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Theoretical Review: Adiabatic Coupler Engineering and Modification in Supporting SDGs 9 Efficient Optic Technology Engineering and Innovation

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ABSTRACT

Objective: *This study aims to describe the application of adiabatic coupler modification in efficient optical coupler engineering and to emphasize its contribution to the achievement of SDG 9 (Industry, Innovation, and Infrastructure).* ***Method:*** *The method used is a literature study through a review of relevant articles and Python software-based analysis to evaluate the impact of coupler modifications, as an effort to strengthen theoretical findings.* ***Results:*** *The results of this study show that the invariance principle-based reverse engineering approach is practical in designing directional couplers on waveguides. Combined with perturbation analysis of the coupled mode equations, this method produces directional couplers that are highly robust to parameter variations such as coupling coefficient and wavelength. However, changes in scale or resonance through Python integration do not significantly affect the apparent deviation of the coupler wave, so the efficiency of the coupler is mainly determined by the coupling coefficient and wavelength variations.* ***Novelty:*** *This study highlights the novelty of utilizing the invariance principle and resonance modification as an efficient and straightforward approach for adiabatic coupler optimization. Furthermore, the results demonstrate the significant contribution of adiabatic couplers to SDG 9 through their support for the development of sustainable optical communication infrastructure, increased energy efficiency, and innovation in next-generation optical technologies.*

INTRODUCTION

The development of resilient infrastructure, inclusive and sustainable industrialization, and increased technological innovation are emphasized in Sustainable Development Goal 9 (SDG 9) as the main pillars of global development (Lyytimäki, 2025). The role of science, technology, and innovation is recognized as key in realizing SDG 9, especially in strengthening the competitiveness of research-based industries and cutting-edge technology (Dzhunushalieva & Teuber, 2024). Research by Lintangesukmanjaya et al. (2025) states that technology integration plays a very strategic role in achieving the SDGs. Technological innovation also has a significant role in strengthening the achievement of SDGs (Fitroni et al., 2025). Utilization of technology in accelerating the implementation of SDGs. One of the technological developments is optical technology, where advances in materials, device design, and photonic integration show great potential to support energy efficiency, system miniaturization, and high-speed communication performance (Wu et al., 2020).

Technological developments are increasingly rapid, especially in the use of optical physics. In the use of technology involving the processing, transmission, and control of light, particularly in integrated optics-based systems and optical communications, the use of optical couplers is very impactful (Agrell et al., 2024). A good optical coupler can have high tolerance to fabrication and wavelength variations, making it more stable under various operating conditions (Longhi, 2009). This technology is also aimed at combining high efficiency, compact design, and optimal transmission fidelity, even in systems with space and time constraints.

A coupler is a component in integrated optics that functions to combine or split light between waveguides (Osornio-Martinez et al., 2025). Its operation is based on the interaction of modes within the waveguide structure, which allows for the controlled transfer of optical energy. In optical physics, the function of a coupler is to combine or split light signals from one fiber to another (Han et al., 2024). Examples of its use can be found in fiber-optic internet networks (FTTH), optical switches, and multiplexers. Therefore, the coupler is one of the essential components in modern optics.

Couplers are key devices in optical communications and integrated optical systems, as they directly regulate light power transfer (Benton et al., 2024). Overall system performance is highly dependent on the efficiency, stability, and fault tolerance of these couplers. However, traditional couplers are still widely used. Despite their high efficiency, traditional couplers often require iterative design processes and complex numerical simulations.

Traditional adiabatic couplers require relatively large device lengths, making system miniaturization difficult. Furthermore, their design is highly sensitive to shape function and fabrication variations, requiring complex iterative optimization. Therefore, a new approach using a "shortcut to adiabaticity" allows for shorter yet more efficient coupler designs, without the need for stringent fabrication controls (Tseng et al., 2014). This innovation also involves invariant-based reverse engineering and perturbation theory, simplifying the design process without repeated iterations.

Another novelty is the analysis of resonance modifications to determine the extent to which waves can interact. Resonance in a coupler enables efficient light transfer when certain conditions are met, but can be an advantage or a challenge, depending on the application. Therefore, this study aims to describe the application of adiabatic coupler modifications in the engineering of efficient invariant-based optical couplers. This type of coupler was chosen because it can transfer energy efficiently in a short time, while remaining robust to disturbances or systematic variations. This makes it ideal for future optical applications that require compact and reliable devices.

By increasing the efficiency and stability of couplers, optical communications can become faster, more energy-efficient, and more reliable, supporting the development of internet networks and data centers. Furthermore, this technology can contribute to the miniaturization of medical devices and optical sensors, positively impacting the healthcare and industrial sectors. SDG 9 itself includes increasing industrial efficiency

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through the adoption of clean technologies, innovation, and the development of advanced infrastructure, which in the context of optical technology means promoting more compact, reliable, and energy-efficient systems (Lyytimäki, 2025).

The development of cutting-edge technologies has been shown to strengthen the achievement of SDGs targets through system efficiency and the utilization of sustainable innovation (Lintangesukmanjaya et al., 2025). With innovations such as adiabaticity in optical coupler design, high transmission efficiency and tolerance to fabrication variations can be achieved, supporting the sustainable industrialization of optical technology (Wu et al., 2020). Therefore, optical coupler engineering and modification are concrete representations of the contribution of cutting-edge technology in strengthening industrial infrastructure and innovation as targeted by SDG 9 (Dzhunushalieva and Teuber, 2024).

RESEARCH METHOD

The conceptualized and used research design is a literature study. In writing this article, the author employs the article study method, also known as the decision-making method, drawing on insights from several previous articles. The literature study research method involves searching for library sources with keywords and research problem formulations that align with the research being conducted (Indahwati et al., 2023; Lintangesukmanjaya et al., 2025). The population used in writing this article is from several sources, including various national and international journals. The main topic discussed is the discussion of a short and intense directional coupler designed with a shortcut to adiabaticity. The results of the analysis are strengthened by resonance modification analysis using "Python" software with the help of AI to obtain a visual design of the resonance coupler modification. The following is the data collection design used:

Figure 1. Research flow (Hadi et al., 2024)

In the context of the article review on the topic of a short and intense directional coupler designed with a shortcut to adiabaticity, the Determining Goals stage focuses on establishing research objectives, such as designing an efficient and compact optical coupler for photonic applications. Furthermore, the Article Review includes a literature review related to optical coupler design techniques, adiabatic principles, and shortcut to adiabaticity methods to find research gaps. The Discovery Modifications stage is used to identify innovations or design improvements, for example, by optimizing the length and coupling strength parameters to make the device more compact and efficient. Finally, Analysis and Generalization are carried out to analyze the research results, compare them with conventional methods, and generalize the findings so that they can be applied to the development of future photonic technologies.

RESULTS AND DISCUSSION

Coupler Analysis with Adiabatic Shortcut

The operating principle of an adiabatic coupler is based on the evolution of a single waveguide local mode (supermode) caused by gradual changes in the device geometry, and the coupling between supermodes can be neglected when the adiabatic condition is met (Ramadan et al., 1998; Syahriar et al., 1998). Thus, an adiabatic coupler generally requires a longer device length. The optimal design of an adiabatic coupler by selecting an optimized shape function where the coupled mode equations describing the coupling between unperturbed waveguide modes are solved by numerical integration using different shape functions.

Therefore, short and strong directional drivers against the variation of the coupling coefficient/wavelength, using perturbation theory analysis is very important (Tseng, 2013). By means of a directional coupler model consisting of two types of waves placed in adjacent states with propagation constants β+ (z) and β- (z) obtain the refractive index or geometry of the two waveguides that vary along the propagation direction (z). Light is coupled in the device at z = 0 and exits at z = L then with a propagation distance obtained

$$\frac{d\boldsymbol{A}}{dz} = - iH_0\,(z)\,\mathbf{A}, \tag{1}$$

By knowing that, $\Omega \equiv \Omega$ (z) (real) is the coupler coefficient, we get,

$$\frac{d}{dz}\begin{bmatrix} A_+ \\ A_- \end{bmatrix} = -i\begin{bmatrix} -\Delta & \Omega \\ \Omega & \Delta \end{bmatrix}\begin{bmatrix} A_+ \\ A_- \end{bmatrix} \tag{2}$$

Equation (1) is equivalent to the time-dependent Schrodinger equation ($\acute{h}$= 1) which describes the dynamics of the interaction of a two-state system driven by coherent laser excitation. To optimize the coupling dynamics, variations in the coupling coefficient/wavelength are carried out. From H_0 (z) as in equation (2), with the dynamic variant $\mathbf{I}_{(z)}$ value obtained,

$$\mathbf{I}_{(z)} = \frac{\kappa}{2}\begin{pmatrix} \cos\theta & \sin\theta\, e^{-i\beta} \\ \sin\theta\, e^{-i\beta} & -\cos\theta \end{pmatrix}, \tag{3}$$

To fulfill the coupling between two waveguides with invariant engineering, mathematical calculations are carried out between equations (2) and (3) with the Lewis-Riesenfeld theory (Tseng et al., 2014), the initial and final states of the system are set in,

$$|\psi\,(z)\rangle = \Sigma\pm c\pm e^{i\gamma\pm(z)}|\varphi\,\pm(z)\rangle, \tag{4}$$

$$|\psi\ (0)\rangle = |2\rangle \quad \text{dan}\ |\psi\ (L)\rangle = |1\rangle, \tag{5}$$

Then Ω (0) = Ω (L) = 0, and H (z) and I (z) traveling on input z = 0 and outputs z = L. Commutivity at the boundary implies that operators share eigenstates so that, the input and output waveguide modes can transform into eigenmodes I(z) smoothly.

Dinamika Kopling Optimal

The optimal coupler in line can maximize the spectral characteristics of the directional coupler according to the variation of the input wavelength (λ) (Paloczi et al., 2004). The results of the analysis of the combination of two types of parameters that obtained the maximum coefficient value and parameter changes are as follows,

$$\Omega = -\ \dot{\theta}\ \sqrt{1 + 4\, M^2 sin^2\theta}\ , \tag{6}$$

$$\Delta = 2\ \dot{\theta}\ \cos\theta\left[M + \frac{1-4a+6a\cos(2\theta)}{1+4\ M^2 sin^2\theta}\right], \tag{7}$$

This can only be true if q_Δ = 0 dan α = -0.206 and the smallest value of the required coupling coefficient, Ω= 14.784. The results of the directional coupler design illustration using a shortcut to adiabaticity in a conventional planar integrated optical platform and performing ray propagation method (BPM) simulations are as follows.

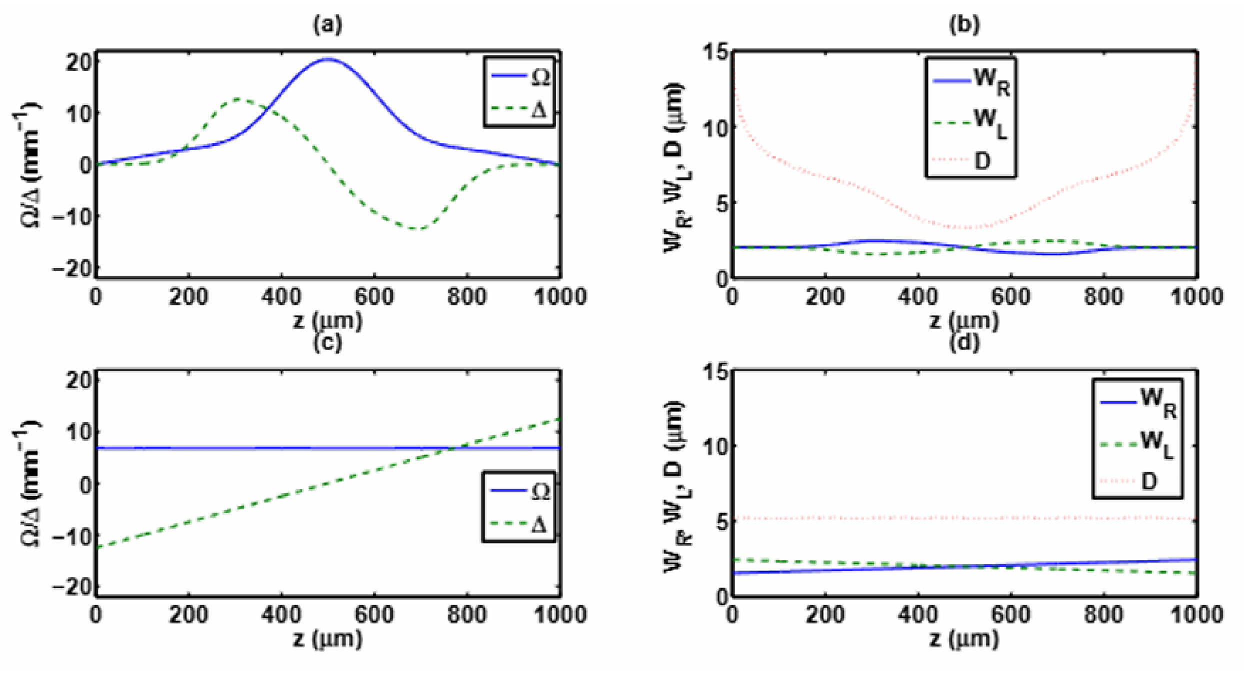

Figure 2. Differences in numerical simulation (Tseng et al., 2014)

Figure 2, explains the difference in simulation results in the primary channel with the design parameters selected as follows: SiO thick 3μm (n = 1.46) on wafers Si (n = 3.48) used for the bottom coating layer, the core consists of a layer of BCB 2.4 μm (n = 1.53), and the top coating is epoxy (n = 1.50). Through BPM simulation, it is verified that the relationship between mismatch Δ and width differences δW can be estimated by a linear relationship (Syahriar et al., 1998; Tseng et al., 2014).

Coupler Efficiency

Previously with the exponential relationship between Ω and Δ which has a linear relationship due to the z function, then an adiabatic coupler is designed with the same length using a linear tapered mismatch. The results of the BPM analysis in Figure 2, are visualized in the design parameters that plot the conversion efficiency as a function of the device length L (interaction length) for the three coupler designs in Figure 3 below,

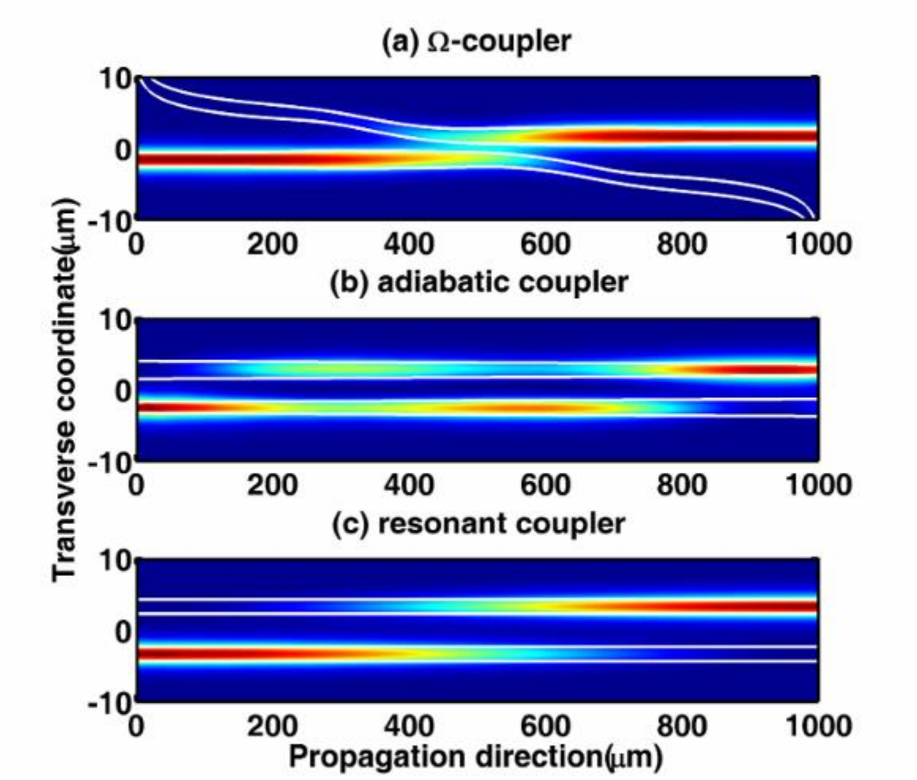

Figure 3. Waveguide geometry and propagation simulation (Tseng et al., 2014)

Figure 3 explains the differences in transverse coordinates obtained from a) Ω coupler, b) adiabatic coupler, and c) resonant coupler. oscillatory behavior in the coupling efficiency, which is characteristic of adiabatic devices due to the limited coupling between supermodes. Thus, complete power coupling can only occur at a certain device length. On the other hand, Ω-coupler shows optimized tolerance to device length variations (interaction length) around the designed length of 1 mm. The resonant coupler exhibits the expected sinusoidal behavior with changes in device length.

By applying optimization of resistance to wavelength variations (Δ-coupler) with a coupler design with a length of L = 1 mm, showing suitability between Ω and Δ and the appropriate waveguide parameters. In this section, the difference in coupling efficiency between Ω coupler, Adiabatic coupler, and resonant coupler look different Ω The coupler has durability and efficiency which continues to increase with each variant Δn (%).

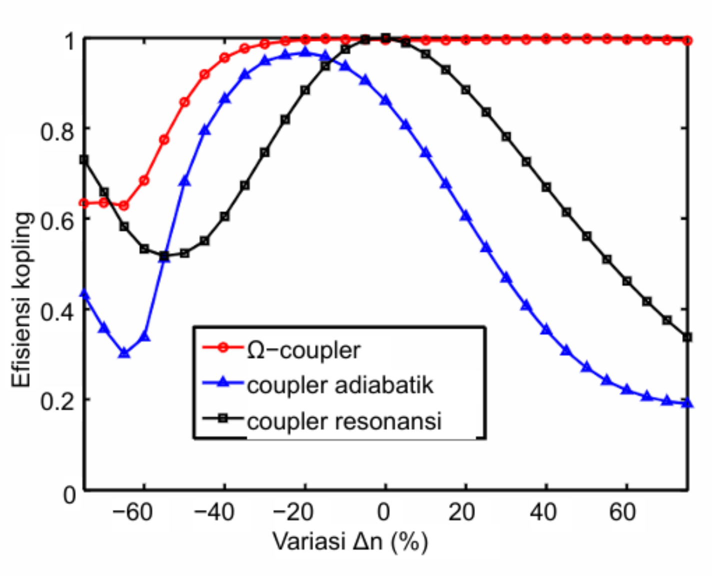

Figure 4. Clutch efficiency (Tseng et al., 2014)

Modification of Adiabticity Coupler with Different Resonances

To modify the coupler through adiabaticity, three types of couplers are examined, as shown in the previous results from the article review in Figure 3. Manipulation and significant variations of the resonance obtained by analyzing Python software in numpy* format are carried out. The results of the coding transfer can be seen in the following figure,

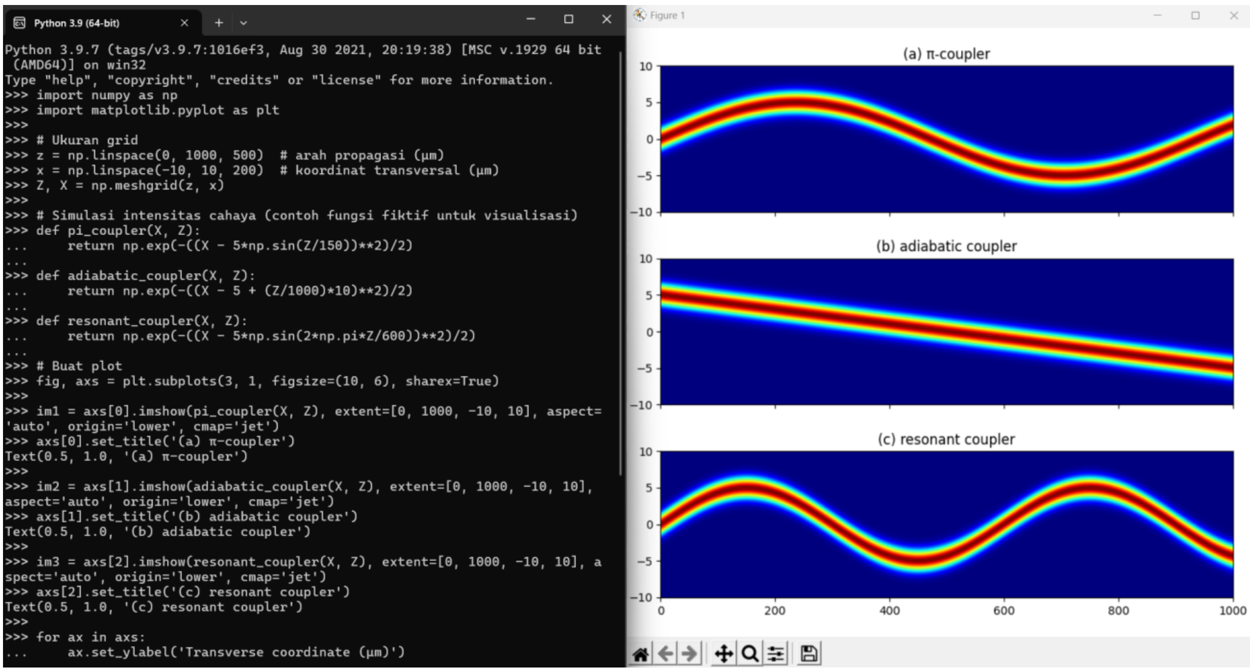

Figure 5. Coupling wave analysis process

By manipulating the size of the propagation and transversal domains, namely:

z = np.linspace(0, 1000, 500) # propagation direction (coupler length)

x = np.linspace(-10, 10, 200) # transverse direction (distance between waveguides)

The value 1000 is changed to 3000 and the values 10 and 10 are changed to -20 and 20 in the display range are changed to to produce a more flexible display area, the following results are obtained,

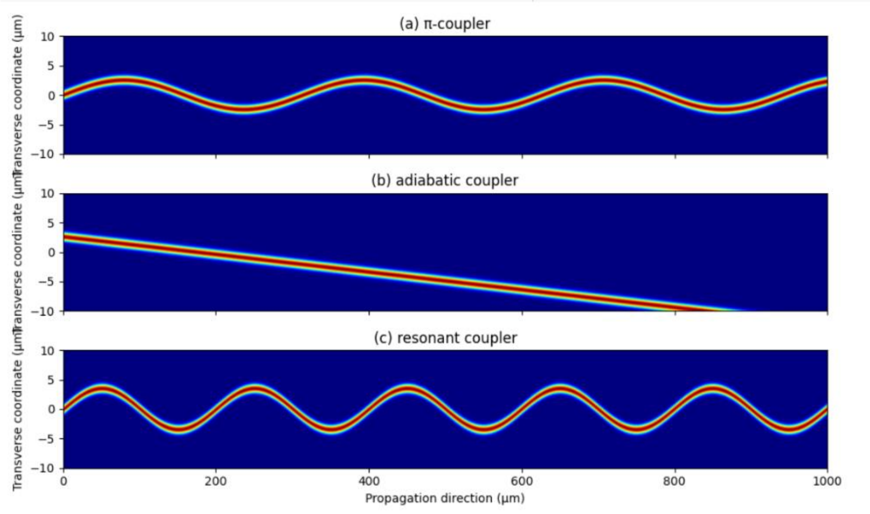

Figure 6. Python design output

To determine the propagation form (intensity function) of each wave Ω coupler, Adiabatic coupler, and resonance coupler. The resonance scope was enlarged to 2N (two times) and the following results were obtained:

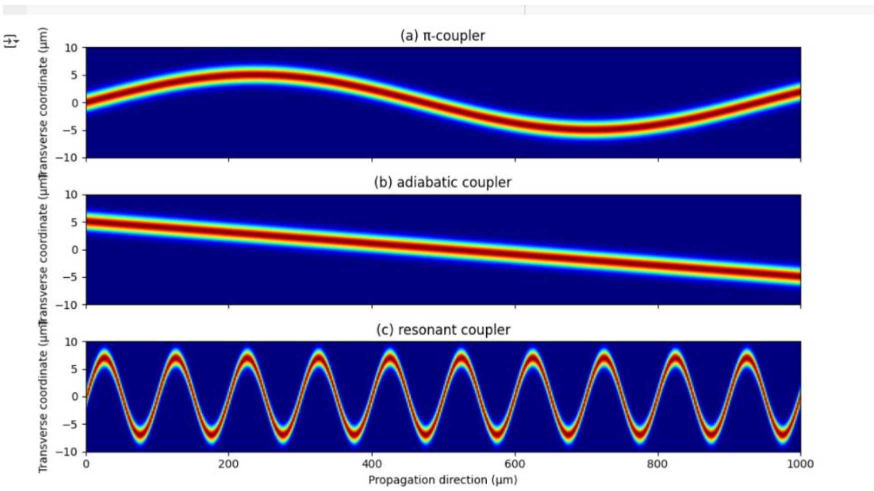

Figure 7. Resonance effect modification

As shown in Figure 7, in waves Ω The coupler is subjected to path amplitude enlargement and frequency changes. In the adiabatic coupler, position changes are carried out, and the transition speed is automatically slowed down from 2N. Finally, in the resonant coupler, the resonance period changes to be slower. So the oscillation speed is faster. In essence, modifying the scale or resonance via Python coding does not alter the actual deviation value in each coupler wave. Changes in coupler efficiency can only be influenced by the coupling coefficient and wavelength variations (Ramadan et al., 1998; Syahriar et al., 1998).

Advantages and Disadvantages of Adiability Couplers

Adiabatic design offers high coupling efficiency when the device length is long enough to satisfy the adiabatic condition, but does not guarantee complete power coupling at the designed device length due to coupling efficiency oscillations resulting from limited coupling between supermodes. Another advantage is high energy efficiency, as there is no heat loss. This results in higher energy efficiency in the system, which in turn triggers thermal stability due to the absence of heat exchange, making the system more thermally stable and suitable for high-precision systems (Cortella et al., 2020). In addition, minimal thermal disturbance is suitable for use in systems where temperature changes can cause functional disturbances (e.g., in optics, microsystems, or high-precision sensors).

The drawback of adiabatic couplers lies in their complex design, especially in environments with variable temperatures. This is apparent when combined with perturbation theory; an invariant-based approach can be used to optimize the robustness of the device to selected faults, resulting in robust directional couplers at shorter lengths than adiabatic devices (Tseng et al., 2014). The robustness of the device to faults exhibits asymmetry around the designed value, which is similar to the characteristics of adiabatic devices; however, adiabaticity is achieved at shorter device lengths. Furthermore, they are susceptible to overheating; in mechanical or electronic systems that generate heat, the absence of heat transfer outward can lead to overheating.

Adiabatic couplers have advantages in supporting SDG 9 (Industry, Innovation, and Infrastructure) because they can provide high efficiency, tolerance to fabrication variations, and compact design (Neder et al., 2024; Wang et al., 2025). These characteristics greatly support the development of integrated photonic devices needed in next-generation optical communications. By minimizing energy losses and remaining stable under various conditions, adiabatic couplers can improve network reliability and reduce power consumption (Liang et al., 2024), thus aligning with the goal of sustainable industrial infrastructure development. Furthermore, their scalability and potential integration on various photonic chip platforms open up opportunities for broader technological innovation, while strengthening the competitiveness of optics-based industries in the era of digital transformation (Su et al., 2025).

Adiabatic coupler technology plays a crucial role in supporting the achievement of SDG 9 (Industry, Innovation, and Infrastructure) because it can improve energy efficiency, reduce power losses, and maintain device performance stability under various operational conditions. These advantages are highly relevant to the needs of the modern optical industry, which demands low-power, high-precision photonic devices that can be integrated into photonic integrated circuits (PICs) platforms to support next-generation communication networks. With minimal thermal interference and the ability to operate at a more compact device size, this technology not only optimizes optical system performance but also contributes to the development of sustainable digital infrastructure, network efficiency, and reduced global energy consumption (Mishra &

Singh, 2023). Furthermore, the integration of adiabatic couplers with large-scale photonic chips opens up opportunities for technological innovation that strengthen the competitiveness of optical-based industries in the era of digital transformation.

However, the main challenges facing the optical industry today are the complexity of device design, sensitivity to manufacturing variability, and the risk of overheating due to limited heat dissipation. Although adiabatic couplers offer high efficiency, their precise and expensive fabrication process hinders mass production, especially for data center applications and large-capacity optical networks. Furthermore, the need for device miniaturization and increased data transmission speeds necessitates innovative approaches such as shortcut to adiabaticity (STA), which maintains adiabatic efficiency at shorter device lengths. Therefore, the development of this technology is key to addressing the industry's need for more energy-efficient, interference-resistant, and economically manufacturable optical devices, while simultaneously supporting the achievement of SDG 9's target of strengthening sustainable and innovative industrial infrastructure.

CONCLUSION

Fundamental Finding: This review article demonstrates that an invariance-based reverse engineering approach has proven effective in designing directional couplers in waveguides. By integrating perturbation analysis of the coupled mode equations, this method is capable of producing directional couplers that are highly robust to parameter variations, such as coupling coefficients and wavelengths. This invariance-based approach also offers an efficient and straightforward method for optimizing the performance of optical devices. **Implication:** These findings confirm that adiabatic coupler design innovations have significant potential to support the development of more efficient, stable, and compact integrated optical technologies. These findings directly contribute to the achievement of SDG 9 (Industry, Innovation, and Infrastructure), as they can support the development of sustainable optical communications infrastructure and drive innovation in next-generation optical technologies. **Limitation:** The Python coding integration analysis used in this study was only able to modify the scale and resonance visually, but did not significantly affect the absolute deviation values of each coupler wave. Thus, the significant changes in coupler efficiency are primarily determined by the coupling coefficient and wavelength variations, not by scale or resonance manipulation alone. **Future Research:** Further research can be directed at assessing the specifications of nonlinear and active materials (e.g., electro-optical) in the design of invariant-based directional couplers. This effort is expected to enable dynamic control of coupling characteristics and light transmission direction, while opening up broader application opportunities in high-precision photonic devices and future optical communication systems.

AUTHOR CONTRIBUTIONS

Rahmatta Thoriq Lintangesukmanjaya contributed to the conceptual framework, research design, and validation process; **Akhmad Iswardani** was involved in methodology development, data analysis, sourcing references, and drafting the manuscript; **Binar Kurnia Prahani** handled data management; **Dwikoranto** was involved in project coordination; **Noval Maleakhi Hulu** was sourcing references, and drafting the manuscript. All listed authors have reviewed and approved the final version of this submission.

CONFLICT OF INTEREST STATEMENT

The authors confirm that there are no conflicts of interest, either financial or personal, that may have influenced the content or outcome of this study.

ETHICAL COMPLIANCE STATEMENT

This manuscript complies with research and publication ethics. The authors affirm that the work is original, conducted with academic integrity, and free from any unethical practices, including plagiarism.

STATEMENT ON THE USE OF AI OR DIGITAL TOOLS IN WRITING

The authors acknowledge the use of digital tools, including AI-based technologies, as support in the research and writing stages of this article. Specifically, Grammerly for a writing aid that offers various advantages, especially in terms of improving the quality and clarity of writing in English. All outputs generated with digital assistance were critically evaluated and revised to ensure academic rigor and ethical standards were upheld. The final responsibility for the manuscript rests entirely with the authors.

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