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14. ABSTRACT

The scientific objective was to identify, classify, and model high-power mode-locked laser systems of current interest to experimentalists and engineers in optical physics. By direct collaboration with members of the physicsand electrical engineering academic community, quantitative models for the systems of interest were developed based upon first principles. These models were studied in appropriate parameter regimes where simplified nonlinear dynamical systems theory could be utilized. The results were then recast in terms of their original experimental context so that the theoretical predictions could be tested. The models have made tremendous impact in the design and optimization of laser cavity performance. In conjunction with the modeling efforts, the mathematical objectives further developed modern methods for quantifying the wave dynamics of nonlinear, dispersive PDEs. In particular, a variety of reduction methods proved invaluable in characterizing the behavior in characterizing the behavior inherent in the mode-locked laser system.

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High-Energy and Ultra-Short Mode-locked Lasers

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During the tenure period of this award, we performed theoretical studies of new approaches to the generation of femtosecond light pulses and optical bullets in mode-locked lasers. New pulse-shaping mechanisms have demonstrated the potential for major impact on ultrafast science, thus the theoretical objective was to push our theory past current rudimentary understanding. Development of improved models proposed here can enable major scientific advances such as the generation of the highest energies delivered from optical fiber lasers. Close collaborations were established with two key experimental groups in order to carry out the objectives of the work: Frank Wise (Applied Physics, Cornell University) and Steven Cundiff (Physics, JILA/Colorado).

The new analytical methods developed are needed now as novel pulse evolutions in lasers promise to greatly enhance the performance of practical instruments. The pulse may undergo large changes in its temporal shape, spectral shape, and phase or frequency as it traverses the laser cavity, which in turn pose severe challenges to mathematical models. Highly-chirped and/or self-similar pulse solutions can exist in the presence of strong dissipation, creating new classes of pulses in fiber lasers that offer remarkable behavior and performance. The quantitative models developed for the mode-locked lasers were studied in appropriate parameter regimes where simplified nonlinear dynamical systems theory can be utilized and stability characterized. The effort was truly interdisciplinary: combining asymptotic and perturbation methods, scientific computation, and rigorous mathematical analysis with models that were based on, and validated by, experimental observations. Special attention was given to recent dimensionality reduction methods developed by our group.

The impact of the proposed research extends well beyond the understanding of nonlinear pulse propagation in laser systems. The concepts developed in this project bear on a range of topics, from the fundamental science of nonlinear dynamical systems to commercial laser instruments. Fiber lasers that generate femtosecond-duration optical pulses have great potential for expanding the range of short-pulse optical techniques into real-world applications such as precision micro-machining, nonlinear optical imaging techniques, including multi-photon and Raman microscopies, and ocular surgery. It is very likely that the performance advances resulting from this work will be duplicated in other research laboratories, and there is strong potential for commercial development and high impact in the higher-energy, ultra-short mode-locking community.

The Kutz research group consists of one postdoctoral fellow (Eli Shlizerman) who was supported jointly on my current AFOSR research grant and the Department of Applied Mathematics. The group also had five graduate students helping to carry forward the objectives of the group: Edwin Ding (PhD expected 2011), Matthew Williams (PhD expected 2012), Jake Grosek (PhD expected 2013 and SMART scholar), Xing Fu (PhD expected 2014), and Pedro Maia (PhD expected 2014). Given the scope of the proposed work, a large talented group was necessary to carry forward the research objectives.

In addition to direct efforts with the group at the University of Washington, there were collaborative efforts with top experimentalists in the field of mode-locking. Most notably there are strong and continuing connections with Prof. Frank Wise of Applied Physics, Cornell University and Prof. Steven Cundiff of Physics and JILA, University of Colorado. More recently, work was established with Prof. Phillipe Grelu of University of Bourgone, Dijon, France. One other notable and long-standing collaborative effort is with Prof. Bjorn Sandstede of Applied Mathematics, Brown University. This group represents a stellar collection of leading researchers in the field and they are an integrable part of the PI, postdoc, and student research efforts as Wise, Cundiff and Grelu provide the experimental background for our efforts.

The focus on fiber lasers results from the major practical advantages they offer because light is contained in a waveguide, so careful alignment of an optical cavity is not required. The potential of fiber has motivated research for nearly two decades, but short-pulse fiber lasers have very little impact compared to their solid-state counterparts. This is due to the fact that fiber lasers have lagged well behind their solid-state counterparts in the key performance parameters – pulse energy and duration. New insights into pulse-propagation physics in the past few years, including a large body of work from my group during the tenure period of this work, have provided glimpses of order-of-magnitude increases in the pulse energy and peak power from femtosecond fiber lasers. For the first time, it is now realistic to design short-pulse fiber devices that compete directly with the existing solid state lasers in performance while offering major practical advantages and substantially reduced cost. However, typically the design and optimization of high-performance devices was impeded by a lack of theoretical understanding of the new modes of operation. However, we have been highly motivated to develop systematic, fundamental understanding of high-energy mode-locked lasers. Indeed, we have greatly advanced the theoretical underpinnings of mode-locked laser theory for both high-power, high-energy lasers and ultra-short (few femtosecond) lasers.

To date, the field of ultrafast science has been built on lasers that generate pulses through phase modulations: most femtosecond lasers generate nonlinear Schrodinger solitons, in essence. The new pulse evolutions we have studied counter 25 years of conventional wisdom in short-pulse generation, by not requiring anomalous dispersion or dispersion control in the cavity. Pulse-shaping is dominated by the dissipative processes, particularly the filtering of a chirped pulse in a cavity. These dissipative solitons have remarkable properties and offer major practical advantages. We have made significant advances in studying the pulse-shaping mechanism in modern laser cavities.

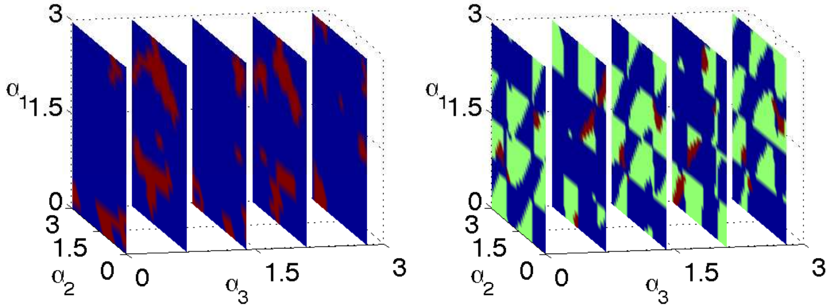

Figure 1: *(left) Experimental operating regions of passive polarizer laser cavity with red denoting stable mode-locking. (right) Theoretical prediction of stable mode-locking regimes in the CQGLE. The green regions satisfy the mode-locking conditions while red regions are stable. This unpublished work is the first to directly compare theory and experiment as a function of the waveplate settings. Indeed, up to this point, other theories were simply unable to make this comparison.*

We have also used our expertise to formulate a potential technology for generating light-bullets in layered waveguide arrays. This builds upon ongoing efforts focused on achieving such goals in waveguide array technologies. This portion of the proposal was built on a successful, ongoing collaborative effort with the Cundiff group at JILA/Colorado. We also proposed a method to extend mode-locking theory by looking beyond the standard center-frequency expansion of Maxwell's equations. Thus mode-locking in context of the short-pulse equation was proposed, the first of its kind to directly address the formation of ultra-short (few femtosecond) pulses. Finally, the full power and mathematical methodology of dimensionality reduction techniques were used with success in characterizing laser dynamics in a succinct and fundamental way.

As evidence of success in our modeling, we were the first to directly compare theoretical and experimental results as a function of the underlying physical parameters in one of the most common fiber lasers to date: the nonlinear polarization rotation laser. And although there is a very large parameter space to explore given the polarizer angles, waveplate angle, birefringence strength and fiber alignment, Fig. 1 indicates that on a qualitative level the initial modeling and the one-to-one correspondence between our asymptotic CQGLE theory and the physical parameters is clearly moving in the right direction.

The following issues were considered: can a quantitative comparison between theory and experiment be made? This has been an outstanding issue for mode-locking. However, our recent results suggests that at least in some limits, direct quantitative validation can be made. How do the operating regimes of the experimental laser cavity map out their operating regimes, i.e. can an equivalent experimental figure like Fig. 1 be produced? How are the stable operating regimes demonstrated in Fig. 1 calculated, enlarged, and maximized? Our methodology is the first of its kind to have directly addressed these issues towards making significant progress in developing the technology infrastructure of mode-locked fiber lasers.