

Optimization of S-shaped Bend Waveguide Using Random Orthogonal Axial Gradient Method

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Keywords: S-shaped bend waveguide; configuration curve optimization; random orthogonal axial gradient method; integrated optics.

Abstract. S-shaped bend waveguides are indispensable in planar light circuits to realize the lateral displacements and connections. High-density integrated optical circuits require S-shaped bend waveguides to be low loss and compact sized. In this paper, the loss mechanism of the S-shaped bend is briefly analyzed first, and then a novel scheme to optimize the waveguide bends is proposed. Using a modified random direction method, the random orthogonal axial gradient method (ROAGM), the configuration curves of the S-shaped bends fitted by polynomials are optimized. Numerical results show that the insertion losses of the optimized configuration curves are much smaller than those of the conventional cosine functions when the space requirement is strict.

Introduction

S-shaped bends are widely used to realize lateral displacements and connections in integrated optical devices, such as the directional couplers, optical switches and arrayed waveguide gratings (AWGs). For the open nature of waveguide bends, power carried by the propagating modes will be radiated when light passes through them. To reduce the power loss in the bends, lots of researches have been done. Besides the cross-section design of waveguides [1, 2], the issue of configuration curve optimization has been studied by many researchers. A theoretical optimized profile of “low-slope” S-bends has been presented by F. J. Mustieles, though only the pure bending loss was considered [3]. Yang and Zhang have proposed configuration optimization methods by using cubic spline curve and B-spline curve interpolations, respectively [4, 5]. The optimization results, however, depend on the initial points selected. Y. Y. Lu has also proposed an optimization method with spline curve interpolation, and a technique of initial points’ neighborhood searching is combined [6]. Although the interpolated spline curves are smooth enough and the transition loss could be reduced, the optimized configuration curves are too complicated to express.

An arbitrary curve can be fitted by polynomials. The advantage of polynomial fitting is that a smooth curve can be expressed by a few parameters. Since the searching directions and ranges of the polynomial coefficients are more difficult to determine, a modified random direction method, the *Random Orthogonal Axial Gradient Method* (ROAGM) is developed in this paper. Simulation results show that the optimized S-shaped bends could reduce the insertion loss greatly, especially when the space constraint is strict.

Insertion loss analysis of S-shaped bends

The S-shaped bend is a bend waveguide connecting two lateral displaced parallel straight waveguides. The radius of curvature along the bend varies gradually to realize the lateral displacement and connection, as shown in Fig. 1. The lateral displacement is noted as D , and the longitudinal displacement is noted as L . Considering from the nature of the bending, the insertion loss of the S-shaped bend includes two parts: pure bending loss and transition loss. The eigenmodes of a bent waveguide are leaky modes. Power will gradually attenuate when light propagates through a bent waveguide. The pure bending loss of a circular waveguide is firstly derived by Marcatili and Miller:

$$a(R) = 8.686C_1 \exp(-C_2 R) (dB/m). \quad (1)$$

where C_1 and C_2 are two constants depending on the waveguide structure and on the shape of optical mode [7, 8], and R is the curvature radius. The transition loss is induced by a mode mismatch of a connection of two waveguides with different curvature radii. Therefore, an S-shaped bend connected by two circular arcs has a minimum pure bending loss, but a great transition loss.

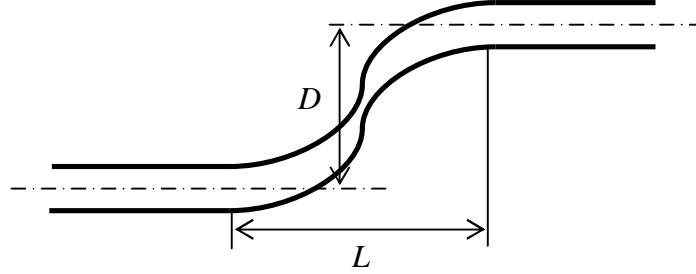


Fig. 1 Schematic of an S-shaped bend waveguide

When the positions of the two lateral displaced waveguides are given, an optimal configuration curve exists to achieve the minimum insertion loss. Generally speaking, an arbitrary configuration curve can be fitted by a polynomial. In this paper, a modified random direction method is developed to find the best configuration curve by searching the polynomial coefficients.

Optimization of S-shaped bends

We are concerned with the S-shaped bend waveguide connecting two straight waveguides with identical refractive-index profiles. The bend waveguide also has the same refractive index profile. Suppose the centre points along the bend waveguide to be optimized satisfy the following function:

$$Cen(z) = -\frac{D}{2} + D \cdot f\left(\frac{z}{L}\right). \quad (2)$$

where $f\left(\frac{z}{L}\right) = \sum_n c_n \left(\frac{z}{L}\right)^n$ is an n -th order polynomial. Based on the analyses above, a low loss configuration curve should meet the following requirements:

- 1) smooth connections between the bend waveguide and the straight waveguides, that means $f(0) = 0$, and $f(1) = 1$;
- 2) smooth transitions between the bend waveguide and the straight waveguides, that means $f'(0) = 0$, and $f'(1) = 0$;
- 3) smooth and monotonous curves are supposed to be efficient and low loss, that means in the range of 0 to L , $f''(z/L) > 0$ and only one inflection point exists.

If the straight waveguides to be connected are single-mode waveguides, the transmission coefficient t can be obtained by:

$$t = \frac{\int u(L) \cdot j_1^* dS}{\int j_1 \cdot j_1^* dS}. \quad (3)$$

where j_1 is the fundamental mode, and $u(L)$ is the output field distribution at $z=L$. The transmittance T is therefore:

$$T = |t|^2. \quad (4)$$

If the straight waveguides to be connected are multi-mode waveguides, the transmittance T is the sum of the transmittance of each mode supported by the waveguide:

$$T = \sum_i |t_i|^2. \quad (5)$$

where $t_i = \frac{\int u(L) \cdot j_i^* dS}{\int u(0) \cdot j_i^* dS}$, j_i is the i -th eigenmode, and $u(0)$ is the input field at $z=0$. To find the best bend that preserves as much power as possible, we solve the optimization problem:

$$\max_{c_1, c_2, \mathbf{L}, c_n} |T|^2. \quad (6)$$

It is obvious that the optimization of the S-shaped bend waveguides is a problem of constraint optimization. The random direction method (RDM) is a classical method for the constraint optimization. The searching path can avoid the penalty area by varying the random generated directions [9] in the RDM. However, the random directions generated in the searching procedure seem to be blind and inefficient. We developed a modified RDM, referred to as the ROAGM in this paper. The procedure of optimization is as follows:

- (a) Start from a randomly initiate point P_0 in Ω ;
- (b) Generate randomly K orthogonal unit vectors $[U_1, U_2, \dots, U_K]^T$ as coordinate axes;
- (c) Search along one of the K axes with one-dimensional gradient method, and get a new optimized point P_1 ;
- (d) Search along the next axis of the K axes from P_1 , and so on until the K axes are all be searched along;
- (e) Finish the optimization if the optimized point P_K met the end criteria, otherwise repeat the steps from (b) to (d).

In order to avoid being trapped into the local optimum point, the simulated annealing (SA) method is also included in the optimization.

Numerical results and discussions

Although approximate loss expressions of waveguide bends have been studied for various types of waveguides, this is not the focus of this paper. Therefore, a more general method, called beam propagation method (BPM) is employed in our optimization [10]. The weakly constraint silica buried waveguide, shown in Fig. 2, is used as an example. The refractive indexes of the core and the cladding are $n_{\text{core}} = 1.4553$ and $n_{\text{clad}} = 1.4444$, respectively. The width and height of the waveguide are $w = 5.5 \text{ } \mu\text{m}$, and $h = 5.5 \text{ } \mu\text{m}$, respectively.

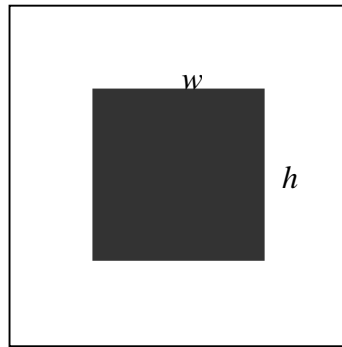


Fig. 2 Cross-section of the buried silica waveguide

For a given lateral displacement of $D = 15 \text{ } \mu\text{m}$, Fig. 3 depicts the insertion losses of the optimized configuration curves with different longitudinal displacements. The 8-th order polynomial is used to fit the configuration curves. The preferred traditional configuration curve of the S-shaped bend is the cosine function [8]. The calculated insertion losses of the cosine-shaped curves are also depicted in Fig. 3. It is revealed that for large longitudinal displacements L , there is no distinguishable difference in the insertion losses between the optimized configuration curves and the cosine-shaped curves. However,

when the longitudinal displacement is less than 500 μm , the insertion losses of the configuration curves with optimized polynomial functions are lower than those of the cosine-shaped curves. For example, the insertion loss of the optimized curve is 0.3503 dB, and the insertion loss of the cosine-shaped curve is 1.2627 dB when $L = 400 \mu\text{m}$. Fig. 4 compares the propagations in these two S-shaped curves ($D = 15 \mu\text{m}$, $L = 400 \mu\text{m}$). The reason is probably that the curvature radii are distributed less evenly along the cosine-shaped curve. As a result, the pure bending loss increases dramatically in the middle section of the cosine-shaped curve when the longitudinal displacement decreases.

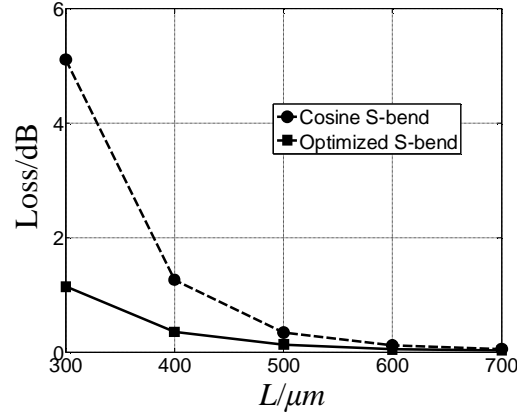


Fig. 3 Insertion losses with different longitudinal displacements L when $D=15 \mu\text{m}$

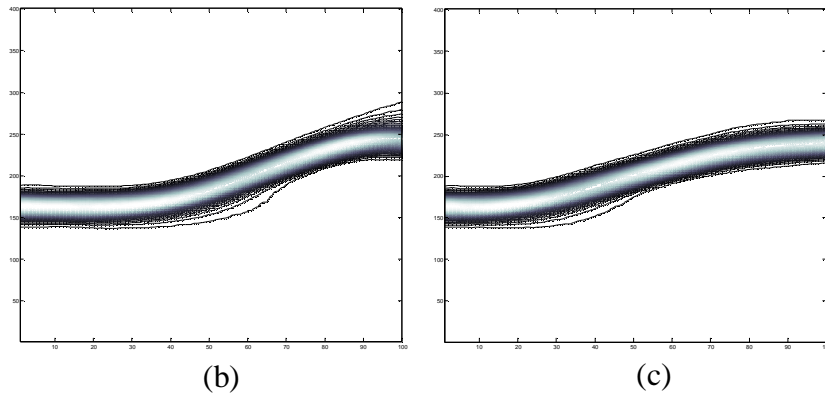
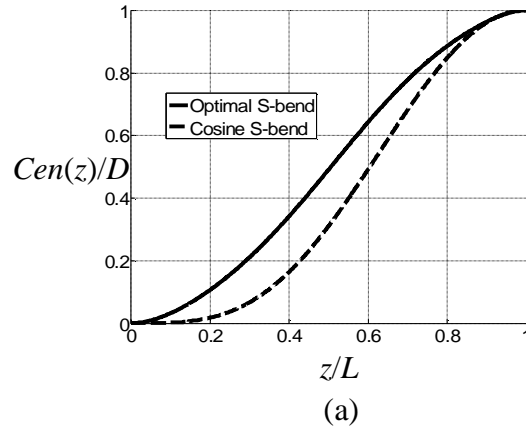


Fig. 4 (a) configuration curves comparison, (b) propagation in a cosine S-bend and (c) propagation in an optimal S-bend

Conclusions

S-shaped bend waveguides with low insertion losses and compact sizes are required in high-density integrated optical circuits. In this paper, the loss mechanism of the S-shaped bend waveguide is briefly analyzed first, and then a novel optimizing scheme for the configuration curve is proposed. Using the random orthogonal axial gradient method (ROAGM), the configuration curves of the S-shaped bends based on polynomial fittings are optimized. Numerical results show that when the space requirement is strict, the insertion losses with the optimized configuration curves are much lower than those with the cosine-shaped bends.

Acknowledgement

This work was supported by the National Natural Science Foundation of China (No. 61107075) and Shanghai Leading Academic Discipline Project (No. S30108).

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