AFRL-AFOSR-JP-TR-2023-0077

The Pure-Quartic Soliton Laser

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UNIVERSITY OF SYDNEY
LEVEL 3, ADMINISTRATION BUILDING F23
THE UNIVERSITY OF SYDNEY, NSW, 2006
AUS

04/17/2023
Final Technical Report

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Air Force Research Laboratory
Air Force Office of Scientific Research
Asian Office of Aerospace Research and Development
Unit 45002, APO AP 96338-5002

REPORT DOCUMENTATION PAGE

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1. REPORT DATE	**2. REPORT TYPE**	**3. DATES COVERED**	
20230417	Final	**START DATE** 20190801	**END DATE** 20220731

4. TITLE AND SUBTITLE
The Pure-Quartic Soliton Laser

5a. CONTRACT NUMBER	**5b. GRANT NUMBER**	**5c. PROGRAM ELEMENT NUMBER**
	FA2386-19-1-4067	
5d. PROJECT NUMBER	**5e. TASK NUMBER**	**5f. WORK UNIT NUMBER**

6. AUTHOR(S)
Martijn de Sterke

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	**8. PERFORMING ORGANIZATION REPORT NUMBER**
UNIVERSITY OF SYDNEY LEVEL 3, ADMINISTRATION BUILDING F23 THE UNIVERSITY OF SYDNEY, NSW 2006 AUS	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**	**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**
AOARD UNIT 45002 APO AP 96338-5002	AFRL/AFOSR IOA	AFRL-AFOSR-JP-TR-2023-0077

12. DISTRIBUTION/AVAILABILITY STATEMENT
A Distribution Unlimited: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Temporal optical solitons are a class of optical pulses arising from the interplay between anomalous dispersion and self-phase modulation (SPM). These pulses can propagate across long distances while maintaining their spectral and temporal shapes, with applications in telecommunications, lasers and optical memories [1-4]. Historically, only solitons balancing SPM and negative second-order dispersion have been studied and used in photonic application. In 2016, solitons arising from fourth-order dispersion and SPM were observed for the first time in silicon photonic crystals [5]. Subsequent theoretical and numerical studies showed that these pulses, “pure-quartic solitons” (PQSs), have the potential to overcome the intrinsically low-energy limit of conventional solitons [6,7]. This work also suggested that modifying the linear properties can significantly enhance the nonlinear properties of these systems [7]. In this project we built and demonstrated the first laser system operating in PQS regime and we experimentally confirm their physical properties [8]. We then extended this initial work and demonstrated that solitons can arise with any negative even order of dispersion [9]. Finally, by advanced tailoring of the linear dispersion we generated a novel a family of high complex pulses consisting of several, equally spaced spectral components that are nonlinearly bound and propagate as a single unit [10]. The associated theory that we developed shows that this leads to enhancement of the effective nonlinear parameter that increases with the number of spectral components. Therefore, this novel technique allows for the generation of ultrashort pulses with low pump energy.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	SAR	5
U	U	U		

19a. NAME OF RESPONSIBLE PERSON	**19b. PHONE NUMBER** *(Include area code)*
JEREMY KNOPP	315-227-7006

Standard Form 298 (Rev.5/2020)
Prescribed by ANSI Std. Z39.18

FINAL REPORT: THE PURE-QUARTIC SOLITON LASER

Section 1: Structured Survey Questions

Award Information

Award number: FA2386-19-1-4067
Principal Investigator: Prof. Martijn de Sterke

Section 2: Technical report

Abstract:

Temporal optical solitons are a class of optical pulses arising from the interplay between anomalous dispersion and self-phase modulation (SPM). These pulses can propagate across long distances while maintaining their spectral and temporal shapes, with applications in telecommunications, lasers and optical memories [1-4]. Historically, only solitons balancing SPM and negative second-order dispersion have been studied and used in photonic application. In 2016, solitons arising from fourth-order dispersion and SPM were observed for the first time in silicon photonic crystals [5]. Subsequent theoretical and numerical studies showed that these pulses, "pure-quartic solitons" (PQSs), have the potential to overcome the intrinsically low-energy limit of conventional solitons [6,7]. This work also suggested that modifying the linear properties can significantly enhance the nonlinear properties of these systems [7]. In this project we built and demonstrated the first laser system operating in PQS regime and we experimentally confirm their physical properties [8]. We then extended this initial work and demonstrated that solitons can arise with any negative even order of dispersion [9]. Finally, by advanced tailoring of the linear dispersion we generated a novel a family of high complex pulses consisting of several, equally spaced spectral components that are nonlinearly bound and propagate as a single unit [10]. The associated theory that we developed shows that this leads to enhancement of the effective nonlinear parameter that increases with the number of spectral components. Therefore, this novel technique allows for the generation of ultrashort pulses with low pump energy.

Accomplishments:

- **Research objectives:**

Our project had two overarching goals: to generate scientific breakthroughs resulting from the initial discovery of the physics governing PQSs, and to use this new physics to create an innovative class of lasers with huge potential for technological impact. We also planned to investigate the characteristics of the PQSs and to build a generic platform for the design of advanced PQS laser cavities. We expected to generate PQSs in a photonic crystal fiber (PCF) with dominant negative fourth-order dispersion, and then to build a laser cavity using this PCF. Finally, we explored an alternative approach to design a waveguide with the required dispersion based on optical fiber with nanoaperture.

1. Design, construct and characterize the first PQS laser
    a. Design and build a laser operating in PQS regime, using a controllable intracavity pulse-shaper allowing for the tuning of the net cavity dispersion.
    b. Characterize the output pulses using spectral, temporal and phase-resolved techniques.
    c. Create a numerical model for the PQS laser pulse formation based on lump shaping and gain elements.
2. Experimentally observe and study ultrashort PQS propagation in photonic crystal fiber (PCF)
    a. Characterize the PCF with the necessary parameters to support the generation of PQSs.

    b. Develop and understand the energy scaling properties and limits of existence of PQSs.
    c. Experimentally characterize PQSs in PCF.
3. Design, construct and characterize an all-fiber PQS laser
    a. Advance the PQS laser model to simulate gain and pulse-shaping in the same medium.
    b. Design and fabricate an erbium-doped PCF to support PQS generation with gain.
    c. Construct and characterize a fiber-based PQS laser using doped and undoped PCF supporting PQS formation and propagation.
4. Design an optical fiber with nanoaperture with negative quartic dispersion for PQS propagation
    a. Design and simulate a nanoaperture optical fiber with dominant quartic dispersion
    b. Simulate PQS generation in a laser cavity including the designed fiber

For the first phase of the project, we built a cavity laser, based on the principle of dispersion-management, incorporating a spectral pulse-shaper. The cavity did not include optical fiber with the appropriate dominant quartic dispersion. This integration of this device allowed for the tailoring of the net-cavity dispersion.
The second and third phases of the project relied on a collaboration with another university with the capabilities of fabricating silica PCFs. We worked with the University of Jena for the fabrication of PCF based on the design we developed [11].
The fourth phase of the project, which will investigate an alternative route for the fabrication of optical fibers supporting PQS generation and propagation. This phase was based on a technique that has been recently developed [12] at the Leibniz Institute of Photonic Technology in Jena, Germany.

- **Details of accomplishments:**

During this reporting period we achieved several of the objectives listed in the previous section. Moreover, some of these achievements led to other significant advances in nonlinear optics and key scientific publications.

1. We fully completed the first phase of the proposed project (**research objective 1**) by building and characterizing the first laser emitting PQS pulses. In particular, we experimentally demonstrated the novel energy scaling properties of the PQSs, which can overcome that of conventional solitons. These results were published in *Nature Photonics* [8] and presented in a couple of invited talks at CLEO US 2020 and SPIE Photonics West 2021.
2. We successfully developed two numerical models to simulate the dynamics of the laser cavity including the pulse-shaper device and in a laser using negative quartic dispersion fibers (**research objectives 1c and 3a**). A detailed description of this model can be found in Refs. [8,13]
3. Building on the versatile laser setup that we developed, we also demonstrated numerically and experimentally the existence of an infinite family of solitons, arising between SPM and any negative even order of dispersion. These results led to a key publication [9] and also triggered further studies to look for analytical solutions of the generalized nonlinear Schrodinger equations [14, 15].
4. Using the flexibility of the experimental setup developed during the first phase, we investigated a novel family of pulses arising from spectrally periodic solitons centered at different frequencies but co-propagating at the same group-velocity [7, 16]. We reported the first experimental observation of this novel family of nonlinear pulses. More importantly, we showed that these pulses have a highly non-uniform carrier that leads to the enhancement of effective nonlinearities. These results demonstrate a novel technique to enhancement nonlinear effects in photonics [10].
5. Following the demonstration that linear dispersion can significantly modify the outcome of nonlinear systems, we study other systems governed by these competing effects. Specifically, we theoretically and numerically studied optical pulses propagating self-similarly in systems with positive even dispersion, Kerr nonlinearity and gain. We derived and found general asymptotic solutions for any even order of dispersion. These results were published in two key papers (Refs. [17, 18]).

6. We investigated an alternative approach to the PCF to achieve dominant negative quartic dispersion in an optical fiber (**research objective 4**). We carried a systematic numerical study of this platform for the physical parameters required. However, our numerical results showed that this approach is currently unsuitable to achieve dominant negative quartic dispersion over a large spectral bandwidth using optical fiber with nanoaperture.
7. We developed a novel theory and performed numerical simulations to describe the evolution of optical pulses under the effects of high-order dispersion. These results provide a new general and intuitive description of these physical effects [19].

- **Communication of results:**

Our project embraced several new underpinning engineering and physics concepts in nonlinear optics and laser physics. The results of this project were mainly disseminated through the publications in international peer-reviewed scientific journal. We published a total of 8 articles, including two key papers in Nature Photonics and Nature Physics, and another one is currently under review (see Publication section). We also presented our results to the scientific community in international conferences. We gave a total of 5 invited presentations, including 3 invited talks at CLEO US 2020, SPIE Photonics West 2021 and Europhoton 2020. Finally, we presented our results to a broader audience via public seminars within Australian, New Zealand and European universities.

Impacts:

- **Development of the principal disciplines of the project**

The simple laser cavity configuration developed in this project offers and exceedingly flexible testbed for the generation and the study of optical pulses arising from the interplay of Kerr nonlinearity and hybrid dispersion – combination of different orders of dispersions. This provides new degrees of freedom to control the shape and energy of optical pulses. This could not only have impact on ultrafast lasers, but also on other areas in which these features are crucial such as on-chip frequency combs, supercontinuum generation, and advanced modulation formats for telecommunication.

- **Other disciplines**

- **Development of human resources**

Following the findings and the results from the development of the first PQS laser, we investigated other nonlinear optical systems in which linear dispersion plays a central role but where so far only second-order dispersion was considered. This idea was the baseline for numerous undergraduate and postgraduate research projects. Each of these projects offers an opportunity for students to learn and work on nonlinear systems either experimentally, numerically, or analytically. In most cases, the outcomes of these research project became part of a publication. For example, after we numerically discovered novel nonlinear pulses, arising from solitons centered at different frequencies, Mr. Lourdesamy performed the experiments that demonstrated their existence, which led to the novel technique to enhance nonlinear effects [10]. By doing so he acquired significant expertise in both experimental and numerical nonlinear optics. Moreover, as his results were published in a high-impact scientific journal and presented at several conferences, it allowed him to improve his communication skills.

- **Describe the impact on teaching and educational experiences**

Following the discovery and experimental demonstration of the enhancement of nonlinear effects through design of the linear dispersion, we considered some associated problems. Among these, we studied how the nonlinear enhancement depends on the number of spectral components forming the pulse compound and whether the enhancement has an upper limit. Parts of these problems were turned into a mathematical challenge designed for undergraduate physics and mathematics students that we posted on the University of

Sydney Physics Society (Physoc) website and that was communicated further to Macquarie University in Sydney and to the University of Auckland in New Zealand. This challenge has been successfully tackled by six groups of students. This led to a better understanding of the underlying physics of the enhancement effect and to another publication that is currently under review [20]. Once this paper has been accepted, we will submit a paper to Australian Physics, the magazine of the Australian Institute of Physics.

- **Describe the impact in this reporting period on physical, institutional, and information resources that form infrastructures**

n/a

- **Impact on society beyond science and technology**

The core research of this project addresses some of the energy limitation inherent to the current technology which has hindered its use in real applications. For example, state-of-the-art spectroscopy makes use of sources that emit broadband coherent light, the generation requires high-energy pulses. Therefore, these light sources require bulky, non-scalable laser systems, which precludes their integration in a small, remote device. The finding of this project forms the baseline for a new generation of simple, integrable and high-energy light sources. Concretely, these laser sources could enhance spectroscopy sensing devices for real-world application, outside laboratories, such as early-detection of bushfires in Australia.

Changes:

- **Changes in approach**

- **Problems or delays**

During this project, we faced two mains problems that impacted our original objectives:

1. The original design of the PCF supporting PQS propagation [11] appeared to be more challenging than anticipated. A first round of fabrication was performed by our colleagues from the University of Jena (Germany). However, after characterization, this first batch of fiber was not suitable for our experiments. This was expected as the fabrication of a PCF with a novel cross-section profile typically requires several iterations to find the adequate parameters.
2. Because of the COVID pandemic, most of the campuses and laboratories were shut down for almost two years, which hindered the possibilities to perform additional rounds of fabrication. Moreover, while our results and findings attracted significant interests from the audience who attended our presentations, developing new collaborations around this topic has also been impacted by the pandemic.

- **Expenditure Impacts**

n/a

- **Significant changes in the use or care of human subjects, vertebrate animals and/or biohazards**

n/a

- **Changes to the primary place of performance from that originally proposed**

n/a

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