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Analysis and design of multimode interference coupler based racetrack resonators with the effects of higher order modes

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Abstract. The design and analysis of a racetrack resonator based on a multimode interference (MMI) coupler are presented in this paper. In order to describe the characteristics of an MMI coupler, a matrix description of the MMI coupler, which takes into account the effect of higher order modes in the structure, is developed. A design approach that is based on this matrix description is proposed. The usefulness of this design method is illustrated by means of an example based on Silicon on Insulator (SOI) technology.

1. Introduction

Racetrack resonators are promising devices for applications in the field of optical communication. Using this structure, basic signal processing functions such as wavelength filtering, routing, switching, modulation, and multiplexing can be achieved [1,2]. Most racetrack resonators have been designed and fabricated using directional couplers or MMI couplers as a coupling element between the ring and the bus waveguides. The coupling element is usually modelled by using a 2x2 universal transmission matrix. However, due to the presence of bent waveguides in the racetrack section, additional higher order modes can be excited at the input of the coupling region [3,4]. They can be coupled then to output fields and have an effect on the transmission characteristics. As a result, this simple model can be applied only in ideal cases in which the device is lossless and the matrix is unitary.

In [3], the design ideas of MMI coupler based racetrack resonators for practical fabrication and designs have been proposed for the first time. It is different from the approach given in [4] for a double-ring resonator; in this paper, we would like to develop the model proposed by [3] for a racetrack resonator in more detail, in which the analyses consider the effect of higher order mode excitation within the racetrack on the performance of the device. Moreover, the geometry parameters of the waveguide are also optimized to achieve a better performance. An overall design approach is proposed which takes this effect into account.

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2. Theory

2.1. Conventional analysis

The general racetrack resonator based on an MMI coupler is shown in Fig.1

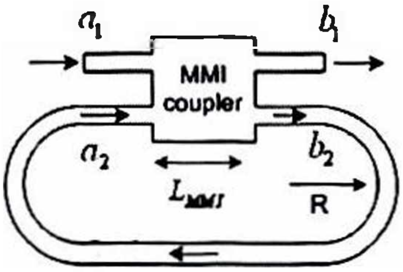

Fig. 1. Geometry of a racetrack resonator based on a MMI coupler.

Here a_i, b_i ($i = 1,2$) are complex amplitudes at the input and output ports, R is the ring radius, and L_{MMI} is the length of the MMI coupler and also is the length of the straight section. In the ideal case, the MMI coupler can be described by a 2x2 transfer matrix and the relations between the complex amplitudes at input and output ports are expressed as [5]

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} \tau & \kappa \\ -\kappa^* & \tau^* \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} \quad (1)$$

$$a_2 = \alpha e^{j\phi} b_2 \quad (2)$$

where τ, κ ($|\kappa|^2 + |\tau|^2 = 1$) are the transmission and coupling coefficients of the MMI coupler. Light propagation through the resonator is characterized by a round-trip transmission loss $\alpha = \exp(-\alpha_0 L_R)$, where α_0 (dB/cm) is the loss coefficient in the core of the optical waveguides. The round trip phase is given by $\phi = 2L_R \pi n_{eff} / \lambda$, where $L_R = L_{MMI} + 2\pi R$ is the racetrack circumference as shown in Fig. 1. $\phi = \beta L_R$ is the phase accumulated over the ring waveguide with propagation constants β, where $\beta = 2\pi n_{eff} / \lambda$, n_{eff} and λ are effective refractive index of the waveguide core and optical wavelength, respectively.

2.2. Modelling of the MMI coupler with the effect of higher order modes

In order to take into account the excitation of higher order modes in the coupling region, an MMI model has been developed, in which a 3x3 transfer matrix is used [3]. By appropriate design, the single mode condition for a straight rib waveguide can be satisfied, but with the presence of bent waveguide sections in the structure, the higher order modes can be excited. In this paper it is assumed that there are only two modes excited in the racetrack region due to the curved waveguide sections. The resulting model is shown in Fig. 2.

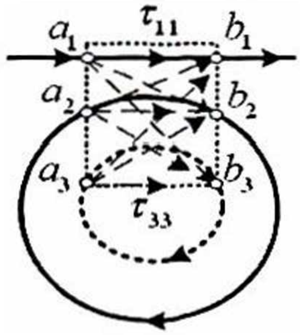

Fig. 2. Model describing the coupling between a ring waveguide and straight waveguide.

The relations between the input and output amplitudes are then given by

$$\begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} = \begin{pmatrix} \tau_{11} & \kappa_{12} & \kappa_{13} \\ \kappa_{21} & \tau_{22} & \kappa_{23} \\ \kappa_{31} & \kappa_{32} & \kappa_{33} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix} \quad (3)$$

$$a_2 = \exp(-\alpha_0 L_R)\exp(j\phi_2) b_2 = \alpha_2 \exp(j\phi_2) b_2 \quad (4)$$

$$a_3 = \exp(-\alpha_0 L_R)\exp(j\phi_3) b_3 = \alpha_3 \exp(j\phi_3) b_3 \quad (5)$$

where a_1, a_2 and b_1, b_2 are the complex amplitudes of the fundamental mode at input and output ports, respectively; a_3, b_3 are amplitudes for the first order modes; and $\kappa_{ij}, \tau_{i,j} (i, j = 1,2,3)$ are the coupling and transmission coefficients between these fields. The round trip phases are given by $\phi_2 = 2L_R \pi n_{eff_1} / \lambda$ for the fundamental mode with effective index n_{eff0} and $\phi_3 = 2L_R \pi n_{eff} / \lambda$ for the first order mode with effective index n_{eff1}.

Substituting (4) and (5) into (3), the amplitude at the output port is given by

$$b_1 = \left\{ \begin{array}{l} \left(\tau_{11} + \kappa_{12}\alpha_2 x_1 e^{j\phi_2}\right) + \\ \alpha_3^2 e^{j\phi_3}\left(\kappa_{13} + \kappa_{12}\alpha_2 x_2 e^{j\phi_2}\right) \dfrac{y_1 + x_1 y_2}{1 - x_2 y_2 \alpha_3 e^{j\phi_3}} \end{array} \right\} a_1 \quad (6)$$

and the normalised transmitted power at the output port is

$$T = \left|\frac{b_1}{a_1}\right|^2 = \left| \begin{array}{l} \left(\tau_{11} + \kappa_{12}\alpha_2 x_1 e^{j\phi_2}\right) + \\ +\alpha_3^2 e^{j\phi_3}\left(\kappa_{13} + \kappa_{12}\alpha_2 x_2 e^{j\phi_2}\right) \dfrac{y_1 + x_1 y_2}{1 - x_2 y_2 \alpha_3 e^{j\phi_3}} \end{array} \right|^2 \quad (7)$$

Here, the parameters x_i and y_i are given by

$$x_1 = \frac{\kappa_{21}}{1 - \alpha_2 \tau_{22} e^{j\phi_2}}, \quad x_2 = \frac{\kappa_{23}}{1 - \alpha_2 \tau_{22} e^{j\phi_2}} \quad (8)$$

$$y_1 = \frac{\kappa_{31} + \alpha_2 \kappa_{32} \kappa_{21} e^{j\phi_2}}{1 - \alpha_2 \alpha_3 \kappa_{32} \kappa_{23} e^{j(\phi_2 + \phi_3)} - \alpha_3 \tau_{33} e^{j\phi_3}} \quad (9)$$

and,

$$y_2 = \frac{\alpha_2 \kappa_{32} \tau_{22} e^{j\phi_2}}{1 - \alpha_2 \alpha_3 \kappa_{32} \kappa_{23} e^{j(\phi_2 + \phi_3)} - \alpha_3 \tau_{33} e^{j\phi_3}} \quad (10)$$

The transmission characteristic is calculated from (7). It will be shown that the excitation of the higher order modes in input waveguides has a strongly effect on the performance of the MMI coupler based devices.

3. Simulation results and discussions

In this section, we design and analyse the device on SOI technology. The rib waveguides were used in our simulations. The parameters used in the simulations are as follows: waveguides with rib width $w = 2\mu m$, etched depth $1.2\mu m$, etched ratio factor $r = 0.6$ to meet the single mode condition for the straight waveguide; and bent waveguide radius $R = 400\mu m$. Signal propagating via a bent waveguide will be lost and bending loss was 3dB at the radius $R = 400\mu m$, and the transition loss between a bent waveguide and a straight waveguide was calculated to be 0.1dB.

It is assumed that the field profile in a straight waveguide is a Gaussian profile with a mode width ω_0. Figure 3 shows the field profiles of a straight waveguide and a bent waveguide with different radii as the parameter.

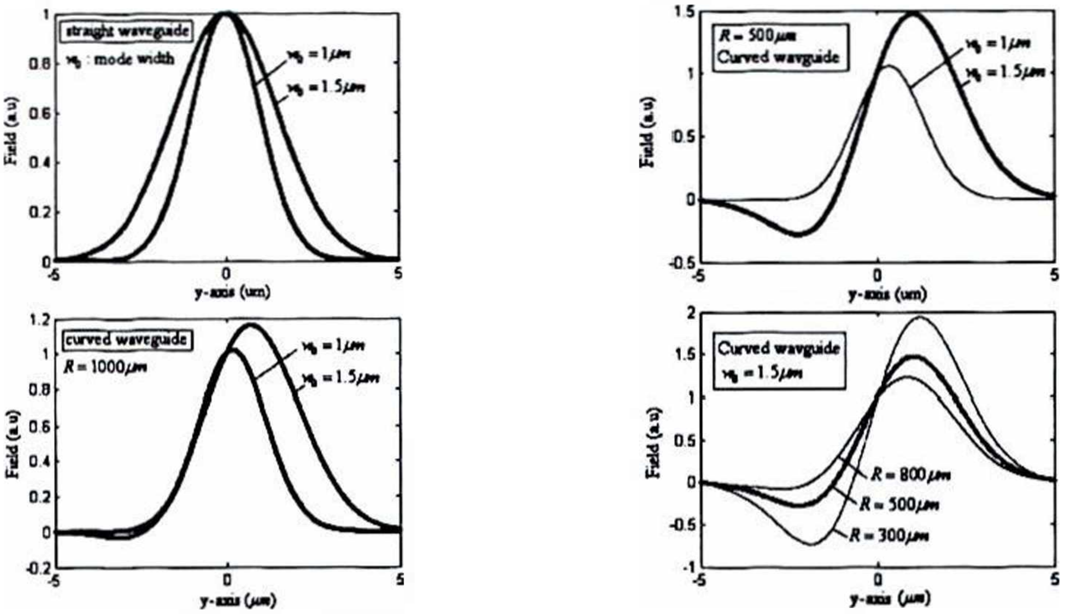

Fig. 3. Field profiles for a straight waveguide and a bent waveguide at different radii.

It is clear that as the radius of the bent waveguide decreases, the higher order mode in the bent waveguide can be excited and it will be coupled to output ports as analysed above.

Figure 4 shows fields at the input waveguide and within the MMI region when the fundamental mode was excited. In this paper, as an example, we consider a racetrack resonator based on a 3dB MMI coupler. The length of the MMI coupler was determined by the analytical analysis to be $226\mu m$ [6] and numerical analysis to be $230\mu m$ for a 3dB coupling ratio as shown in Fig. 4.

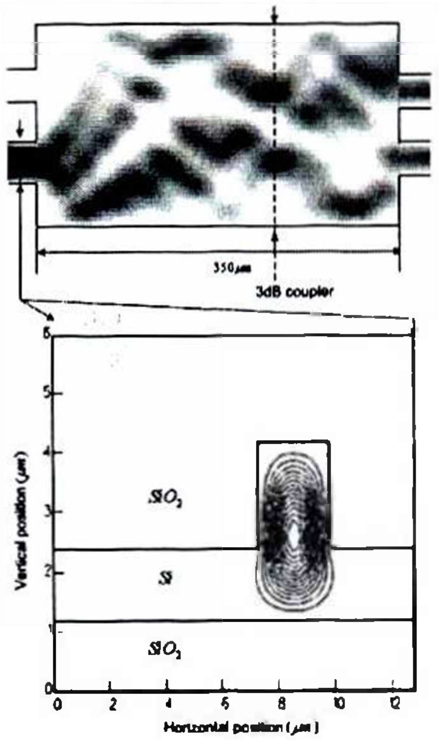

Fig. 4. Fields at the input waveguide and within MMI region with the excitation of the fundamental mode.

Due to the presence of the bent waveguides, the excitation of higher order modes can occur if the radius of bent waveguides is too small; thus a part of power within the higher order modes will be coupled to the fundamental mode and higher order modes at output waveguides. As shown in Fig.5, the power of the first order mode excited in input waveguide is coupled to the two output ports.

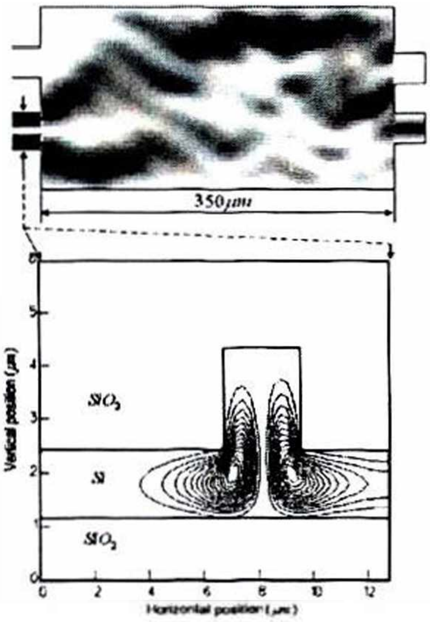

Fig. 5. Fields at the input waveguide and within MMI region with the excitation of the first order mode.

With the excitation of the higher order mode within the coupling region, it is better to model the MMI coupler using a 3x3 transfer matrix as shown earlier in the paper. Therefore, the transmission and coupling coefficients need to be calculated. By exciting the fundamental mode at the input port a_1, the transmission coefficient $|\tau_{11}|^2$, along with the coupling coefficients to the other output port and to the higher order mode in the racetrack, can be calculated at different lengths of the MMI coupler as shown in Fig. 6.

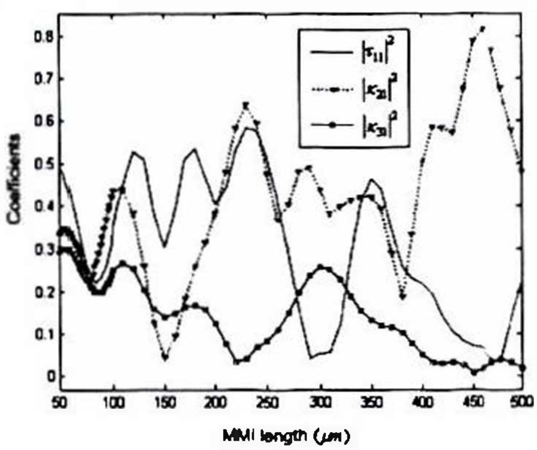

Fig. 6. Matrix coefficients of the fundamental mode at input port 1 coupled to output ports.

Similarly, by exciting the fundamental mode and higher order mode at the input bent waveguide, the other transmission and coupling coefficients can be calculated as shown in Figs. 7 and 8.

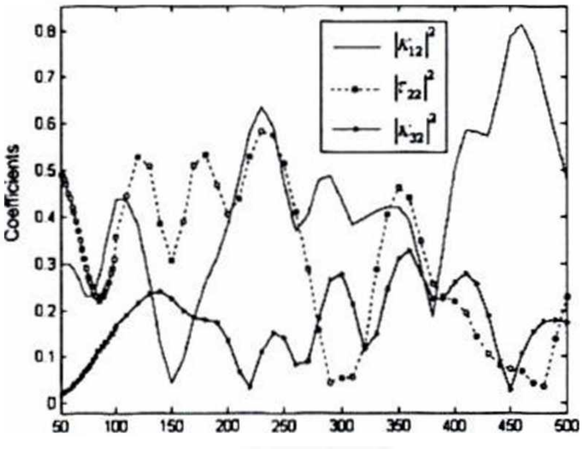

Fig. 7. Matrix coefficients of the fundamental mode at input port 2 coupled to output ports.

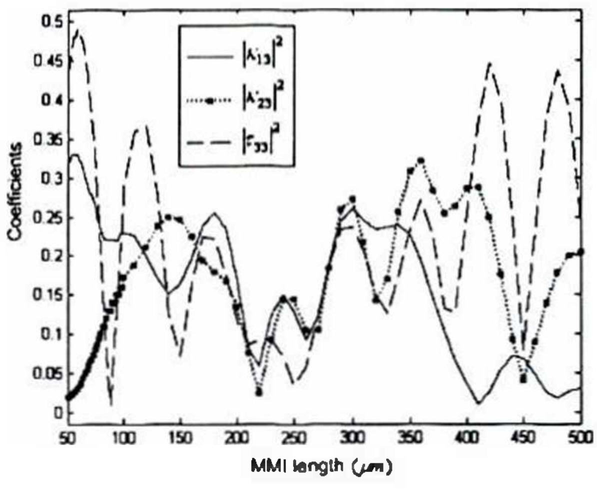

Fig. 8. Matrix coefficients of the higher order mode at input port 2 coupled to output ports.

It is obvious that the effects of the higher order modes within the coupling region are not neglected in the design and analysis of the device. From the designers point of view, the waveguide parameters should be chosen optimally to obtain both single mode operation and low losses. Therefore, we would like to propose five steps in the design as follows:

First step: determine the waveguide geometry to meet the single mode condition following by Soref's well-known condition for a straight waveguide [7].

Second step: Optimise the waveguide parameters to obtain an acceptable level of loss for the desired racetrack radius.

Third step: Design the MMI couplers.

The transmission characteristic of the device is then calculated and checked against the desired performance specifications.

And the last step is that fine tuning of the dimensions and tolerance analysis can then be carried out using a more accurate numerical analysis

Based on the above design steps, transmission characteristics of the device were simulated. Figure 9 shows the transmission characteristic for the ideal case, in which it is assumed that higher order modes were not excited in the bent waveguide sections and losses were not considered; for the case in which bending and transition loss are taken into account; and finally for the case in which higher order mode excitation as well as losses were considered.

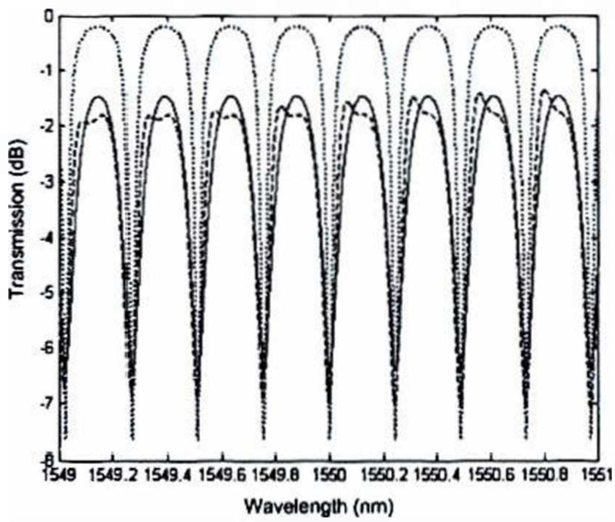

Fig. 9. Transmission characteristics of the device at the MMI length $230\mu m$ (3dB coupler) for an ideal case (dotted line), a case taking into account the losses (solid line), and a case including both the effect of higher order modes and the losses (dashed line).

It is obvious that the excitation of the higher order modes in the coupling region has strong effects on the performance of the device. Therefore, the bent waveguide radius and waveguide geometry should be designed carefully to mitigate against these effects.

4. Conclusion

In this paper, we have presented a method for analysing and designing a racetrack resonator based on the MMI coupler, in which we have considered the effects of exciting the higher order modes on the device characteristics. A novel design procedure which takes into account the losses caused by bent waveguides and the excitation of the higher order modes has been developed. This allows one to design a racetrack resonator with desired characteristics in practice.

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Phân tích và thiết kế các bộ vi cộng hưởng dùng thiết bị giao thoa đa mode MMI có xét đến ảnh hưởng của các mode bậc cao

Lê Trung Thành

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Bài báo đưa ra phương pháp phân tích và thiết kế các bộ vi cộng hưởng quang dùng thiết bị giao thoa đa mode MMI (multimode interference). Bởi sự có mặt của ống dẫn sóng Ring trong cấu trúc thiết bị, nên không như các nghiên cứu trong trường hợp lý tưởng được đưa ra trước đây, thiết bị MMI trong phân tích của chúng tôi được đặc trưng bằng một ma trận 3x3 thay vì ma trận 2x2, trong đó ảnh hưởng của các mode bậc cao được nghiên cứu. Để dễ dàng tích hợp với các thiết bị điện tử, sợi quang hiện có, cũng như tận dụng được công nghệ chế tạo vi mạch hiện thời, và giảm kích thước của mạch, thiết bị được thiết kế và mô phỏng trên công nghệ Silicon.