Optimization of line-tapered MMI devices using a genetic algorithm

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We discuss the optimal design of line-tapered multimode interference (MMI) devices using a genetic algorithm (GA). A 1×4 MMI device is designed as a numerical example. Compared with the conventional design based on self-imaging theory, the present method demonstrates superior performance with low insertion loss and small non-uniformity.

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Recently, multimode interference (MMI) devices have gained popularity due to their excellent performances in compactness, high fabrication tolerance, and wide optical bandwidth[1,2]. The self-imaging theory is commonly used to determine the geometrical parameters of a MMI coupler. However, a MMI coupler designed by the self-imaging theory cannot provide optimal performances in many cases, particularly when the waveguide is weakly guiding[3]. In addition, the large lengths associated with generic straight MMI devices can lead to an undesirable demand on space in optical waveguide circuits[4]. For the purpose of improving performance and reducing the lengths of MMI devices, tapered structures associated with the genetic algorithm (GA) are used to optimize the designs.

In this letter, we choose a 1×4 line-tapered buried silica-on-silicon MMI coupler as a numerical example. Figure 1 shows the schematic structure of the coupler. The minimum and maximum widths and the length of the MMI section are denoted by W_0, W_1, and L_m, respectively. The input (output) waveguides have a width of W_t. When the line-tapered multimode waveguide varies slowly, the self-imaging properties remain[5].

The width of the line-tapered multimode waveguide is given by

$$W(z) = W_0 + \frac{(W_1 - W_0)z}{L_\mathrm{m}}, \quad (1)$$

where z represents distance in the light propagation direction.

The effective MMI width of the line-tapered structure can be obtained from[6]

$$W_\mathrm{e}(z) = W_\mathrm{g} + W(z), \quad (2)$$

for which the Goos-Hänchen shift is given by[7]

$$W_\mathrm{g} = \left(\frac{\lambda}{\pi}\right)\left(\frac{n_\mathrm{c}}{n_\mathrm{r}}\right)^{2\sigma}\frac{1}{\sqrt{n_\mathrm{r}^2 - n_\mathrm{c}^2}}, \quad (3)$$

where λ is the free space wavelength of light; n_r and n_c are the refractive indices of the core and the cladding of the tapered MMI, respectively; σ=0 for TE polarization and σ=1 for TM polarization.

By defining L_π as the beat length of the two lowest-order modes, we can obtain[8]

$$L_\pi = \frac{\pi}{\beta_0 - \beta_1} = \frac{4n_\mathrm{r}(W_0 + W_\mathrm{g})(W_1 + W_\mathrm{g})}{3\lambda}. \quad (4)$$

For a 1×4 MMI coupler, the length of the MMI section L_m is determined by

$$L_\mathrm{m} = \frac{1}{4}\left(\frac{3L_\pi}{4}\right) = \frac{n_\mathrm{r}(W_0 + W_\mathrm{g})(W_1 + W_\mathrm{g})}{4\lambda}. \quad (5)$$

In our design, the refractive indices of the core and cladding are assumed to be 1.47 and 1.46, respectively. The height of the core layer is 5 μm. The free space wavelength is 1.55 μm. The width of the access waveguides is 4 μm, and the maximum and minimum widths

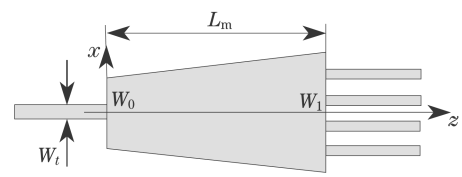

Fig. 1. Schematic of a 1×4 line-tapered MMI coupler.

of the line-tapered MMI section are 80 and 60 μm, respectively. According to Eq. (5), the length of the MMI section should be 1235.7 μm.

For a MMI device, the most important performances are the insertion loss L_i and non-uniformity F_{n-u}, which are defined respectively as[9]

$$F_{n-u} = -10\lg\left(\frac{P_{min}}{P_{max}}\right), \quad (6)$$

$$L_i = -10\lg\left(\sum_i \frac{P_i}{P_{in}}\right), \quad (7)$$

where P_i is the output power at the ith waveguide, P_{in} is the input power, and P_{min} and P_{max} are the minimum and maximum values of all P_i. Exact mode analysis[10] is used to calculate the loss and non-uniformity of the 1×4 MMI device.

The three-dimensional beam propagation method (3D-BPM)[11] is used to simulate the light propagation in the line-tapered MMI device. And the grid size is 0.02×0.02×0.02 (μm) in (x, y, z) coordinate. The output field distribution at the end of MMI section is shown in Fig. 2. From the simulation results, we can see that the non-uniformity and insertion loss are not so good for the MMI device designed by the self-imaging theory.

GA is used to improve the performances of the MMI device. The idea of GA came from Charles Darwin's theory of evolution. And it is a computer-based searching technique patterned after the genetic mechanisms of biological organisms, which is often used to search the global optimum value of multi-target problems[12,13].

For a fixed minimum width (60 μm) of the line-tapered MMI section, the non-uniformity and insertion loss are determined by these parameters: the width W_t of the access waveguides, the length L_m and the effective width $W_e(z)$ of the MMI section. GA is used below to find the optimal values for these parameters in order to achieve the optimal performances of the device.

Since the 1×4 MMI device has multiple output waveguides, we choose the fitness function associated with F_{n-u} and L_i of the output waveguides. The fitness function is defined as

$$F = e^{-(F_{n-u}+L_i)}. \quad (8)$$

From Eq. (8), we know that smaller non-uniformity and insertion loss give larger fitness values.

GA begins with the initial population. After the initial population is generated, the corresponding values of the fitness are calculated. If all fitness values are below a target value, a subsequent generation of trial devices is created, where the probability of a chromosome becoming a parent is proportional to its value of F. The roulette wheel scheme is used to carry out the selection (the procedure to choose parents) in this letter. And a single-point crossover of the two parent chromosomes is used and the crossover point is chosen randomly for every pair of parents. Mutation is then applied for the offspring and a small percentage of the genes may be changed to the opposite values (0 to 1 or 1 to 0). The probabilities of crossover and mutation are 0.3 and 0.001, respectively. Successive generations of devices are modeled until the target figure of merit is achieved. After selection, crossover, and mutation in each iteration, the computer finds the global maximum after a number of iterations. After 240 generations, GA gives the optimized results.

The output light distribution at the end of the MMI section is shown in Fig. 3. Comparing Fig. 3 with Fig. 2, we can see that for the MMI coupler optimized by GA, the loss and non-uniformity has been greatly improved.

To make a clear comparison between the performances of a conventional MMI coupler and a GA-optimized one, we summarize their values in Table 1. From the table we can know that for the self-imaging theory based MMI

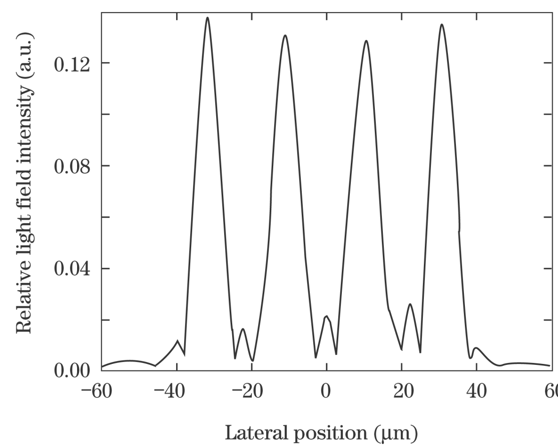

Fig. 2. Field distribution at the end of MMI section based on self-imaging theory.

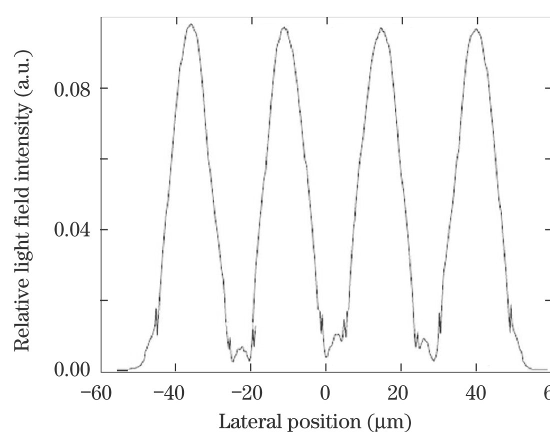

Fig. 3. Field distribution at the end of MMI section optimized by GA.

Table 1. Results of Self-Imaging Theory and GA

Parameter	Self-Imaging	GA
W_1 (μm)	80	80.82
W_t (μm)	4	6.2
L_m (μm)	1235.7	1287.6
Out Position	±10.36	±10.46
(μm)	± 31.08	±31.39
Non-Uniformity (dB)	0.68	0.072
Insertion Loss	1.87	0.031

coupler, the non-uniformity and insertion loss are about 0.68 and 1.87 dB, respectively. When the GA optimization is used, the corresponding values are reduced to 0.072 and 0.031 dB, respectively.

In conclusion, to achieve good results for the non-uniformity and insertion loss, GA has been used to optimize the structure of line-tapered MMI coupler. It has been shown that GA is an effective optimization method for designing a MMI device with good performance. Furthermore, the total device size is about 25% shorter than that of a straight MMI coupler.

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References

1. B. R. West and S. Honkanen, Opt. Express **12,** 2716 (2004).
2. C. Yan, W. Peng, and H. Li, Chin. Opt. Lett. **5,** 516 (2007).
3. Q. Wang, J. Lu, and S. He, Opt. Commun. **209,** 131 (2002).
4. K. A. Latunde-Dada and F. P. Payne, J. Lightwave Technol. **25,** 834 (2007).
5. R. Ulrich and G. Ankele, Appl. Phys. Lett. **27,** 337 (1975).
6. H. Wei, J. Yu, X. Zhang, and Z. Liu, Opt. Lett. **26,** 878 (2001).
7. L. B. Soldano and E. C. M. Pennings, J. Lightwave Technol. **13,** 615 (1995).
8. Q. Yan, J. Yu, and Z. Liu, Chin. J. Semicond. (in Chinese) **24,** 133 (2003).
9. Y. Shi and D. Dai, Opt. Commun. **271,** 404 (2007).
10. E. R. Thoen, L. A. Molter, and J. P. Donnelly, IEEE J. Quantum Electron. **33,** 1299 (1997).
11. J. Yamauchi, J. Shibayama, O. Saito, O. Uchiyama, and H. Nakano, J. Lightwave Technol. **14,** 2401 (1996).
12. P. Yang, Y. Liu, W. Yang, M. Ao, S. Hu, B. Xu, and W. Jiang, Chin. Opt. Lett. **5,** 497 (2007).
13. J. Y. Ye, X.-C. Yuan, and G. Y. Zhou, Proc. SPIE **4594,** 118 (2001).