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Modal propagation analysis in waveguides for the design of evanescent wave photonic biosensors

Análisis de propagación modal en guías de onda para el diseño de biosensores fotónicos de onda evanescente

MSc. Jesús Álvarez Guerrero[1], Ing. Jhon Jairo Vejar Caballero[2], PhD. Byron Medina Delgado[2], PhD. Jhonattan Córdoba Ramírez[3], PhD. Ferney Orlando Amaya Fernández[4]

[1] **Universidad Libre,** *Faculty of Engineering, Research Group on Competitiveness and Sustainability for Development, Cúcuta, Norte de Santander, Colombia.*
[2] **Universidad Francisco de Paula Santander,** *Faculty of Engineering, Research Group in Technology, Innovation and Society, Cúcuta, Norte de Santander, Colombia.*
[3] **Universidade Federal de Minas Gerais,** *School of Engineering, Research Group on Light Propagation and Photonics, Belo Horizonte, Minas Gerais, Brazil.*
[4] **Universidad Pontificia Bolivariana,** *School of Engineering, Group for Research and Development of Applications in Information and Communication Technologies, Medellín, Antioquia, Colombia.*

Correspondence: *jesus.alvarezg@unilibre.edu.co*

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Abstract: This paper presents a modal propagation analysis of Strip and Rib waveguides with silicon and SU-8 cores, aimed at designing evanescent wave photonic biosensors. The objective was to determine structural configurations that optimize device sensitivity, with a focus on single-mode and bimodal operating conditions. The study was conducted through numerical simulations using the Finite Element Method in COMSOL Multiphysics. Various combinations of materials, core heights of 220 and 600 nm, and operating wavelengths of 633 and 1550 nm were analyzed to evaluate the behavior of TE and TM propagation modes and the variation of the effective refractive index with respect to the waveguide width. The main outcome is a design table summarizing the optimal core width ranges for each configuration, serving as a practical tool for developing highly sensitive and manufacturable biosensors. Additionally, the presented methodology can be applied to the design of integrated photonic circuits in diverse fields such as telecommunications and optical computing.

Keywords: Integrated Photonics, Photonic Biosensors, Photonic Waveguides.

Resumen: En este artículo se presenta un análisis de propagación modal en guías de onda tipo Strip y Rib con núcleo de Silicio y SU-8, orientado al diseño de biosensores fotónicos de onda evanescente. El objetivo fue determinar las configuraciones estructurales que optimicen la sensibilidad de estos dispositivos, considerando las condiciones de operación mono y bimodal. El estudio se llevó a cabo mediante simulaciones numéricas utilizando el método de elementos finitos en el software COMSOL Multiphysics. Se analizaron distintas combinaciones de materiales, alturas del núcleo de 220 y 600 nm y longitudes de onda de 633 y 1550 nm, con el fin de observar el comportamiento de los modos de propagación TE y TM y la variación del índice de refracción efectivo respecto al ancho de la guía mediante las curvas de dispersión. Como principal resultado, se generó una tabla de diseño que resume los rangos óptimos de ancho del núcleo para cada configuración, lo que constituye una herramienta práctica para el desarrollo de biosensores altamente sensibles y fabricables. Además, la metodología presentada puede aplicarse al diseño de circuitos integrados fotónicos en diversas áreas, como telecomunicaciones y computación óptica.

Palabras clave: Biosensores Fotónicos, Fotónica Integrada, Guías de Onda Fotónicas.

1. INTRODUCTION

Currently, humanity is immersed in the fourth industrial revolution, a stage marked by the convergence of emerging technologies including artificial intelligence, the internet of things, data science, cloud computing and high-capacity communications networks. These technologies are rapidly transforming all productive sectors, making it possible to move from traditional environments to interconnected and optimized ecosystems, such as smart cities [1]. This technological scenario requires significant advances in three fundamental axes: data collection, information transport and, the efficient processing of large volumes of data.

In this context, integrated photonics has emerged as a key technological platform, capable of responding to the demands of these new applications, thanks to characteristics such as bandwidths in the order of terahertz (THz), petabit transmission rates per second (Pb/s), and ultra-fast processing using photonic computing [2], [3]. Evanescent wave photonic biosensors have established themselves as one of the most promising applications within this discipline, offering highly sensitive, miniaturizable, multiplexable, and real-time detection solutions, which makes them essential tools for sectors such as health, food safety and environmental monitoring [4].

Among the photonic structures commonly implemented in biosensors are interferometers [5], [6], [7], [8], resonant rings [9], [10], photonic crystals [11], [12], [13] and surface plasmon-based devices [14], [15], [16].

These structures are manufactured to a greater extent on silicon-based technologies and have reached detection limits of the order of 10^{-7} to 10^{-9} refractive index units, allowing the detection of extremely low concentrations, even up to the level of picograms per milliliter (pg/mL) [17].

However, in recent years, the use of polymeric materials such as SU-8 for the design of biosensors has gained interest, due to their advantages in terms of low cost, ease of manufacture and possibility of being used in disposable devices. These materials present significant challenges, such as low refractive index contrast between the core and the coating, which limits sensor sensitivity. Therefore, the challenge in the design of polymeric biosensors is to optimize the dimensions and modal configuration of the waveguides, so that the interaction between the evanescent field and the analyte is maximized [18].

Based on the above, the first step for the implementation of any integrated photonic device is the design of the waveguides, since it determines the conditions of light propagation and, therefore, the sensitivity, selectivity, and performance of the final device. There are several types of planar waveguides, such as Rib, Strip, channel, grooved and diffuse structures, each with optical characteristics that depend on both its geometry and the refractive index contrast between the core and the coating. The choice of the right structure is conditioned by the specific application to be developed, as well as by the technological manufacturing capabilities available. This article discusses Rib and Strip-type waveguides, due to their structural simplicity, high efficiency in optical field confinement and manufacturability in silicon and polymer platforms such as SU-8, especially in biosensing applications.

In order to determine the most suitable dimensions for these waveguides, a modal propagation analysis is performed using the finite element method (FEM) using numerical simulations in COMSOL Multiphysics software. The methodology includes the definition of global parameters, geometries, and materials, as well as the meshing configuration and physical studies, with the aim of observing the energy distribution and propagation modes (TE and TM) in different configurations. Core heights of 220 and 600 nm and operating wavelengths of 633 and 1550 nm are analyzed, which correspond respectively to light sources in the low-cost visible spectrum and to the telecommunications band, and which are consistent with the technological capabilities of the OptMALab collaborating laboratory of the Federal University of Minas Gerais, in Brazil.

As the main result of this work, a design table is constructed that summarizes the core width ranges for which the Rib and Strip waveguides operate in single-mode and bimodal regimes, considering the different materials, heights, and wavelengths. This table represents a high-value tool for the design of photonic biosensors, as it allows the selection of optimal dimensions that maximize the sensitivity of the device, avoid unwanted modes, and facilitate its manufacture. The analysis presented lays the foundation for later stages of advanced polymer biosensor design, including integration with functional materials such as graphene to improve performance in high-precision biomolecular sensing applications.

2. THEORETICAL FRAMEWORK

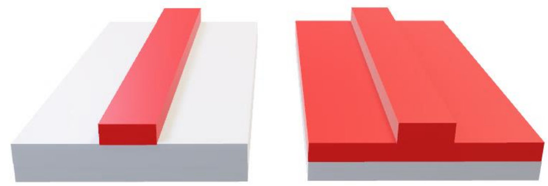
This section presents the fundamental theoretical concepts to understand the operation of evanescent field photonic biosensors, emphasizing their physical structure and the description of the optical phenomenon that allows the detection of an analyte from variations in some of the light propagation parameters within the waveguide.

2.1. Photonic Waveguides

Photonic biosensors are one of the most important applications of integrated photonics, where it seeks to manufacture miniaturized devices of nanometric order within a chip in which it is sought to manipulate light waves to detect an analyte in a chemical sample.

Integrated photonics can manufacture a wide variety of photonic components such as interferometers, resonant rings, photonic crystals, among others; which are used as transducers in the design of biosensors, in which the design of the waveguides is key to achieve the highest possible sensitivity.

Optical waveguides are dielectric structures with circular, rectangular or elliptical cavities or tubes of nanometric dimensions that allow the guidance of light waves, usually in the infrared or visible spectrum. A wide variety of rectangular waveguides are used in integrated photonics; however, this work focuses on propagation analysis in waveguides type Strip and Rib such as those shown in the Fig. 1.



(a) (b)

Fig. 1. *Photonic Waveguides: (a) Strip (b) Rib*
Source: *own elaboration*

2.2. Modal Propagation

The propagation of light through planar waveguides, as well as in the optical fiber itself, is based on the principle of internal total reflection, in which it must be met that the refractive index of the core is greater than the refractive index of the coating and that the angle of incidence at the core-coating interface is greater than the critical angle for the light to remain confined in The Wave Guide.

According to the above, a ray of light with a random angle cannot propagate. The light must hit at certain angles so that it can spread. Therefore, the propagation angle within the waveguides is discretized and each of the permitted values excites the so-called Propagation Modes.

In Fig. 2 it is shown graphically how propagation modes are formed, particularly the fundamental mode (m=0) and the first-order mode (m=1). The solid and dotted lines represent the trajectories of the positive and negative phase fronts, respectively. In Fig. 2 it is shown how energy maxima are formed in the central part of the waveguide and minima at the extremes due to constructive and destructive interference of waves. Similarly, it occurs with the first-order mode, where maxima are formed in the first and third quarters of the waveguide, while minima are formed in the center and ends of the waveguide, resulting in the formation of two energy lobes as illustrated in the Fig. 2b [19].

Additionally, the propagation modes are related to the polarization components of the electromagnetic waves, so that these can be transverse electric (TE) or transverse magnetic (TM) which are mainly characterized by having zero electric field or magnetic field component respectively in the direction of propagation.

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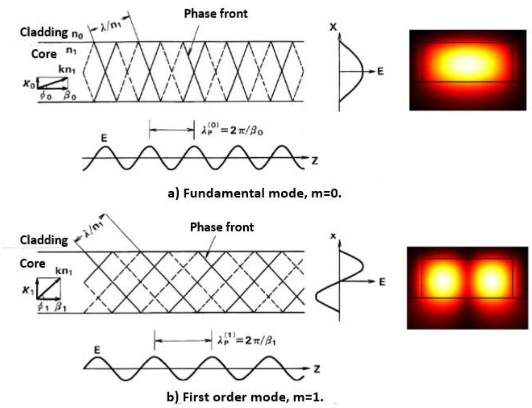
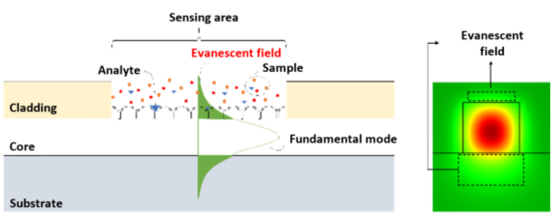


__Fig. 2.__ Formation of Propagation Modes.
(a) Fundamental Mode (b) First Order Mode
***Source:** adapted from [19]*

2.3. Evanescent Wave Biosensors

The evanescent wave refers to a standing wave that is formed at the interface between two different refractive index media such as the case of the core and the coating of a planar waveguide, in which thanks to the principle of total internal reflection, all light is expected to remain confined within the core of the waveguide, however, the light is not fully reflected off the interface, but a small portion of light penetrates the reflective medium. This small penetrated electromagnetic field is what is known as an evanescent wave [20]. This phenomenon is illustrated in Fig. 3.



a) b)

__Fig. 3.__ Evanescent Wave Biosensors:
(a) Principle of Operation (b) Modal Propagation
***Source:** own elaboration*

Fig. 3**Fig. 3**a show the profile of a planar waveguide used as a biosensor. There it is presented that the evanescent field of the fundamental mode penetrates the core-coating and core-substrate interfaces, in the same way, in Fig. 3b the distribution of electromagnetic field within the core of the waveguide is shown and the portions of light that penetrate both the substrate and the coating are evidenced.

In evanescent wave sensors, a bioreceptor layer is located at the core-coating interface that is responsible for capturing the desired analyte. In such a way that when a biosensing event occurs, one or more of the properties of the wave propagating through the waveguide may change due to the interaction of the evanescent field with the analyte. These variations are proportional to the amount of analyte present in the sample [21].

One of the main advantages offered by these biosensors is their high sensitivity, however, compared to other biosensing methods, they offer advantages such as selectivity and specificity, remote sensing, immunity to electromagnetic interference, direct and real-time detection, multiplexing capability, biocompatibility, label-free detection scheme, miniaturization capability, and ease of integration into more complex platforms. All these advantages have allowed the market for optical biosensors to grow in recent years for various applications such as environmental monitoring, food safety, drug development, biomedical research, health care and clinical analysis [7].

3. METHODOLOGICAL ASPECTS

The evanescent wave principle is used in different types of photonic transducers for the design of highly sensitive biosensors. Among the most commonly used structures are resonant rings, SPRs, photonic crystals, and interferometers such as the Mach Zehnder Interferometer (MZI) shown in Fig. 4.

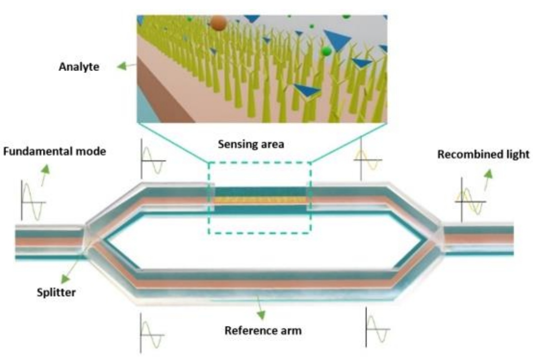


__Fig. 4.__ Evanescent Wave Biosensor using MZI transducer
***Source:** own elaboration*

The first step in the implementation of any photonic transducer is the design and analysis of the waveguide modal propagation, in order to determine the appropriate dimensions to operate in a region where abrupt changes in the effective refractive index occur for small variations in the refractive index of the sensing area thus, guaranteeing high sensitivity in biosensing devices.

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To carry out the analysis described above, there are currently software tools that allow numerical and propagation analysis in a way that is very close to reality. In this work, the Comsol Multiphysics program is specifically used, which is based on the FEM method. Therefore, the methodology used for the analysis and design of the waveguides is based on the steps suggested by the FEM method: definition of global parameters, definition of geometry, definition of materials, definition of meshing, definition of physics, definition of the type of study and finally the modal propagation analysis as illustrated in Fig. 5.

The images presented in Fig. 5 show the definition of the geometry, meshing, and propagation of the first three propagation modes of a waveguide Strip. The simulation was configured with the parameters contained in the Table 1.

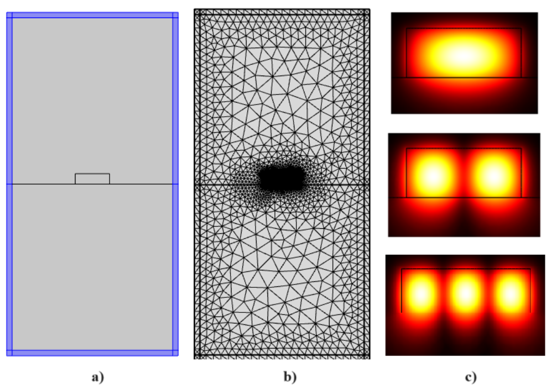

Fig. 5. *FEM method for waveguide analysis:*
(a) Geometry (b) Meshing (c) Modal Propagation
Source: *own elaboration*

The modal analysis technique allows to observe the energy distribution of the different propagation modes in the waveguide core as shown in Fig. 5 and to obtain the dispersion curves of the modes in which the variation of the effective index of the different propagation modes is shown, both TE and TM, with respect to the variation of the waveguide width. These are very important as they allow you to define the dimensions of the waveguides to obtain high levels of sensitivity.

Table 1: *Strip Waveguide Simulation Parameters*

Name	Expression	Description
λ	633[nm]; 1550[nm]	Wavelength (λ)
f	c/λ	Frequency; (f) c: speed of light in a vacuum
$\mathbf{w_g}$	10[um]	Contour width
$\mathbf{h_g}$	20[um]	Contour height
$\mathbf{w_{st}}$	700[nm]	Core Width
$\mathbf{h_{st}}$	600[nm]	Core Height
$\mathbf{n_{cl}}$	1	Refractive index of the coating
$\mathbf{n_{co}}$	1.57 for SU-8	Core refractive index
$\mathbf{n_s}$	1.444	Substrate refractive index
PML	Lamb/2	The perfectly fitted cape

Source: *own elaboration*

In this work, the analysis focuses mainly on two types of waveguides: Strip and Rib, since they are two of the most common and simplest structures in the manufacturing process. Similarly, two operating wavelengths are selected: 1550 nm, which is the wavelength of telecommunications in the near infrared, and 633 nm, which is a light source in the visible spectrum and therefore of low cost. Finally, two possible thicknesses are selected for the waveguides: 220 and 600 nm, according to the information provided on the manufacturing capabilities of the OptMALab laboratory of the Federal University of Minas Gerais, with whom we work in collaboration. In Table 2 the main parameters considered in the simulation campaign are summarized.

Table 2: *Parameters considered in the simulation campaign of modal dispersion curves*

Waveguide Type	Material	Thickness (nm)	Operating Wavelength (nm)
Strip and Rib	Silicon	600	633
			1550
		220	633
			1550
	SU-8	600	633
			1550
		220	633
			1550

Source: *own elaboration*

Finally, Silicon and SU-8 polymer are selected as the core material of the waveguides that correspond to the main manufacturing material of photonic integrated circuits and an alternative to generate low-cost and single-use integrated respectively.

4. RESULTS

The main purpose of the results is to establish a set of design dimensions for photonic waveguides oriented to the design of evanescent wave biosensors. Numerical simulations are presented using the FEM method in Comsol Multiphysics. The analysis focuses on two types of waveguides: Strip and Rib, using Silicon and SU-8 as core materials, with operating wavelengths of 633 nm and 1550 nm,

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and two core heights: 220 nm and 600 nm, as described in the previous section.

Initially, the dispersion curves for both Silicon and SU-8 Strip waveguides are presented as core materials, with a height of 600 nm and a wavelength of 633 nm. This with the aim of determining the mono and bimodal operating ranges of the waveguides and the range of variation of the effective refractive index. For example, Fig. 6 shows the modal behavior of the Silicon waveguide in which a clearly multimodal operation is evidenced.

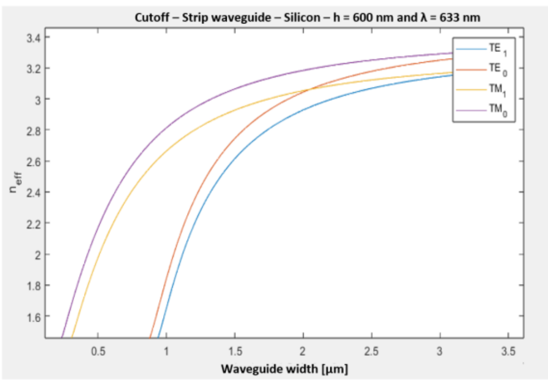

Fig. 6. *Dispersion curves of the Strip waveguide with Silicon core*
Source: *own elaboration*

Fig. 6 shows the variation of the effective refractive index n_{eff} for the fundamental and first-order modes (TE_0, TE_1, TM_0 y TM_1) propagating in the waveguide. It is observed that the Transverse Magnetic modes (TM_0 y TM_1) appear first for guide widths close to 250–300 nm, while the Transverse Electrical modes (TE_0 y TE_1) begin to propagate above 800 to 900 nm. This indicates that, with Silicon, it is possible to design single-mode or bimodal guides in a relatively narrow range of widths (0.25 to 0.9 μm), which is ideal for biosensing with high sensitivity, by keeping the number of excitable modes under control.

Another relevant aspect is to select the most appropriate width for the waveguide, which in the case of evanescent wave biosensors must correspond to the section of the modal curve with the greatest variation in n_{eff} in order to obtain the greatest possible sensitivity when the interaction of the analyte with the evanescent field occurs. Thus, in the case of the Silicon waveguide analyzed, an adequate waveguide width is between 500 and 600 nm if working with any of the TM modes or between 1.1 or 1.2 μm for the TE modes. This waveguide has the particularity that both for the fundamental and first-order TM and TE modes appear almost simultaneously in each case. Ideally, you should select the mode with the steepest curve as it would have the highest sensitivity.

On the other hand, Fig. 7 shows the same type of guide, but with a SU-8 polymer core. Unlike the Silicon waveguide, both magnetic and electric fundamental modes (TM_0 y TE_0) appear almost simultaneously around 500 nm. Subsequently, first-order modes appear near 1.2 μm.

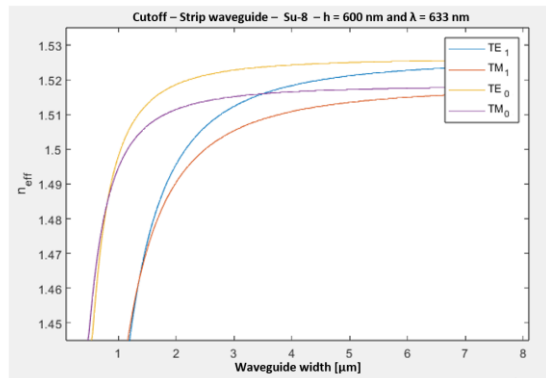

Fig. 7. *Dispersion Curves of the Strip Waveguide with SU-8 Core*
Source: *own elaboration*

By comparing the curves of Silicon in Fig. 6 and those of SU-8 in Fig. 7, the great difference in the levels of variation of n_{eff} can be identified. While the Silicon waveguide goes from 1.6 to 2.6 refractive index units in the high sensitivity zone, the SU-8 waveguide barely goes from 1.45 to 1.5 refractive index units. This behavior allows us to evidence the reason for the low sensitivity of the biosensors designed in the polymer platform compared to those of Silicon.

Despite this disadvantage of polymeric biosensors, several strategies have been proposed to compensate for the low contrast of the refractive index of the material, such as the use of hybrid structures with 2D materials. For example, in [18] a polymeric biosensor with a double graphene monolayer is described that significantly improves the sensitivity of the device. In this line, although in this section the dispersion curves obtained for type guides are explicitly presented Strip with a Silicon and SU-8 core, the same modal analysis procedure is applied for all combinations of material, core height, and wavelength considered in this study, including type guides Rib. The consolidated results are presented in Table 3, which summarizes the core width ranges for which the guides operate in single-mode or bimodal mode according to the defined structural and optical parameters. This table is the main technical result of the work, as it guides the dimensional design of photonic biosensors with criteria of sensitivity, efficiency, and manufacturing feasibility.

Table 3: *Strip waveguide dimensions for single-mode and bimode operation*

Wave guide	Material	h (nm)	λ (nm)	Single-mode range	Bimodal Range
Strip and Rib	Silicon	600	633	$0.25 \leq w \leq 0.3$	$0.3 \leq w \leq 0.8$
			1550	$0.1 \leq w \leq 0.3$	$0.3 \leq w \leq 0.55$
		220	633	$0.2 \leq w \leq 0.4$	$0.4 \leq w \leq 0.6$
			1550	$0.3 \leq w \leq 0.6$	$0.6 \leq w \leq 0.9$
	SU-8	600	633	$0.5 \leq w \leq 1.2$	$1.2 \leq w \leq 2$
			1550	$3 \leq w \leq 6$	$6 \leq w \leq 10$
		220	633	$1.8 \leq w \leq 3.8$	$3.8 \leq w \leq 5.8$
			1550	> 10	> 10

Source: *own elaboration*

The results presented at the Table 3, in addition to establishing the mono and bimodal operating ranges, allow a qualitative comparison between the Silicon and polymer platforms, evidencing that, although Silicon presents a higher refractive index contrast and therefore better confinement conditions and sensitivity, SU-8-based devices offer relevant advantages in terms of low cost and ease of manufacture. making them attractive for single-use applications or resource-constrained environments. The generated design table thus becomes a versatile tool to guide both optical design and manufacturing decisions, allowing the selection of the most appropriate type of guide, width and material according to the specific requirements of the biosensor. This analysis provides a solid foundation for later phases of development, such as the incorporation of advanced materials and the integration of multiple functions within a single photonic biosensing chip.

5. CONCLUSIONS

This paper presents an analysis of modal propagation in Strip and Rib waveguides made of Silicon and SU-8, with the purpose of establishing design criteria for evanescent wave photonic biosensors. The methodology focuses on numerical simulations based on the FEM method with which different combinations of materials, core thicknesses and operating wavelengths are evaluated, in order to determine the ranges of dimensions that allow operation in single-mode and bimodal regimes.

The results obtained show that waveguides made of Silicon have a greater variation of the effective refractive index and, therefore, a greater sensitivity, while SU-8 structures, although limited by their low refractive index contrast, offer advantages in terms of low cost and ease of manufacture.

Likewise, it is highlighted that the methodological process implemented for the analysis of waveguides, based on the structured application of the FEM method, constitutes a fundamental basis for the design of photonic integrated circuits. This approach is not only applicable to the development of biosensors, but is essential in the design of photonic components for telecommunications systems, photonic computing, and optical signal processing, where precise control of propagation modes is decisive for the functional performance of the devices.

Finally, the design data shown in the Table 3 It summarizes the optimal core widths for each configuration and represents a key tool for engineers and researchers interested in the development of miniaturized biosensors with high sensitivity and manufacturability. This study constitutes a solid basis for later stages of development, such as the integration of advanced materials such as gold or graphene, or the implementation of hybrid structures that enhance the sensitivity of polymeric devices. Similarly, its applicability in low-cost photonic platforms is projected, with potential use in clinical, biomedical, or environmental environments where single-use or easily scalable solutions are required.

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REFERENCES

[1] J. S. Gracias, G. S. Parnell, E. Specking, E. A. Pohl, and R. Buchanan, “Smart Cities—A Structured Literature Review,” *Smart Cities 2023, Vol. 6, Pages 1719-1743*, vol. 6, no. 4,

pp. 1719–1743, Jul. 2023, doi: 10.3390/SMARTCITIES6040080.

[2] N. L. Kazanskiy, M. A. Butt, and S. N. Khonina, “Optical Computing: Status and Perspectives,” *Nanomaterials 2022, Vol. 12, Page 2171*, vol. 12, no. 13, p. 2171, Jun. 2022, doi: 10.3390/NANO12132171.

[3] G. Rademacher *et al.*, “Peta-bit-per-second optical communications system using a standard cladding diameter 15-mode fiber,” *Nature Communications 2021 12:1*, vol. 12, no. 1, pp. 1–7, Jul. 2021, doi: 10.1038/s41467-021-24409-w.

[4] J. Wang *et al.*, “Sensitivity enhancement of bimodal waveguide interferometric sensor based on regional mode engineering,” *Optics Express, Vol. 32, Issue 6, pp. 10274-10283*, vol. 32, no. 6, pp. 10274–10283, Mar. 2024, doi: 10.1364/OE.519015.

[5] S. Prasanna Kumaar and A. Sivasubramanian, “Design of a high-sensitivity polymer double-slot waveguide sensor for point-of-care biomedical applications,” *Sensors International*, vol. 5, p. 100255, Jan. 2024, doi: 10.1016/J.SINTL.2023.100255.

[6] J. C. Ramirez, L. M. Lechuga, L. H. Gabrielli, and H. E. Hernandez-Figueroa, “Study of a low-cost trimodal polymer waveguide for interferometric optical biosensors,” *Opt Express*, vol. 23, no. 9, p. 11985, May 2015, doi: 10.1364/oe.23.011985.

[7] H. Wang *et al.*, “Optofluidic chip with directly printed polymer optical waveguide Mach-Zehnder interferometer sensors for label-free biodetection,” *Biomedical Optics Express, Vol. 15, Issue 5, pp. 3240-3250*, vol. 15, no. 5, pp. 3240–3250, May 2024, doi: 10.1364/BOE.523055.

[8] C. Zhao, L. Xu, and L. Liu, “Ultrahigh Sensitivity Mach−Zehnder Interferometer Sensor Based on a Weak One-Dimensional Field Confinement Silica Waveguide,” *Sensors (Basel)*, vol. 21, no. 19, Oct. 2021, doi: 10.3390/S21196600.

[9] N. L. Kazanskiy, S. N. Khonina, and M. A. Butt, “A Review of Photonic Sensors Based on Ring Resonator Structures: Three Widely Used Platforms and Implications of Sensing Applications,” *Micromachines 2023, Vol. 14, Page 1080*, vol. 14, no. 5, p. 1080, May 2023, doi: 10.3390/MI14051080.

[10] K. M. Yoo *et al.*, “Lab-on-a-chip optical biosensor platform: a micro-ring resonator integrated with a near-infrared Fourier transform spectrometer,” *Optics Letters, Vol. 48, Issue 20, pp. 5371-5374*, vol. 48, no. 20, pp. 5371–5374, Oct. 2023, doi: 10.1364/OL.492172.

[11] A. G. Kumela *et al.*, “A review on hybridization of plasmonic and photonic crystal biosensors for effective cancer cell diagnosis,” *Nanoscale Adv*, vol. 5, no. 23, pp. 6382–6399, Nov. 2023, doi: 10.1039/D3NA00541K.

[12] F. Parandin, Z. Rahimi, A. Moloudi, F. Heidari, and M. Mehdi Parandin, “A comprehensive review of blood component detection utilizing One-Dimensional, Two-Dimensional, and photonic crystal fiber biosensors,” *Results in Optics*, vol. 16, p. 100671, Jul. 2024, doi: 10.1016/J.RIO.2024.100671.

[13] E. Rafiee, “Photonic Crystal based Biosensor for Diagnosis of Kidney Failure and Diabetes,” *Plasmonics*, vol. 19, no. 1, pp. 439–445, Feb. 2024, doi: 10.1007/S11468-023-02014-5/METRICS.

[14] S. Bhaskar, “Biosensing Technologies: A Focus Review on Recent Advancements in Surface Plasmon Coupled Emission,” *Micromachines 2023, Vol. 14, Page 574*, vol. 14, no. 3, p. 574, Feb. 2023, doi: 10.3390/MI14030574.

[15] N. Ravindran *et al.*, “Recent advances in Surface Plasmon Resonance (SPR) biosensors for food analysis: a review,” *Crit Rev Food Sci Nutr*, vol. 63, no. 8, pp. 1055–1077, 2023, doi: 10.1080/10408398.2021.1958745.

[16] A. K. Singh, M. Anwar, R. Pradhan, M. S. Ashar, N. Rai, and S. Dey, “Surface plasmon resonance based-optical biosensor: Emerging diagnostic tool for early detection of diseases,” *J Biophotonics*, vol. 16, no. 7, p. e202200380, Jul. 2023, doi: 10.1002/JBIO.202200380.

[17] M. C. Estevez, M. Alvarez, and L. M. Lechuga, “Integrated optical devices for lab-on-a-chip biosensing applications,” *Laser Photon Rev*, vol. 6, no. 4, pp. 463–487, Jul. 2012, doi: 10.1002/LPOR.201100025.

[18] A. V. R. Portes *et al.*, “Electro-optical biosensor based on embedded double-monolayer of graphene capacitor in polymer technology,” *Polymers (Basel)*, vol. 13, no. 20, Oct. 2021, doi: 10.3390/polym13203564.

[19] K. Okamoto, *Fundamentals of Optical Waveguides*, Segunda Edición. 2006.

[20] P. Patel, Dr. V. Mishra, and A. Mandloi, "Optical Biosensors: Fundamentals & Trends," 2010.

[21] A. F. Gavela, D. G. García, J. C. Ramirez, and L. M. Lechuga, "Last advances in silicon-based optical biosensors," Feb. 24, 2016, *MDPI AG*. doi: 10.3390/s16030285.