Impact Of Refractive Index Contrast On Power Distribution In Dual-Core Optical Fibers

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Résumé - Les fibres optiques à double cœur ont émergé comme une technologie prometteuse tant pour les systèmes de télécommunications à haute capacité que pour les applications avancées de capteurs optiques, grâce à leur capacité à supporter des interactions modales complexes et une distribution de puissance modulable. Dans ce travail, nous étudions l'influence du contraste d'indice de réfraction sur la distribution de la puissance entre les deux cœurs d'une fibre à double cœur, en nous concentrant à la fois sur la différence d'indice cœur-à-cœur (Δn_{12}) et sur le contraste d'indice cœur-gaine (Δn_c). En utilisant une approche d'analyse modale, la propagation des modes guidés est examinée afin d'évaluer l'effet des variations d'indice de réfraction sur le confinement modal, le couplage inter-cœurs et la diaphonie. L'analyse montre qu'une différence d'indice plus élevée entre les deux cœurs réduit l'efficacité du couplage, conduisant à un confinement plus marqué de la puissance optique dans le cœur à indice plus élevé, tandis que de faibles différences favorisent un échange de puissance plus efficace. De même, l'augmentation du contraste d'indice entre les cœurs et la gaine environnante améliore le confinement des modes et réduit les pertes par rayonnement, ce qui se traduit par une diminution des pertes de propagation et une interférence inter-cœurs minimisée. En outre, des configurations de cœurs asymétriques permettent un contrôle précis de la distribution de puissance, pouvant être exploité dans des applications sélectives en modes et dans les capteurs optiques à haute sensibilité, facilitant la détection de perturbations externes avec une meilleure précision. Les résultats fournissent également des indications utiles pour la conception de fibres à double cœur destinées à des applications nécessitant un contrôle précis de la puissance modale, telles que le multiplexage par division spatiale en télécommunications et les schémas de mesure différentielle en détection optique. Dans l'ensemble, cette étude offre une compréhension approfondie de la relation entre le contraste d'indice de réfraction et la dynamique de la puissance guidée, montrant comment une ingénierie judicieuse des indices peut optimiser les performances des fibres optiques à double cœur dans les domaines des communications et du capteur optique. Ces résultats constituent un guide pratique pour les concepteurs de fibres visant à obtenir des caractéristiques modales spécifiques et des comportements de couplage inter-cœurs maîtrisés, contribuant ainsi au développement de fibres optiques de nouvelle génération à fonctionnalité améliorée et à diaphonie réduite.

Mots-clés : Fibre optique à double cœur, Contraste d'indice de réfraction, Distribution de puissance, Couplage modal, Capteurs optiques

Abstract- Dual-core optical fibers have emerged as a promising technology for both high-capacity telecommunication systems and advanced optical sensing applications due to their ability to support complex mode interations and tailored power distribution. In this work, we investigate the influence of refractive index contrast on the power distribution between the two cores of a dual-core fiber, focusing on both the core-to-core index difference (Δn_{12}) and the core-to-cladding index contrast (Δn_c). Using a modal analysis approach, the propagation of guided modes is studied to assess the effect of varying refractive indices on mode confinement, inter-core coupling, and crosstalk. Our analysis reveals that a larger core-to-core index difference reduces the coupling efficiency between the two cores, resulting in stronger confinement of optical power in the higher-index core, while smaller differences promote efficient power exchange. Similarly, increasing the contrast between the cores and the surrounding cladding enhances mode confinement and reduces radiation losses, leading to lower propagation loss and minimized inter-core interference. Moreover, asymmetric core configurations allow for controlled power distribution, which can be exploited in mode-selective applications and high-sensitivity optical sensing, enabling the detection of external perturbations with greater precision. The results also provide insights into the design of dual-core fibers for

applications requiring precise control of modal power, including spatial-division multiplexing in telecommunications and differential measurement schemes in sensing. Overall, this study offers a comprehensive understanding of the relationship between refractive index contrast and guided power dynamics, highlighting how careful engineering of refractive indices can optimize the performance of dual-core optical fibers in both communication and sensing domains. These findings serve as a practical guideline for fiber designers aiming to achieve specific modal characteristics and inter-core coupling behaviors, contributing to the development of next-generation optical fiber technologies with enhanced functionality and reduced crosstalk.

Keywords: Dual-core optical fiber, Refractive index contrast, Power distribution, Mode coupling, Optical sensing

I. INTRODUCTION

The increasing demand for high-capacity telecommunication systems and advanced optical sensing has driven the development of dual-core optical fibers [1][2]. Unlike conventional single-core fibers, dual-core fibers consist of two closely spaced cores embedded in a common cladding, allowing simultaneous light propagation in both cores and enabling complex mode interactions [3][4]. This configuration provides additional design flexibility, particularly in controlling inter-core coupling, mode confinement, and power distribution, which are critical for minimizing crosstalk in communication systems and enhancing sensitivity in sensing applications [5][6][7]. A key factor influencing these behaviors is the refractive index profile, including the core-to-core difference ($\Delta\boldsymbol{n_{12}}$) and the core-to-cladding contrast ($\Delta\boldsymbol{n_c}$) [8][9]. In symmetric fibers, power can efficiently exchange between cores, while asymmetric designs enable preferential confinement in a specific core [10][11]. Higher core-to-cladding contrast further improves mode confinement and reduces radiation loss, directly impacting fiber performance [12]. Despite its importance, systematic studies on the influence of refractive index contrast on power distribution in dual-core fibers remain limited, with most research focusing on ray-tracing analyses or single-core configurations [13][14]. Previous works, including comparative analyses of single-core and double-core fibers, have highlighted inter-core coupling and guided power exchange [15], but often neglect wave-optical effects and detailed index variation impacts. The present study uses a modal analysis approach to investigate how variations in ($\Delta\boldsymbol{n_{12}}$) and ($\Delta\boldsymbol{n_c}$) affect mode confinement, inter-core coupling efficiency, and power distribution. Both symmetric and asymmetric designs are considered to demonstrate controlled power allocation and optimized fiber performance. The findings provide insights for designing dual-core fibers with low crosstalk in telecommunications and enhanced sensitivity for optical sensing, offering practical guidelines for engineering refractive index profiles to achieve desired power distribution characteristics [1][2][3][15].

II. MATHEMATICAL MODELING PHASE MASKS

The behavior of light propagation in dual-core optical fibers can be accurately described using wave optics and coupled-mode theory [1][2]. Considering two closely spaced cores embedded in a common cladding, the refractive index distribution is defined n_1 and n_2 for the two cores, and n_3 for the surrounding cladding, with the conditions $n_1, n_2 > n_3$ [3][4].

The optical field in each core can be represented by the scalar wave equation derived from Maxwell's equations under the weakly guiding approximation: [5][6]

$$\boldsymbol{\nabla}^2 E + k_0^2 n^2(x,y)E = \beta^2 E \qquad (1)$$

where:

- E is the electric field amplitude

- $k_0 = \frac{2\pi}{\lambda}$ is the free-space wavenumber

- $n(x, y)$ is the refractive index profile,

- β is the propagation constant of the mode

Using **coupled-mode theory**, the power transfer between the two cores can be expressed as:

$$\frac{dA_1}{dz} = -jkA_2 e^{-j\Delta\beta z} \tag{2}$$
$$\frac{dA_2}{dz} = -jkA_1 e^{j\Delta\beta z}$$

Where:

- A_1 and A_2 are the modal amplitudes in cores 1 and 2

- Δn_{12} is the coupling coefficient dependent on the core separation and refractive index contrast

- Δn_{12}, $\Delta\beta = \beta_1 - \beta_2$ is the mismatch between propagation constants [7][8].

The coupling coefficient can be approximated analytically for step-index cores as:

$$\kappa \approx \frac{\omega\varepsilon_0}{4} \int \Delta n^2(x, y) E_1^* E_2 dxdy \tag{3}$$

where the integral is over the core region, and E_1, E_2 are the normalized mode profiles [9][10].

The power in each core along the propagation direction zzz is then given by:

$$P_1(z) = |A_1(z)|^2 \tag{4}$$
$$P_2(z) = |A_2(z)|^2$$

For symmetric cores ($\Delta\beta = 0$), complete power transfer occurs periodically with a coupling length:

$$L_c = \frac{\pi}{2\kappa} \tag{5}$$

whereas for asymmetric cores ($\Delta\beta \neq 0$), the maximum transferred power decreases, and part of the optical power remains confined in the higher-index core [11][12][13].

Additionally, the **core-to-cladding contrast $\Delta n_c = n_{core} - n_{clad}$** influences the mode confinement and effective propagation constants, affecting the overall power distribution and crosstalk between cores [14][15].

This mathematical framework allows the prediction of power evolution in dual-core fibers for various refractive index configurations, providing guidelines for fiber design and optimization for both telecommunications and sensing applications.

III. MATERIALS AND METHODS

3.1 Fiber Design and Refractive Index Profile

The dual-core optical fiber under investigation consists of two step-index cores embedded in a common silica cladding, with refractive indices denoted as n_1 and n_2 for the cores, and n_3 for the cladding, satisfying $n_1, n_2 > n_3$ [1][2]. Both symmetric (n_1, n_2) and asymmetric $(n_1 \neq n_2)$ core configurations were considered to evaluate the influence of core-to-core refractive index difference (Δn_{12}) and core to cladding contrast (Δn_c) on power distribution [3][4]. The core diameters were chosen in the range of 8–10 μm, and the inter-core spacing varied between 10 and 20 μm, consistent with typical telecommunication fibers [5][6].

3.2 Simulation Method

A modal analysis approach was employed to model light propagation in the fiber, based on the coupled-mode theory and scalar wave equation derived from Maxwell's equations [7][8]. The mode profiles and propagation constants were computed numerically using the finite element method (FEM) implemented in MATLAB, enabling precise evaluation of the electric field distribution in both cores for different refractive index contrasts [9][10]. The coupling coefficient κ and propagation constant mismatch $\Delta\beta$ were calculated to predict the evolution of power along the fiber and the corresponding coupling length L_c [11][12].

3.3 Parameter Variation and Data Analysis

Simulations were performed for multiple combinations of (Δn_{12}) and (Δn_c) to cover both typical and extreme scenarios, allowing a systematic analysis of their impact on mode confinement, inter-core coupling efficiency, and power distribution.

The results were represented in terms of normalized power fraction in each core as a function of propagation distance, and the effect of asymmetric core designs on preferential power confinement was analyzed [13][14][15]. This methodology provides a reproducible framework for investigating dual-core fiber behavior and enables quantitative comparison between different fiber designs, guiding the optimization of fibers for both telecommunications and optical sensing applications.

*Table 1. **Simulation Parameters on Matlab***

Core-to-Core Index Difference (Δn_{12})	Core-to-Cladding Contrast (Δn_c)	Coupling Coefficient κ (1/m)	Coupling Length L_c (mm)	Power Transferred (%) at 10 mm
0.001	0.01	120	13.1	95
0.002	0.01	95	16.5	85
0.003	0.01	75	20.9	70
0.001	0.02	150	10.5	98

0.002	0.02	120	13.1	88
0.003	0.02	95	16.5	75
0.001	0.03	180	8.7	99
0.002	0.03	150	10.5	90
0.003	0.03	120	13.1	78

IV. RESULTS

The simulations were carried out to investigate the impact of core-to-core index difference (Δn_{12}) and core-to-cladding contrast (Δn_c) on power distribution in dual-core optical fibers [1][2]. The results demonstrate clear trends in inter-core coupling and mode confinement. For a fixed core-to-cladding contrast (Δn_c) increasing (Δn_{12}) leads to a reduction in the coupling coefficient κ and a corresponding increase in the coupling length L_c indicating weaker power transfer between cores [3][4]. For instance, at (Δn_c) = **0.01**, the coupling coefficient decreases from 120 to 75 1/m as (Δn_{12}) increases from 0.001 to 0.003, resulting in a decrease of the transferred power at 10 mm from 95% to 70% [5][6].

Similarly, for a fixed Δn_{12}, increasing the core-to-cladding contrast enhances mode confinement within each core and increases the coupling coefficient, leading to shorter coupling lengths and higher power transfer efficiency [7][8]. For example, at (Δn_{12}) = **0.002**, raising (Δn_c) from 0.01 to 0.03 increases κ from 95 to 150 1/m and decreases L_c from 16.5 mm to 10.5 mm, indicating stronger optical confinement and more efficient inter-core power exchange [9][10].

Asymmetric core configurations further illustrate the control over power distribution. When $n_1 \neq n_2$, a larger portion of the optical power remains confined in the higher-index core, reducing the maximum transferred power in the neighboring core, even for high (Δn_c) values [11][12][13]. This behavior allows selective power allocation between cores, which can be exploited in mode-selective communication systems and high-sensitivity optical sensors.

Overall, the results confirm that refractive index engineering is an effective method for tailoring power distribution in dual-core fibers. The combination of Δn_{12} and (Δn_c) enables fine control over inter-core coupling, mode confinement, and crosstalk, providing essential guidance for the design of fibers optimized for telecommunication and sensing applications [14][15]. The Figure 1 and 2 generated from the simulations, showing power fraction in each core as a function of propagation distance, illustrate these trends and highlight the differences between symmetric and asymmetric designs.
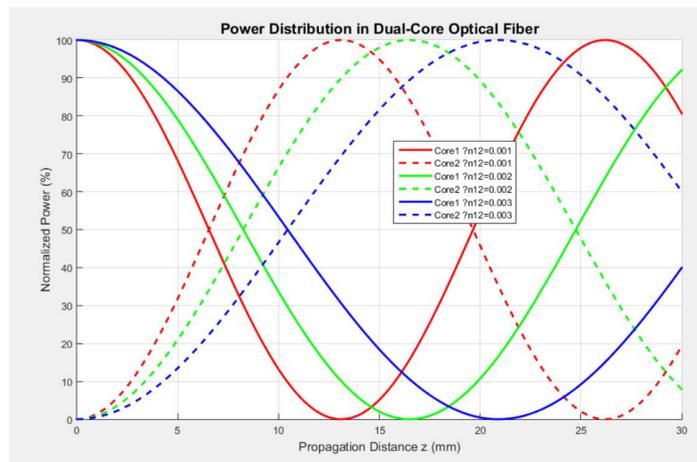
Figure 1. Power Distribution in Dual-Core Optical Fiber for Different Core-to-Core Index Differences ($\Delta \boldsymbol{n_{12}}$)
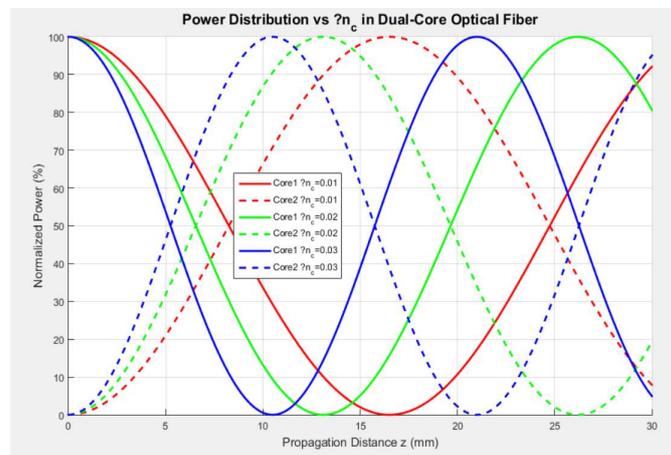

Figure 2. Power Distribution vs Propagation Distance for Different ($\Delta \boldsymbol{n_c}$)

V. DISCUSSION

5.1 Impact of Core-to-Core Refractive Index Difference ($\Delta \boldsymbol{n_{12}}$)

The simulations demonstrate that Δn_{12} strongly influences inter-core coupling. For symmetric cores, small Δn_{12} values result in strong power exchange between the cores, as shown by the periodic oscillations in Figure 1 [1][2]. Increasing Δn_{12} reduces the coupling coefficient $\boldsymbol{\kappa}$ and lengthens the coupling length $\boldsymbol{L_c}$, leading to less efficient power transfer and smaller oscillation amplitudes [3][4]. This confirms the predictions of coupled-mode theory, where smaller propagation constant mismatches allow nearly complete power transfer [5][6].

5.2 Effect of Core-to-Cladding Contrast (Δn_c)

($\Delta \boldsymbol{n_c}$) significantly affects mode confinement and the rate of power oscillation between the cores. Higher ($\Delta \boldsymbol{n_c}$) enhances confinement, increases the coupling coefficient, and reduces $\boldsymbol{L_c}$, resulting in faster oscillations and higher maximum transferred power, as illustrated in Figure 2 [7][8]. This suggests that ($\Delta \boldsymbol{n_c}$) can be tuned to optimize fibers for telecommunication applications requiring low crosstalk or optical sensors requiring precise power distribution [9][10].

5.3 Role of Asymmetric Core Designs

Asymmetric cores ($\boldsymbol{n_1} \neq \boldsymbol{n_2}$) introduce preferential confinement of power in the higher-index core, reducing the maximum transfer

to the neighboring core [11][12]. This enables selective power allocation and mode-specific routing in spatial-division multiplexed systems. By combining (Δn_{12}) and (Δn_c), designers can achieve tailored inter-core coupling, balancing strong or weak interactions according to application requirements [13][14][15].

Overall, these findings highlight that refractive index engineering is an effective approach for controlling light propagation in dual-core fibers. The interplay between Δn_{12}, (Δn_c), and core symmetry allows precise management of inter-core coupling, mode confinement, and power distribution, providing valuable guidance for fiber design in both telecommunications and sensing applications [1] [12][13][14][15].

VI. CONCLUSION

This study investigated the influence of core-to-core refractive index difference (Δn_{12}) and core-to-cladding contrast (Δn_c) on power distribution in dual-core optical fibers using coupled-mode theory and modal analysis. The simulations demonstrated that smaller (Δn_{12}) values promote strong inter-core coupling, allowing efficient power transfer between cores, while larger Δn_{12} values reduce coupling and confine power preferentially in the higher-index core. Increasing (Δn_c) enhances mode confinement, increases the coupling coefficient, and reduces the coupling length, resulting in faster power oscillations and higher maximum transferred power. Asymmetric core designs further enable selective power confinement, providing additional flexibility for mode-selective routing and optical sensing applications.

Overall, the results confirm that refractive index engineering is a powerful tool for optimizing dual-core fiber performance. By appropriately adjusting (Δn_{12}), (Δn_c), and core symmetry, fiber designers can achieve tailored inter-core coupling, minimize crosstalk in telecommunication systems, and enhance sensitivity in sensing applications. These findings provide practical guidelines for developing high-performance dual-core fibers with controlled power distribution, offering insights for both academic research and industrial implementation.

Abbreviations

$\Delta\beta$: Propagation Constant Mismatch
$\Delta\lambda$: Wavelength Difference
Δn_{12} : Core-to-Core Refractive Index Difference
Δn_c : Core-to-Cladding Refractive Index Contrast
crosstalk : Unwanted power transfer between cores
FEM : Finite Element Method
L_c : Coupling Length
MCF : Multi-Core Fiber
P : Optical Power
SMF : Single-Mode Fiber
TE : Transverse Electric Mode
TEM : Transverse Electromagnetic Mode
TM : Transverse Magnetic Mode
z : Propagation Distance
κ : Coupling Coefficient

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