Ultra-compact silicon multimode waveguide bends based on special curves for dual polarizations

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ABSTRACT. Multimode waveguide bends (MWBs) with very compact sizes are the key building blocks in the applications of different mode-division multiplexing (MDM) systems. To further increase the transmission capacity, the silicon MWBs for dual polarizations are of particular interest considering the very distinct mode behaviors under different polarizations in the silicon waveguides. Few silicon MWBs suitable for both polarizations have been studied. In this paper, we analyze several dual-polarization-MWBs based on different bending curve functions. These special curve-based silicon MWBs have the advantages of easy fabrication and low loss compared with other structures based on subwavelength structures, such as gratings. A comparison is made between the free-form curve (FFC), Bezier curve, and Euler curve, which are used in the bending region instead of a conventional arc. The transmission spectra of the first three TE and TM modes in the silicon multimode waveguide with a core thickness of 340 nm are investigated. The simulation results indicate that, with the premise of having the same effective radius, which is only 10 μm in this paper, the six-mode MWB based on the FFC has the optimal performances, including an extremely low loss < 0.052 dB and low crosstalk below −25.97 dB for all six modes in the wide band of 1500 to 1600 nm. The MWBs based on the Bezier and Euler curve have degraded performances in terms of the loss and crosstalk. The results of this paper provide an efficient design method of the polarization insensitive silicon MWBs, which may leverage research for establishing complicated optical transmission systems that incorporate both the MDM and polarization-DM technology.

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1 Introduction

With the sharply increasing demand for the bandwidth of data transmission, on-chip optical interconnects have attracted great interest for their potential to break the bandwidth-bottleneck in optical communications. To increase the transmission capacity of optical networks, various multiplexing technologies have been proposed; these include the wavelength-division multiplexing (WDM), 1 polarization-division multiplexing (PDM), 2 mode-division multiplexing (MDM), 3 etc. Among these technologies, WDM and PDM have been widely utilized, and MDM is currently...
becoming more and more attractive because of its ability to further increase the link capacity significantly, which has almost been pushed to its limit by the commercial WDM systems.

In MDM systems, multiple guided modes of each wavelength in the multimode waveguide can be simultaneously utilized to carry the independent signals, thus efficiently enhancing the capacity for each wavelength channel. To realize an on-chip MDM system, various devices have been proposed; these include the multimode waveguide crossing, \(^4\) mode (de)multiplexers, \(^5\) multi-mode switches, \(^7\) and multi-mode waveguide bends. \(^9\)–\(^11\) As an essential component, the waveguide bends are used to change the propagation direction of the guided light. As a result, a sharp waveguide bend is of great importance to achieving high density photonic integrated circuits. \(^9\)–\(^11\)

However, the multi-mode waveguide bends in the silicon-on-insulator (SOI) nanophotonic circuits suffer serious problems of transmission efficiencies and inter-mode crosstalk compared with single mode bends. For a single-mode silicon waveguide bend, low excess loss is easily achieved with a small bending radius because of the high index contrast, \(^12\) and no inter-mode crosstalk is caused because the single-mode condition is maintained the entire time. But when it comes to a sharp multi-mode waveguide bend, the inter-mode coupling between different eigen-modes occurs due to the mode field mismatch at the junction of the straight waveguide and the bending part. The silicon multi-mode waveguide usually requires a large bending radius that is at least two orders of magnitude larger than that of the single mode waveguide to relieve this mode mismatch. To tackle this problem, curve engineering and mode engineering are often applied to reduce the bending radius. In the first one, special curves are used to design the waveguide bends; \(^14\)–\(^17\) among these, Bezier curves and Euler curves are the most widely used. These types of bends use curves with gradually changing radii to reduce the mode mismatch at the interface between the straight and bent waveguide. Multimode waveguide bends (MWBs) of this kind supporting three to four modes with the effective bending radii of 20 to 45 \(\mu\)m have been proposed, \(^14\)–\(^17\) with the theory crosstalk level of around \(-23\) to \(-25\) dB. However, a four-mode MWB with a bending radius smaller than 20 \(\mu\)m with acceptable performance is usually difficult to achieve with this kind of curve function. The other method utilizes mode converters to convert the modes in the straight waveguide into the distorted modes in the bent waveguide, or vice versa, to reduce the inter-mode coupling. \(^10\)–\(^11\),\(^18\) The smallest radius of 10 \(\mu\)m was realized for a waveguide bend with top subwavelength gratings (SWGs) supporting three modes. \(^11\) In addition to these two mechanisms, the vertical multi-mode waveguide is also used to acquire a small bending radius because it is single-mode in the lateral dimension; \(^19\) however, it is less popular due to it having a larger aspect ratio that is unsuitable for fabrication. In addition, the transformation optics method is also proposed to transform the straight waveguide in virtual space into a bent waveguide in physical space. \(^9\),\(^20\),\(^21\)

It is well known that polarization insensitive devices are favorable for further exploiting the bandwidth of the transmission system. However, there are few silicon MWBs that can support dual polarizations proposed in previous works due to the large polarization dependence in most silicon nanophotonic components. Fortunately, the multimode bends with special curves might have a much smaller polarization dependence, which makes it possible to design polarization insensitive bends with them. In Ref. \(^22\), a waveguide bend was proposed to support dual polarizations by inducing an Euler-curve assisted with the SWGs with an equivalent radius of 10 \(\mu\)m. This waveguide bend can support six-mode transmission with low excess losses (<0.23 dB) and crosstalk (< \(-26.5\) dB) based on the fact that the multimode bends using the Euler curves can have similar performances for dual polarizations. However, because the grating structure needs to be shallow-etched, second lithography and an etching step are needed, which increases the fabrication complexity and cost. The excess losses are also slightly raised by the scattering of the gratings, which may become an issue when a large number of bends are cascaded. A review of recent advances in high-performance silicon polarization processing devices also mentions the above device as the only examples of the polarization insensitive silicon MWBs.\(^25\) In a previous work, we proposed an ultra-compact silicon MWB structure based on a special curve, named the free-form curve (FFC).\(^24\),\(^25\) Based on this curve, a four-mode MWB with the radius of 15 \(\mu\)m with ultra-low loss and crosstalk was designed. This FFC-MWB had the advantages of simple fabrication by avoiding the SWGs and better performance than other special curve-based MWBs. The FFC can be also used for an MWB with dual polarizations. In this paper, we study several
polarization-insensitive MWBs based on the FFC, Bezier curve, and Euler curve, respectively. The equivalent radius is set to be \( R_{eq} = 10 \mu m \), and the width of the access waveguide is 1.2 \( \mu m \). The transmission properties of the TE\(_0\), TE\(_1\), TE\(_2\), TM\(_0\), TM\(_1\), and TM\(_2\) modes are simulated, and the behaviors of these curves are discussed.

2 Structure and Simulation

2.1 Multimode Waveguide Bend Based on the Double Free-Form Curve

It is known from the previous literature that the difference between the refractive indices of the TM and TE modes decreases synchronously with the decrease of the radius. By contrast, the propagation loss and inter-mode crosstalk both increase when the radius shrinks. Considering the compactness of the MWBs, an equivalent radius of \( R_{eq} = 10 \mu m \) is selected in this paper. The proposed structure is built in the SOI platform with a 340-nm-thick top Si layer and a 2-\( \mu m \)-thick SiO\(_2\) buried layer, and the top cladding material is also chosen to be SiO\(_2\). It has been pointed out that a thicker layer (instead of 220 nm) of the Si core helps to reduce the polarization dependence.\(^{23}\) In addition, this design requires the width \( W \) of the access waveguide to be 1.2 \( \mu m \) to support the transmission of the first three order TE and TM modes with the central operating wavelength of 1550 nm.

In our previous work, the design of an MWB based on the FFC was proposed.\(^{24}\) The FFC is a smooth curve with an inconstant curvature radius of every point on it that can be defined freely. In practice, it is set to be self-symmetric and discretized by a series of arcs with different radii for to save time. The MWB based on the single FFC has a constant width in the bending region,\(^{24,25}\) whereas in this paper, we use a modified design in which the inner and outer boundaries of the bend are two separate FFCs, which makes the waveguide width variable in the bending region, as shown in Fig. 1. This double FFC (DFFC) setup can increase the flexibility of the parameter adjustment and further decrease the bending radius. In the inset of Fig. 1, a detailed description of an FFC with the segment number \( 2N = 6 \) (only three arc segments are shown here due to the symmetry, \( N \) is the number of the parameters for one FFC) can be seen. Adjacent arcs share the same tangent at the connection point to avoid additional scattering. To minimize the bending radius, the radius of the \( i \)th arc \( R_i \) should decrease monotonically from the beginning of the curve to the center of symmetry. In the simulation,\(^{25}\) the discretization number \( N \) should be large enough to ensure better results from the optimization and is chosen as 20 for both the inner and outer FFC considering the performance and simulation time.\(^{25}\) The 3D finite difference time domain (FDTD) method is used to calculate the crosstalk and excess loss of the proposed MWB. The definition of the figure of merit (FOM) function is related to the crosstalk and excess loss, and the FOM function is defined in the following equation as\(^{23}\)

![Fig. 1 Schematic diagram of the double FFCs based on the inverse design.](image)
\[ FOM = 1 - \frac{1}{n} (1 - \alpha) \sum_{i=1}^{n} (1 - T_i) - \frac{1}{n} \alpha \sum_{i=1}^{n} X_i, \]

where \( X_i \) and \( T_i \) represent the inter-mode crosstalk and transmittance of the \( i \)th mode, respectively, and \( \alpha \) represents the weight factor of the crosstalk in the FOM function. An initial value of \( \alpha = 0.5 \) is suitable for most situations because both the loss and crosstalk are important to the device’s performance.

The optimization algorithm called direct range search is applied here to optimize the combination of a series of arcs with the radii ranging from \( R_1 \) to \( R_N \).\(^{25}\) The optimization steps of the DFFC are briefly summarized as follows.

First, we set a suitable value for the maximum radius of curvature \( R_{\text{max}} \) (e.g., \( R_{\text{max}} = 10 \times R_{eq} \)); then an optimization of \( R_i \) (\( i \) from 1 to \( N \)) is subsequently carried out for curves A and B. For the search of \( R_i \), the value of \( R_i \) is sampled in the range from \( R_{i-1} + 1 \) to \( R_{i-1} - 1 \) (from \( R_{\text{max}} \) to \( R_2 \) for \( R_1 \)) at equal intervals of 50 to 100 steps. The value of \( R_i \) is kept or discarded depending on the FOM value. All of the arc radii on curves A and B are optimized in loops until the FOM meets the predefined criterion.

Typically, after tens of hours of optimization by the algorithm, the optimal structure of the DFFC-based MWB is obtained. The theoretical results of the crosstalk and excess loss in the wavelength range of 1500 to 1600 nm are calculated, as shown in Fig. 2 below.

It can be seen from Fig. 2 that the polarization insensitive MWB with the bending radius of only 10 \( \mu \)m presents very good transmission characteristics of extremely low loss and low crosstalk for all six studied modes. It should be noted that the solid lines correspond to the crosstalk, and the dashed lines correspond to the excess loss in Fig. 2. Within the wavelength range of 1500 to 1600 nm, the highest excess loss of each mode is in the range of 0.01 to 0.052 dB, and the worst crosstalk of each mode is in the range of \(-25.97\) to 31.46 dB.

### 2.2 Multimode Waveguide Bend Based on the Bezier Curve

Because the shape of a cubic Bezier curve is mainly controlled by parameter \( B \), four points \((0,0), (R(1-B),0), (R,B), \) and \((R,R)\) can determine a such curve, as shown in Fig. 3(a). For multimode waveguides, having the gradient curvature radius of this curve can be used to minimize the mode mismatch at the junction of the straight and curved waveguides.\(^{26-28}\) To minimize the crosstalk between the various modes and maximize the transmission efficiency of each mode, the parameter \( B \) that controls the shape of the curve is adjusted. Usually, a smaller value of the parameter \( B \) tends to have a larger radius at the starting point of the Bezier curve. This is helpful for reducing the mode mismatch at the junction between the straight and bending waveguides. However, for a fixed equivalent radius, a larger radius at the beginning means a larger radius gradient along the curve, which increases the radiation loss and crosstalk. When \( B = 0.45 \), the Bezier curve is close...
to the standard arc. In the following we use the MWB structure composed of two separate Bezier curves as the inner and outer boundaries of the bending part to have a better performance, which is different from most of the existing literature in which the two boundaries are independent with a constant waveguide width.\textsuperscript{26–28} The main parameters of these two curves are $B_1$ and $B_2$, respectively. When $B_1$ equals $B_2$, we calculate the insertion loss and crosstalk with different $B$ values when the TE\textsubscript{0} mode is input, as illustrated in Fig. 3(b). The structure tends to have a better performance when $B$ is within the range of [0.1, 0.4]. Therefore, when optimizing the MWB with two separate Bezier curves as the two boundaries, we set the parameter scanning range to be 0.1-0.4 for $B_1$ and $B_2$.

After tens of hours of calculation with the 3D FDTD method, the results are determined and are plotted in Fig. 4. The value of the FOM is plotted with the $B$ parameters of the MWB. The definition of the FOM here is the same as for the DFFC-MWB as in Eq. (1). The position with the highest FOM is marked as the $M$ point in Fig. 4, where $B_1$ and $B_2$ are 0.2 and 0.12, respectively. Figure 5 gives the transmission behaviors of all modes in the optimized Bezier-MWB. It should be noted that the solid lines correspond to the crosstalk, and the dashed lines correspond to the excess loss in Fig. 5. Within the investigated wavelength range of 1500 to 1600 nm, both the losses and crosstalk are worse than those of the DFFC-MWB with the same radius. The highest excess loss of each mode is in the range of 0.03 to 0.18 dB, and the worst crosstalk of each mode

![Figure 3](image1.png)

**Fig. 3** (a) Bezier curves corresponding to different $B$ (Bezier numbers, dimensionless). (b) Relationship between the parameter $B$ and mode transmission efficiencies (when input mode is TE\textsubscript{0} mode).

![Figure 4](image2.png)

**Fig. 4** Plotted FOM values with the scanned $B$ parameters of the Bezier curves.
is in the range of −20.44 to 27.1 dB. Still, the overall performance of the Bezier curve-MWB is also acceptable.

2.3 Multimode Waveguide Bend Based on the Euler Curve

The Euler curve has a similar property as the Bezier curve in terms of the changing curvature radius along the curve itself and can also be used in the design of waveguide bends.29,30 According to the mathematical definition, the curvature of an Euler curve is variable and increases linearly along the curve, as shown in Fig. 6. A recent design of silicon MWBs based on the Euler curve supported the simultaneous transmission of 4TM modes with the equivalent bending radius of 45 μm.14 The main definition of the curvature radius of the Euler curve is shown as Eqs. (2) and (3). The coordinates of any point on the curve is derived according to the following equations:

\[
\frac{d\theta}{dL} = \frac{1}{R} = \frac{L}{A^2} + \frac{1}{R_{\text{max}}}, \tag{2}
\]

\[
A = \left[ L_0 \left( \frac{1}{R_{\text{min}}} - 1/R_{\text{max}} \right) \right]^{1/2}, \tag{3}
\]

\[
x = A \int_{0}^{L/A} \sin \left( \frac{\theta^2}{2} + \frac{A\theta}{R_{\text{max}}} \right) d\theta. \tag{4}
\]
Among them, \( R \) is the curvature radius of any point \((x, y)\) on the curve, \( L \) is the length of the curve from the starting point \((0, 0)\) to this point \((x, y)\), \( A \) is a constant, and \( L_0 \) is the total length of the whole curve.

In our design, to improve the performance of the MWB as much as possible with the same equivalent radius as the other curves, we also adjust the inner and outer boundaries of the bending waveguide as two independent Euler curves. Similar to the FFC, we set the center of the curve as the symmetric center and the minimal point in terms of the curvature radius. Because the equivalent radius is fixed as 10 \( \mu m \), the whole curve can be defined when the radius at the starting point is selected. In the previous work, an \( R_{\text{max}} \) of 600 \( \mu m \) is chosen to reduce the mode mismatch. The \( R_{\text{min}} \) and \( R_{\text{eq}} \) are 20 and 45, respectively. In this paper, the equivalent radius is much smaller, and a large \( R_{\text{max}} \) requires a large radius gradient, which may increase the radiation loss and inter-mode crosstalk. Thus, we sampled different values of \( R_{\text{max}} \) to estimate a proper range for fine scanning. The results show that the values of 100 ~ 300 are reasonable for \( R_{\text{max}} \).

According to this, we calculate the spectral performances of the MWB represented by the FOM function when the initial radius \( R_{\text{max}} \) of both inner and outer Euler curves are scanned. In Fig. 7, the FOM values are plotted with different \( R_{\text{max}} \). Here the maximum bending radii corresponding to the inner and outer curves are designated as \( R_{\text{max}} \) and \( R_{\text{max}} \) respectively. The FOM function is kept the same as Eq. (1), and the marked M point represents the parameters for the maximal FOM value.

After the optimization, the best combination point achieved is marked as M (260,100). Under this condition, minimum radii of the inner and outer curves are calculated by the above formula to obtain the optimized curves, which can support the transmission of all six modes.

Figure 8 gives the excess losses and crosstalk in the wavelength range of 1500 to 1600 nm when the six modes are transmitted, respectively. It should be noted that the solid lines correspond to the crosstalk, and the dashed lines correspond to the excess loss in Fig. 8. In the whole band, the highest excess loss of each mode is in the range of 0.02 to 0.14 dB, and the worst crosstalk of each mode is in the range of −15.1 to 34.4 dB. Compared with the two other curves, the average excess loss and crosstalk are both higher. The losses are still lower than those of the SWG-Euler based MWB, but the crosstalk exceeds −20 dB for some modes. This result implies that the equivalent bending radius is too small for the Euler curve to find a feasible design for highly efficient multimode transmission with the current setup. However, the crosstalk is still much lower than that of a conventional arc-bend waveguide with a radius of 10 \( \mu m \), which is as high as −8.4 dB.

In Table 1, a comparison of different polarization insensitive MWBs is made, including the design in the previous work. By comparison, the curve-based MWBs have smaller insertion losses than the design with sub-wavelength gratings on top. The losses and crosstalk of the MWB
based on the Euler curve are obviously higher because this curve fails to achieve a high performance with such a sharp bending, even when the bend is composed of two separate Euler curves. This is also the reason that the SWGs are applied to assist the highly efficient bending together with the Euler curve in the literature. The double FFC-based MWB has similar crosstalk behavior as the SWG-Euler MWB with a much lower loss. In addition, the fabrication step of the FFC-MWB is simple and cost-efficient, and the tolerance is also good according to the experimental results given in Ref. 25.

In Fig. 9, we also show the curvature distributions of the designed MWBs corresponding to different kinds of curves. In Fig. 9(d), a comparison of the curvature radius distributions of three different types of curves is made when their initial radii are similar. The Bezier curve is one of the boundaries of the optimal bend where the maximal radius is near 90 μm. When \( R_{\text{max}} \) of the Euler curve is set as the same value, it can be seen that the radius gradient is larger than that of the

![Fig. 8 Simulated excess losses and crosstalk of the six modes in the Euler curve-MWB.](image)

![Table 1 Excess loss and crosstalk of different MWB designs for dual polarizations (\( \lambda = 1500 \) to 1600 nm).](table)

| References | Optimization curve | Excess loss (dB) | Crosstalk (dB) | Simulation time (h) |
|------------|--------------------|-----------------|---------------|---------------------|
| Ref. 22    | Euler with SWGs    | <0.23           | <−26.50       | —                  |
| This work  | FFC                | <0.05           | <−25.97       | 9                   |
| Bezier curve |                  | <0.18           | <−20.44       | 16                  |
| Euler curve |                  | <0.14           | <−15.12       | 12                  |

Fig. 9 (a), (b), and (c) The curves of curvature radius corresponding to the inner and outer radii of double FFCs, Bezier curves, and Euler curves, respectively. (d) The comparison of these curves when the initial radii are set to be similar.
Bezier curve at the beginning. This may be the reason that the losses and crosstalk of the Euler-MWB are higher because the radius is changing fast when the straight eigen-modes are coupled into the bent modes. Although the slope variation of the radius values in the free-from curve is not monotonous, still we can observe that the average gradient for more than half of the segments [from segment 1 to 13 in Fig. 9(d)] is even smaller than that of the Bezier curve. This also implies the benefit of an FFC, in which the radius and its gradient can be controlled freely. In theory, no particular function is capable of giving a better performance because the FFC can fit in any specific curve. Thus, we believe the FFC-based MWB for dual polarizations has great potential in the applications of the polarization processing devices.

Due to their simple structures, the main cause of fabrication error for the MWBs is the deviation of the designed waveguide width introduced in the exposure and etching step. In Fig. 10, as an example, we show the performances of all three types of curves related to the width deviation. For the consideration of clearance and text length, we only give the calculated loss and crosstalk values of the TE0 and TM0 modes at the center wavelength of 1550 nm. The trends for the other modes are quite similar and are not plotted here. The ΔW is the assumed width deviation introduced in the fabrication steps, and the value range of ΔW is set to be −30 ~ 30 nm, with a step size of 15 nm. For the MWBs with the DFFC and Euler curve, the losses are slightly worse when the width is shifted but are still very low in the whole range of −30 ~ 30 nm. The crosstalk is increased for a level around −10~15 dB in the whole range. This means that, if the bending radius of the original designs with these two curves are increased a

Fig. 10 Performance of the first TE and TM modes at the center wavelength of 1550 nm are given when the width deviations are set from −30 to 30 nm. (a) and (b) Double free curve, (c) and (d) Euler curve, and (e) and (f) Bezier curve and select TE0 and TM0 as the input mode, respectively.
little to obtain a lower crosstalk say –40 dB, a width error of 20 to 30 nm could be acceptable. However, for the Bezier curve, both the loss and crosstalk increase greatly when the width is shifted. This implies that the fabrication tolerance of the MWB with the Bezier curve is obviously lower than those of the other two types.

3 Conclusion
In this design, we mainly focused on the silicon MWBs suitable for both polarizations based on special curves due to their characteristics of easy fabrication and relatively low loss. MWBs based on the FFC, Bezier curve, and Euler curve were simulated and discussed. The theoretical results showed that, in a very sharp bending of 10 μm, the FFC-based MWB had the optimal transmission properties. The insertion losses of the first three TE and TM modes were extremely small at the level of 0.003 ~ 0.05 dB in the wide band of 1500 to 1600 nm, and the highest crosstalk of different modes was around −25.97 ~ −31.46 dB in the whole wavelength band. The results of this paper provide an efficient method for designing the ultra-compact and high performance MWBs for dual polarizations.

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Data Availability
Data will be made available on request.

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