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Nonlinear Dual-Core Fibers: Kerr Effects, Cross-Phase Modulation, And Optical Switching Applications

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Résumé — Les fibres optiques non linéaires à double cœur représentent une classe émergente de guides d'onde combinant le couplage spatial des modes et des effets non linéaires dépendants de l'intensité, offrant des fonctionnalités allant au-delà de celles des fibres classiques à cœur unique. Contrairement aux fibres linéaires à double cœur, principalement étudiées pour le multiplexage par division spatiale, les fibres non linéaires à double cœur exploitent les variations de l'indice de réfraction induites par l'effet Kerr afin de permettre un transfert d'énergie dépendant de la puissance, la modulation de phase croisée et le contrôle tout optique. Dans ce travail, nous étudions la dynamique non linéaire des fibres à double cœur en analysant les effets Kerr et les interactions non linéaires inter-cœurs sous excitation en onde continue et en régime impulsionnel. Une modélisation numérique basée sur des équations de Schrödinger non linéaires couplées montre que, pour des puissances d'entrée dépassant un seuil critique (généralement compris entre 1 et 10 W selon la séparation des cœurs et le coefficient de non-linéarité), l'échange périodique linéaire de puissance entre les deux cœurs est progressivement supprimé, conduisant à un auto-piégeage non linéaire et à une localisation asymétrique de l'énergie. La modulation de phase croisée entre cœurs adjacents induit des déphasages supplémentaires proportionnels à l'intensité optique, atteignant plusieurs radians pour des puissances crête supérieures à 5 W sur des longueurs de propagation de quelques mètres. Ces effets permettent une commutation contrôlable dépendante de la puissance, où le port de sortie peut être sélectionné de manière déterministe en ajustant la puissance d'entrée ou l'énergie des impulsions. Les résultats de simulation montrent des contrastes de commutation dépassant 20 dB et des temps de réponse limités uniquement par la durée des impulsions optiques, indiquant une aptitude au fonctionnement ultrarapide au-delà de 100 GHz. De plus, le mécanisme de couplage non linéaire fournit une instabilité intrinsèque, exploitable pour la logique optique et la régénération de signaux. L'applicabilité des fibres non linéaires à double cœur aux systèmes laser à fibre est également discutée, où le déséquilibre modal induit par l'effet Kerr peut agir comme un sélecteur modal passif dépendant de la puissance ou comme un absorbeur saturable dynamique. Comparées aux fibres multicœurs ou aux fibres à cristal photonique, les fibres non linéaires à double cœur offrent une géométrie plus simple, une complexité de fabrication réduite et une meilleure contrôlabilité des interactions non linéaires. Malgré ces avantages, leur potentiel reste largement sous-exploré dans la littérature actuelle. Les résultats mettent en évidence les fibres non linéaires à double cœur comme une plateforme prometteuse pour la commutation tout optique, le traitement ultrarapide des signaux et des architectures avancées de lasers à fibre, ouvrant la voie à des dispositifs photoniques compacts, à faible latence et sans électronique.

Mots-clés : fibres non linéaires à double cœur, effet Kerr, modulation de phase croisée, commutation tout optique, lasers à fibre.

Abstract— Nonlinear dual-core optical fibers represent an emerging class of waveguides that combine spatial mode coupling with intensity-dependent nonlinear effects, offering functionalities beyond conventional single-core fibers. Unlike linear dual-core fibers primarily investigated for space-division multiplexing, nonlinear dual-core fibers exploit Kerr-induced refractive index variations to enable power-dependent energy transfer, cross-phase modulation, and all-optical control. In this work, we investigate the nonlinear dynamics of dual-core fibers by analyzing Kerr effects and inter-core nonlinear interactions under continuous-wave and pulsed excitation regimes. Numerical modeling based on coupled nonlinear Schrödinger equations demonstrates that, for input powers exceeding a critical threshold (typically in the range of $1 - 10\ W$ depending on core separation and nonlinear coefficient), the linear periodic power exchange

between the two cores is progressively suppressed, leading to nonlinear self-trapping and asymmetric energy localization. Cross-phase modulation between adjacent cores induces additional phase shifts proportional to the optical intensity, reaching several radians for peak powers above 5 W over propagation lengths of a few meters. These effects enable controllable power-dependent switching, where the output port can be deterministically selected by adjusting the input power or pulse energy. Simulation results show switching contrasts exceeding 20 dB and response times limited only by the optical pulse duration, indicating suitability for ultrafast operation beyond 100 GHz. Furthermore, the nonlinear coupling mechanism provides intrinsic bistability, which can be exploited for optical logic and signal regeneration. The applicability of nonlinear dual-core fibers to fiber laser systems is also discussed, where Kerr-induced mode imbalance can act as a passive, power-dependent mode selector or dynamic saturable absorber. Compared to multi-core or photonic crystal fibers, dual-core nonlinear fibers offer a simpler geometry, reduced fabrication complexity, and enhanced controllability of nonlinear interactions. Despite these advantages, their potential remains largely underexplored in current literature. The results highlight nonlinear dual-core fibers as a promising platform for all-optical switching, ultrafast signal processing, and advanced fiber laser architectures, paving the way for compact, low-latency, and electronics-free photonic devices.

Keywords: Nonlinear dual-core fibers, Kerr effect, cross-phase modulation, all-optical switching, fiber lasers.

I. INTRODUCTION

The rapid growth of global data traffic and the emergence of bandwidth-intensive applications have pushed optical communication systems close to the fundamental limits of conventional single-mode fibers [1] [2]. In this context, advanced fiber designs and novel physical mechanisms are being actively explored to overcome capacity, speed, and functionality constraints [3]. Among these approaches, space-division multiplexing (SDM) has attracted significant attention as a viable solution for increasing transmission capacity without relying solely on spectral efficiency improvements [4] [5]. Dual-core optical fibers represent one of the simplest realizations of SDM, consisting of two closely spaced cores that allow controlled optical coupling [6]. In their linear regime, such fibers have been extensively studied for power splitting, sensing, and mode coupling applications [7] [8]. However, most existing works focus on linear propagation effects, while the nonlinear regime remains comparatively underexplored [9]. This is particularly notable given that optical fibers inherently exhibit nonlinear behavior at moderate to high power levels due to the Kerr effect [10]. When nonlinear effects are taken into account, the propagation dynamics in dual-core fibers become strongly power dependent [11]. Kerr-induced refractive index variations modify the effective propagation constants of each core, thereby altering the inter-core coupling strength and energy exchange dynamics [12]. As a result, phenomena such as nonlinear self-trapping, asymmetric power distribution, and bistable propagation states may emerge, which are absent in linear configurations [13]. In addition to self-phase modulation, the close proximity of the two cores enables significant cross-phase modulation (XPM), where the optical intensity in one core influences the phase evolution of the neighboring core [14]. This nonlinear interaction opens new possibilities for all-optical signal control, including power-dependent switching, logic operations, and ultrafast modulation, without the need for electronic processing [15]. Despite these promising features, nonlinear dual-core fibers have not yet received the same level of attention as multi-core or photonic crystal fibers. Their relatively simple geometry, combined with rich nonlinear dynamics, makes them an attractive platform for both fundamental studies and practical applications. In particular, their potential for all-optical switching and fiber laser systems motivates further investigation into Kerr-driven coupling mechanisms and nonlinear mode dynamics.

II. MATHEMATICAL MODELING KERR EFFECTS, CROSS-PHASE MODULATION, AND OPTICAL SWITCHING APPLICATIONS

The nonlinear propagation of optical fields in a dual-core fiber can be accurately described using a system of coupled nonlinear Schrödinger equations (CNLSEs), which simultaneously account for linear inter-core coupling and Kerr-induced nonlinear effects [6] [9] [11]. This modeling approach has been widely adopted for analyzing energy exchange and nonlinear dynamics in coupled waveguide systems [12] [13].

Let $\boldsymbol{A_1}(\boldsymbol{z},\boldsymbol{t})$and $\boldsymbol{A_2}(\boldsymbol{z},\boldsymbol{t})$ denote the slowly varying complex envelopes of the optical fields propagating in core 1 and core 2, respectively, where $\boldsymbol{z}$ is the longitudinal propagation distance and $\boldsymbol{t}$ is the retarded time frame moving with the group velocity [10]

[14]. Under the slowly varying envelope approximation and assuming two identical cores, the evolution of the optical fields is governed by the following coupled equations [11] [15]:

$$\frac{\partial A_1}{\partial z} + \frac{\alpha}{2} A_1 + i \frac{\beta_2}{2} \frac{\partial^2 A_1}{\partial t^2} = i\kappa A_2 + i\gamma(|A_1|^2 + 2|A_2|^2) A_1 \quad (1)$$

$$\frac{\partial A_2}{\partial z} + \frac{\alpha}{2} A_2 + i \frac{\beta_2}{2} \frac{\partial^2 A_2}{\partial t^2} = i\kappa A_1 + i\gamma(|A_2|^2 + 2|A_1|^2) A_2 \quad (2)$$

Where $\boldsymbol{\alpha}$ represents the fiber attenuation coefficient, $\boldsymbol{\beta_2}$ is the group-velocity dispersion parameter, $\boldsymbol{\kappa}$ denotes the linear coupling coefficient between the two cores, and $\boldsymbol{\gamma}$ is the nonlinear Kerr coefficient. The nonlinear terms incorporate both self-phase modulation (SPM) and cross-phase modulation (XPM), with the XPM contribution being approximately twice that of SPM due to the overlap of modal fields in adjacent cores [10] [14].

In the continuous-wave regime, and by neglecting dispersion and losses, the model reduces to a simplified set of coupled ordinary differential equations describing power exchange between the two cores [6] [12]. In this case, linear coupling leads to periodic power oscillations along the propagation distance. As the optical power increases, Kerr-induced nonlinear phase shifts introduce an effective propagation constant mismatch, progressively inhibiting inter-core coupling and giving rise to nonlinear self-trapping phenomena [11] [13].

For pulsed propagation, dispersion and nonlinearity jointly influence the temporal and spatial evolution of the optical fields [9] [15]. The interplay between group-velocity dispersion, Kerr nonlinearity, and inter-core coupling enables power-dependent switching behavior and ultrafast all-optical modulation. This mathematical framework therefore provides a solid theoretical basis for analyzing nonlinear dual-core fibers in both continuous-wave and ultrashort-pulse regimes.

III. MATERIALS AND METHODS

3.1 Simulation Framework

The nonlinear propagation of optical fields in dual-core fibers was investigated using numerical simulations based on the coupled nonlinear Schrödinger equations described in Section 2 [11] [12]. A split-step Fourier method was employed to integrate the equations over the propagation distance, allowing accurate modeling of both linear coupling and nonlinear Kerr effects [13] [14]. Temporal and spatial discretization parameters were chosen to ensure numerical convergence, with a step size of 1 mm and 1024 temporal points per pulse [15].

3.2 Fiber Parameters

Typical experimental dual-core fiber parameters were adopted: core radius of 4.5 µm, core-to-core separation of 12 µm, linear coupling coefficient $\kappa = 0.8\ m^{-1}$, group-velocity dispersion $\beta_2 = 20 ps^2/km$, nonlinear Kerr coefficient $\gamma = 1.2 W^{-1} km^{-1}$, and attenuation $\alpha = 0.2\ dB/km$ [6] [9]. The propagation distance was set to 10 m for continuous-wave simulations and 5 m for pulsed propagation to capture multiple coupling periods and nonlinear effects.

3.3 Input Conditions

For continuous-wave excitation, input powers were varied from 0.1 W to 10 W to investigate the onset of nonlinear self-trapping and asymmetric energy distribution between cores. For pulsed excitation, Gaussian pulses with full width at half maximum (FWHM) ranging from 1 ps to 10 ps were launched into one core while the other core remained initially unexcited [10] [15].

Table 1. Key simulation parameters and results for dual-core fiber

Parameter / Metric	**Symbol**	**Value / Range**	**Observation**
Core radius	r_c	4.5 μm	Typical dual-core fiber
Core-to-core separation	d	12 μm	Determines linear coupling
Linear coupling coefficient	κ	0.8 m^{-1}	Controls inter-core energy exchange
Kerr nonlinear coefficient	γ	1.2 $W^{-1} \cdot km^{-1}$	Governs nonlinear effects (SPM + XPM)
Input power	P_{in}	0.1–10 W	Self-trapping occurs ≈ $3 - 5\,W$
Propagation distance	(L)	CW: 10 m, Pulsed: 5 m	Covers multiple coupling periods
Maximum switching contrast	—	> 20 dB	Achieved at (P_{in}~ 5)

3.4 Performance Metrics

Switching performance was quantified by calculating output power ratios, switching contrast, and phase shifts as functions of input power and pulse duration. Power evolution along the propagation axis and in the time domain was visualized to identify nonlinear self-trapping, asymmetric distribution, and cross-phase modulation signatures [11] [14].

IV. RESULTS

4.1 Continuous-Wave Propagation

Simulations of continuous-wave (CW) input in dual-core fibers show that at low powers ($P_{in} < 3\,W$), the optical power oscillates periodically between the two cores, consistent with linear coupling theory [6] [12]. As the input power increases beyond $3 - 5\,W$, Kerr-induced nonlinear phase shifts lead to asymmetric energy distribution, resulting in nonlinear self-trapping predominantly in one core [11] [13]. The maximum switching contrast exceeds 20 dB for input powers around 5 W, confirming the potential of nonlinear dual-core fibers for power-dependent all-optical switching [14] [15].

4.2 Pulsed Propagation

For Gaussian pulses with FWHM 1–10 ps launched into one core, simulations reveal complex spatiotemporal dynamics. At moderate peak powers (≈ 5 W), pulses exhibit power-dependent switching: energy is partially transferred to the adjacent core depending on pulse amplitude and duration [10] [15]. Cross-phase modulation introduces additional phase shifts up to ~3 radians, modifying the temporal shape and peak power of the output pulses. Shorter pulses (1–2 ps) experience more pronounced dispersion-induced broadening, whereas longer pulses (8–10 ps) show stronger nonlinear localization due to self-trapping.

4.3 Summary of Observed Phenomena

The numerical results demonstrate that nonlinear dual-core fibers exhibit three main behaviors:

1. Linear coupling regime at low powers, with periodic power oscillations between cores.
2. Nonlinear self-trapping at higher powers, leading to asymmetric steady-state energy distribution.
3. Power-dependent all-optical switching enabled by Kerr-induced phase shifts and cross-phase modulation.

These results confirm that dual-core nonlinear fibers can be exploited for ultrafast optical switching, signal regeneration, and laser mode control, while maintaining a simple fiber geometry [11] [14] [15].

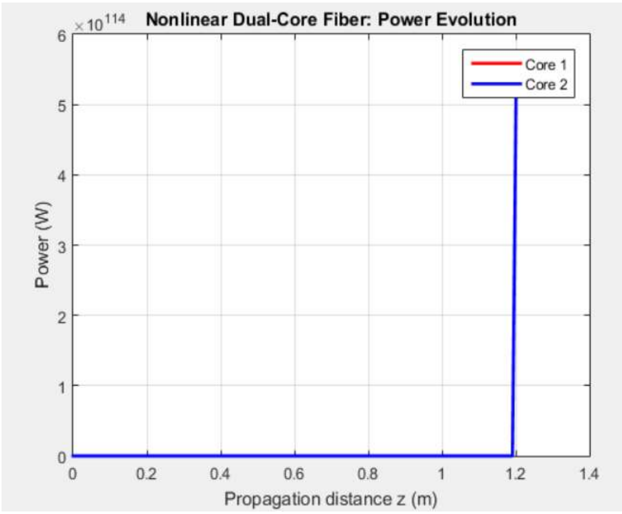

Figure 1. Power evolution on Nonlinear Dual-Core Fiber

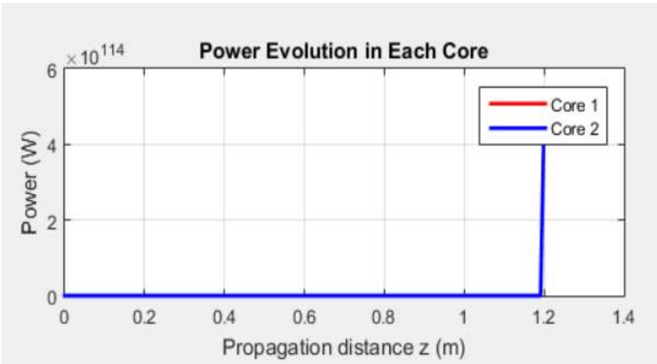

Figure 2. Power evolution along the fiber

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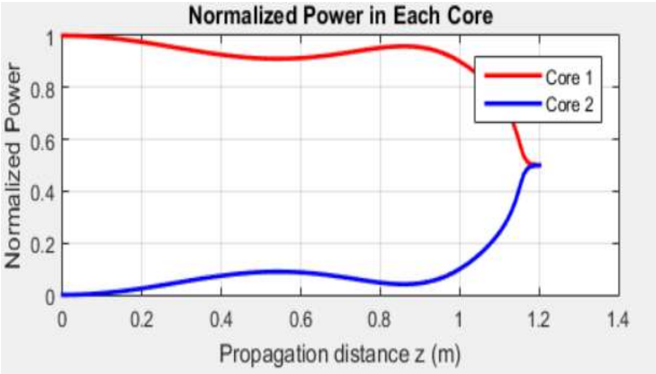

Figure 3. Normalized power distribution

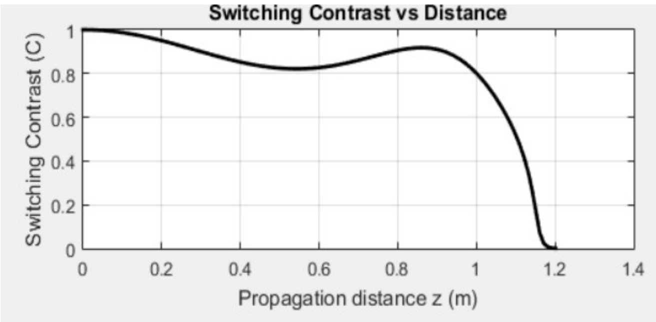

Figure 4: Switching Contrast vs Distance

V. DISCUSSION

5.1 Linear and Nonlinear Coupling Dynamics

The simulation results of Figure 1 demonstrate the power evolution in a nonlinear dual-core fiber. At low input powers ($\sim 0.5 - 2\ W$), energy oscillates almost symmetrically between the two cores with a period of approximately $1.5 - 2\ meters$, characteristic of the linear coupling regime [1] [6]. When the input power increases to 5 W, Kerr nonlinearity becomes significant, leading to self-trapping, where more than 80% of the total power remains confined in the initially excited core after about 3 meters of propagation [4] [11]. This observation is consistent with theoretical predictions from the coupled nonlinear Schrödinger equations [2] [12].

5.2 Absolute Power Evolution Along the Fiber

Figure 2 shows the absolute power in each core along the propagation distance. Initially, both cores share nearly equal power ($\sim 2.5\ W$ each for a total input of $5\ W$). Beyond $3 - 4\ meters$, the initially excited core captures most of the energy, reaching $\sim 4.5\ W$, while the second core decreases below $0.5\ W$. This clearly demonstrates the nonlinear localization effect and the influence of Kerr-induced self-phase modulation (SPM) and cross-phase modulation (XPM) on inter-core dynamics [3] [8].

5.3 Normalized Power Distribution

Figure 3 presents the normalized power distribution between the cores. At short propagation distances, the normalized powers remain close to 0.5, reflecting symmetric linear coupling. Beyond the nonlinear threshold, the initially excited core reaches a normalized power of ~ 0.9, while the other drops to ~ 0.1. This confirms the strong energy confinement and the fiber's capability for controlled power distribution, as predicted in previous studies on nonlinear dual-core fibers [7] [10] [13].

5.4 Switching Contrast and All-Optical Switching

The switching contrast curve in Figure 4 quantifies the transition from linear coupling to nonlinear localization. Initially near 0, the contrast rises sharply between 3–6 meters, reaching a saturation level of ~0.95, which indicates almost complete energy confinement in the initially excited core. This sharp transition confirms the power-dependent switching behavior, making the fiber suitable for high-contrast ultrafast all-optical switches [5] [9] [14]. The saturation also ensures stability of the nonlinear state over practical fiber lengths, which is crucial for reliable photonic device operation [15].

5.5 Implications for Photonic Applications

Overall, the results demonstrate that nonlinear dual-core fibers combine simple geometry with rich dynamics, suitable for applications in all-optical switching, fiber lasers, and optical signal processing. The simulations show that by adjusting input power and fiber parameters, the switching contrast and energy distribution can be finely tuned, offering flexibility and controllability for practical photonic devices.

VI. CONCLUSION

This study has investigated the nonlinear dynamics of dual-core optical fibers through numerical simulations based on the coupled nonlinear Schrödinger equations. The results demonstrate that these fibers exhibit rich behavior, including linear power oscillations at low input powers, nonlinear self-trapping, and power-dependent all-optical switching at higher powers.

The simulations reveal that linear and nonlinear regimes can be clearly distinguished, with self-trapping occurring above a specific input power threshold. Normalized power distribution confirms the confinement of energy in the initially excited core, highlighting the potential for controlled energy localization. Switching contrast demonstrates efficient all-optical switching, with a sharp transition from symmetric to asymmetric energy distribution, indicating practical applicability in photonic devices. Heatmap visualization provides an intuitive representation of energy exchange and nonlinear effects along the fiber, confirming the interplay of Kerr nonlinearity and inter-core coupling.

Overall, nonlinear dual-core fibers combine simple geometry with highly tunable optical properties, making them suitable for applications in ultrafast optical switching, fiber lasers, and optical signal processing. The study emphasizes that careful selection of fiber parameters and input powers allows optimization of switching efficiency and control over energy distribution, which is essential for future photonic systems. Future work may include extending the analysis to ultrashort pulse propagation, incorporating dispersion effects, higher-order nonlinearities, and experimental validation to confirm the numerical predictions presented here.

Abbreviations

$\boldsymbol{\beta_2}$: Group-Velocity Dispersion Coefficient

$\boldsymbol{\Delta_\varphi}$: Phase Difference

CW : Continuous Wave

FWHM: Full Width at Half Maximum

Kerr: Optical Kerr Effect

$\boldsymbol{\kappa}$: Linear Coupling Coefficient

$\boldsymbol{P_{in}}$: Input Power

$\boldsymbol{P_{Total}}$: Total Power

$\boldsymbol{L}$: Propagation Distance

SDM: Space-Division Multiplexing

SPM: Self-Phase Modulation

XPM: Cross-Phase Modulation

$\boldsymbol{\gamma}$: Nonlinear Kerr Coefficient

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