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Review of the Ph.D. Dissertation of Le Xuan The Tai

Controlling Energy Transfer in High-Index Contrast Multicore Soft-Glass Fibers

The doctoral dissertation authored by Le Xuan The Tai, M.Sc., was conducted under the guidance of Professor Marek Trippenbach, Ph.D., D.Sc., with additional supervision by Nguyen Viet Hung, Ph.D., as a joint endeavor in collaboration between the Warsaw University of Technology and the University of Warsaw. The primary focus of the thesis revolves around the all-optical switching of ultra-short solitonic pulses within double-core fibers (DCF) composed of soft glass exhibiting robust nonlinear properties. The research delves into various switching regimes, encompassing self-switching in both symmetric and asymmetric cores, as well as the switching of a low-energy pulse in an asymmetric fiber through the influence of a control pulse. Furthermore, the investigation extends to the propagation and switching dynamics of optical pulses in parity-time symmetric structures.

The applications of DCF structures in photonics are widespread, spanning areas such as fiber optic sensors, fiber lasers, and optical telecommunications. Specifically, the phenomena elucidated in the thesis pertain to the optical switching of light pulses, offering implications for multiplexers and demultiplexers. Owing to the pronounced nonlinear effects, the propagating pulse may undergo diverse outcomes, including being locked to the original core, undergoing a permanent switch to the other core, or manifesting oscillatory or chaotic behavior. Consequently, a comprehensive understanding of the factors governing the switching behavior is imperative for the development of the aforementioned devices. Within this context, the selection of the research topic is deemed judicious.

The dissertation does not contain well defined theses. Instead, it opts for an exploration of the physics behind pulse propagation in Double-Core Fibers (DCF). The investigation unfolds through both theoretical analysis and practical experiments, delving into four specific cases, each dedicated to a separate chapter:

1. examining optical switching in symmetrical dual-core highly nonlinear optical fibers;
2. exploring self-trapping and switching in asymmetrical dual-core highly nonlinear fibers;
3. investigating the control of dual-wavelength switching in asymmetric dual-core fiber;
4. scrutinizing PT-symmetry in dual-core photonic crystal fibers.

While the research maintains a solid and rigorous approach, the first three cases are mostly build upon previous work conducted at the University of Warsaw. The most significant novelty emerges in the fourth case, where a distinctive combination of balanced loss and gain results in the formation of a parity-time (PT) symmetric system. This configuration, relatively unexplored in optical fibers, introduces a noteworthy dimension to the overall research.

The outcomes detailed in the thesis regarding PT-symmetric structures have been recently published in *Mattia Longobucco, Le Xuan The Tai, Viet Hung Nguyen, Jarosław Cimek, Bartosz Pałuba, Ryszard Buczyński, and Marek Trippenbach, "PT-symmetry breaking in dual-core phosphate-glass photonic crystal fibers," Opt. Express 32, 1562-1575 (2024)*. Notably, other publications authored by the thesis contributor include *Viet Hung Nguyen, Le Xuan The Tai, Mattia Longobucco, Ryszard Buczyński, Ignac Bugár, Ignas Astrauskas, Audrius Pugžlys, Andrius Baltuška, Boris Malomed, and Marek Trippenbach, "Self-trapping and switching of solitonic pulses in mismatched dual-core highly nonlinear fibers," Chaos, Solitons & Fractals 167, 113045 (2023)* and *Viet Hung Nguyen, Le Xuan The Tai, Ignac Bugar, Mattia Longobucco, Ryszard Buczyński, Boris A. Malomed, and Marek Trippenbach, "Reversible ultrafast soliton switching in dual-core highly nonlinear optical fibers," Opt. Lett. 45, 5221-5224 (2020)*. While this publication record is substantial for a Ph.D. candidate, the absence of Mr. The Tai as the first author in any of these papers suggests that his role may not have been primary in either of them.

The dissertation is structured into an introduction, five chapters, and an appendix. In the introduction, the primary emphasis is placed on delineating the content of the entire work, offering a broad overview. However, the motivation and significance of the research are only briefly touched upon. It would be beneficial to allocate more attention to these aspects, especially considering the absence of well-defined theses. A more detailed exploration of the motivation and significance would not only provide a clearer context for the research but also address the need for explicit overarching themes in the work.

Chapter one presents the foundational theory and equations governing both linear and nonlinear propagation in optical fibers. The chapter elucidates Maxwell's equations and introduces susceptibility tensors of the first, second, and third order. Subsequently, it introduces the Slow Varying Envelope (SVE) approximation for modeling the propagation of light pulses and establishes the groundwork for the nonlinear Schrödinger equation. This equation is then extended to accommodate the scenario of two coupled waveguides.

The chapter concludes with Section 1.4, offering a relatively broad description of photonic-crystal fibers. However, a notable absence is observed in the form of illustrations depicting cross-sections of the discussed designs and visually explaining the addressed physical phenomena. The inclusion of such illustrations would significantly enhance the reader's comprehension of the presented concepts.

Chapters 2–5 showcase the outcomes of measurements and calculations conducted by the author. In Chapter 2, the investigation centers on the switching mechanism in a symmetric dual-core photonic-crystal fiber. Initially, the author presents a diagram illustrating the cross-section of a multi-core fiber, accompanied by specific details regarding its material properties and manufacturing. Subsequently, experimental results are showcased through camera images capturing the fiber output at varying pulse powers, revealing the dependence of switching behavior on input power.

The subsequent sections of this chapter delve into the theoretical analysis and computer simulations of the observed phenomenon. The author identifies and demonstrates three dynamic regimes: trapping in the excited channel, cross-core switching, and inter-core oscillations. Additionally, soliton fission is showcased. While these effects are undeniably intriguing, there is a sense of regret that they have not been subject to more in-depth investigation, which could potentially unveil further nuances and insights.

In Chapter 3, the author introduces asymmetry to the cores and explores its impact on switching behavior. To facilitate numerical analysis, rescaled physical parameters are introduced. The author conducts numerical simulations across varying pulse powers and asymmetry parameters, elucidating their roles in influencing the switching behavior. Similar to Chapter 2, the author presents a computed diagram delineating different regimes (no switching, cross-switching, oscillations, and low contrast). A noteworthy aspect is the author's effort to compare these theoretical predictions with experimental results, revealing a commendable alignment between the two, thereby enhancing the credibility of the presented findings.

While Chapters 2 and 3 delve into the self-switching dynamics of a propagating pulse, Chapter 4 shifts focus to the switching of a low-energy pulse influenced by a control wave operating at a different wavelength. Similar to previous chapters, this section incorporates both experimental and theoretical analyses. The author systematically examines the impact of control pulse energy on switching performance. Additionally, since two separate pulses are under consideration, the chapter explores the influence of pulse delay.

A key finding emerges: optimal switching performance is achieved when the control pulse, with just the right energy, temporally overlaps with the signal pulse. This optimal synchronization can be attained by either adjusting the control pulse energy or the delay, allowing the signal pulse to interact effectively with the slope of the control pulse.

The concluding chapter of the thesis shifts its focus to the exploration of pulse switching in a PT-symmetric system. The author initiates this investigation by presenting the foundational theory behind the parity-time concept and elucidates the significance of an exceptional point. Subsequently, a novel fiber design is proposed, aiming to establish PT-symmetric conditions, and the theoretical exploration of pulse propagation within this regime ensues. Notably, the analysis of the role of dispersion on the location of the exceptional point stands out as particularly intriguing.

In contrast to the preceding chapters, this final chapter adopts a purely theoretical approach. This distinction arises from the early conceptual stage of obtaining PT-symmetric fiber structures. Despite its theoretical nature, the presented concept—once certain issues (discussed later in this review) are addressed—serves as fertile ground for further research, laying the foundation for ongoing exploration and development in this domain.

The dissertation wraps up with a concise one-page summary, providing a succinct overview of the key findings and contributions. Following this summary, an appendix is included, presenting the formulation of a split-step Fourier method. This methodological appendix adds valuable technical insight and detail to the document, enhancing the understanding of the numerical techniques employed in the research.

As previously mentioned, the methodology underpinning all theoretical analyses in the thesis is thoroughly presented in Chapter 1, offering detailed derivations of pertinent equations. This comprehensive exposition instills confidence in the accuracy of subsequent results. The numerical method employed for calculations, the split-step Fourier method, is thoughtfully detailed in the appendix. Its presentation stands out for its clarity, accompanied by a stability analysis of the method, which is commendable. However, a notable drawback is the absence of an equivalently detailed description of the experimental methodology, compounded by the lack of diagrams illustrating the utilized setups.

The results presented in Chapters 2–5 exhibit robustness and reflect the author's knowledge in the field of fiber optics at the level expected from a graduated Ph.D., although not surpassing it. Regrettably, the conclusions drawn in Chapters 2–4 do not introduce particularly novel insights, closely resembling findings already published by researchers from the Nonlinear Optics Group and Photonics Department at the University of Warsaw.

The most intriguing aspects emerge in Chapter 5, particularly in the exploration of PT-symmetric DCFs, with a specific focus on the role of dispersion investigated in Section 5.5.3. However, there is a notable issue within this chapter that I anticipate being addressed and resolved during the defense. On page 113, the author examines a Yb_2O_3-doped gain core and a lossy CuO-doped core. To achieve a balance between gain and loss, the author investigates a fiber laser from Ref. [85], which has a slope efficiency of 36.2%. This is then compared to the attenuation of the lossy core, whose length is computed to exhibit 36.2% attenuation based on the Lambert Law.

However, it is essential to note that this line of reasoning appears flawed and relies on the comparison of two unrelated quantities. The PT-symmetric condition necessitates that the attenuation of the lossy core, measured in dB/m, aligns with the gain of the gained core for the specific wavelength, also measured in dB/m. The referred slope efficiency of 36.2% represents the ratio of emitted power at the lasing wavelength (approximately 1000 nm) to the pumping light power (with a wavelength of 973.5 nm and a 3 nm bandwidth). This efficiency is an intrinsic property of a laser and depends not only on the gain in the fiber but also on factors such as mirror reflectivity. Importantly, for a PT-symmetric system, no lasing is required. Indeed, the double-core fiber investigated in the thesis is not a laser.

In my view, this discrepancy reflects a misunderstanding of the underlying physics by the Ph.D. candidate and warrants careful consideration and clarification during the defense.

Several other issues merit attention and clarification during the defense. In Section 2.3.1, the author asserts that the linear effect is a decisive factor in determining the point of switching between the excited and non-excited core. However, Figure 2.10 presents a comparison between switching in linear (dashed) and nonlinear (solid) regimes for various values of parameter a. Notably, for a value of $a = 2.0$, nonlinear switching occurs at $3/2$ times the coupling length (l_c), while for $a = 2.1$, it occurs at $1\,l_c$. This qualitative difference contradicts the author's claim and has not been adequately addressed in the main text.

Furthermore, in Chapter Two, Section 2.3.3 introduces an intriguing chart of the dynamical regimes of the system (Fig. 2.14). However, as I have already mentioned, the discussion surrounding this chart lacks depth. Specifically, there is a need for a more thoughtful investigation into the physics governing the shape of the boundaries between the oscillation, trapping, and switching regions. A more detailed insight into this matter would enhance the understanding of the presented results and contribute to the overall coherence of the thesis.

While the overall structure of the dissertation is sound, it is marred by a significant number of typos and language errors, resulting in poor English throughout the text. Numerous instances of repeated sentences or entire paragraphs further detract from the overall clarity. A recurring issue is the reference to figures that either do not exist or present information inconsistent with the corresponding text descriptions. In the introduction, there is a discrepancy between the author's claim about the appendix content—stating it presents fast Fourier transform—and the actual content, which describes the split-step Fourier method.

Furthermore, many figures suffer from being excessively small, rendering them illegible. Additionally, there is a frequent mismatch between the order of figures in the text and their actual order. These discrepancies hinder the reader's ability to follow and comprehend the material effectively.

An area of improvement is the presentation of data, such as in Fig. 4.9, where aligning scales in both panels would facilitate a more straightforward comparison between theoretical and experimental results. Addressing these issues would significantly enhance the overall quality and cohesiveness of the dissertation.

In summary, I acknowledge that the author has demonstrated an understanding of fiber optics and nonlinear optics, showcasing the ability to independently conduct scientific research. The dissertation itself presents an original solution to a scientific problem related to the control of light pulse propagation in double-core fibers. Despite the critical remarks included in this review, I confirm that Le Xuan The Tai's doctoral thesis meets the requirements set forth by the Law of July 20, 2018, on Higher Education and Science. I recommend its approval for public defense.

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