

REVIEW ARTICLE

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Advancements in ultrafast photonics: confluence of nonlinear optics and intelligent strategies

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Abstract

Automatic mode-locking techniques, the integration of intelligent technologies with nonlinear optics offers the promise of on-demand intelligent control, potentially overcoming the inherent limitations of traditional ultrafast pulse generation that have predominantly suffered from the instability and suboptimality of open-loop manual tuning. The advancements in intelligent algorithm-driven automatic mode-locking techniques primarily are explored in this review, which also revisits the fundamental principles of nonlinear optical absorption, and examines the evolution and categorization of conventional mode-locking techniques. The convergence of ultrafast pulse nonlinear interactions with intelligent technologies has intricately expanded the scope of ultrafast photonics, unveiling considerable potential for innovation and catalyzing new waves of research breakthroughs in ultrafast photonics and nonlinear optics characters.

Introduction

Ultrafast pulses have widespread applications, encompassing optical frequency metrology^{1–3}, precision ranging^{4–6}, precision manufacturing^{7–10}, and astronomical observation^{11,12}. Distinguished from conventional solid-state lasers, fiber lasers, which are characterized by their flexible waveguides, provide notable advantages¹³ including the elimination of collimation requirements, superior beam quality, and cost efficiency, thereby establishing themselves as a primary focus of research in the field of ultrafast lasers¹⁴ while concurrently offering an ideal platform for the exploration of nonlinear effects^{15,16}. The generation of a picosecond (ps) or femtosecond-scale (fs) ultrafast pulses relies predominantly on Q-switching (QS)^{17,18} and mode-locking methodologies^{19–21}. However, QS generally produces pulse durations on the nanosecond scale, thereby necessitating mode-locking techniques to achieve pulse

widths at least an order of magnitude narrower than those generated by QS²². Fiber-based mode-locking techniques, which consist of active mode-locking, passive mode-locking (PML), and hybrid mode-locking, have been widely investigated for ultrafast pulse generation. Unlike active and hybrid mode-locking that necessitate the introduction of modulating devices within the resonator, leading to increased complexity and limited applicability, PML has become the most extensively applied and thoroughly researched method²³ due to the inherent advantages of its compact structure, easy-to-implement, and capability of generating femtosecond pulses²⁴.

In the pursuit of enhancing pulse energy, output power, etc., researchers have continuously explored novel PML mechanisms and advanced laser materials, leading to the constant introduction of various mode-locking techniques. Current research trends predominantly explore saturable absorbers based on nanomaterials^{25,26}, nonlinear optical loop mirrors (NOLMs)^{27,28}, nonlinear multimode interference (NLMMI)^{29,30}, and nonlinear polarization evolution/rotation (NPE/NPR)^{31–33}. Mamiyev oscillators, etc. Among these, the PML of fiber lasers based on NPR which exploits polarization control and Kerr nonlinearity³⁴, has garnered attention due to structural simplicity^{34,35,36} and rich dynamical states^{36–38}.

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Photonics Nonlinear Optics And Ultrafast Phenomena

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