REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
11-8-95

3. REPORT TYPE AND DATES COVERED
Final 7/1/92 - 6/30/95

4. TITLE AND SUBTITLE
Application of X-ray Nanolithography to the Fabrication of Optoelectronic Integrated Circuits

5. FUNDING NUMBERS
DAAL03-92-G-0291

6. AUTHOR(S)
Prof. Henry I. Smith

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Research Laboratory of Electronics
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139-4307

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARO 30362.7-EL-SDI

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 *(Maximum 200 words)*

As a result of the research carried out under this grant, we have laid the foundation for an entirely new approach to high performance optoelectronic components for all-optical networks utilizing wavelength-division multiplexing. We have developed both the required nanofabrication technology and the basic components. This work will be continued and expanded under DARPA sponsored MURI funding. New grating-based components that promise even higher performance than those described here have recently been conceived, something that would not have occured except for this grant. These more advanced components will be pursued under the MURI program which will commence in early 1996.

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)

Final Report

to

Army Research Office
on
Grant DAAL 03-92-G-0291

"Application of X-ray Nanolithography to the Fabrication of Optoelectronic Integrated Circuits"

by

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

Principle Investigator: Professor Henry I. Smith

Period of Performance: July 1, 1992 to June 30, 1995

1.0 Statement of the Problem Studied:

Optical fibers have the potential to increase by several orders of magnitude the information carrying capacity of both civilian and military communication networks. However, existing optical fiber communication systems fall far short of this potential, in large measure because of the need to convert from optical to electronic domains for many functions, e.g., multiplexing and demultiplexing. One very attractive solution is to develop all-optical networks in which the conversion from optical to electronic will take place only at the final user terminal. Under this grant we have been developing technologies that will enable the fabrication of components for all-optical networks.

The essential problem in fabrication of components for all-optical communication networks is that the tools developed for the semiconductor industry are inappropriate for the task. This is because of the requirement in optical components for long-range spatial-phase coherence. In addition, 100nm and sub-100nm features are required.

Under this grant we have developed techniques of spatial-phase-locked electron-beam lithography (SPLEBL), x-ray nanolithography (XRN), and reactive-ion etching (RIE) compatible with the requirements of long-range spatial-phase coherence, and applied them to the fabrication of distributed-feedback (DFB) lasers and high performance optical filters. This work has demonstrated the efficacy of SPLEBL and XRN as applied to the specific problems of fabricating components for all-optical networks.

2.0 Summary of Results:

As a result of the research carried out under this grant, we have laid the foundation for an entirely new approach to high performance optoelectronic components for all-optical networks utilizing wavelength-division multiplexing. We have developed both the required nanofabrication technology and the basic components. This work will be continued and expanded under DARPA sponsored MURI funding. New grating-based components that promise even higher performance than those described here have recently been conceived, something that would not have occured except for this grant. These more advanced components will be pursued under the MURI program which will commence in early 1996.

2.1 Approach:

The techniques of optical lithography, interferometric lithography, electron-beam lithography, and x-ray nanolithography were combined with reactive-ion etching in ways that yielded the resolution, spatial coherence, geometric control, and area coverage required by high performance optoelectronic components. Many aspects of the above techniques are unique to the MIT Nanostructure Laboratory, e.g., x-ray nanolithography, nanometer-precision x-ray mask alignment, and spatial-phase-locked electron-beam lithography. The latter is a new paradigm for such lithography that utilizes a fiducial grid, produced by interferometric lithography, to ensure long-range spatial-phase coherence in electron beam lithography. One of the objectives of our work was to develop methodologies that would be compatible with future high-volume, low-cost manufacturing.

2.2 Research Vehicles:

As research vehicles to drive the development of advanced fabrication technologies we chose to develop channel-dropping filters (CDF's) illustrated in Fig. 1, and distributed feedback (DFB) lasers.

2.3 Optoelectronic Device Results:

Optical filters, consisting of quarter-wave-shifted distributed-Bragg gratings, having a variety of resonance locations, and etched to a variety of depths in silica ridge waveguides, were fabricated. This is illustrated in Fig. 2. These filters had

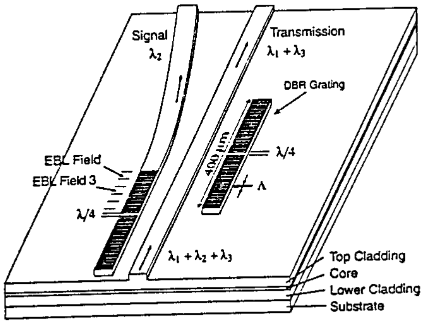


Fig.1 Schematic of the integrated resonant channel-dropping filter, a component for wavelength-division multiplexing in future all-optical networks.

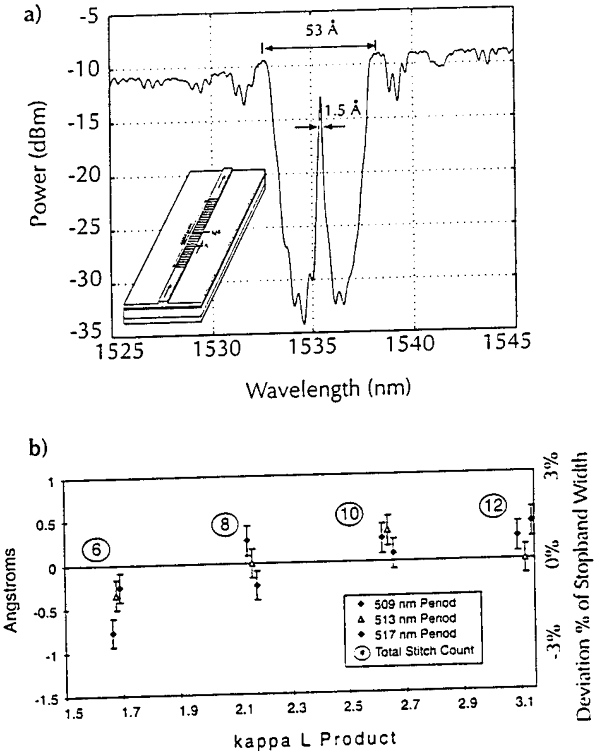


Fig. 2 (a) The optical transmission response of a single-pole filter written across nine e-beam fields. The stopband width is 53 Å and the resonance FWHM linewidth is approximately 1.5 Å. (b) The measured deviation from the stopband center of resonances from 12 resonators of different lengths and periods. The encircled numbers and the number of field stitchings.

the highest performance achieved anywhere in the world. The specific figures-of-merit were: Q (greater than 40,000), resonance location (within 0.05 nm of stopband center). Pass-band transmission characteristics followed theory to better than a fraction of a dB, the limit of measurement capability. A number of key technologies, described below, were perfected and combined to achieve this result. Grating filters spanned up to 12 distinct fields of the e-beam lithography system, yet the stitching error was less than 4 nm.

A variety of higher-order optical filters (Gaussian, Butterworth and Chebyshev) were fabricated. These filters differed from those described above in that there were several quarter-wave phase steps along the length of individual grating filters, as indicated in Fig. 3. The performance of these higher-order filters, illustrated in Fig. 4, was not as ideal as in the single-phase-step filters.

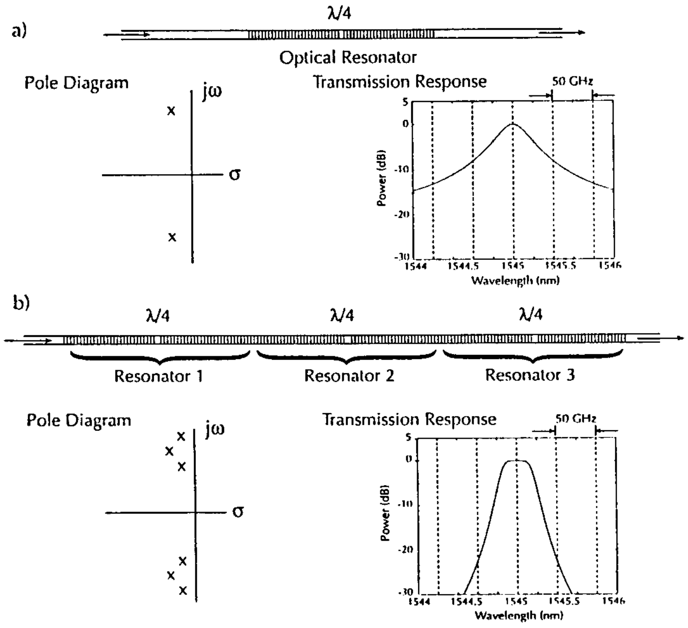


Fig. 3 (a) A Bragg grating with a single quarter-wave shift at the center can be modeled as a single-pole filter near resonance. The pole diagram shows one complex conjugate pole pair. The transmission response shows the filter spectrum near resonance, with 50 GHz spaced lines indicating the channel locations of a WDM system.

(b) Three coupled single-pole resonators create a multiple-pole filter, as indicated on the pole diagram. With proper grating design, the near-resonance spectrum can look like that shown in the transmission response.

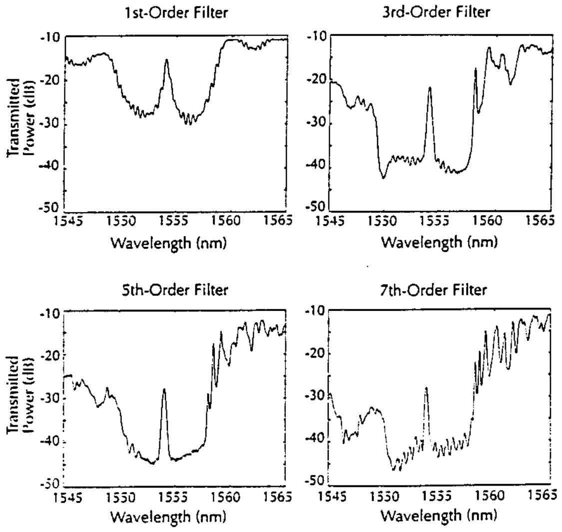


Fig. 4 The optical transmission reponse of first-, third-, fifth-, and seventh-order Gaussian multiple-pole filters. While the 0.1 nm resolution limit of the optical spectrum analyzer does not well resolve the center filter response, the side lobes on the long-wavelength side of the stopband are indicative of a Gaussian multiple-pole filter response.

Nevertheless this exercise demonstrated the effectiveness of our theoretical models, and the general strategy.

2.4 Progress in Nanofabrication Technology Development:

(1) We have developed a form of the spatial-phase-locked e-beam lithography (SPLEBL), which we call the segmented fiducial grid, that has proven effective down to the sub-nanometer domain, as shown in Fig. 5.

(2) Patterns were written on x-ray nanolithograph masks using the SPLEBL technique. The x-ray masks were then processed and used with our on-axis interferometric mask alignment scheme to expose gratings in optical waveguides. This process represents a significant advance over existing technology in industry or other research labs. This advance is reflected in the high performance of the optical filters.

(3) Developed methods for reactive ion etching directly on x-ray mask membranes. Helium backside cooling was used to avoid overheating and promote anisotropic etching.

(4) Developed methods of achieving side-coupled gratings immediately adjacent to waveguides using ion implantation, x-ray lithography, and reactive ion etching. These gratings are used in a novel DFB configuration shown in Fig. 6. Gratings of 406 nm period, with 1 to 8 line-to-period ratios, were etched in InP-based MBE-grown materials, as shown in Fig. 7. X-ray lithography is particularly valuable in achieving such linewidth control.

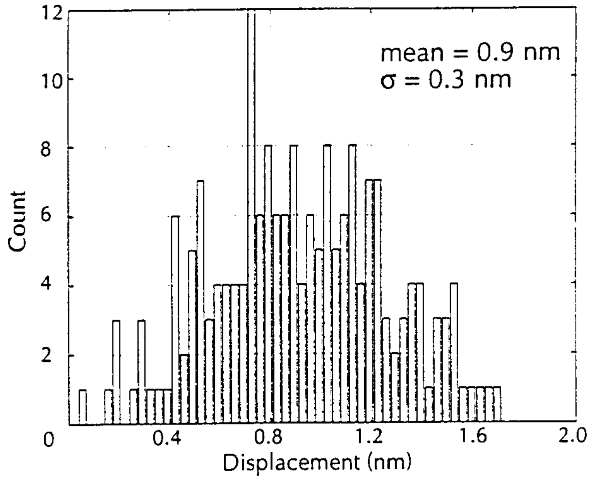


Fig. 5 Distribution of a representative subset of interfield stitching errors on an x-ray mask as measured between the e-beam field border and a fiducial reference grating prior to writing the grating segments.

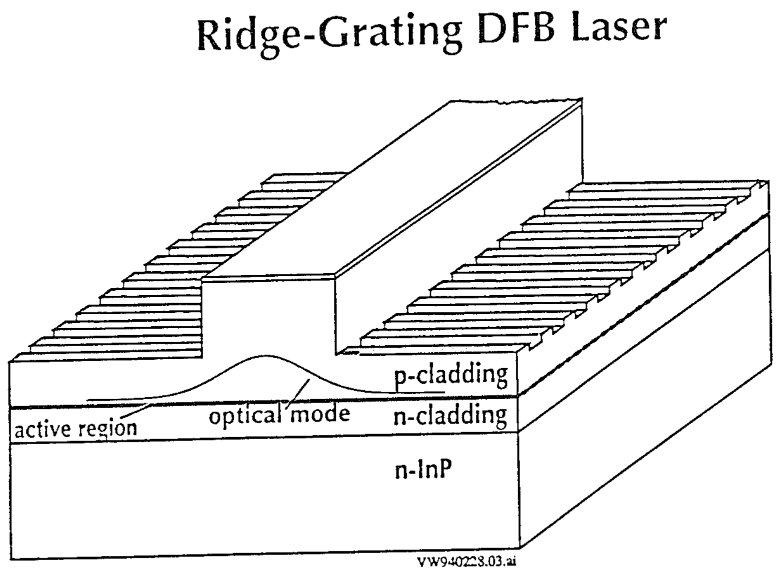
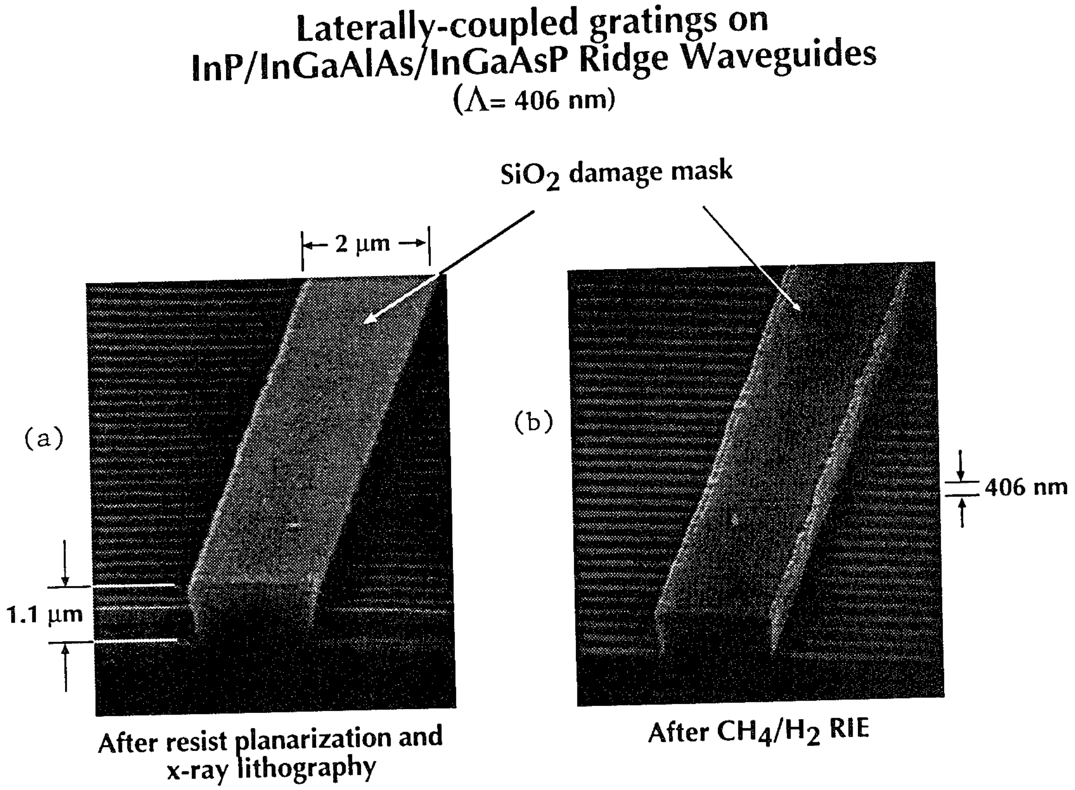


Fig. 6 Schematic of distributed feedback (DFB) laser configuration in which the grating which provides feedback is adjacent to the ridge waveguide, thereby avoiding the problem of overgrowth on a grating.



After resist planarization and x-ray lithography

After CH_4/H_2 RIE

Fig. 7 Lateral gratings defined adjacent to a 1.1-µm-high InP/InGaA1As/InGaAsP ridge waveguide. The grating has a period of 400 nm, which is appropriate for a second-order DFB laser at 1.3 µm. The silicon dioxide damage mask serves both as an RIE etch mask as well as an ion implantation damage mask. (a) Scanning electron micrograph of a 406-nm-period lateral grating exposed in PMMA by x-ray lithography; (b) scanning electron micrograph of lateral gratings defined by CH_4/H_2 RIE.

3.0 Participating Scientific Personnel:

3.1 Graduate Students:

Vincent V. Wong, Research Assistant. Ph. D. received August 1995. Currently employed at SDL, San Jose, CA

Juan Ferrera, Research Assistant

Jay Damask, Intel Fellow

Tom Murphy, NSF Fellow

3.2 Staff:

Professor Henry I. Smith, Principle Investigator

Scott Silverman, Research Engineer. Responsible for scanning electron beam lithography system including spatial-phase-locked beam lithography.

Euclid Moon, Research Specialist. Responsible for the x-ray nanolithography system and the x-ray mask alignment system (interferometric-broad-band imaging system)

James D. Carter, Research Specialist. Responsible for interferometric lithography and reactive ion etching

4.0 Publications:

4.1 Journal Articles

J. Ferrera, V.V. Wong, S. Rishton, V. Boegli, E.H. Anderson, D.P. Kern, and H.I. Smith, "Spatial-Phase-Locked Electron-Beam Lithography: Initial Test Results", J. Vac. Sci. Technol. B 11, 2342-2345 (1993).

V.V. Wong, W.-Y. Choi, J. Carter, C.G. Fonstad, and H.I. Smith, "Ridge-Waveguide Sidewall-Grating Distributed Feedback Structures Fabricated by X-ray Lithography", J. Vac. Sci. Technol. B 11, 2621-2624 (1993).

V.V. Wong, J. Ferrera, J. Damask, J. Carter, E. Moon, H.A. Haus, H.I. Smith, and S. Rishton, "Spatial-Phase Locked E-Beam Lithography and X-ray Lithography for Fabricating First-Order Gratings on Rib Waveguides", J. Vac. Sci. Technol. B 12, 3741-3745 (1994).

V.V. Wong, J. Ferrera, J.N. Damask, T.E. Murphy, and H.I. Smith, "Distributed Bragg Grating Integrated-Optical Filters: Synthesis and Fabrication", J. Vac. Sci. Technol. B, Nov/Dec 1995.

V.V. Wong, A. Yasaka, and H.I. Smith, "Resist Planarization over Topography using Ion Implantation", J. Vac. Sci. Technol. B, Nov/Dec 1995.

4.2 Conference Presentations

W.-Y. Choi, V.V. Wong, J.C. Chen, H.I. Smith, and C.G. Fonstad, "Design and Fabrication using X-ray Lithography of Ridge-Waveguide Distributed Feedback Structures on InP", International Conference on InP and Related Compounds, Santa Barbara, March 1994.

J.N. Damask, V.V. Wong, J. Ferrera, H.I. Smith, and H.A. Haus, "Optical Distributed-Feedback Channel-Dropping Filters: Design and Fabrication", LEOS '93, 6th Annual Meeting, San Jose, CA, November 15-18, 1993. (Invited Paper)

J.N. Damask, V.V. Wong, J. Ferrera, H.I. Smith, and H.A. Haus, "High-Coherence QWS Gratings for Optoelectronic Devices: Why Spatial-Phase-Locked E-Beam Lithography is Necessary", Fiber Communications Conference '94, San Jose, CA, February 20-25, 1994.

J.N. Damask, V.V. Wong, J. Ferrera, H.I. Smith, and H.A. Haus, "Highly-Coherent Electron-Beam-Written Quarter-Wave-Shifted Distributed Bragg Resonators for Channel-Dropping Filters", Optical Fiber Communications Conference '95, San Diego, CA, February 26 - March 3, 1995.

4.3 Theses

J. Ferrera, "Highly Coherent Gratings for Optoelectronics: An Application of Spatial-Phase-Locked Electron Beam Lithography", B.S. and M.S. Thesis, Department of Electrical Engineering and Computer Science, MIT, May 1994.

V.V. Wong, "Fabrication of Distributed Feedback Devices Using X-ray Lithography", Ph.D. Thesis, Department of Electrical Engineering and Computer Science, MIT, August 1995.