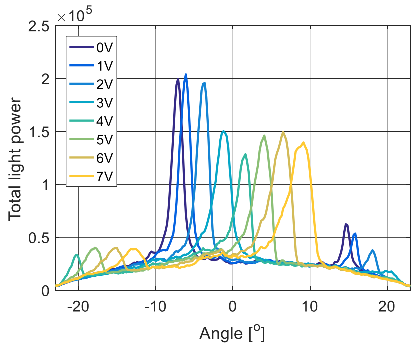

Fig. 5 Beam profiles for a serpentine OPA with triple-bar elements and 2-μm pitch, showing variation versus electrical bias.

IV. Conclusion

We have presented the design and characterization of one dimensional OPAs with narrow beams, wide tuning angle, and simple electrical controls. We find the Ta scattering element offers wide flexibility in optimizing the output beam, but multi-element scatterers are necessary for the best performance. This type of feature is useful in matching the coupling strength of the element to the total length of the array and apodizing the array for lower sidelobe level.

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