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SOI multimode waveguide bend with radially bridged SWGs for broadband (de)multiplexing -INVITED

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Abstract. A novel broadband multimode waveguide bend is proposed that supports the propagation of multiple TE modes on a silicon-on-insulator platform. The gradient curvature bend utilizes trapezoidal subwavelength grating (SWG) segments, connected by adiabatically tapered radial strips to achieve efficient mode (de)multiplexing. The inclusion of the radial strips offers an extra degree of design freedom, allowing the realization of a multimode bend with only one single full etch step. The access waveguide has a width of 2.075 μm with an effective radius of 10 μm. Propagation loss for all modes remains below 2.96 dB, and intermodal crosstalk has a maximum of -19 dB across a broad bandwidth of 100 nm, centred at 1550 nm. This work presents an excellent design choice for broadband mode-division multiplexing operations.

1 Introduction

As the demand for increased signal capacity in optical networks grows, many solutions have been explored to increase the number of possible waveguide channels. In particular, mode-division multiplexing (MDM) has become a popular option that transmits a signal through each spatial mode of a waveguide. The main drawback of MDM systems is their large footprint, which often requires large waveguide widths, with even larger bend radii on the order of millimeters. Small radius bends induce large mode propagation losses from the modal mismatch at the straight-bent interface, as well as the high radiation leakage of the higher order modes. Furthermore, higher order modes suffer from the generation of asymmetric outputs due to the asymmetry of their modal profiles within the multimode waveguide bend (MWB).

A common implementation of multimode bends makes use of a mode converter (MC) region that deforms the mode profiles prior to entering the bend [1,2]. Most MC assisted bends are optimized to two particular mode orders and cannot be easily scaled up. 45-degree corner bends that utilize total-internal reflection have been shown to effectively scale up to high order spatial modes simply by increasing the width of the bus waveguide [3]. The main drawback in this approach is that they require significantly larger widths than the minimum width required to propagate a given mode order, negating any benefit from footprint reduction.

By far the most promising implementation of MWBs is a combined solution of gradient curvature and gradient index bends. Replacing a standard circular bend profile with an alternate scheme such as Euler or Bezier curves reduces the index mismatch at the straight-bent transition interface [4], while smoothly varying the curvature to a maximum at the midpoint of the bend. The optimal bend on the silicon-on-insulator (SOI) platform followed an empirically derived curve [5] based on the minimization of the propagation loss.

To compensate for the radial asymmetry of the bend's index profile on-chip transformation optics can be applied. Early attempts at this approach employed a custom grayscale lithography process [6], varying the height of a 500 nm thick silicon layer such that the inner edge was taller than the outer edge. Although successful, this approach is severely limiting due to the custom fab process utilized, and has largely been superseded by SWG segment engineering.

Trapezoidal subwavelength grating (SWG) segments are commonly employed when designing SWG bends, where the inner radius has a larger duty cycle than that of the outer radius [7]. It has been used extensively for single-mode bends but has recently found use in multimode bends as well, successfully maintaining the symmetry of modes up to TE_2/TM_2 at a radius as small as 10 μm [8,9]. However, these multimode bends require an extra partial etch step for the SWG layer in order to keep propagation losses low.

In this work, we propose a novel design that adopts the trapezoidal SWG segments, connected by adiabatically tapered radial strips. The radially bridged SWG design provides a greater degree of freedom in tailoring the index gradient, making it possible to realize the bends with only one single etch step.

2 Device Structure and Simulation

The widely available 220 nm SOI platform was chosen. A width of 2.075 μm was chosen to ensure the first 5 propagating modes were of TE polarization. The target radius was selected to be 10 μm to achieve negligible bend

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radiation loss. The pitch of the SWG segments was selected to be 220 nm to ensure that the device operates in the subwavelength regime when centred at 1550 nm, while leaving a reasonable buffer above the minimum feature size of a typical e-beam lithography process.

Fig. 1 illustrates the design geometry of the proposed multimode bend. The MWB was engineered by first calculating an optimal curve with an effective radius of 10 µm, and segmenting the curve into coordinates spaced exactly 220 nm apart.

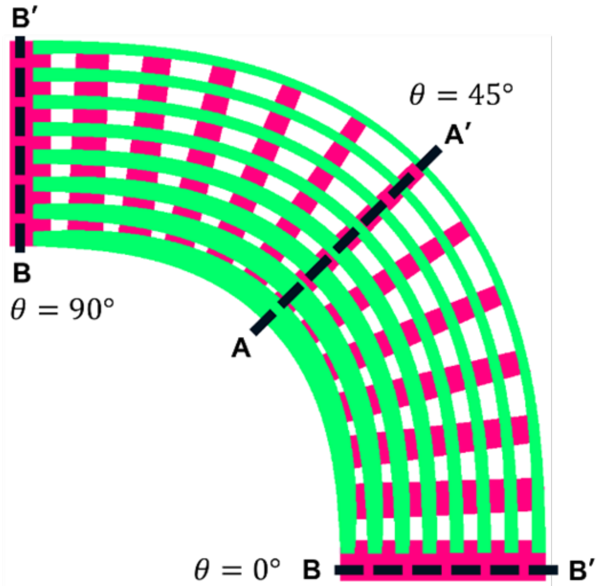

Fig. 1. A schematic of the multimode bend geometry illustrating the changing dimensions of the trapezoidal segments (red) and the adiabatically tapered radial strips (green), from θ=0° to θ=90°. The point of the maximum curvature along line AA' at θ=45°.

Each of these coordinates has a corresponding curvature which reaches a maximum at the midpoint, as picture in Fig. 2. As the curvature changes along the bend it is used as a variable to slowly vary both the trapezoidal SWG duty cycles as well as the widths of the radial strips.

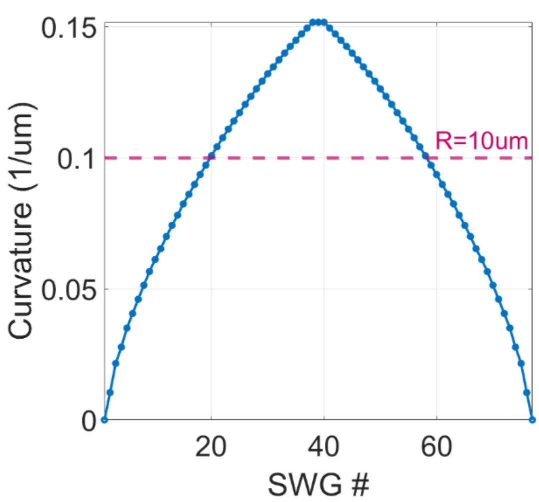

Fig. 2. Curvature at each SWG segment along the bend. A circular bend with an equivalent radius has a constant curvature denoted by the red dashed line.

By increasing the dimensions of the SWG segments on the inner radii and decreasing the dimensions of the segments on the outer radii, an index gradient could be tailored to compensate for the bend asymmetry. The starting SWG duty cycle is 60% for both the inner and outer radii. At the point of the maximum curvature (as shown by the dashed line AA' in Fig. 1), the duty cycle has been tapered down to 50% and 42% for the inner and outer radii, respectively, and is depicted in Fig. 3.

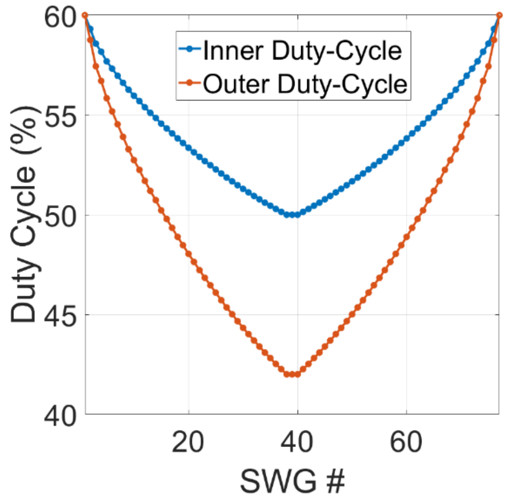

Fig. 3. Variation in SWG duty-cycle along the inner and outer edges along the curve.

The duty cycle ratio was set to ensure compliance with a minimum feature size of 60 nm for feasible fabrication. All the radial strips begin and end with a width of 170 nm at BB', with the inner four strips increasing in width until the point of maximum curvature AA', and the outer four strips decreasing in width. The maximum inner width and the minimum outer width of the strips were optimized through parameter sweeps. The innermost strip has a maximum width of 180 nm, while the outermost strip has a width of 130 nm, as depicted in Fig. 4.

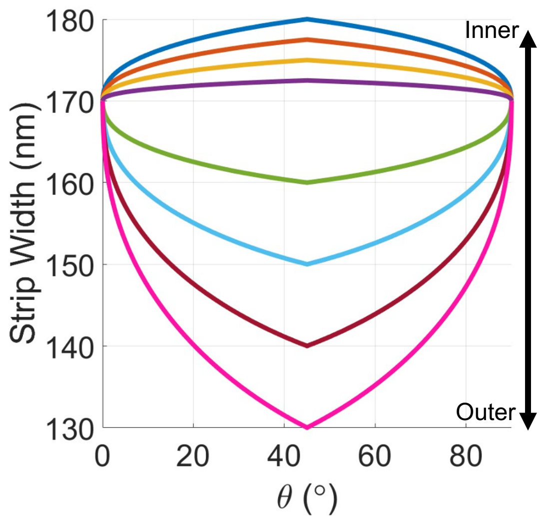

Fig. 4. Variation in radial strip width along the curve. The inner four strips increase in width and the outer four decrease in width.

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Lumerical FDTD was used to simulate the field propagation of the first four TE modes through the bend geometry. The bend was optimized by selecting the geometry that maximized the mode overlap ratio for each mode at the output port of the bend. The field profile distributions for the first four TE modes are shown in Fig. 5.

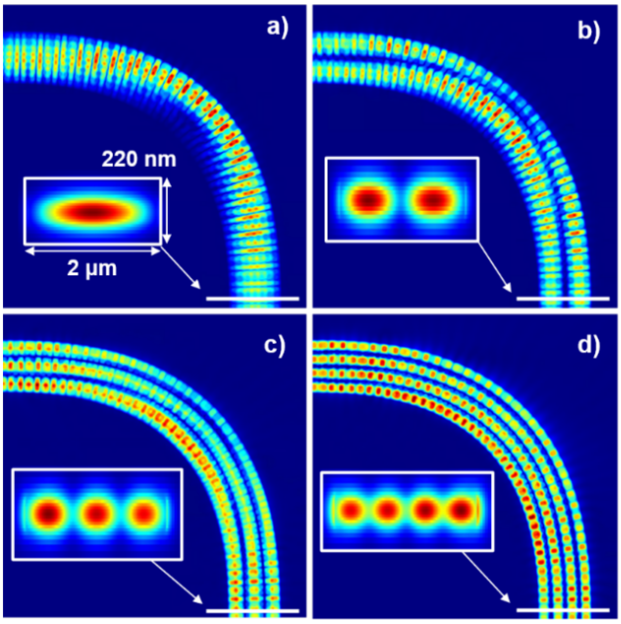

Fig. 5. Field distributions of the first four TE modes propagating through the proposed multimode waveguide bend: **a)** TE_0, **b)** TE_1, **c)** TE_2, **d)** TE_3.

Fig. 6 illustrates the transmission spectra centred at 1550 nm across a bandwidth of 100 nm when injecting each of the first four TE modes. It can be seen that the propagation loss remains below 2.14 dB, 1.64 dB, 2.96 dB, and 2.81 dB for TE_0, TE_1, TE_2, and TE_3, respectively. The maximum intermodal crosstalk is -19.65 dB, -19.01 dB, -19.05 dB, and -27.76 dB for TE_0, TE_1, TE_2, and TE_3, respectively.

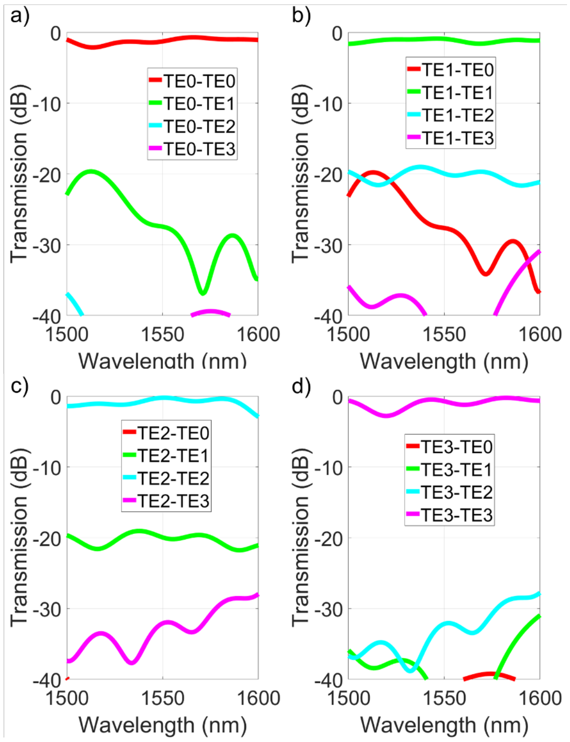

Fig. 6. Simulated transmittance spectra for the first four TE modes: **a)** TE_0, **b)** TE_1, **c)** TE_2, **d)** TE_3.

3 Conclusion

In conclusion we have successfully demonstrated an efficient and broadband multimode bend design for the first four TE modes, using radially bridged trapezoidal SWG segments. The bends have been shown to maintain the symmetry of the field profiles with low propagation losses and intermodal crosstalk over a bandwidth of 100 nm. This design could be easily scaled up to include additional TE and TM modes. Compact multimode bends are an essential building block for creating dense photonic circuits. High capacity mode (de)multiplexing networks will benefit greatly from the reduced footprint afforded by these bends.

References

1. C. Sun, Y. Yu, G. Chen, X. Zhang, Opt. Letters, **42**, 15 (2017)
2. W. Chang, L. Lu, D. Liu, M. Zhang, OFC, (2018)
3. Y. Wang, D. Dai, Opt. Exp., **28**, 7 (2020)
4. B. Dorin, W. Ye, Opt. Exp, **22**, 4 (2014)
5. M. Bahadori, M. Nikdast, Q. Cheng, K. Bergman, JLT, **37**, 13 (2019)
6. L. Gabrielli, D. Liu, S. Johnson, M. Lipson, Nat. Comm., **3**, 1217, (2012)
7. Z. Wang, X. Xu, D. Fan, Y. Wang, Scientific Reports, **6**, 24106 (2016)
8. H. Wu, C. Li, L. Song, H. Tsang, J. Bowers, D. Dai, Laser Photonics Rev., **13**, 1800119, (2019)
9. Y. Wang, D. Dai, JLT, **38**, 15 (2020)