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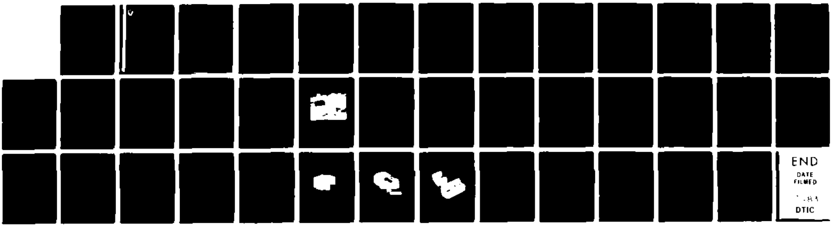

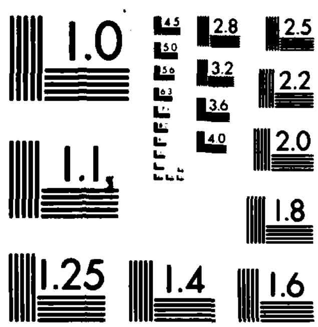

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RESEARCH AND DEVELOPMENT TECHNICAL REPORT
CECOM–82–C–J071–1

MULTIWAVELENGTH BIDIRECTIONAL COUPLER–DECOUPLERS

H. W. YEN AND J. MYER

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3011 Malibu Canyon Road
Malibu, CA 90265

March 1983

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Multiwavelength Coupler-Decoupler
Wavelength Division Multiplexer
Fiber Optic Coupler

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This is an exploratory program to develop, fabricate and test a family of active and passive, single and two-fiber, fiber optic multiwavelength, bidirectional, coupler-decoupler modules. The goal of the contract is to have each member of the coupler-decoupler (multiplexer-demultiplexer) family be capable of coupling energy into, and decoupling energy out of, a single optical transmission line, using a minimum of four wavelengths for the simultaneous full duplex transmission of a minimum of four optical channels.

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The coupler-decoupler will be designed for low throughput loss (<5 dB per channel, per single pass) and minimum crosstalk (no more than -35 dB of the received optical signal. The modules fabricated during the program will be evaluated for their ability to meet military environmental requirements, particularly with respect to temperature. The approach uses the miniature planar Rowland spectrometer configuration recently developed at Hughes Research Laboratories (HRL) for NASA, as the basic building block for constructing the coupler-decoupler required for this program, eliminating the need for collimating optics, prisms, or thin film filters.

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INTRODUCTION AND SUMMARY

A. AIMS AND OBJECTIVES

Under the present contract, Hughes Research Laboratories (HRL) is pursuing an exploratory program to develop, fabricate and test a family of fiber optic multiwavelength, bidirectional, coupler-decoupler modules. The goal of the contract is to have each member of the coupler-decoupler (multiplexer-demultiplexer) family be capable of coupling energy into, and decoupling energy out of, a single optical transmission line, using a minimum of four wavelengths for the simultaneous full duplex transmission of a minimum of four optical channels.

The coupler-decoupler will be designed for low throughput loss (<5 dB per channel, per single pass) and minimum crosstalk (no more than -35 dB of the received optical signal). The modules fabricated during the program will be evaluated for their ability to meet military environmental requirements, particularly with respect to temperature. Our approach uses the miniature planar Rowland spectrometer configuration recently developed at Hughes Research Laboratories (HRL) for NASA, as the basic building block for constructing the coupler-decoupler required for this program, eliminating the need for collimating optics, prisms, or thin film filters.

An efficient, high resolution wavelength multiplexer-demultiplexer is the key component for the simultaneous transmission of several signals of different optical wavelengths through a single optical fiber. Wavelength diversity will greatly expand the capacity and versatility of future fiber optic links. For example, each wavelength or optical frequency can serve as the carrier for signals of several users or systems multiplying the signal carrying capacity of a link by the number of wavelengths used; widely differing signals (analog or digital) of different bandwidth or data rate can each be transmitted with a different wavelength, allowing a variety of traffic to be carried simultaneously over a single optical fiber; users may couple energy into and out of an existing fiber optic link without requiring access to electronic modems.

In our work, the coupler-decoupler will be referred to as passive or active, depending on whether or not it requires electrical power for operation.

B. TECHNICAL APPROACH

The goals of this program are to develop four types of multiwavelength coupler-decouplers to provide at least four channels of bidirectional communication through either a two-fiber line or a single-fiber line. Figure 1(a) and 1(c) depict a passive and an active coupler-decoupler for two-fiber operation. The passive module is terminated with optical fiber connectors with no electrical connections made to the module. On the other hand, active modules contain the electrooptical emitters and detectors with feedthroughs for sending and receiving TTL-compatible digital signals. Figures 1(b) and 1(d) are passive and active devices for single-fiber operation. Each module will interface with multimode graded index glass optical fibers with a numerical aperture (NA) of 0.2, core diameter of 50μm, and outer diameter of 125μm.

C. PLANAR ROWLAND SPECTROMETER FOR FIBER OPTIC WAVELENGTH MULTIPLEXING/DEMULTIPLEXING

As discussed in our proposal for the present contract, a number of wavelength demultiplexers have been constructed using plane gratings, interference filters and graded index rod lenses. These so-called three-dimensional microoptic devices require rigid support for the 3-D adjustment of input and output fibers in the focal plane. The alternate two-dimensional approach employed in the present program uses multimode slab waveguides as rigid structures for multiplexers/demultiplexers.

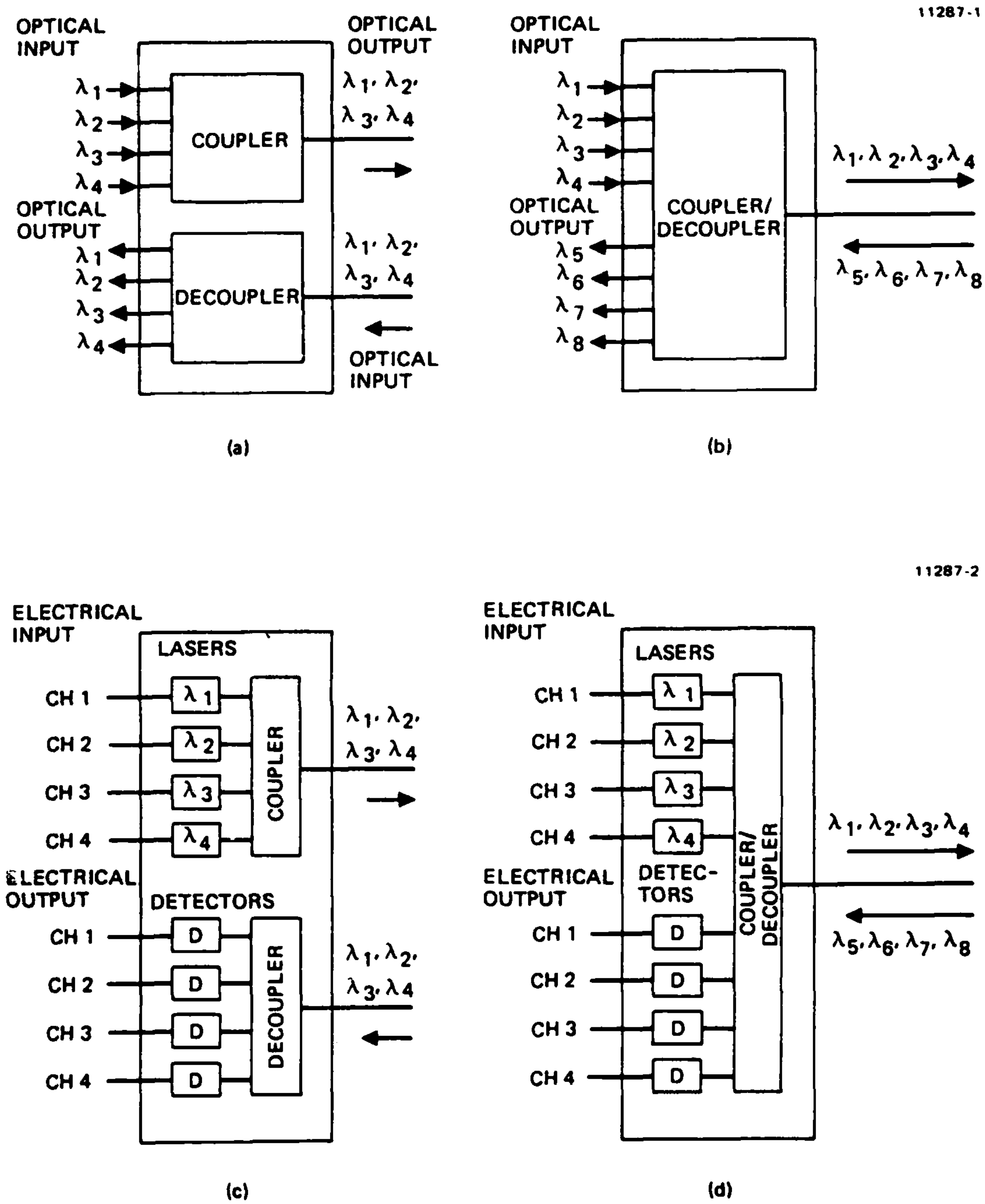

Figure 1 Four types of coupler-decouplers. (a) For passive, two-fiber transmission, (b) for passive, one-fiber transmission, (c) for active two-fiber transmission, and (d) for active, one fiber transmission.

The geometry and operation of the Rowland device is shown in Figure 2. The structure consists of a low loss planar optical waveguide with a pair of cylindrical surfaces. The back surface, which supports a reflection grating, has a radius of curvature R. The opposite surface, to which the input and output fibers are attached, is located distance R away from the grating and has a radius of curvature R/2. In figure 3, assume that a point source C emits light that is confined to a plane and covers an angle $\angle ACB$. Using a geometrical argument, the ray CA incident on the grating at point A sees an incident angle $\angle OAC$ (since OA is the normal to the grating surface at A). The ray CA will be diffracted and become ray AD, according to the grating equation

$$\sin(\angle OAC) + \sin(\angle OAD) = \frac{m\lambda}{nd}$$

where m is the diffraction order, λ is the wavelength, n is the index of refraction of the medium, and d is the grating constant. Now, consider a second ray, CB with an incident angle at point B of $\angle OBC$. If both A and B are not too far away from the tangent point of the two circles at O′, then both A and B can be approximated as being on the small circle as well as on the large one. As a result,

$$\angle OAC = \angle OBC.$$

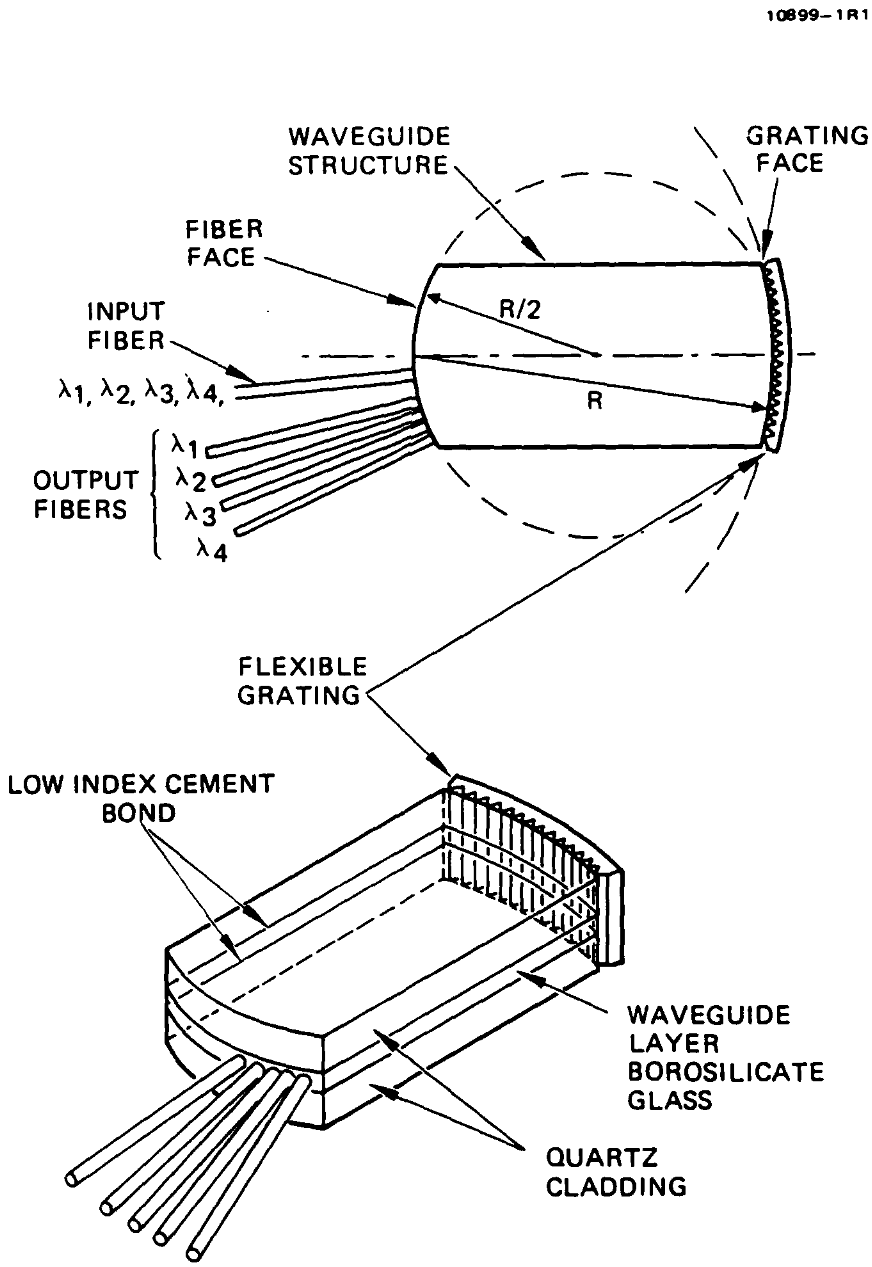

Figure 2. Planar waveguide Rowland coupler-decoupler.

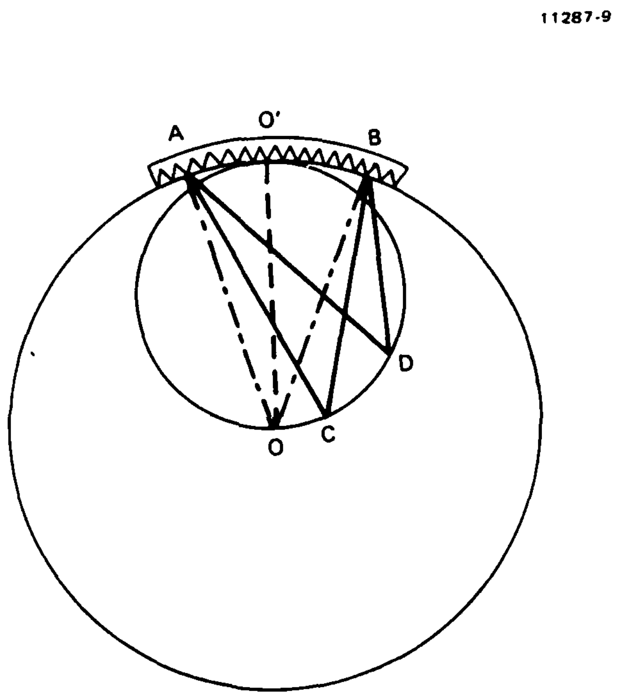

Figure 3. Rowland circle geometry.

Thus, the diffracted ray from point B will also pass through D, since, from equations (1) and (2), we have

$$\angle CAD = \angle CBD.$$

Likewise, for ray CO′ the diffracted ray is O′D. We conclude that a structure, as shown in figure 2, can diffract and focus a diverging light source originating at point C to point D on the small circle. Since the output from a multimode fiber resembles that of a diverging point source, it is reasonable to expect that an image of the input fiber (located at C) will appear at point D. From geometric optics, the structure is a one-to-one imaging system. However because of aberration, diffraction, and grating imperfection, the image will be distorted.

In the discussion above, we considered only imaging in one horizontal plane. In reality, the ouput of a multimode fiber diverges in two dimensions. By incorporating a planar waveguide structure into the design we confine and eliminate the fiber output in the vertical direction and form a planar two-dimensional array which resembles the case just discussed. Therefore, a planar Rowland spectrometer combines the operation of a diffraction grating with a concave mirror to achieve spectral point-to-point imaging. It is potentially rugged and does not require any additional focusing or collimating optics.

In commercial Rowland spectrographs, the beam divergence or ratio of ruled grating width to the project distance (A-B/A-C) ranges between 1/10 and 1/30. In research instruments, this ratio can be as low as 1/60 to reduce the effects of aberration and the divergence of blaze angle. In our miniature planar Rowland structure we must accomodate a very large divergence of 1/2. Conventional ruling processes are not able to engrave the required deep curvatures for such a large divergence and novel processes such as holographic patterning and anisotropic etching must be investigated for application in this program.

In previous work at HRL, planar optical waveguides were formed by epoxying thin microscope cover glasses (75 μm-thick) between two microscope slides. Dimensions of these early waveguides were 5.08 cm long and 2.54 cm wide. The cylindrical end faces of these waveguides were polished to have radii of 2.54 cm at the fiber input-output face and 5.08 cm at the grating face. Dimensional tolerances were kept under tight control to avoid severe defocusing and aberration of the output spot. Numerical aperture in these early waveguides was not controlled.

In the present program we have enlarged the overall dimensions of the miniature planar waveguide to 8 cm x 4 cm with corresponding radii of curvature. This small increase in dimension eases the edge tolerance requirements of the cylindrical lens surface and simplifies the lapping process. As in our previous work, we chose a dimensional tolerance of $\pm 25 \mu m$.

We have designed and built cylindrical lapping tooling for these dimensions and have found glasses and bonding cements that should give us control over the numerical aperture of the planar waveguide while keeping absorption and reflection losses to a minimum. The overall thickness dimension of the waveguide structure was chosen to be between 9 and 12 millimeters to permit operation over a wide temperature range and under severe shock and vibration.

D. OUTLINE OF RESULTS OBTAINED DURING THE FIRST SIX MONTHS OF THE PROGRAM

During the first half-year of the Multiwavelength Bidirectional Coupler-Decoupler contract we surveyed the market for raw materials and commercially available components. Orders were placed for suitable supplies. It was decided to grind and polish the cylindrical surfaces of the planar Rowland waveguides in the Hughes Research Laboratories optical shop. In our prior experience with outside optical suppliers, we had found them to be either slow, costly, or unable to produce the difficult cylindrical surface required for the Rowland device. Apparently very few optical houses have the skill and special tooling needed to form the precise edge surfaces of the planar Rowland waveguide. Therefore, we designed and built the optical tools to establish this competence in-house (see figure 4).

In a brief study of commercial glass suppliers we found glasses that match the index and numerical aperture of the connecting fiber. We found that most commercial plate glass has a planar inclusion flaw layer with a different refractive index than the remainder of the glass plate (see figure 5). We developed a grinding process to remove this layer and form the thin optical planar waveguide. In this process we use a gradual progression of finer abrasives in approaching the final dimensions of the waveguide layer.

Great difficulties were encountered in our efforts to obtain short focal length gratings (grating width to imaging distance ratio of 1/2) from commercial sources. The only grating supplier willing to take on this task circumvented this problem

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Figure 4. Cylindrical lapping machine.

by dividing the grating into four zones with converging blaze angles which compromised resolution and efficiency of the resultant grating.

A novel concept by Hugh Garvin of HRL may solve this problem. It employs a holographically-patterned and anisotropically-etched thin, single crystal, silicon wafer which is deformed to follow the curvature of the Rowland spectrograph. Early experiments on this approach appear promising.

We are still searching for a laminating bond of optical quality and low refractive index. Table 1 shows the problem; optical cements have either an index of refraction that is too high for our waveguides (we need an index of less than 1.47) or they do not adhere to glass to form a mechanically rugged moisture-resistant bond. During the next six month period we expect to solve the problem of the bonding cement for the planar waveguide, grind and polish guiding layers to the required thickness, and grind and polish our first cylindrical Rowland surfaces. We will acquire thermoelectrically-cooled laser modules and continue our experiments leading to a short focal length high efficiency grating.

TABLE I

12525-1

REFRACTIVE INDEX OF SOLIDIFIED RESIN

	SPECIFIED	MEASURED	COMMENTS
CYANO ACRYLATES	1.487	1.494	NO GLASS ADHESION
NORLAND OPTICAL ADEHESIVE #60	1.56	1.5504	
NORLAND OPTICAL ADEHESIVE #61	1.56	1.5535	
CONOPTIC EN-30		1.507	
EPOTEK 394	1.394	1.397	SOLVENT TYPE FOR COATINGS ONLY
TPX (HOT FUSED)	1.463	1.463	NO GLASS ADHESION

E. ACCOMPLISHMENTS DURING THE FIRST SIX MONTHS OF THE COUPLER-DECOUPLER CONTRACT

1. Market Surveys

During the first six months of the contract we collected technical data on commercially available raw materials and components needed for the coupler-decoupler. The following number of suppliers were contacted and price and technical information was obtained from most of them.

gratings - 4 firms
solid state lasers - 10 firms
optical glasses - 9 firms
thermoelectric modules - 3 firms
fiber optic connectors - 11 firms
optical fibers - 9 firms
cylindrical polishers - 6 firms
optical cement manufacturers - 5 firms

2. Diagnostic Disassembly Process for Planar Waveguides

To permit separation of the optical effects of the guiding glass layer and the laminating cement, a decomposition process for the cement was developed and successfully tested. The laminated sandwich is cooked for 24-48 hours in a mixture of 80% vol anhydrous H_2SO_4 and 20% vol HNO_3. All bonding cements tested to date have yielded to this treatment. Using this process, it is now possible to delaminate completed planar waveguide structures and measure the thickness of the guiding layer over the whole area.

3. Central Flaw Layer in Hot-Formed Commercial Glass Sheets

Certain hot-formed glass plates include a central layer with a different index of refraction than the rest of the plate. (See figure 5.) While the number of our samples is limited and does not allow us to draw a general conclusion, it seems that this layer is the result of the hot plate glass drawing process, and appears in all the samples we have tested to date. Therefore, we must grind and polish the waveguide layer to less than half the thickness of the plate from which it is made in order to eliminate this absorbent flaw layer.

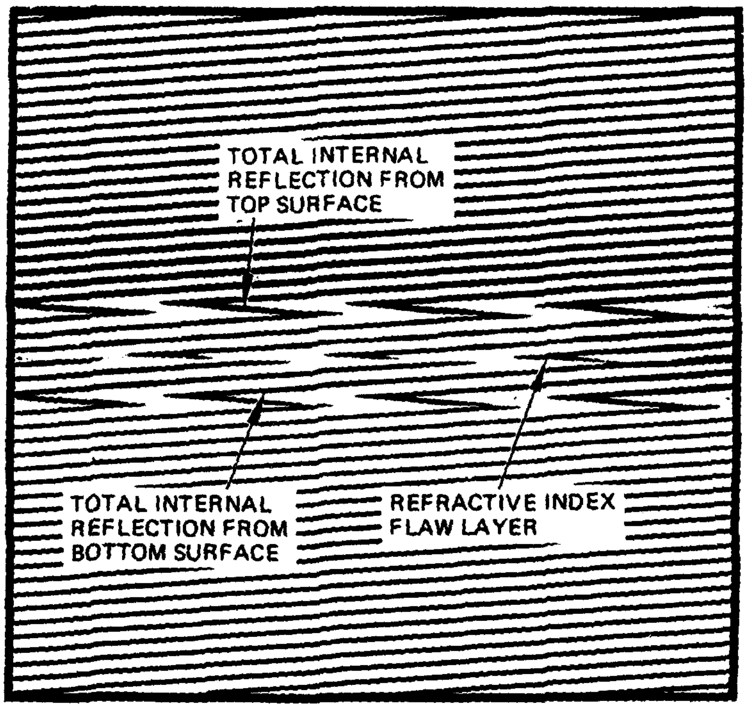

Figure 5. Flaw layer in plate glass.

4. Grinding and Polishing Process for Waveguide Layer

Early attempts during the last six months to form the ultrathin (50-80-micrometers-thick) waveguide layer by grinding and polishing resulted in total destruction of this layer. Refinements in the grinding and polishing sequence and control of the abrasive particle size distribution led to a successful process in which the grit size is reduced as the final layer thickness is approached. The exact sequence and grit sizes must still be refined further before the process can be documented. This process sequence promises to give a high production yield.

5. Design and Index Selection for Planar Waveguides

Seven glass and plastic pairs were analyzed for optimum match with the 0.20 NA fiber optic waveguide (see Table II). The final and best combination consisted of a planar core of Pyrex "high reliability" glass with an index of 1.4719 and a cladding of "water free" quartz plates with an index of 1.4588. This combination gives a numerical aperture of 0.2004 closely matching the numerical aperture of the input and output fibers.

6. Master Tooling for Cylindrical Laps

Preparation of cylindrical surfaces for the Rowland body requires precision cylindrical laps with a precisely controlled radius of curvature. Precision master laps are

TABLE II

Some Potential Planar Waveguide Glass Pairs

CORE TYPE	CORE INDEX	CLADDING TYPE	CLADDING INDEX	NUMERICAL APERTURE
K7	1.51112	K10	1.50137	0.171
Pyrex	1.4722[a]	Quartz	1.4582[a]	0.2025
BK7	1.51680	K10	1.50137	0.216
LLF1	1.54814	LLF6	1.53172	0.225
F2	1.62004	F5	1.60342	0.231
BaF4	1.60562	BaF3	1.58267	0.2705
Acrylic	1.49	TPX[b]	1.463	0.282

(a) as measured (b) Poly Methyl Pentene

required to control the grinding radius of these working laps and if necessary to resize them. When we made the decision to fabricate the Rowland bodies at HRL we immediately placed orders for the necessary fine grain cast iron and initiated the design of these tools. Conventional cylinder lapping tools are fixed half-rounds which wear unevenly. We have designed and built rotating master laps which incorporate an escapement. These laps maintain their precise cylindrical surface by revolving during lapping. (See figure 4.)

7. <u>Laser Diode Package Standardization</u>

During the market survey of solid state laser diodes it was found that the majority of laser manufacturers can supply a package which includes the thermoelectric cooler needed for wavelength stabilization. Our efforts to design a common thermoelectric cooler base for all lasers were therefore abandoned and a search for a concensus on the laser package design was started. We found that all potential suppliers were either already using or could adapt to the Isotronics-type package (see figure 6). An order for empty, dummy packages was placed to enable us to prove the test kit design without endangering the costly lasers.

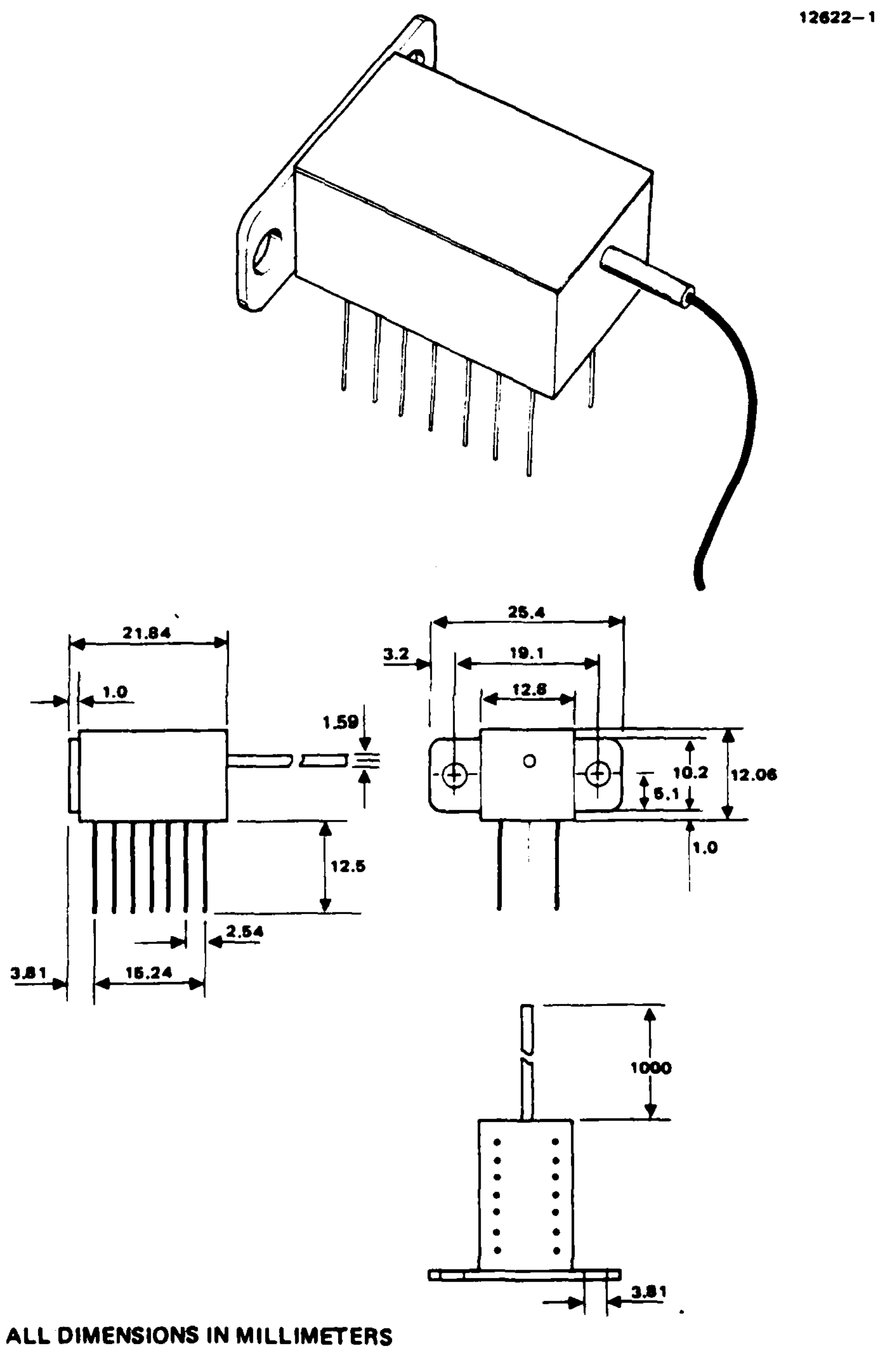

Figure 6. Isotronics Type P1-4110-S-20 fiber optic plug in package.

8. Connecting Fiber Optic Cable

We ordered and received 1 kilometer of Valtec type MG05-DW-PN40025 single fiber 50/125 micrometer cable with 0.20 numerical aperture. This cable will serve as the interconnect for the system.

9. Single Crystal Silicon Gratings

An ideal grating for our coupler-decoupler should combine the optical efficiency of a blazed grating with the ease of fabrication of an interference or holographic grating. In ruled concave gratings the facet angle of the ruling tool can only be set correctly for one point on the grating surface. As the ruling tool moves away from this point, and owing to the curvature of the blank, the blaze angle becomes progressively more in error and the local efficiency of the grating falls. (See figure 7.) This is not a serious problem in shallow gratings with long imaging distances, such as used in spectrographs. However in the deep curvature coupler-decoupler grating this effect reduces grating efficiency significantly. Our earlier gratings were ruled in four sections with different settings of the ruling diamond in an attempt to reduce this effect and increase grating efficiency. The results were not satisfactory. Figures 8 and 9 illustrate this problem. In

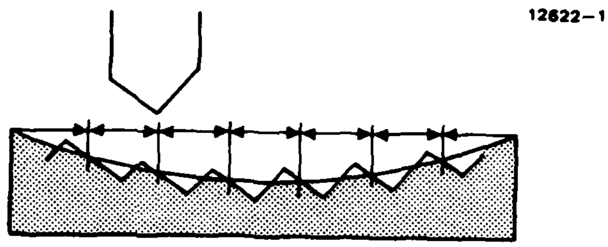

Figure 7. Ruling a concave diffraction grating.

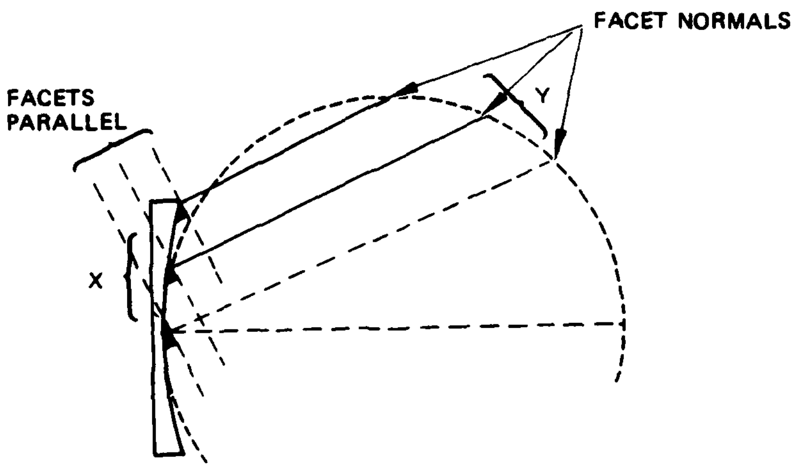

Figure 8. Facet angles on a ruled grating.

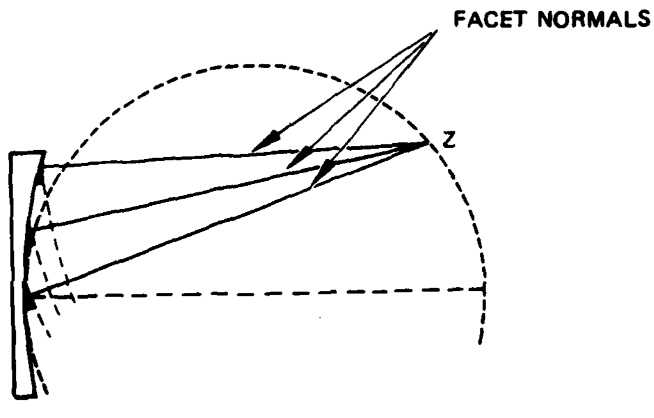

Figure 9. Facet angles on an ideal concave single wavelength grating.

figure 8, typical parallel facets, produced by a ruling engine, reflect parallel rays along facet normals. In this case the diffracted energy is spread diffusely along the Rowland circle and only a small part of the grating "x" diffracts efficiently toward the output region "y." When the facets lie on concentric cylinders with a common center at the output region, as shown in figure 9, most of the energy of a particular waveglength is collected at the output "z."

Ideally, and for maximum grating efficiency, it is desirable to change the spacing and the angle of the facets along the surface of the concave grating. To our knowledge no such grating has yet been made because of the *conflicting requirements* of the process of preparation. Hugh Garvin of HRL recently proposed a grating made on a thin,single-crystal, silicon platelet of suitable orientation by holographic photolithography and formed by an anisotropic etch. This platelet is then bent to conform to the miniature Rowland geometry of our coupler. First experiments to test this new concept are now underway.

10. Design of Test Set

Design and construction of the coupler-decoupler test fixture was completed. Consisting of three modules, it combines the necessary ruggedness with a novel precision adjustment for wavelength tuning. Attached photographs show the completed structure of the set.

The Rowland module, figure 10, incorporates the planar Rowland spectrometer optics and the five fiber supports with their precision adjustments (one input fiber and four output fibers).

The wavelength-adjusting sockets, shown in figure 11, drive a precision, fine-pitch, worm gear which moves the corresponding fiber support through a half degree arc for each socket revolution. Miniature tubular guides made from hypodermic needle tubing will be designed for attachment to these fiber supports and will hold the fiber ends in exact juxtaposition with the planar waveguide layer. Special tooling was developed to form the fine pitch threads on the wavelength-adjusting drive circles.

The laser module supports the photo detectors or the laser sources with their thermoelectric coolers. Cooling fins aid in the removal of waste heat.

The fiber coupler module, shown in figure 12, supports the passive input-output fiber connections. All three modules can be assembled into more complex systems.

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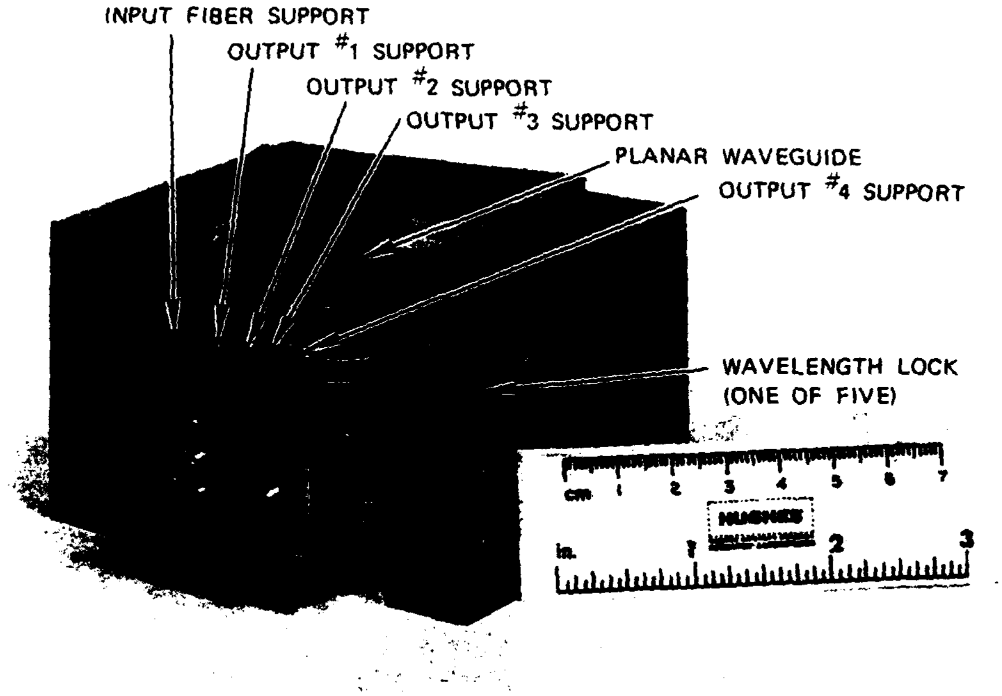

Figure 10. Rowland module.

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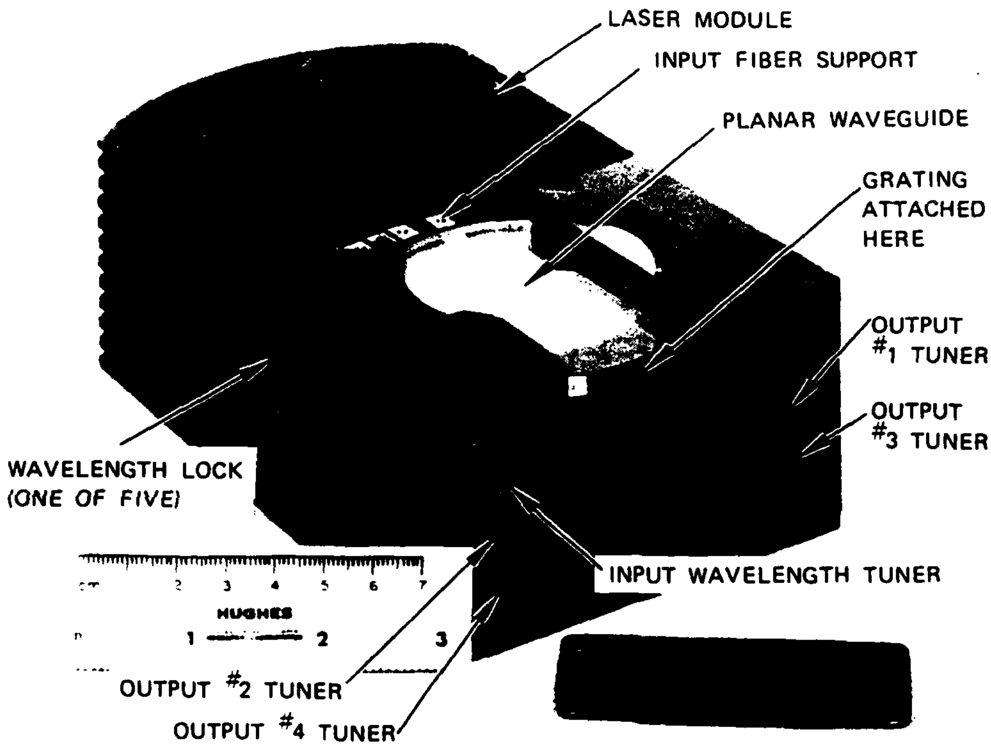

Figure 11. Rowland module with laser module.

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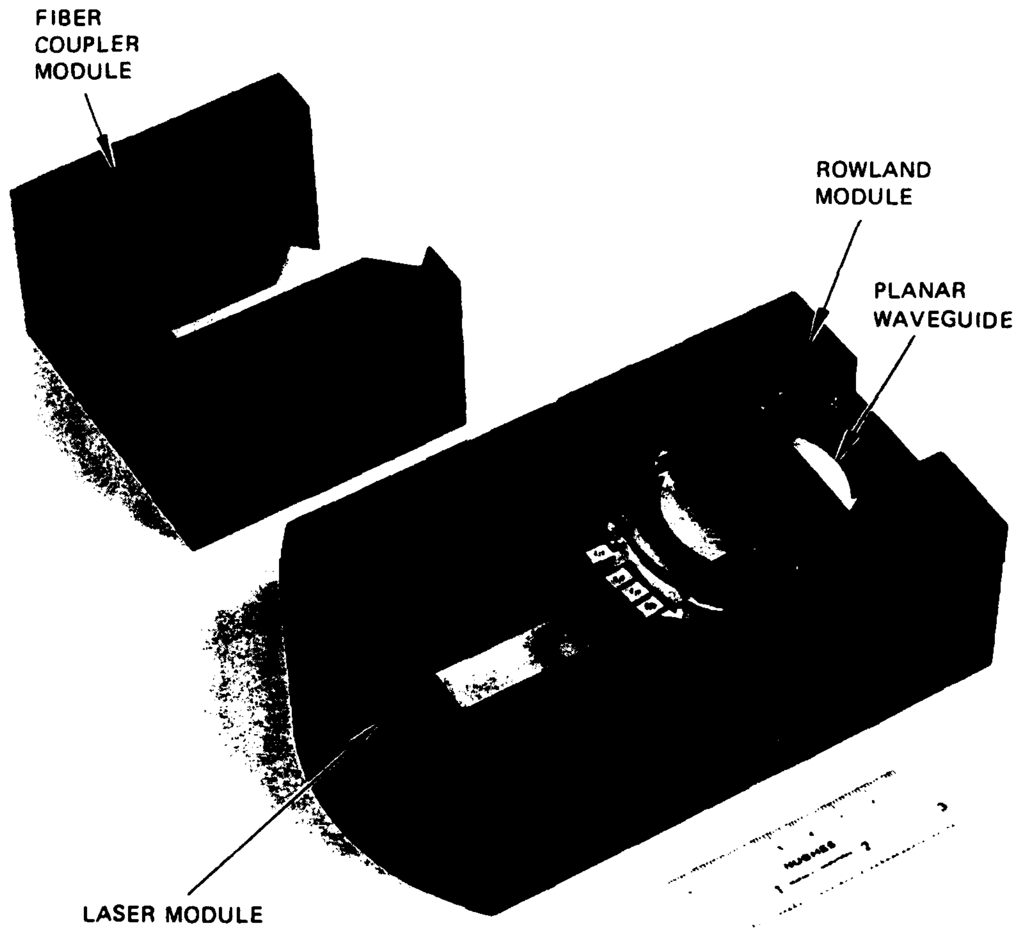

Figure 12. Fiber coupler, laser and Rowland modules.

11. Optical Cement Studies

We had hoped that by this time an optical laminating cement with useful mechanical and optical properties would have been found, but the most recent candidate, Conoptic EM-30, a urethane polymer, failed the refractive index test. The indices of the separate resin and catalyst constituents of this polymer were low enough to be promising (1.497 and 1.452) but the polymerized solid had an index of 1.5068, too high for our waveguide design. Refractive indices of other optical cements are shown in table 1. The search for a slow setting cement with a refractive index below 1.470 and good mechanical properties continues.

F. CONCLUSIONS AND RECOMMENDATIONS

The groundwork for the construction of both active and passive couplers-decouplers was laid with information, raw materials, and components. New processes for the fabrication of key components were developed and tested.

In the coming months, we expect to solve the low index laminar-bonding problem and prepare our first planar waveguide Rowland bodies. Our search for new processes to obtain efficient small radius gratings will continue. Measurements to determine the optical attributes of components and complete systems will be started.

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