Reduction in Crosstalk Using Uniform Germanium Strips for Dense Integration of Photonic Waveguides

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Abstract
The requirement of low crosstalk between the neighboring waveguides should be considered essentially, in order to achieve the compact photonic integrated circuit (PIC), which includes photonic waveguides. Literature shows that the lower crosstalk can be realized by using the silicon-on-insulator (SOI) based waveguide, having an appropriate separation between them. The current work is focused on reducing the waveguide separation to further improve the photonic integration over the PICs. This has been achieved by inserting the germanium strips between the photonic waveguides. The investigations of the impact of variations in heights and widths of germanium strip have demonstrated that the crosstalk can be reduced by a significant amount, which provides noteworthy improvement in coupling length. The maximum coupling lengths of 81,578 μm, 67,099 μm, and 66,810 μm have been achieved at their respective end-to-end separations of 300 nm, 250 nm, and 200 nm, and their corresponding minimum crosstalk values have been noted as −29.40 dB, −27.71 dB, and −27.70 dB. Moreover, the analysis to realize the coupling length for Ge-strip, have been compared with the Si-, and Si₃N₄-strips. The approach presented in the current work can be utilized for the design of many compact photonic applications, such as polarization splitter, integrated photonic switches, etc.

Keywords Photonic waveguide · Germanium strip · Coupling length · Crosstalk

1 Introduction
The photonic waveguides and its related devices are attracting more and more attention due to its high bandwidth capabilities, very less propagation delay time, and smaller size. Different structures of photonic waveguide, such as strip, rib, and slot waveguide, can be used for different applications [1, 2]. The realization of dense photonic integration is essentially required for the efficient and compact design of photonic integrated circuits (PICs), where the array of waveguides is closely placed [3, 4]. However, due to the reduced waveguide spacing, some part of the field may couple with the field of the adjacent waveguides, which may result in higher crosstalk (CT) on the array of waveguides. Hence, the reduction of the crosstalk between the nearby waveguides is a crucial and challenging issue, to produce the compact and dense PICs [5]. However, the high-index and low-index regions of the photonic waveguide, with comparatively larger refractive-index contrast, may results in significant light confinement through the core of photonic waveguides. Hence, it causes the smaller crosstalk between the nearby waveguides, and supports to the denser packing of the PICs. Recently, many authors have proposed different techniques to reduce the crosstalk between the adjacent photonic waveguides [6, 7]. The authors in [7] have presented the approach of subwavelength silicon-gratings technique for the photonic waveguide, to manipulate the guided light over the PICs, and hence, to reduce the crosstalk. The silicon gratings show the high index, in the parallel direction of the interface. This leads to the fast decay of evanescent field, which is essentially leaked from the waveguide core. Based on this principle, the investigations of the three subwavelength strips between two adjacent waveguides have been done in [8], to improve the crosstalk performance. The authors in [8] have demonstrated the negligible crosstalk for the waveguide...
spacing of 350–500 nm, at the wavelength of 1.55 μm. The method presented by the authors is effective for both strongly- and weakly-confined photonic modes, for a wide range of operational wavelengths. Further, by changing the dimensions of the silicon strip array, it is possible to control the penetration depth of the evanescent waves, and hence, the coupling lengths between waveguides [9]. The authors have obtained the higher coupling lengths of 2.1 mm, 8.5 mm, 3.32 cm, 1.71 cm, and 1.07 cm, corresponding to the number of strips of one, two, three, four, and five, respectively; while, the waveguide separation has been considered as 500 nm. Further, many applications based on the coupling phenomenon of the compact photonic waveguides have been reported recently in literature, such as polarization/mode converters [10, 11], ultra-sharp waveguide bends [12], integrated photonic switches [13], etc.

The current work is focused on the investigations of the mode characteristics of the silicon waveguide, to comprehend its performance in respect of the crosstalk, and scalability. For the considered structure with two photonic waveguides, the height, and width have been considered respectively as, 220 nm, and 500 nm, which represents the one of the standard photonic waveguide dimension. Some of the authors have reported the attenuation loss [14] and group velocity dispersion [15], for the individual photonic waveguide with its standard dimensions, including the above considered dimension. As in the current work, the photonic waveguides have the standard dimensions of 220 × 500 nm; hence, it can be considered that its attenuation loss as well as group velocity dispersion is at its acceptable level, to achieve the compact design of photonic waveguide structures over the PICs. The analysis has been done for the different end-to-end waveguide spacing, ranging from 200 nm to 300 nm. The authors in [8] have reported 1000 μm of coupling length, for the waveguide separation of 300 nm. However, in the current work, by using three uniform germanium strips with their height variations, the coupling length of ~81,578 μm, has been obtained for the same waveguide spacing. Furthermore, with the lower waveguide spacing of 200 μm, the coupling length up to 66,810 μm has been obtained, which ultimately demonstrates very low crosstalk, and hence, dense photonic integration over the PICs.

2 Design Structure and Parameters

2.1 Design of Proposed Structure

The design of the proposed structure has been illustrated in Fig. 1, which consists of two adjacent ridge waveguides, with three germanium strips inserted between them. The widths of core of ridge waveguide, and inserted strips have been denoted respectively as, w1, and w2; whereas, their respective heights are considered as h1, and h2. The end-to-end waveguide spacing, and the strip gaps have been assumed respectively as, g1 and g2; while, the spacing between ridge waveguide to strip has been kept as g2. Moreover, for the mode analysis, the height of strips have been varied. The material used for core of ridge waveguide is silicon, while the same for the strip is germanium, with their respective refractive index values of 3.45 and 4.21, at the operating wavelength of 1.55 μm [16, 17]. Therefore, in the current investigations, two photonic waveguides have been considered with strips in between them, and the waveguide dimensions have been chosen precisely to satisfy the single-mode propagation. Therefore, in the calculation of coupling length only fundamental mode has been considered. In literature [18, 19], it has established that for this type of photonic waveguide structures, the fundamental TE mode dominates. Hence, the current work is mainly focused on the fundamental TE propagating mode, and for the estimation of the coupling length, the effective refractive indices of both the symmetric and antisymmetric modes (i.e., n_s and n_a) have been considered. Further, the other materials have also been used for the strips, such as, Si and Si3N4, where, Si3N4 has the refractive index of approx.1.9, at the operating wavelength of 1.55 μm. At this operating wavelength, the refractive index contrast of Si-Air-Si (3.48–1-3.48) is lesser than the refractive index contrast of Si-Air-Ge (3.48–1-4.21), as the refractive index contrast of Ge-Air is decently greater than that of the Si-Air. The authors in [3] have examined the impact of insertion of strip, which leads into high index contrast, and presented its influence on coupling length.

2.2 Coupling Length

Basically, during the light propagation through the photonic waveguide, there may be some amount of leakage of light, which may cause the coupling of modes with the adjacent photonic waveguide. The length over which the optical power is fully transferred from one waveguide to the adjacent waveguide, is known as the coupling length [11]. Therefore, the photonic waveguide having length greater than the coupling length, may have the negligibly small power in the parent
photonic waveguide, and more power in adjacent waveguide. Therefore, the main focus of the current work is to obtain the higher coupling length between two neighboring waveguides, in such a way that the individual signals in both the nearby waveguides can propagate effectively. The coupling length can be expressed as [20],

\[ L_c = \frac{\lambda}{2(n_s - n_a)} \]  

where, \( n_s \) and \( n_a \) represent respectively the real part of symmetric and antisymmetric mode indices, and \( \lambda \) is the operating wavelength.

### 2.3 Propagation Length

The propagation length can be expressed as the waveguide length over which the propagating power reduces to \( 1/e \) of its total power, and can be expressed as [20],

\[ \text{Propagation length} = \frac{\lambda}{4\pi \times \text{Im}(n_{\text{eff}})} \]  

Hence, it is clear that propagation length is highly dependent on the imaginary part of the effective refractive index, i.e., \( \text{Im}(n_{\text{eff}}) \), of the guided photonic mode.

### 2.4 Crosstalk (CT)

The closely placed photonic waveguides over the PICs, may cause the overlap of their individual mode fields, and hence, there may be crosstalk [21, 22] between them. Therefore, the investigations on crosstalk performance between the two nearby photonic waveguides, is essentially required to achieve the high photonic integration in the photonic chip. The crosstalk between two neighboring waveguides can be estimated as [20, 21],

\[ \text{Crosstalk(CT)} = 10 \log_{10} \left[ \sin \left( \frac{\pi L_0}{2L_c} \right) \right]^2 \]  

where, \( L_0 \) and \( L_c \) are respectively the propagation distance, and the coupling length. Further, the value of \( L_c \), is reliant on the waveguide spacing and waveguide dimensions. It has been observed that with a larger gap between the waveguides, a larger coupling length can be achieved, after the propagation distance, and hence, introduces a smaller crosstalk [21]. Therefore, in this work, the main focus is to realize the significantly larger coupling length.

### 3 Simulation Results

The modal investigations in the current work, have been done with the help of the finite element method (FEM) based COMSOL Multiphysics. To discretize the waveguide geometry model, the extremely fine mesh size has been chosen for the simulations. Further, to address the losses during the mode propagation, the scattering boundary condition has been used. The height \( (h_1) \) and width \( (w_1) \) of both the ridge waveguide have been fixed respectively as, 220 nm, and 500 nm. Moreover, the width \( (w_2) \) of the strip, and spacing \( (g_2) \) between the strips are related with an empirical relationship: \( 3w_2 + 4g_2 = g_1 \). In this work, three different values of end-to-end waveguide spacing have been considered, i.e., \( g_1 = 300 \text{ nm}, 250 \text{ nm}, \text{ and } 200 \text{ nm} \), with \( w_2 = 30 \text{ nm}, \text{ and } 50 \text{ nm} \), for the extensive analysis. The electric field distributions along the z-direction, for both symmetric and antisymmetric modes, have been illustrated respectively in Fig 2a and b, at \( g_1 = 250 \text{ nm}, w_2 = 50 \text{ nm}, \text{ and } h_2 = 168 \text{ nm} \). The effective refractive index corresponding to symmetric and antisymmetric modes are 2.41959 and 2.419577, respectively. It has been observed that for the lesser difference between the effective refractive indices of symmetric and antisymmetric modes, the coupling length is higher. Therefore, as for the particular value of Ge-strip height, the values of effective refractive index of symmetric and antisymmetric modes are very close to each other, and hence, the higher coupling length has been achieved. Further, the electric field distributions along the z-direction, for both symmetric and antisymmetric modes, have also been shown in Figs. 3 and 4, respectively for \( g_1 = 300 \text{ nm}, w_2 = 50 \text{ nm}, h_2 = 154 \text{ nm}, \text{ and } g_1 = 200 \text{ nm}, w_2 = 30 \text{ nm}, h_2 = 385 \text{ nm} \). Moreover, similar mode distributions have also been obtained with the other considered values of width \( \text{ \( w_2 \) } \) and height \( \text{ \( h_2 \) } \), for the analysis of various modal characteristics in the subsequent subsections.

Further, for silicon strips inserted between the adjacent photonic waveguides, the electric field distributions along the z-direction, for both symmetric and antisymmetric modes, have been shown respectively in Fig. 5a and b, at \( g_1 = 300 \text{ nm}, w_2 = 30 \text{ nm}, h_2 = 220 \text{ nm} \). The effective refractive index corresponding to symmetric and antisymmetric modes have been achieved as 2.413021 and 2.409023. Similarly, the electric field distributions along the z-direction, for both symmetric and antisymmetric modes, have been illustrated respectively in Fig 6a and b, for silicon nitride (Si$_3$N$_4$) strips inserted between the adjacent photonic waveguides, at \( g_1 = 300 \text{ nm}, w_2 = 30 \text{ nm}, \text{ and } h_2 = 220 \text{ nm} \). The effective refractive index corresponding to symmetric and antisymmetric modes are obtained as 2.394417 and 2.405449. Further, it has been noted that the differences between the effective refractive indices of symmetric and antisymmetric modes are comparatively larger, which leads to the lower coupling length.

### 3.1 Coupling Length \( (L_c) \) Analysis Using Ge Strip

In order to examine the performance of the proposed structure, in terms of the coupling length, initially \( g_1 \) is assumed as
300 nm, with two considered values of strip width \((w_2)\) of 30 nm, and 50 nm. To obtain the values of coupling length, for \(g_1 = 300 \text{ nm}\), the height \((h_2)\) of all the Ge-strips have been varied uniformly up to 400 nm. Fig 7a, b and c shows the variations in coupling length in terms of height \((h_2)\), for both the considered values of \(w_2\). From the Fig. 7a, it is clear that the values of the coupling length increase and attains a peak value at \(h_2 = 233 \text{ nm}\), and 154 nm, respectively for \(w_2 = 30 \text{ nm}\), and 50 nm. Their respective peak values of coupling length have been observed as 38557 \(\mu\text{m}\), and 62500 \(\mu\text{m}\), that are comparatively very high values. After that it decreases with the increasing values of \(h_2\). During the simulations, it has been established that for \(w_2 = 45 \text{ nm}\), the coupling length has been achieved as 81,578 \(\mu\text{m}\), at \(h_2 = 164 \text{ nm}\). Therefore, it clearly demonstrates that for end-to-end waveguide separation of 300 nm, one can achieve the very high coupling length. Further, it has been observed that the obtained variations in the coupling length follows the comparable trend, as presented in Fig. 3c of Ref. [8], for the similar values of strip height \((h_2)\). Further, the similar analysis, for \(g_1 = 250 \text{ nm}\), have been done by varying \(h_2\) uniformly up to 400 nm, for \(w_2 = 30 \text{ nm}\), and 50 nm. The relationship between the coupling length and \(h_2\) has been estimated, and illustrated in Fig. 7b, for \(g_1 = 250 \text{ nm}\). Once again, the coupling length varies in the same fashion, and attains a peak value at \(h_2 = 230 \text{ nm}\), and 168 nm, respectively for \(w_2 = 30 \text{ nm}\), and 50 nm. However, their corresponding peak values of coupling length have been achieved respectively as, 64583 \(\mu\text{m}\), and 62000 \(\mu\text{m}\), which are comparatively lower values, as achieved with \(g_1 = 300 \text{ nm}\). However, again for \(w_2 = 45 \text{ nm}\), the higher coupling length of 67099 \(\mu\text{m}\) has been obtained, at \(h_2 = 171 \text{ nm}\). Furthermore, it has been observed that the propagation of the mode is considerably influenced by the choice of height and width of germanium strips. This further results to the change in their respective effective refractive index values, and hence, the coupling length. The variations in the values of the coupling length concerning to \(h_2\), for \(g_1 = 200 \text{ nm}\), has been shown in Fig. 7c. It has been found that, for the lower strip width, i.e., \(w_2 = 30 \text{ nm}\), the light can propagate, and the peak coupling length has been achieved as, 66,810 \(\mu\text{m}\), at \(h_2 = 385 \text{ nm}\). Whereas, for \(w_2 = 50 \text{ nm}\), light propagation is not significant, which results in extremely low value of coupling length, up to ~182 \(\mu\text{m}\), as illustrated in Fig. 7c.

### 3.2 Coupling Length \((L_c)\) Analysis Using Si/Si\(_3\)N\(_4\) Strip

Similarly, the analysis of variations in coupling length have also been done for Si- and Si\(_3\)N\(_4\)-strips, instead of Ge-strip, which is placed between two silicon waveguide, which have been shown respectively in Fig 8a, b and c, for \(g_1 = 300 \text{ nm}\), 250 nm, and 200 nm. These variations in coupling length, in terms of \(h_2\), have been analyzed for the same values of strip

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**Fig. 2** Electric field distributions for (a) symmetric, and (b) antisymmetric modes, at \(g_1 = 250 \text{ nm}\) for \(w_2 = 50 \text{ nm}\), and \(h_2 = 168 \text{ nm}\), with Ge as strips

**Fig. 3** Electric field distributions for (a) symmetric, and (b) antisymmetric modes, at \(g_1 = 300 \text{ nm}\) for \(w_2 = 30 \text{ nm}\), and \(h_2 = 154 \text{ nm}\), with Ge as strips
widths, i.e., $w_2 = 30 \text{ nm}$, and $50 \text{ nm}$. The figures clearly demonstrate that the coupling length is varying slowly, and attains the peak value, as obtained with Ge-strip. Here, for the Si-strips, the larger coupling lengths have been observed, as compared to the Si$_3$N$_4$-strips. The corresponding maximum values of coupling lengths for the Si-strip are $3029 \mu m$, and $997 \mu m$, and for the Si$_3$N$_4$-strip are $220 \mu m$, and $193 \mu m$, respectively, at $w_2= 30 \text{ nm}$, and $50 \text{ nm}$, and $g_1 = 300 \text{ nm}$. Similarly, for $g_1 = 250 \text{ nm}$, the corresponding maximum values of coupling lengths for Si-strips have been obtained as $437 \mu m$, and $302 \mu m$, and for Si$_3$N$_4$-strips, the coupling lengths have been achieved as, $87 \mu m$, and $121 \mu m$, at their respective $w_2 = 30 \text{ nm}$, and $50 \text{ nm}$. While, for $g_1 = 200 \text{ nm}$, the corresponding maximum values of coupling lengths for Si-strips are $216 \mu m$, and $302 \mu m$, and the same for Si$_3$N$_4$-strips are $74 \mu m$, and $73 \mu m$, at their respective $w_2= 30 \text{ nm}$, and $50 \text{ nm}$. These analyses have clearly shown that the coupling lengths for Ge-strip have very high values, as compared to that with Si/ Si$_3$N$_4$ strips. Therefore, the obtained results have established that the proposed approach for introducing uniform Ge-strips, can be used as a promising technique to diminish the crosstalk level between the two neighboring photonic waveguides.

### 3.3 Propagation Length Analysis Using Ge Strip

With Ge-strips between the photonic waveguides, the values of propagation length have been obtained by utilizing the Eq. (2), and shown respectively in Fig. 9a, b and c, for $g_1 = 300 \text{ nm}$, $250 \text{ nm}$, and $200 \text{ nm}$. The changes in the values of propagation length in terms of $h_2$, have been observed for the same values of strip widths, i.e., $w_2 = 30 \text{ nm}$, and $50 \text{ nm}$. From the figure, it is clear that with the increasing $h_2$, propagation length is decreasing, for all the considered values of $g_1$. However, a small change in propagation length pattern can be observed at the peak value of coupling length. For $g_1 = 300 \text{ nm}$, Fig. 9a depicts that the propagation lengths are $115 \text{ mm}$, and $144 \text{ mm}$, respectively at $h_2= 233 \text{ nm}$, and $154 \text{ nm}$, where the peak coupling lengths have been achieved. Whereas, for $g_1 = 250 \text{ nm}$, the propagation length have been noted as $112 \text{ mm}$, and $72 \text{ mm}$, at their respective strip heights ($h_2$) of $230 \text{ nm}$, and $168 \text{ nm}$. While, for $g_1 = 200 \text{ nm}$ and $w_2 = 30 \text{ nm}$, the propagation length is only $87 \text{ mm}$, at the point of peak coupling length, i.e., $h_2 = 385 \text{ nm}$. Moreover, for $w_2 = 50 \text{ nm}$ with $g_1 = 200 \text{ nm}$, it has been examined that the propagation length is very low, and after $h_2 = 340 \text{ nm}$, it attains nearly zero value, which is mainly due to the non-propagation of mode. Whereas, with $w_2 = 30 \text{ nm}$, the light...
Fig. 6 Electric field distributions for (a) symmetric, and (b) antisymmetric modes, at \( g_1 = 300 \text{ nm} \) for \( w_2 = 30 \text{ nm} \), and \( h_2 = 220 \text{ nm} \), with \( \text{Si}_3\text{N}_4 \) as strips.

Fig. 7 Relationship between coupling length and Ge-strip height, for \( w_2 = 30 \text{ nm} \), and \( 50 \text{ nm} \) at (a) \( g_1 = 300 \text{ nm} \), (b) \( g_1 = 250 \text{ nm} \), and (c) \( g_1 = 200 \text{ nm} \).
can confine adequately, and provides a moderate propagation length with high coupling length.

### 3.4 Crosstalk Analysis Using Ge Strip

The values of crosstalk between the Ge-strips based photonic waveguides, have been calculated by using the Eq. (3), where, it can be observed that crosstalk is reliant on propagation distance, and coupling length. Here, the propagation length ($L_0$) has been assumed as, 100 nm. The minimum crosstalk for $g_1 = 300$ nm has been obtained as $-29.40$ dB, at a point of coupling length of 81,578 μm. While, for $g_1 = 250$ nm, it is nearly obtained as $-27.71$ dB, which is corresponding to the coupling length of 67,099 μm. However, for $w_2 = 30$ nm with $g_1 = 200$ nm, the similar crosstalk level of $-27.70$ dB has been obtained, at the corresponding point of coupling length of 66,810 μm. In general, the crosstalk $\leq -30$ dB, can be assumed as negligible crosstalk between the neighboring photonic waveguides, as stated in [21], where authors have chosen the optical filters and Y-branch, to evaluate the photonic integration density. Moreover, the waveguide separation, corresponding to the crosstalk, $\leq -30$ dB, can be considered as the decoupled separation [21], at which the negligible crosstalk can be obtained between the nearby photonic waveguides.

### 4 Discussion and Comparison

As noted in Eq. (3), the crosstalk between the photonics waveguides is essentially dependent on their coupling length. Therefore, the main objective of the proposed work is to achieve the larger coupling length for the smaller waveguide separation. Here, to achieve the larger coupling length, three germanium strips have been inserted between the two neighboring photonic waveguides, and the impact of variations in their height have been investigated. The maximum values of coupling length have been observed as 81,578 μm, 67,099 μm, and 66,810 μm, at their respective waveguide spacing of 300 nm, 250 nm, and 200 nm. Previously, many researchers have reported different (lower) values of coupling

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Fig. 8 Relationship between coupling length and Si/Si$_3$N$_4$ strip height, for $w_2 = 30$ nm, and 50 nm at (a) $g_1 = 300$ nm, (b) $g_1 = 250$ nm, and (c) $g_1 = 200$ nm.
length, for the similar waveguide structures. Table 1 shows the comparison of coupling lengths of the proposed design structure based on three germanium strips, with the previously reported waveguide structures. The authors in [8] have realized the coupling length of 1000 μm for the 300 nm of waveguide separation; while, in the current work, it has been observed 81,578 μm with same waveguide spacing of 300 nm. Hence, the presented method of inserting the uniform Ge-strips, can

**Table 1** Comparison of coupling length of the proposed design structure with previously reported results

| Sr. No. | Reported work | Coupling length | Remarks |
|---------|---------------|-----------------|---------|
| 1.      | 2020 [8]      | 1000 μm         | Separation =300 nm, 3 Si-strips |
| 2.      | 2018 [3]      | 4000 μm         | Centre-to-Centre separation=1000 nm, w=475 nm 5 Si-strips |
| 3.      | 2017 [9]      | 8500 μm         | Separation=500 nm, 2 Si-strips |
| 4.      | 2017 [9]      | 332,000 μm      | Separation=500 nm, 3 Si-strips |
| 5.      | 2016 [7]      | 3880 μm         | Separation=500 nm, 2 Si-strips |
| 6.      | Proposed work | 81,578 μm       | g₁=300 nm for w₂=45 nm, and h₂=164 nm 3 Ge-strips |
| 7.      | Proposed work | 67,099 μm       | g₁=250 nm for w₂=45 nm, and h₂=171 nm 3 Ge-strips |
| 8.      | Proposed work | 66,810 μm       | g₁=200 nm for w₂=30 nm, and h₂=385 nm 3 Ge-strips |
be utilized as a promising approach to minimize the crosstalk between the two nearby photonic waveguides, and thus, to achieve the dense integration over the PICs.

5 Conclusion

In this work, the impact of the uniform germanium strips, inserted between the two neighboring integrated photonic structures, have been illustrated to accomplish the lower crosstalk between two nearby photonic waveguides/devices. The maximum coupling lengths of 81,578 \(\mu\)m, 67,099 \(\mu\)m, and 66,810 \(\mu\)m have been achieved, at their respective waveguide separations of 300 nm, 250 nm, and 200 nm, which demonstrates the noteworthy enhancement, as compared to the recent research works. The lower crosstalk in the range of -27 dB to -29 dB have been realized with the proposed waveguide structure, which is beneficial to accomplish the dense photonic integrated platform. Further, the analysis for realizing the coupling length for Ge-strip, has been extended for the strips of other materials, such as silicon and silicon nitride. These investigations state that the Ge-strips can provide the superior coupling length as compared to that obtained with Si-/Si\(_3\)N\(_4\)-strips. Further, the dimension of the proposed waveguide structure can be enhanced to improve the performance of the device, with respect to the crosstalk, and coupling length. The approach introduced in the current work can be beneficial for the development various photonic applications, such as integrated photonic switches, ultra-sharp waveguide bends, etc.

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