An ultra-compact half-wavelength pitch silicon waveguide array with very low crosstalk is proposed and analyzed in this work. We first show the design of a pair of low-crosstalk silicon waveguides with only half-wavelength spacing, where the placement of two thin silicon strips asymmetrically in between the waveguides is key to having very low crosstalk. We next extend this nano-structured two-waveguide design to form a low-crosstalk half-wavelength pitch silicon waveguide array. Coupled-mode theory shows that, for an array length of 1 mm, the insertion loss of the input waveguide is as low as \(-0.13\) dB for the TE-like mode at 1550 nm, and the crosstalk in all other waveguides remains below about \(-18\) dB. This half-wavelength pitch waveguide array also exhibits a favorable fabrication error tolerance when taking into account the waveguide width variations in practice. It offers a promising platform for realization of integrated optical phased arrays for solid-state lidars with a large field of view.

Integrated on-chip silicon optical phased arrays (OPAs) are one of the crucial parts in light detection and ranging (lidar) that are used in many applications (e.g., autonomous vehicles and aerial mapping) due to their capability of solid-state beam steering [1–6]. In order to implement 180° beam-steering range, it requires that the pitch of a periodic optical waveguide emitter array shall be one-half of the wavelength [6]. However, at such a small pitch, crosstalk between adjacent conventional optical waveguides is very strong, preventing independent phase and/or amplitude control of emitters fed by these waveguides. For current silicon OPAs, there is a strong tradeoff between their steering angles and the pitches of the feeding arrays, and their waveguide emitters are thus usually placed micrometers apart to alleviate crosstalk but sacrifices steering angles [2,5]. For an ordinary OPA with half-wavelength pitch, crosstalk can be suppressed directly by minimizing the propagation length [7], while its size is too small for practical commercial applications.

To solve this problem, several methods have been put forward. For instance, novel nanophotonic structures such as metamaterial waveguides [8,9], corrugated waveguides [10], and non-uniform sparse apertures [11] can be used to implement a low-crosstalk OPA. Also, creating large phase mismatches in the waveguide array is another effective approach to decrease crosstalk between waveguide elements. It can be realized by way of a curved waveguide array [12,13] or varying the width of waveguides [6,14], which have been proven extremely successful in suppressing crosstalk in closely spaced OPAs with pitches down to one half of the wavelength [6,12].

In this Letter, we propose an all-dielectric-based nano-structured silicon photonic waveguide array with a pitch of one half of the wavelength at 1550 nm. It contains only two basic repeating elements, i.e., a pair of largely phase-mismatched silicon waveguides with the exact same width but having two asymmetrically placed thin silicon strips in their gap. We show that when these two strips are properly positioned, the splitting of mode indices can be considerable resulting in a strong phase mismatch and thus inhibiting the power transfer between waveguides. The asymmetric placement of the strips also facilitates the extension of this nano-structured two-waveguide design to form a low-crosstalk half-wavelength pitch silicon waveguide array by alternately flipping the positions of these two strips in the gaps of the waveguide array. Our theoretical investigation suggests that this array exhibits \(-0.13\) dB insertion loss (IL) for a length of 1 mm and \(-26.08\) dB peak crosstalk between nearest-neighbor waveguides at 1550 nm, which agrees well with our numerical simulations. Our concept here offers an effective and feasible approach to significantly reduce the crosstalk in closely packed waveguide arrays, shedding light on the possibilities of realizing solid-state lidars with large beam-steering angles.

Our proposed two-waveguide structure is designed on a silicon-on-insulator (SOI) wafer with a 220 nm top silicon layer on a buried silicon-dioxide layer, as shown in Fig. 1(b). Different from the conventional coupled two-waveguide system in Fig. 1(a), our structure contains additional two thin strips asymmetrically placed between two neighboring
waveguides. In this system, the crosstalk $P_{1-2}/P_1$ can be given by [15]

$$P_{1-2}/P_1 = F \sin^2 \left( \frac{\pi L}{2L_C} \right),$$  \hspace{1cm} (1)

where $L_C = \pi/[2\sqrt{(\Delta \beta/2)^2 + \kappa^2}]$, $F = 1/[(\Delta \beta/(2\kappa))^2 + 1]$, and $F$, $L$, $\Delta \beta$, $\kappa$ represent the maximum crosstalk $(P_{1-2}/P_1)_{\text{max}}$, propagation length, propagation constant difference, and coupling strength, respectively. Because when $L$ equals $L_C$, crosstalk $P_{1-2}/P_1$ reaches maximum, i.e., $F$, increasing $L_C$ to a value far larger than the waveguide length and decreasing $F$ to almost zero are the two most effective approaches to lower crosstalk. Here, we use the second approach, but in our case, as shown in Fig. 1(b), we use two exactly the same silicon waveguides instead of different waveguides [6,14]. The mode symmetry of these two identical waveguides is broken by the introduction of two thin silicon strips asymmetrically placed in the gap of the waveguides. These two strips perturb the evanescent mode fields of the two identical waveguides. In this way, a strong phase mismatch could be achieved that can lead to a very small $F$. To illustrate the efficacy of our approach, we set the wavelength of operation $\lambda$ to be 1550 nm, and the corresponding refractive indices of Si, SiO$_2$, and air are set as 3.4757, 1.444, and 1, respectively. The width of two silicon waveguides is set as 500 nm to support a single TE-like supermode (major electric field component along $x$ axis) of the 16-waveguide array calculated by CMT (blue colored symbols) and COMSOL Multiphysics (red colored symbols), respectively. Overall, the calculated indices by these two approaches are in good quantitative agreement. The supermodes

The low-crosstalk two-waveguide structure can be used as a building block to build an array of low-crosstalk half-wavelength pitch silicon waveguides. It is formed by alternately flipping the locations of these two strips within the gaps of the waveguide array, as shown in Fig. 2. There are only two repeating composite nano-structured waveguides [i.e., WG A and WG B denoted in Fig. 2(a)] in our proposed array. Peak crosstalk between nearest-neighbor waveguides is largely reduced due to large phase mismatch between WG A and WG B, and the coupling length between next-nearest-neighbor waveguides is increased drastically, which is very helpful in reducing the crosstalk for a short array. In detail, the number of silicon waveguides in our array $N$ is set to be 16 for an illustration purpose, and its eigenmodes and light propagation behavior are calculated via coupled-mode theory (CMT) [17,18] and verified by numerical simulations using COMSOL Multiphysics and three-dimensional finite-difference time domain (3D FDTD).

Figure 3(a) illustrates the effective index of each quasi-TE supermode (major electric field component along $x$ axis) of the 16-waveguide array calculated by CMT (blue colored symbols) and COMSOL Multiphysics (red colored symbols), respectively. Overall, the calculated indices by these two approaches are in good quantitative agreement. The supermodes

![Fig. 1. Cross-section diagrams of (a) conventional and (b) our proposed coupled two-waveguide system. The calculated (c) peak crosstalk $10 \log (F)$ and (d) $L_C$ versus different locations $(x_1, x_2)$ of two 60-nm-wide silicon strips at $\lambda = 1550$ nm. The parameters used in calculations satisfy: $s = 775$ nm, $-s/2 + 280$ nm $< x_1$, $x_2 < s/2 - 280$ nm, $x_2 - x_1 > 60$ nm.](image1)

![Fig. 2. Schematic configuration of our proposed waveguide array. (a) Cross-section view. (b) 3D view. The light propagation direction is $x$ axis.](image2)

![Fig. 3. (a) Effective indices of 16 quasi-TE eigenmodes in three sets: a boundary set (circle), an odd set (upward-pointing triangle), and an even set (downward-pointing triangle). Blue and red symbols are results calculated by CMT and COMSOL Multiphysics, respectively. (b)–(e) Normalized intensity profiles of two typical modes (b), (c) mode 2 and (d), (e) mode 3) from the even and odd sets by using COMSOL Multiphysics and CMT, respectively.](image3)
can be grouped into three different sets. The first set contains all the boundary modes with their main field localized in the boundary waveguides [circles and denoted as modes 1 and 16 in Fig. 3(a)]. The second set is an even set that contains all the modes with their main field localized in even-numbered waveguides [downward-pointing triangles and denoted as modes 2, 4, 6, 8, 10, 12, and 14 in Fig. 3(a)]. The normalized intensity profile of a typical mode from this set is obtained using COMSOL Multiphysics and CMT and plotted in Figs. 3(b) and 3(c). The last set is an odd set that accounts for all the modes with their main field localized in odd-numbered waveguides [upward-pointing triangles and denoted as modes 3, 5, 7, 9, 11, 13, and 15 in Fig. 3(a)]. A typical example of the mode from this set is plotted in Figs. 3(d) and 3(e). In practice, the boundary states can be ignored by adding dummy waveguides to both sides of the array, and here we focus on the other two sets in the following discussions. Mode coupling in this array can be classified into two major categories. The first one involves coupling between next-nearest-neighbor waveguides that are either odd numbered or even numbered. In this case, the coupling issue can be solved by eigenmode decomposing with eigen basis composed of all the modes in the same set with a matching parity to the waveguides. Notice that the mode effective indices are highly degenerate in either of the two sets with the largest effective-index difference $\Delta n_{\text{eff}}$ about $10^{-5}$, corresponding to a shortest $L_C$ on the order of $10^{-2}$ m. Therefore, the coupling and crosstalk between next-nearest-neighbor waveguides is prohibited by making the length of the array much shorter than the $L_C$. The second category involves coupling between nearest-neighbor waveguides that consist of one odd-numbered waveguide and one even-numbered waveguide. Eigenmode decomposition of the initial field in these two waveguides results in both sets of the eigenmodes. Because the average effective-index difference $\Delta n_{\text{eff}}$ between the two sets is about 0.04, corresponding to a large phase mismatch for the inter-set modes, the crosstalk between nearest-neighbor waveguides is largely reduced.

The mode information above is used to study the transmission properties and crosstalk performance of our silicon waveguide array. For an illustration purpose, the length of the array is set as 1 mm, and the input waveguide is set to the seventh waveguide (WG7). The results shown in Figs. 4(a) and 4(b) indicate that the transmission of WG7 remains almost unity with a very low IL of only about $-0.13$ dB, and the transmission of all other waveguides remains below $-18$ dB. These superior performance metrics imply very low crosstalk between the input waveguide and the rest of the waveguides in the array, and in fact, the crosstalk is below $-26$ dB for nearest-neighbor waveguides. There are also a few other interesting properties of this array. Notice that the waveguides that are symmetrically about WG7 have almost the same transmission due to negligible boundary effect and week power coupling between waveguides. The transmission in all even-numbered waveguides has a clear oscillatory pattern with an oscillation period roughly equal to $2L_C$ as the propagation length increases, while the transmission in all the odd-numbered waveguides, except the input WG7, increases monotonically due to a large coupling length between next-nearest-neighbor waveguides. In addition, for either even-numbered waveguides or odd-numbered waveguides, the coupling from WG7 becomes weaker as the spacing between two waveguides increases. Therefore, the peak transmission decreases monotonically for waveguides farther away from the input waveguide.

The transmission behavior of our proposed low-crosstalk array is investigated via full vectorially 3D FDTD. The device length here is limited to a shorter length, 100 μm as opposed to 1 mm in analytic CMT calculation, in order to run the FDTD simulation within our computational capability. Nevertheless, the characteristic propagation behavior of this array can still be illustrated here. Figures 4(c) and 4(d) depict the intensity distribution of our array and, for comparison, a conventional waveguide array without any strips placed in between waveguides. The input waveguide for both arrays is set as WG7. Clearly, the power launched into the conventional waveguide array spreads out from the input waveguide and gradually starts to couple into a good portion of the waveguides inside the whole array, while the power launched into our proposed array is tightly concentrated in the input waveguide with barely observable crosstalk. It is also further verified from the numerical simulation data that the peak crosstalk from WG7 into WG6, 8 and WG5, 9 are $-26.3$ dB and $-41.2$ dB, respectively, and these numbers are in good qualitative agreement with our analytic results from CMT discussed above.

In practice, both light scattering induced by microscopic waveguide width variations due to the fabrication errors [14,19,20] and constant changes in fabricated waveguide dimensions from designed dimensions may account for major crosstalk fluctuations in our proposed low-crosstalk silicon waveguide array. Here, we focus mainly on their impacts on the crosstalk fluctuation in our proposed array, and the results discussed below are obtained by assuming a 1 mm long 16-waveguide array with WG7 as the input one. For the first case, the width variation can be modeled as sidewall roughness with two parameters, the standard deviation of the waveguide width ($\sigma$) and its autocorrelation length ($l_c$) along the waveguide [20–22]. In general, waveguide sidewall roughness depends on both lithography and etching processes, and considering the use of electron beam lithography (EBL) for fabricating our array in future, it typically results in $\sigma$ and $l_c$ on the order of a few nanometers and a few dozens of nanometers, respectively [14,19,23]. Table 1 shows the effect of sidewall roughness on the transmission and crosstalk fluctuation in our proposed low-crosstalk silicon waveguide array.

![Fig. 4. Power transmission as a function of the propagation length. (a), (b) Transmission calculated by CMT for the odd-numbered waveguides and even-numbered waveguides, respectively. (c), (d) Numerically simulated normalized intensity distributions for our array and a conventional array as a comparison.](image-url)
roughness on the crosstalk of our array for several sets of roughness parameters. In our calculations, based on each set of roughness parameters in Table 1, the width variations of both silicon waveguides and strips have been analyzed, and 100 arrays are generated statistically with normal distributions and then analyzed via CMT. Our results show that the crosstalk between the input waveguide WG7 and its neighboring waveguides WG5-6 and WG8-9 is hardly affected by the sidewall roughness. The averaged crosstalk for arrays with modeled sidewall roughness remains the same as that of an ideal array, and its standard deviation is at least four orders of magnitude smaller than the averaged crosstalk. For the second case, Table 2 presents the calculated crosstalk performance of our array with constant changes in waveguide width, which varies monotonically from −20 to 20 nm. The results show that the proposed array works well despite such common discrepancies in waveguide width. These results strongly suggest that our proposed nano-structured silicon waveguide array holds considerable merit in favorable fabrication tolerance.

In conclusion, we have proposed the design of a half-wave-length pitch silicon waveguide array with significant crosstalk reduction. The array is built on a pair of silicon waveguides with half-wavelength spacing. This particular pair of waveguides has two silicon nano-strips placed asymmetrically in their gap that break their geometric symmetry, giving rise to below −20 dB crosstalk. By alternatively flipping the spatial arrangement order of this pair of waveguides, a low-crosstalk half-wave-length pitch silicon waveguide array is created. Our analysis shows that this array has an IL less than −0.13 dB and peak crosstalk less than −26 dB between nearest-neighbor waveguides and close to −19 dB between next-nearest-neighbor waveguides. Our results indicate that our design is also robust to reasonable fabrication errors coming mainly from the waveguide width variations. We believe this silicon waveguide array could be very promising in realizing the integrated OPAs for solid-state lidars with wide-angle beam-steering range.

### Table 1. Effect of Sidewall Roughness on the Crosstalk Performance of Our Proposed Array

<table>
<thead>
<tr>
<th>Sidewall Roughness</th>
<th>IL (dB)</th>
<th>Peak Crosstalk (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ = 0, l = 0</td>
<td>−0.13</td>
<td>−0.14</td>
</tr>
<tr>
<td>σ = 3 nm, l = 30 nm</td>
<td>−0.13 (7.87 × 10⁻⁶)</td>
<td>−0.14 (3.13 × 10⁻⁵)</td>
</tr>
<tr>
<td>σ = 5 nm, l = 30 nm</td>
<td>−0.13 (1.31 × 10⁻³)</td>
<td>−0.13 (2.02 × 10⁻³)</td>
</tr>
<tr>
<td>σ = 7 nm, l = 30 nm</td>
<td>−0.13 (1.84 × 10⁻⁵)</td>
<td>−0.13 (3.21 × 10⁻⁵)</td>
</tr>
</tbody>
</table>

### Table 2. Effect of Constant Changes in Waveguide Width on the Crosstalk Performance of Our Proposed Array

<table>
<thead>
<tr>
<th>Waveguide Width (nm)</th>
<th>IL (dB)</th>
<th>WG7</th>
<th>Peak Crosstalk (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>480</td>
<td>−0.17</td>
<td>−24.92</td>
<td>−17.37</td>
</tr>
<tr>
<td>490</td>
<td>−0.14</td>
<td>−25.51</td>
<td>−18.92</td>
</tr>
<tr>
<td>500</td>
<td>−0.13</td>
<td>−26.08</td>
<td>−18.95</td>
</tr>
<tr>
<td>510</td>
<td>−0.14</td>
<td>−26.52</td>
<td>−18.69</td>
</tr>
<tr>
<td>520</td>
<td>−0.16</td>
<td>−26.96</td>
<td>−18.13</td>
</tr>
</tbody>
</table>

### Funding.
National Basic Research Program of China (2015CB659400); Natural Science Foundation of Jiangsu Province (BK20150057); Fundamental Research Funds for the Central Universities (021314380100).

### REFERENCES