

Methodology Article

Comparative Analysis of Single-Core and Double-Core Optical Fibers

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Abstract

This work presents a detailed comparative study of single-core and concentric double-core optical fibers, highlighting their potential advantages for telecommunication applications. Using theoretical and numerical analysis, we examine key parameters including numerical aperture, acceptance angle, V-number, mode capacity, guided power fraction, and radial profiles of the fundamental mode. The double-core fiber exhibits a higher numerical aperture of 0.095 and an acceptance angle of 27.1° , compared to 0.078 and 19.6° for the single-core fiber, enabling more efficient light capture. The normalized frequency parameter (V-number) increases from 6.37 in the single-core fiber to 10.4 in the double-core design, resulting in a total of 54 guided modes versus 20 in the single-core fiber. Radial analysis shows that the fundamental mode is primarily confined within the inner core, with partial extension into the outer core. This distribution facilitates controlled modal coupling and flexible power management, which can be beneficial for multimode transmission or high-power applications. Although the guided power fraction remains 100% in both fiber types, the dual-core structure significantly reduces mode leakage and enhances confinement efficiency, highlighting its potential for robust signal transmission. The comparative results suggest that concentric double-core fibers provide a practical approach to increasing mode diversity and improving light confinement without introducing excessive complexity in fiber fabrication. The dual-core design also aligns with the requirements of advanced telecommunication strategies such as space-division multiplexing, where efficient distribution of multiple spatial channels is essential. Moreover, the dual-core architecture serves as a foundation for further optimization, including tailored core spacing, refractive index engineering, and controlled inter-core coupling, to maximize transmission capacity and signal stability. Overall, the findings demonstrate that double-core fibers offer clear advantages in terms of mode management, power confinement, and flexibility for high-capacity optical systems. These results provide valuable insights for future experimental studies and the development of next-generation multimode and high-performance fiber designs.

Keywords

Optical Fiber, Single-core Fiber, Double-core Fiber, Mode Confinement, V-number, Guided Power, Radial Profile

1. Introduction

The Optical fiber is a type of cable used to transmit information at high speed over long distances. Unlike traditional

copper cables, which use electrical signals, fiber optics use light to transmit data. Thanks to its ability to carry large

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amounts of data and its resistance to disturbances, it is widely used in telecommunications networks and plays an essential role in our modern connectivity.

While single-core fibers are well-studied, a two-core fiber could offer potential advantages such as better power management, improved mode confinement, and reduced interference. [1, 2] In this work, we study a concentric dual-core fiber and compare it to a conventional single-core fiber using theoretical and numerical modeling. [3, 4]

2. Mathematical Modeling of the Fiber

The initial idea regarding the use of optical fibers in telecommunications is to take advantage of the phenomenon of total internal reflection to confine light within a glass fiber with a very good transmission coefficient and thus transmit information over long distances. [5]

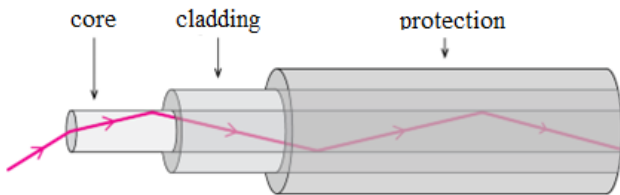


Figure 1. Propagation of beams in an optical fiber.

2.1. Refractive Index Profile

The refractive index profile describes the variation of the refractive index n of an optical medium as a function of position. [5]

For a single-core fiber:

$$n(r) = \begin{cases} n_{core}, & r \leq a \\ n_{cladding}, & r > a \end{cases} \quad (1)$$

n_{core} : refractive index of core

$n_{cladding}$: refractive index of cladding

2.2. Numerical Aperture and Acceptance Angle

The Numerical Aperture (NA) is the maximum angle at which a light ray can enter an optical fiber (or a waveguide) and still be guided by total internal reflection. [6, 7]

The numerical aperture (NA) is defined by the following formula:

$$NA = \sqrt{n_{core}^2 - n_{cladding}^2} \quad (2)$$

$$\theta_{max} = \arcsin(NA) \quad (3)$$

NA: numerical aperture (NA)

2.3. Normalized Parameter V and Mode Number

The normalized frequency parameter V is:

$$V = \frac{2\pi a}{\lambda} \cdot NA \quad (4)$$

V : Normalized frequency parameter

a : Core radius of the optical fiber

λ : Wavelength of the light in free space

NA: Numerical aperture of the fiber

And the approximate number of guided modes for a circular fiber is:

$$M \approx \frac{V^2}{2} \quad (5)$$

M : Approximate number of guided modes in a circular optical fiber

V : Normalized frequency parameter (V -number)

2.4. Guided Power Fraction

The guided power fraction is calculated as the ratio of the power confined within the core (s):

$$\text{Guided power fraction} = \frac{N_g}{N} \times 100\% \quad (6)$$

N_g : Number of rays (or power) guided in the core

N : Total number of rays (or total power) launched into the fiber

3. Materials and Methods

Designing a dual-core fiber requires selecting materials with a controlled difference in refractive index between the core and cladding regions. To achieve this, we will implement the presence of two cores in the mathematical modeling of the fiber and then simulate the results in MATLAB. [8]

3.1 Refractive Index Profile of the Dual-Core Fiber

By implementing the presence of two cores in the refractive index profile, we obtain the dual-core fiber:

For a concentric dual-core fiber:

$$n(r) = \begin{cases} n_{1a} & 0 \leq r \leq r_0 \text{ (Inner core)} \\ n_{1b} & r_0 \leq r \leq r_1 \text{ (outer core)} \\ n_2 & r_0 \leq r \leq r_1 \text{ (cladding)} \end{cases} \quad (7)$$

According to this modeling, we will thus have two cores represented by n_{1a} and n_{1b} .

3.2. Numerical Aperture and Acceptance Angle of the Dual-Core Fiber

In the case of the numerical aperture:

$$NA = \sqrt{n_{1a}^2 - n_2^2} \quad (8)$$

$$NA_{outer} = \sqrt{n_{1b}^2 - n_2^2} \quad (9)$$

NA : aperture of the inner core

NA_{outer} : Numerical aperture of the outer core

n_{1a} : Refractive index of the inner core

n_{1b} : Refractive index of the outer core

n_2 : Refractive index of the cladding

The dual-core fiber exhibits a slightly higher numerical aperture (inner core) and a wider acceptance angle, allowing more rays to be guided.

3.3. Normalized Parameter V and Mode Calculation for the Dual-Core Fiber

For the dual-core fiber, the total number of modes is estimated by:[7]

$$M_{total} \approx \frac{V_{inner}^2}{2} + \frac{V_{outer}^2}{2} \quad (10)$$

M_{total} : Total number of modes

V_{inner} and V_{outer} : are the normalized frequencies (V-numbers) of the inner and outer cores, respectively.

The V-number and the number of guided modes is higher in the dual-core fiber due to the contribution of both cores. At the outer core, additional modes are supported, improving the overall light confinement.

3.4. Guided Power Fraction

The guided fraction for the case of our double-core fiber is defined as: N is the total number of rays, and N_g is the number of rays satisfying the guiding condition.

$$\text{Guided power fraction} = \frac{N_g}{N} \quad (11)$$

The guiding condition is satisfied when the free-space wavenumber, $n(r)$ is the refractive index profile of the fiber, and β is the propagation constant of the mode.

$$k_0^2 n^2(r) - \beta^2 > 0 \quad (12)$$

k_0 : free-space wavenumber.

$n(r)$: refractive index profile

β : propagation constant

According to this modeling, the double-core fiber guides a higher fraction of the input power. The power distribution is concentrated in the inner core, but the outer core also carries a significant amount of power.

3.5. Simulation Method

The numerical simulations were performed using MATLAB. The parameters used are:

Table 1. Simulation Parameters of the Double-Core Optical Fiber.

Parameter	Single-Core	Double-Core
Core index	1.48	1.485 / 1.460
Cladding index	1.45	1.44
Core radius	4 μm	4 μm / 8 μm
Wavelength	1.55 μm	1.55 μm

The objective is to trace 50 rays randomly initialized within the acceptance angle for each fiber. This allows for a comparison between the current single-core fiber and our double-core fiber prototype.[8]

4. Results

In this study, we compare the key characteristics of single-core and double-core optical fibers in terms of acceptance angle, number of modes, guided power, and radial profile. The objective is to assess how the fiber structure influences its guiding properties.

Table 2. result of parameter in simple and dual core fiber.

Parameter	Simple core fiber	dual-core fiber
Acceptance angle [°]	19.6	27.1
Guided power [%]	100	100
V-number	6.37	10.4
Number of modes	20	54

The following result represents the comparison of the radial profile of our dual-core fiber with that of the single-core fiber.

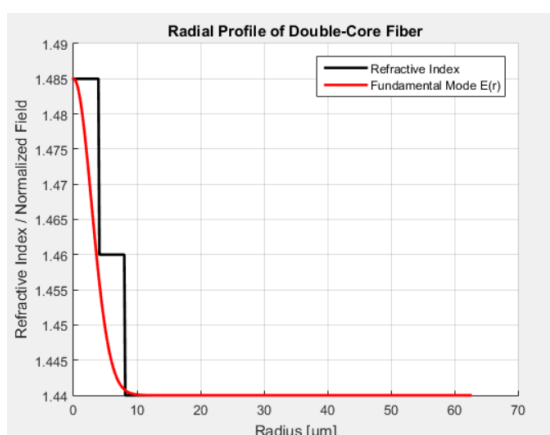


Figure 2. Comparison of the radial profile of a dual-core fiber.

The figure 3 illustrates the comparison between the radial profile of a dual-core fiber and that of a single-core fiber.

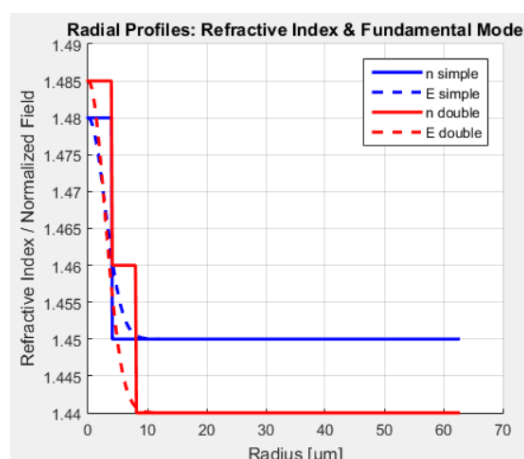


Figure 3. Comparatif du profil radial des fibres à simple cœur et à double cœur.

The last figure shows the comparison of the parameters of our dual-core fiber with those of the single-core fiber.

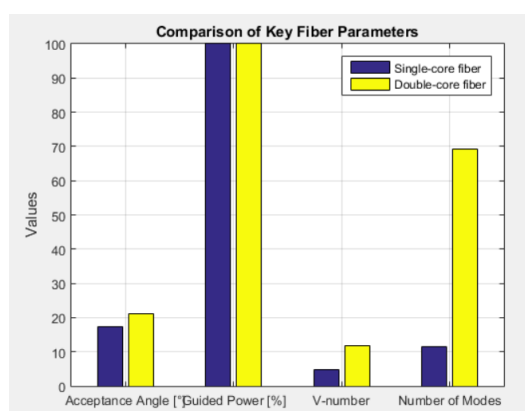


Figure 4. Comparison of the main parameters between the two modeling approaches.

5. Discussion

5.1. Radial Profiles and Fundamental Mode

The radial profiles of the refractive index $n(r)$ and the normalized electric field $E(r)$ reveal clear differences between single core and double core fibers. In the single core fiber, the core shows a uniform refractive index, and the fundamental mode is tightly confined along the fiber axis, guiding essentially a single mode [3, 11]. In the double-core fiber, the refractive index shows two distinct steps, corresponding to the inner and outer cores [4]. The fundamental mode is mainly confined in the inner core but partially extends toward the outer core, allowing controlled mode spreading and potential inter-core coupling [6, 7].

5.2. Guiding Properties and Modal Analysis

The double-core fiber has a higher numerical aperture and a wider acceptance angle, which improves light confinement [3]. The total number of supported modes increases from 20 in the single-core fiber to 54 in the double-core fiber, showing enhanced modal diversity [4]. This increase aligns with the behavior predicted for multilayer optical waveguides, where additional cores raise the V-number and support more modes [6, 7].

5.3. Light Confinement and Performance Implications

The dual-core design allows more efficient power distribution, reducing leakage and enhancing confinement efficiency [3, 10]. Compared to single-core fibers, this architecture provides a practical balance between ease of fabrication and optical performance [4]. Better confinement is particularly advantageous for high-power or nonlinear fiber systems, where light leakage can significantly impact efficiency [12]. Similar studies on dual-core and multilayered fibers confirm that such structures improve mode control and guided power [13].

5.4. Applications in Optical Communication

These findings are relevant for advanced optical communication strategies, such as space-division multiplexing (SDM), which rely on multiple spatial channels to increase transmission capacity [14]. Concentric dual-core fibers provide effective power distribution and reduced intermodal interference, offering a simpler alternative to complex SDM fibers while achieving comparable performance [15].

5.5 Validation and Future Work

The trends observed in guided power and mode distribution are consistent with theoretical predictions and prior

studies, confirming the advantages of dual-core fibers in mode management and overall performance [8, 9]. These results lay the groundwork for experimental validation and development of high-capacity multimode fiber systems [12, 13]. Future research could focus on optimizing core spacing, tailoring refractive index profiles, and exploring inter-core coupling effects to further enhance transmission efficiency, signal stability, and potential sensing applications [14, 15].

6. Conclusion

The comparative study of single-core and concentric double-core optical fibers demonstrates the clear advantages of the dual-core structure in terms of light guidance, mode capacity, and power distribution. The double-core fiber exhibits a higher numerical aperture and acceptance angle, which enhances light capture and reduces mode leakage. The V-number and total number of guided modes are significantly higher in the dual-core fiber, increasing from 20 to 54 modes, thereby providing greater modal diversity and supporting more complex signal transmission schemes.

Radial analysis of the refractive index and fundamental mode reveals that most light is confined within the inner core, while the outer core facilitates controlled modal coupling. This feature allows for improved confinement efficiency and more flexible power management, which can be particularly advantageous for high-power or multimode applications. The dual-core design thus represents a balance between fabrication simplicity and enhanced optical performance, offering an intermediate solution between conventional single-core fibers and more complex microstructured or photonic crystal fibers.

These findings have important implications for modern telecommunication strategies, including space-division multiplexing, where efficient management of multiple spatial channels is essential. The dual-core architecture can improve signal stability, reduce intermodal interference, and optimize power distribution across the fiber. Furthermore, the results provide a foundation for future research on experimental validation, optimization of core spacing, refractive index engineering, and coupling effects to further enhance fiber performance.

Concentric double-core fibers offer significant improvements over single-core designs in terms of mode confinement, guided power distribution, and modal capacity. Their structural versatility and enhanced performance make them a promising candidate for next-generation high-capacity optical communication systems and multimode fiber applications.

Abbreviations

n	Refractive Index
NA	Numerical Aperture

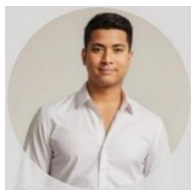
Conflicts of Interest

The authors declare that they have no financial or personal relationships that could inappropriately influence the work reported in this study. No funding or support from commercial or external organizations was received, and the research was conducted independently. The authors confirm that there are no competing interests related to the methods, results, or conclusions presented in this manuscript.

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Biography



Randriana Heritiana Nambinina Erica is a lecturer and researcher at the University of Antananarivo and a faculty member at the École Supérieure Polytechnique d'Antananarivo. He is also a doctoral candidate within the EDSTII doctoral school, specializing in telecommunications. His

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Research Field

Randriana Heritiana Nambinina Erica: Telecommunication, transmission, optical fiber, optical communication, Signal Processing

Andriamanalina Ando: Telecommunications, Control Systems, Signal Processing