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13. ABSTRACT *(Maximum 200 words)*

We have completed basic theoretical studies of optical storage loops using solitons and phase-sensitive amplifiers (PSAs) and did detailed modeling of ongoing experiments performed in the Department of Electrical Engineering at Northwestern. The goal was to resolve the technical details associated with making a working storage device. We 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. In the later case, the configuration studied was one in which a mode-locked fiber laser is used as a clock recovery device; we derived theoretical estimates for the timing jitter reduction that can be obtained with this device.

In the area of pulse propagation, we investigated work on polarization-mode dispersion and have examined the use of dispersion management to improve transmission performance. Such techniques have also been demonstrated to be useful in fiber lasers (in that cantext known as stretched-pulse mode-locking).

In the area of wavelength conversion, we made several trips to the Air Force Research Laboratories in Dayton, OH to discuss issues and research needs with the group there headed by Dr. Ken Schepler. It was determined that key issues that are needed to be supported are numerical and analytical modeling of optical parametric oscillators (OPO) that use quadratic crystals with periodic polling to quasi-phase-match conversion of the pump lasers.

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Final Technical Report
1 November 96 -- 31 January 00

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OBJECTIVES

The original goal of this project was to investigate mathematically methods for controlling optical soliton communication systems and fiber lasers. Such methods of control are important for applications involving the generation and processing of high-speed optical bit streams. Specific devices to be investigated include: optical memory loops using phase-sensitive optical amplifiers; switches, timing regenerators, and nonlinear amplifiers using nonlinear optical loop mirrors. These devices can be thought of loosely as basic optical `circuit elements' for the next generation of high-speed information processing systems. Another area investigated was a new method for controlling streams of high-speed optical pulses using periodic optical phase conjugation.

Another goal added to this project in response to AF needs was to advance the state of the art of mid-infrared laser technology. The Air Force has a critical need for agile-wavelength infrared laser sources to be used as key components in countermeasures systems, laser-based radars, and remote sensing devices. Optical parametric oscillators employing periodically-poled materials such as lithium niobate are widely regarded as a leading candidate for mid-infrared laser systems satisfying Air Force requirements.

The techniques used to investigate these problems were two-fold: theoretical analyses using singular perturbation methods, and numerical computations. These techniques were used simultaneously and in parallel, so that information obtained with one technique was immediately available to help guide the investigations with the other. In addition to the more practical reasons for investigating these problems, the results to be obtained are also expected to have significant scientific relevance to areas of study concerned with dynamical systems, nonlinear wave propagation, and solitons.

STATUS OF EFFORT

We have completed basic theoretical studies of optical storage loops using solitons and phase-sensitive amplifiers (PSAs) and did detailed modeling of ongoing experiments performed in the Department of Electrical Engineering at Northwestern. The goal was to resolve the technical details associated with making a working storage device. We 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. In the later case, the configuration studied was one in which a mode-locked fiber laser is used as a clock recovery device; we derived theoretical estimates for the timing jitter reduction that can be obtained with this device.

In the area of pulse propagation, we investigated work on polarization-mode dispersion and have examined the use of dispersion management to improve transmission performance. Such techniques have also been demonstrated to be useful in fiber lasers (in that context known as stretched-pulse mode-locking).

In the area of wavelength conversion, we made several trips to the Air Force Research Laboratories in Dayton, OH to discuss issues and research needs with the group there headed by Dr. Ken Schepler. It was determined that key issues that are needed to be supported are numerical and analytical modeling of optical parametric oscillators (OPO) that use quadratic crystals with periodic polling to quasi-phase-match conversion of the pump lasers.

ACCOMPLISHMENTS/NEW FINDINGS

o We modeled all-optical storage rings using parametric gain to compensate loss and reduce noise. Based upon these studies, experiments were performed at Northwestern demonstrating the feasibility of the technique. Further work has since been done at NTT Optical Network Systems Laboratories in Japan. Researchers there have demonstrated that phase-sensitive amplifiers are effective for suppressing amplitude noise (Elect. Lett., 32 1996 p. 677; Opt. Lett., 22 1997 p.1). They have also demonstrated the phase-locking of a pump light source to an incoming signal using an optical phase-locked loop (Optical Amplifiers and Their Applications Postdeadline Paper 5, August 1997). This development is key to the potential application of such amplifiers.

o We analyzed the timing jitter reduction achieved by an all-optical clock recovery device. In this situation, an incoming bit stream (with timing jitter) is used to mode-lock a fiber laser. Since the fiber-laser's response time is much longer than the bit period or the round trip time of the laser, the laser responds only to an average over many input pulses. In this way, the laser locks onto the average repetition rate of the input signal, thus averaging out much of the timing jitter. We derived a theoretical estimate for the efficiency of the timing jitter reduction which agrees quite well with simulations and with experiments.

o We proposed an advantageous dispersion management scheme for wavelength-division-multiplexed soliton transmission, in which optimal launch points are obtained whose locations are independent of the fibers' dispersion parameters. Since using such optimal launch points minimizes dispersively shed radiation, it is therefore possible to simultaneously optimize the transmission in several different channels. For the particular case of a two-step dispersion map, we have shown this result can be achieved by properly choosing the fiber lengths. We have also used our models to optimize the placement of the amplifiers in such dispersion maps.

o Randomly varying birefringence leads to nonlinear polarization-mode dispersion (PMD) in addition to the

well-known linear PMD. We have calculated the variance of the field fluctuations produced by this nonlinear PMD. Knowing the size of these fluctuations is useful for assessing when nonlinear PMD is important and for its proper incorporation in fast numerical algorithms. We also derived the equilibrium probability distributions for the PMD coefficients, and tracked the evolution of the polarization state's probability distribution from its initial delta-function distribution to its steady-state uniform distribution on the Poincare sphere.

o We have begun numerical modeling efforts of wavelength conversion and have developed a first version of a simulation code that includes both diffraction and thermal heating due to signal, idler and pump absorption.

PERSONNEL SUPPORTED

* Faculty

William L. Kath, Northwestern University

* Post-Docs

Dr. Tian-Shiang Yang
Dr. Gino Biondini

* Graduate Students

Mr. Michael Mills
Mr. Brian Marks
Mr. Richard Moore

* Other (please list role)

PUBLICATIONS

* SUBMITTED

* Books/Book Chapters

* Journals

* Conferences

* ACCEPTED

* Books/Book Chapters

* Journals

Controlling short optical pulses with phase-sensitive amplification, J. Opt. Soc. Amer. B, 14 (1997), pp. 1371-1379 (with Christopher G. Goedde and Prem Kumar).

Timing-jitter reduction in a fiber laser mode locked by an input bit stream, Opt. Lett., 22 (1997), pp. 979-981 (with Anne Niculae).

Analysis of enhanced-power solitons in dispersion-managed optical fibers, Opt. Lett., 22 (1997), pp. 985-987 (with Tian-Shiang Yang).

All-optical storage of a picosecond-pulse packet using parametric amplification, IEEE Photonics Tech. Lett. 9 (1997), pp. 1020-1022 (with Glenn Bartolini, Darwin K. Serkland and Prem Kumar).

A modified conservation law for the phase of the nonlinear Schroedinger soliton, Methods and Appl. of Analysis, vol. 4 (1997), pp. 141--155.

Nonlinear polarization-mode dispersion in optical fibers with randomly varying birefringence, J. Opt. Soc. Amer. B, vol. 14 (1997), pp. 2967-2979 (with P. K. A. Wai, C. R. Menyuk and J. W. Zhang).

Rate multiplication of a 59-GHz soliton source at 1550 nm, J. Lightwave Technol., vol. 16 (1998), pp. 670-677 (with D. K. Serkland, G. D. Bartolini, P. Kumar and A. V. Sahakian).

Optimal dispersion maps for wavelength-division-multiplexed soliton transmission, Optics Lett., vol. 23 (1998), pp. 597-599 (with T.-S. Yang and S. K. Turitsyn).

Pulsed degenerate optical parametric oscillator based on a nonlinear fiber Sagnac interferometer, Optics Lett., vol. 23 (1998), pp. 795-797 (with D. K. Serkland, G. D. Bartolini, A. Agarwal and P. Kumar).

Long-term storage of a soliton bit stream using phase-sensitive amplification: Effects of soliton-soliton interactions and quantum noise, Optics Communications, v. 157 (1998), pp. 310-326 (with Antonio Mecozzi, Prem Kumar and Christopher G. Goedde).

Analysis of all-optical clock recovery using a mode-locked fiber laser, Physica D, v. 123 (1998), pp. 244-254 (with Anne Niculae).

The multiple-scale averaging and dynamics of dispersion-managed optical solitons, Journal of Engineering Mathematics, v. 36 (1999), pp. 163-184 (with T.-S. Yang and S. K. Turitsyn).

``Magic" dispersion maps for multi-channel soliton transmission, submitted to IEEE J. Quantum Elect., v. 36 (2000), pp. 290-299 (with S. K. Turitsyn, M. Fedoruk and T.-S. Yang).

Radiation loss of dispersion-managed solitons in optical fibers, Physica D, in press (with T.-S. Yang).

* Conferences

Refereed:

Analysis of nonlinear polarization-mode dispersion in optical fibers with randomly varying birefringence, OFC Technical Digest, Vol. 6, 1997, pp. 257-258 (with P. K. A. Wai, C. R. Menyuk and J. Zhang).

Rate doubling of a highly stable soliton source, OFC Technical Digest, Vol. 6, 1997, pp. 292-293 (with D. K. Serkland, G. D. Bartolini, P. Kumar and A. V. Sahakian).

A highly-stable 59 GHz soliton source at 1550 nm, OSA Ultrafast Electronics and Optoelectronics Technical Digest, 1997, pp. 69-71 (with D. K. Serkland, G. D. Bartolini, P. Kumar and A. V. Sahakian).

All-Optical Storage of a Picosecond-Pulse Packet Using Parametric Amplification, Optical Amplifiers and Their Applications Technical Digest, 1997 (Optical Society of America), pp. 247-250 (with G. D. Bartolini, D. K. Serkland and P. Kumar).

Optimal dispersion maps for wavelength-division multiplexed soliton transmission, Optical Fiber Communication Technical Digest, Vol. 2, 1998, pp. 124-125 (with T.-S. Yang).

Stable multiple pulses in optical fibers with phase-sensitive amplification, Nonlinear Guided Waves and Their Applications Technical Digest, Vol. 5, 1998, pp. 264-266.

A highly-stable 59 GHz soliton source at 1550 nm, OSA TOPS on Ultrafast Electronics and Optoelectronics, Vol. 13, 1997, pp. 23-26. (with G. D. Bartolini, D. K. Serkland, P. Kumar, D. W. Anthon and D. L. Sipes).

Optimal launching of solitons in dispersion-managed optical fibers, in ``Mathematical and Numerical Aspects of Wave Propagation", J. A. DeSanto, Ed., 1998, SIAM (with T.-S. Yang and S. K. Turitsyn).

Radiative losses due to pulse interactions in birefringent nonlinear optical fibers, in ``Mathematical and Numerical Aspects of Wave Propagation", J. A. DeSanto, Ed., 1998, SIAM (with N. F. Smyth).

Frequency shifts in a nonlinear optical loop mirror switch induced by control pulse spreading, in ``Mathematical and Numerical Aspects of Wave Propagation", J. A. DeSanto, Ed., 1998, SIAM (with M. J. Mills).

Effect of filters on soliton interactions in wavelength-division-multiplexed systems, in ``Mathematical and Numerical Aspects of Wave Propagation", J. A. DeSanto, Ed., 1998, SIAM (with M. J. Mills).

Analysis of all-optical clock recovery using a mode-locked fiber laser, in ``Nonlinear Waves and Solitons in Physical Systems", R. Camassa, J. M. Hyman and B. P. Luce, Eds., North-Holland, 1998 (with A. Niculae).

Optimal prechirping for dispersion managed transmission of return to zero pulses, Optical Fiber Communication Technical Digest, 1999, pp. 249-251 (with T.-S. Yang).

Dispersion maps with amplifier placement optimized for massive WDM, European Conference on Optical Communication Technical Digest, Vol. 1 (1999), pp. 400-401 (with B. S. Marks and S. K. Turitsyn).

Studies on signal propagation in optical fibers with randomly varying birefringence, in ``New Trends in Optical Soliton Transmission Systems", Proceedings of the Symposium held in Kyoto, Japan, 18--21 November 1997. A. Hasegawa, ed., Dordrecht, Netherlands: Kluwer Academic Publishers, 1998, p. 69 (with P. K. A. Wai, D. Marcuse and C. R. Menyuk).

Unrefereed:

Experiments on soliton pulse storage using phase-sensitive amplification, Proceedings of the Optical Society of America 1996 Annual Meeting (with Glenn Bartolini, Darwin K. Serkland, and

Prem Kumar).

INTERACTIONS/TRANSITIONS

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

Invited talks:

``High bit-rate data transmission in nonlinear optical fibers", Workshop on Complex and Nonlinear Systems, University of Chicago, May 1999.

``Analysis of chirped return-to-zero pulse propagation in dispersion-managed optical fibers", Session on Nonlinear Waves in Optics, International Conference on Nonlinear Evolution Equations and Wave Phenomena: Computation and Theory, International Association for Mathematics and Computers in Simulation (IMACS), University of Georgia, April 1999.

Invited talk, ``Optimal launching of solitons in wavelength-division-multiplexed dispersion-managed optical fibers", OSA Workshop on Novel Solitons and Nonlinear Periodic Structures, Victoria, British Columbia, March 1998.

Invited minisymposium talk, ``Optimal launching of solitons in dispersion-managed optical fibers," SIAM Conference on Mathematical and Numerical Aspects of Wave Propagation, Golden, Colorado, June 1998.

Invited minisymposium talk, ``Radiative losses due to pulse interactions in birefringent nonlinear optical fibers," SIAM Conference on Mathematical and Numerical Aspects of Wave Propagation, Golden, Colorado, June 1998.

Contributed talks:

``Analysis of all-optical clock recovery using a mode-locked fiber laser", invited talk, 17th Annual International Conference on Nonlinear Waves and Solitons in Physical Systems, Center for Nonlinear Studies, Los Alamos National Laboratory, May 1997.

``Optical pulse dynamics in dispersion managed fibers", Fourth SIAM Conference on Applications of Dynamical Systems, Snowbird, Utah, May 1997.

``Switching-induced timing jitter in nonlinear optical loop mirrors", Fourth SIAM Conference on Applications of Dynamical Systems, Snowbird, Utah, May 1997.

``Analysis of nonlinear polarization-mode dispersion in optical fibers with randomly varying birefringence", Fourth SIAM Conference on Applications of Dynamical Systems, Snowbird, Utah, May 1997.

``Analysis of nonlinear polarization-mode dispersion in optical fibers with randomly varying birefringence", Optical Fiber Communications Conference, sponsored by the Optical Society of America, Dallas, February 1997.

``A highly-stable 59 GHz soliton source at 1550 nm", Ultrafast Electronics and Optoelectronics Conference, sponsored by the Optical Society of America, Lake Tahoe, March 1997.

``Timing jitter reduction in a laser mode-locked by an input bit-stream", Fourth SIAM Conference on Applications of Dynamical Systems, Snowbird, Utah, May 1997.

``Frequency shifts in a nonlinear optical loop mirror switch induced by control pulse spreading," SIAM Conference on Mathematical and Numerical Aspects of Wave Propagation, Golden, Colorado, June 1998.

``Effect of filters on soliton interactions in wavelength-division-multiplexed systems," SIAM Conference on Mathematical and Numerical Aspects of Wave Propagation, Golden, Colorado, June 1998.

``Stable multiple pulses in optical fibers with phase-sensitive amplification," Conference on Nonlinear Guided Waves and Their Applications, sponsored by the Optical Society of America, Victoria, British Columbia, April 1998.

``Stability of pulses with phase-sensitive amplifiers," Northwestern University, Department of Mathematics, May 1998.

``Optimal dispersion maps for wavelength-division multiplexed soliton transmission systems," Optical Fiber Communications Conference, sponsored by the Optical Society of America, San Jose, February 1998.

``Power enhancement and optimal launching of dispersion-managed solitons" Workshop on Nonlinear Optics, Arizona Center for Mathematical Sciences, University of Arizona, October 1997.

``Modeling of quasi-phase-matched optical wavelength conversion", Workshop on Nonlinear Optics, Arizona Center for Mathematical Sciences, University of Arizona, September, 1999.

``Dispersion maps with amplifier placement optimized for massive WDM," European Conference on Optical Communication, Nice, France, September 1999.

``Dynamics of wavelength-division-multiplexed transmission of return-to-zero pulses in dispersion-managed optical fibers," Fifth SIAM Conference on Applications of Dynamical Systems, Snowbird, Utah, May 1999.

``Radiation loss of dispersion-managed solitons in optical fibers," Fifth SIAM Conference on Applications of Dynamical Systems, Snowbird, Utah, May 1999.

``Multiple-scale averaging and optimum amplifier placement in multi-channel dispersion-managed soliton transmission," Fifth SIAM Conference on Applications of Dynamical Systems, Snowbird, Utah, May 1999.

``Multiple-scales averaging of parametric gain equations with periodic domain poling," Fifth SIAM Conference on Applications of Dynamical Systems, Snowbird, Utah, May 1999.

``Optimal prechirping for dispersion-managed transmission of return-to-zero pulses," Optical Fiber Communication Conference and the International Conference on Integrated Optics and Optical Fiber Communication, San Diego, February, 1999.

``Have we exploited glass fully yet?" Northwestern University

Technology Review, McCormick School of Engineering, March, 1999
(with Prem Kumar).

* Consultative And Advisory Functions To Other Laboratories And Agencies

Visitor, July and August, 1999 to University of Maryland Baltimore
County, Professor Curtis Menyuk

* Transitions

NEW DISCOVERIES, INVENTIONS, OR PATENT DISCLOSURES

Patent applied for:
``High-stability soliton source"

Patent applied for:
``Optimizing launch points for dispersion-managed solitons"

HONORS/AWARDS