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PULSE PROPAGATION IN INHOMOGENEOUS OPTICAL FIBERS

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PULSE PROPAGATION IN INHOMOGENEOUS OPTICAL FIBERS

The last year has seen exciting advances in all-optical "photonic" technology. One of the most important of these is the development by Huang's group at AT&T Bell Laboratories of an optical "computer" based on S-seed semiconductor devices, reported in *Time* magazine.¹ Another is the transmission of solitons over 11,000 km in optical fiber with erbium doped amplifier sections by Linn Mollenauer and co-workers at AT&T Bell Laboratories, reported in *The New York Times*.² A third advance which is less mature and has therefore attracted less attention from the popular media is the demonstration for the first time of four-port optical fiber switches with cascadability, fan-out capability, and level restoration.³⁻⁵ These switches are all based on solitons in birefringent optical fibers, and Menyuk's studies^{6,7} of dragging and trapping in these fibers are often cited as an important contribution to the switch designs. Optical fibers are attractive for use as switches because their nonlinearity $\times$ length product is higher by several orders of magnitude than any solid state device. Conversely, the lengths of fiber required are about 0.5 km, implying switching latencies of about 1 μ s. Network and computer designs which are compatible with these large latencies exist.^{8,9} At the same time, the search continues for solid state materials which have large nonlinearity $\times$ length products and at the same time much higher nonlinearities than optical fibers.¹⁰

Menyuk and his co-workers are participating in several of these developments. We have collaborated with Linn Mollenauer and his co-workers in a study of randomly varying birefringence,¹¹ a study which we are continuing and which also has potential impact on coherent communication schemes.¹² We have collaborated with Mohammed Islam of AT&T Bell Laboratories in studies of optical fiber switches,¹³ and one of our students will spend at least three months and possibly twelve months at AT&T Bell Laboratories to work with Dr. Islam. Dr. Menyuk will also be visiting Dr. Islam's laboratory during part of the summer. We have completed work on interferometric switches.¹⁴ With Gary Carter, formerly of MIT-Lincoln Laboratory, now an associate professor at UMBC, we expect to begin experimental studies of pulse propagation in optical fibers. The Food and Drug Administration is lending us a color center laser and related optics with a value $\sim$ \$120,000 on a long-term basis. We will pay for an optical table (\$6,700) and Gary Carter will pay to retrofit it ($\sim$ \$20,000). With Ray Chen, formerly of GTE Laboratory, now an associate professor at UMBC, we are carrying out studies of ribbed waveguides and Y-junctions¹⁵ in configurations which Dr. Chen and his co-workers are investigating experimentally.

During the previous year, we carried out work on both optical fibers and solid state devices, although the solid state device work was preliminary in nature and, with the exception of a payment to a consultant, Dr. Ray Hawkins of LLNL, was supported by internal university funds (DRIF).

The optical fiber work can best be described by reference to particular publications. Interferometric switches based on a Mach-Zender configuration have long been used in solid state devices¹⁶ and have been proposed for use in optical fibers.¹⁷ The optical fiber switches use a soliton of one polarization to switch the phase of another polarization by a fixed amount in one arm, while in the other arm the soliton propagates unchanged. By controlling the phase, it is possible to control whether these solitons interfere constructively or destructively. A difficulty is that in birefringent fibers, solitons create "shadows" when they interact and are no longer in a pure polarization state. The paper "Pulse propagation in an elliptically birefringent medium" by Menyuk derives the equations governing soliton interactions in a birefringent fiber and shows that this problem disappears at $\theta \simeq 35^\circ$, where θ is the ellipticity angle. Such fibers can be created by spinning bow-tie preforms as they are drawn.¹⁸ In a later paper, "Soliton switch using birefringent optical fibers," by Chen, Wai, and Menyuk, we study the soliton interaction when $\theta \neq 35^\circ$ and determine the impact of shadow creation on the interferometric switches. While interest in this switch has waned, as it is hard to stabilize and more likely configurations cited in the Introduction now exist, our calculation of shadow magnitudes and their effects have proved useful in other switching configurations.

In more recent work, we have been collaborating with Dr. Islam of AT&T Bell Laboratories who is building dragging and trapping switches. The experiments have been limited by the Raman effect, and we have been investigating this phenomenon. It was first necessary to establish the equations to be solved; the results are reported in "Raman effect in birefringent optical fibers" by Menyuk, Islam, and Gordon which has been submitted to *Optics Letters*. We also describe in a qualitative way the effect of the different Raman interaction terms. This paper has already proved useful as two other groups, one at IBM and the other at the University of Arizona, are working on similar problems and got the basic equations wrong (which they now concede). Another paper describing the numerical solution of these equations is now in preparation.

We have also begun to consider soliton evolution and interaction in optical fibers with randomly varying birefringence. Initial work on a simple model in which the polarization flips randomly between two axes of birefringence is reported in "Resistance of solitons to the effects of polarization dispersion in optical fibers" by Mollenauer, Smith, Gordon, and Menyuk. This birefringence is considered to be the leading candidate to explain the observed long-distance interaction between solitons.¹⁹ Our results suggest that the long-range interaction can be removed by decreasing the dispersion of the fiber and, indeed, that has proved to be the case.²⁰ Work on a more realistic model of the birefringence, including the possibility of strength fluctuations, is now in progress. There is reason to suspect, as discussed in subsection C, that when the birefringence strength fluctuates, its effect on signals will be enhanced. Since this case is the most realistic, its examination is imperative. Work to date has proceeded slowly, largely because Dr. Wai, who intended to work on this project, only recently became available to devote substantial time to it. Dr. Wai will now be working full-time on this project, and we anticipate that the rate of progress will accelerate.

Finally, we have carried out some fundamental studies in which Hamiltonian tech-

niques are used to derive the basic equations describing birefringent fibers and some simple fiber properties are discussed. The results are reported in the manuscript "Hamiltonian reduction of Maxwell's equations in dielectric waveguides" which has been submitted to *Physica D*.

The papers mentioned in the previous paragraphs can all be found in Appendix A, along with the Introduction to a review paper, to appear as a book chapter, and some conference presentations.

The work on solid state devices has passed through a formative stage and has been largely supported to date by internal University of Maryland funding (DRIF). We have begun by building codes to determine the normal modes of ribbed waveguides²¹ and Y-junctions.²² In the former case, we have effectively neglected dielectric variations in the direction of propagation. In the latter case, we have kept the transverse variation in one dimension but have neglected variations in the other dimension. (See ref. 15 for a discussion of the relationship between the two approximations.) We have used a standard finite element method in the former case²³ and the beam propagation method in the latter case.²⁴ Both codes have been successfully debugged and run on test problems in the last two months. They will now be modified and run on problems of physical and technological interest.

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10. One idea being actively pursued at present by several research groups is to use quantum well devices at wavelengths far from the bandgap edge. While this approach will substantially reduce the nonlinearities which have been observed, the absorption should be reduced even more. The hope is that attractive nonlinearities can still be maintained while increasing the nonlinearity $\times$ length product. (N. Doran, British Telecom and R. Ramaswamy, U. Florida, Gainesville; private communication to C. Menyuk.)
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14. C. J. Chen, P. K. A. Wai, and C. R. Menyuk, *Opt. Lett.* **15**, 477 (1990). Another paper is in preparation.
15. In the "real" world of physical devices, this distinction is artificial. The devices must guide the radiation in the transverse direction while providing coupling along the direction of propagation. To model these devices, one can begin by examining the transverse structure. An example is shown in Fig. 1. One determines an effective index by solving for $k_z(\omega)$, the wavenumber as a function of frequency, in the guide. Given

the effective index, one can treat coupling problems with one transverse dimension as shown schematically in Fig. 2. Thus, in studying rib waveguides and Y-junctions, we are studying two aspects of the same devices.

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