Compact and efficient large cross-section SOI rib waveguide taper optimized by a genetic algorithm

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ABSTRACT

A genetic algorithm is applied to optimize a taper between a large cross-section silicon-on-insulator (SOI) rib waveguide and a single-mode fiber to achieve an ultra-compact and highly efficient coupling structure. The coupling efficiency is taken as the objective function of the genetic algorithm in the taper optimization process. To apply the optimization algorithm, the taper is segmented into several sections. Three encoding forms and a two-step optimization strategy are adopted in the optimization process, resulting in a 10μm long taper with a coupling efficiency of 93.30% in quasi-TE mode at 1550nm. The characteristics of the optimized taper including the field profile, spectrum and fabrication tolerances in both horizontal and vertical directions are investigated via a three dimensional eigenmode expansion (EME) method, indicating that the optimized taper is compatible with the prevailing integrated circuit (IC) processing technology.

Keywords: Silicon-on-insulator (SOI), rib waveguide, taper, optimization, genetic algorithm

1. INTRODUCTION

In recent years, the wide application of SOI material in the field of silicon photonics has made the processing of photonic devices compatible with the mature integrated circuit (IC) processing technology which provides the possibility of micro opto-mechatronics integration in one single chip [1-2]. Due to the large refractive index difference of SOI material, the cross-sectional width of single mode SOI waveguide is in the submicron order of magnitude so that a complex coupling structure is needed for the waveguide to couple with the standard single mode optical fiber [3-5]. Researches have shown that certain rib dimensions can lead to large cross-section single mode SOI waveguides which can be efficiently coupled to single-mode optical fiber through end face coupling [6-8]. In this coupling form, a taper is usually arranged at the end of the rib waveguide, through which the waveguide mode is converted to the same size as the fiber mode [9]. In the previous works, the tapers usually have simple shapes like linear and parabolic curves [10-11]. Although these tapers have the advantages of simple designs and easy fabrication processes, the size of the tapers are usually too large for further integration.

With the development of micro machining technology and the progress of computer simulation technology, structural optimal methods based on various mathematical algorithms are increasingly being applied in the design of silicon based photonic devices [12-17]. Among them, genetic algorithm is widely applied to the optimization of photonic devices for its wide range of feasible solutions, group search characteristic, intrinsic heuristic and implicit parallelism. In [18-19] a genetic algorithm was used to optimize the coupling structure between a SiO2-SiON-SiO2 waveguide and a single mode optical fiber, and an improvement of exceeding 2 dB in the waveguide-to-fiber coupling efficiency was achieved with a 140μm long taper. In [20-21] a genetic algorithm was applied to optimize an SOI nano taper between two SOI waveguides with widths of 0.5μm and 2.0 μm and a transmission of 85% was reached with a taper of only 1μm in length.

In this paper, we apply an improved genetic algorithm to optimize the taper between an SOI rib waveguide with large cross section and a standard single-mode optical fiber. Three encoding forms and a two-step optimization strategy are

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adopted in the optimization process. The optimized structure has advantages of compact size and high coupling efficiency. The algorithm applied is described in Section 2, and the optimization process is described in Section 3. In Section 4 the optimization results are analyzed and discussed, and the conclusions of this work are given in the last section.

2. ALGORITHM

Genetic algorithm is a kind of the evolutionary algorithms, which is a random global search and optimization strategy based on the concept of gene recombination, gene mutation and natural selection in the process of biological evolution in nature [22].

The basic steps applying genetic algorithm to optimize the taper coupler between a single-mode rib waveguide and a single mode optical fiber is shown in Fig. 1. Firstly, the taper needs to be transformed into discrete genetic code, i.e. segmented into several sections which can be easily processed by the optimization program. A coding string uniquely represents a taper structure, as an individual in the genetic algorithm. Then a certain number of coding strings are set as the initial population. The coupling efficiency is selected as the objective function, and a mapping relationship between the objective function and the fitness function is established. The fitness function value is set as the evaluation criteria of the population quality of each iterative process. Appropriate number of individuals are selected for reproduction (including replication, gene recombination and gene mutation) according to their fitness function values to obtain a new population and complete a genetic iteration. The above steps are repeated until the population is convergent when the individual of the extreme value of the target function is obtained. The final taper structure is then obtained after decoding.

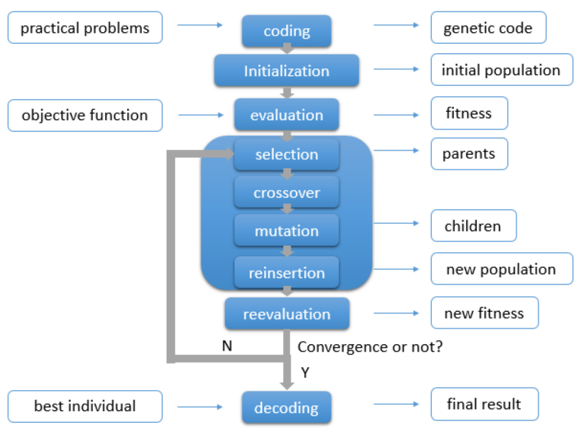

Fig.1. Basic process of adopting genetic algorithm for taper optimization

In addition, the optimization of the optical waveguide coupling structure also needs to take into account the actual processing conditions. According to the structure characteristics of SOI rib waveguide, the transmission mode of a rib waveguide is determined by both its rib height and rib width [7]. The ideal situation is to optimize both parameters. But in practice, the rib height is related to the etching depth, and the change of rib height will inevitably lead to multi-step lithography which brings much more difficulties in fabrication. In this paper, we set the rib height of the taper structure consistent with the target waveguide. Once the rib height is determined, the influence of rib width on the waveguide mode is decisive. Therefore, only the change of the rib region of the taper with a specific length is necessary during the optimization process. Thus, the optimized taper can be easily processed through a one-step lithography process.

3. SETUP

3.1 Encoding

Encoding is the process of abstracting practical problems into digital codes that programs with genetic algorithms can handle, which is a key step to apply genetic algorithms to the optimization of integrated optical devices. Generally, the digital codes will be able to fully express the characteristics of the devices to be optimized, and with which the subsequent operations such as recombination and mutation are easy to carry out.

In this work, the goal of the optimization is to obtain high efficiency coupling between a single-mode optical fiber and a single mode large cross-section SOI rib waveguide. The coupling structure including a single mode fiber, a taper and an SOI rib waveguide is shown in Fig. 2.

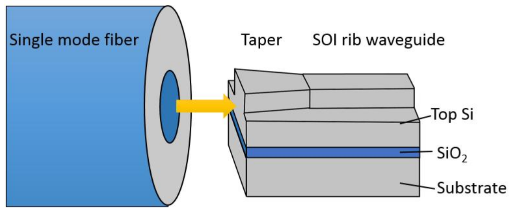

Fig. 2. The coupling structure of single mode fiber and SOI rib waveguide

A case is taken for example to illustrate the optimization process. In this case a Corning SMF28 single-mode fiber is used and the SOI rib waveguide used is shown in Fig.3, with a rib width W=2.5μm, inner rib height H=10μm and outer rib height h=5μm, meeting the single mode condition of SOI rib waveguide with large cross-section [23, 24]. The oxide layer height of the SOI is 2μm which is thick enough to prevent the bottom leakage. A great advantage of using SOI to fabricate rib waveguides is that the thickness of top silicon layer can be customized according to the inner rib height of the rib waveguide. In our case, the SOI top silicon is customized to 10μm which is the same as the inner rib height of the large cross-section rib waveguide discussed in this article. So the slab and rib height vary by the same amount, and the rib height error can fully reflects the etch depth variation.

In this case, the taper will be made discrete of several cells after encoding. In order to compact the taper, the width of each cells is defined in [0, 20]μm, the total length of the device is set to 10μm. Referring to the existing lithography process condition, 20 cells with length of 0.5μm are set.

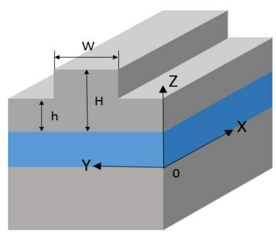

Fig.3. The structure of SOI rib waveguide

Three forms including rectangle, polygon and spline are adopted in encoding according to the structure characteristics of the large cross-section rib waveguide. The conventional and encoding formed tapers are shown in Fig.4. Due to the symmetry mode along the transmission axis of the single-mode fiber and the rib waveguide, the following encoding forms are in accordance with the symmetrical way.

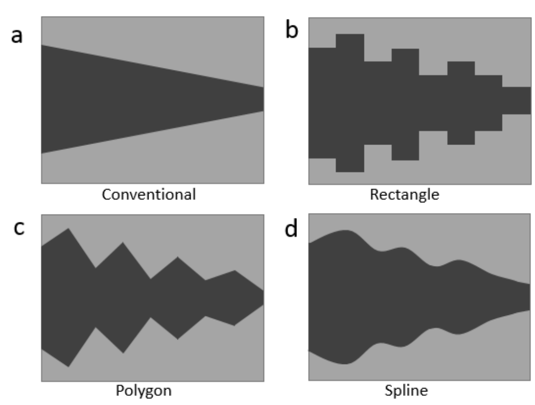

Fig.4. Structure of conventional taper (a) and three encoding formed tapers including rectangle (b), polygon (c) and spline (d)

In the rectangle encoding form, the rib region of the taper with a length of L is divided into N segments equally, each segment is a rectangle with a width of W_i and a length of L/N as shown in Fig.4 (b). Then each taper can be uniquely represented as a coding string [W_1 W_2 ... W_N]. The one-dimensional matrix is an individual for genetic algorithm optimization, where each Wi represents a gene. A population of M individuals can be represented by a matrix of M × N.

In the polygon encoding form, the rib region of the taper is divided into N segments equally. N+1 points are taken and connected with linear lines orderly, each of which has a vertical coordinate of y_i as shown in Fig.4(c). The taper can also be uniquely represented as a coding string [y_1 y_2 ... y_{N+1}] and A population of M individuals can be represented by a matrix of M × (N+1). The spline encoding form is the same as the polygon except the points are connected with cubic spline lines as shown in Fig.4 (d).

3.2 Objective and fitness function

The optimization objective is described by the objective function of which the maximum or minimum value is obtained as the final optimal result. For specific targets, the objective function values often vary widely, making it difficult to reflect the average performance of the population. In practical applications, the objective function is converted to a single valued continuous non-negative fitness function which can be used as an evaluation index of the quality of the population. And it is the fitness function value that determines the probability of the individual to be reproduced.

For taper optimization, the objective function can be set as the coupling efficiency of the single-mode fiber and the SOI rib waveguide. In our case, the coupling efficiency is obtained from the scattering matrix solved by eigenmode expansion (EME) method with a perfect matched layer (PML) boundary condition, which is the same as [21]. The number of modes of EME is set to be 10 to ensure both the accuracy and efficiency of the calculation. The corresponding fitness function can be obtained by a simple linear transformation shown in formula (1), where F represents the objective function, a the coefficient and f the fitness function.

$$f = aF + b \tag{1}$$

To ensure the fitness function of the distinction, so as to avoid pre-mature of the iteration, a simulated annealing algorithm is adopted to enhance the genetic algorithm [25]. The fitness function is stretched to ensure that its value is always differentiated in the process of genetic algorithm, which makes the individual advantage more obvious. The method using simulated annealing to stretch the fitness is shown in formula (2) and (3), where *f'* is the individual fitness, *M* is the population size, g is the genetic iteration generation, *T* is the annealing temperature and T_0 is the initial annealing temperature.

$$f' = \frac{e^{f/T}}{\sum_{i=1}^{M} e^{f/T}} \tag{2}$$

$$T = T_0(0.99^{g-1}) \tag{3}$$

3.3 Optimization strategy

In the iterative process of genetic algorithm optimization, the length of each cell is fixed and only the width of each cell is variable. A two-step optimization strategy is used to improve the iteration efficiency. In the first step, the width varies in a coarse-precision. In specific, for a certain cell the width varies among [0, 20]μm with a step size of 1μm. Thus we can get the approximate optimal result W in a shorter iteration. In the second step, a high-precision optimization iteration is conducted. The approximate result W is set as the Initial value and varied among [W-0.5, W+0.5]μm with the step size of 0.1 nm. In the situation the approximate result is upper limit (20μm) or lower limit (0), the variation range is set to [19.5, 20]μm and [0, 0.5]μm. After the second step, the taper is further optimized.

4. SETUP

4.1 Conventional taper

The total insertion loss of the coupling between a single-mode optical fiber and an optical waveguide is composed of transmission loss, Fresnel reflection loss, alignment error loss and the mode field mismatch loss. The light transmission loss is usually a minor part of the insertion loss. And in the condition of ideal alignment and perfect index matching, the alignment error and the Fresnel reflection can be effectively reduced. So the coupling loss is mainly derived from the mode field mismatch loss.

The mode fields of the single mode optical fiber and the SOI rib waveguide in fundamental quasi-TE mode are calculated through a finite-difference eigenmode (FDE) method as shown in Fig.5. The parameters used to calculate the fiber mode including the fiber core index Ncore=1.44, fiber core diameter dcore=8.2μm, fiber cladding index Ncladding=1.43486 and the fiber cladding diameter dcladding=100μm. There is an air cladding on top of the waveguide.

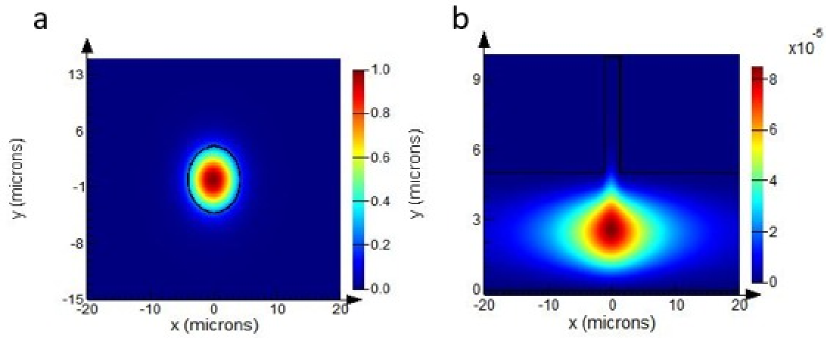

Fig.5. Transverse field distribution of fundamental quasi-TE mode of an approximation of Corning SMF28 single-mode fiber (a) and SOI rib waveguide (b)

When the rib waveguide is directly butt-coupled with the optical fiber, an optimal coupling efficiency of 34% and an overlap of 40.26% can be obtained due to the mode field mismatch both in size and shape. Considering the fiber-waveguide coupling with a conventional taper, the width of the input end of the taper is scanned to obtain an optimal width of 13μm and the width of the output end is set to be 2.5μm which is the same with that of the target SOI rib waveguide. The fiber-waveguide coupling efficiency at the input of the taper is 74.8%, and the overlap between modes of fiber and the waveguide (W=13μm) is 90.43%.

The relationship between the length of the taper and the coupling efficiency is studied through a taper length scanning as shown in Fig.6. We can see from the result that in order to achieve a coupling efficiency higher than 80%, the length of the taper must be more than 1000μm which is too long for one-chip integration. Additionally, there is a peak when the length of the taper is near 15μm, which worth further study.

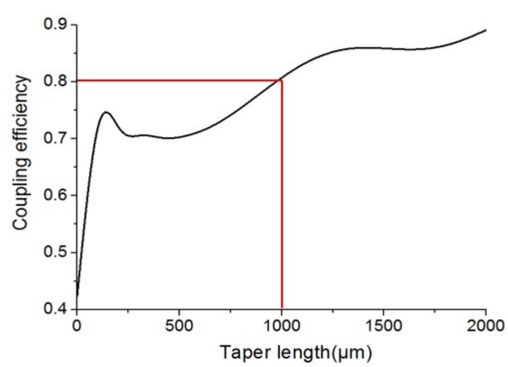

Fig.6. Relationship between taper length and coupling efficiency of a conventional

4.2 Optimization by genetic algorithm

To obtain a more compact and more efficient coupling structure, a taper with a length of 10μm is selected to be optimized by a genetic algorithm. Three encoding forms including rectangle, polygon and spline and a two-step optimization strategy are adopted in the optimization process. The initial population is set to have 20 individuals, and the termination generation is set to be 100.

4.2.1 Iteration results

The approximate optimal results of the three encoding forms are obtained by a 100- step coarse-precision iteration procedure each, as shown in Fig.7. The horizontal axis in the figure is for the number of the iterations, the vertical axis is for the coupling efficiency. The red circles are for the coupling efficiency of the best individuals, and the blue ones are for the population average performance.

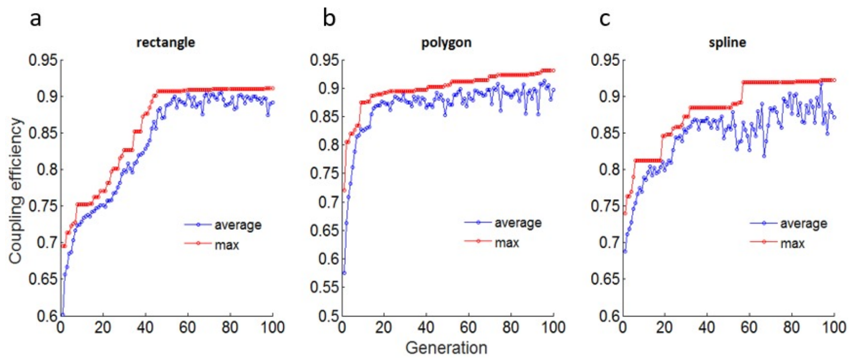

Fig.7. Results of coarse-precision iterations of rectangle (a) polygon (b) and spline (c)

It can be clearly seen from Fig.7 that the optimal and average coupling efficiencies increase rapidly in first generations, and with the increase of iteration generations, the increase slow down gradually and finally tend to convergence. That's because the individuals with good fitness values get better opportunities to reproduce and pass the gene code to next generation during the genetic algorithm iteration. A population with good fitness will be established after several generations and the small difference in fitness makes the population gradually stabilized. In the later iteration generations, the optimal coupling efficiencies get steady while the average coupling efficiencies fluctuate in a small scale because of the crossover and mutation of the genetic algorithm. For all three forms, the iterations gain convergence in 100 generations, the polygon form gains the fastest convergence and reaches a coupling efficiency of 93.12%. The rectangle and spline forms reach a coupling efficiency of 91.04% and 92.47% respectively.

The best individuals of the coarse-precision iteration procedure are set to be the initial individuals of the high-precision optimization. The final optimal result is obtained after another 100-step iteration procedure, as shown in Fig.8. Similar to the coarse-precision iterations, the polygon form gains the fastest convergence in less than 50 generations. The final coupling efficiency is 91.94%, 93.30% and 92.49% for rectangle, polygon and spline form respectively.

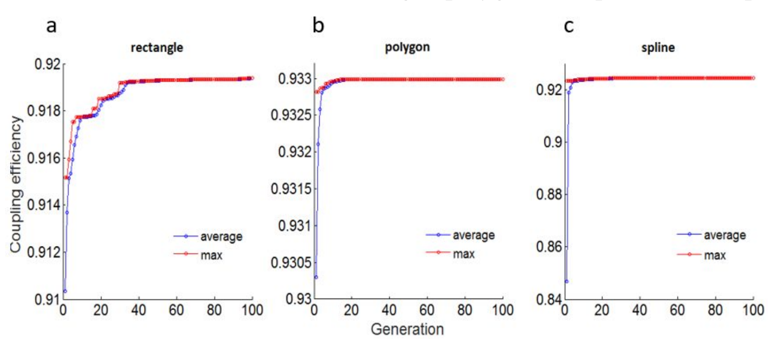

Fig.8. Results of high-precision iterations of rectangle (a) polygon (b) and spline (c)

The use of genetic algorithm in taper optimization results in an ultra-compact and highly efficient coupling structure. A proper encoding form can effectively improve the optimization results and reduce the time the iteration required. Thus, a satisfying result can be obtained with genetic algorithm after iterations of only a few generations.

4.2.2 Taper structure and mode field

The final optimized tapers of the three encoding forms are obtained after the high-precision iteration. The structure shapes (the fiber and taper are shown in pink and blue-green separately) and the transverse field distributions of the fundamental quasi-TE mode in both horizontal and vertical directions of all three forms coded tapers are shown in Fig.9. The transverse field distributions are shown as absolute value of slices in xy plane at z=2μm and in xz plane at y=0.

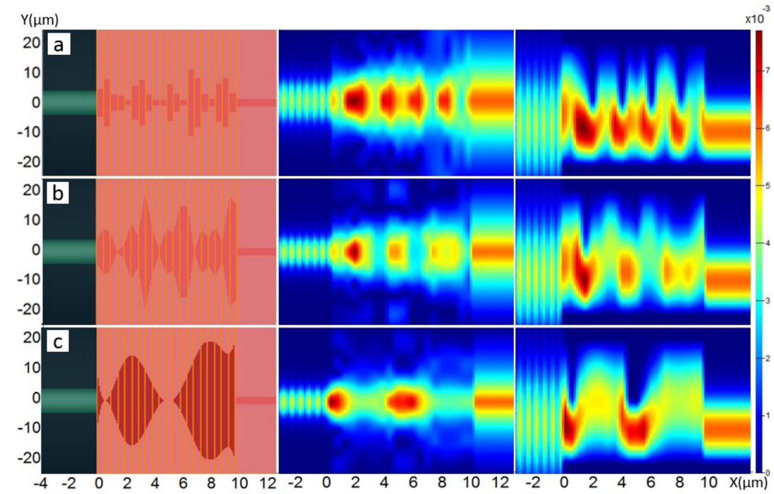

Fig.9. The optimized shapes and transverse field distribution of fundamental quasi-TE mode in horizontal and vertical directions of rectangle (a) polygon (b) and spline (c) formed taper

It can be seen that the change of the rib width will not only affect the mode size and mode shape, but also change the height of the mode. All three formed tapers convert the input Gaussian fiber mode into output rib waveguide mode effectively. Since the optimized taper structure and the field mode are both approximate periodic, it can be inferred that the taper can be further shortened with only one cycle of the periodic structure.

4.2.3 Performance analysis

To study the spectra of the optimized tapers, a wavelength scan of the three kinds of taper structure is carried out, and the relationship between coupling efficiency and wavelength is shown in Fig.10.

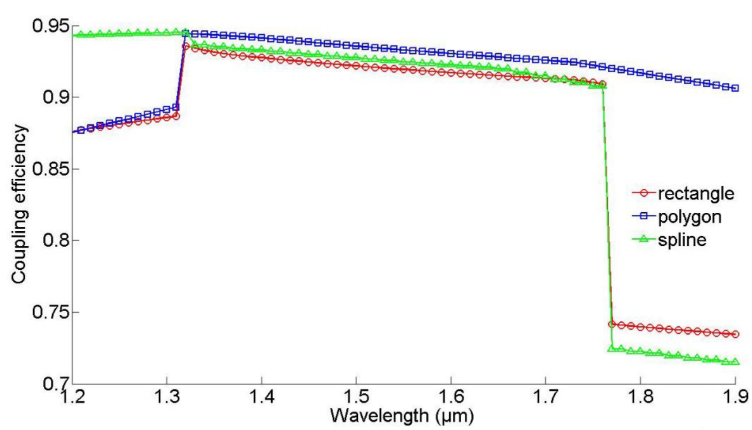

Fig.10. Spectra of the optimized tapers

It can be seen that the coupling has very high efficiency in a certain range, so the structure has a large bandwidth for efficient coupling. In the region from 1.34μm to 1.75μm, all three formed tapers get coupling efficiency higher than 90% and in which the polygon formed taper gets the highest efficiency. In the region from 1.2μm to 1.34μm, the spline formed taper get an efficiency near 95% and the other two formed tapers get lower than 90%. While in the region from

1.75μm to 1.9μm, the polygon formed taper obtain an efficiency near 90% but other two formed tapers get lower than 75%.

The fabrication tolerances of the three encoding formed tapers in both horizontal and vertical directions are investigated via changing the width and the height of the rib structure through a 3D EME method. The relationships between coupling efficiency and fabrication errors in horizontal (error in rib width W) and vertical directions (error in rib height h) for three encoding formed tapers are shown in Fig.11 and Fig.12 respectively.

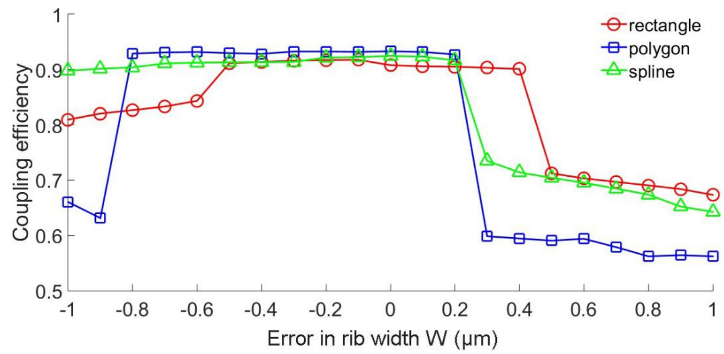

Fig.11. Fabrication tolerances of the three encoding formed tapers in horizontal direction

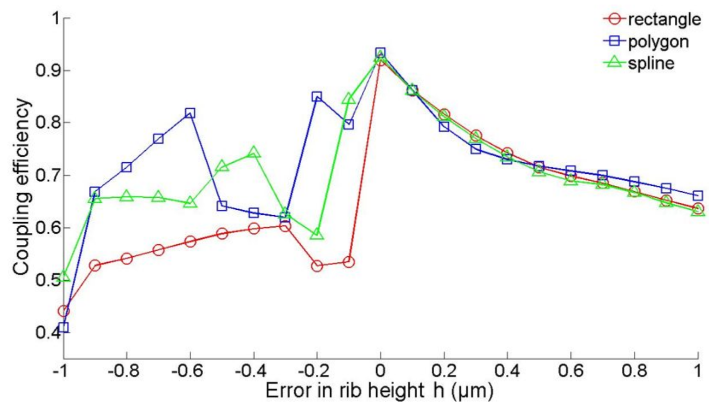

Fig.12. Fabrication tolerances of three encoding forms tapers in vertical direction

It can be concluded from the simulation results that in horizontal, the fabrication tolerance of a coupling efficiency of 90% is about -0.5μm to 0.2μm, while in vertical, the coupling efficiency is much more sensitive to fabrication error and the fabrication tolerance of a coupling efficiency of 90% is about -0.1μm to 0.1μm.

The research on the fabrication tolerances provides guidance to the fabrication process. When fabricating the device, there are different demands in line width and etch depth. As the coupling efficiency is more sensitive to the fabrication error in the vertical direction, the lithography precision should be set to 0.2μm while the etch precision should be set to 0.1μm to achieve a taper with an efficiency higher than 90%. With the prevailing fabrication technology, the processing error of deep UV lithography can be controlled in 0.2μm, and the ICP etching error can be controlled within 0.1μm. And because of the top silicon of the SOI chip can be customized, the structure needs only one single step exposure process, which avoids the misalign error of multilayer technology. So the optimized tapers have the advantage of easy to fabricate.

The optimization processes are based on specific parameters including the operating wavelength (λ=1550μm) and the structure parameters of objective waveguide (H=10μm, h=5μm). When the parameters are out of a certain range, the optimized tapers may not necessarily meet the single mode condition nor conduct insulation transmission, which will cause discontinuous changes of the transmission modes. Therefore, the coupling efficiencies decline dramatically in Fig.10 may be due to the abrupt changes of modes in the tapers at a critical wavelength (in the case of rectangle coded taper, the wavelength at 1.32μm and 1.74μm). Similarly, deformations in the horizontal and vertical directions of the optimized tapers will change the optical transmission modes as well. When the deformations reach a critical value, the modes have a sudden change, resulted in the discontinuity of the coupling efficiencies in Fig.11 and Fig.12. From the simulation results, the coupling efficiencies of the optimized tapers are more sensitive to the processing error in the vertical direction.

4.3 Further improvement

Having obtained a 10μm long taper with a coupling efficiency higher than 90%, the optimization process with genetic algorithm can be still further improved from the following aspects.

1. Refining cells. For segmented encoding, increasing the number of segments within a fixed length (i.e., shortening the length of Wi) can furtherly improve the coupling efficiency. But it will increase the amount of computation and raise the machining accuracy requirement. So the balance between the segment numbers and the practical computation and fabrication capability is important to the optimization.

2. Optimizing algorithm. The genetic algorithm can be further optimized with sub populations, distributed algorithm, nonlinear fitness function and other optimization algorithms to avoid local convergences, speed up computation and improve coupling efficiency.

5. CONCLUSION

A genetic algorithm is adopted to optimize the facet coupling structure, i.e. the taper, between a single mode optical fiber and a single mode SOI rib waveguide with large cross-section. In the optimization process, the coupling efficiency is used as the objective function of the genetic algorithm. Three encoding forms including rectangle, polygon and spline and a two-step optimization strategy including coarse-precision and high-precision are adopted in the optimization process. The optimal results are obtained after 100 generations of coarse-precision iterations and another 100 generations of high-precision iterations. Finally, a coupling efficiency as high as 93.30% is obtained by the optimized coupling structure with an encoding form of polygon and a length of only 10μm. All the three formed tapers get coupling efficiencies higher than 90%. The characteristics of the coupling structure including the bandwidth, mode field and processing tolerances are investigated. It is proved that the optimized coupling structure not only has a large bandwidth, but also has a good processing tolerance which is compatible with the prevailing IC process. In addition, the method can be applied to optimize other silicon photonic structures as well.

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