The Influence of Geometry on the Loss of Curved Slot Waveguide

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Abstract. In curved slot waveguide devices, there are often waveguide bending situations. Under certain conditions, the smaller the waveguide bending geometry, the more compact device structure; the smaller the bending geometry, the greater the loss caused by waveguide bending. Based on the study of the loss of a curved slot waveguide, this paper combines the geometric dimensions with it to study the influence of the loss. A new method for calculating the loss coefficient caused by the bending of the waveguide: the effective refractive index method with fixed interference correction. Through this method, the relationship between the bending loss coefficient and the width, height and radius of curvature of the dielectric waveguide is analyzed and calculated. Compare the calculation result with the result calculated by the pattern analysis method. Finally, the results were discussed and analyzed. The conformal transformation method and the normalization method of the geometrical size to the bending loss of the waveguide are analyzed, the relationship between the bending geometrical size of the curved narrow slot waveguide and the bending loss is obtained, and the empirical formula for the bending loss is established. From the formula, four Curves of waveguide bending size and bending loss of a common material. Experimental research results show that with the improvement of bending waveguide loss theory and coupling mechanism, low-loss transmission can be achieved under small bending dimensions, so that the integration of overall geometrical dimensions is the development trend of bending.

Keywords: Geometry, Curved Waveguide, Loss Waveguide, Refractive Index Method

1. Introduction
Regarding the geometrical size of the waveguide loss caused by bending, the more mature theories now include the mode analysis method, the beam propagation method and the conformal transformation method. It is known that the mode analysis method generally uses the electromagnetic vector at the boundary matching condition of the rectangular waveguide interface [1]. Therefore, the derivation process is often quite cumbersome, and the final bending loss coefficient form is also very complicated, which is not conducive to the actual processing; both VP and conformal transformation
methods need to be converted into two-dimensional form first, and the processing is not concise enough, and each There are certain defects [2-3]. The curved rectangular dielectric waveguide and its coordinate system is small and according to the effective refractive index method of fixed perturbation correction, when the fixed perturbation correction is introduced to the refractive index of some areas, the result will have much higher accuracy than the traditional method. Only one of them needs to be analyzed here [4].

In waveguide devices, there are often waveguide bending situations. Under certain conditions, the smaller the waveguide bending radius, the more compact the device structure; the smaller the bending radius, the greater the loss caused by the waveguide bending will be the greater the loss caused by the waveguide bending is mainly the coupling loss And radiation loss, this loss due to radiation is also called bending loss [5-6]. At present, there are many methods for analyzing the loss of a bent waveguide. The most widely used methods are the conformal transformation method, the eigenvalue expansion method and the normalization method. These methods are based on the conformal transformation method. It is obtained by theoretical analysis and computer simulation, and lacks relevant experimental verification [7]. The bending loss of the geometrical waveguide is carefully analyzed, and various theoretical calculation results are compared with experimental values. However, due to the variety of materials used to make waveguides, new materials are constantly appearing. Therefore, there is no theory that has universal The guiding significance of [8].

A waveguide is actually an optical component that confines light to propagate in the waveguide layer. The light propagates in the ideal waveguide material, and there is no energy emission, which causes losses. The scattering loss is mainly related to the material preparation process [9]. Due to the randomness of material defects, high-quality epitaxial waveguide chips can be prepared by optimizing the growth method, and the volume scattering loss plays a negligible role in the scattering loss. Therefore, the scattering loss is mainly caused by the surface scattering loss. The surface scattering loss is mainly related to the geometry and surface roughness of the waveguide. The larger the waveguide width, the smaller the scattering loss. The surface roughness of the waveguide is related to the manufacturing process, such as the fineness of the lithographic printing plate, the residue on the surface of the waveguide, the smoothness of the waveguide end surface, the pattern transfer accuracy, the etching accuracy and the smoothness of the sidewall [10].

2. Algorithm Optimization

2.1 Bending Geometry Loss

The loss can be divided into two parts: pure bending loss and transition loss. The bending loss coefficient can be expressed as:

\[ \alpha(R) = C \exp(-C_0 R) \]  

(1)

In the above formula, R is the radius of curvature of the curved section, and C, C_0 have nothing to do with R and are determined by the corresponding straight waveguide.

Among them, \( R = |(1 + y'')^2 y''' - 1| \) represents the 1st derivative and 2nd derivative of the function \( Y \) respectively. The expression of \( c \) is more complicated. It can be seen that the total loss \( a_t \) can be expressed as:

\[ a_t = \int_0^L \sqrt{1 + y'^2} \, dx \]  

(2)

Can be transformed into:

\[ a_t = \int_0^L \alpha(R) \sqrt{1 + y'^2} \, dx \]  

(3)

In the above formula, \( L \) is the path of wave transmission.

2.2 Simulation and Calculation of the Optimized Route of Slot Waveguide Loss
Firstly, the commonly used ascending arc sine function curve and cosine function curve are given. The expression of the rising arcsine bending waveguide is:

\[ y(x) = \frac{h}{L} x - \frac{h}{2\pi} \sin\left(\frac{2\pi x}{L}\right) \]  

(4)

The expression of the cosine function type curved slot waveguide is:

\[ y(x) = h(1 - \cos\frac{2\pi}{L}) \]  

(5)

Then perform image simulation and loss calculation for all function expressions, comprehensively considering the relationship between branch ratio and loss, according to mathematical theory, it can meet the solution of the 5th power function, so the equation of the curved structure can be assumed as:

\[ y = a^+ + b^- + c^+ + d^+ + e^+ + f^+ \]  

(6)

According to the above-mentioned mathematical algorithm formula, using \( a, b, c, d, e, f \) as undetermined constants, and substituting the boundary conditions into the above formula, you can obtain:

\[ a = \frac{6h}{L^5}, b = -\frac{15h}{L^5}, c = \frac{10h}{L^3}, d = 0, e = 0, f = 0 \]  

(7)

Similarly, if in order to better make the beginning and end have a better degree of bending, add \( y''(0) = 0 \) or \( y''(L) = 0 \), theoretically this will get better With the smooth curve of, 7 boundary conditions are obtained, so that the two 6th power functions can be determined as:

\[ y = \frac{10h}{L^6} x^6 - \frac{24h}{L^5} x^5 + \frac{15h}{L^4} x^4 \]  

(8)

However, in principle, it can be solved infinitely, but from the MATABLE drawing and the integration of the curve, it can be seen that the transmission distance of the solution to the 9th power is significantly increased. The longer the distance means the intrinsic absorption and scattering loss of the optical signal. The larger is, the current industrial fiber is near the 1.3µm band, and its loss is in the range of 0.3dB/km~0.4dB/km, and the absorption loss and scattering loss of the slot waveguide of the geometrically curved route are much larger.

3. Modeling Method

3.1 Conversion Theory Modeling between \( E_x \) and \( E_z \)

The geometrical refractive index change caused by the bending effect defined by the following formula, so in the bending waveguide model, the refractive index change caused by bending satisfies \( \Delta n_x = \Delta n_z \). Under the conditions of isotropic material and nonlinear medium, the electric field is divided into two components, the horizontal and vertical components, and then the first Maxwell equation can be extended as follows:

\[ \Delta \varepsilon \cdot (n^2 \hat{E}_x) + n^2 \frac{\partial n^2}{\partial z} \hat{E}_z = \frac{\nabla_t n^2}{n^2} \hat{E}_x - \frac{\partial E_x}{\partial x} \]  

(9)

According to the derivation of \( \nabla_t n^2 \):

\[ \nabla_t n^2 = \left( \frac{\partial n^2}{\partial x} \mu_x + \frac{\partial n^2}{\partial y} \mu_y \right) E_x = \frac{\partial n^2}{\partial x} E_x \]  

(10)

For an S-Bend-type curved waveguide, \( L_0 \) and \( L_y \) are used to represent the length and height of the curved waveguide, due to different operational differences:

\[ dx = h_0 \pi \frac{z}{L_0} \sin\left(\frac{z}{L_0} \pi\right)dz \]  

(11)

Then, based on the amplitude distribution of the waveguide mode, the equation is obtained:
\[
\frac{\partial E_x}{\partial x} = T_x E_x
\]  

Finally, the amplitude partial derivative equation between the two polarization components is derived:

\[
\frac{\partial E_x}{\partial x} + \frac{1}{N_{eff}^2} \frac{\partial n^2}{\partial x} E_x = -\left[ \frac{1}{N_{eff}^2 \pi h_0 \sin(\pi z/L_0)} + T_x \right] E_x
\]

It is defined as a theoretical model for the conversion of \( E_x \) polarization state to \( E_z \) polarization state. And then obtain the corresponding normalized power value:

\[
\eta_x = E_x E_z^* \]

Finally, the total optical power output value is:

\[
\eta_{tot} = \eta_x + \eta_y + \eta_z
\]

Therefore, the loss value dB of the geometrical bending slot waveguide caused by the bending of the waveguide can be expressed as:

\[
L_{bd} = -10 \log_{10}(\eta_{tot})
\]

3.2 Numerical Results of Modeling and Simulation Results of Simulation
First, by selecting two combined curved waveguides with different refractive index differences for modeling and numerical calculation comparison, the refractive index differences of the geometrical curved waveguides selected in this paper are 0.85% refractive index difference and 1.58% refractive index difference, and then different refractions are obtained. The channel dimensions (width height) of the single-mode waveguide corresponding to the rate-difference bending waveguide are: 8.0x8.0µm and 5.0x3.0µm. According to the equation, use MATLAB programming to obtain the bending radius conversion coefficients corresponding to the two curved waveguides with different refractive index differences, and then select the bending radius of 2.35mm for the two curved waveguides with different structures, and then the corresponding bending loss coefficients are respectively. The values are 7.0/mm and 2.55/mm, and finally the relationship between the numerical power conversion efficiency and the waveguide mode of the transmission distance corresponding to the curved waveguide with different refractive index differences is obtained.

4. Comparative Analysis of Results
4.1 Algorithm Simulation Results

| Geometrically curved waveguide | S-bend | Effective refractive index |
|--------------------------------|--------|-----------------------------|
| Refractive index difference\(\Delta n\)(%) | Curvature size M | TE | TF |
| 0.85% | 2.35mm | 1.4327 | 1.4561 |
| 1.75% | 1.35mm | 1.4653 | 1.4653 |

| Geometrically curved waveguide | Output amplitude value |
|--------------------------------|------------------------|
| Refractive index difference\(\Delta n\)(%) | \(E_x\) | \(E_y\) | \(E_z\) |
| 0.85% | 0.8198 | 0.005 | 0.069 |
| 1.75% | 0.9877 | 0.0312 | 0.09 |
By comparing the results in Table 1 and Table 2, it is concluded that the numerical simulation results calculated by theoretical modeling are consistent with the FDTD simulation results. For example, with the refractive index difference of 0.85% and 1.75%, the numerical simulation results of the conversion efficiency of $E_x$ to $E_y$ are 0.00001 and 0.0001, respectively, while the simulation results of the FDTD software are 0.0006 and 0.069, respectively. Obviously, the two simulation results for the 1.75% waveguide are very close, while the two simulation results for the 0.75% waveguide have a certain difference. The possible reason is that the bending loss coefficient (2.25/µm) selected in the numerical simulation and the FDTD simulation are inconsistent; the same two refractive index difference curved waveguides, the numerical simulation results of the conversion efficiency of $E_x$ to $E_z$ are 0.065 (including the bending loss coefficient 7.0/µm) and 0.078, while the FDTD software simulation results are 0.055 and 0.08, respectively. So the two sets of results are very close.

Figure 1. The height variation curve of the bending loss coefficient of geometrical dimensions

As can be seen from Figure 1, from the above analysis, it can be seen that the height and width of the cross-section of the curved narrow waveguide have an important influence on the bending loss coefficient, so the bending loss of the S-shaped rectangular waveguide also has an important influence. When the width and height of the cross section of the waveguide are 5-10 µm, the bending loss can be reduced to a minimum. Through the theoretical analysis of the bending loss of the geometrically curved slot waveguide, it can be known that the bending loss of the waveguide has a great relationship with the cross-sectional size of the waveguide, and through simulation calculation, it is concluded that the bending loss of the cosine-type function is the smallest. Therefore, in order to reduce the bending loss of the waveguide, the cosine-type function should be selected as much as possible in the design of the geometrically curved slot waveguide.

4.2 The Influence of Geometrical Size Bending Slot Waveguide Loss

Waveguide loss can be roughly divided into the following two situations: First, light is transmitted in the waveguide. Due to the bending of the waveguide, the light cannot be completely confined in the waveguide channel during the transmission process, which causes energy loss. Second, in the process of light transmission in the waveguide, the light in the curved waveguide channel will generate energy radiated to the substrate or the upper cladding, which will cause energy loss during the transmission process. The main reason for mode coupling loss is the loss caused by mismatch. For example, there is a large gap between the straight waveguide and the curved waveguide, the waveguide size and the fiber size, and the mismatch of the two waveguides with different transmission constants will cause a certain degree of loss. When the beam is transmitted in a curved waveguide, the curvature of different positions of the curved waveguide will cause mode coupling loss. Another factor that affects the transmission loss of the optical waveguide is the roughness of the waveguide surface. The roughness of the waveguide surface is mainly affected by the processing technology and the processing process.
5. Result
This article introduces the influence of curved waveguides on geometric dimensions, and analyzes the loss mechanism of curved waveguides, including transmission loss, radiation loss and mode conversion loss. This article summarizes the design solutions to reduce the loss of the curved waveguide from seven aspects: waveguide material, bending shape, waveguide type parameters (width, bending height), mode field distribution, curved waveguide bending shape and other new waveguide structures. This article reviews the application of geometrical dimensions in the loss of curved-slot waveguides and prospects for its application. This article uses the wide-angle method and the effective refractive index method to simulate the waveguide. This conclusion provides us with an effective basis for making complex devices. By analyzing the root causes of bending loss and transition loss, a series of high-order power function expressions that meet the conditions of low bending loss are solved. Compared with the previous sine and cosine functions, the loss has been significantly reduced, indicating that the bending at high branch ratio. This expression has low loss under the route. Finally, an optimized route and calculation for a geometric long and wide waveguide are designed. It can be seen from the simulation that the transmission performance is excellent and the distribution is uniform, and the geometric dimensions will stop the loss of the curved slot waveguide in the future. The production has very good guiding significance.

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