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6. AUTHOR(S)
Professor Curtis R. Menyuk

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Maryland Baltimore County
CSEE Department
5401 Wilkens Avenue
Baltimore, MD 21228-5398

8. PERFORMING ORGANIZATION REPORT NUMBER

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13. ABSTRACT *(Maximum 200 words)*

The research was aimed at determining the impact of nonlinearity on the distribution of the differential group delay due to nonlinearity. And at determining the length scale over which polarization mode dispersion (PMD) yields the well-known asymptotic Maxwellian distribution. Professor Kath assisted with both projects. The work in both projects was presented at conferences and is being prepared for publication. In the first project, we simulated a large number of different fibers using parameters that MCl/Worldcom supplied to us. We found that the nonlinearity induces a significant chirp. This chirp can interact with the second-order PMD to substantially affect the final distribution of the differential group delay (DGD). In some cases, it can even reverse the effect of the usual first-order PMD, leading to a "PMD improvement." In the second project we solved the Fokker-Planck equation for the evolution of the polarization dispersion vector on the Poincare sphere. We found that the distribution approaches a MaxWellian distribution in approximately 50 correlation lengths. Since this length is only 5 km at most in real fibers, we concluded that the asymptotic distribution will always be observed at the endpoint of real systems. Nonetheless, there is a persistant correlation between the final polarization state and the DGD (length of the polarization dispersion vector). We are working with experimentalists to verify these results.

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FINAL TECHNICAL REPORT FOR "Prototyping & Optimization of Ultra-High Speed Fiber Optic Links" AFOSR Grant # F49620-96-1-0439.

Submitted by: Curtis R. Menyuk, Professor, UMBC

There are several significant technical accomplishments realized from this research grant. The following sections are organized to highlight the activity and accomplishments by category. The work was carried out under the direction of Professor Menyuk and his two CO-PI's Professor Gary Carter and Professor Yung-Jui Chen. Each section will identify the responsible PI/CO-PI.

Phased Array Waveguide Grating Routers (Professor Chen): Phased array waveguide grating routers (PAWG) have been proposed for use in WDM systems for a variety of applications including multiplexing, demultiplexing, and add-drop functions. The research carried out for this project has concentrated on two important aspects of these devices. The first area investigated is use of these devices as real-time monitors in WDM systems. The concept involves using adjacent input channels on the device. On the output of the device these two inputs will give outputs in adjacent channels with slightly different output versus wavelength curves. The curves are shifted in the peak transmission wavelength per channel if properly designed. By forming the ratio of these two outputs one obtains a discriminator curve for the actual wavelength of the input. This ratio can then be fed back or monitored to correct source drift. This is particularly important in dense-WDM systems. Models have been developed which have been validated on experimental devices. These models show that by careful design one can achieve an optical wavelength discrimination of 0.08nm/dB.

A second area of research centers around the assessment of the role of photo-mask resolution on the performance of the PAWG devices. In particular one would like to reduced channel cross-talk in DWDM systems to improve performance. A sophisticated statistical and physical model was developed to address the effects of a variety of fluctuations on the cross-talk. The model was tested against measured cross-talk in actual devices fabricated with varying amounts of mask resolution. Excellent agreement was obtained between the data and the model. The model was then used to look at cross-talk improvements with increasing resolution. While significant gains were observed for increased resolution alone, power variation due to variations in waveguide loss, etc. can significantly decrease the potential benefits at the higher resolutions (standard deviations of path-length error less than 25 nm). This research indicates that it should be possible to reduce channel cross-talk to the – 40 dB level.

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Y. J. Chen and Haifeng Li, "Planar waveguide WDM technology: from components to systems," *SPIE Proceedings*, vol CR71, pp. 75-107, 1999.

High Speed Data Transmission and Modeling (Professors Carter and Menyuk): This research has concentrated on developing methods for transmitting single channel data at high data rates over very long distances. The research performed as part of this project has directly led to the understanding of important parameters that control communication performance for dispersion-managed soliton data formats. In particular, the aim of the research was to increase our data rates above 10 Gigabits/sec. We had developed all of the experimental technology to carry out the transmission of 20 Gigabits/sec, but were unable to achieve transmission with low error rates past a few thousand km. Careful experimental observation revealed that our return-to-zero pulses had energy in the neighboring bit slot (50 psec away). Following that lead we used numerical models to show that the energy at the next bit-slot needed to be at least 25 dB down from the peak to prevent pulse-to-pulse interactions for the parameters of our experiment. This led us to purchase a short pulse, high repetition-rate source, with negligible tails at the next bit slot. Using this source we successfully achieved 20 Gbit/s transmission over 20,000 km at low error rates. In addition we developed a model for single channel transmission that replicated all of the significant experimental results including bit-error rates. We then used this model to design a 40 Gbit/s experiment which thus far has achieved transmission over 6400 km at low error rates.

As an outgrowth of the dispersion-managed soliton research, a number of groups (including ours) have predicted that dispersion-managed solitons could exist in a dispersion map even where the path-averaged dispersion is normal. The key factor allowing this is the fact that dispersion-managed solitons have a varying bandwidth within a dispersion map. Thus, even though a low power (linear) pulse would experience path-averaged normal dispersion, a higher power (nonlinear) pulse would experience a net anomalous dispersion due to bandwidth variation. We carefully studied, both experimentally and theoretically, the propagation of dispersion-managed solitons near zero path-averaged dispersion. We were successful in reaching normal path-averaged dispersion (the first such demonstration). One of the major outcomes of our research was that this "normal" dispersion soliton is very sensitive to parameter variation making it undesirable for real communication systems.

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"Tolerance of Dispersion-Managed Soliton Transmission to the Shape of the Input Pulses", V. S. Grigoryan, G. M. Carter, and C. R. Menyuk, IEEE Photonics Technology Letters, VOL. 12, NO. 9, SEPTEMBER 2000, pp.1165-1167.

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"Experimental Demonstration of Long-Distance Dispersion-Managed Soliton Propagation at Zero Average Dispersion, " V.S. Grigoryan, R.-M. Mu, G.M. Carter, and C.R. Menyuk, Photonics Technology Letters vol. 12, pp. 45-46 (2000).

"Transmission of Dispersion-Managed Solitons at 20 Gbit/s Over 20,000 km", Gary M. Carter, Ruo-Mei Mu, Vladimir Grigoryan, Curtis R. Menyuk, Pranay Sinha, Thomas F. Carruthers, Michael L. Dennis, and Irl N. Duling III, Electronics Letters vol. 35, pp. 233-234 (1999).

Polarization Mode Dispersion (Professor Menyuk with Dr. E. Ibragimov, Professor W. Kath, and Professor J. Yang)

The research with Dr. Ibragimov was aimed at determining the impact of nonlinearity on the distribution of the differential group delay due to nonlinearity. The research with Professor Yang was aimed at determining the length scale over which polarization mode dispersion (PMD) yields the well-known asymptotic Maxwellian distribution. Professor Kath assisted with both projects. The work in both projects was presented at conferences and is being prepared for publication.

In the first project, we simulated a large number of different fibers using parameters that MCI/Worldcom supplied to us. We found that the nonlinearity induces a significant chirp. This chirp can interact with the second-order PMD to substantially affect the final distribution of the differential group delay (DGD). In some cases, it can even reverse the effect of the usual first-order PMD, leading to a "PMD improvement."

In the second project with Dr. Yang, we solved the Fokker-Planck equation for the evolution of the polarization dispersion vector on the Poincare sphere. We found that the distribution approaches a Maxwellian distribution in approximately 50 correlation lengths. Since this length is only 5 km at most in real fibers, we concluded that the asymptotic distribution will always be observed at the endpoint of real systems. Nonetheless, there is a persistant correlation between the final polarization state and the DGD (length of the polarization dispersion vector). We are working with experimentalists to verify these results.

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1. E. Ibragimov, C. R. Menyuk, and W. Kath, "PMD-Induced Reduction of Nonlinear Penalties in Terrestrial Optical Fiber Transmission, "Optical Fiber Communication Conference, Baltimore, MD (March 5-10, 2000), paper WL3.

2. J. Yang, W. L. Kath, and C. R. Menyuk, "PMD Probability Distribution For Arbitrary Distances," Conference on Lasers and Electro-Optics, San Francisco, CA (May 7-12, 2000), paper CML2.