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6. AUTHORS William L. Kath	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Northwestern University 2145 Sheridan Road Evanston, IL 60208	8. PERFORMING ORGANIZATION REPORT NUMBER
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13. ABSTRACT *(Maximum 200 words)*

Specifically, we have investigated mathematically the dynamics of pulses in nonlinear optical fibers, helped design a highly-stable 60 GHz soliton source, investigated methods for controlling solitons using phase-sensitive amplifiers (PSAs), modeled the application of PSAs to optical storage loops and other optical devices, studied timing jitter in mode-locked erbium fiber lasers, and explored a new method for controlling streams of high-speed optical pulses using periodic optical phase conjugation.

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The Stability and Dynamics of
Optical Waveguides, Lasers, and Amplifiers

AFOSR Grant F49620-93-1-0084

Progress Report
1 September 96 -- 31 August 97

and

Final Technical Report
15 December 1992 -- 15 October 1997

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OBJECTIVES

The focus of this project has been the development and use of mathematical techniques to improve the understanding of technologies important for the generation and processing of high-speed optical bit streams. Such enabling technologies are important for the design of next-generation optical systems capable of handling large amounts of information all-optically at high rates of speed, and in systems capable of collecting such information and transmitting it to a central location for processing.

Specifically, we have:

- o investigated mathematically the dynamics of pulses in nonlinear optical fibers
- o helped design a highly-stable 60 GHz soliton source

- o investigated methods for controlling solitons using phase-sensitive amplifiers (PSAs)
- o modeled the application of PSAs to optical storage loops and other optical devices
- o studied timing jitter in mode-locked erbium fiber lasers
- o explored a new method for controlling streams of high-speed optical pulses using periodic optical phase conjugation

STATUS OF EFFORT

A no-cost extension was requested in the fall of 1996 to finish work on this project. We have now completed basic theoretical studies of optical storage loops using solitons and phase-sensitive amplifiers (PSAs); a main goal was the modeling of ongoing experiments in the Department of Electrical Engineering here at Northwestern. Additional research still needs to be performed, however, to resolve the technical details associated with making a working storage device. We have also performed studies of the dynamics and control of optical solitons in other situations, such as the effect of random birefringence on long-distance propagation and timing jitter in erbium-doped fiber lasers. One measure of the progress in all areas (which we believe to be good) is evidenced by the list of accomplishments including:

- o 15 publications in journals
- o 9 publications in refereed conference proceedings
- o 57 presentations at conferences and seminars (including 9 invited talks).

ACCOMPLISHMENTS/NEW FINDINGS

High-speed communication is an important technology both for military and civilian applications, particularly as methods of collecting larger and larger amounts of raw data of various types become available. To increase the information rate beyond that of current systems, it is necessary to do more and more processing of the signal optically, which requires new technologies and optical devices. We are continuing to develop the mathematical techniques necessary to model the physical system behavior in such situations.

All aspects of a high-speed optical communication systems have been explored. In such systems, a high-speed source is necessary, hence our work on a stable 60 GHz soliton source. The information stream generated by the source must be transmitted via optical fiber to a receiver (or receivers), and we have therefore performed studies of the propagation dynamics of

nonlinear pulses in optical fiber under realistic conditions. At a network node (the receiver side), the information needs to be processed and either further transmitted or delivered to its final destination. The necessitates optical storage devices such as fiber loops (which act as short-term buffers in a high-speed optical router) and erbium-doped fiber lasers which are mode-locked by the input signal (which serve to re-time the input signal as the front end of a nonlinear switch), and which we have also investigated.

In addition to the technological goals, an additional focus has been on the improvement of the mathematical methods used in the study of such systems, and in human resource development through the training of graduate students and postdoctoral associates in these areas.

PERSONNEL SUPPORTED

* Faculty

  William L. Kath, Northwestern University

* Post-Docs

  Dr. Christopher G. Goedde
  Dr. Tian-Shiang Yang

* Graduate Students

  Ms. Cheryl V. Hile
  Ms. Anne Niculae
  Mr. Michael Mills
  Mr. Brian Marks

* Other (please list role)

  Mr. Arnold D. Kim (undergraduate research)

PUBLICATIONS

* SUBMITTED

* Books/Book Chapters

* Journals

* Conferences

* ACCEPTED

* Books/Book Chapters

* Journals

Phase sensitive amplifiers for ultra-long distance soliton propagation, in Optics in 1993, (a collection of articles selected each year to highlight principal advances in optics), Optics and Photonics News, December 1993 (with Prem Kumar, J. Nathan Kutz, and Ruo-Ding Li).

Long-distance pulse propagation in nonlinear optical fibers using periodically-spaced parametric amplifiers, Optics Letters, 18 (1993), pp. 802-804. (with J. Nathan Kutz, Ruo-Ding Li and Prem Kumar).

Combating dispersion with parametric amplifiers, IEEE Photonics Technology Letters, 5 (1993), pp. 669-672 (with Ruo-Ding Li, Prem Kumar and J. Nathan Kutz).

Dispersion compensation with phase-sensitive amplifiers, J. of Lightwave Technology, 12 (1994), pp. 541-549 (with Ruo-Ding Li and Prem Kumar).

Stochastic simulation of pulses in nonlinear-optical fibers with random birefringence, J. Opt. Soc. Amer. B, 11 (1994), pp. 818-825 (with T. Ueda).

Pulse propagation in nonlinear optical fiber-lines that employ phase-sensitive parametric amplifiers, J. Opt. Soc. Amer. B, 11 (1994), pp. 2112-2123 (with J. Nathan Kutz, Cheryl V. Hile, Ruo-Ding Li and Prem Kumar).

Soliton evolution and radiation loss for the Korteweg-de Vries equation, Physical Review E, 51 (1995), pp. 661-670 (with Noel Smyth).

Long-term storage of a soliton bit stream using phase-sensitive amplification, Optics Letters, 19 (1994), pp. 2050-2052 (with Antonio Mecozzi, Prem Kumar, and Christopher G. Goedde).

Compensation of the soliton self-frequency shift with phase-sensitive amplifiers, Optics Letters, 19 (1994), pp. 2077-2079 (with Christopher G. Goedde and Prem Kumar).

Soliton evolution and radiation loss for the nonlinear Schroedinger equation, Physical Review E, 51 (1995), pp. 1484-1492 (with Noel Smyth).

Pulse propagation in nonlinear optical fibers with phase-locked phase-sensitive amplifiers, Optics Letters, 20 (1995), pp. 557-559, (with Anne Niculae).

Periodic amplification and conjugation of optical solitons, Optics Letters, 20 (1995), pp. 1366-1368 (with Christopher G. Goedde and Prem Kumar).

Stability of pulses in nonlinear optical fibers using phase-sensitive amplifiers, SIAM J. Applied Math, 56 (1996), pp. 611-626 (with J. Nathan Kutz).

Stabilizing dark solitons by using periodic phase-sensitive amplification, Optics Letters, 21 (1996), pp. 465-476 (with Arnold D. Kim and Christopher G. Goedde).

A numerical and asymptotic solution of Maxwell's equations for nonlinear optical pulse propagation, J. Opt. Soc. Amer. B, 13 (1996), pp. 1135-1145 (with Cheryl V. Hile).

* Conferences (Refereed)

A numerical and asymptotic solution of Maxwell's equations for nonlinear optical pulse propagation, Integrated Photonics Research Technical Digest, Vol. 10 (1993) pp. 308-311 (with Cheryl V. Hile).

Stable long-distance pulse propagation in nonlinear optical fibers using periodically-spaced parametric amplifiers, Integrated Photonics Research Technical Digest, Vol. 10 (1993) pp. 48-50 (with J. Nathan Kutz, Ruo-Ding Li and Prem Kumar).

Long-distance pulse propagation in nonlinear optical fibers by using periodically-spaced parametric amplifiers, Quantum Electronics and Laser Science Technical Digest, Vol. 12 (1993), p. 289 (with J. Nathan Kutz, Ruo-Ding Li and Prem Kumar).

Phase sensitive optical amplifiers, Integrated Photonics Research Technical Digest, Vol. 11 (1994), pp. 316-318 (with Ruo-Ding Li and Prem Kumar).

Optical pulse shaping using phase-sensitive amplification, Integrated Photonics Research Technical Digest, Vol. 11 (1994), pp. 319-321 (with Prem Kumar and Jerome E. Oleksey).

Long-term storage of a soliton bit-stream using phase sensitive amplification, Nonlinear Guided Wave Technical Digest, Vol. 6

(1995), pp. 97-99 (with Antonio Mecozzi, Prem Kumar and Christopher G. Goedde).

Periodic conjugation of optical solitons, Nonlinear Guided Wave Technical Digest, Vol. 6 (1995), pp. 136-138 (with Christopher G. Goedde and Prem Kumar).

Nonlinear polarization-mode dispersion in optical fibers with randomly varying birefringence, CLEO Technical Digest, Vol. 9 (1996), p. 42 (with P. K. A. Wai, C. R. Menyuk and D. Marcuse).

Timing jitter reduction in a laser mode-locked by an input bit-stream, Nonlinear Guided Wave Technical Digest, Vol. 15 (1996), pp. 170-172 (with Anne Niculae).

INTERACTIONS/TRANSITIONS
* Participation/Presentations At Meetings, Conferences, Seminars, Etc

``Timing jitter reduction in a laser mode-locked by an input bit-stream'', Department of Applied Mathematics, California Institute of Technology, November 1996.

``Timing jitter reduction in a laser mode-locked by an input bit-stream'', Workshop on Nonlinear Optics, Arizona Center for Mathematical Sciences, University of Arizona, October 1996.

``Timing jitter reduction in a laser mode-locked by an input bit-stream'', Conference on Nonlinear Guided Waves and Their Applications, Optical Society of America, Cambridge, England, August 1996.

``Solitons in nonlinear optical fibers,'' Department of Mathematical Sciences, Rensselaer Polytechnic Institute, May 1996.

``Stochastic methods for randomly birefringent optical fibers,'' Corning, Inc., May 1996.

``Periodic amplification and conjugation of optical solitons,'' Department of Mathematical Sciences, Rensselaer Polytechnic Institute, May 1996.

``Long-term storage of a soliton bit-stream using phase-sensitive amplification,'' Corning, Inc., May 1996.

``Long-term storage of a soliton bit-stream using phase-sensitive amplification,'' United States Air Force Rome Laboratories, May 1996.

``Solitons in nonlinear optical fibers: a tutorial''; invited review talk, Workshop on Mathematical Methods in Nonlinear Optics (part of the Conference on Current and Future Directions in Applied Mathematics), Notre Dame University, April 1996.

``Periodic amplification and conjugation of optical solitons,'' Department of Mathematics, University of Delaware, February 1996.

``Controlling solitons in nonlinear optical fibers using parametric amplification,'' Department of Mathematics, University of Maryland, College Park, February 1996.

``Long-term storage of a soliton bit-stream using phase-sensitive amplification,'' Institute for Physical Sciences and Technology, University of Maryland, College Park, February 1996.

``Long-term storage of a soliton bit-stream using phase-sensitive amplification,'' Department of Engineering Sciences and Applied Mathematics, Northwestern University, January 1996.

``Long-term storage of a soliton bit-stream using phase-sensitive amplification,'' Lincoln Laboratories, December 1995 (presented by Prem Kumar).

``Controlling solitons in nonlinear optical fibers using parametric amplification''; Special Session on Nonlinear Applied Analysis, Joint Meeting of the American and Mexican Mathematical Societies, Guanajuato, Mexico, December 1995 (Also, invited to co-organize the session).

``Solitons in nonlinear optical fibers''; invited talk, Midwest PDE Seminar, Department of Mathematics, Northwestern University, November 1995.

``Periodic amplification and conjugation of optical solitons,'' Department of Mathematics, University of Michigan, October 1995.

``Soliton control in nonlinear optical fibers using parametric amplification,'' Workshop on Nonlinear Optics, Arizona Center for Mathematical Sciences, University of Arizona, Tucson, Arizona, October 1995.

``Controlling solitons in nonlinear optical fibers using parametric amplification''; invited talk, Symposium in Applied Mathematics: Nonlinear Waves, Dynamics, Asymptotic Analysis and Physical Applications (in honor of Martin Kruskal's 70th birthday), University of Colorado, August 1995.

``Long-term storage of a soliton bit-stream using phase-sensitive amplification''; invited talk, Workshop on Wave Propagation in

Random and Other Complex Media, Institute for Mathematics and its Applications, University of Minnesota, November 1994.

``Phase-sensitive amplification of pulses in nonlinear optical fibers''; invited talk, Workshop on Computational Wave Propagation, Institute for Mathematics and its Applications, University of Minnesota, September 1994.

``Equivalent particle dynamics for solitons, with applications to birefringent optical fibers''; invited talk, European Science Foundation Study Centre on Nonlinear Optics and Guided Waves, International Centre for Mathematical Sciences, Edinburgh, Scotland, August 1994.

``Stochastic methods for randomly birefringent optical fibers''; European Science Foundation Study Centre on Nonlinear Optics and Guided Waves, invited talk, International Centre for Mathematical Sciences, Edinburgh, Scotland, August 1994.

``Long-distance pulse propagation in nonlinear optical fibers with phase-sensitive amplification''; invited talk, European Science Foundation Study Centre on Nonlinear Optics and Guided Waves, International Centre for Mathematical Sciences, Edinburgh, Scotland, August 1994.

``Phase sensitive optical amplifiers''; invited talk, Integrated Photonics Research (IPR) Topical Meeting, sponsored by the Optical Society of America, San Francisco, CA, February, 1994 (with Prem Kumar).

``Stable pulse propagation in nonlinear optical fibers using lumped phase-sensitive amplifiers''; Workshop on Nonlinear Optics, University of Arizona, Tucson, AZ, September 1993.

``Dispersion compensation with phase-sensitive amplifiers''; Workshop on Nonlinear Optics, University of Arizona, Tucson, AZ, September 1993.

``Controlling solitons in nonlinear optical fibers using parametric amplification'', Department of Mathematics, University of Delaware, March 1995.

``Controlling solitons in nonlinear optical fibers using parametric amplification'', Department of Mathematics, Duke University, February 1995.

``Long-term storage of a soliton bit-stream using phase-sensitive amplification'', Conference on Applications of Dynamical Systems, sponsored by the Society for Industrial and Applied Mathematics, Snowbird, Utah, May 1995.

``Long-term storage of a soliton bit-stream using phase-sensitive amplification'', Nonlinear Guided Wave Topical Meeting, sponsored by the Optical Society of America, Dana Point, California, February, 1995.

``Long-term storage of a soliton bit-stream using phase-sensitive amplification'', Workshop on Nonlinear Optics, Arizona Center for Mathematical Sciences, University of Arizona, Tucson, Arizona, October 1994.

``Phase conjugation of optical solitons'', Conference on Applications of Dynamical Systems, sponsored by the Society for Industrial and Applied Mathematics, Snowbird, Utah, May 1995.

``Phase conjugation of optical solitons'', Nonlinear Guided Wave Topical Meeting, sponsored by the Optical Society of America, Dana Point, California, February, 1995.

``Phase conjugation of optical solitons'', Workshop on Nonlinear Optics, Arizona Center for Mathematical Sciences, University of Arizona, Tucson, Arizona, October 1994.

``Pulse propagation in nonlinear optical fibers with phase-locked phase-sensitive amplifiers'', Conference on Applications of Dynamical Systems, sponsored by the Society for Industrial and Applied Mathematics, Snowbird, Utah, May 1995.

``Stability of pulses in nonlinear optical fibers using phase-sensitive amplifiers'', Conference on Applications of Dynamical Systems, sponsored by the Society for Industrial and Applied Mathematics, Snowbird, Utah, May 1995.

``Radiation damping for the nonlinear Schroedinger equation'', Society for Industrial and Applied Mathematics Annual Meeting, San Diego, California, July 1994.

``Radiation and soliton evolution for the Korteweg-de Vries equation'', Society for Industrial and Applied Mathematics Annual Meeting, San Diego, California, July 1994.

``Pulse propagation in nonlinear optical fibers with phase-locked phase-sensitive amplifiers'', Society for Industrial and Applied Mathematics Annual Meeting, San Diego, California, July 1994.

``Numerical studies of pulse dynamics in nonlinear optical fibers with phase-sensitive amplifiers'', Society for Industrial and Applied Mathematics Annual Meeting, San Diego, California, July 1994

``Compensation of the soliton self-frequency shift with phase-sensitive amplifiers'', Society for Industrial and Applied Mathematics Annual Meeting, San Diego, California, July 1994

``Compensation of the soliton self-frequency shift with phase-sensitive amplifiers'', Rocky Mountain Workshop on Nonlinear Optics and Optical Communications, Breckenridge, CO, April 1994

``Phase-sensitive amplification of pulses in nonlinear optical fibers'', Department of Mathematics, University of Chicago, October 1994

``Phase-sensitive amplification of pulses in nonlinear optical fibers'', Rocky Mountain Workshop on Nonlinear Optics and Optical Communications, Breckenridge, CO, April 1994

``Phase-sensitive amplification of pulses in nonlinear optical fibers'', Department of Applied Mathematics, California Institute of Technology, January 1994

``Phase-sensitive amplification of pulses in nonlinear optical fibers'', Program in Applied Mathematics, University of Colorado at Boulder, November, 1993

``Phase-sensitive amplification of pulses in nonlinear optical fibers'', Courant Institute of Mathematical Sciences, New York University, October, 1993

``Phase-sensitive amplification of pulses in nonlinear optical fibers'', Department of Mathematics and Center for Applied Mathematics and Statistics, New Jersey Institute of Technology, October, 1993

``Optical pulse shaping using phase-sensitive amplification'' Integrated Photonics Research Topical Meeting, sponsored by the Optical Society of America, San Francisco, California, February, 1994

``Phase-sensitive optical amplifiers'', Air Force Office of Scientific Research, September 1993.

``Long-distance pulse propagation in nonlinear optical fibers using periodically-spaced parametric amplifiers'', Society for Industrial and Applied Mathematics Annual Meeting, Philadelphia, July 1993

``Long-distance pulse propagation in nonlinear optical fibers using periodically-spaced parametric amplifiers'', Quantum Electronics and Laser Science Conference, sponsored by the

Optical Society of America, Baltimore, MD, May 1993

``Mathematical aspects of soliton propagation in nonlinear optical fibers'', Program in Applied Mathematics, Brown University, April 1993

``Mathematical aspects of soliton propagation in nonlinear optical fibers'', Department of Mathematics, University of Michigan, January 1993

``Stable long-distance pulse propagation in nonlinear optical fibers using periodically-spaced parametric amplifiers'' Integrated Photonics Research Topical Meeting, sponsored by the Optical Society of America, Palm Springs, California, March 1993

``A numerical and asymptotic solution of Maxwell's equations for nonlinear optical pulse propagation'' Integrated Photonics Research Topical Meeting, sponsored by the Optical Society of America, Palm Springs, California, March 1993

* Consultative And Advisory Functions To Other Laboratories And Agencies

Visits were made by the PI during the grant period to Lincoln Laboratories (December), Rome Air Force Laboratories (April), and Corning, Inc., Research Laboratories (May). The objective was two-fold: to report the results of the work being funded by this project, principally the research on optical storage of solitons using phase-sensitive amplifiers. Lincoln Laboratories has several ongoing projects concerned with optical storage, and researchers there expressed their desire to be kept informed of progress with the experiments and theory being performed at Northwestern. Additional areas of possible collaboration were also discussed.

* Transitions

One of the projects worked on during the year was the modeling of a highly-stable 60 GHz soliton source; this was done in direct collaboration with joint experiments performed at Northwestern by Prem Kumar and ATx, Inc., of Naperville, IL (contact: Dr. Don Sipes). The experiments resulted in a working prototype device, and the potential for commercial realization was significant enough that a patent application has been filed by Northwestern and ATx.

NEW DISCOVERIES, INVENTIONS, OR PATENT DISCLOSURES

Patent Application: ``A highly-stable 60 GHz soliton source at 1550 nm''

HONORS/AWARDS

W.L. Kath, National Science Foundation Presidential Young Investigator Award, 1985-1990