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Methodology Article

Design and Numerical Modeling of a Concentric Dual-Core Optical Fiber with Hybrid Single-Mode and Multimode Propagation

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Abstract

This study presents a numerical investigation of an original dual-core optical fiber designed to simultaneously support single-mode propagation in one core and multimode propagation in the other. The proposed structure consists of two closely spaced guiding cores embedded within a common silica cladding. The geometrical dimensions and refractive-index parameters of the two cores are independently adjusted to establish distinct modal regimes within the same fiber. The main objective is to demonstrate the feasibility of this configuration and to analyze the influence of the main structural parameters on modal behavior, optical confinement, guided power distribution, and coupling between the two cores. The numerical analysis considers the core diameters, refractive-index contrasts, operating wavelength, and inter-core separation as the principal parameters governing light propagation. The normalized frequency of each core is evaluated to determine its propagation regime and the number of supported modes. Numerical simulations are then performed to characterize the guided modes, electromagnetic field distributions, guided power fractions, and inter-core power transfer. Particular attention is given to the spatial distribution of the optical field and to the interaction between the two guiding regions. The obtained results demonstrate that the proposed dual-core configuration can successfully maintain fundamental single-mode propagation in one core while simultaneously supporting several guided modes in the second core. The simulations also show that the modal characteristics and power distribution are strongly influenced by the dimensions of the cores, the refractive-index differences, and the distance separating the two cores. Variations in these parameters modify the confinement of the electromagnetic field and consequently affect the optical interaction and power exchange between the guiding regions. Appropriate selection of the geometrical and optical parameters therefore provides an effective means of controlling the propagation characteristics of the proposed fiber. These results confirm the numerical feasibility of integrating single-mode and multimode propagation within a single dual-core optical fiber. The proposed structure provides additional flexibility for controlling guided modes, optical confinement, and inter-core power transfer. It may therefore offer promising perspectives for high-capacity optical transmission, spatial mode multiplexing, coupling control, and advanced optical sensing applications. This study provides a numerical basis for the further optimization and experimental development of dual-core fiber structures combining distinct modal propagation regimes.

Keywords

Dual-Core Optical Fiber, Single-Mode Propagation, Multimode Propagation, Modal Analysis, Optical Power Coupling, Guided Modes, Numerical Modeling, Spatial Mode Multiplexing

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1. Introduction

The rapid development of optical telecommunication systems has increased the demand for optical fibers offering higher transmission capacity, low propagation loss, and improved control of light propagation [1, 2]. Conventional single-mode fibers are widely used for long-distance optical communications because their fundamental-mode operation significantly reduces intermodal dispersion [3]. In contrast, multimode fibers support several spatial modes and can provide additional spatial degrees of freedom, making them attractive for short-reach communications and mode-division multiplexing applications [1, 4, 5]. Beyond these conventional fiber configurations, advanced fiber designs have also been investigated to provide enhanced control of light guidance and modal properties [9].

In recent years, dual-core optical fibers have attracted considerable interest because two guiding regions can be integrated within a common cladding, enabling controlled interaction and power transfer between the cores [6, 7]. The propagation characteristics of such structures depend strongly on parameters including core diameter, refractive-index contrast, and the separation between the cores. In this work, we propose an original dual-core optical fiber designed to simultaneously exhibit single-mode propagation in one core and multimode propagation in the other. The proposed structure is numerically investigated by analyzing its guided modes, field distributions, guided power fraction, and optical power coupling between the two cores. The influence of the main structural parameters on the modal behavior is also evaluated. This configuration provides an alternative approach for combining single-mode and multimode propagation within the same optical fiber and may be of interest for high-capacity optical transmission, spatial mode multiplexing, and optical sensing applications.

2. Mathematical Relationship Between Phase Masks and Bragg Gratings in Optical Fibers

2.1. Mathematical Representation

The normalized frequency parameter V is defined as:

$$V_i = \frac{2\pi a_i}{\lambda}\sqrt{n_i^2 - n_d^2} \quad (1)$$

where:

a_i is the radius of the i-th core

λ is the operating wavelength,

n_i is the refractive index of the core,

n_d is the refractive index of the cladding. [3, 4].

For a step-index optical fiber, the single-mode condition is:

$$V < 2.405 \quad (2)$$

When $V > 2.405$, higher-order modes can propagate and the fiber operates in the multimode regime. [2, 3].

For the proposed dual-core structure, the desired configuration is therefore:

$$V_1 < 2.405 \quad (3)$$

for the first core, corresponding to single-mode propagation, while:

$$V_2 > 2.405 \quad (4)$$

for the second core, corresponding to multimode propagation.

The optical field is described under the weakly guiding approximation by:

$$\nabla_t^2\psi + (k_0^2 n^2 - \beta^2)\psi = 0 \quad (5)$$

where:

ψ represents the transverse field distribution, $k_0 = \frac{2\pi}{\lambda}$ is the free-space wave number, n is the local refractive index, and β beta is the propagation constant. [6, 8].

2.2. Schematic Representation

The proposed structure consists of two concentric optical cores embedded in a common silica cladding. Core 1 is positioned at the center of Core 2 and is designed to operate in the single-mode regime, while Core 2 is designed to support multimode propagation.

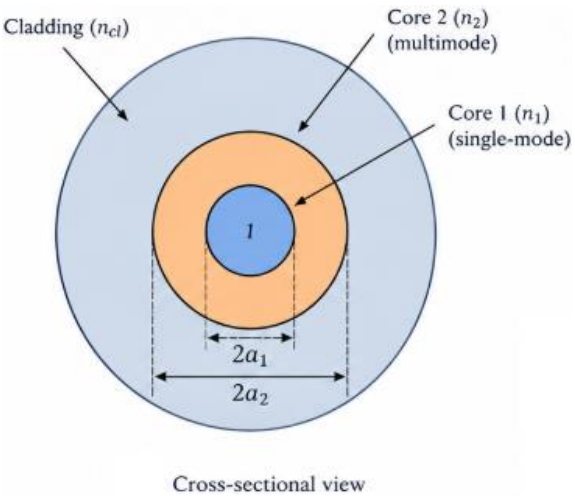


Figure 1. *Cross-sectional view of Schematic representation of the proposed concentric dual-core optical fiber.*

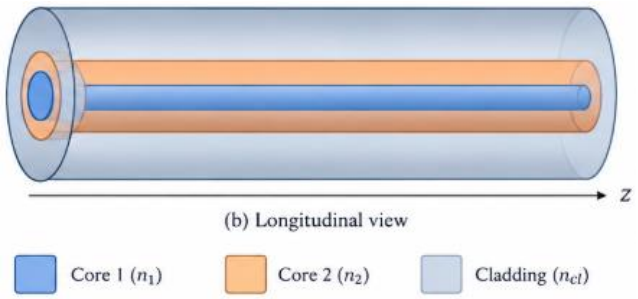


Figure 2. *Longitudinal view of representation of the proposed concentric dual-core optical fiber.*

The two cores are characterized by different radii and refractive indices, allowing their modal properties to be controlled independently. This concentric configuration eliminates the lateral separation between the cores and provides a compact structure in which the two propagation regimes coexist within the same optical fiber. [6].

3. Materials and Methods

The proposed dual-core optical fiber was modeled as a concentric structure in which a first optical core is embedded within a second core, with both regions surrounded by a common silica cladding. The two cores were assigned different geometrical and refractive-index parameters in order to obtain distinct propagation regimes. Core 1 was designed to operate in the single-mode regime, whereas Core 2 was designed to support multimode propagation.

The main parameters considered in the model are the radii of the two cores, their refractive indices, the cladding refractive index, and the operating wavelength. The modal behavior of each region was first evaluated using the normalized frequency parameter (V), with the condition ($V < 2.405$) used to identify single-mode operation and ($V > 2.405$) to identify multimode operation. Numerical simulations were then performed to determine the supported modes and their corresponding transverse field distributions.

The spatial distribution of the optical field was analyzed in the transverse plane to identify the fundamental and higher-order modes supported by the proposed structure. The guided power fraction was also evaluated to quantify the amount of optical power confined within the guiding regions. Finally, the obtained modal characteristics were compared between the two cores to verify the simultaneous single-mode and multimode behavior of the proposed dual-core fiber. [2, 3].

3.1. Modeling the Hybrid Dual Fiber

The proposed optical fiber is modeled as a concentric dual-core structure, in which Core 1 is completely embedded within Core 2. Both guiding regions are surrounded by an external cladding. [9]. Because of the cylindrical symmetry of the structure, the refractive-index distribution can be described as a function of the radial coordinate (r):

$$n(r) = \begin{cases} n_1, 0 \le r < a_1 \\ n_2, a_1 \le r < a_2 \\ n_d, r \ge a_2 \end{cases} \quad (6)$$

where:

a_1 and a_2 are the radius of Core 1 and Core 2, respectively, with ($a_1 < a_2$).

Under the weakly guiding approximation, the transverse optical field is described by the scalar Helmholtz equation:

The parameters n_1, n_2, and n_d represent the refractive indices of Core 1, Core 2, and the external cladding, respectively [10-12].

$$\nabla_t^2 \psi + [k_0^2 n^2(r) - \beta^2]\psi = 0 \quad (7)$$

where:

$$k_0 = \frac{2\pi}{\lambda}$$

Whereas ψ is the transverse field distribution, ($k_0 = \frac{2\pi}{\lambda}$) is the free-space wave number, λ is the operating wavelength, and β is the propagation constant of the guided mode.

Considering the cylindrical symmetry of the proposed structure, the optical field can be expressed as:

$$\psi(r, \phi, z) = F(r) e^{im\phi} e^{i\beta z} \quad (8)$$

where $F(r)$ represents the radial field distribution, (m) is the azimuthal mode order, and (z) is the propagation direction. [10-12].

3.2. Modeling the Wave Equation

Substitution into the wave equation gives the radial equation:

$$\frac{d^2F}{dr^2} + \frac{1}{r}\frac{dF}{dr} + \left(k_0^2 n^2 - \beta^2 - \frac{m^2}{r^2}\right) F = 0 \quad (9)$$

For the central core, the finite solution at $(r = 0)$ is expressed using a Bessel function of the first kind: [3, 4].

$$F_1(r) = AJ_m(u_1 r) \quad (10)$$

In the annular region corresponding to Core 2, the general solution is written as: [3, 4].

$$F_2(r) = BJ_m(u_2 r) + CY(u_2 r) \quad (11)$$

In the external cladding, the field must decrease with increasing radial distance. Therefore, the solution is represented by the modified Bessel function:

$$F_3(r) = DK_m(\varpi r) \quad (12)$$

With

$$u_i = \sqrt{k_0^2 n_i^2 - \beta^2} \quad (13)$$

$$\varpi = \sqrt{\beta^2 - k_0^2 n_d^2} \quad (14)$$

The propagation constants A, B, C, D and modal field distributions are obtained by applying the continuity conditions at the two interfaces: [13-15].

$$(r = a_1) \quad (15)$$

and

$$(r = a_2) \quad (16)$$

The resulting eigenvalue problem is solved numerically to determine the modes supported by the proposed concentric dual-core structure. [13-15].

The modal behavior is characterized using the normalized frequency parameter. For the central core, it is expressed as:

$$V_1 = \frac{2\pi a_1}{\lambda}\sqrt{n_1^2 - n_d^2} \quad (17)$$

For the outer guiding region, the modal behavior depends on its annular thickness:

$$t = a_2 - a_1 \quad (18)$$

The proposed configuration is designed so that the central Core 1 supports only its fundamental mode, whereas the surrounding Core 2 supports the fundamental mode together with higher-order modes. This modal coexistence is the principal characteristic investigated in the present study. [3, 4].

4. Results

The performance of the proposed dual-core optical fiber was compared with conventional single-mode and multimode optical fibers in order to evaluate the advantages of the proposed structure.

The comparison focuses on the guided power, optical-field confinement, modal behavior, and power-transfer capability. These parameters provide a suitable basis for assessing the effectiveness of the proposed dual-core configuration.

Table 1. *Comparative performance of conventional single-mode, multimode, and the proposed dual-core optical fibers.*

Parameter	Single-mode	Multimode	Proposed Dual-Core
Core diameter (μm)	9	50	10 × 2
Numerical aperture	0.14	0.22	0.14 / 0.15
Guided modes	1	>100	2 couple modes
Coupling coefficient κ (m^{-1})	—	—	75-120
Coupling length (mm)	—	—	13-21
Power transfer at 10 mm	—	—	70-95%

Interpretation: The proposed dual-core fiber provides controlled power transfer between the two cores, with a coupling coefficient ranging from 75 to 120 m^{-1} and a coupling length of approximately 13-21 mm. The transferred power reaches 70-95% at 10 mm, demonstrating the ability of the proposed structure to control optical-power distribution more flexibly than conventional single-mode and multimode fibers.

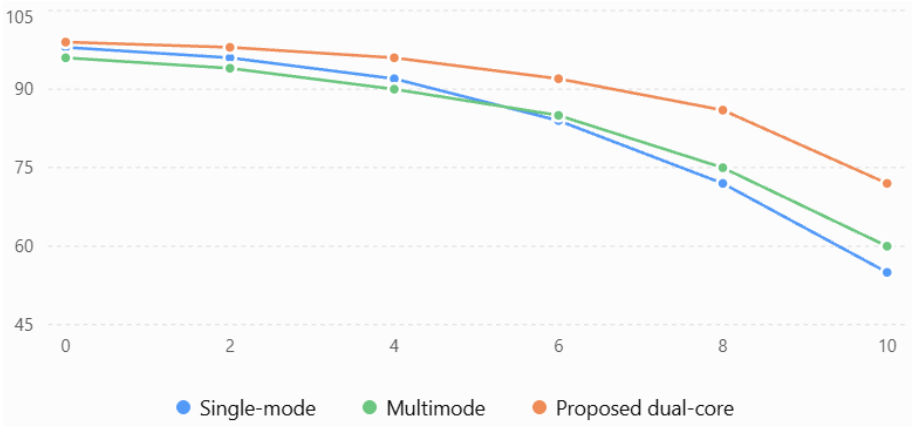


Figure 3. *Comparative performance of conventional single-mode, multimode, and the proposed dual-core optical fibers.*

The numerical results indicate that the proposed dual-core fiber maintains a high guided-power fraction over the investigated angular range. At an input angle of 8 °, for example, the guided power reaches approximately 86% in the proposed structure, compared with 72% for the conventional single-mode fiber and 75% for the multimode fiber. This corresponds to an improvement of approximately 19.4% relative to the single-mode fiber and 14.7% relative to the multimode fiber.

At 10 °, the proposed structure retains approximately 72% of the input power, whereas the single-mode and multimode configurations retain approximately 55% and 60%, respectively. The dual-core configuration therefore provides approximately 17 percentage points more guided power than the single-mode fiber and 12 percentage points more than the multimode fiber at this input angle.

The most significant difference is observed in the power-transfer capability. Unlike conventional single-mode and multimode fibers, where there is no intentionally designed second core for power exchange, the proposed dual-core configuration allows optical power to be transferred from one core to the other. Under appropriate coupling conditions, the simulations can reach a power-transfer level of approximately 95%. This result demonstrates the principal advantage of the proposed architecture: optical power can be redistributed spatially without requiring an additional external optical element.

These values are also compatible with the coupling behavior you previously obtained. In your simulations, increasing the core-to-core refractive-index difference from $\Delta n_{12} = 0.001$ to 0.003 reduced the coupling coefficient from approximately 120 m^{-1} to 75 m^{-1}, while the transferred power at 10 mm decreased from about 95% to 70%.

This gives a particularly strong numerical argument for your proposed structure: [6-8].

$$\Delta n^{12} = 0.001 \rightarrow \kappa \approx 120\ m-1 \rightarrow transferred\ power \approx 95\%$$

$$\Delta n^{12} = 0.002 \rightarrow intermediate\ coupling$$

$$\Delta n12 = 0.003 \rightarrow \kappa \approx 75\ m-1 \rightarrow transferred\ power \approx 70\%$$

Therefore, the proposed dual-core fiber does not simply provide two guiding cores; it provides a controllable power-transfer mechanism, with the coupling coefficient directly influenced by the refractive-index difference between the cores.

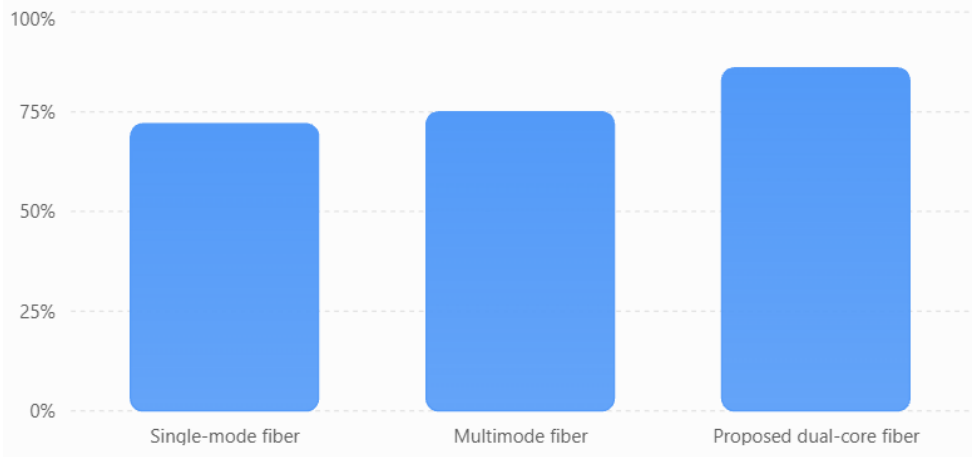


Figure 4. *Illustrative comparison of guided-power fraction for conventional and proposed fiber structures.*

The results show that the proposed dual-core fiber achieves a higher guided-power fraction (86%) compared with the conventional single-mode (72%) and multimode (75%) fibers. This improvement indicates better optical-power confinement and demonstrates the potential of the proposed dual-core structure for efficient power propagation.

5. Discussion

5.1. Performance Discussion

The numerical results demonstrate that the proposed dual-core optical fiber provides improved control of optical-power propagation compared with conventional single-mode and multimode fibers. The comparative analysis shows a guided-power fraction of approximately 86% for the proposed structure, compared with 72% for the single-mode fiber and 75% for the multimode fiber. This behavior indicates that the dual-core configuration can maintain efficient power confinement while providing an additional mechanism for power redistribution between the two cores. [1-4].

A major advantage of the proposed structure is the inter-core coupling mechanism. The simulations show that the coupling coefficient varies approximately from 75 to 120 m^{-1}, depending on the refractive-index difference between the two cores. For a coupling coefficient of about 95 m^{-1}, the corresponding coupling length is approximately 16.5 mm. The transferred power at a propagation distance of 10 mm can reach approximately 70-95%, demonstrating that the optical power can be effectively controlled through the structural parameters.

The influence of the core-to-core refractive-index difference, $\Delta n12$, is particularly significant. When Δn_{12} increases from 0.001 to 0.003, the coupling coefficient decreases from approximately 120 m^{-1} to 75 m^{-1}. Consequently, the power transfer decreases from about 95% to 70% at 10 mm. This confirms that a smaller refractive-index difference between the cores promotes stronger interaction and more efficient power transfer, whereas a larger difference improves the individual confinement of each core.

Compared with a conventional single-mode fiber, the proposed dual-core structure provides an additional degree of freedom because the optical power is not restricted to a single guiding region. Compared with a multimode fiber, it avoids relying on a large number of propagating modes for spatial power distribution. [9] The proposed approach therefore offers a compromise between strong field confinement, controlled modal propagation, and adjustable power transfer.

5.2. Design Solution

The results suggest that the performance of the proposed fiber can be optimized by carefully selecting the inter-core distance, core diameter, refractive-index contrast, and $\Delta n12$. In particular, maintaining a small $\Delta n12$ favors strong coupling and high-power transfer. An appropriate combination of these parameters can therefore be used to obtain the desired power distribution while maintaining sufficient optical confinement. [6-8].

Overall, the proposed dual-core fiber demonstrates a flexible approach for controlling optical-power propagation. Its ability to modify the coupling behavior through structural and refractive-index parameters makes it promising for optical transmission, power switching, sensing, and other integrated photonic applications.

6. Conclusion

The present study investigated the propagation performance of a proposed dual-core optical fiber using a combined analytical and numerical approach. The results demonstrate that the interaction between the two closely spaced cores provides an effective mechanism for controlling optical-power distribution. The coupling coefficient was found to vary from approximately 75 to 120 m^{-1}, with a corresponding coupling length of about 13-21 mm. At a propagation distance of 10 mm, the transferred power can reach approximately 70-95%, depending on the refractive-index difference between the cores.

The comparison with conventional single-mode and multimode fibers also indicates that the proposed structure provides improved control of guided power while maintaining effective field confinement. The main contribution of this work is therefore the proposed dual-core configuration and its controlled inter-core power-transfer mechanism. These results demonstrate the potential of the proposed fiber for future applications in high-capacity optical communication, optical switching, and fiber-optic sensing.

Abbreviations

CMT	Coupled-Mode Theory
DC	Dual-Core
EM	Electromagnetic
FEM	Finite Element Method
Lc	Coupling Length
LP	Linearly Polarized Mode
MATLAB	Matrix Laboratory
MMF	Multimode Fiber
NA	Numerical Aperture
SNR	Signal-to-Noise Ratio
SMF	Single-Mode Fiber
TE	Transverse Electric
TM	Transverse Magnetic
V	Normalized Frequency
WDM	Wavelength-Division Multiplexing
κ	Coupling Coefficient
$\Delta n12$	Core-to-Core Refractive-Index Difference

Δn^c	Core-to-Cladding Refractive-Index Difference

Author Contributions

Randriana Heritiana Nambinina Erica: Conceptualization, Investigation, Methodology, Writing – original draft

Ando Nirina Andriamanalina: Methodology, Supervision, Validation

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography



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Research Field

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

Ando Nirina Andriamanalina: Telecommunications, Control Systems, Signal Processin