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PULSE PROPAGATION IN INHOMOGENEOUS OPTICAL WAVEGUIDES

Progress Report

9/15/92 - 9/14/93

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PULSE PROPAGATION IN INHOMOGENEOUS OPTICAL WAVEGUIDES

I. Accomplishments in 1992-1993

There have been exciting advances in the past year in the field of trans-oceanic, all-optical communications. The development of a system in which repeaters are replaced with erbium-doped optical amplifiers continues apace. At present, the focus at AT&T is upon the development of an NRZ (non-return to zero) communication system based upon propagation near the zero dispersion point. The NRZ system has made significant progress with the construction of a 10,000 km testbed and the determination that a system operating at 5 Gb/sec is feasible.¹ However, the recent discovery that filtering the optical signal dramatically reduces the effects of noise in a soliton system²⁻⁴ has made it apparent that it will be possible to multiplex soliton systems, which is not possible with NRZ systems. To date, transmission at 10 Gb/sec over 20,000 km has been achieved.

Birefringence plays an important, and not altogether understood, role in the both NRZ⁵ and soliton⁶ systems. The effect of randomly varying birefringence was recently discovered to play an important role in limiting the attainable bit error rates in NRZ systems. The effect on soliton systems is still unknown but is expected to be significant. In order to elucidate this situation, better models of the randomly varying birefringence are required. To date, almost all the work relevant to soliton propagation has assumed that the fiber birefringence and the polarization phase are completely randomized at regular intervals.⁶⁻⁹ An exception is the recent work of Ueda and Kath,¹⁰ but this work focuses on a limit in which the decorrelation length is short compared to the beat length which may not be realistic for most fibers. Poole and co-workers,¹¹⁻¹³ using a coupled mode approach due to Marcuse,¹⁴ have been studying the effect of randomly varying birefringence in a model which effectively assumes that the decorrelation length of the axes of birefringence is long compared to the beat length and a high degree of regularity in the evolution which also may not be realistic.

In the past year, we have begun investigating the implication of a Langevin model for the decorrelation in which we assume, effectively, an exponentially decreasing autocorrelation of the fiber birefringence and then determine the autocorrelation of the field. The key parameter is the ratio of the beat length to the assumed autocorrelation length of the fiber birefringence. While there are some limits where we can obtain analytical results, we need to use a numerical approach to obtain complete information over the entire parameter regime. We have found that the decorrelation length of the field is minimized by having a beat length on the order of the decorrelation length of the fiber birefringence. This case is optimal in a communication system because it minimizes the polarization dispersion. Two other works on birefringence, related to the conditions to obtain fibers without nonlinear polarization rotation and to describe the connection between our work and the earlier

work of Poole and co-workers¹¹⁻¹² are now in preparation and have been presented at the 1992 OSA Annual Meeting in Albuquerque, NM. During this period, Dr. Menyuk has been asked to give several invited talks to discuss his group's work on randomly varying birefringence.

In closely related work, we have begun an effort to examine wavelength and polarization division multiplexing. The idea is to determine the limits which nonlinear effects and differential gain impose on one's ability to carry out wavelength division multiplexing. This work is at an early stage. We have also published fundamental work supporting the hypothesis that solitons are robust with respect to Hamiltonian deformations. Further work on this issue is ongoing in collaboration with Dr. R. J. Hawkins of Lawrence Livermore National Laboratory.

Our work on lasers has been highly productive. The figure-8 laser¹⁵ and the fiber ring laser¹⁶ on which we have focused our attention are both examples of passively modelocked lasers with fast saturable absorbers. These systems have been studied to date using two almost diametrically opposite approaches. In the first approach, which is computational, one simulates the entire evolution of light within the laser, starting from noise. In the second approach, which is analytical, one uses an idealization in which the pulse evolution during a single pass through the laser is assumed to be small to obtain a simple equation, closely related to the Ginzburg-Landau equation, which describes the evolution. One then determines the equilibria of this equation and their stability. Determining the stability is a crucial step since only *stable* equilibria can occur in nature; yet, it is a step that is hard to carry out analytically, and work to date^{17,18} has relied on approximate methods which require considerable *a priori* physical insight into the form that the most unstable perturbations will have.

Our approach is conceptually identical to the analytical approach, but the stability calculation is done numerically. From a computational standpoint, the problem then reduces to determining the eigenvalues and eigenvectors of moderate-size matrices—a much-studied problem for which rapid and efficient methods of solution exist.¹⁹ This approach retains a major advantage of the analytical approach over complete simulations, which is that a wide range of the parameter space which is available to the experimentalist can be explored, while allowing one to eliminate approximations in the stability calculation. We have applied this approach to figure-8 lasers and fiber ring lasers.^{15,16}

We are examining both a laser's ability to self-start from noise and to stably modelock. Conditions for both have been obtained. The work on passive modelocking has been submitted to *Optics Letters*, and we will shortly be submitting another paper on self-starting and begin writing a long paper describing the global dynamics of both types of these lasers. While nothing has yet appeared in print on this issue, except for one paper whose focus is on simulations, we have been discussing our work with our experimental colleagues, and Dr. Menyuk has already been invited to give a talk on this subject at the Optical Society's *Nonlinear Guided Waves Topical Meeting*, to be held in Cambridge, England next September. This work will be reported in detail in the Ph.D. thesis of Mr. C.-J. Simon Chen, who is expected to graduate within the coming month.

Our work on solid state devices has taken a highly interesting turn. There have

been several attempts in the literature to compare split step Fourier transform schemes to finite-difference schemes.²⁰⁻²² While reviewing this issue in systems which are radiative, we found that we needed highly accurate solutions for comparison purposes. To do so, we combined Richardson extrapolation with an explicit scheme and discovered that it allowed us to stabilize a normally unstable scheme. Using transverse Richardson extrapolation, as well as extrapolation during the evolution, we routinely obtain accuracies of one part in 10^{-8} or better. Our ability to use an explicit scheme, rather than the usual implicit scheme, is very significant because the implicit scheme vectorizes poorly. The additional overhead inherent in the Richardson extrapolation is almost compensated for by the use of an explicit scheme. It appears that this discovery may have a significant impact on how computation of wave propagation in solid state devices is done—particularly when there are two or more transverse dimensions. We have submitted one paper for publication on this subject and another is in preparation. We have also presented these results at the Optical Society's *Integrated Photonics Research Topical Meeting*, held in Palm Springs, CA in March.

Also, the opportunity arose for us to begin a collaboration with Drs. T. C. Huang and G. Simonis of the Army Research Laboratory in Adelphi, MD, studying light propagation in switches with electronically modulated indices of refraction.^{23,24} Dr. Huang started his work on this subject while a student of Dr. L. Coldren at U. C. Santa Barbara, which is considered to be one of the country's best solid state device groups, and he has continued this work at the Army Research Laboratory. For the past two months, he has been visiting our group on a weekly basis to collaborate in the theoretical effort. As a consequence of our work, Mr. Chinni, a member of our group, has been included as a co-author on two presentations, one at the *Integrated Photonics Research Topical Meeting*, held in Palm Springs, CA in March and the other at the *Conference on Lasers and Electro-Optics*, held in Baltimore, MD in May. Unfortunately, we do not appear in the program in either case because our collaboration came too late for Mr. Chinni's name to be included in the official program.

A list of our publications and conference presentations is included in the next section.

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II. Publications and Conference Presentations in 1992-1993

Journal Publications:

1. C.J. Chen, P.K.A. Wai, and C.R. Menyuk, "Soliton Fiber Ring Laser," *Optics Lett.* **17**, 417-419 (1992).
2. C.R. Menyuk, "Soliton Robustness in Optical Fibers," (*J. Opt. Soc. Am. B*, to appear).
3. C.-J. Chen, P.K.A. Wai, and C.R. Menyuk, "Stability of Passively Modelocked Lasers," (submitted to *Optics Letters*).
4. I.N. Duling, III, P.K.A. Wai, C.-J. Chen, and C.R. Menyuk, "Operation of a Nonlinear Loop Mirror in a Cavity," (submitted to *IEEE J. Quantum Electron.*).
5. V.R. Chinni, C.R. Menyuk, and P.K.A. Wai, "Accurate Solution of the Paraxial Wave Equation Using Richardson Extrapolation," (submitted to *IEEE Photon. Tech. Lett.*).

Conference Proceedings:

1. C.R. Menyuk and P.K.A. Wai, "Soliton Propagation in an Optical Fiber With Randomly Varying Birefringence," in *Proceedings of the Tenth Symposium on Energy Engineering Science*, edited by O.P. Manley (Office of Scientific and Technical Information, Oak Ridge, TN, 1992), pp. 233-240.
2. C.R. Menyuk and P.K.A. Wai, "Simulations of Solitons in Birefringent Optical Fibers," in *Advances in Computer Methods for Partial Differential Equations VII*, edited by R. Vichnevetsky, D. Knight, and G. Richter (IMACS, New Brunswick, NJ, 1992), pp. 510-516.

Conference Presentations: (indicates an invited presentation)*

1. V.R. Chinni, C.R. Menyuk, and Y.J. Chen, "Propagation Characteristics of GaAs/AlGaAs QW Ridge Waveguides," S.P.I.E. Conference on Emerging Optoelectronic Technologies, Bangalore, India (Dec. 16-21, 1991).
2. C.R. Menyuk, "A Recipe For Soliton Robustness in Optical Fibers," Integrated Photonics Research Topical Meeting, New Orleans, LA (April 13-16, 1992), paper TuI4.

- *3. C.R. Menyuk, "Soliton Propagation in an Optical Fiber With Randomly Varying Birefringence," Tenth Symposium on Energy Engineering Science, Argonne, IL (May 11–13, 1992).
- *4. C.R. Menyuk, "Simulations of Solitons in Birefringent Optical Fibers," IMACS-PDE7 Conference, New Brunswick, NJ (June 21–24, 1992).
- 5. P.K.A. Wai, C.R. Menyuk, and H.H. Chen, "Polarization Dispersion in Randomly Varying Birefringence Fiber," Optical Society of America Annual Meeting, Albuquerque, NM (Sept. 20–25, 1992), paper ThF4.
- *6. C.R. Menyuk, "Soliton Robustness and Hamiltonian Deformations in Optical Fibers," SIAM Conference on Applications of Dynamical Systems, Snowbird, UT (Oct. 15–19, 1992).
- *7. C.R. Menyuk, "Solitons in Birefringent Optical Fibers," Integrated Photonics Research Topical Meeting, Palm Springs, CA (March 22–24, 1993), paper ITuF1.
- 8. V.R. Chinni, C.R. Menyuk, and P.K.A. Wai, "Accurate Solution of the Paraxial Wave Equation Using Richardson Extrapolation," Integrated Photonics Research Topical Meeting, Palm Springs, CA (March 22–24, 1993), paper ITuI3.
- 9. T.C. Huang, G.J. Simonis, M. Stead, R.P. Leavitt, J. Bradshaw, J. Pham, and V.R. Chinni, "Compact GaAs/AlGaAs Waveguide Optical Switch With Adjustable Y-Junction," Integrated Photonics Research Topical Meeting, Palm Springs, CA (March 22–24, 1993), paper ITuA4.
- 10. T.C. Huang, G.J. Simonis, L.A. Coldren, and V.R. Chinni, "Optical Switch Constructed From Field-Induced Waveguides," Conference on Lasers and Electro-Optics, Baltimore, MD (May 2–7, 1993), paper CThH6.

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