The Potential of Silicon Photonic Device Based on Tapered MMI Structure

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***Abstract*— Tapered multimode interference (MMI) structure has recently been utilized on multiple fabrications of the silicon photonics device. This type of structure has the potential for the production of small device for various applications. Various designs have been made in order to produce a compact design of MMI. This paper will discuss recent research on the different tapered MMI structure and its performances when simulating different structures (linear, parabolic, exponential and etc.). The use of tapered structure device allows wider waveguides separation, as compared to a straight MMI device.**

***Index Terms*— MMI coupler; tapered structure**

I. Introduction

The MMI device is one of possible components of the Mach Zehnder Interferometers (MZI) for splitting and combining purposes. By using the MZI, various applications of devices can be designed, such as the optical sensors, optical filter, optical modulators, optical switches and optical add-drop multiplexers [1,2]. The MZI can also be applied to the micro ring-resonators in order to reduce the modulation voltage and improve the linearity of the device [3,4]. This device has excellent performances at it has larger optical bandwidth, low loss and less complicated MMI design compared to other structures [5,6]. The optimization of the MMI design structure is analysed in order to produce a better performance device.

The size of MMI needs to be compact in order to allow compatibility with other devices. The possible ways to reduce the size of the MMI structure is by choosing a suitable imaging technique (general or restricted) within the MMI region and tapering the device [7].

In the next section, the MMI structure that has been proposed by other researchers are reviewed in terms of the technique used and the performance of the design structure.

II. Multimode Interference Device

A. Self Imaging Principle

Multimode interference (MMI) device is synonymous with the self imaging principle. The self-imaging principle has been described in detail in [8]. The central structure of MMI is designed as a waveguide to support the light propagation from the beginning through the end of the waveguide structure.

The width and length of the MMI are related to each other. With the available value of the MMI width, the calculations of the length of the MMI region required for the imaging of the structure are gained by using Equation 1:

$$L_\pi = \frac{\pi}{\beta_0 - \beta_1} \simeq \frac{4 n_r W_e^2}{3\lambda_0} \qquad (1)$$

where n_r is the effective refractive index of the waveguides, W_e is the effective width of the MMI region, and λ_o is the free-space wavelength [8]. The illustration of the self imaging principle is produced by [5-7] and [8-14]. The theory produces structures which are able to propagate light in any number of modes, which are generally referred as NxM MMI couplers. N is referred as the input and M is the output of the MMI waveguides.

B. The Design Structure Analysis

The reduction of the width and length of the MMI structure can be seen when using the tapered MMI structure. Besides, the insertion loss (IL) and the non-uniformity are the feature that is carried out to see the performance improvement of different design structures. The insertion loss can be defined as:

$$IL = 10 \ \log_{10} \frac{P_{in}}{P_{out}} \qquad (2)$$

where P_{in} is the power input of the MMI and P_{out} is the power at the output waveguide. The non-uniformity can be defined as:

$$NU = 10 \ \log_{10} \frac{P_{min}}{P_{max}} \qquad (3)$$

where the P_{min} is the minimum power of the output waveguide and the P_{max} is the maximum of the output waveguide [6]. In designing a structure, the lowest insertion loss and non uniformity are likely to be the best design structure.

III. Recent Research

A. Linear Tapered Design

Shi et al. [6] proposed a project to improve the performance of the MMI device using a linear tapered design structure. The tapered structure of the device is designed at the input and output waveguides. The 3D-BPM program is used for the simulation of the design.

The self imaging principle and the modal propagation are used to produce the whole MMI structure. Based on this principle, a folded image of the MMI structure is produced.

Figure 1 shows a linear tapered of 1x4 MMI device design by the authors. As can be seen in the figure, the structure is tapered in the input and output waveguides.

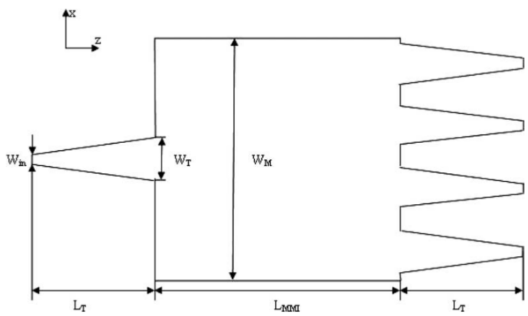


Figure 1: The linear tapered device [6]

The width of the input waveguide is 4.0 µm, the MMI width of the device is 60 µm and the MMI length of the device is 2089 µm. The length of the structure is optimized by the 3D-BPM software. The imaging quality of this design is improved by using the modal propagation analysis (MPA). This analysis is used since the design has more than two output waveguides. Besides, this analysis is used since it can give an overview of the basic mechanism of the design. The output waveguides are then located at x = 23.3, 7.9, -7.9 and -23.3 µm.

It can be analysed that the insertion loss decreases as the width of the taper increases. Besides, the non-uniformity of the power input/output of the design is also stated. In this research, it shows that the loss is decreasing as the tapered structure is used. Table 1 shows the analysis gained from the simulation of the design structure.

Table 1
The comparison of insertion loss and non-uniformity before and after using tapered structure.

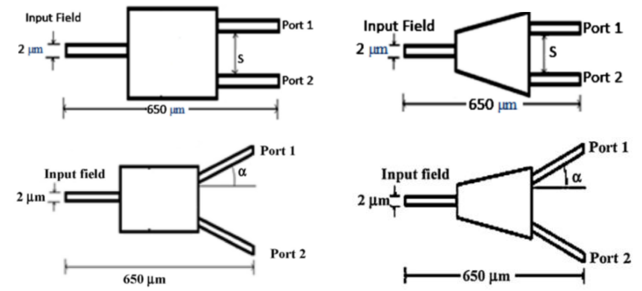
	Non-tapered MMI	Tapered MMI
Insertion Loss (dB)	1.2127 dB	0.076 dB
Non-uniformity (dB)	0.5509 dB	0.068 dB

Chack et al. [5] also had designed a structure using linear tapered MMI design structure. The focus of this journal is on the effects of using different values of separation distances (s) and arm angle (α) on both non-tapered and tapered MMI structure. The used of the self imaging principle is also utilized in this design. Besides, this journal also highlights that the design of the tapered MMI structure used is the combination of a series of prism sections.

Table 2 shows the schematic diagram of the non-tapered and tapered MMI structure. All of the structures use 650 µm as the length. The separation distances are varied from 4 µm to 12 µm, while the arm angle (α) values are taken ranging from 0° to 6°.

Table 2
The schematic diagram of the non-tapered and tapered MMI structures having variations in the arm separation and angle [5]

Non-tapered Structure	Tapered Structure



The effect of electric field intensity of each structure is observed. The results show that when the separation distance is in the intermediate value, the electric field intensity is at the highest. Furthermore, the electric field intensity increases, while the arm angle is increasing. Besides, the tapered MMI structure gives a better electric field intensity rather than the typical MMI design structure.

Chack et al. [12] utilized the linear tapered design on the input and output waveguides of the MMI structure. The purpose of this paper is to compare the typical and tapered MMI design structure while having different input wavelength (1310 nm and 1550 nm). Besides varying the input wavelengths, the design is also simulated using the transverse electric (TE) and transverse magnetic (TM) polarizations.

Both structures have optimized width and length, as shown in

Figure 2. The parameters shown are used in both structures (typical and tapered MMI) to make comparison in terms of their insertion loss (IL) and extinction ratio (ER).

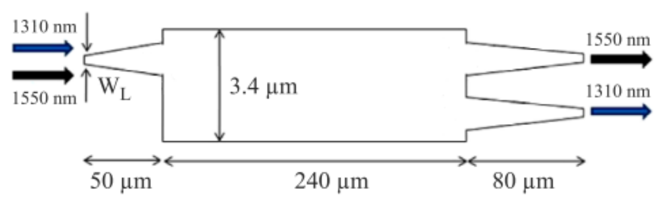


Figure 2: The proposed schematic design of tapered input/output waveguide MMI demultiplexer [12]

Table 3 and Table 4 shows the analysis of the structures in term of its insertion loss (IL) and extinction ratio (ER). While applying different wavelength to the input structure, the IL and ER gained from the tapered MMI structure has better results than the typical MMI structure, in which the structure with the lowest IL and the highest ER is the best structure simulated.

Table 3
The IL and ER gained when the wavelength, λ = 1310 nm

Polarization		Typical MMI	Tapered MMI
TE	IL (dB)	1.421	0.546
	ER (dB)	16.433	17.107
TM	IL (dB)	1.630	0.809
	ER (dB)	13.490	19.365

Table 4
The IL and ER gained when the wavelength, λ = 1550 nm

Polarization		Typical MMI	Tapered MMI
TE	IL (dB)	0.857	0.255
	ER (dB)	11.288	19.487
TM	IL (dB)	0.677	0.482
	ER (dB)	14.970	23.394

B. Parabolic Tapered Design

Wei et al. [13] involve in simulation and experimental research on the 1x2 parabolic taper MMI design. This design is utilized in their study in order to provide a suitable separation between the waveguides which contributes to the coupler's loss.

Figure 3 shows the design used in the research. The MMI section of the coupler uses the parabolic tapered structure. Besides, the S-bend waveguides were used in order to separate the output waveguide before it was connected to the MMI structure. The width and length of the structure is the most important in producing a precise output image.

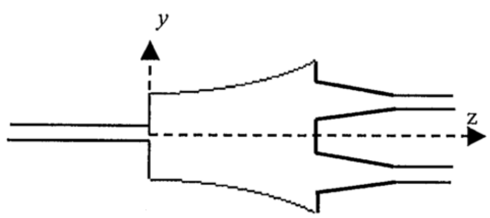


Figure 3: The parabolic tapered design structure [13]

The design enables reduction of the MMI length. It also gives a highly uniformed device output with a uniformity of 0.28 dB and excess loss of only 9.9 dB. These results are measured through the fabrication of the coupler.

Since this structure has been fabricated, the results gained are more reliable. Here, the loss exists due to various reasons. Among the reasons are the facet reflection, input and output coupling and sidewall roughness [13]. This structure can be suitably used as the 3 dB power splitter as has been proven in the fabrication results.

Levy et al. [7] utilized the parabolic tapered MMI structure to design a device with larger number of input and output waveguides, N x N MMI device (N > 2). When using the self imaging principle, the structure can exceed to several millimetres in length when a number of output ports are used. These are not convenient to be used in any desired application.

In order to reduce the device size, the choice of self imaging type can be considered, either general or restricted [8]. General interference (GI) is said to be independent of the mode excitation; while the restricted interference (RI) has the modes excitation alone. Besides choosing the imaging type, the device is suggested to have a taper to the MMI design.

Figure 4 shows the design of the devices using a parabolic tapered structure with four tilted input and output waveguides. The device performance analysis has been conducted using the 2D-BPM simulations to state the device size and the power splitting performance.

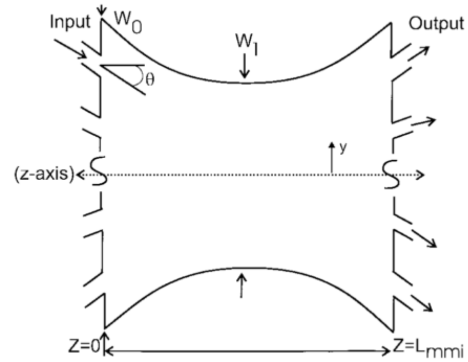


Figure 4: The 4 x 4 MMI device (parabolically tapered MMI, tilted waveguides)

Tilting the input and output waveguides will allow the optical imaging across the device. This will eventually improve the device output power and the splitting ratio of the device. The splitting ratio is calculated by having the power of individual output waveguide to the total power of the output waveguides.

From the simulation of the 4 x 4 MMI device, it is shown that the device has an almost ideal splitting ratio, which is 25% for each waveguides. Moreover, while reducing half of the length of the conventional MMI structure, the splitting ratio varies from ±2% of the ideal value (23% - 27%).

C. Comparison between Linear and Parabolic Tapered Design

Levy et al. [14] utilized the 3D beam propagation program in simulating the taper design structure. The performance of both parabolic and linear taper was compared and analysed. The device is designed as such a structure in order to reduce the proximity limitations of the structure. For this purpose, the waveguides of the splitter need to be well separated.

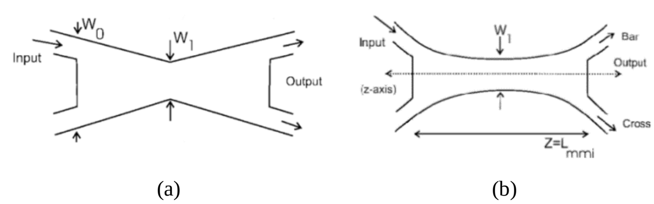


Figure 5: (a) The linear tapered MMI structure; (b) the parabolic tapered MMI structure [14]

Figure 5(a) shows the design of MMI device using the linear taper and Figure 5(b) shows the parabolic taper structure of the device designed by the authors. The use of the self imaging principle is utilized in this paper. The design from Figure 5 shows that it folded in two folded images either it is fold vertically (x-axis) or horizontally (z-axis). Besides, the design has the output waveguides tilted to the same angle of the MMI tapered design. The design has a tilted access waveguide to ensure that the input optical image is in the phase with respect to the end of the MMI region: This is to make sure an equal image at the input and output of the device.

The 3D-BPM is used in computing and analysing the device performances, which are the splitting ratio, the length and total transmission of the structure as a function of normalized width variation, dΩ.

$$d\Omega = (W_0 - W_1) \;/\; W_0 \qquad (3)$$

In this case, all the width change in the design were calculated and the performance analysis was observed. The splitting ratio of the parabolic tapered device remains unchanged as compared to the untapered device. It is shown that, the parabolic tapered device has only 0.8 dB of loss and a length of 33 µm (59% shorter than untapered device).

The author also discussed the RI and GI imaging difference of the untapered device. RI devices have better tolerance for the change of width compared to the GI devices. Besides, the influence of taper to the design of the width change shows that as the width is reduced, the taper increases.

Furthermore, the parabolic structure allows better fabrication tolerance with the increased flexibility of the device. Moreover, by using the parabolic structure, wider access of the waveguides is allowable. This will not only help in minimizing the waveguide propagation, but it also reduces bending losses, while having a short length device. This device shows the improvement in performance and reduction of device size.

D. Comparison between Exponential And Parabolic Tapered Design

Wu et al. [10,13] introduced an exponential coupler design that is compared to the parabolic design structure. The design structure is simulated using the 2D BPM. The performance of the structure is examined through the size reduction, total optical transmissions, the wavelength response and also the fabrication tolerance of the structure.

Figure 6 shows the design that has been utilized by the author. The exponential tapered is made in the multimode region. The waveguides used a conventional straight design. For the input waveguide, it is located in the middle of the multimode region and for the output waveguide, which is located at $W_o/4$ and $3W_o/4$. As can be seen in Figure 6, the design is in a folded image within the z-axis.

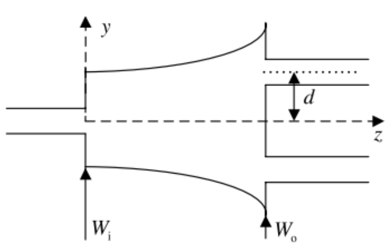


Figure 6: The exponential tapered device [15]

In terms of size, the parabolic structure exhibits longer device compared to the exponential tapered device. However, the tapered design demonstrates better total power output than the exponential tapered structure. The output power optimization given by the exponential tapered device proves that it has a smaller transmission loss compared to the parabolic device.

Nevertheless, both tapered MMI device structures show similarity in terms of the properties of the optical transmission to the normalized width variation, dΩ. Besides, both structures have the same wavelength response characteristics.

E. Comparison between Parabolic And Other Tapered Design

The comparison between the parabolic tapered design with the elliptic and cosinusoidal taper of MMI device have been made by Levy et al. [7]. These are the possible designs that can be used in order to reduce the length of the MMI device. The authors use the tapering technique to utilize the larger modes of MMI device. Since the number of waveguides is increasing, the same goes to the length of the devices.

The tapered of NxN devices is suggested to be in parabolic tapered structure with a tilted access waveguide. This could improve the power splitting in the devices to all the waveguides while operating.

The parabolic demonstrates the smallest length compared to the elliptic and cosinusoidal tapered structure. The uniformity in the output between the nearest edges to the inner waveguides is similar, regardless the increasing number of waveguide.

IV. CONCLUSION

By having the tapered MMI structure, a better device could be obtained. First of all, the tapered structure design structure will help in reducing the bend loss in MMI design. Besides that, it could also reduce the waveguide propagation. Meanwhile, the optimization of the performance shows that the taper structure has better power gain and loss reduction.

ACKNOWLEDGMENT

The authors would also like to thank Universiti Teknikal Malaysia Melaka (UTeM) for the support.

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