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Loss mechanisms in dielectric optical micro-bends

R. Stabile,[1] K.A. Williams[1]

[1]Eindhoven University of Technology
Inter-University Research Institute COBRA on Communication Technology
Department of Electrical Engineering,
Postbus 513, 5600 MB Eindhoven, The Netherlands.

Micro-bend waveguides are an important enabler for the interconnection of photonic components in large-scale integrated circuits. There is however limited understanding of how losses scale with bend radii. A detailed analysis is performed using two-dimensional finite difference time domain simulations for straight waveguides interconnected by 180° micro-bends. Modal overlap optimization at each straight-waveguide to micro-bend junction is successfully performed to give low losses for radii above 20 μm. However, at reduced radii, simply optimizing the lateral offset between waveguides is insufficient for fabrication tolerance and losses are critically defined by the mode-matching between straight guides and micro-bend structures.

Introduction

Large-scale photonic integration requires the routing of single-mode waveguides in arbitrary directions within a very small turning radius [1,2]. Approaches including photonic bandgap waveguides, [3] total internal reflection mirrors, [4] and air trench technologies [5] can require very tight tolerance fabrication steps and impose constraints on waveguide rotation angles. Microbends, however, allow arbitrary waveguide rotation and the possibility of conventional lithographical fabrication techniques. Nevertheless, in these waveguide systems, mode excitation entering and leaving the microbends can have critical impact on net optical losses. Sidewall scattering losses [6] are also degraded through the mandatory use of deep etch waveguiding in low radii bends. [1] Whispering gallery modes in microdiscs[6, 7] exploit an "optical inertia" to confine light within an inner caustic radius, allowing the scope to reduce such scattering losses through the removal of inner sidewall losses.

In this paper we study microbends with varying inner and outer radii to quantify intrinsic losses for regimes operating with whispering gallery modes through to waveguides with single confined modes. This allows insight into regimes for efficient low-loss ultracompact bends with a high degree of fabrication tolerance.

Two dimensional FDTD simulation

Loss mechanisms in micro-bends are studied by performing 2D finite difference time domain (FDTD) simulations with the Omnisim commercial solver [8]. Straight single mode waveguides are interconnected by micro-discs as shown schematically in Fig 1. Modal overlap optimization at straight-to-bend junctions is obtained through the choice of lateral offset [9]. Both inner and outer radii are varied to explore fabrication tolerant regimes. To comply with the requirement for same plane input excitation and output probing in the simulation tool, 180° microbends are studied but arbitrary angles are also feasible in practice. Deep etched straight waveguides connect the deep etch 180° microbends. The resulting high lateral index contrast gives strong optical confinement and reduced radiation losses. The waveguide width is fixed to 1.5 μm to support a single transverse mode. A vertical effective refractive index of 3.28 is calculated for the waveguide in an InGaAsP/InP waveguide using an effective index mode solver.

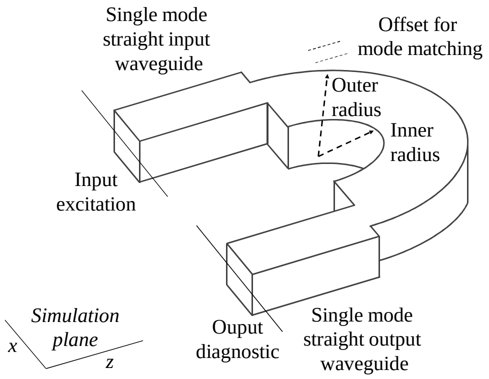

Fig. 1 – Schematic of the simulated micro-bend highlighting the design variables.

Outer radius: Micro-disc bends

Initial calculations focus on the role of the outer radius on net losses for microdisc bends. The inner radius is therefore set to zero. Optimum offset is selected for each simulated radius by scanning the displacement between the outer edge of the straight waveguides and the outer disc radius. Selected offset values which give the minimum net loss are shown in Fig. 2*a*. Lower values of outer radius require increased offset values between bend and straight guides to balance the more pronounced optical mode shift. Outer radii larger than 20 μm show a much reduced requirement for an offset, due to a negligible optical mode shift.

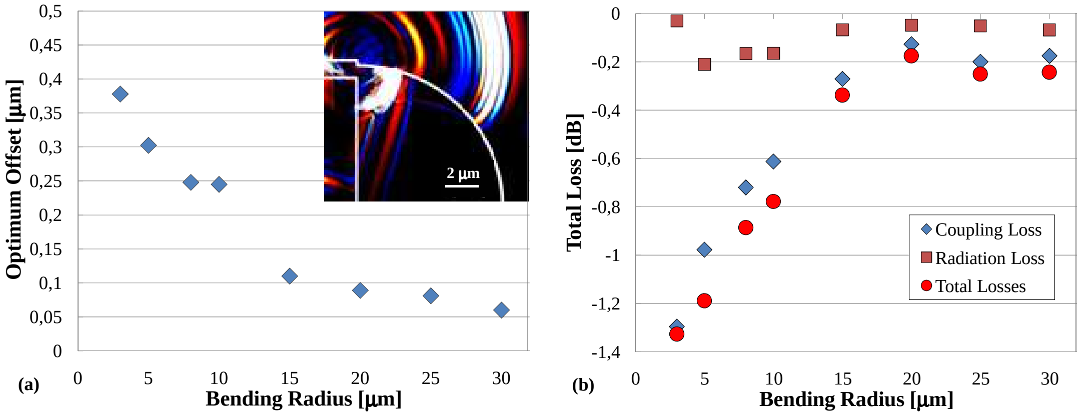

Fig. 2 – (*a*) Optimal offset at the straight-to-bend junctions. Inset: screen capture of *x*-component of the electric field after the input side offset. (*b*) Losses in micro-disc bends for varied radius.

A screen capture from the 2D simulation tool is shown as an inset to Fig. 2*a*. The fundamental mode is shown propagating from the straight waveguide into a 10 μm radius 180° disc. An optimal offset between straight waveguide and microdisc is used. The input fundamental mode produces an excitation that propagates along the waveguide from left to right. A time envelope was set to give a sinusoidal pulse of duration 1.4ps to ensure that the pulse of radiation has completely traversed the waveguide circuit by the end of the calculation. The plot shows the amplitude of the *x*-component of the electric field. Positive amplitudes are shown on a black-red-yellow-white scale, and negative amplitudes are shown on a black-blue-cyan-white scale. After the offset, less than 1% of the input mode power is transformed into radiation modes, while remaining power couples into disc whispering gallery modes. The power coupled to the fundamental mode of the output waveguide is calculated once the light has propagated around the complete circuit to estimate losses.

Radiation and coupling losses are calculated for 180° microdiscs bends with radii from 30 μm down to 3 μm and optimum waveguide offsets and plotted in Fig. 2*b*. Radiation loss remains near constant and represents only a minor contribution of total loss, even when approaching small radial values. This results from the strong confinement of the light in the waveguide. Total losses remain low for radii between 20 μm and 30 μm. At radii above 30 μm (not shown) there is evidence of higher order disc mode excitation which leads to reduced coupling into an output fundamental mode. At much lower radial values, losses increase with decreasing radius as a result of imperfect coupling into the bend, despite the mode offsetting optimisation in Fig. 2*a*.

Inner radius: Transition to waveguide bends

To quantify the role of the inner radial side-wall on intrinsic losses, the transition between a micro-disc and a micro-ring was studied: the inner radius was increased from zero up to the value defining the single mode waveguide. Loss from fundamental input mode to fundamental output mode was studied scanning both inner and outer radii at optimum offsets.

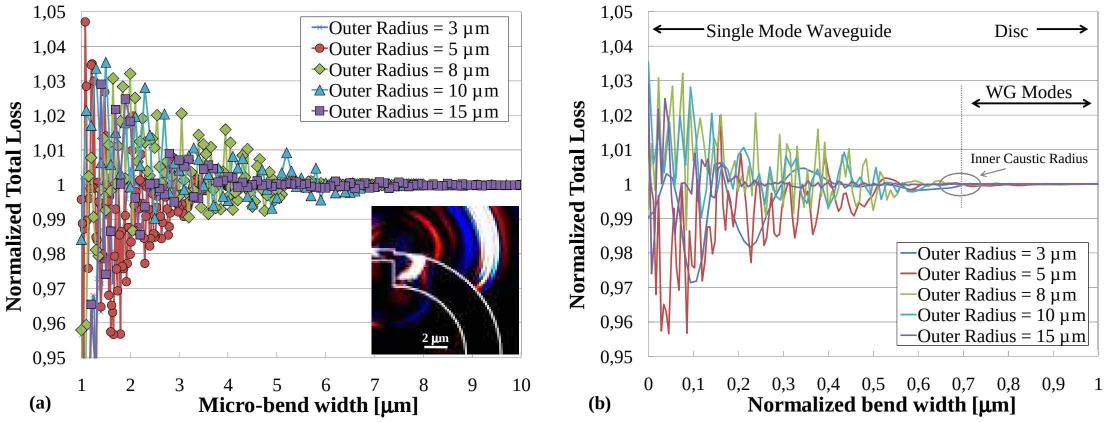

Fig. 3 – (*a*) Loss normalised to microdisc loss for micro-rings of varying waveguide widths. Inset: screen capture of intensity profile of the field coupling into the ring-bend. (*b*) Normalized losses replotted as a function of ring width scaled by radius.

Fig. 3*a* shows the total loss in linear units for fundamental mode input to fundamental mode output in the 180° micro-bend system. The values are normalized to the previously determined loss values in the 180° micro-disc in Fig. 2*b* for ease of comparison. For outer radii exceeding 8 μm, the total loss in the ring is generally lower than that observed for the micro-disc. For smaller values of outer radius the bend loss can be higher than that observed for the micro-disc. This behavior can be attributable to the largest number of higher order radial modes which can be excited by the fundamental input mode excitation.

The screen-shot in the inset of Fig. 3*a* shows the electric field evolving after the input offset to the microbend. As inner radius increases towards a fundamental mode micro-ring system, the coupling of the fundamental mode into disc radial modes reduces.

Loss is shown to be critically sensitive to microbend waveguide width as the single mode waveguide width of 1.5 μm is approached. The changes in mode coupling for variations of just tens of nanometres in waveguide width have important implications for component variability in large circuits.

To provide further insight, Fig. 3*b* shows the normalized microbend loss as a function of the ring waveguide width normalized to outer radius:

$$W_{\mathrm{normalised}} \quad = \quad (R_{\mathrm{outer}} - R_{\mathrm{inner}} - W_{\mathrm{single\ mode}})/(R_{\mathrm{outer}} - W_{\mathrm{single\ mode}})$$

$W_{\mathrm{single\ mode}}$ denotes the 1.5 μm width for the single mode straight waveguides. A normalized width of zero tends to the single mode microring. The unity normalized width tends to the micro-disc design. Fig. 3*b* indicates regimes where sensitivity of loss to the critical waveguide width dimension may be removed for $W_{\mathrm{single\ mode}} > 0.7$. This is equivalent to $R_{\mathrm{inner}} < 0.3\ (R_{\mathrm{outer}}\text{-}W_{\mathrm{single\ mode}})$ and corresponds to the inner caustic radius $R_{\mathrm{inner\ caustic}} = (n_{\mathrm{cladding}}/n_{\mathrm{core}})\ R_{\mathrm{outer}}$ [10] for $n_{\mathrm{clad}}/n_{\mathrm{core}} = 0.304$. It is noted that modes in a bend may only be considered to be whispering gallery modes if the inner caustic radius lies between the inner and outer interfaces. The observed critical sensitivity of loss to radial parameters is particularly marked for values approaching the caustic radius. Here modes in the curved waveguide are defined by both the inner and outer sidewalls. In the whispering gallery mode regime ($0 \leq R_{\mathrm{inner}} \leq R_{\mathrm{inner\ caustic}}$), however, light no longer reaches the inner sidewall and the inner sidewall no longer plays a role in waveguiding and scattering losses. [6]

Conclusions

A detailed 2D finite difference time domain study is performed into fabrication tolerant microbends. Complex modal interaction is observed resulting in high sensitivity of losses to critical fab dimensions. Careful choice of radii does however allow optimum mode excitation and relaxed fabrication tolerance in low-loss microbends.

References

[1] L.H. Spiekman, Y.S. Oei, E.G. Metaal, F.H. Groen, P. Demeester, M.K. Smit, *IEE Proc.-Optoelectron.*, 142, 61, 1995.

[2] C. Manolatou, S.G. Johnson, S. Fan, P.R. Villeneuve, H.A. Haus, and J.D. Joannopoulos, *Journal of Lightwave Technology*, 17, 1682, 1999.

[3] A. Mekis, S. Fan, J. D. Joannopoulos, *Physical Rev. B*, 58, 4809, 1998.

[4] P. Buchmann and H. Kaufmann, *Journal of Lightwave Technology*, 3, 785-787, 1985.

[5] J. Yamauchi, M. Ikegaya, and H. Nakano, Microw. *Optical Technol. Lett.*, 5, 251, 1992.

[6] S.C. Hagness, D. Rafizadeh, S.T. Ho, and A. Taflove, *Journal of Lightwave Technology*, 15, 2154, 1997.

[7] T. Baba, *IEEE International Conference on Indium Phosphide and Related Materials*, 63, 2001.

[8] OMNISIM Software, *Photon Design*.

[9] E.G. Neumann, *IEE Proc. H*, 129, 278, 1982.

[10] J. Heebner, R. Grover, T. Ibrahim, *Optical Microresonators, Theory, Fabrication and Applications*, Springer, 2008.