Design of an ultra-compact low-crosstalk sinusoidal silicon waveguide array for optical phased array

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Abstract: In this work, an ultra-compact low-crosstalk sinusoidal silicon waveguide array is proposed and analyzed. We first design a pair of low-crosstalk sinusoidal silicon waveguides with a pitch of 695 nm, where the sinusoidal bends are the key to reduce the crosstalk between waveguides. Then, based on this idea, we propose a low-crosstalk sinusoidal silicon waveguide array with a 695 nm pitch. The simulation results show that for an array length of 100 µm, the insertion loss is as low as 0.08 dB, and the crosstalk is lower than −26 dB at 1550 nm. The 695 nm pitch waveguide array also exhibits a favorable fabrication error tolerance when taking into account the waveguide width variations in practice. Moreover, within the acceptable range of crosstalk, the center-to-center distance between adjacent waveguides of this array can be further reduced to 615 nm. Since the pitch is related to the power consumption and beam-steering range of the optical phased array, our design provides an effective method to build the emitter for an energy-efficient optical phased array with a large field of view.

1. Introduction

Chip-scale optical phased arrays (OPAs) hold promise for ultra-fast inertia-free beam-steering [1], arbitrary beam-forming flexibility [2], as well as CMOS-compatible manufacture at a massive scale [3] due to the rapid development of photonic integrated circuits (PICs). These merits render the scheme a phenomenal candidate for applications including light detection and ranging (LIDAR) [4,5], holographic displays [6], and free-space optical communications [7].

In order to implement a 180° beam-steering range, the pitch of the waveguide in emitter array is required to be 775 nm (a half of 1550 nm wavelength) [8–11]. Note that, light is relatively weak-confined in the dielectric waveguides, which stands in contrast to the electromagnetic wave in the metallic lines. Then, when the pitch in the array is reduced to 775 nm, the crosstalk between adjacent waveguides will increase, preventing independent phase and amplitude modulation between the waveguides. Thus, waveguide emitters of current silicon OPAs are usually placed several micrometers apart, which can effectively reduce the crosstalk but sacrifice the steering range. Therefore, an important research direction of the existing OPAs is to reduce the emitter pitch as much as possible without increasing the crosstalk between adjacent waveguides, and then obtain a large steering range.

To achieve this goal, many schemes have been proposed. For example, by utilizing the sparse array with a non-uniform emitter spacing [4,12–14], the side lobes can be suppressed without affecting the beam-steering process. However, this scheme sacrifices power of the main lobe, which would be unfavorable regarding power-critical applications such as LIDAR. Also, creating large phase mismatch in the waveguide array is another effective method to reduce the crosstalk between waveguide elements, which can be realized by bent waveguides with different radii [9]. Note that, the minimum pitch of such demonstrated emitter array is 800 nm, which is still larger than the half-wavelength pitch. In order to implement a 180° beam-steering range, a low-crosstalk...
half-wavelength pitch waveguide array by minimizing the propagation length is proposed [10]. In that scheme, crosstalk of $-11$ dB is realized at half-wavelength spacing. Note that, such method is maybe not conducive to commercial packaging due to the short waveguide length. Furthermore, an ultra-compact half-wavelength pitch silicon waveguide array with very low crosstalk is proposed [15]. The array is built on a pair of silicon waveguides with half-wavelength spacing. In that design, there are two thin silicon strips located between adjacent waveguides in the array to destroy the geometric symmetry. The insertion loss of the array is as low as 0.13 dB at 1550 nm, and the crosstalk remains below about $-18$ dB. However, the minimum gap between the strip and the waveguide is 27.5 nm, which is challenging in fabrication.

In this paper, we propose a simple but very effective method to build the emitter of the OPA based on a sinusoidal silicon waveguide array. In the design, the waveguide width, gap width, pitch and waveguide length of the array are set to 500 nm, 195 nm, 695 nm and 100 $\mu$m, respectively. For the TE-like mode light, our simulation results show that the insertion loss is as low as 0.08 dB, and the crosstalk is kept below $-26$ dB at 1550 nm. Furthermore, within the acceptable range of crosstalk, the center-to-center distance between adjacent waveguides of this array can be reduced to 615 nm. Since the pitch in the emitter is relative to the steering angle and power consumption as mentioned in the discussion section, our design with a smaller pitch can be used to implement a 180° beam-steering range and effectively reduce the power consumption compared with the waveguide emitter with 775 nm pitch. Thus, we believe this structure provides a functional component to realize an energy-efficient OPA of solid-state LIDARs with a large field of view.

2. Device structure and principle

To illustrate the principle, we first discuss a conventional two-waveguide system which consists of two parallel symmetric straight waveguides, as shown in Figs. 1(a) and 1(b). Two waveguides with same width, $W$ and height, $H$ are separated by a gap, $G$. Here, we define the center-to-center distance between two waveguides as $S$. The optical coupling between these two waveguides can be explained by the super-mode theory. When the light is injected into one of the waveguides, it excites the symmetric and antisymmetric super-modes supported by the structure. And the propagation constants of the two super-modes are $\beta_+$ and $\beta_-$, respectively. When the spacing between two waveguides is large enough, the propagation constants of the two super-modes are equal. However, when the two waveguides are close, the difference of the super-mode propagation constants, $\Delta \beta = \beta_+ - \beta_- \neq 0$, results in the periodic transmission of optical power between waveguides. In two parallel symmetrical straight waveguides, we can express the power transmission coefficient, $t^2$, and the coupling coefficient, $k^2$, along the propagation direction, $x$, as [16]

$$t^2 = \frac{P_{\text{through}}}{P_{\text{in}}} = \cos^2\left(\frac{x}{2} \Delta \beta\right)$$

$$k^2 = \frac{P_{\text{cross}}}{P_{\text{in}}} = \sin^2\left(\frac{x}{2} \Delta \beta\right)$$

where $P_{\text{in}}$, $P_{\text{cross}}$, and $P_{\text{through}}$ are the power of input, cross, and through ports, respectively.

It has been shown both theoretically [17] and experimentally [18] that sinusoidal waveguides in a two-waveguide system depicted in Fig. 1(c) can effectively suppress the power exchange between the waveguides by setting $\Delta \beta_{\text{bent}}$ (the difference of the sinusoidal waveguide super-mode propagation constants) to zero. According to [17,18], $\Delta \beta_{\text{bent}}$ of such system can be expressed as

$$\Delta \beta_{\text{bent}} = \Delta \beta J_0 \left(\frac{4\pi^2(W + G)n_{\text{eff}}A}{P \lambda_0}\right)$$

where $J_0$ is the zero-order Bessel function, $n_{\text{eff}}$ is the effective refractive index of a single waveguide with cross-sectional dimensions $W$ and $H$. Moreover, $A$ and $P$ are the amplitude and
Fig. 1. Schematics of the conventional two-waveguide system and the sinusoidal two-waveguide system, (a) and (b) the 3D view and the top view of the conventional two-waveguide system, (c) and (d) the 3D view and the top view of the sinusoidal two-waveguide system.

The period of a sinusoidal waveguide, respectively, as shown in Fig. 1(d). For the first zero point of the Bessel function, we can obtain the optimal amplitude, \( A_{\text{opt}} \), that can set \( \Delta \beta_{\text{bend}} \) to zero:

\[
A_{\text{opt}} = 2.405 \frac{AP}{4\pi^2(W + G)\eta_{\text{eff}}} \tag{4}
\]

Based on above analysis, we design a pair of sinusoidal silicon waveguides with a 695 nm pitch. The width, height, and period of the waveguides are set to 500 nm, 220 nm, and 10 µm, respectively. And the number of periods are 10. According to analysis, the amplitude is optimized to be 532 nm. The power distribution of such device is simulated by the finite-difference time-domain (FDTD) method, as shown in Fig. 2(a). One can find that the power distribution of sinusoidal silicon waveguides is concentrated on the input waveguide with barely observable crosstalk. The transmission spectrum is shown in Fig. 2(b). Note that, the insertion loss is as low as 0.05 dB, and the crosstalk is lower than \(-27\) dB at 1550 nm.

Fig. 2. Simulation results of a pair of sinusoidal silicon waveguides with 695 nm spacing, (a) the power distribution, (b) the transmission spectrum.
Then, based on this idea and above designed parameters, we propose a low-crosstalk sinusoidal silicon waveguide array, as shown in Fig. 3. The array is built on a 220-nm-thick silicon-on-insulator (SOI) platform. Here, the bottom cladding is silicon oxide (SiO\(_2\)) and the top cladding is air. The refractive indices of SiO\(_2\), air and Si are set to 1.444, 1, and 3.4757, respectively. The length of the array is 100 \(\mu\)m, which is sufficient for the optical waveguide emitter array. Note that, compared with the SiO\(_2\) top cladding, the optical field confinement in waveguides can be enhanced with the air top cladding. Thus, the optical coupling and optical crosstalk can be suppressed. Meanwhile, Eqs. (3)\(\sim\)(4) are derived from sinusoidal two-waveguide system. For the waveguide array, the coupling condition between the nearest waveguides is a little different from that in the two-waveguide system. Based on the coupled mode theory [16] and further simulations, the change of coupling condition might be slight. Thus, these two equations could still be used to obtain the design parameters of the array with a suppressed optical crosstalk. Moreover, the optical performance of the array can then be simulated by FDTD simulations. Furthermore, the number of waveguide elements in our array is set to be 16, due to the limitation of computing resource. A low-crosstalk sinusoidal silicon waveguide array with a larger number of waveguide elements could still be obtained, since the insertion loss and crosstalk of the array are only related to the waveguides close to the input waveguide.

![Fig. 3. Schematic configuration of the sinusoidal silicon waveguide array, (a) the 3D view, (b) the cross-section view (W = 500 nm, H = 220 nm, S = 695 nm, G = 195 nm), (c) the top view (P = 10 \(\mu\)m, A = 532 nm).](image)

In this waveguide array, the mode coupling between the waveguides can be divided into two main categories. The first one involves the coupling between nearest-neighbor waveguides with a 695 nm pitch. As previously stated, by designing sinusoidal two-waveguide system, the crosstalk between the nearest waveguides is greatly reduced. The second category involves the coupling between next-nearest-neighbor waveguides composed of three sinusoidal waveguides, which have more complicated coupling paths (for example, between input waveguide \#i and waveguide \#i+2, light can be coupled from waveguide \#i to \#i+1 then to \#i+2, or from \#i to \#i+2). If the coupling path is from waveguide \#i to \#i+1 then to \#i+2, it can be considered as the coupling between the nearest waveguides. According to the previous analysis, the crosstalk between the two waveguides can be effectively suppressed. Then, we consider the coupling path from
waveguide $i$ to waveguide $i+2$. Note that, the center-to-center distance between them is 1.39 µm. According to Eq. (3), we can calculate its propagation constant difference, $\Delta \beta_{\text{bent}} = -91 \, \text{rad/m}$. Then, the maximum coupling length $L_C$ is $\sim 0.035$ m, which is given by $\pi / \epsilon_D \beta_{\text{bent}} \epsilon$ [18–21]. Therefore, the coupling between waveguide $i$ and waveguide $i+2$ is prohibited by making the length of the array much shorter than the $L_C$. Based on the analysis above, the issue of coupling between the next-nearest-neighbor waveguides can be solved.

The optical performance of our sinusoidal waveguide array is then evaluated by FDTD simulations. Figures 4(a) and 4(b) show the simulated power distribution of the proposed sinusoidal waveguide array and the conventional waveguide array. To illustrate their difference, the input waveguides of both arrays are set to WG8. From the figure, one can find that the power distribution of the sinusoidal waveguide array is concentrated on the input waveguide, while the power launched into the conventional waveguide array diffuses from the input waveguide and gradually begins to couple into most of the waveguides inside the whole array. Note that, similar results would be obtained by selecting other waveguides as input waveguides, since the array is a periodic structure.

The transmission spectra of our proposed low-crosstalk waveguide array are shown in Figs. 4(c) and 4(d). For the TE-like mode, the insertion loss is as low as 0.08 dB and the transmission in all other waveguides is kept below about $-26$ dB at 1550 nm. These superior performance metrics mean that the crosstalk between the input waveguide and the rest of the waveguides in the array is very low. Meanwhile, in our design, the coupling between next-nearest waveguides is suppressed due to the spacing between the waveguides. And, the coupling between nearest-neighbor waveguide is suppressed based on the characteristics of the sinusoidal waveguide. However, due to a slight deviation in design parameters, the coupling between nearest-neighbor waveguides cannot be eliminated to be zero. Based on the simulation, one can find that the crosstalk values of nearest waveguides (WG7 and WG9) and next-nearest waveguides (WG6 and WG10) happen...
to be close. Furthermore, for other waveguides, the coupling becomes weaker as the spacing between WG8 and other waveguides increases.

Figure 5 presents the spectral statistics of the array. In this simulation, each transmission channel from a given input waveguide #i to the output waveguide #j is evaluated. We can note that the insertion loss of all input waveguides are as low as 0.1 dB, and the peaks of all crosstalk channels are in the range from $-30$ dB to $-25$ dB. Hence, the array works well for the LIDAR.

![Figure 5](image1.png)

**Fig. 5.** The transmission statistics of all transmission channels. For light input into a given waveguide #i, transmission of all sixteen waveguides, $j = 1, 2, \ldots, 16$, are measured ($16 \times 16 = 256$ transmission statistics in total for different $i$). The symbol/color for each output channel is shown in the legend.

![Figure 6](image2.png)

**Fig. 6.** The fabrication tolerance of the designed sinusoidal waveguide array. (a) waveguide width variation, (b) sinusoidal amplitude variation, (c) pitch variation, (d) waveguide thickness variation.
In addition, we studied the fabrication tolerance of the designed sinusoidal waveguide array. Figures 6(a)–6(b) show the transmission spectrum and the max crosstalk when a waveguide width variation $\Delta W$, sinusoidal amplitude variation $\Delta A$, pitch variation $\Delta P$, waveguide thickness variation $\Delta H$ are introduced. As shown in Fig. 6, at 1550 nm, the proposed waveguide array still works well with the results that the insertion loss is as low as 0.4 dB, and the crosstalk is lower than $-13$ dB when the fabrication error is as large as $\pm 20$ nm. These results suggest that our proposed sinusoidal waveguide array holds considerable merit in favorable fabrication tolerance.

3. Discussion

For an end-fire OPA, the beam steering is realized by incrementing the phase difference for all elements in the waveguide array given by [5]

$$\sin \theta = \frac{\lambda_0 \phi}{(2\pi S)}$$  (5)

here $\theta$ is the steering angle of the antenna, $\lambda_0$ is the input wavelength, $\phi$ is the phase increment between adjacent waveguides, which is changed by phase shifters connected to each waveguide in a real array. And $S$ is the center-to-center distance between adjacent waveguides. According to Eq. (5), for a certain $\theta$, the ratio of $\phi/S$ can be determined. Thus, if $S$ decreases, $\phi$ also decreases. Note that, $\phi$ is in a proportional relationship with the power consumption, which could be expressed as [5,10,22]

$$\phi = \alpha P$$  (6)

where $P$ is the power consumption, and $\alpha$ is a constant related to the way of the phase control. Therefore, $S$ is proportional to the power consumption of the OPA in the beam steering application. Then, we define a factor $P_{\text{saved}}$, which is the ratio of the power saved by our array as the emitter of the optical phased array to the power consumed by the array with 775 nm pitch in the case of steering the same angle, that is $P_{\text{saved}}=(P_0-P_1)/(P_0=(S_0-S_1)/S_0$. Here, $P_0$ is the power consumption of the array with a pitch ($S_0$) of 775 nm, while $P_1$ is the power consumption of our designed array with a smaller pitch $S_1$. Thus, compared with an emitter array with the pitch of 775 nm, $P_{\text{saved}}$ is 10% for the emitter based on our 695 nm pitch array and 10% power can be saved in the beam steering.

Moreover, we study the minimum waveguides spacing that can be implemented for such sinusoidal waveguide array. As waveguide spacing decreases, we only change the amplitude of the sinusoidal waveguide to suppress the crosstalk. In this regard, we set crosstalk less than $-10$ dB as an acceptable standard. Simulated results are presented in Table 1, where IL is the insertion loss of input waveguide, $CT_{\text{max}}$ is the max crosstalk in all other waveguides. When the pitch between waveguides is 655 nm, the amplitude is set to 557 nm. The transmission of WG8 (input waveguide) remains a very low insertion loss of only about 0.1 dB, and the crosstalk remains below $-22$ dB. Also, when the pitch between waveguides is 615 nm, the amplitude is set to 584 nm. In this condition, the insertion loss of WG8 (input waveguide) is as low as 0.78 dB, and the crosstalk in all other waveguide remains below about $-12$ dB. Compared with the emitter based on a 775 nm pitch waveguide array, $\sim 21\%$ power can be saved if 615 nm pitch sinusoidal waveguide array is used.

| Pitch (nm) | IL (dB) | $CT_{\text{max}}$ (dB) | $P_{\text{saved}}$ |
|------------|---------|------------------------|-------------------|
| 695        | 0.08    | $-26.05$               | 10.3%             |
| 655        | 0.10    | $-22.34$               | 15.5%             |
| 615        | 0.78    | $-12.79$               | 20.6%             |
Figures 7(a) and 7(b) show the corresponding simulated power distribution of arrays with a pitch of 655 nm and 615 nm, respectively. From the figures, we can see that the power distribution of the both arrays is concentrated on the input waveguide, while the power of the 615 nm pitch waveguide array gradually slightly couples into WG7, WG9, WG6 and WG10 as the propagation distance increases.

4. Conclusion

In conclusion, we have proposed and analysed the design of a low-crosstalk sinusoidal silicon waveguide array for the emitter of the OPA. Our analysis shows that this 695 nm pitch array has an insertion loss less than 0.08 dB and crosstalk less than −26 dB. The numerical simulation shows that the waveguide array is also robust to reasonable fabrication errors for the variation of the waveguide width. Within the acceptable range of crosstalk, we discuss the minimum waveguide spacing of the array that can be implemented. Analysis results show that the sinusoidal waveguide array has an insertion loss less than 0.78 dB, and the crosstalk in all other waveguides remains below about −12 dB at a 615 nm pitch. Since the pitch in the emitter is relative to the power consumption and the steering angle, our design can be used to implement a 180° beam-steering range and also effectively reduce the power compared with the waveguide emitter with 775 nm pitch. To the best of our knowledge, it is one of the waveguide array with smallest spacing proposed to date. We believe that this kind of silicon waveguide array will be very promising in realizing the integrated OPAs of the solid-state LIDAR with a wide-angle beam control range.

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Disclosures

The authors declare no conflicts of interest.

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