REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-02-

0274

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE 7/18/2002

3. REI Final 4/1/1996 - 1/15/2002

4. TITLE AND SUBTITLE

Advanced Optoelectronic Components for All-Optical Networks

5. FUNDING NUMBERS

F49620-96-1-0126

6. AUTHOR(S)

Prof. Jeffrey H. Shapiro

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Research Laboratory of Electronics
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Office of Scientific Research/
110 Duncan Avenue, Suite B115
Bolling Air Force Base, DC 20332-8080

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

D451/00

11. SUPPLEMENTARY NOTES

The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (A

Under AFOSR Grant F49620-96-1-0126, "Advanced Optoelectronic Components for All-Optical Networks," we have worked to develop key technologies and components to substantially improve the performance, and potentially lower the cost, of future optical networks. Our multidisciplinary team comprised MIT faculty and research staff whose collective expertise spans optical materials, optical component fabrication, ultrafast optics, optical communications, and network architecture. The specific objectives of our program were to:

- develop key technology components for all-optical networks that employ time-division multiplexing (TDM)
- develop key technology components for all-optical networks that employ wavelength-division multiplexing (WDM)
- perform ancillary studies of noise behavior, dispersion management, and other issues relevant to all-optical networks

In this final report we briefly summarize our accomplishments over the entire grant period, 1 April 1996 through 15 January 2002. Many additional details can be found in our annual progress reports, and all our work has been extensively documented in archival journals (see Publications, below).

20020909 145

14. SUBJECT TERI

. NUMBE

. PRICE CODE

17. SECURITY CL OF REPORT

. LIMITATION OF ABSTRACT

UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

FINAL REPORT

Advanced Optoelectronic Components
for All-Optical Networks

U.S. Air Force Office of Scientific Research
Grant F49620-96-1-0126

Covering the Period
April 1, 1996 – January 15, 2002

Submitted by

Jeffrey H. Shapiro
Principal Investigator

Hermann A. Haus, Erich P. Ippen,
Leslie A. Kolodziejski, and Henry I. Smith
Senior Investigators

July 19, 2002

Research Laboratory of Electronics
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139-4307

RESEARCH SUMMARY

Under AFOSR Grant F49620-96-1-0126, "Advanced Optoelectronic Components for All-Optical Networks," we have worked to develop key technologies and components to substantially improve the performance, and potentially lower the cost, of future optical networks. Our multidisciplinary team comprised MIT faculty and research staff whose collective expertise spans optical materials, optical component fabrication, ultrafast optics, optical communications, and network architecture. The specific objectives of our program were to:

- develop key technology components for all-optical networks that employ time-division multiplexing (TDM)
- develop key technology components for all-optical networks that employ wavelength-division multiplexing (WDM)
- perform ancillary studies of noise behavior, dispersion management, and other issues relevant to all-optical networks

In this final report we briefly summarize our accomplishments over the entire grant period, 1 April 1996 through 15 January 2002. Many additional details can be found in our annual progress reports, and all our work has been extensively documented in archival journals (see Publications, below).

TDM Components

Senior Investigators: Prof. H.A. Haus, Prof. E.P. Ippen, Prof. L.A. Kolodziejski

The TDM components that we have worked on are: short-pulse, high-rate fiber lasers; glass-waveguide lasers with saturable Bragg mirrors; fiber-loop memories; and nonlinear optical filters.

Short-Pulse, High-Rate Lasers

Solitons are the natural source choice for TDM because of their intrinsic resistance to dispersive pulse spreading. TDM all-optical networks require laser sources that produce pulse streams with 1–10 ps pulse durations, 10–20 Gbps repetition rates, excellent environmental stability, and low timing jitter. Modelocking is the best way to generate reliable pulse streams, hence simultaneous achievement of all of the preceding desiderata from modelocked fiber and glass-waveguide lasers was the central thrust of our work on TDM sources. Among our many achievements in the area of short-pulse, high-rate lasers are the following.

- We realized 4.4-fold pulse narrowing below the Kuizenga-Siegman limit by exploiting soliton formation in active harmonic modelocking.

- We demonstrated intracavity phase-modulation synchronization in a passively modelocked fiber laser that yielded 60 dB of supermode suppression, and we used the output from this laser to drive an optical amplifier and supercontinuum fiber to obtain a 350-nm-wide spectrum. This source, covering the spectral region from 1350 to 1700 nm, is the broadest band high-repetition-rate laser to date.

- We have modeled and measured the timing recovery dynamics of fiber lasers, a topic of considerable interest for clock recovery in optical networks or optical analog-to-digital conversion. Amplitude perturbations were shown to decay exponentially with a time constant proportional to the fiber length divided by the product of modulation depth times the square of the pulsewidth. Phase perturbations were shown to decay in a damped oscillatory manner, with underdamped, critically damped, and overdamped behavior all being possible, depending on parameter values.

- We have demonstrated a saturable-absorber modelocked glass waveguide laser, employing an Er/Yb co-doped waveguide to achieve higher gain—hence a shorter active region and more compact design—than can be realized with erbium alone. This laser produced a 162 MHz repetition rate train of 1 ps pulses with more than 60 dB of sidemode suppression.

- An essential component of the Er/Yb waveguide laser was a distributed-Bragg reflector saturable absorber mirror. This mirror was designed and grown as part of our effort in saturable-absorber mirror engineering. Other mirror designs were optimized for use in a linear Er-doped fiber laser, and for pulse-intensity stabilization of an actively harmonically-modelocked fiber laser, see below.

- We have demonstrated that a two-photon absorption (TPA) mirror can provide 55 dB of sidemode suppression and complete elimination of pulse dropouts in a harmonically modelocked ring laser. The TPA mirror is stable, compact, polarization insensitive, and does not require solitonic effects to achieve this excellent laser stabilization behavior.

Fiber-Loop Memories

TDM networks require optical buffers to store as much as 10 kbits for 100's μs to enable such network functions as rate conversion and header recognition. In 1992, Haus and Mecozzi at MIT predicted that such a memory could be constructed from a fiber loop with gain, anomalous group-velocity dispersion, an appropriate filter and modulation. Doerr and Wong at MIT demonstrated a fiber-loop memory, in 1994, which was followed by collaboration with the group at MIT Lincoln Laboratory. As part of AFOSR Grant F49620-96-1-0126, we worked to suppress the transient relaxation oscillations in these memories, and sought architectures that obviated the need for synchronous loading. Our principal achievement in this area was the development of the asynchronous optical buffer. In this system, we were demonstrated preservation of a random stream of ones and zeros for 157 μs, representing 1600 circulations of the fiber loop. Moreover, the demonstrated storage time was not limited by the memory, but rather by the maximum trigger delay of our measurement system.

Nonlinear Optical Filters

Nonlinear optical mirrors can be self-switching devices. We have demonstrated self-switching, arising from dispersion imbalance, in such structures. With this technique we were able to create a nonlinear filter in which short pulses are transmitted but continuous-wave (cw) interference is not. Our initial tests showed more than 22 dB suppression of cw light with more than 30% transmission of pulsed light. This filter was then used to obtain 7 dB of sensitivity enhancement in a 10 Gbps communication receiver.

WDM Components

Senior Investigators: Prof. H.A. Haus, Prof. L.A. Kolodziejski, Prof. H.I. Smith

The WDM components that we have worked on are: channel-dropping filters; high index contrast integrated optics; and optical frequency comb generators.

Channel-Dropping Filters

WDM networks need components to drop and add wavelengths with low insertion loss and high efficiency. Our approach, which originates from theory due to Lai and Haus at MIT, is to use quarter-wave shifted Bragg gratings in a design that combines a single side coupled receiver (SSCR) with a resonant optical reflector (ROR). Precision grating fabrication is crucial to the development of such channel-dropping filters. Toward that end, we have developed a dual-layer hard mask process that achieves the 1:1000 grating-period precision needed. This process opens up fabrication opportunities for a variety of integrated optics devices. A second vital fabrication issue with respect to the channel-dropping filters is the necessity of growing epi layers on top of corrugated surfaces *without* incurring mass transport which would destroy the integrity of these underlying gratings. Here we have shown that low-temperature removal of the native oxide is the key to pattern preservation, as proven by our photoluminescence and triple-axis diffraction diagnostic studies. In addition to its importance for fabrication of channel-dropping filters, our mastery of surface-corrugation overgrowth is relevant to development of distributed feedback lasers and quantum-wire structures.

High Index Contrast Integrated Optics

The use of high index contrast (~3:1) dielectric materials, in conjunction with microwave design principles from the 1940's and 1950's, affords the opportunity for dense optical integration. We have used coupled-mode theory and 2-D finite-difference time-domain (FDTD) calculations to analyze and design a variety of important integrated optical devices. Some specific examples are as follows.

- By placing an appropriate microresonator at the corner, we have shown that a right-angle waveguide bend can be realized with high transmission and low reflection.
- By appropriately combining two of the right angle bends—merging their resonators—we have obtained a T-junction design that has high-transmission and low re-

flection. This T-junction outperforms and is more compact than a conventional integrated optics Y-splitter.

- By placing an appropriate microresonator at the crossing between two orthogonal waveguides, we have suppressed crosstalk and reflections while preserving high transmission. This low-crosstalk waveguide crossing offers significant benefits for high-density optical integration.

Optical Frequency Comb Generators

We have investigated and implemented the technique of resonant velocity-matched electro-optic modulation for generating an ultrawide optical frequency comb that can be utilized as a multi-channel wavelength generator. In a prototype experiment including partial intracavity dispersion compensation, we have generated an optical frequency comb over a span of 16 nm centered at 1064 nm with a 17-GHz channel spacing. While the results were encouraging, recent advances in ultrawide comb generation using femtosecond modelocked lasers have produced spectacular results with comb spans in excess of several hundreds of nm.

Noise and Dispersion Studies

In support of our technology work, we pursued several ancillary studies aimed at issues relevant to all-optical networks. For example, we performed experiments that verified the non-Gaussian photocurrent statistics of amplified spontaneous emission (ASE) from optical amplifiers. Erbium-doped fiber amplifiers are what makes optical networks possible. Standard sensitivity analyses employ Gaussian probability densities for ASE noise, even though this is not quantum-mechanically correct. We have also explored the impact of polarization-mode dispersion (PMD) on soliton propagation. PMD presents a severe limit on long-haul, high-rate communication systems. Nonlinear (soliton) propagation is considerably less sensitive to PMD than ordinary, linear propagation. We have quantified this advantage through calculations for both uniform and dispersion-managed fiber. Finally, we have developed a unified definition for noise figure that applies, in a consistent manner, to both microwave and optical amplilfiers.

Personnel

Research under AFOSR Grant F49620-96-1-0126 was performed by the following personnel.

Principal Investigator: Prof. Jeffrey H. Shapiro

Senior Investigators: Prof. Hermann A. Haus, Prof. Erich P. Ippen, Prof. Leslie A. Kolodziejski, and Prof. Henry I. Smith

Research Staff: Dr. Jay N. Damask, Dr. Brent E. Little, Dr. Gale S. Petrich, and Dr. Franco N.C. Wong

Postdoctoral Associates: Dr. Markus Joschko, Dr. Patrick Langlois, and Dr. Mordechai Margalit

Graduate Students: Igor Balk, L. Reggie Brothers, Yijiang Chen, Patrick C. Chou, Alexei A. Erchak, Juan Ferrera, Juliet T. Gopinath, Matthew E. Grein, J. Todd Hastings, Joseph C. Huang, Leaf A. Jiang, David J. Jones, M. Jalal Khan, Elisabeth M. Koontz, Michael H. Lim, Christina Manolatou, Aleksandra Markina, Jeremy M. Milikow, Thomas E. Murphy, Lynn E. Nelson, Elisa C. Pasquali, Naimish S. Patel, Thomas R. Schibli, Erik R. Thoen, William S. Wong, and Charles X. Yu

Publications

Journal Articles

The following journal articles report research funded (at least in part) by AFOSR Grant F49620-96-1-0126.

1. J.N. Damask, "Practical Design of Side-Coupled Quarter-Wave shifted Distributed-Bragg Resonant Filters," J. Lightwave Tech. **14**, 812 (1996).

2. J. Ferrera, M.L. Schattenburg, and H.I. Smith, "Analysis of Distortion in Interferometric Lithography," J. Vac. Sci. Technol. B **14**, 4009 (1996).

3. E.M. Koontz, M.H. Lim, V.V. Wong, G.S. Petrich, L.A. Kolodziejski, H.I. Smith, K.M. Matney, G.D. U'Ren, and M.S. Goorsky, "Preservation of Rectangular-Patterned InP Gratings Overgrown by Gas Source Molecular Beam Epitaxy," Appl. Phys. Lett. **71**, 1400 (1997).

4. L.R. Brothers and N.C. Wong, "Dispersion Compensation for Terahertz Optical Frequency Comb Generation," Opt. Lett. **22**, 1015 (1997).

5. W.S. Wong, S. Namiki, M. Margalit, E.P. Ippen, and H.A. Haus, "Self-Switching of Optical Pulses in Dispersion-Imbalanced Nonlinear Loop Mirrors," Opt. Lett. **22**, 1150 (1997).

6. L.E. Nelson, D.J. Jones, K. Tamura, H.A. Haus, and E.P. Ippen, "Ultrashort-Pulse Fiber Ring Lasers," Appl. Phys. B **65**, 277-294 (1997).

7. D.J. Jones, L.E. Nelson, H.A. Haus, and E.P. Ippen, "Diode-Pumped Environmentally Stable Stretched-Pulse Fiber Laser," IEEE Select. Topics in Quantum Electron. **3**, 1076 (1997).

8. B.E. Little and T. Murphy, "Design Rules for Maximally Flat Wavelength-Insensitive Optical Power Devices using Mach-Zehnder Structures," IEEE Photon. Tech. Lett. **9**, 1607 (1997).

9. J.S. Foresi, P.R. Villeneuve, J. Ferrera, E.R. Thoen, G. Steinmeyer, S. Fan, J.D. Joannopoulos, L.C. Kimerling, H.I. Smith, E.P. Ippen, "Photonic-Bandgap Microcavities in Optical Waveguides," Nature **390**, 143 (1997).

10. D.J. Jones, K.L. Hall, H.A. Haus, and E.P. Ippen, "Asynchronous Phase-Modulated Optical Fiber Ring Buffer," Opt. Lett. **23**, 177 (1998).

11. D.J. Jones, S. Namiki, D. Barbier, E.P. Ippen, and H.A. Haus, "116-fs Soliton Source based on an Er-Yb Codoped Waveguide Amplifier," IEEE Photon. Tech. Lett. **10**, 666 (1998).

12. D.J. Jones, H.A. Haus, L.E. Nelson, and E.P. Ippen, "Stretched-Pulse Generation and Propagation," IEICE Trans. Electron. **E81-C**, 180 (1998).

13. B.E. Little, J.S. Foresi, G. Steinmeyer, E.R. Thoen, S.T. Chu, H.A. Haus, E.P. Ippen, L.C. Kimerling and W. Green, "Ultra-Compact Si-SiO_2 Microring Resonator Optical Channel Dropping filter," IEEE Photon. Tech. Lett. **10**, 549 (1998).

14. B.E. Little, H.A. Haus, J.S. Foresi, L.C. Kimerling, E.P. Ippen and D.J. Ripin, "Wavelength Switching and Routing using Absorption and Resonance," IEEE Photon. Tech. Lett. **10**, 816 (1998).

15. G.D. U'Ren, M.S. Goorsky, E.M. Koontz, M.H. Lim, G.S. Petrich, L.A. Kolodziejski, V.V. Wong, and H.I. Smith, "Analysis of Lattice Distortion in High-Quality In-

GaAsP Epitaxial Overgrowth of Rectangular-Patterned InP Gratings," J. Vac. Sci. Technol. B **16**, 1381 (1998).

16. H.A. Haus, "The Noise Figure of Optical Amplifiers," IEEE Photon. Tech. Lett. **10**, 1602 (1998)

17. Y. Chen and H.A. Haus, "Dispersion-Managed Solitons with Net Positive Dispersion," Opt. Lett. **23**, 1013 (1998).

18. W.S. Wong, P.B. Hansen, T.N. Nielson, M. Margalit, S. Namiki, H.A. Haus and E.P. Ippen, "In-Band Amplified Spontaneous Emission Noise Filtering with a Dispersion-Imbalanced Nonlinear Loop Mirror," J. Lightwave Tech. **16**, 1768 (1998).

19. D.J. Jones, Y. Chen, H.A. Haus, and E.P. Ippen, "Resonant Sideband Generator Stretched-Pulse Fiber Lasers," Opt. Lett. **23**, 1535 (1998).

20. W.S. Wong, H.A. Haus, L.E. Jiang, P.B. Hansen and M. Margalit, "Photon Statistics of Amplified Spontaneous Emission Noise in a 10-Gbit/s Optical Preamplified Direct-Detection Receiver," Opt. Lett. **23**, 1832 (1998).

21. E.R. Thoen, E.M. Koontz, M. Joschko, P. Langlois, T.R. Schibli, F.X. Kärtner, E.P. Ippen, and L.A. Kolodziejski, "Two-Photon Absorption in Semiconductor Saturable Absorber Mirrors," Appl. Phys. Lett. **74**, 3927 (1999).

22. C. Manolatou, M.J. Khan, S. Fan, P.R. Villeneuve, H.A. Haus, J.D. Joannopoulos, "Coupling of Modes Analysis of Resonant Channel Add/Drop Filters," IEEE J. Quantum Electron. **35**, 1322 (1999).

23. C. Manolatou, S.G. Johnson, S. Fan, P.R. Villeneuve, H.A. Haus, and J.D. Joannopoulos, "High-Density Integrated Optics," J. Lightwave Technology **17**, 1682 (1999).

24. E.M. Koontz, G.D. U'Ren, M.H. Lim, L.A. Kolodziejski, M.S. Goorsky, G.S. Petrich, and H.I. Smith, "Overgrowth of (In,Ga)(As,P) on Rectangular-Patterned Surfaces Using Gas Source Molecular Beam Epitaxy," J. Crystal Growth **198/199**, 1104 (1999).

25. M.J. Khan, C. Manolatou, S. Fan, P.R. Villeneuve, H.A. Haus, J.D. Joannopoulos, "Coupling of Modes Analysis of Multipole Symmetric Resonant Add/Drop Filters," IEEE J. Quantum Electron. **35**, 1451 (1999).

26. M.E. Grein, L.A. Jiang, H.A. Haus, E.P. Ippen, "Timing Restoration Dynamics in an Actively Modelocked Fiber Laser", Opt. Lett. **24**, 1687 (1999).

27. P. Langlois, M. Joschko, E.R. Thoen, E.M. Koontz, F.X. Kärtner, E.P. Ippen, and L.A. Kolodziejski, "High Fluence Ultrafast Dynamics of Semiconductor Saturable Absorber Mirrors," Appl. Phys. Lett. **75**, 3841 (1999).

28. M.H. Lim, J. Ferrera, K.P. Pipe and H.I. Smith, "A Holographic Phase-Shifting Interferometer Technique to Measure In-Plane Distortion", J. Vac. Sci. Technol. B **17**, 2703 (1999).

29. M.H. Lim, T.E. Murphy, J. Ferrera, J.N. Damask and H.I. Smith, "Fabrication Techniques for Grating-Based Optical Devices," J. Vac. Sci. Technol. B **17**, 3208 (1999).

30. E.M. Koontz, G.S. Petrich, L.A. Kolodziejski, and M.S. Goorsky, "Overgrowth of Submicron-Patterned Surfaces for Buried Index Contrast Devices (Invited),"

Semiconductor Science and Technology **15**, R1 (2000).

31. C.X. Yu, H.A. Haus, E.P. Ippen, W.S. Wong, and A. Sysoliatin, "A Gigahertz-Repetition-Rate Modelocked Fiber Laser for Continuum Generation," Opt. Lett. **25**, 19 (2000).

32. E.R. Thoen, M.E. Grein, E.M. Koontz, E.P. Ippen, H.A. Haus, and L.A. Kolodziejski, "Stabilization of an Active Harmonically Mode-locked Fiber Laser using Two-photon Absorption," Opt. Lett. **25**, 948 (2000).

33. M. Joschko, P. Langlois, E.R. Thoen, E.M. Koontz, E.P. Ippen, and L.A. Kolodziejski, "Ultrafast Hot-Carrier Dynamics in Semiconductor Saturable Absorber Mirrors," Appl. Phys. Lett. **71**, 1383 (2000).

34. E.R. Thoen, E.M. Koontz, D.J. Jones, D. Barbier, F.X. Kärtner, E.P. Ippen, and L.A. Kolodziejski, "Erbium-Ytterbium Waveguide Laser Mode-Locked with a Semiconductor Saturable Absorber Mirror," IEEE Photon. Tech. Lett. **12**, 149 (2000).

35. E.R. Thoen, J.P. Donnelly, S.H. Groves, K.L. Hall, and E.P. Ippen, "Proton Bombardment for Enhanced Four-Wave Mixing in InGaAsP-InP Waveguides," IEEE Photon. Tech. Lett. **12**, 311 (2000).

36. H.A. Haus, "Noise Figure Definition Valid from RF to Optical Frequencies (Invited),", IEEE J. Sel. Topics in Quantum Electron. **6**, 240 (2000).

37. J.T. Hastings, F. Zhang, J.G. Goodberlet, and H.I. Smith, "Two-Dimensional Spatial-Phase-Locked Electron-Beam Lithography via Sparse Sampling," J. Vac. Sci. Technol. B **18** 3268, (2000).

38. T.E. Murphy, M.K. Mondol, and H.I. Smith, "Characterization of Field Stitching in E-Beam Lithography using Moiré Metrology," J. Vac. Sci. Technol. B **18**, 3287 (2000).

39. J.T. Hastings, F. Zhang, J.G. Goodberlet and H.I. Smith, "Improved Pattern-Placement Accuracy in E-Beam Lithography via Sparse-Sample Spatial-Phase Locking," Microelectronic Engineering **53**, 361 (2000).

40. J.T. Gopinath, E.R. Thoen, E.M. Koontz, M.E. Grein, L.A. Kolodziejski, and E.P. Ippen, "Recovery Dynamics in Proton-Bombarded Semiconductor Saturable Absorber Mirrors," Appl. Phys. Lett. **78**, 3409 (2001).

41. T.E. Murphy, J.T. Hastings and H.I. Smith, "Fabrication and Characterization of Narrow-Band Bragg-Reflection Filters in Silicon-on-Insulator Ridge Waveguides," Journal of Lightwave Technology, **19**, 1938 (2001).

42. H.J. Eisler, V.C. Sundar, M.G. Bawendi, M. Walsh, H.I. Smith, and V. Klimov, "Color-Selective Semiconductor Nanocrystal Laser," Appl. Phys. Lett. **80**, 4614 (2002).

43. L.A. Jiang, M.E. Grein, E.P. Ippen, C. McNeilage, J. Searls, and H. Yokoyama, "Quantum-Limited Noise Performance of a Mode-Locked Laser Diode," Opt. Lett. **27**, 49 (2002).

44. M.E. Grein, L.A. Jiang, H.A. Haus, E.P. Ippen, C. McNeilage, J.H. Searls, and R.S. Windeler, "Observation of Quantum-Limited Timing Jitter in an Active, Harmonically Modelocked Fiber Laser," Opt. Lett. **27**, 957 (2002).

Conference Presentations

The following conference presentations reported research funded (at least in part) by AFOSR Grant F49620-96-1-0126.

1. E.M. Koontz, M.H. Lim, V.V. Wong, G.S. Petrich, L.A. Kolodziejski, H.I. Smith, M.S. Goorsky, and K.M. Matney, "Overgrowth of InGaAsP Materials on Rectangular-Patterned Gratings using GSMBE," IEEE Proceedings of the 9th International Conference on InP and Related Materials, May 11-15, Hyannis, MA, 1997.

2. G.D. U'Ren, K.M. Matney, M.S. Goorsky, M. Wormington, E.M. Koontz, M.H. Lim, V.V. Wong, G.S. Petrich, L.A. Kolodziejski, and H.I. Smith, "Triple Axis Diffraction Studies of InGaAsP/InP Epitaxial Overgrowth Grating Structures," 46th Annual Denver X-Ray Conference, Aug. 4-8, Steamboat Springs, CO, 1997.

3. E.M. Koontz, M.H. Lim, V.V. Wong, G.S. Petrich, L.A. Kolodziejski, H.I. Smith, G.D. U'Ren, K.M. Matney, M.S. Goorsky, and M. Wormington, "Analysis of Lattice Distortions in High Quality InGaAsP Epitaxial Overgrowth of Rectangular-Patterned InP Gratings," North American Conference on Molecular Beam Epitaxy, Oct. 5-8, Ann Arbor, MI, 1997.

4. L.A. Kolodziejski, E.M. Koontz, G.S. Petrich, G.D. U'Ren, M.S. Goorsky, M.H. Lim, and H.I. Smith, "Overgrowth of (In,Ga)(As,P) on Patterned Surfaces using Gas Source Molecular Beam Epitaxy (Invited)," Tenth International Conference on Vapor Growth and Epitaxy, July 26-31, Jerusalem, 1998.

5. E.P. Ippen, D.J. Jones, W.S. Wong, L.E. Nelson. and H.A. Haus, "Fiber Devices for Ultrahigh-Speed Photonics," in *Topics in Optics and Photonics*, Optical Society of America, Washington DC, 1998.

6. E.P. Ippen, D.J. Jones, L.E. Nelson, and H.A. Haus, "Ultrafast Fiber Lasers," in *Ultrafast Phenomena XI*, Springer Verlag, 1998.

7. W.S. Wong, H.A. Haus, L.A. Jiang, P.B. Hansen, and M. Margalit, "Photon Statistics of Amplified Spontaneous Emission Noise in a 10 Gb/s Optically Preamplified Lightwave Direct Detection Receiver," paper WT4, LEOS '98, Orlando, FL.

8. W.S. Wong, J.D. Moores, J. Korn, and H.A. Haus, "Photon Statistics of NRZ Signals in a High-Bit-Rate Optically Preamplified Direct Detection Receiver," paper WM24, OFC '99, San Diego, CA.

9. E.R. Thoen, E.M. Koontz, D.J. Jones, F.X. Kärtner, E.P. Ippen, L.A. Kolodziejski, and D. Barbier, "Suppression of Instabilities and Pulsewidth Limitation by Two-Photon Absorption in Modelocked Lasers," paper CThL1, Conference on Lasers and Electro-Optics, Baltimore, MD, May 1999.

10. E.R. Thoen, E.M. Koontz, D.J. Jones, P. Langlois, F.X. Kärtner, E.P. Ippen, L.A. Kolodziejski, and D. Barbier, "Picosecond Pulses from an Er/Yb Waveguide Laser Passively Modelocked with a Semiconductor Saturable Absorber Mirror," paper CWA3, Conference on Lasers and Electro-Optics, Baltimore, MD, May 1999.

11. M.E. Grein, L.A. Jiang, H.A. Haus, and E.P. Ippen, "A Study of the Dynamics Governing Timing Restoration in the Actively Modelocked Soliton Laser," paper

CTuJ1, Conference on Lasers and Electro-Optics, Baltimore, MD, May 1999.

12. T.R. Schibli, E.R. Thoen, E.M. Koontz, F.X. Kärtner, E.P. Ippen, and L.A. Kolodziejski, "Suppression of Modelocked Q-switching and Multiple Pulse Break-up by Two-Photon Absorption," in Ultrafast Optics Conference, Ascona, Switzerland, July 1999.

13. T.E. Murphy, B.E. Little and H.I. Smith, "Wavelength-and Polarization-Insensitive Integrated Directional Couplers using Mach-Zehnder Structures," in Integrated Photonics Research, OSA Technical Digest, pp. 138–140 (1999).

14. D.J. Ripin, J.T. Gopinath, H.M. Shen, F.X. Kärtner, E.P. Ippen, A.A. Erchak, G.S. Petrich, L.A. Kolodziejski, and U. Morgner "A Few-Cycle Cr4+:YAG Laser," presented at the Conference on Lasers and ElectroOptics, Long Beach, CA, May 19-24, 2002.

15. A.A. Erchak, D.J. Ripin, J.T. Gopinath, H.M. Shen, F.X. Kärtner, G.S. Petrich, L.A. Kolodziejski, and E.P. Ippen, "Large Scale Oxidation of AlAs Layers for Broadband Saturable Bragg Reflectors," presented at the Conference on Lasers and ElectroOptics, Long Beach, CA, May 19-24, 2002.

16. J.T. Hastings, M.H. Lim, J.G. Goodberlet and H.I. Smith, "Optical Waveguides with Apodized Gratings via Direct-Write Spatial-Phase-Locked E-Beam Lithography," presented at the 2002 International Conference on Electron, Ion, Photon Beam Technology and Nanofabrication, May 28-31, 2002, Anaheim, CA. (2002).

Patent

The following patent represents intellectual property developed under AFOSR Grant F49620-96-1-0126.

1. J.N. Damask, T.E. Murphy, J. Ferrera, M.H. Lim, H.I. Smith, and H.A. Haus, "Wavelength-Selective Optical Add/Drop Switch," U.S. Patent 5,915,051, June 22, 1999. Patent has been licensed to Clarendon Photonics.

Technology Transfer

The following technology transfers occurred under AFOSR Grant F49620-96-1-0126.

- Fiber lasers developed under our MURI program were used in the DARPA-sponsored TDM test bed
- Fiber loop memories developed under our MURI program were used in the DARPA-sponsored TDM test bed
- A fsec laser developed under our MURI program was used at Lucent Technologies Bell Laboratories as the source for a 2000-channel WDM demonstration
- The quantum-limited timing jitter of our fiber lasers has made them a key component of the DARPA Photonic A/D Converter Technology (PACT) Program.
- The MIT lithography work won the Lemelson-MIT Student Prize for Innovation in 2000.
- Clarendon Photonics has licensed the patent "Wavelength-Selective Optical Add/Drop Switch."