Optimization of parabolic tapered multimode interference (MMI) couplers using Taguchi method for photonic integrated circuits

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The growing demand for higher bitrates and faster modulation speeds has fueled the advancement of photonic integrated circuits (PICs). Multimode interference (MMI) couplers, critical for splitting and combining light in optical devices, are key components in systems such as Mach-Zehnder interferometers (MZIs), optical modulators, switches, and multi/demultiplexers. This study focuses on optimizing the performance of parabolic MMI couplers by examining the effects of varying the input tapered width and the input/output waveguide lengths. Simulations were conducted using OptiBPM software to model optical field propagation, while the OptiBPM Analyzer was utilized to evaluate insertion loss (IL) and output power. The optimization process employed the Taguchi method, using an L9 orthogonal array (OA) to minimize insertion loss and enhance performance. The optimal design identified through this method resulted in optical power output of 0.9874, insertion loss of 0.1439 dB and a high S/N ratio of 16.8388, with the input tapered width at input waveguide (IW) identified as the most significant factor, contributing 35.67% to overall performance. These results underscore the potential of the optimized MMI coupler for advancing future photonic technologies.

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1. Introduction

MMI couplers are vital components in photonic integrated circuits (PICs), essential for devices such as Mach-Zehnder interferometers (MZIs), modulators, and multiplexers. Their role in accurately splitting and combining light is crucial for the overall efficiency and performance of these devices, which drives the need for optimizing MMI coupler designs.

In recent years, significant research has been directed toward optimizing MMI couplers by exploring various tapering structures, including linear, parabolic, and exponential tapers [1-5]. For instance, Jin et al. [6] developed a parabolic MMI coupler for 2×2 silicon optical switches, achieving low insertion loss and maintaining a high extinction ratio across different paths. Similarly, Ma et al. [7] introduced a dual-polarization, dual-mode silicon 3dB beam splitter using a shallow-etched MMI coupler, which effectively handled polarization while minimizing device size. Guan and Frandsen [8] also contributed to this field by developing an all-silicon Mach-Zehnder interferometer that uses multimode waveguides to reduce thermal sensitivity, highlighting another critical aspect of MMI coupler applications. However, these studies primarily relied on empirical methods without systematically optimizing performance across multiple parameters.

While these advancements are notable, the lack of comprehensive optimization strategies in these studies leaves room for improvement. For example, the work by Jin et al. [6] did not fully explore systematic optimization methods like the Taguchi method, which could have further reduced insertion loss and improved output power. Additionally, the fiber optic micro-curvature sensor developed by Cardoso et al. [9] used a Mach-Zehnder interferometer configuration, demonstrating the relevance of MMI couplers in sensing applications, but also highlighted the challenges of insertion loss in practical implementations. The absence of systematic optimization in these works suggests a need for more sophisticated approaches to achieve optimal performance in MMI coupler designs.

The Taguchi method offers a novel and systematic approach for optimizing MMI coupler designs by simultaneously analyzing multiple parameters. Recent studies, such as the work by Gurugubelli et al. [10], have demonstrated the effectiveness of the Taguchi method in optimizing engineering processes, reducing experimental effort while achieving optimal outcomes. Applying this method to MMI coupler optimization allows for a more comprehensive understanding of the trade-offs between different design parameters, such as insertion loss and output power.

This study uniquely contributes to the field by applying the Taguchi method to optimize parabolic MMI couplers, resulting in a significantly reduced insertion loss of 0.1439 dB. This approach not only addresses gaps in the existing literature but also sets a new benchmark for MMI coupler performance in photonic integrated circuits. The systematic optimization process ensures that the design is robust and can be reliably reproduced in practical applications.

The optimized design presented in this study has significant implications for the future of PIC technology. Future research could apply the Taguchi method to other components within PICs or explore additional tapering structures to achieve further performance enhancements. This study establishes a robust framework for optimization that could drive future innovations in photonic device design.

1.1. Tapered Multimode Interference (MMI) Coupler

The Multimode Interference (MMI) coupler is a compact and sensitive device. The predominant focus of current research is on minimizing the dimensions of the MMI, while preserving its performance, by altering its structural design. According to [11], the length required for self-imaging is determined by equation (1):

$$L\pi = 4nrWe^2/3\lambda o \tag{1}$$

where:

nr = effective refractive index of waveguide

We = effective width of MMI region

λo = free space wavelength

The insertion loss can be determined by the equation (2):

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

where: P_{in} = input power

P_{out} = output power

However, the performance of MMI couplers, particularly in terms of insertion loss and output power, is inherently linked to the design of the input and output waveguides. The introduction of tapering in these regions has emerged as a pivotal strategy for optimizing MMI coupler performance.

Tapering involves gradually altering the width of the waveguide as light transitions into or out of the MMI region. This modification serves to match the mode profiles between the waveguide and the multimode section more efficiently, thereby reducing reflection losses and enhancing the power transfer to the output ports. The literature identifies three primary tapering structures: linear, parabolic, and exponential. Among these, the parabolic taper has garnered significant attention due to its superior performance in minimizing insertion loss and maintaining high output power.

Linear tapering involves a straightforward, gradual increase or decrease in waveguide width. While effective in reducing mode mismatch, linear tapers do not account for the complex mode evolution that occurs within the multimode region, potentially leading to suboptimal performance in certain high-density applications. As such, while linear tapering is an improvement over non-tapered designs, it may not always provide the lowest possible insertion loss or the highest output power [12-13].

Exponential tapering offers a more aggressive approach, with the waveguide width changing according to an exponential function. This type of taper is designed to minimize reflection losses by ensuring that the transition between different waveguide sections is smooth. However, the rapid change in width can lead to challenges in maintaining mode uniformity across the taper, which may affect the device's overall performance, particularly in applications requiring precise control over optical signal propagation [15].

The parabolic taper represents a balanced approach between linear and exponential tapering. In a parabolic taper, the waveguide width changes according to a parabolic function, which provides a gradual but non-linear transition that better accommodates the natural evolution of modes within the multimode region. This tapering method has been shown to significantly enhance the performance of MMI couplers by minimizing insertion loss and maximizing output power.

Parabolic tapers are particularly effective in reducing the beat length within the MMI region, which is crucial for achieving efficient self-imaging—a phenomenon where the optical field replicates itself at specific intervals within the multimode section. By shortening the beat length, parabolic tapers allow for more compact device designs without sacrificing performance. This capability is especially valuable in the design of dense PICs, where space is at a premium, and maintaining low insertion loss is critical [13-19].

1.2. OptiBPM simulation tool

OptiBPM is a sophisticated simulation tool based on the Beam Propagation Method (BPM), developed by Optiwave Corporation. It is designed to model the propagation of light in dielectric waveguides, making it particularly suitable for simulating photonic integrated circuits (PICs). The simulation tool employs the Helmholtz equation to approximate the propagation of the optical field within the waveguide structures. The software allows for both 2D and 3D simulations.

2D simulations are typically used for faster, less resource-intensive simulations. In 2D mode, the X-axis represents the vertical (transverse) direction, and the Z-axis represents the horizontal (propagation) direction. This is particularly useful for modeling simple waveguide cross-sections where depth variations are minimal. In addition, the OptiBPM software allows the user to define various parameters critical to the simulation such as the refractive index, boundary conditions and polarization.

The simulation workflow typically starts with the CAD design of the waveguide structure, where the physical dimensions and refractive index profile of the MMI coupler are defined. The user then runs a BPM simulation, which computes the light propagation along the waveguide. This simulation can visualize the optical field distribution, allowing for the identification of potential issues such as mode overlap or excessive reflection at interfaces.

The OptiBPM analyzer provides critical output metrics such as insertion loss which is calculated by comparing the input and output power of the waveguide. Insertion loss is a crucial performance metric for MMI couplers, where lower values indicate more efficient designs.

Another metric is the output power. This metric is essential for determining the splitting ratio of the MMI coupler, ensuring that the optical power is distributed correctly between the output ports.

1.3. Taguchi optimization method

The Taguchi method is a robust statistical approach used for optimizing complex processes by systematically varying multiple parameters and identifying the optimal configuration. It is particularly useful in reducing the number of experimental runs needed to achieve an optimized design, making it ideal for applications in photonic device design.

The core of the Taguchi method lies in its use of orthogonal arrays (OAs) to systematically explore the parameter space. In this study, an L9 orthogonal array was employed, which is designed for experiments involving four factors, each at three levels. This array reduces the number of required experiments from 81 (in a full factorial design) to just 9, significantly reducing the computational and experimental effort.

The Taguchi method establishes the signal-to-noise (S/N) ratio to determine optimal levels for each parameter and assess parameter variation. SNL is used to optimize the system when the response is maximum ("Larger is better"), while SNS is used to optimize the system when the response is minimum ("Smaller is better") as depicted in equations (3) and (4) respectively [20].

SNL is used when the purpose is to maximize the response. The S/N is determined with the larger the better [17].

$$SN_L = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{yi^2}\right] \quad (3)$$

SNS used when the intention is to minimize the response. The S/N ratio can be determined, with the smaller the better [17].

$$SN_S = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}yi^2\right] \quad (4)$$

where n is the sample size, y is the insertion loss.

The Taguchi method also ensures that the optimized design is robust against variations in manufacturing processes. By focusing on minimizing the S/N ratio, the design is made less sensitive to noise factors, ensuring consistent performance across different manufacturing batches and operating conditions [21-22].

2. Experimental

2.1. Design of Parabolic Tapered MMI Coupler

The various tapering structures of the multimode interference (MMI) coupler are modeled using OptiBPM.

The common simulation parameters used for all designs in this study are shown in Table 1.

Table 1. Simulation parameters

Simulation Parameter	Value
Waveguide Refractive Index	3.45
Cladding Refractive Index	1.0
Wavelength	1550 nm
Reference Index	Mod
Polarization	TE
Bpm Solver	Paraxial
Boundary Condition	TBC

The design of the 1×2 parabolic tapered MMI coupler is based on several fixed design parameters, including MMI region width/length, and output tapered width for input/output waveguide, as shown in Fig. 1.

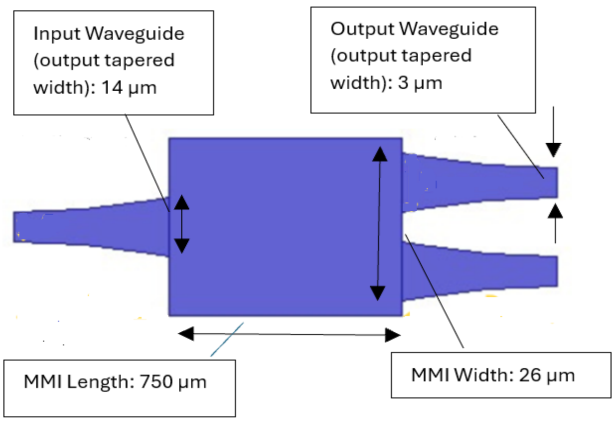


Fig. 1. Fixed design parameters in 1x2 Parabolic Tapered MMI coupler

Meanwhile, four control factors were identified as critical to the performance of the MMI coupler as depicted in Fig. 2:

- Input tapered width at the input waveguide (IW): This affects the mode matching between the input waveguide and the MMI region, influencing both IL and output power.
- Input tapered width at the output waveguide (OW): This is crucial for ensuring efficient power transfer to the output waveguides.
- Input Waveguide Length (IL): This determines the interaction length of the input light with the MMI region, affecting the mode evolution.
- Output Waveguide Length (OL): Like the input length, this parameter controls the coupling efficiency to the output waveguides.

The values for the control factors were varied for optimization purpose as depicted in Fig. 2.

Previous research has shown that determining these factors is critical and has a direct impact on the insertion loss (IL) [17,23].

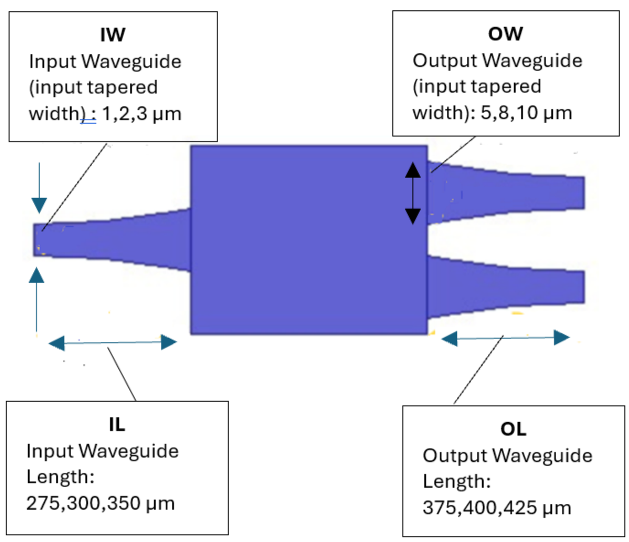


Fig. 2. Control factors in 1x2 parabolic tapered MMI coupler

2.2. Design of experiment

The simulations were conducted using the L9 orthogonal array in the Taguchi method, which requires three values of control factors that significantly impact the power output of the device [24]. Consequently, the three level values shown in Table 2 were selected according to the L9 orthogonal array. Meanwhile the L9 orthogonal array of the Taguchi method was designed using Minitab with four control parameters and three levels for a 1×2 parabolic tapered MMI coupler, as shown in Table 3.

Table 2. Control factor and level for 1x2 parabolic tapered MMI coupler

Symbol	Control Factor [μm]	Level 1	Level 2	Level 3
A	IW	1	2	3
B	OW	10	8	5
C	IL	275	300	350
D	OL	375	400	425

Table 3. L9 orthogonal array and response value for 1x2 parabolic tapered MMI coupler

Experiment	Process parameter			
	IW [μm]	OW [μm]	IL [μm]	OL [μm]
1	1	10	275	375
2	1	8	300	400
3	1	5	350	425
4	2	10	300	425
5	2	8	350	375
6	2	5	275	400
7	3	10	350	400
8	3	8	275	425
9	3	5	300	375

3. Result and analysis

The 1x2 parabolic tapered MMI coupler was designed with a width of 26 μm and a length of 750 μm, determined by the self-imaging principle. As depicted in Fig. 3, this configuration enabled efficient optical field propagation across the coupler's multimode region. Fig. 4 illustrates the optical field propagation simulation using the OptiBPM software, which provided insights into the distribution of light intensity and power splitting at the output ports.

The performance was evaluated based on the total output power across both waveguide arms, with an optimal power splitting ratio of 0.5. Fig. 5 presents the output power and corresponding insertion loss for each experiment in the L9 orthogonal array. Among the experiments, Experiment 8 achieved the highest power ratio (0.9756) and the lowest insertion loss (0.1073 dB). In contrast, Experiment 3 exhibited the highest insertion loss (1.7457 dB) and the lowest output power (0.669), illustrating the importance of control factor selection for optimal device performance.

The results underscore that the parabolic taper significantly enhances the efficiency of the MMI coupler by reducing beat length and minimizing mode mismatch. This leads to a reduction in insertion loss and an improvement in power transfer to the output waveguides, as demonstrated by the low insertion loss of 0.1439 dB in the optimized design.

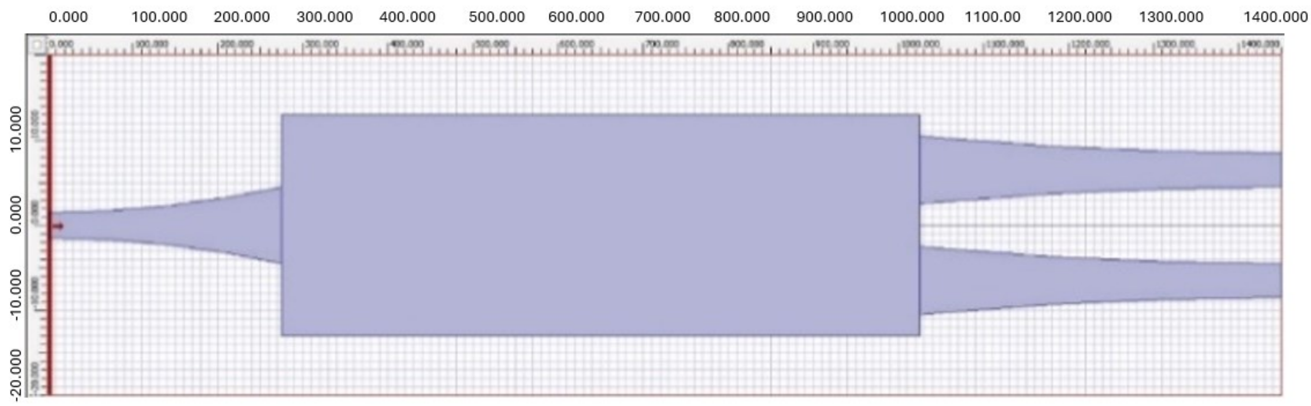


Fig. 3. Parabolic tapered 1x2 MMI coupler structure in OptiBPM Designer, Experiment 8

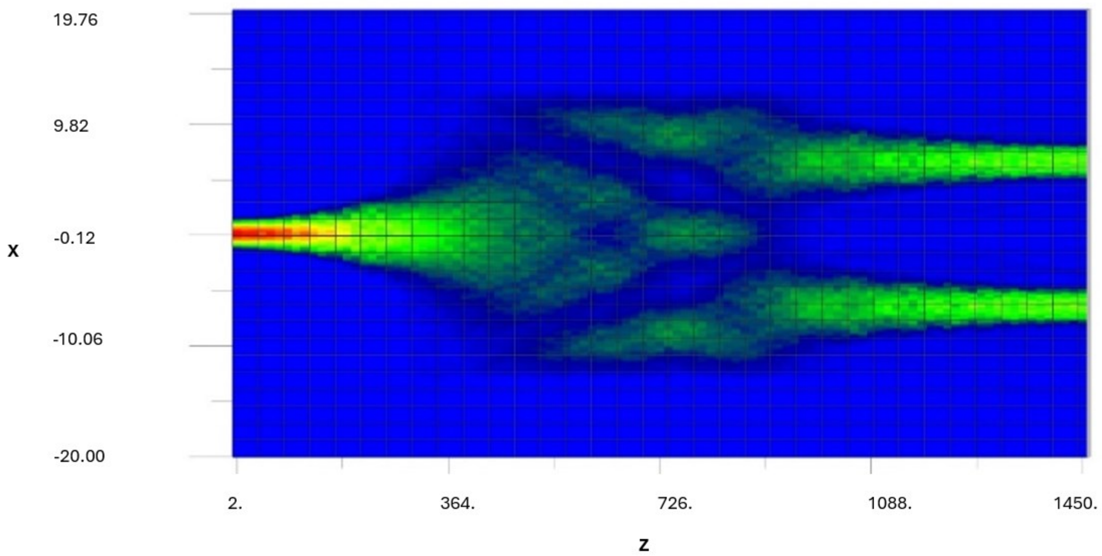
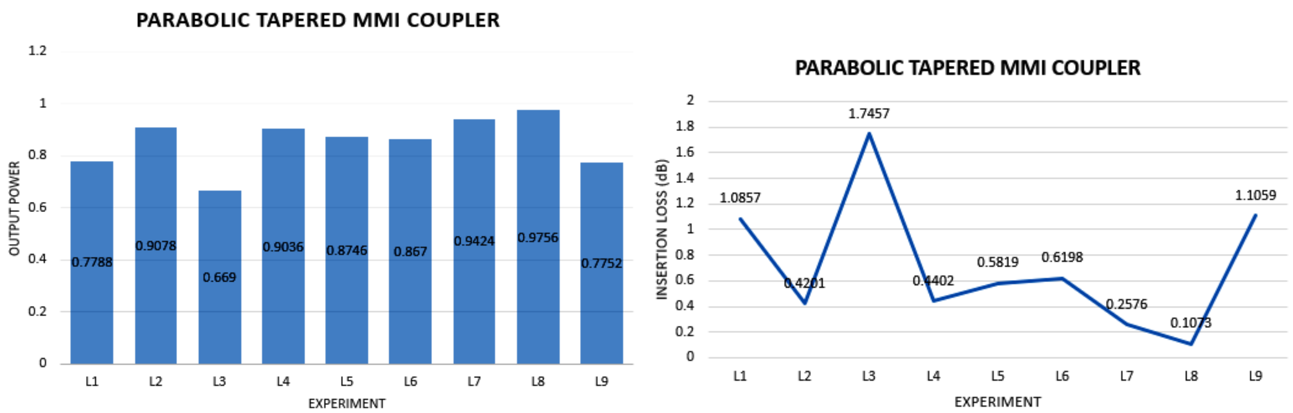


Fig. 4. Optical field propagation of parabolic tapered 1x2 MMI coupler in OptiBPM Analyzer, Experiment 8



(a) (b)

Fig. 5. Parabolic tapered MMI coupler (a) Output power, (b) Insertion loss

The Taguchi method employs the S/N ratio to assess the robustness of a design by quantifying the deviation of performance metrics from their optimal values. In this study, the S/N ratio was calculated to evaluate the impact of four control factors— input tapered width at the input waveguide (IW), input tapered width at the output waveguide (OW), input waveguide length (IL), and output waveguide length (OL)—on the insertion loss.

Table 4 provides the S/N ratios for each experiment, highlighting the influence of each control factor on insertion loss. The analysis revealed that the input tapered width at the input waveguide (IW) was the most significant factor, contributing 35.67% to the device's performance. Meanwhile, the input tapered width at the output waveguide (OW), input waveguide length (IL) and output waveguide length contributed (OL) 30.43%, 21.88%, and 12.02%, respectively (Fig. 6). These findings emphasize the importance of precise design of the input and output taper regions to achieve optimal mode matching and power transfer.

The S/N response plot in Fig. 7 illustrates the optimal levels for each control factor, which correspond to input tapered width at the input waveguide (IW) of 3 µm, input tapered width at the output waveguide (OW) of 8 µm, input waveguide length (IL) of 275 µm, and output waveguide length (OL) of 400 µm. This configuration yielded an insertion loss of 0.1439 dB and an S/N ratio of 16.8388, demonstrating the robustness of the optimized design.

These results highlight the critical role of input tapered width in minimizing insertion loss, as this parameter governs the efficiency of mode coupling between the input waveguide and the multimode region. The optimization process further confirms that careful design of both the input and output waveguide geometries is essential for reducing reflections and maximizing output power.

Table 4. Response with calculated S/N ratios for parabolic tapered MMI coupler

Experiment	Insertion loss (dB)	S/N ratio (Smaller is better)
1	1.0857	-0.7142
2	0.4201	7.5329
3	1.7457	-4.8394
4	0.4402	7.1270
5	0.5819	4.7030
6	0.6198	4.1550
7	0.2576	11.7811
8	0.1073	19.3880
9	1.1059	-0.8743

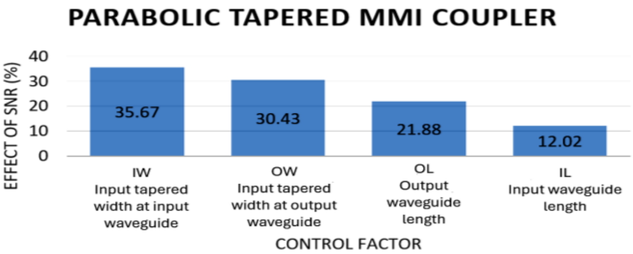


Fig. 6. Percentage of control factor on the parabolic tapered MMI coupler performance

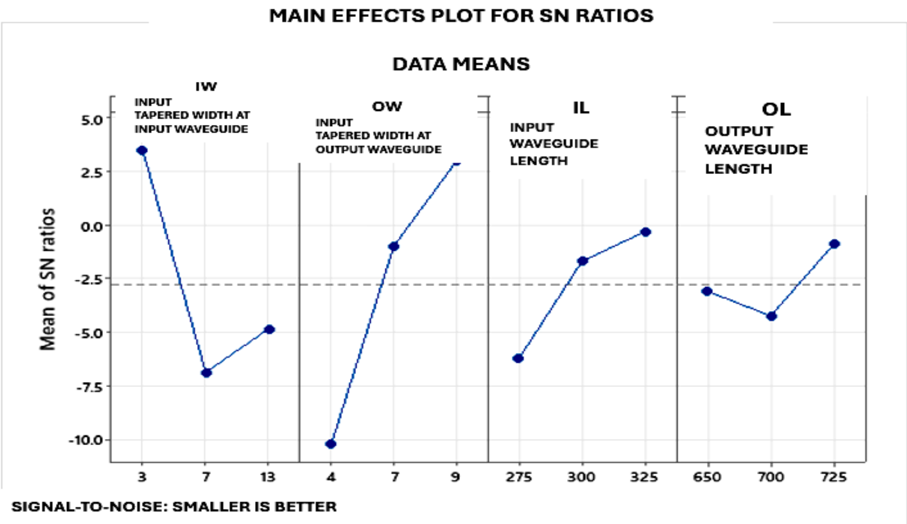


Fig. 7. Factor effect plot for parabolic tapered MMI coupler

The analysis of the simulation results reveals that the input tapered width at the input waveguide (IW) is the most influential factor in determining the performance of the parabolic tapered MMI coupler. Specifically, the input tapered width at the input waveguide contributes 35.67% to the overall performance, as measured by the insertion loss (IL) and output power. This significant impact underscores the importance of accurately designing the input taper to ensure efficient mode matching between the input waveguide and the MMI region.

The optimized input tapered width achieved in this study minimizes reflections and mode mismatch, leading to a reduction in insertion loss to 0.1439 dB. This low insertion loss is critical for practical applications in photonic integrated circuits (PICs), where energy efficiency and signal integrity are paramount. The result demonstrates that careful optimization of the input taper can lead to substantial performance improvements in MMI couplers, making them more suitable for high-density PICs [25].

While the input tapered width at input waveguide was the dominant factor, the output waveguide length and input tapered width at the output waveguide also play crucial roles in the overall performance. The input tapered width at the output waveguide significantly influences the power distribution across the output ports, affecting the splitting ratio and output power. The optimized input tapered width at the output waveguide ensures a balanced power distribution with minimal insertion loss, contributing to the overall efficiency of the coupler.

The output waveguide length was optimized to ensure that the light propagates through the MMI region and transitions into the output waveguides with minimal loss. This length optimization is particularly important for achieving the desired phase relationships between the propagating modes, which is critical for maintaining low insertion loss and high output power.

The use of the Taguchi method, particularly the L9 orthogonal array, allowed for an efficient exploration of the design space with a minimal number of simulations. The S/N ratio analysis provided insights into the robustness of the design, ensuring that the optimized parameters not only improve performance but also make the coupler less sensitive to variations in manufacturing processes.

The optimal design identified through this method resulted in optical power output of 0.9874, insertion loss of 0.1439 dB and a high S/N ratio of 16.8388, indicating a robust and efficient design. Figs. 8 and 9 depicts the structure and optical propagation of the optimized design. This demonstrates the effectiveness of the Taguchi method in optimizing complex photonic devices where multiple interacting parameters need to be balanced.

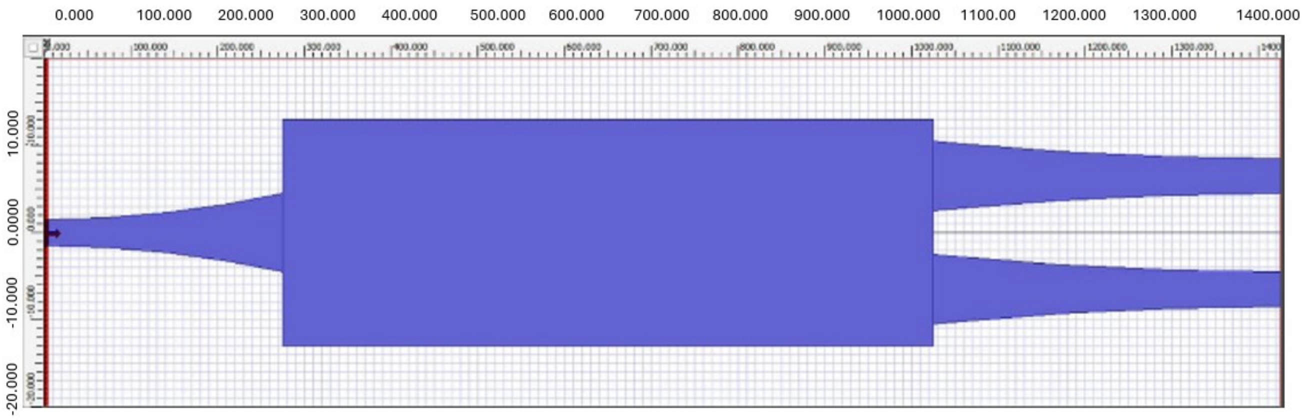


Fig. 8. Parabolic tapered 1x2 MMI coupler structure of optimized design

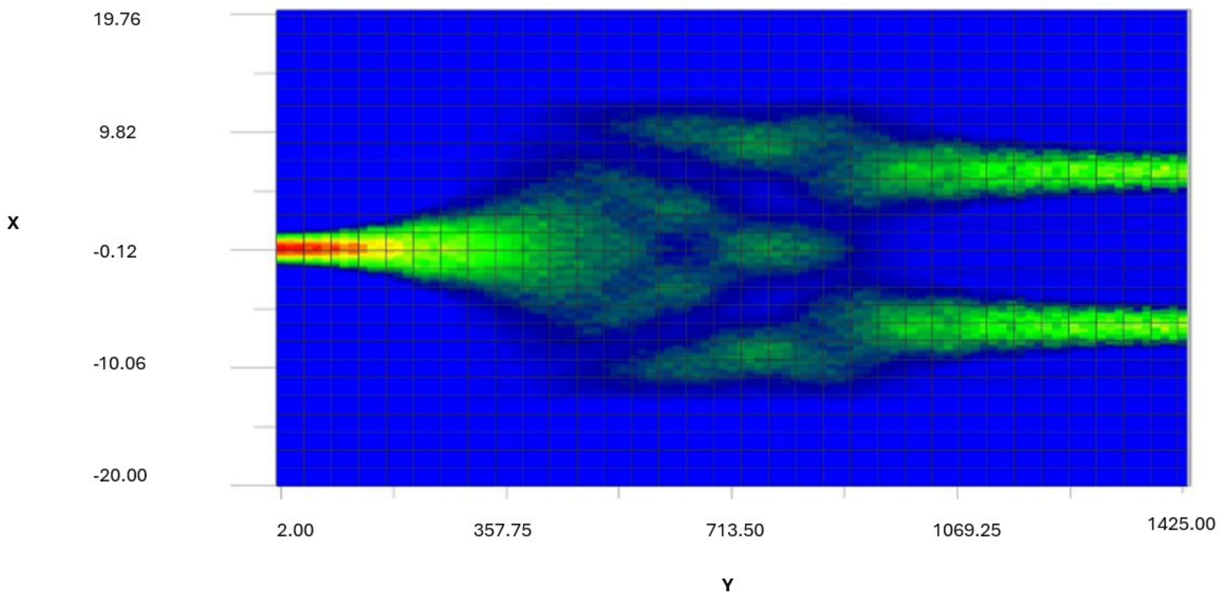


Fig. 9. Optical field propagation of parabolic tapered 1x2 MMI coupler of optimized design

3.1. Comparison with previous work

Comparing to other MMI coupler designs in the literature, the optimized design in this study offers a competitive edge. The insertion loss achieved in this study is lower than many reported values for similar devices, highlighting the success of the optimization process. For instance, previous designs reported insertion losses in the range of 0.2 dB to 4.0 dB, indicating that the approach used in this study provides a significant improvement.

The MMI coupler is a crucial component in photonic integrated circuits due to its compact size and sensitivity. Research in this field primarily aims to optimize the structure of MMI couplers to achieve a balance between reduced size and maintained or improved performance.

Table 5 compares the performance of various MMI couplers, including the optimized tapered MMI coupler from this research, against previous studies. Key performance metrics such as dimensions and insertion loss are considered. The MMI coupler's compact design is essential for integration into photonic circuits. The research focuses on structural modifications to reduce the size without compromising performance. A critical parameter indicating the efficiency of the coupler. Lower insertion loss signifies better performance. Meanwhile, smaller dimensions are preferred for compactness, but they must be balanced with performance metrics like insertion loss.

Table 5. Performance of different tapered structure of MMI couplers

Research	Dimension [μm]	Insertion Loss (dB)
Dual-polarization Dual-mode Silicon 3dB Beam Splitter Based on Shallow Etched Multimode Interference Coupler [12]	2x2 splitter, W= 5 L= 85.5	1.8000
Parabolic MMI coupler for 2× 2 silicon optical switch with robustly high extinction ratio for four paths [17]	2x2 splitter, W= 2.4 L= 6.5	0.4000
Design of 4-channel AWG multiplexer/demultiplexer for CWDM system [26]	1x4 splitter, W= 10.1 L= 80	2.7800
An ultracompact 3× 1 MMI power-combiner based on Si slot-waveguide structures [14]	3x1 splitter, W= 3.5 L= 9.82	0.0870
Basic building blocks development for a SiN platform in the visible range [27]	1x2 splitter, W =5 L=41	4.0
This research	1x2 splitter, W=26 L=750	0.1439

4. Conclusion

The results of this study have important implications for the design of future photonic integrated circuits. The ability to achieve low insertion loss with a robust design process enhances the potential for integrating MMI couplers into various PIC applications, including modulators, switches, and multiplexers. Additionally, the methodologies used in this study, particularly the application of the Taguchi method, can be extended to optimize other components within PICs, further advancing the field.

Future work could explore the application of this optimization process to other tapering structures, such as exponential or hyperbolic tapers, to determine if further performance gains can be achieved. Additionally, experimental validation of the simulated results through fabrication and testing of the optimized design would be a logical next step to confirm the practical applicability of the findings.

Furthermore, this research aligns with several Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation, and Infrastructure) and SDG 7 (Affordable and Clean Energy). By enhancing the efficiency and reliability of photonic devices, this study contributes to the development of advanced technological infrastructure and promotes innovation. Additionally, the improved performance of photonic integrated circuits can lead to more energy-efficient technologies, supporting the transition to cleaner energy solutions.

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