Low-loss Silicon Dual-mode Waveguide Bend with 900nm Width and 3μm Radius

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***Abstract*—We present a silicon dual-mode waveguide bend with a width of 900nm and an effective radius of 3μm, which exhibits low-loss and low-crosstalk characteristics. A self-adapted particle swarm optimization algorithm is developed to design the structure, which can generate the optimal structure with minimal intervention. The device is fabricated using electron beam lithography. The measured insertion losses for TE_0 and TE_1 modes are less than 0.02 dB and 0.09 dB per 90°, respectively, across the entire C band. The measured inter-mode crosstalk is less than −22.4 dB per 90°.**

Keywords—Silicon photonics, Multi-mode waveguide bend, Inverse design, Particle swarm optimization

I. INTRODUCTION

Optical devices in photonic integrated circuits require close arrangement to minimize footprint and cost. However, the packing density is constrained by the minimum bending radius of waveguides. Smaller bend radius enables higher-density layouts, which facilitate a more integrated optical system with more devices in a smaller space. To further enhance the integration, multiple modes can be employed for optical signal transmission.

The conventional method for designing small-radius bends typically involves the use of established functions, such as Euler (or cycloid) spirals [1-6]. However, this approach entails considerable time and effort to identify the optimal function and its coefficients. The inverse design method leverages algorithms for automated design [7-9], which can alleviate the design challenge and conserve the designer's resources. Moreover, since it searches for the optimal structure from a broader parameter space, it often yields devices with superior performance than those obtained by conventional methods. Nevertheless, the inverse design algorithm itself also poses some difficulties and requires a steep learning curve, such as adjoint algorithm [7], neural network algorithm, etc., which can be daunting for those unfamiliar with them. Particle swarm optimization algorithm (PSO), as a very classic heuristic algorithm, has also been extensively applied in silicon optical device inverse design [10]. However, particle swarm algorithm tends to get trapped in local optima, has low search precision and needs substantial tuning in practical design.

To overcome the aforementioned issues, we enhance the traditional particle swarm optimization algorithm by balancing its local and global search abilities. Most importantly, our algorithm requires minimal human involvement; it only needs a suitable range of structural parameters to search within and it will automatically obtain the optimal result in that range. We refer to our improved algorithm as self-adapted particle swarm optimization algorithm (SAPSO).

We use this algorithm to design a silicon dual-mode waveguide bend with a width of 900 nm and an effective radius of 3 μm. It can support TE_0 and TE_1 modes, with the simulated insertion losses being less than 0.018dB and 0.07dB per 90°, respectively. The simulated crosstalk between the two modes is less than −27.9dB/90°. The device is fabricated by electron beam lithography and dry etching. The measured insertion losses of the two modes are less than 0.02dB and 0.09dB per 90°, respectively, and the inter-mode crosstalk is less than -22.4dB/90°. Experimental results agree well with the numerical simulation, indicating the feasibility and reliability of the proposed algorithm.

II. DESIGN PRINCIPLE

Figure 1 shows a schematic diagram of a silicon dual-mode waveguide bend. We select a channel waveguide with a width of 900 nm to support the first two quasi-TE modes. To achieve an effective radius of 3 μm, we fix four points A, B, E and F such that OA and OE have lengths of 2.55 μm each and form a 90-degree angle at O. We also fix AB and EF at widths of 900 nm each. The line OCD bisects the right angle at O into two equal parts. We denote OC and CD as R_2 and W_2 respectively; these are the only two structural parameters that vary in our algorithm. To ensure smooth transitions between straight sections and bent sections, we use cubic spline interpolation to fit points on both inner parts (ACE) and outer parts (BDF).

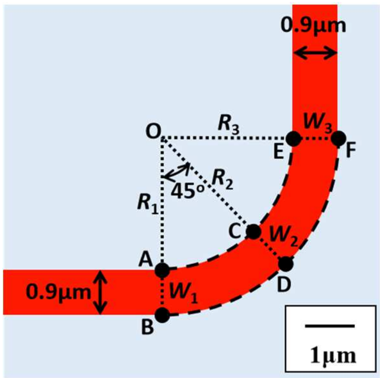

Fig.1 The structure of the silicon dual-mode waveguide bend

The values of R_2 and W_2 are automatically adjusted by the so-called self-adapted particle swarm optimization (SAPSO) we have developed. The main equation of the SAPSO algorithm is as follows,

$$\boldsymbol{v} = \omega\boldsymbol{v} + c_1 r_1(\boldsymbol{p_{best}} - \boldsymbol{x}) + c_2 r_2(\boldsymbol{g_{best}} - \boldsymbol{x}) + Rr \quad (1)$$

$$\boldsymbol{x} = \alpha\boldsymbol{g_{best}} + (1-\alpha)\boldsymbol{x} + \boldsymbol{v} \quad (2)$$

where $\boldsymbol{v}$ is the speed of particle movement, $\boldsymbol{x}$ is the current position of the object, $\boldsymbol{p}_{\mathbf{best}}$ is the optimal position of the individual, $\boldsymbol{g}_{\mathbf{best}}$ is the optimal position of the group, ω is the inertia weight, c_1 is the personal best weight, c_2 is the global best weight, R is the random factor, α is the global best weight, r, r_1 and r_2 are random numbers from 0 to 1.

The calculation formula of coefficients in (1) and (2) is as follows,

$$\omega = \begin{cases} \omega_s + (\omega_e - \omega_s)\frac{f_g}{f_{aim}} & f_g \le f_{aim} \\ 0 & f_g > f_{aim} \end{cases} \quad (3)$$

$$R = R_s + (R_e - R_s)\frac{f_g}{f_{target}} \quad (4)$$

$$\alpha = \frac{i-1}{N-1} \quad (5)$$

where f_g is the group optimum, f_{aim} is the value we set close to our target figure of merit (FOM), f_{target} is our target FOM, ω_s is the inertia weight designated for the first iteration, R_s is the inertia weight designated for the first iteration, ω_e is the inertia weight designated for the iteration, which satisfies $f_g = f_{aim}$, R_e is the inertia weight designated for the iteration, which satisfies $f_g = f_{target}$, N is the total number of particles in the population, and i is the serial number of the particle (i = 1,2,…,N).

From (1) to (5), we can see that there are many parameters involved in the algorithm, but there are certain principles for the selection of parameters. The parameter that has the greatest impact on the search ability of the algorithm is R, and the values of ω, c_1 and c_2 only need to be kept small, about one fifth of R. The maximum value of R is about one tenth of the maximum variation range. The minimum value of R will determine the local search ability of the algorithm. The parameters are set according to the above principles. The algorithm will automatically adjust the parameters according to the current calculation results, and the optimal target structure can be obtained without manual intervention.

III. Simulation and Measurement Results

The SAPSO algorithm is used for device design. Figure 2 (a) and (b) show the electric field distribution of simulated TE_0 and TE_1 modes, respectively. The simulation results show that the TE_0 mode insertion loss is less than 0.018dB/90°, the TE_1 mode loss is less than 0.07dB/90°, and the crosstalk between modes is less than −27.9dB/90°. Figure 2 (c) shows the 3D finite-different time-domain (FDTD) simulation results of the transmission loss and inter-mode crosstalk for the two modes.

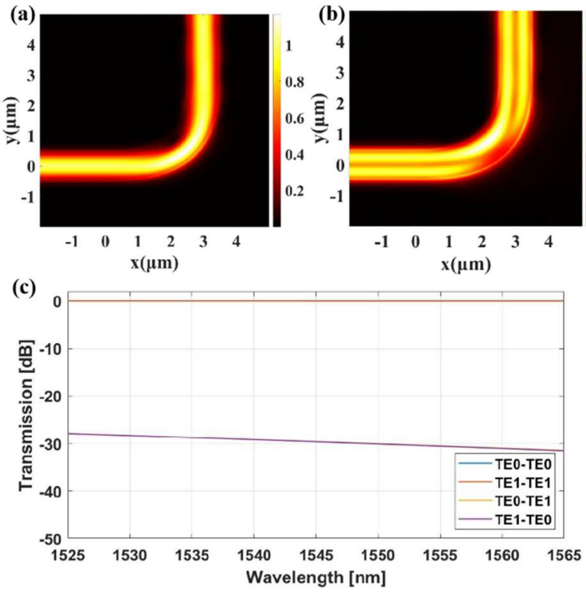

Fig.2 Simulated electric fields of (a) the TE_0 mode and (b) the TE_1 mode. (c) Simulation results of insertion losses and inter-mode crosstalk per 90 degrees.

We used electron beam lithography to fabricate our waveguide bend. Figure 3 shows a scanning electron microscope (SEM) image of our device. In our experiments, we measured transmission losses of less than 0.02 dB/90°and 0.09 dB/90° for TE_0 and TE_1 modes, respectively, using the cut-back method. The inter-mode crosstalk is found to be less than −22.4 dB/90° for our device. Figure 4 presents the measurement results for our device. Figure 5 compares our measurement results with simulation results for the two modes.

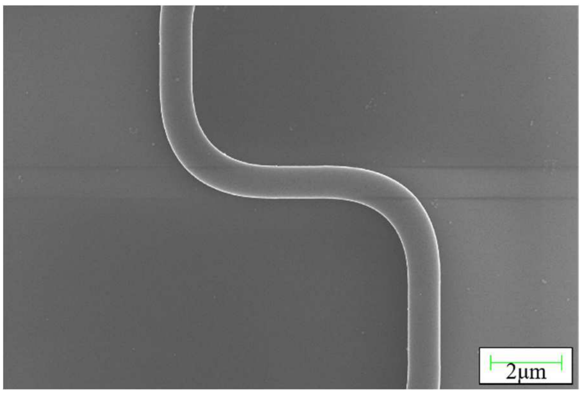

Fig.3 The SEM picture of a curved waveguide with two waveguide bends

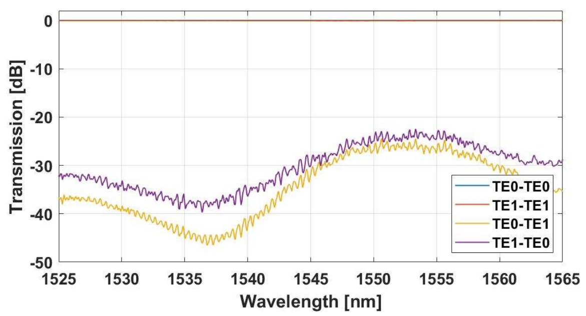

Fig.4 The measured results of the silicon dual-mode waveguide bend

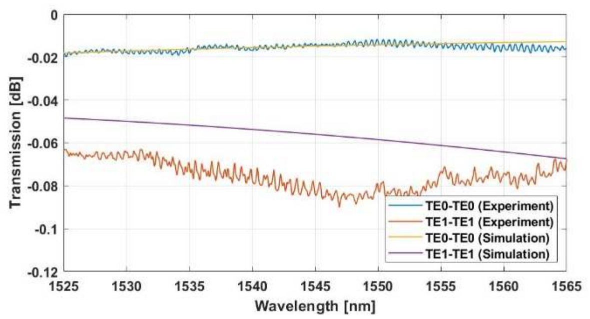

Fig.5 The comparison between simulation and experimental results

IV. Conclusion

We propose a self-adapted particle swarm optimization algorithm to design a silicon dual-mode waveguide bend with a width of 900 nm and an effective radius of 3 μm. The simulated transmission losses of TE_0 and TE_1 modes are less than 0.018dB/90° and 0.07dB/90°, respectively, in the whole C-band. The simulated inter-mode crosstalk is lower than −27.9dB/90°. The device is fabricated by electron beam lithography. The measured insertion losses of TE0 and TE1 modes are less than 0.02dB/90° and 0.09dB/90°, respectively. The measured inter-mode crosstalk is lower than −22.4dB/90°. The experimental results verify the feasibility of our optimization algorithm.

We develop a self-adapted particle swarm optimization algorithm by modifying the conventional particle swarm optimization algorithm. Our algorithm can find the optimal solution within a given range with minimal human input, which greatly reduces the time and effort required by researchers. Our algorithm's principle can also be generalized to other applications, and it is especially useful for designing nanophotonic devices.

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