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Modelling Of Different Tapered Structures of Multimode Interference (MMI) Couplers

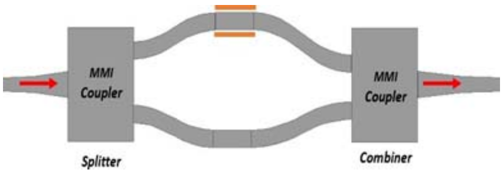
***Abstract**. This paper discusses the performance of different tapered structures of MMI Couplers. This research studies the effect on MMI coupler performance by varying MMI width, MMI length and also tapering the input/output waveguide. The performance was measured by observing the output power ratio and insertion loss (IL). The linear, parabolic, exponential, symmetrical and non-tapered MMI coupler were modelled using Finite difference beam propagating method (BPM). Each model was simulated in the OptiBPM simulator 2D to illustrate the optical field propagation. Furthermore, the output power and insertion loss were measured in OptiBPM Analyzer. Parabolic tapered with a width of 26 µm has produced the lowest insertion loss of 0.27 dB. On the other hand, the non-tapered MMI coupler has the worst performance of 1.67 dB. A minimum length of 278 m can be used to build the symmetrical tapered MMI coupler, which also turns out to be the most compact one. This study showed that the device's low insertion loss and small size have highlighted its potential for use in photonics applications.*

Streszczenie. *W tym artykule omówiono działanie różnych stożkowych konstrukcji łączników MMI. Te badania badają wpływ na wydajność sprzęgacza MMI poprzez zmianę szerokości MMI, długości MMI, a także zwężenie falowodu wejścia/wyjścia. Wydajność mierzono obserwując stosunek mocy wyjściowej i tłumienność wtrąceniową (IL). Liniowy, paraboliczny, wykładniczy, symetryczny i niestożkowy sprzęgacz MMI modelowano za pomocą metody propagacji wiązki różnic skończonych (BPM). Każdy model został poddany symulacji w symulatorze 2D OptiBPM w celu zilustrowania propagacji pola optycznego. Ponadto zmierzono moc wyjściową i tłumienie wtrąceniowe w OptiBPM Analyzer. Paraboliczny zwężający się o szerokości 26 µm wytworzył najniższe tłumienie wtrąceniowe na poziomie 0,27 dB. Z drugiej strony, niezwężany łącznik MMI ma najgorszą wydajność 1,67 dB. Minimalna długość 278 m pozwala na zbudowanie symetrycznego stożkowego łącznika MMI, który okazuje się również najbardziej kompaktowy. Badanie to wykazało, że niskie straty wtrąceniowe i niewielkie rozmiary urządzenia uwydatniły jego potencjał do wykorzystania w zastosowaniach fotonicznych.* (***Modelowanie różnych stożkowych struktur sprzęgaczy interferencji wielomodowych (MMI)**.*)

Keywords: MMI Coupler; Optical Modulator; Power Splitter
Słowa kluczowe: sprzęgacz MMI, modulacja optyczna

Introduction

The MMI coupler is commonly used in Mach-Zehnder interferometer (MZI) optical modulator, multiplexing/ demultiplexing devices, logic gates, power splitters/couplers, switches, attenuators, and lasers. Figure 1 displays the MMI coupler in MZI modulator. Multimode interference (MMI) coupler is a compact and sensitive device. Most of the research focuses on reducing the size of MMI by modifying the structure and improving the performance. The structure of MMI is divided into two categories, tapered and non-tapered. Previous research suggests that tapering the structure enhances the overall performance of the coupler [1]–[3].



Fig/ 1: MMI Couplers in MZI optical modulator

Recent research shows that MMI performs better than Y- coupler, novel star coupler, and directional coupler. The analysis has been made in terms of the extinction ratio where MMI is approximately >32dB whilst Y-coupler and novel star are only 10dB and 14dB respectively [4]. Compared to Y-coupler, MMI has better modulation efficiency and insertion loss of 2.53% and 17% respectively [5].

Multimode Interference (MMI) Waveguide

The MMI central structure acts as a waveguide for light propagation from input to output. The MMI couplers can be utilized to split and combine the light signal in association with the MZI optical modulator design. Figure 2 shows the image of the basic MMI splitter design. This splitter layout allows an efficient optical signal transfer across the device in a shorter length. The MMI structure's width and length are crucial in modelling the device.

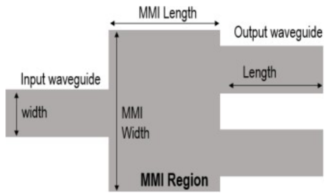


Fig. 2: The schematic diagram of the MMI splitter.

Self-imaging is a phenomenon of multimode waveguides where an input field profile is repeated at periodic intervals in single or multiple images along the propagation path of the guide [6]. The beam emitted into the regions will go through diffractions and interferences, resulting in the creation of many focal planes. After a beat duration Lπ of the MMI field, the input image will be reformatted once more. The MMI coupler's output waveguides are used to retrieve signals from the MMI's input [7]. The length required for self-imaging is given by equation (1):

(1) $$L\pi = 4n_rW_e^2 / 3\lambda_0$$

where $\boldsymbol{n_r}$ is the effective refractive index of waveguide. $\boldsymbol{W_e}$ is the effective width of MMI region and $\boldsymbol{\lambda_o}$ is the free space wavelength [6]. Some of the important parameters to be considered in modelling difference tapered MMI couplers are extinction ratio (ER), insertion loss (IL), modulation efficiency (VL), length, and width [5]. The insertion loss can be determined by the equation (2):

$$I_L = 10 \log_{10} P_{in} / P_{out} \quad (2)$$

where the P_{in} is the power input and P_{out} is the output power.

Tapered Structure of MMI couplers

Tapering at the input and output waveguide of MMI gives a significant improvement in increasing the extinction ratio, reducing the insertion loss and minimising the size of the optical device. The tapered structure can be classified into three different groups such as linear tapered [4], [8], [9], parabolic tapered [10]–[12] and exponential tapered [13]. Figure 3 shows the classification of MMI based on tapered structure. This research will be focusing on modelling the different types of tapered structures of multimode interference (MMI).

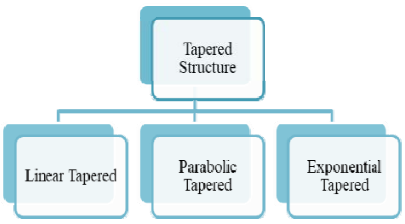


Fig. 3: The classification of MMI based on their tapered structure

A linear tapered structure has been proposed by [4] to improve the performance of multimode interference MMI coupler in Mach-Zehnder Interferometer (MZI) optical modulator. The design proposed is based on the structure of a 1x2 symmetric power splitter, as shown in Figure 4.

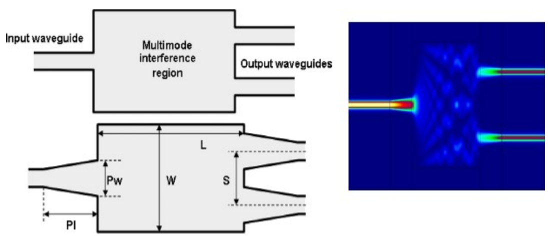


Fig. 4: The linear tapered of 1x2 MMI structure design [4]

This result highlights that sub-1-dB losses are achieved as the port width is increased above 1000 nm, close to the predicted value of 900 nm and large static extinction ratios are achieved (≤32dB), but the MZI extinction ratio is insensitive mainly to MMI port width.

Another researcher shows interest in analyzing the effects of manipulating the separation distances (s) and arm angle (α) on non-tapered and tapered MMI structures [9]. The researcher also highlights the tapered MMI structure used as the combination of the series of prism sections. Figure 5 shows the linear tapered design and its simulation result.

The researcher summarizes that varying the input wavelength reduces the insertion loss (IL) to 0.225 dB, while the non-tapered IL is 0.857 dB.

A parabolic tapered structure has been proposed by [11] to improve the performance of multimode interference MMI coupler in a Mach-Zehnder Interferometer (MZI) optical modulator. The simulation result obtains from OptiBPM shows that the beat length (Lπ) of parabolic tapered MMI is half (0.5%) of the standard MMI structure.

Another researcher [13] proposes an exponentially tapered design and compared the design with a parabolic tapered MMI structure. The result shows that the exponential tapered need less dimension with high output power compared to parabolic tapered.

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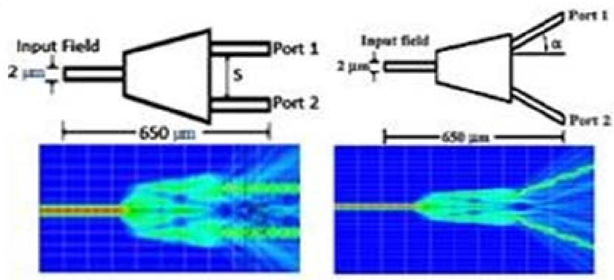


Fig.e 5: The tapered design and the simulation result

Design of the MMI Couplers

The structure design focuses on tapering the input and output waveguide of the NxM 1x2 power splitter. Important parameter generated from the simulation process is gathered and manipulated to determine the insertion loss (IL) produces by each design. The modification is made to the tapered design if the performance is not exceeding the expected level.

Parameters and the dimension of the tapered MMI coupler were set according to the theoretical design dimension base on the mathematical formulation. Figure 6 displays the crucial parameter for designing and modelling the different tapered structures of the MMI coupler. All designs in this project employed the same parameter as stated.

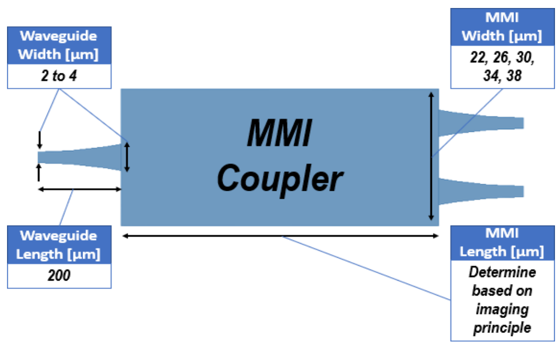


Fig. 6: Design parameter of 1x2 MMI Coupler

This research focuses on modelling five (5) structures of MMI Coupler, a non-tapered, linear, parabolic, exponential, and symmetrical tapered.

The different tapered structures of multimode interference (MMI) coupler were modelled using OptiBPM, a 2-dimensional beam propagation method software by Optiwave Corporation. The software uses a mathematical manipulation equation Helmholtz approximation as its propagation model to allow light propagation in a dielectric medium. The equation can simplify the simulations, reduce the processing time and for better computer memory management.

The process of creating and simulation the multimode interference (MMI) coupler in OptiBPM must undergo a step-by-step procedure. It is very crucial to determine all the important parameters defined accordingly to produce an accurate result. Figure 7 shows the process involved.

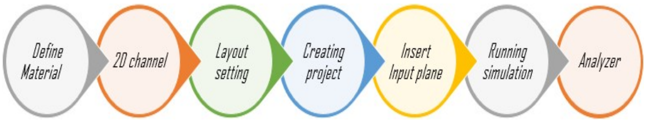
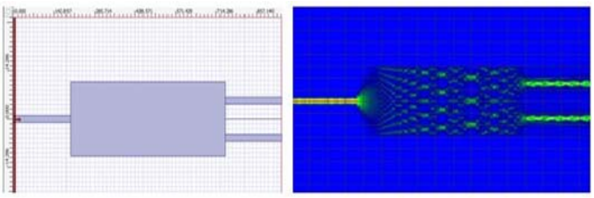


Fig. 7: The process of designing and simulation in OptiBPM

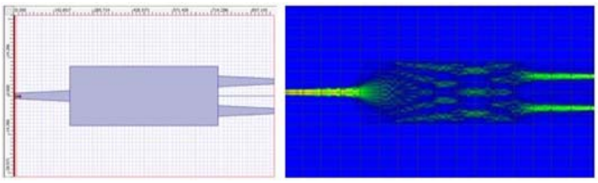
Although this research intends to model different tapered structures of multimode interference (MMI) coupler, some standard parameters need to be defined to ease the performance comparison. Table 1 displays the common simulation parameter in this research.

Table 1. The common simulation parameters

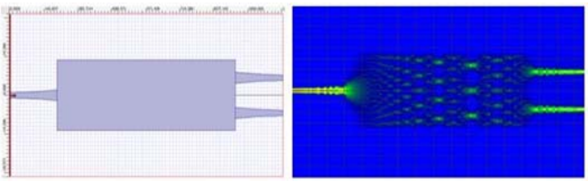
Parameter	Value
Waveguide refractive index	3.45
Cladding refractive index	1.0
Wavelength (nm)	1550
Reference Index	Mod
Polarization	TE
BPM Solver	Paraxial



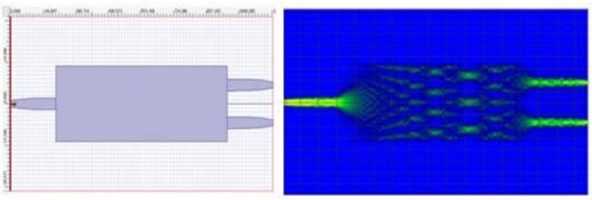
(a) Non-tapered MMI Coupler



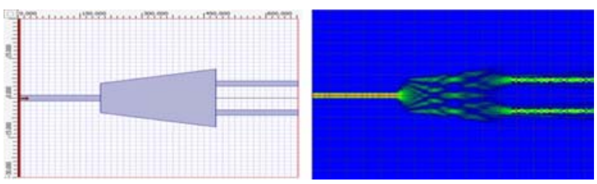
(b) Linear tapered MMI Coupler



(c) Parabolic tapered MMI Coupler



(d) Exponential tapered MMI Coupler



(e) Symmetrical tapered MMI Coupler

Fig. 8: Five tapered structures of MMI couplers

Results

Each design structure of MMI Coupler were created based on five widths, 22 μm, 26 μm, 30 μm, 34 μm and 38 μm. At the same time, the length of each design is set depending on the self-imaging principle. The effect on MMI performance by varying MMI width, MMI length and tapering the input/output waveguide were observed and discussed in terms of the output power and insertion loss (IL). The 1x2 MMI Coupler modelling process was performed on the waveguide layout designer tools.

The first design is a non-tapered MMI coupler, as illustrated in Figure 8 (a). The width of 30 μm has achieved the highest splitting ratio compared to the other width. Figure 8 (b) displays the 22 μm width linear tapered MMI coupler. At this dimension, the linear tapered has produced the lowest insertion loss. The third design in this research is a parabolic tapered MMI coupler. The lowest insertion loss occurs at the width of 26 μm as illustrated in Figure 8 (c). As shown in Figure 8 (d), exponential tapered has achieved the highest splitting ratio and produced optimal output power at the width of 34 μm. The last modelled tapered MMI coupler is symmetrically tapered. This design produces the lowest insertion loss at the dimension varies from 11 μm to 22 μm of width.

Figure 9 displays the insertion loss of five MMI couplers with different tapered structures which have been successfully designed and simulated. Parabolic tapered with a width of 26 μm has produced the lowest insertion loss of 0.27 dB, followed by exponential tapered with 0.34 of insertion loss. Meanwhile, the insertion losses for linear and symmetrical tapered are 0.56 and 1.38, respectively. In addition, the symmetrical tapered structure can be formed at a minimum length of 278 μm as depicted in Figure 10.

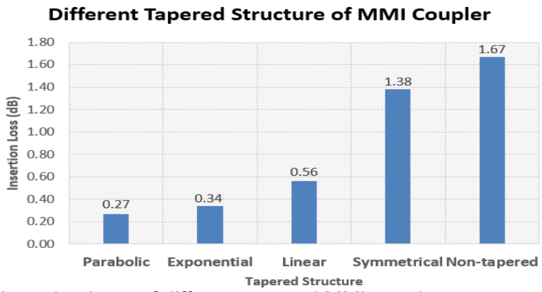


Fig. 9: Insertion Loss of different tapered MMI couplers

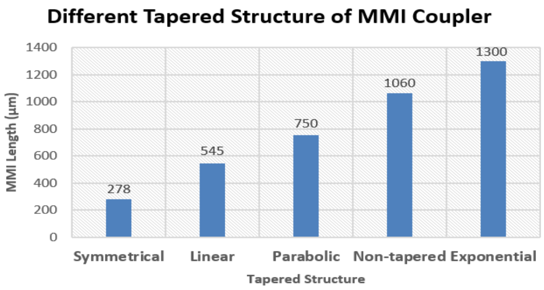


Figure 10: Length of different tapered MMI Couplers

Conclusion

The lowest insertion loss of 0.27 dB, generated using parabolic tapering with a width of 26 μm, is comparable to earlier work [14-15]. The parabolic tapered structure has a tilted waveguide, which allows for improved optical signal splitting. Furthermore, this allows the phase tilt of the optical signal along the coordinate system to the end of the structure. Meanwhile, the symmetrical tapered is the most compact MMI coupler that can be produced with a minimum length of 278 μm. Although the symmetrical tapered insertion loss is higher than parabolic tapered, it would be a good option for an optical system that focuses on a compact device.

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