Optical Phased Arrays in Silicon on Insulator for Optical Wireless Systems

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Abstract: Optical phased array antennas (OPAs) have significant potential for optical beam steering, which has the application to high speed optical wireless links. In this paper, the characteristics of a two dimensional OPA with a structure composed of 2×2 and 4×4 antenna elements are verified. Beam steering by wavelength tuning of -0.16°/nm is measured and a required steering range of 1.97 ° is achieved within a -3dB coverage range of 5° in the theta direction and 7° in the phi direction.

1. Introduction

The degree of directivity of a beam between a transmitter and receiver has a significant effect on the minimisation of loss and therefore on the maximisation of the data capacity of a wireless communication channel. Phased array antennas have had a major impact upon approaches to beam forming and beam steering in wireless communication systems at radio frequencies [1]. A phased array antenna consists of a collection of antenna elements that are combined in reception by summing their output signals after applying a suitable programmable phase-shift. In transmission, the combiner is replaced by a splitter that distributes the signal to the antennas via the phase shifters. As electromagnetic wave propagation is reciprocal, for the same phase settings, the array has the same radiation pattern in transmission and in reception. By adjusting the phase delays between the elements on the array, the main lobe of the radiation pattern of the array may be steering to a desired angle.

The demand for bandwidth has placed considerable pressure on the crowded the radio frequency spectrum and has lead to the serious consideration of optical wireless links as an alternative approach to high speed wireless communication systems. Optical phased arrays (OPAs) are attractive because of the capability of rapid, high gain and precise beam steering which is possible by tuning the phase relationship between the antenna elements within the arrays which contrast to the slow beam steering capability of bulky optomechanical beam steering devices in present use [1]. The implementation of a fully integrated OPA in a silicon-based material platform is compact and potentially low-cost [2]. In this implementation, the phase tuning is possible using fixed delay lines combined with wavelength tuning and exploiting the thermo-optic effect using waveguide sections equipped with electrical heating elements. [3]. It is possible to achieve to a full beam steering in 2 dimensions by combination of both methods [2].

2. Characteristics of the structures

The individual antenna elements are preferably small to ensure a broad radiation pattern from any individual element to maximise the angular scanning range of the array. Figure 1 shows a schematic of a 4×4 structure [2]. The elements consist of focusing diffractive grating couplers fabricated on silicon on insulator (SOI) photonic integration platform [4]. A grating coupler is one of the most efficient means of interfacing between integrated optical circuits and free space, or an optical fibre. In this structure, a 1D grating coupler was used which is followed (in the uplink direction) by a taper to adjust the lateral size of the incident beam to the submicron waveguide width. Grating couplers are more flexible than edge couplers, because it is possible to locate the structure on any position on the chip, and not necessarily on the edges [2], [4], which also facilitates testing.

The structure was designed on SOI with an oxide thickness of 2µm. The silicon top layer thickness is 220nm with the etching depth of 70nm for making the grating coupler and 220nm for waveguide and multimode interference (MMI) splitters [2]. The SOI platform provides a high contrast waveguide circuits capability which eases the manufacturing and enhances the performance of small components needed for dense integrated circuits. In this structure focusing grating couplers are used to decrease the length of the taper between the grating coupler and the waveguide

[4]. The same element structure was employed in the 2×2, 4×4 and 16×16 arrays that were fabricated.

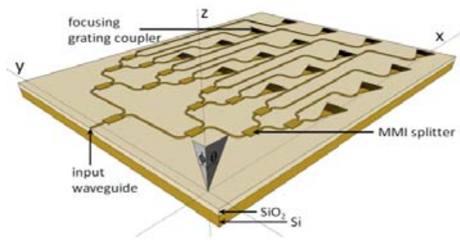

Fig.1 Schematic of a 4×4 OPA on SOI, with the grating couplers as elements [2]

3. Far field radiation pattern of the array antennas

The far-filed radiation pattern is observed by using a microscope of objective to form in its real focal plane the Fourier transform of the field created at the sample and then imaging that plane onto the image sensor of a lens-less camera using a telescope relay [2], [6]. The far field patterns depend on the number and size of elements and the spacing between them on the chip [5]. Figure 2 shows the far field pattern at a wavelength of 1550 nm of a 2×2 OPA with the spacing between the elements of 45 µm in the theta direction and 35 µm in the phi direction

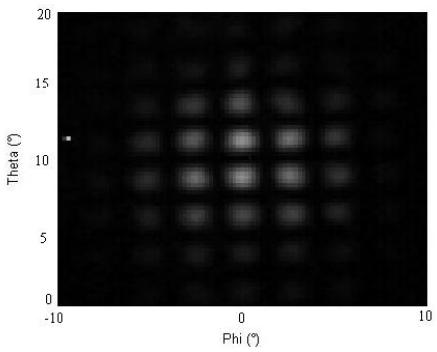

Fig. 2 Measured far field pattern at a wavelength of 1550 nm of a 2×2 OPA

The beam width of the grating lobes are in inverse proportion to the overall size of the array aperture [3], [7].

$$\Delta\theta_{FWHM} \approx \frac{0.886\lambda_0}{N\Lambda\cos\theta}$$

where $\Delta\theta_{FWHM}$ is the Full Width Half Maximum (FWHM) beam width, N is the number of elements, Λ is the distance between elements, and θ is the angular position of the grating lobe, all measured along the relevant dimension of the array.

Table 1 provides the FWHM grating lobe width in theta direction, for the 2×2 and 4×4 arrays with spacing between the elements of 45 µm in theta direction. So, by increasing the number of elements from 4 to 16 in the antenna array, the FWHM beam width of the grating lobe decreases from 0.90° to a narrower grating lobe with a width of 0.58°.

N	d(µm)	$\Delta\theta_{FWHM,\text{th}}$ (Degrees)	$\Delta\theta_{FWHM,\text{meas}}$ (Degrees)
4	45	0.92°	0.90°
16	45	0.46°	0.58°

Table 1. Parameters of the structure of 2D OPA in the θ-direction at the wavelength 1550 nm

4. Beam steering

The array factor is one of the important terms in the calculation of the far field radiation pattern of optical array antennas [8]. The far field radiation is the product of the array factor and the far field radiation pattern of an individual grating coupler. These are calculated as complex amplitudes which are then converted to the radiation intensity pattern by taking the modulus squared and normalising appropriately. Consequently, unimodular phase factors in the individual terms may be neglected in the analysis. The array factor can be written as T(θ,Φ) [2]:

$$T(\theta,\Phi) = \sum_{m=0}^{M-1}\sum_{n=0}^{N-1} A_{mn} e^{-j\boldsymbol{\beta}_{mn}} e^{\mathbf{K}.\mathbf{S}_{\mathbf{mn}}}$$

where $\boldsymbol{K}$ is the wave vector, $\boldsymbol{A_{mn}}$ is the amplitude and β_{mn} is the phase of the signal received or driving the individual element indexed by (n, m) with position vector $\mathbf{S_{mn}}$ [2]. Hence:

$$\mathbf{K}.\mathbf{S_{mn}} = k_0(m\Lambda_x sin\theta + n\Lambda_y sin\Phi)$$

The phase delay for a structure with a waveguide delay section of length ΔL_{mn} is [2]:

$$\beta_{mn} = n_{eff}\frac{2\pi}{\lambda}\Delta L_{mn}$$

where n_{eff} is the effective index for TE-like mode on the waveguide on the chip. This relationship shows that phase tuning is possible by changing the wavelength. This results in beam steering if the delay sections are chosen to have length:

$$\Delta L_{mn} = m\Delta L$$

The angles at which the peaks in the array factor occur can be obtained from:

$$sin\theta = \frac{\mathrm{q}}{\Lambda} + \mathrm{n_{eff}}\frac{\Delta L}{\Lambda}$$

and the steered angle in θ direction can be calculated [2] from:

$$\frac{d\sin\theta}{d\lambda} = \frac{q}{\Lambda} + \frac{dn_{eff}}{d\lambda}\frac{\Delta L}{\Lambda}$$

Where q is the order of the delay and negative in the case of our calculations, and Λ is the spacing between the elements. Figure 3 shows the shift in the far field pattern of a 2×2 OPA by changing the wavelength from 1550 nm to 1552 nm. The beam angle sweep in the θ direction for a wavelength sweep around 1550 nm and a 2×2 structure with 45µm spacing between the elements and 47µm delay line increments was calculated as -0.164° / nm, which closely agrees with the experimentally observed sweep of -0.162° /nm.

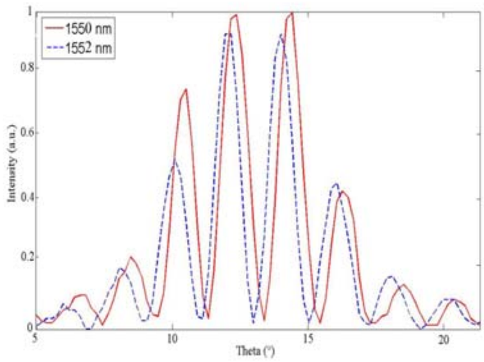

Fig. 3. Shift of the far field pattern in 2×2 OPA by changing the wavelength from 1550 nm to 1552 nm

For a 4×4 structure with the same element spacing and delay line increments in θ direction, the measurement obtained was -0.179°/nm. The reason for this discrepancy with theory is increased experimental uncertainty in the measurement due to the narrower beam width of the 4×4 structure relative to the size of the pixels of the image sensor. This issue caused difficulties in distinguishing between grating lobes in measurements of the far field radiation pattern of 16×16 structures, which had a beam width of only 0.1151°. A 1.97 ° free-spectral range of the grating lobes is predicted by theory and defines the maximum required steering range (the array factor is periodic). The free spectral range of the lobes in both structures was in agreement with theory and the -3dB coverage range due to the radiation pattern of the individual elements is close to 5° in the theta direction and 7° in phi direction, which corresponds to a solid angle of 0.003π sr. For a 2D OPA, beam steering in two dimensions can be completed by thermo-optic phase tuning in the orthogonal direction [4].

5. Conclusions

The characteristics of the far field pattern and beam steering using a 2D OPA were verified. The beam widths of 2×2 and 4×4 structures were obtained in the measurements and agreed with theoretical predictions. The error in the measurements methods used increase as the dimensions of the array increases. Beam steering using a 2D OPA is possible by wavelength tuning with the assistance of delay lines. The beam steering obtained was close to -0.16 °/nm for 2×2 and 4×4 structures with the same parameters for the delay lines lengths and spacing. This value agrees with the theoretical prediction. Beam steering using 2D OPA is possible by combining wavelength tuning and thermo-optic phase tuning.

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