BALKAN JOURNAL OF ELECTRICAL & COMPUTER ENGINEERING, Vol. 13, No. 3, September 2025
Research Article

Design and Optimization of Oxide Material-Based Single-Mode Rib Waveguides for Photonic Integrated Circuits

Huriye Gencal, Mustafa Demirtas and Umut Aydemir

***Abstract*— The primary objective of this study is to design single-mode rib waveguide structures using oxide-based materials. To achieve this goal, the waveguide dimensions including width and height were optimized to ensure reliable single-mode operation. Optimization was performed using the particle swarm optimization (PSO) algorithm. The effective refractive index (n_{eff}), a critical parameter for waveguide design, was calculated and evaluated to confirm suitability for single-mode propagation. Additionally, the influence of various oxide materials commonly used in passive photonic components, including integrated optical waveguides, was comparatively analyzed.**

Simulation results provided a comparison of effective refractive indices for rib waveguides fabricated from different oxide materials. Optimal geometric parameters ensuring minimal propagation losses and maximum mode purity were identified through these simulations. Overall, this work offers a comprehensive optimization strategy for oxide-based rib waveguides, contributing valuable insights toward enhancing the performance of integrated photonic devices.

Index Terms— **Rib waveguide, oxide-based materials, single mode, propagation losses, effective refractive index (n_{eff}), integrated photonics.**

I. Introduction

PHOTONIC INTEGRATED CIRCUIT (PIC) technologies play a crucial role in fields such as communication systems, sensing platforms, and quantum information processing, thanks to their advantages including high bandwidth, low power consumption, and integration capability and maintenance of modal purity. In this context, single-mode waveguides are particularly advantageous because they exclusively support the fundamental mode, thereby eliminating unwanted effects such as dispersion and inter-modal interference, resulting in high-quality signal transmission [1].

While silicon-based waveguides have traditionally been widely utilized, their limitations, including the absence of second-order optical nonlinearity and relatively high optical losses, have increased interest in alternative material platforms [2], [3]. Among these, oxide materials with varying refractive indices, notably amorphous Al_2O_3, HfO_2, and TiO_2 have attracted considerable attention for next-generation dielectric waveguide cores owing to their wide bandwidth, thermal stability, and compatibility with CMOS fabrication processes. Typically combined with SiO_2, substrates, these materials enable the formation of high-index contrast structures, thus ensuring strong mode confinement. In this work, the selection of Al_2O_3, HfO_2, and TiO_2 enables a direct comparison across low, medium, and high refractive index regimes. This approach allows a systematic investigation of how index contrast affects the confinement factor, while also taking advantage of each material's proven CMOS compatibility, strong thermal stability, and mature fabrication methods, qualities that make them strong candidates for practical implementation in integrated photonic systems.

Al_2O_3 facilitates low-loss optical transmission in the 1.48–1.61 µm wavelength range and is particularly notable for its amorphous Özden et al. demonstrated that Al_2O_3 rib waveguides, with dimensions around 0.5 µm thickness and approximately 3.5 µm width, could achieve polarization-insensitive single-mode transmission for both TE and TM polarizations [4]. Further research from the same group showed that a slab thickness of approximately 125 nm limits the number of supported modes and minimizes losses, achieving propagation losses as low as ~0.04 dB/cm using ALD [5]. Additionally, erbium-doped Al_2O_3 waveguides have been developed into integrated optical amplifiers exhibiting a net gain of 13.7 dB/cm [6]. Hafnium dioxide (HfO_2) offers a higher refractive index (~2.0), enabling more compact waveguide designs. In particular, Jaramillo et al. introduced an HfO_2 – Al_2O_3 composite platform deposited via ALD that demonstrated single-mode waveguide losses around 0.25 dB/cm at 729 nm and 2.6 dB/cm at 405 nm, along with intrinsic quality factors up to 2.6×10^6 in visible microresonator devices [7]. Titanium dioxide (TiO_2), with a refractive index reaching approximately 2.3, provides strong modal

Huriye Gencal, is with Department of Electrical Electronics Engineering University of Bursa Uludag University, Bursa, Turkey, (e-mail: huriyegencal@gmail.com).
https://orcid.org/0000-0002-6460-1177

Mustafa Demirtas, is with Department of Electrical Electronics Engineering University of Bursa Uludag University, Bursa, Turkey, (e-mail: mustafademirtas@uludag.edu.tr).
https://orcid.org/0000-0001-6832-4341

Umut Aydemir, is with Department of Electrical Electronics Engineering University of Bursa Uludag University, Bursa, Turkey, (e-mail: umutaydemir@uludag.edu.tr).
https://orcid.org/0000-0001-5396-4610

Manuscript received Jul 02, 2025; accepted Aug 18, 2025.
DOI: 10.17694/bajece.1733035

confinement, especially beneficial for visible wavelength applications. However, the high index introduces strong dispersion and surface scattering effects, necessitating precise control of single-mode conditions. Evans et al. achieved single-mode TiO_2 waveguides by employing core films 260 nm thick and widths between 0.8–1.2 µm, reporting losses of ~1.2 dB/cm at 1550 nm. However, in cases where higher surface quality was not achieved, edge roughness could elevate losses significantly (4–28 dB/cm) [8].

The above studies demonstrate that high refractive index oxide materials can effectively produce single-mode rib waveguides. Nevertheless, careful optimization of geometric parameters such as rib width, slab thickness, and total waveguide height is essential for precise control of mode number [1], [9]. Recently, heuristic methods such as particle swarm optimization (PSO), integrated with optical simulation tools, have emerged as powerful approaches for designing high-performance single-mode waveguides [10], [11]. In this study, the optimum geometric parameters ensuring single-mode operation in rib waveguides made from Al_2O_3, HfO_2, and TiO_2 were determined based on effective refractive index (n_{eff}) analyses, and their performance was evaluated through simulations. The ultimate goal is to contribute systematically to the design of low-loss, high modal purity waveguides suitable for integrated photonic systems.

II. DESIGN AND OPTIMIZATION METHODOLOGY

In the analysis of optical waveguides, certain fundamental parameters are essential for characterizing and comparing device performance. [12] The effective refractive index (n_{eff}) is defined as the ratio of the mode's propagation constant (β) to the free-space wave number (k_0) expressed as:

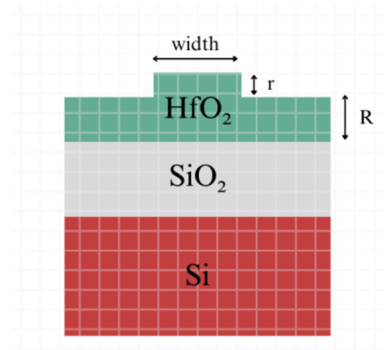
$$n_{eff} = \beta / k_0 \tag{1}$$

Another important metric is the confinement factor (Γ), which represents the proportion of the optical field energy confined within the core region of the waveguide. It can be calculated using:

$$\Gamma = \frac{\iint_{core} |E|^2 \, dxdy}{\iint_{total} |E|^2 \, dxdy} \tag{2}$$

where represents the mode's electric field intensity. These parameters form the basis for interpreting the simulation results presented in this study. The designs focused on rib-structured optical waveguides were numerically designed using high refractive index oxides, specifically TiO_2 [8], HfO_2 [7], and Al_2O_3 [5]. The waveguide structures were constructed on a Si substrate, incorporating a SiO_2, buffer layer beneath the core region. Each core was formed by the selected dielectric oxide, with the rib region defined on top of a supporting slab layer. Fig. 1 illustrates schematic cross-sectional views of the rib waveguide geometries developed for each material. The physical characteristics of these waveguides are described by key geometrical parameters, including rib slab height (R), rib height (r), and waveguide width.

The optical performance of the waveguides was investigated using the Lumerical MODE simulation software, employing the Eigenmode Solver module, which is based on the finite element method (FEM). The simulations were conducted at a wavelength of 1550 nm, a value selected for its critical importance in optical communication applications. For each material, wavelength-dependent refractive index values reported in the literature were utilized. To prevent unphysical reflections at the simulation boundaries, perfectly matched layer (PML) boundary conditions were implemented. All essential simulation parameters used in this study are summarized in Table I. Critical optical properties, such as the effective refractive index (n_{eff}) and propagation losses, were analyzed in detail based on the simulation results.



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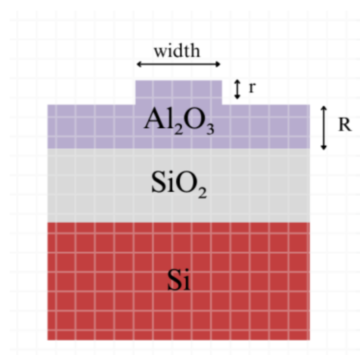

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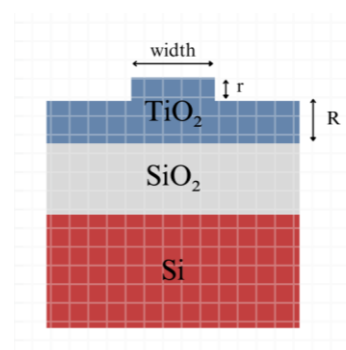

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Fig.1. Schematic cross-sectional views of rib waveguides based on (a) HfO_2, (b) Al_2O_3, and (c) TiO_2.

TABLE I Key parameters used in waveguide simulations

Parameter	**Value**
Wavelength (λ)	1550 nm
Core Materials	TiO_2, HfO_2, Al_2O_3
Cladding (Lower Layer)	SiO_2
Bottom Substrate	Si
Rib Height (r)	0.3–0.7 µm (optimized)
Slab Height (R)	0.05–0.3 µm (optimized)
Waveguide Width	0.2–1.5 µm (optimized)
Simulation Method	Eigenmode Solver
Boundary Conditions	PML (Perfectly Matched Layer)

The analyses were conducted to ensure exclusive support for the fundamental mode while effectively suppressing higher-order modes. In this context, the optimization of structural parameters, specifically the rib width and height, was carried out using the PSO algorithm implemented within the MATLAB environment. PSO is a heuristic optimization technique in which multiple candidate solutions, referred to as particles, explore the solution space by adapting their positions based on both their individual optimal experiences (*pBest*) and the globally best-known solution within the swarm (*gBest*) [11], [12].

Each particle in the PSO approach represents a unique combination of waveguide dimensions, such as width and height. Throughout successive iterations, the particles iteratively adjust their positions, generating new candidate solutions informed by their historical best solutions as well as the optimal solutions identified by the collective swarm.

An automated optimization process was implemented by establishing a bidirectional interface between Lumerical MODE and MATLAB software to determine the optimal geometric parameters of rib-structured oxide-based waveguides. For each material (TiO_2, HfO_2, and Al_2O_3), rib width and height parameters were optimized using the PSO algorithm, with the process extending up to 150 iterations to ensure optimal single-mode operation conditions [13].

As illustrated in detail in Fig. 2, the PSO algorithm initially generated random parameter sets (rib width and height) for each particle in the MATLAB environment, defining these as vectors [11]. These parameters were automatically transferred to the Lumerical MODE software through an Application Programming Interface (API). Subsequently, Lumerical MODE generated corresponding waveguide geometries and performed modal analyses using its Eigenmode Solver module. This analysis computed the supported modes and their associated effective refractive indices (n_{eff}), as well as spatial distributions of the optical field and mode profiles. Following this step, the optical parameters computed within the Lumerical environment were transmitted back to MATLAB via the API.

Each particle's solution was then evaluated using a fitness function. This fitness function was designed with a criterion that required only the fundamental mode to have n_{eff}> 1.44, while higher-order modes were constrained to n_{eff}≤ 1.44. If second or higher-order modes exceeded this threshold, a penalty term was activated, significantly increasing the total cost function and consequently excluding such structures from consideration. Thus, the algorithm favored configurations that strictly supported single-mode propagation.

Throughout each iteration, both the particles individual best-known solutions (*pBest*) and the overall population's best solution (*gBest*) were updated, subsequently generating new geometric parameters informed by these optimal results. This iterative optimization loop, sustained for 150 iterations, successfully identified optimal rib width and height parameters for each material that ensured single-mode propagation and optimal effective refractive indices. Consequently, systematic design strategies for oxide-based waveguides with high index contrast, low loss, and high modal purity were effectively established.

III. RESULT&DISCUSSION

Due to its high refractive index (~2.4 at 1550 nm), TiO_2 exhibits strong mode confinement, and PSO identified optimal waveguide dimensions as a width of 1.36 µm, a slab height (R) of 0.5489 µm, and a total height of 0.7 µm. The obtained objective function value of -2.2687 indicates exclusive fundamental mode propagation with significant mode confinement, highlighting the suitability of this geometry for compact, high-performance photonic integration. In contrast, HfO_2, having a moderately high refractive index (~1.87 at 1550 nm), offers smoother mode transitions compared to TiO_2. The optimized geometry for HfO_2 was determined to be a width of 1.5 µm, slab height of 0.5668 µm, and total height of 0.7 µm. These parameters suggest that HfO_2 performs optimally at slightly larger dimensions, effectively satisfying single-mode conditions. Its gentle modal transition characteristic could be particularly advantageous for applications requiring low back-reflection. Al_2O_3, which has a relatively lower refractive index (~1.65 at 1550 nm), is commonly employed in passive circuits aimed at minimizing optical losses. The PSO optimization for Al_2O_3 resulted in an optimal waveguide width of 1.5 µm, a slab height of 0.4996 µm, and a total height of 0.7 µm. Although Al_2O_3 exhibits limited mode confinement due to its lower index contrast, it offers low dispersion and broad-bandwidth capabilities, and its high thermal stability makes it suitable for integration into sensor and laser systems.

The parameters obtained from pso algorithm-based optimization for each of the three materials are summarized in Table II. Comparing these waveguide designs, TiO_2 provided the strongest mode confinement and yielded the highest objective function value. Meanwhile, HfO_2 exhibited balanced mode propagation with a larger rib height at similar widths, whereas Al_2O_3 maintained single-mode operation despite lower index contrast at the width limit. These findings

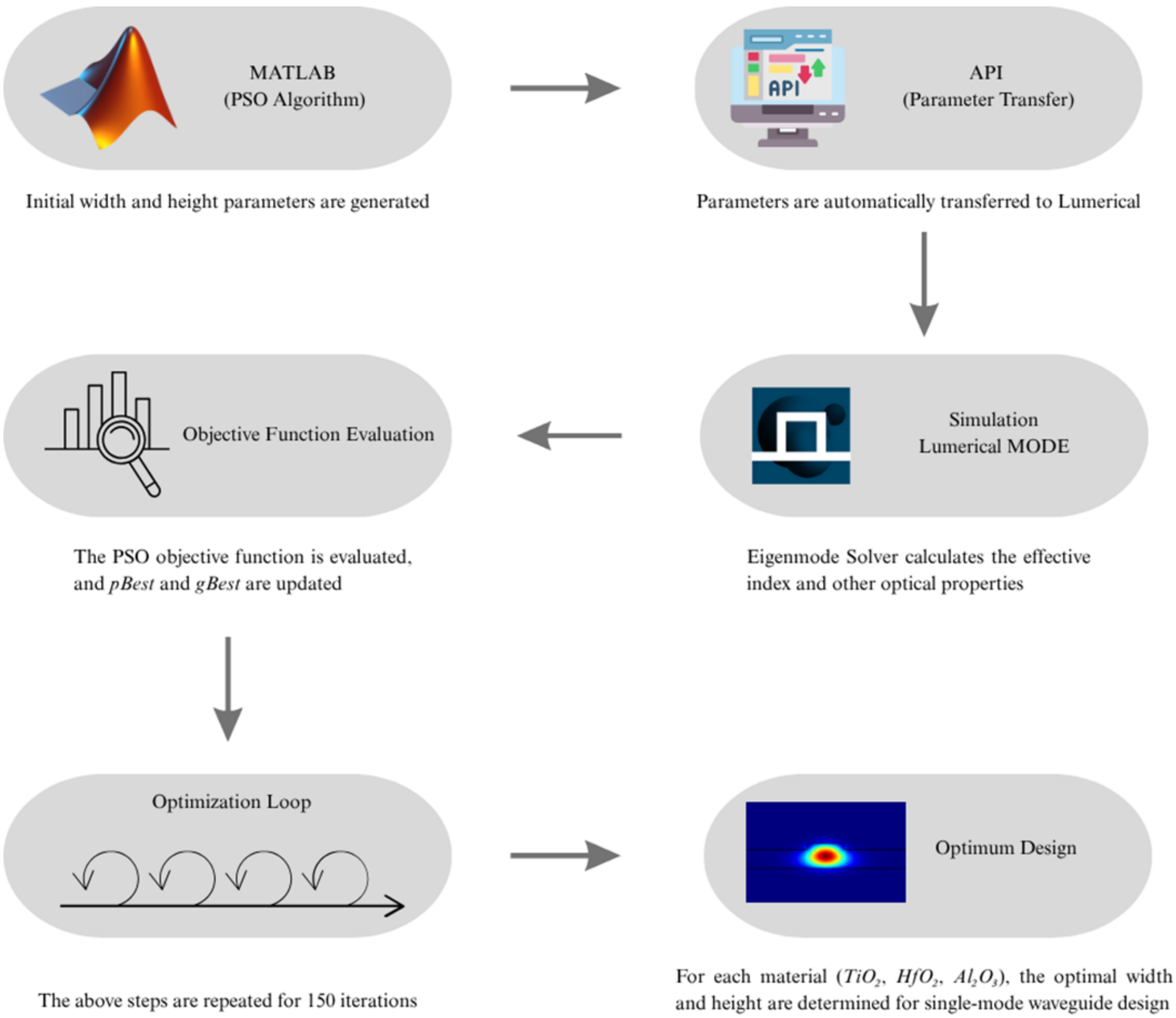


Fig.2. PSO-based waveguide design loop via MATLAB–Lumerical interface

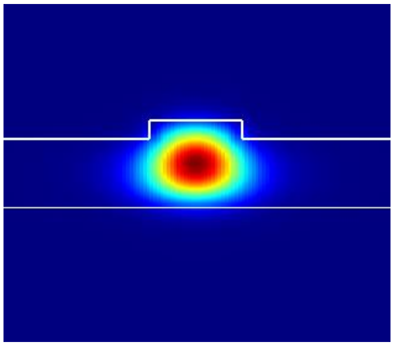
demonstrate that each material offers distinct advantages TiO_2 for compact mode confinement, HfO_2 for balanced guidance, and Al_2O_3 for low-loss broadband transmission allowing optimized designs tailored to specific application requirements.

TABLE II Optimal Design Parameters and Confinement Efficiencies for Single-Mode Rib Structures

Material	Optimal Width	Optimal R	Total Height	Objective Function	Confinement Factor
TiO_2	1.36	0.5489	0.7	-2.2687	94.54%
HfO_2	1.5	0.5668	0.7	-1.7302	84.8%
Al_2O_3	1.5	0.4996	0.7	-1.6081	76.86%

In optical waveguides, the confinement factor is a critical parameter that indicates the fraction of light confined within the waveguide core, directly reflecting the optical guiding efficiency of the structure. A high confinement factor contributes to reduced optical losses and enhanced transmission efficiency. Through our optimization studies, confinement factors of 94.54% for TiO_2, 84.8% for HfO_2, and 76.86% for Al_2O_3 were achieved. These results highlight that TiO_2 provides the strongest mode confinement due to its high refractive index, while HfO_2 demonstrates balanced confinement performance. Although the confinement factor for Al_2O_3 is slightly lower compared to the other materials, its structure remains beneficial for applications requiring low optical loss and broad bandwidth capabilities.

In this study, the modal analysis of the waveguides focused primarily on TE polarization. While both TE and TM modes were evaluated during the analysis, the optimization process resulted in final designs that exclusively support the fundamental TE_0 mode. For the optimized geometries, TM and higher-order modes remain in cutoff. This outcome confirms that the waveguides operate with high modal purity in TE polarization.



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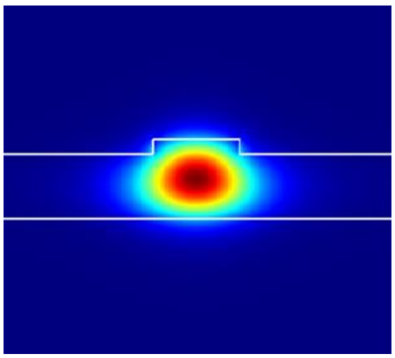

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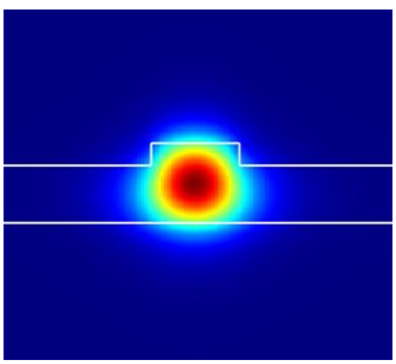

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Fig.3. Electric field distributions of the fundamental mode in rib waveguide structures optimized with the following materials: a) TiO_2, b) HfO_2, and c) Al_2O_3.

The electric field profiles shown in Fig. 3 illustrate how the fundamental mode (TE₀) is confined within the core region of waveguides optimized for each material. In the TiO_2-based structure, the maximum electric field intensity is highly concentrated at the center of the waveguide core, with minimal leakage to the surrounding regions. This result is consistent with TiO_2's high refractive index, providing strong mode confinement and aligning with the observed high confinement factor (94.54%). For the waveguides made of HfO_2 and Al_2O_3, the fundamental mode remains effectively confined within the core; however, the electric field distribution exhibits a smoother transition, extending slightly into the surrounding regions. Particularly for Al_2O_3, the comparatively lower refractive index results in a modestly greater mode leakage beyond the core.

Overall, the electric field profiles obtained for the rib waveguides optimized with these three different materials demonstrate effective confinement of the mode within the core region, thus ensuring single-mode operation. Variations in material properties notably influence mode confinement and field distribution, significantly impacting the determination of optimal design parameters for specific application scenarios.

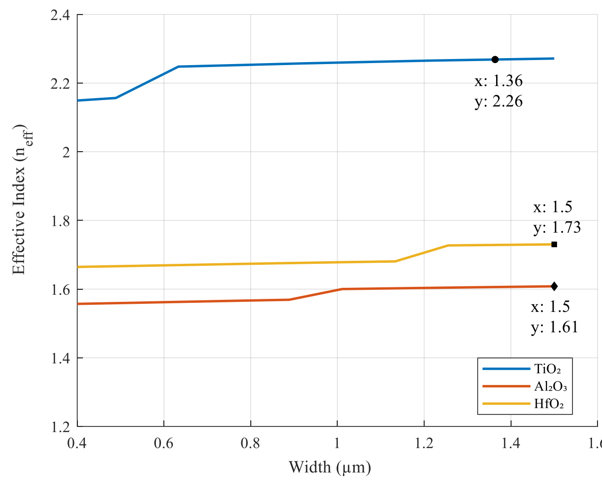

Fig.4. Effective Refractive Index Variation with Width for TiO_2, HfO_2, and Al_2O_3

To investigate the effect of waveguide width on the effective refractive index (n_{eff}), simulations were conducted in which the width parameter was systematically varied over a defined range for three different materials: TiO_2, HfO_2, and Al_2O_3. As shown in Fig. 4, the resulting plots reveal a general trend where n_{eff} increases with increasing width. At narrower widths, the mode confinement within the waveguide core is insufficient, resulting in lower n_{eff} values and greater leakage of the optical field into the surrounding regions. As the width increases, the optical mode becomes more tightly confined within the core, causing a sharp rise in n_{eff}. This trend continues up to a threshold value corresponding to the upper limit of single-mode operation, beyond which the waveguide begins to support higher-order modes, thus violating the single-mode condition. Through PSO-based optimization, the optimal width values were determined for each material, ensuring that only the fundamental mode is supported and that mode confinement is maximized. These optimal points are also marked in Fig. 4 to highlight the transition region. In Figure 4, the blue curve representing the TiO_2 waveguide shows that although effective index values above 1.326 are observed for larger widths, this corresponds to the onset of higher-order mode formation. The objective of this study is to strictly maintain single-mode operation; therefore, the maximum n_{eff} value ensuring the single-mode condition for TiO_2 was set at 1.326. The results indicate that TiO_2 achieves optimal single-mode operation at comparatively smaller widths, while Al_2O_3 and HfO_2 require broader geometries to reach their respective optimal confinement conditions. These findings underscore the critical influence of material refractive index and geometry on the confinement characteristics and allowable single-mode range of the waveguide.

In conclusion, detailed analysis of n_{eff} as a function of width clearly visualized in Fig. 4 along with identification of the single-mode boundary, is essential for achieving both optical efficiency and modal purity in waveguide design. The optimized widths derived from this study ensure maximum mode confinement and robust single-mode performance for each material-geometry combination.

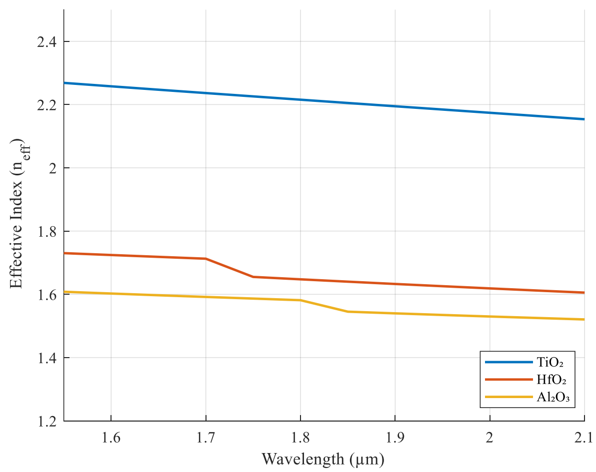

Fig.5. Effective Refractive Index Variation with Wavelength for TiO_2, HfO_2, and Al_2O_3

In the conducted simulations, the wavelength was varied from 1.55 μm to 2.1 μm to analyze the effective refractive index (n_{eff}) behavior of waveguide structures composed of three different materials: TiO_2, HfO_2, and Al_2O_3. For the wavelength sweep simulations, the refractive indices of the materials were not assumed constant; instead, wavelength-dependent refractive index data reported in the literature for each oxide material were used. As illustrated in Fig. 5, the results indicate that n_{eff} gradually decreases with increasing wavelength for all materials. Notably, at a wavelength of 1.55 μm, each material exhibits its highest n_{eff} value, suggesting that the waveguide most effectively supports the fundamental mode and achieves optimal mode confinement at this wavelength. As the wavelength approaches 2.1 μm, a noticeable decline in n_{eff} is observed. These trends are directly linked to the variation in refractive index among the materials; TiO_2, with its high index contrast, maintains effective mode confinement more robustly even at longer wavelengths.

Generally, the reduction in effective refractive index with increasing wavelength corresponds to weaker mode confinement within the waveguide core and increased optical leakage into the cladding or surrounding media. Therefore, achieving the highest possible TiO_2 at the target application wavelength is crucial for optimal waveguide performance. In conclusion, the TiO_2 -based design demonstrates the strongest mode confinement and highest effective refractive index at 1.55 μm, while HfO_2 and Al_2O_3 exhibit more significant performance degradation as the wavelength increases. These findings, as presented in Fig. 5, underscore the importance of material selection and geometric optimization tailored to the operating wavelength in the design of advanced photonic circuits.

IV. Conclusion

This study presents a comparative analysis of oxide-based dielectric materials specifically TiO_2, HfO_2, and Al_2O_3 focused on the design of single-mode rib waveguides. Utilizing a custom-developed API interface between Lumerical MODE and MATLAB, the PSO algorithm was employed to efficiently determine the optimal width and height parameters for each material. The primary objective was to ensure that the waveguide supports only the fundamental mode, thereby enhancing modal purity.

Simulation results reveal that TiO_2, owing to its high refractive index, delivers superior mode confinement and a compact mode profile. HfO_2 exhibits a more balanced modal distribution, whereas Al_2O_3, despite a broader mode profile, offers advantages for broadband and low-loss applications. Across all materials, the effective refractive index (n_{eff}) was observed to decrease gradually with increasing wavelength, reaching peak values at 1.55 μm.

These findings underscore the critical role of material selection and structural optimization in determining the optical performance of waveguides. The comprehensive comparison provided in this work offers a unique and practical perspective for researchers and designers aiming to achieve single-mode operation in integrated photonic circuits. Moreover, the methodology and results presented here are readily adaptable to other material systems or device geometries, making the approach broadly applicable to advanced photonic design efforts.

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BIOGRAPHIES

Huriye Gencal received her B.Sc. degree in Electrical and Electronics Engineering from Manisa Celal Bayar University, Manisa, Turkey, in 2019. She completed her M.Sc. degree in Electrical and Electronics Engineering at Bursa Technical University, Bursa, Turkey, in 2021. She is currently pursuing her Ph.D. degree at the Department of Electrical and Electronics Engineering, Bursa Uludag University, Turkey. Her research interests include photonic integrated circuits and optical waveguide design.

Mustafa Demirtaş received the B.Sc. degree in electrical and electronics engineering and industrial engineering from Dumlupınar University, Kütahya, Turkey in 2009 and 2010, respectively, and the M.Sc. and Ph.D. degrees in electrical and electronics engineering from the Anadolu University, Eskişehir, Turkey, in 2014 and 2019, respectively. From 2012 to 2019, he was a Research Assistant with the Department of EEE at Anadolu University and Eskişehir Technical University. He is an Assistant Professor with the Department of EEE at the Bursa Uludag University. His research interests include atomic layer deposition and related thin film process, novel 2D materials, integrated optics/photonic devices, and on-chip solid-state amplifiers and lasers.

Umut Aydemir received the M.S. and Ph.D. degrees from the Department of Physics, Faculty of Arts and Sciences, Gazi University, Ankara, Turkey, in 2010 and 2015, respectively. He is working as an Assoc. Professor with the Department of Electrical and Electronics Engineering, Uludag University, Turkey. His research areas involve semiconductor material based microelectronic and photonic devices.