# OPTIMIZED DESIGN OF MMI COUPLERS BASED MICRORESONATORS

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***ABSTRACT:*** *This paper presents an optimized design for racetrack resonators based on Multimode Interference (MMI) couplers on the silicon on insulator (SOI) platform. The design approach takes into account the effects of bend and transition losses within the racetrack waveguide. For the first time, new positions and geometries of access waveguides are suggested and optimized to improve device performance.*

***Key words:*** *Optical waveguides, multimode interference (MMI) coupler, single mode, silicon on insulator (SOI).*

## 1. INTRODUCTION

Racetrack resonators (also called microresonators in this paper) are basic building blocks for applications in the field of optical communications. Using this structure, basic signal processing functions such as wavelength filtering, routing, switching, modulation, and multiplexing can be achieved [1]. Most racetrack resonators have been designed and fabricated using directional couplers as a coupling element between the ring and the bus waveguides [2]. However, with the advantages of the relaxed fabrication tolerances and the ease of integration of these devices into more complex photonic integrated circuits, small size, and low excess loss, MMI couplers have been used instead of using directional couplers [3].

Operation of the MMI devices is based on the self-imaging principle in which an input field profile is reproduced in single or multiple images at periodic intervals along the propagation direction of the waveguide [4]. In a bent waveguide, the modal field shifts outwards as the radius of curvature is decreased. Therefore, one of the most challenging problems for using MMI couplers in the racetrack resonators is effects of the bent waveguides on the performance of the device [5].

This paper considers the effects of the bent waveguides on the performance of a racetrack resonator based on MMI couplers. The waveguide parameters then are optimized to guarantee both single mode operation and the bend loss, and transition loss at an acceptable level. The positions of access waveguides entering the MMI region are also optimized to obtain a high quality of the self-images within the MMI region, thus better performance of the device can be obtained.

## 2. THEORY AND OPTIMIZATION ANALYSIS

A general microresonator based on an MMI coupler is shown in Fig. 1.

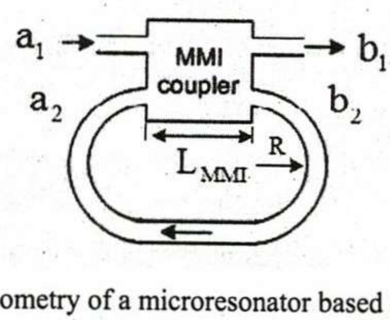


**Fig. 1** Geometry of a microresonator based on an MMI coupler

where $a_i, b_i$ $(i=1,2)$ are the complex amplitudes at the input and output ports. This terminology follows that of Yariv [6]. $L_{MMI}$ is the length of the MMI coupler. The structure includes two curved waveguide sections of radii R connecting with each other via a straight section with a length of $L_{MMI}$.

The signal propagating through the curved waveguides will cause loss and thus affects the MMI response. Bend loss arises from the curved nature of a curved waveguide. The mode shifts towards the outer edge of the curved waveguide and significant power may be radiated outwards. Transition loss occurs when a curved waveguide is coupled to a straight waveguide. There have been many approaches to estimate these losses by using both analytical analyses and numerical methods. A rigorous calculation of these losses requires a full vectorial mode solver and can be very time consuming.

Here, an analytical approach for the design will be used. This approach would be suitable for implementation using silicon on insulator (SOI) rib waveguides. This method is based on the work of Marcuse [7]. When comparing this analytical model with the three dimensional beam propagation method (3D-BPM) results [8], it is shown that there is quite good agreement. Therefore, this analytical approach is useful and suitable for calculating the bend loss. In addition, it enables the designer to easily optimize the waveguide parameters to obtain the best performance.

In the following analysis, reflections (apart from those at outer walls of the MMI region) will be neglected. By using the effective index method (EIM), a three dimensional (3D) rib waveguide can be reduced to a two dimensional (2D) model as shown in Fig. 2 [9]. The EIM method is implemented by splitting the waveguide in one direction into a series of planar waveguide structures. Each section can be represented by an effective refractive index by solving the dispersion equation for that slab waveguide. The procedure of the EIM method and its application to an SOI rib waveguide is demonstrated in Fig. 2. The EIM is well-suited for analyzing 3D waveguide structures having low index contrast. It has also been applied to SOI rib waveguides.

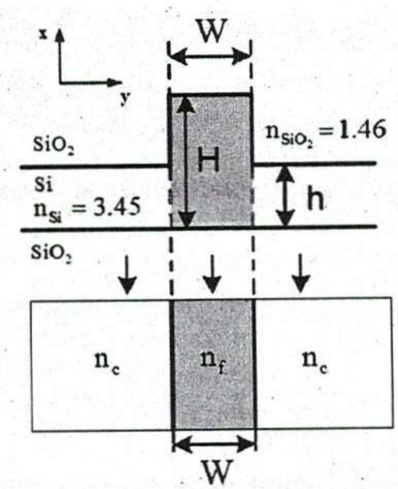


**Fig. 2** 3D waveguide structure and its decomposition into planar waveguides ($n_f$ and $n_c$ are the effective refractive indices of the core and cladding region)

After having obtained the effective indices numerically, the attenuation coefficient $\alpha_b$ of a curved waveguide having a radius of R can then be determined by using Marcuse's formula [7]

$$\alpha_b = \frac{1}{2}\frac{\alpha_y^2}{k^3 n_e (1+\alpha_y \frac{W_a}{2})}(\frac{k_y^2}{n_f^2 - n_c^2})\exp(\alpha_y W_a)\exp(-\frac{2\alpha_y^3}{3n_e^2 k^2}R) \quad (1)$$

where $\alpha_y = k\sqrt{n_e^2 - n_c^2}$, $k_y = k\sqrt{n_f^2 - n_e^2}$, $k = 2\pi/\lambda$ and $n_e$ is the effective index of the equivalent slab waveguide (For a single mode waveguide, $n_e = n_{e0} = \beta_0 / k$, where $n_{e0}$ is the effective refractive index of the fundamental mode).

The bend loss in dB of a curved waveguide with radius R and angle $\gamma$ (in radians) then is given by

$$L_b = -10\log_{10}[\exp(-\alpha_b \gamma R)] \quad (2)$$

Figure 3 presents the bend loss as a function of the curved waveguide radius at different angles $\gamma$. The parameters used for the simulations are the step ratio $\sigma = h/H = 0.68$ ($\sigma$ is the ratio of the height of the side regions to that of the rib centre) and the width of the waveguide $W_a = 1\mu m$.

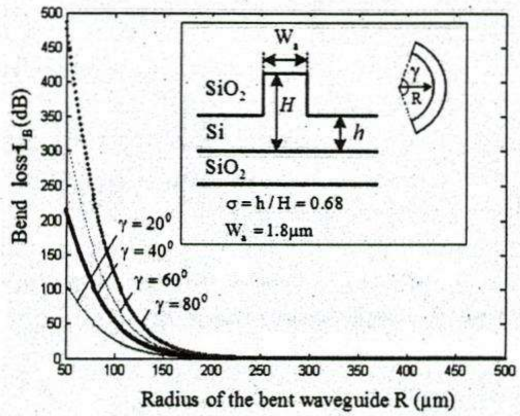


**Fig. 3** Estimate of bend loss at different radii, using Marcuse's analysis

Figures 4 and 5 show the bend loss at a variety of waveguide widths and step ratios respectively.

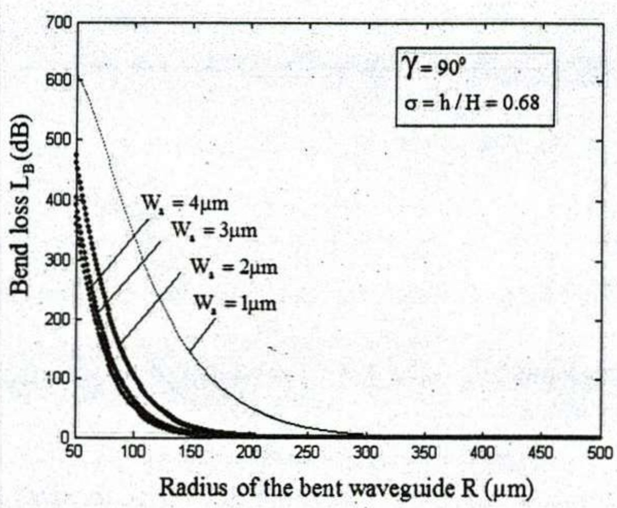


**Fig. 4** Estimate of bend loss for a variety of waveguide widths

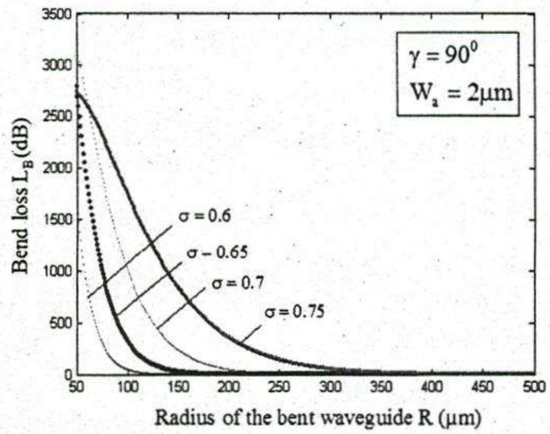


**Fig. 5** Estimate of bend loss at different values of the step ratio $\sigma = h/H$

It is clear that the bend loss strongly depends on the waveguide parameters. By increasing the curved waveguide radius, the bend loss decreases significantly. But this results in an undesirable increase in circuit size. Similarly, increasing the waveguide width or decreasing the step ratio will reduce the bend loss. However, in order to achieve a high density of integrated optical components, the bend radius should be as small as possible. Therefore, to reduce the bend loss, the waveguide width can be increased or the step ratio ($\sigma = h/H$) can be decreased. However, these parameters have effects on meeting the single mode operation condition of the straight waveguide. The design strategy followed in this paper is to optimize these parameters in order to satisfy the single mode condition for the straight waveguides and also limit the bend loss to an acceptable level. By employing Soref's criterion [10], an optimized structure for an SOI rib straight waveguide is obtained as follows: rib waveguide width $W_a = 2\mu m$, lateral slab height $h = 1.8\mu m$ and rib height (thickness) $H=3\mu m$ at the centre operating wavelength $\lambda = 1550nm$.

If the field profile in a straight waveguide is approximated by a Gaussian profile having a mode width of $\omega_0$, then the transmission loss $\alpha_{st}$ at a straight-to-curved section transition with an offset value of d and a radius of R can be calculated by [11]

$$\alpha_{st} = \frac{\exp(-\frac{d^2}{2\omega_0^2})\left[1+\frac{(kn_f\omega_0)^2 d}{2R}\right]^2}{\left[1+\frac{(kn_f\omega_0)^4\omega_0^2}{2R^2}\right]} \quad (3)$$

Here the mode width $\omega_0$ is the spot size at which the power has dropped to l/e of its maximum value [12, 13]. The mode width $\omega_0$ is determined by fitting a Gaussian function to the field profile of the waveguide. This field profile can be found by solving the dispersion equation of the equivalent slab waveguide [14].

The transition loss in dB then is given by

$$L_{st} = -10\log_{10}(\alpha_{st}) \quad (4)$$

One approach to reduce the transition loss is to introduce optimal offsets at a straight-curved transition so that the field peak in the straight waveguide is matched with the field peak in the curved waveguide. Therefore, it is necessary to determine this optimum offset value for the desired radius of the curved waveguide. The optimal values of offsets and the transition loss at these optimal values are shown in Fig. 6 and 7. By using this approach, one can quickly obtain the required optimal offsets for the device.

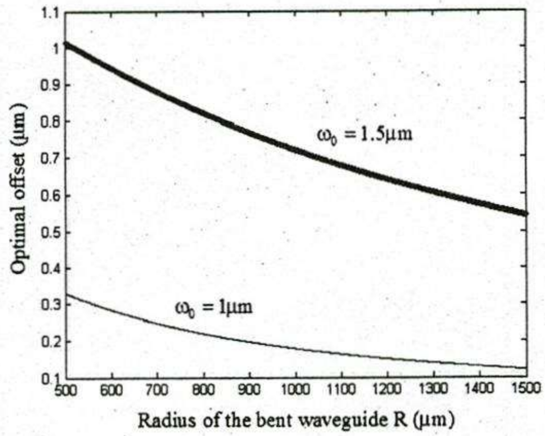


**Fig. 6** Optimal offset as a function of curved waveguide radii at different mode widths

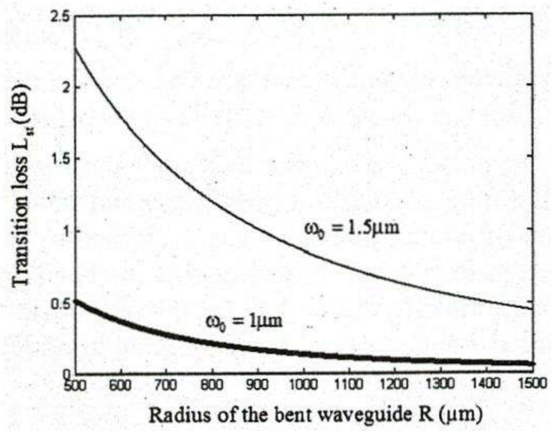


**Fig. 7** The dependence of the transition loss $L_{st}$ on the radius at optimal offsets

From the designer's point of view, the total loss is an important parameter. Therefore, the total loss for different radii needs to be determined so that an appropriate radius, which keeps the total loss small, can be chosen. For example, the above design strategy can be applied to a 3dB MMI coupler based on the restricted interference theory using an SOI rib waveguide. The parameters for the waveguide are: rib width $w_a = 2\mu m$, lateral slab height $h = 1.8\mu m$ and rib height $H = 3\mu m$. The 3D waveguide structure is converted into an equivalent 2D structure with a cladding index of $n_c = 3.4272$ and core index of $n_f = 3.4413$. The mode width $\omega_0$ of this waveguide by solving the dispersion equation [14] is found to be $\omega_0 \approx 1\mu m$.

The resulting loss curves are shown in Fig. 8, where the insert box shows the loss curves for curved waveguide radius R varying from 400 to $1000\,\mu m$. In order to keep the total loss low, the curved waveguide radius is chosen to be $R = 500\mu m$. Bend loss at this radius is $0.01dB/180^0$ and the optimal offset is $0.31\mu m$. The transition loss is 0.5dB. The length of the

MMI coupler for a 3dB (or 50/50) coupling ratio is determined by the analytical analysis (the conventional guided mode propagation method [9]) to be $L_{MPA} = 226\mu m$ and numerical analysis to be $L_{MMI} = 230\mu m$.

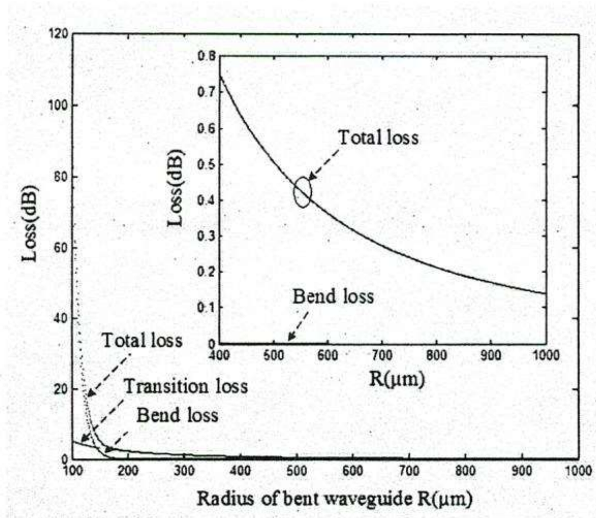


**Fig. 8** Loss curves at different radii of the curved waveguide

Overall transmission characteristics of the device can now be simulated. It is assumed that the loss coefficient of the SOI rib waveguide [15] is $\alpha_0 = 0.1dB/cm$. Figure 9 shows the transmission characteristic for an ideal case in which only the transmission loss is considered and for the case in which the transmission loss, bend loss and transition loss are all taken into account. The extinction ratio of the microresonator is decreased by around 5dB when bend and transition losses are included in the design. It is clear that the bend and transition losses greatly affect device performance. Optimizing the design for curved waveguides and offsets between straight waveguides and curved waveguides is therefore quite important.

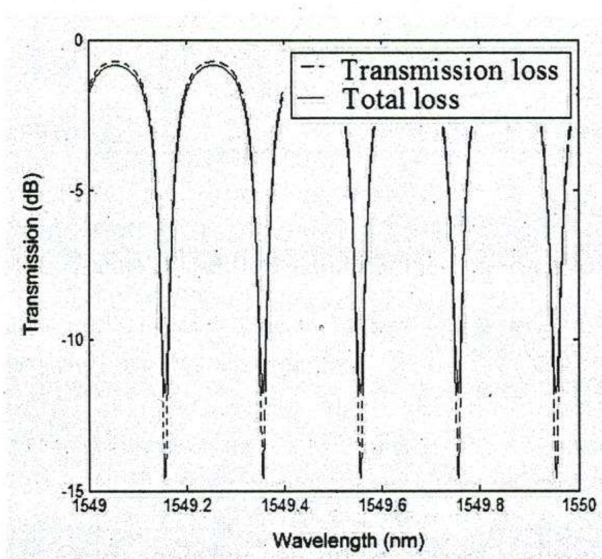


**Fig. 9** Transmission characteristics of a 2x2 MMI based microresonator with and without taking into account the effects of the bend and transition losses

In addition, due to the presence of the curved waveguides, the field along the curved waveguide will move towards the outer cladding region. This results in a lateral shift in the peak of the field at the end of the curved waveguide, at input port 2 as shown in Fig. 10, where the MMI width is $W_{MMI} = 12\mu m$. This phenomenon will cause loss due to modal dispersion in the MMI region and incomplete matching of the input access waveguide modes with the superposition of the MMI modes. In order to overcome this problem, the access waveguide should be shifted by $0.31\ \mu m$ to compensate for lateral field shift in the curved waveguide. Thus, a better match of the modes in the access waveguide with the superposition of the MMI modes can be obtained. By using numerical analysis, the optimized MMI length is found to be $L_{MMI} = 233\mu m$. The normalized output powers at the bar (output port 2) and cross port (output port 1) are about 0.45 and 0.48, respectively. The computed excess loss is 0.31dB and the imbalance is 0.28dB.

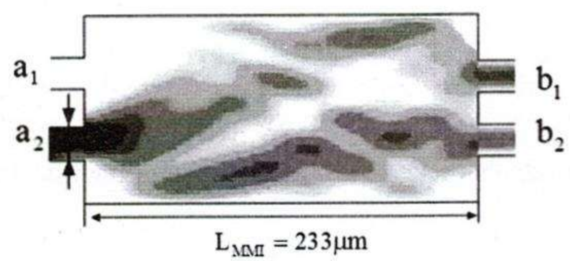


**Fig. 10** Power distribution after going via a curved waveguide and coming into the input port of the MMI coupler. The simulation was carried out using the 3D-EME

Figure 11 shows the field propagation through the MMI coupler when the access waveguide has been shifted to compensate for the modal displacement in the curved waveguide. In this case, the simulation shows that the length of the MMI coupler should be decreased to $232\mu m$ in order to obtain a 50/50 power splitting ratio at the output ports. The normalized output powers at the bar (output port 2) and cross port (output port 1) are 0.48 and 0.47, respectively in this case. The excess loss is 0.23dB, but the imbalance is only 0.09dB.

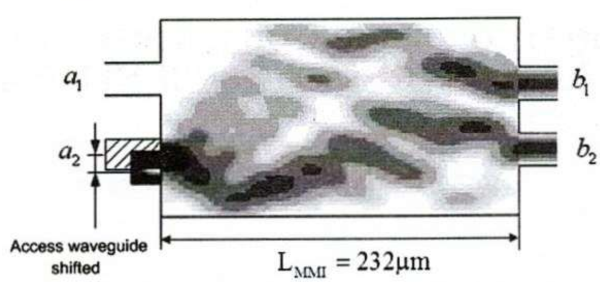


**Fig. 11** Power distribution after going via a curved waveguide and entering to the input port of the MMI coupler and field in MMI coupler with modal displacement of the access waveguide

Figure 12 compares the performance of devices having (a) only the transmission loss (ideal case) (b) the conventional MMI coupler with the MMI loss and (c) MMI coupler with shifted access waveguides. Note that in this simulation, only transmission and MMI losses are considered.

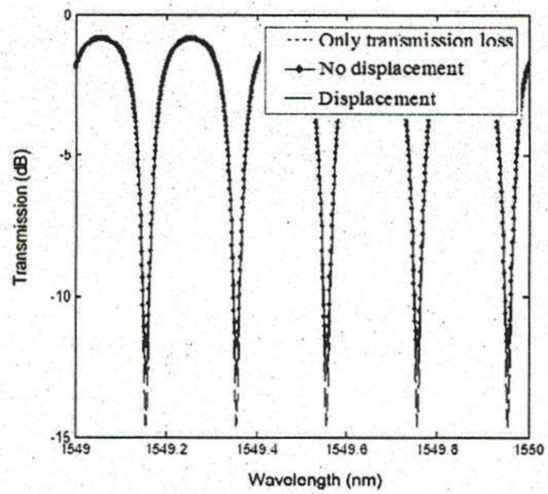


**Fig. 12** Transmission characteristics of the device for three cases (a) ideal case (only transmission loss) (b) no displacement of access waveguides and (c) with optimized displacement of access waveguides

It is clear that by shifting the access waveguide, the extinction ratio of the device can be increased by 1dB.

## 3. CONCLUSION

We have presented the optimized design of a racetrack resonator based on MMI couplers. The effects of bent waveguides on the device characteristics have been considered. Waveguide parameters are optimized by using both the analytical analysis and numerical analysis in order to keep the bend loss and transition loss at an acceptable level. For the first time, the position of the access waveguide has been optimized to compensate the modal displacement in the bent waveguide. This approach allows one to improve device performance.

## THIẾT KẾ TỐI ƯU BỘ VI CỘNG HƯỞNG QUANG DÙNG CẤU TRÚC GIAO THOA ĐA MODE TRÊN CÔNG NGHỆ SILICON

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***TÓM TẮT:*** *Bài báo đề xuất phương pháp thiết kế tối ưu các thiết bị vi cộng hưởng quang dùng cấu trúc giao thoa đa mode trên công nghệ silicon. Suy hao do cấu trúc ống dẫn sóng ring và suy hao ghép giữa các ống dẫn sóng được tính toán và tối ưu. Vị trí và cấu trúc ống dẫn sóng được tối ưu để nâng cao chất lượng của thiết bị.*

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