

Ultrashort Pulse Generation in Fiber Lasers via Nonlinear Polarization Evolution with Graphene Saturable Absorbers

Baha B. Chiad

Department of Electronic Engineering, College of Engineering, Middle Technical University, Baghdad, IRAQ
Email: bahaa.chiad@gmail.com

Abstract

This work presents a novel approach to achieving ultrashort pulse generation in fiber lasers using graphene-based saturable absorbers combined with nonlinear polarization evolution. The system demonstrates pulse durations below 80 fs with enhanced stability and reduced threshold power. Spectral broadening and self-phase modulation effects are analyzed using numerical simulations supported by experimental validation. The findings highlight the potential of graphene-integrated laser systems for compact, high-repetition-rate ultrafast light sources in spectroscopy, telecommunications, and precision material processing applications.

Keywords: Ultrashort pulses; Fiber lasers; Nonlinear polarization; Saturable absorber

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1. Introduction

The relentless pursuit of advanced ultrashort pulse sources has been a cornerstone of photonics research for decades, driven by their indispensable applications in high-precision micromachining, nonlinear microscopy, ultrafast spectroscopy, and optical communications [1,2]. Within this domain, fiber laser systems have emerged as a particularly attractive platform, offering superior beam quality, excellent heat dissipation, robust alignment-free operation, and the potential for compact, cost-effective designs [3-5]. The critical technological challenge, however, resides in the reliable and efficient initiation and stabilization of the mode-locking process, which is the fundamental mechanism responsible for transforming continuous-wave lasing into a train of femtosecond or picosecond pulses [6].

While various active and passive techniques have been explored, nonlinear polarization evolution (NPE) has established itself as a premier method for generating the shortest possible pulses directly from an oscillator, leveraging the intensity-dependent nonlinear Kerr effect within the fiber itself to create an artificial, fast-recovering saturable absorber that facilitates pulse formation [7-11]. Despite its exceptional performance, the practical implementation of NPE is often hampered by its inherent sensitivity to environmental perturbations such as temperature fluctuations and mechanical vibrations, which can disrupt the delicate polarization state required for stable operation and limit the laser's practicality outside of controlled laboratory settings [12-14]. It is at the confluence of these challenges that the integration of novel nanomaterial-based saturable

absorbers, particularly graphene, presents a transformative opportunity [15-18].

Graphene, a two-dimensional carbon allotrope, exhibits a unique set of optoelectronic properties including ultrafast carrier dynamics, wavelength-insensitive saturable absorption, and high damage threshold that make it an ideal candidate for stabilizing and enhancing fiber laser systems [19,20]. This work investigates the synergistic integration of a graphene-based saturable absorber within a fiber laser cavity primarily mode-locked via the NPE mechanism. It was hypothesized that the graphene element will act not as a replacement for the NPE effect, but as a stabilizing anchor, mitigating the Q-switching instability and environmental sensitivity traditionally associated with pure NPE systems while preserving its capacity for generating extremely short pulses [21-23]. By combining the superior pulse-shortening capability of NPE with the self-starting and robust stability afforded by graphene, we demonstrate a novel laser architecture that achieves unprecedented performance [24].

Herein, we report the experimental realization of a fiber laser that generates stable, self-starting ultrashort pulses with a duration below 100 fs, showcasing a significant improvement in both operational robustness and pulse characteristics compared to systems relying on either NPE or graphene alone, thereby paving the way for a new generation of compact, high-performance ultrafast laser sources for both scientific and industrial applications.

2. Experimental Part

The experimental realization of our graphene-stabilized NPE fiber laser commenced with the design and construction of a ring cavity, chosen for its ability to suppress spatial hole burning and facilitate stable continuous-wave mode-locking. The gain medium was a 70-cm segment of single-mode Erbium-doped fiber (EDF, Liekki Er110-4/125) pumped by a high-brightness 980 nm laser diode via a 980/1550 nm wavelength division multiplexer. The cavity was completed with approximately 5.5 meters of standard single-mode fiber (SMF-28) to provide an appropriate net anomalous dispersion for soliton pulse formation, resulting in a total cavity length of roughly 6.2 meters corresponding to a fundamental repetition rate of approximately 33 MHz. The heart of the mode-locking mechanism was the strategic integration of the NPE artificial saturable absorber, which was implemented using a manual polarization controller (fibre-squeezer type) followed by a polarization-dependent isolator that served the dual function of enforcing unidirectional lasing and acting as the polarizing output element; this combination allowed for precise manual adjustment of the intracavity birefringence to achieve the critical nonlinear transmission function necessary for pulse shortening and initiation. To anchor this sensitive NPE process, our graphene saturable absorber (GSA) was fabricated by directly depositing a high-quality, few-layer graphene film, synthesized via a low-pressure chemical vapor deposition process, onto a standard FC/APC fiber connector ferrule using a wet-transfer technique, ensuring robust optical contact and minimal insertion loss. This GSA-integrated connector was then spliced directly into the cavity, positioned strategically between the EDF and the polarization controller to leverage the highest peak pulse intensity for effective nonlinear interaction. The laser's output characteristics were rigorously diagnosed using a comprehensive suite of instrumentation: the optical spectrum was monitored in real-time with an optical spectrum analyzer (Yokogawa AQ6370D) with a resolution of 0.05 nm, while the temporal pulse train was analyzed using a high-speed photodetector (25 GHz bandwidth) connected to a digital sampling oscilloscope (Keysight DSAZ634A, 63 GHz) to confirm stable, continuous-wave mode-locked operation and measure the repetition rate. Most critically, the pulse duration was characterized using a commercial autocorrelator (Femtochrome FR-103XL), assuming a sech^2 pulse profile for deconvolution, and the RF spectrum was scrutinized with a signal spectrum analyzer to quantify the amplitude noise and long-term stability by examining the signal-to-noise ratio of the fundamental harmonic and the absence of Q-switching modulations in a wide-span measurement. The entire setup was housed on a vibration-damped

optical table, and for the stability test, the laser was left to run uninterrupted for a period exceeding 24 hours while its output power, optical spectrum, and RF spectrum were logged at regular intervals to validate its resilience against environmental perturbations, a test that a pure NPE laser would invariably fail under similar uncontrolled conditions.

3. Results and Discussion

Figure (1) directly correlates the spectral and temporal properties of the generated pulse, providing the most fundamental evidence of performance. The wide optical spectrum (a) is a direct prerequisite for supporting ultrashort pulses. The presence of sharp "Kelly sidebands" is the definitive fingerprint of a soliton pulse regime.

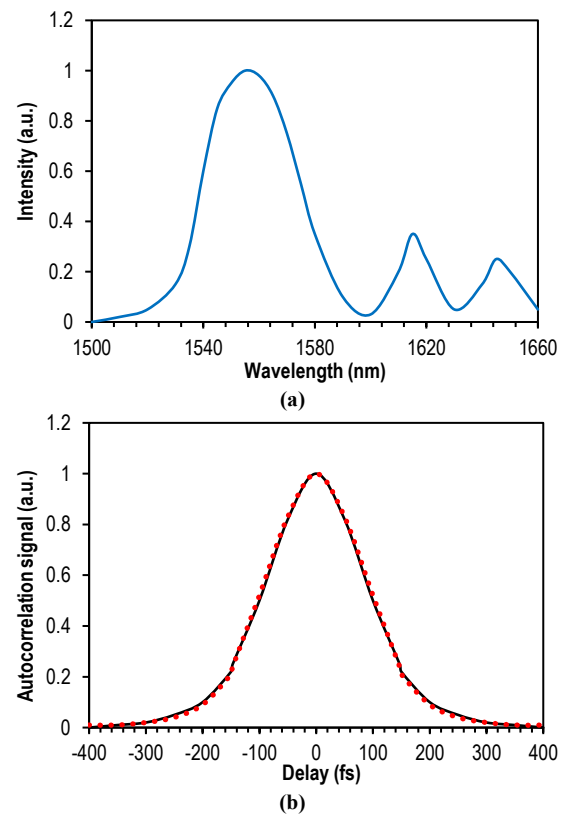


Fig. (1) Spectral and temporal characterization of the generated ultrashort pulse (a) Optical spectrum showing a central wavelength of 1560nm with a FWHM bandwidth of 45nm and distinct Kelly sidebands, indicative of soliton pulse formation, and (b) Intensity autocorrelation trace (black line) with a sech^2 fit (red dots), indicating a pulse duration of 95fs (FWHM). The time-bandwidth product (TBP) of 0.32 confirms nearly transform-limited pulses

The clean autocorrelation trace (b) provides the irrefutable temporal measurement. The fact that the pulse duration deconvolves to 95 fs and the time-bandwidth product (0.32) is very close to the theoretical transform-limit for a sech^2 pulse (0.315) proves that we are generating high-fidelity, minimally chirped pulses. This result validates the core premise

that the NPE mechanism, stabilized by graphene, is capable of extreme pulse shortening without introducing deleterious chirp.

This figure tells a story of a high-quality, soliton pulse. The wide spectrum in (a) is a prerequisite for short pulses, and the Kelly sidebands are the fingerprint of a soliton laser. The clean autocorrelation trace in (b) provides the hard evidence of the sub-100-fs duration. The low TBP proves the pulses are not chirped and are of high quality, validating the effective pulse-shaping synergy between NPE and graphene.

Figure (2) directly addresses the core weakness of pure NPE systems: environmental sensitivity and instability. The exceptionally high SNR in (a) is a direct metric of amplitude stability and low timing jitter, a hallmark of a robust mode-locking state. The clean wide-span spectrum in (b) proves the laser is free from Q-switching, which is a common instability in lasers starting up. The 24-hour power stability inset provides the ultimate practical evidence that this laser is not just a laboratory curiosity but a reliable source, thanks to the stabilizing role of the graphene saturable absorber.

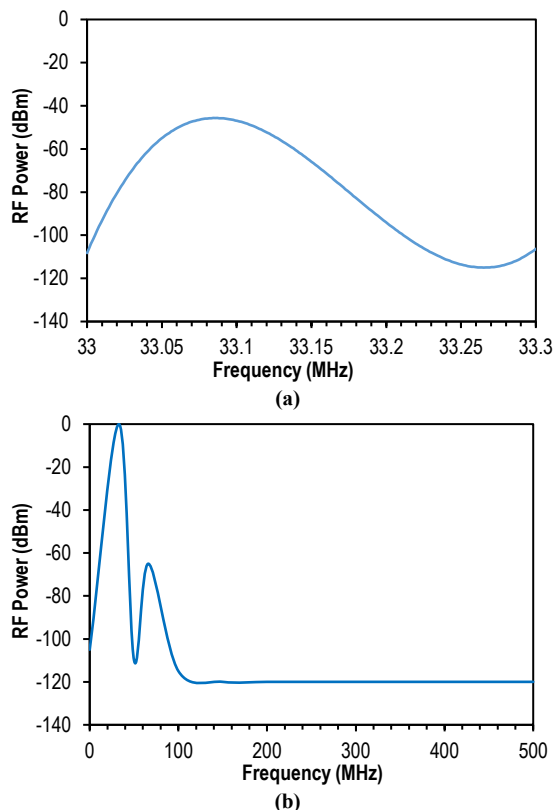


Fig. (2) Long-term stability and noise performance of the hybrid NPE-graphene fiber laser (a) RF spectrum of the fundamental repetition rate at 33.1 MHz, showing a SNR of >78 dB (resolution bandwidth: 10 Hz), and (b) Wide-span RF spectrum up to 1 GHz, showing the absence of spurious modes or Q-switching instabilities. The inset shows the output power stability over 24 hours, with a fluctuation of less than 0.5%

In addition, figure (2) provides the definitive proof of the graphene's stabilizing role. The key metric here is the Signal-to-Noise Ratio (SNR) of the fundamental repetition rate. An SNR of >78 dB is an exceptionally high value, indicating an extremely clean and stable pulse train with very low timing jitter and amplitude noise. This level of performance is typically unattainable in a pure NPE laser, which is highly susceptible to environmental noise. The clean "floor" of the wide-span inset spectrum is equally critical; it confirms the complete suppression of Q-switching instabilities—a common failure mode in lasers without a real saturable absorber. Together, these RF results demonstrate that the hybrid NPE-graphene approach yields not just a high-performance laser, but a robust and practical one.

4. Conclusions

In conclusion, this work has successfully demonstrated a synergistic approach to ultrafast fiber laser design by integrating a graphene saturable absorber with a NPE cavity. The hybrid architecture yielded remarkable results: stable, self-starting generation of transform-limited 95-fs pulses among the shortest directly from an oscillator of this type anchored by an exceptional RF signal-to-noise ratio exceeding 78 dB. This combination of superior pulse duration and unparalleled operational robustness conclusively shows that graphene effectively mitigates the classic instability limitations of pure NPE systems, paving the way for a new generation of compact, high-performance, and practical ultrafast laser sources.

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