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13. ABSTRACT (Maximum 200 words)  This proposal requested instrumentation to make our direct writing instrumentation at Columbia capable of submicrometer overlay and registration and to provide new capability for testing integrated optical devices. This instrumentation thus included the purchase of new more rugged laser systems and optical stages and optics. Additional computers were needed to update the control systems for the apparatus and make them more compatible with in situ control. In addition two new, more-stable laser tubes were included to improve writing reliability. Additional instrumentation for subsequent lithographic patterning was also to be purchased. Finally a new optical system for testing The fabrication quality was to be purchased.
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**FINAL REPORT**

For Contract F49620-98-1-0271  
For the period 03/01/98 – 02/29/00

**“DURIP: Instrumentation for Precision Rapid Prototyping of Systems for  
Optoelectronic Circuits and Devices”**

Principal Investigator:  
Richard M. Osgood, Jr.

Submitted to:  
Air Force Office of Scientific Research/NE

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Submission date: May 31, 2000

## **FINAL REPORT**

### **DURIP: Instrumentation for Precision Rapid Prototyping of Systems for Optoelectronic Circuits and Devices**

Richard M. Osgood, Principal Investigator

## **RESEARCH SUMMARY**

### **I. Abstract**

This proposal requested instrumentation to make our direct writing instrumentation at Columbia capable of submicrometer overlay and registration and to provide new capability for testing integrated optical devices. This instrumentation thus included the purchase of new more rugged laser systems and optical stages and optics. Additional computers were needed to update the control systems for the apparatus and make them more compatible with in situ control. In addition two new, more-stable laser tubes were included to improve writing reliability. Additional instrumentation for subsequent lithographic patterning was also to be purchased. Finally a new optical system for testing The fabrication quality was to be purchased.

### **II. Instrumentation Requested**

#### **A). Precision Writing Instrumentation**

State-of-the-art integrated optical circuits such as ultra-compact MMI's and optical delay circuits require extreme precision in patterning, with tolerance requirements sometimes below  $0.1\mu\text{m}$ . Our prior laser writing apparatus was unstable during laser

writing and did not take into account deviations at the sample plane due, for example, to yaw in the system. This limited reproducibility to  $\sim \pm 0.5\mu\text{m}$ , even though the stages had motion control ability of less than  $0.1\mu\text{m}$ .

As a result of this program we have now purchased new optics and electronics which will enable us to achieve  $0.1\mu\text{m}$  or better precision and reproducibility. We have purchased two additional items of equipment for improving the precision of our laser prototyping systems. The first was simply a replacement of our UV laser tubes which were now aged to the point where reliability was suspect and power drifts were serious. Second, a more rugged optical delivery system and stage was purchased and installed. The third items were two separate pieces of laboratory hardware needed to improve the repeatability and yield of our photoresist-based process. They include, for example a state-of-the-art resist spinner with controls, and a laboratory oven. These items helped control the required resist thickness control and uniform degree of baking.

#### **B). Enhanced Test Setup**

Our instrumentation is to be used to fabricate optical devices such delay lines and resonant filters. There are relatively complex optical circuits and thus a new testing setup was required to improve the measurement of such devices. These newly purchased system included, new test laser, power meter, and improved optical amounts and stages.

#### **C). Items Fabricated with New Optics Apparatus**

An example of a circuit, which was fabricated and tested with this setup, is given in the Section IV.

	AFOSR	Columbia	TOTAL
<b>III. LIST OF PURCHASES</b>			
<b>A) NEW UV LASERS:</b>			
Coherent Laser Group: Head Assembly	\$10,530		
Lambda Physik, Inc.: Lasers	\$16,079		
Spectra Physics: Laser, Reflector	\$40,509		
Cost Sharing:			
Lambda Physik, Inc.: Laser		\$1,909	
<b>New UV Lasers Total:</b>	<b>\$67,118</b>	<b>\$1,909</b>	<b>\$69,026</b>
<b>B) NEW CONTROL COMPUTERS:</b>			
Dell Computer, Corp.: Dimension, Minitowers	\$10,047		
Page Computer: Monitor and Printer	\$1,186		
Penguin Computing System	\$4,875		
<b>New Control Computers Total:</b>	<b>\$16,108</b>	<b>\$0</b>	<b>\$16,108</b>
<b>C) NEW TEST OPTICAL SETUP:</b>			
CVI Laser Corp: Optics	\$1,473		
Edmund Scientific: Mini Electromagnet, Transla. Sl	\$2,240		
Electrophysics Corp.: TV Camera Monitor Powers :	\$6,212		
ILX Lightware: Temp. Control, Current Source	\$2,000		
KBK, Inc.: Laser Diode, Isolator Fiber	\$5,230		
Melles Griot: Polarizer Holder, Lens	\$845		
Micro Optics: SMS Stand Fluorescent Ring	\$1,949		
New Focus, Inc.: Translation Stage	\$707		
Newport Corp.: Beamsplitter, Cables, Differential Micrometer, Laser Diode Mnt., Power Meter, IR Det. Accessories	\$3,217		
Omicron Associates: Grid & Screen Pack	\$5,050		
Optics for Research: Coupling Lens, Object. Lens,	\$1,005		
Opto Sigma Corp: Base, Holder	\$799		
Oriel Corp: Beamsplitter, Ret Plate	\$1,631		
Thorlabs, Inc.: Adapter Plate, Collimator, Supplies	\$479		
Cost Sharing:			
Fischer Scientific: Lens and Fiber		\$484	
Newport Corp: Convex Lenses, Fiber Mount		\$592	
Paul evans: Quad Filter		\$16,800	
Thorlabs, Inc.: Connector, Coupler, Big. Polar. Cont.,		\$559	
<b>New Test Optical Setup Total:</b>	<b>\$32,837</b>	<b>\$18,435</b>	<b>\$51,272</b>
<b>D) FABRICATION EQUIPMENT:</b>			
Specialty Coating: Spin Coating System	\$5,684		
Fischer Scientific: Combust. Tube	\$91		
Omega Engineering: Thermocouple	\$41		
Cost Sharing:			
Fischer Scientific: Furnace, Fabr. Equip.		\$665	
Micro Chem. Corp.: Developer		\$196	
<b>Fabrication Equipment Total:</b>	<b>\$5,815</b>	<b>\$861</b>	<b>\$6,677</b>
<b>E) SMALL ACCESSORIES:</b>			
Edmund Scientific: Optical Supplies	\$257		
Thorlabs, Inc.: Prism Mount, Mounting Hardware	\$216		
Sumitomo Osaka: cement, Paper Spl. Phase Comj	\$1,940		
<b>Small Accessories AFOSR \$ Total:</b>			
Cost Sharing:			
Crystal Technology, Inc.: Wafers		\$730	
<b>Small Accessories Total:</b>	<b>\$2,413</b>	<b>\$730</b>	<b>\$3,143</b>
<b>TOTAL:</b>	<b>\$124,291</b>	<b>\$21,935</b>	<b>\$146,226</b>

#### **IV. Example of PIC Fabricated with System: Fabrication of a Compact 1x2 MMI Power Splitter Using Corner Reflectors**

Integrated multimode imaging (MMI) devices possess the ability to efficiently perform a variety of beamsplitting functions with a minimum of loss. An important issue in designing such devices is the minimization of device footprint, which in the case of small MMI devices can be limited by need for S-bends in the input and output waveguides. Recently Chung, Dagli, and their coworkers showed that a low-loss and efficient MMI-based 1x2 beam splitter in GaAs/AlGaAs could be made using turning mirrors at the output end of the device. The use of turning mirrors allows for a compact arrangement of input/output waveguides since abrupt bends can be realized with the mirror. Their work showed that good performance could be achieved using this approach. In addition, it showed that such a device contained a number of subtle and non-obvious design considerations, including mirror surface finish and waveguide geometries.

In this report we fabricated an alternate design for this device using the InP/ InGaAsP material system. The design uses two etch depths to provide different levels of confinement for the waveguiding structure, which allows loss reduction in the input and output waveguides and yet high confinement in the free-space region of the MMI structure. The fabrication of device was investigated using a laser lithographic prototyping system for the patterning in one of the two etch steps along with reactive ion etching (RIE) for pattern transfer. Laser patterning is a rapid and potentially simple approach to fabricating photonic devices; our results here show that it is capable of satisfying the MMI tolerances and the surface finish on the turning mirrors for this device. Measurements of the fabricated MMI devices are compared to the results obtained from beam propagation method (BPM) simulations.

The device wafers were grown by chemical beam epitaxy on (100)  $n^+$  InP: S-doped at  $10^{18} \text{ cm}^{-3}$ . The device structure consists of a  $0.6\mu\text{m}$ -thick undoped InGaAsP layer ( $\lambda_{\text{gap}}=1.1\mu\text{m}$ ) grown on an InP:S-doped substrate and surrounded by  $0.5\mu\text{m}$ - and  $0.8\mu\text{m}$ -thick layers of undoped epitaxial InP for the lower and upper cladding layers, respectively.

A computer-controlled laser lithographic prototyping system was used for patterning because it allowed rapid changes in design and fabrication. This technique can produce higher contrast, with good reproducibility, than conventional contact lithography with AZ5214IR photoresist if image reversal is used. The lithography system consists of a 360nm Ar-ion laser source, an attenuator, a shutter, and an x-y-z stepping-motor platform. The laser power could be attenuated via a rotatable  $\lambda/2$ -plate and a fixed Glan prism. The sample rests on an x-y-z stepping motor platform, with a step size of  $0.1\mu\text{m}$  along each axis. Both the translation stages and the light shutter are computer controlled using a CAD file containing the device geometry to be drawn.

Accurate mirror positioning and surface-roughness minimization of the corner reflectors require a precise etching process. In order to etch a smooth, vertical etch profile, a single 800Å SiO<sub>2</sub> layer, formed by e-beam evaporation, was used for the etching mask. SiO<sub>2</sub> was selected after investigating the dependence of the mirror surface of the mask material on the thin-film material, including dielectrics, metals, and photoresist. In the case of a metal mask, the pattern linewidth could not be easily controlled due to the proximity effect of the substrate. In the case of photoresist, strong erosion of mask edge and uncontrollable sidewall hydrocarbon polymer deposition, during RIE processing, presented a significant problem.

In the first step of the patterning process, photoresist was spun over the SiO<sub>2</sub>-coated layer and then exposed using the laser lithography system. The pattern was transferred into the SiO<sub>2</sub> layer by CF<sub>4</sub> RIE. The etching rate in SiO<sub>2</sub> was 30nm/min using 60W of rf power. The RIE system used a turbomolecular pump with 500l/s pumping speed to provide a chamber base pressure in the 10<sup>-6</sup> Torr range. Fabrication of the corner reflectors requires smooth, highly anisotropic etched surfaces and precise positioning of the reflecting surface. To achieve this position accuracy required control of the laser power and the stage velocity. After etching of the SiO<sub>2</sub> mask layer, the photoresist is removed. Finally, the surface ion-damaged semiconductor layer and any residual photoresist were removed by immersion in sulfuric acid.

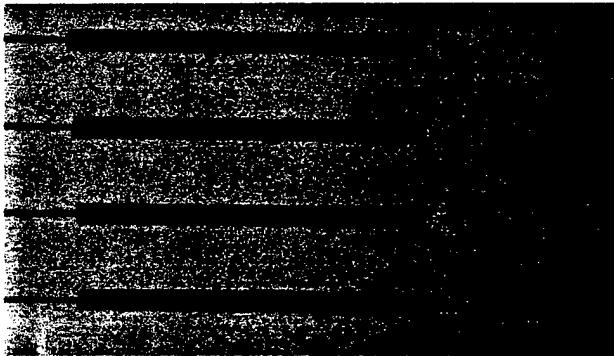
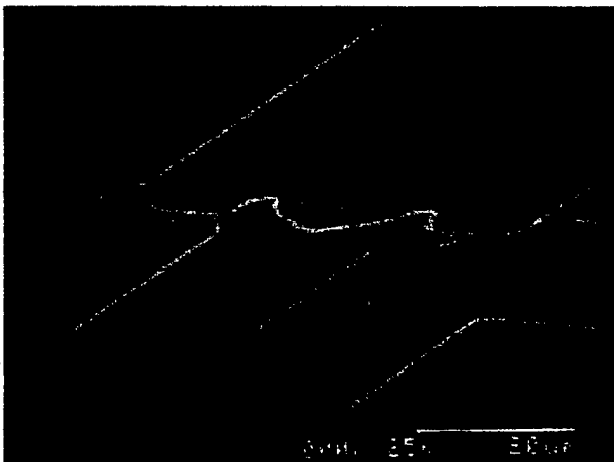


Figure 1. Scanning electron micrograph of the entire 1x2 MMI power splitters with corner reflectors; Bottom: a closeup of the mirror region and the two exit waveguides. The horizontal line seen in bottom panel results from the two regions having shallow and deep etch depths.



Two different etch depths were used [see Fig. 1]. In the first etch step, methane etching (see below), with the SiO<sub>2</sub> mask, was used to transfer the entire device pattern to an etch depth of 0.6μm. This step enabled the input and output waveguides to be formed with a shallow depth so as to achieve low propagation loss. However, for the multimode imaging region of this device, a deep-etched structure is needed to reduce the Goos-Hanchen shift and thus more closely match the ideal modal dispersion required for imaging. As a result, a subsequent and separate etch step using conventional lithographic patterning was required to etch more deeply the MMI mode mixing region and the corner reflectors. The horizontal line in Fig. 1 shows clearly the region (lower part of the micrograph) having the deeper etch<sup>1</sup>. Both etching steps used methane/hydrogen (20% CH<sub>4</sub>, 80%H<sub>2</sub>) reactive ion etching. The RIE conditions were 60W(0.26W/cm<sup>2</sup>), 40mTorr working pressure, -483V d.c. bias and 30sccm flow rate to achieve a 2.2μm etch depth in the InGaAsP/InP heterostructure system. The etching rate of InP base system was 50nm/min with the above conditions. During etching of the corner reflectors, the presence of hydrocarbon polymer on sidewalls is deleterious because this polymer increases the roughness of etched surface and decreases the anisotropic etch characteristic. Thus in the etch process, O<sub>2</sub>-descuming for 90s was used after each 10min etching interval. A scanning electron micrograph of a fabricated device, shown in the Fig. 1, indicated that the etched surface was smooth and anisotropic. After etching, the SiO<sub>2</sub> layer was removed by immersion in dilute hydrofluoric acid and the fabricated device carefully cleaved to obtain clean facets.

The above process was used to fabricate a series of strip-loaded straight waveguides and 1×2 MMI power splitters with corner reflectors, each with a different length of the MMI section, as shown in the top panel of Fig. 1. To further investigate the characteristics of fabricated mirrors, we also fabricated a Mach-Zehnder structure by connecting two passive 1×2 MMI power splitters.

The fabricated devices were tested by butt-coupling a pigtailed 1.55μm laser diode(TE) to the sample and imaging the output onto an IR camera and photodetector. An aperture, mounted on a translation stage, was used to measure the power separately from each device output port.

Measurements were made on several reference, straight waveguides along the [011] direction and on MMI devices with different MMI lengths. A near-field pattern, obtained for a device with  $L_{\text{mmi}}=428\mu\text{m}$ , is shown in Fig. 2. The measured splitting ratio was typically 50%/50%. The propagation loss was measured by using the Fabry-Perot resonance method on the straight reference waveguide section. The mean value of the propagation loss of the nine reference waveguides was 0.5dB/cm with the end facet reflectance of ~ 0.31. The resulting temperature scan showed the Fabry-Perot-resonance characteristics of a single-mode waveguide. The total loss of the device was measured by performing transmission measurements with respect to the straight reference guides and

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<sup>1</sup> The output waveguides did not quite follow the original design approach mentioned before, i.e. they are also deep etched for fabrication reason (see discussion later in the text).

found to be 2.5dB. These measurements were compared to 3D simulations of the device to evaluate the various contributions to the device loss. It was found that the input coupling and MMI imaging loss is only 0.1dB, but the output coupling loss is about 1.8dB. This chief contribution to the loss is due to the mismatch between the MMI section and the two deep-etched output coupling waveguides and could in fact be eliminated with a design which placed the border between the deep and shallow etch at the junction of the output waveguide and the MMI region. The design used here placed the boundary further back in the strip guide because the patterning required was somewhat simpler. Finally, the above loss analysis indicates that the mirror loss is as low as 0.3dB/facet. The above measurements were only done for TE polarization. The loss for TM polarization should be marginally higher because the mirror position was optimized for TE. In fact, simulation showed that the perfect mirror position for TM is different from that for TE by  $0.1\mu\text{m}$ , which would contribute an additional 0.09dB loss for TM polarization. While systematic measurements were not made, the TE and TM performances were comparable.

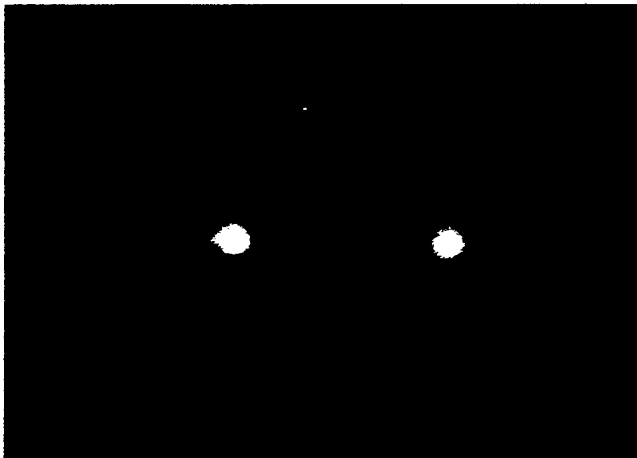


Figure 2. Near field pattern of a fabricated  $1\times 2$  power splitter showing the signal output through the two exit waveguides.