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Final Technical Report

Optical Fiber for Acoustic Sensor Applications

Prepared by
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Principal Investigator

Prepared for the
Naval Research Laboratory
Contract No. N00014-89-C-2455

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St. Paul, Minnesota 55144



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1.0 INTRODUCTION

This final technical report summarizes the research and development efforts performed by 3M on the development of optical fiber for acoustic sensor applications under Naval Research Laboratory Contract Number N00014-89-C-2455.

2.0 PROGRAM OBJECTIVES

2.1 Initial Program Objectives

The initial objectives of this program were to develop long lengths of both acoustically sensitive and acoustically insensitive optical fiber for hydrophone applications. These objectives included the development of both "depressed well" and "matched cladding" waveguide designs and the development of acoustically sensitive and acoustically insensitive polymer coating designs.

2.2 Modified Program Objectives

At the request of NRL, the program objectives were modified (contract modification P00002) to the development of long lengths of optical fiber with small diameter coatings. An additional modification (contract modification P00006) was made to increase the deliverable quantity of this fiber.

3.0 WORK PERFORMED

During the initial portion of the contract, fiber designs for both "matched clad" coupler fiber and "depressed well" sensor fiber were completed. Initial experiments toward the fabrication of acoustically sensitive and acoustically insensitive coatings were also performed.

Upon modification of the program objectives, emphasis was shifted to the development of sensor fibers with thin polymeric coatings. With the concurrence of NRL personnel, the "coupler" fiber design developed during the initial portion of the contract was selected as the waveguide design to be used for this portion of the contract performance.

The coating development began with the formulation, characterization, and fabrication of samples of fibers with various coating formulations and coating thicknesses. Samples of these fibers were then supplied to NRL personnel for evaluation. With the concurrence of NRL personnel, a coating design was then selected and long lengths of fiber with this design were fabricated and delivered to NRL.

Additional short samples of fiber with unusually thin cladding/coating combinations were also fabricated and delivered to NRL for evaluation.

3.1 Original Milestones

| <u>Milestone No.</u> | <u>Description</u> | <u>Status</u> |
|----------------------|---|---------------------------------|
| 1 | Coupler Fiber: #2km of single mode suitable for operation at 1300nm and designed specifically for fabrication of fiber couplers to be prepared and submitted to NRL for evaluation. | Completed |
| 2 | Acoustic Sensing Fiber: 2km of single mode fiber specifically designed to be sensitive to acoustic energy to be prepared and submitted to NRL for evaluation. | Not Completed due to SOW change |
| 3 | Reference Fiber: 2 km of single mode fiber specifically designed to be insensitive to acoustic energy to be prepared and submitted to NRL for evaluation. | Not Completed due to SOW change |

3.2 Modified Milestones (P00002)

| | | |
|---|---|-----------|
| 1 | 125 μ m coated fiber- 20-30km of fiber suitable for single mode operation at 1300nm and with a total coated diameter of less than 125 μ m to be fabricated and delivered to NRL for evaluation. | Completed |
| 2 | 100 μ m coated fiber: Short samples of fiber suitable for single mode operation at 1300nm and with a total coated diameter of <100 μ m to be fabricated and submitted to NRL for evaluation. | Completed |

3.3 Modified Milestones (P00006)

| | | |
|---|---|-----------|
| 1 | 125 μ m coated fiber: Quantity of fiber described in 3.2, Milestone 1, increased from 20-30km to 40km | Completed |
|---|---|-----------|

3.4 Fiber Design

Separate fiber designs were selected for coupler development (3.4.1) and for the sensor fiber development (3.4.2). Although the fibers have different constructions, careful matching of the mode field diameters was achieved to minimize fiber splice loss. After the modification in the program Statement of Work (3.2), and with the concurrence of NRL personnel, the coupler fiber design was selected as the basis for all coating development activities.

3.4.1 COUPLER FIBER DESIGN

For this program, a single mode fiber design with an "index matched" structure was chosen for the coupler fiber design. It is well known that this design approach is optimum for the fabrication of fused/tapered single mode couplers. Target specifications for this fiber are listed in Table 1.

Table 1

| | |
|----------------------|------------|
| Operating Wavelength | 1300nm |
| Cutoff wavelength | <1230nm |
| Attenuation | <2.0db/km |
| Cladding Diameter | 80 μ m |
| Numerical Aperture | 0.16 |

Using conventional MCVD technology, the design of the coupler was completed and evaluation samples were delivered to NRL personnel for evaluation.

3.4.2 SENSOR FIBER DESIGN

For this program, a single mode fiber with a "depressed well" structure was chosen for the sensor fiber design. In this design, a low index fluorosilicate well surrounds a silica core which has been lightly doped with germanium oxide. This design approach allows the simultaneous minimization of intrinsic attenuation (Rayleigh scattering) and extrinsic attenuation (macro and micro-bending). Target specifications for this fiber are listed in Table 2.

Table 2

| | |
|----------------------|------------|
| Operating Wavelength | 1300nm |
| Cutoff wavelength | <1230nm |
| Attenuation | <0.5db/km |
| Cladding Diameter | 80 μ m |
| Numerical Aperture | 0.16 |

Using conventional MCVD technology, the design of the sensor fiber was completed and evaluation samples were delivered to NRL personnel for evaluation.

3.5 Fiber Coating Development

During this program, technology to fabricate thin single layer ultraviolet curable coatings for optical fiber was developed. The majority of this development effort was oriented toward fiber with a coated diameter of $\sim 125\mu$ m, while some exploratory work for fibers with a coated diameter of $<100\mu$ m was carried out. For this technology, the two areas of material formulation and the coating technique were investigated.

3.5.1 MATERIAL FORMULATION

Conventional acrylate coatings for optical fiber are available with a wide variety of properties. During this program, several coating formulations were investigated. Figure 5 in Bimonthly Activity Report No. 12 (see the Appendix) shows Weibull strength distributions (dynamic fatigue) for 80μ m clad/ 125μ m coated fibers with "hard" and "soft" coating formulations. These results clearly show that harder coatings have higher

mechanical strength and fewer defect sites. This is due to the superior resistance of the hard coating to damage from routine handling procedures experienced by the fiber during the fiber draw and measurement process. As a result of this work, a standard hard coat (Desotech #103) was selected for all final fabrication experiments.

3.5.2 COATING APPLICATION TECHNOLOGY

Standard fiber coating application utilizes a rigid die applicator technology. For fiber with very thin coatings, this approach becomes very difficult due to the very small die openings required to produce the desired coating diameter. 3M has developed a fiber coating technology which facilitates control of the coating diameter during the fiber drawing process. Figure 9 in Bimonthly Activity Report No. 10 (see the Appendix) shows typical coating diameter statistics taken for 125 μ m coating diameter during final fabrication experiments. This technology was also used to fabricate short samples of fibers with coating diameters of <100 μ m.

3.6 Fiber Drawing and Coating

Optical preforms described in Section 3.4 were drawn into fiber in a zirconia induction furnace and coated with UV cured acrylate using the coating application technology described in Section 3.5.

3.7 Physical and Optical Measurements

For all fiber samples, routine optical measurements performed include attenuation, second mode cutoff, mode field diameter, ESI parameters (core radius, delta, and numerical aperture), and fiber refractive index profile. In addition, routine mechanical measurements performed include fiber diameter and ovality, core diameter and ovality, and core/cladding concentricity. All measurement results have been reported to NRL during the performance of the contract.

3.8 Analysis

Throughout the program, analysis of results was performed by 3M. These results were communicated to NRL. 3M results and feedback from NRL personnel were used to guide additional experiments.

3.9 Technical Liaison with NRL

During the program, technical liaison was maintained with NRL personnel. Results were communicated through both technical reports and telephone conversations. Feedback from NRL was used along with 3M analysis to guide development efforts and to produce fibers which met the needs of NRL personnel.

4.0 DELIVERABLES

48km of optical fiber were delivered to NRL throughout the contract performance period. A summary of sample characteristics is presented in Table 3. Detailed results for these fibers may be found in the Appendix.

Table 3

| <u>Date</u> | <u>Description</u> | <u>Sample length</u> |
|-------------|-----------------------------------|----------------------|
| 4/25/90 | 80µm Sensor Fiber 200 µm coatings | 200m |
| 4/25/90 | 80µm Coupler Fiber 200µm coatings | 200m |
| 4/2/91 | 80µm Coupler Fiber 125µm coating | 6500m |
| 8/14/91 | 80µm Coupler Fiber 125µm coating | 5585m |
| 9/6/91 | 80µm Coupler Fiber 125µm coating | 6650m |
| 12/30/91 | 80µm Coupler Fiber 125µm coating | 2998m |
| 5/8/92 | 80µm Coupler Fiber 125µm coating | 6621m |
| 8/10/92 | 80µm Coupler Fiber 125µm coating | 5520m |
| 10/30/92 | 80µm Coupler Fiber 125µm coating | 6000m |
| 8/12/92 | 70µm Coupler Fiber 100µm coating | 1000m |
| 8/12/92 | 60µm Coupler Fiber 90µm coating | 1000m |
| 10/30/92 | 80µm Coupler Fiber 125µm coating | 6000m |

5.0 DISCUSSION

During the performance of this contract, two designs for 1300nm, 80µm single mode fiber were successfully developed. Technology to apply thin single layer ultraviolet curable acrylate coatings to these fibers was also developed. The effect of coating properties on the fiber strength was also demonstrated. Fibers with unusually small cladding diameters were also fabricated and delivered to NRL for evaluation. During the performance of the contract, 48km of fiber was delivered to NRL for evaluation. All contract deliverables and milestones were successfully completed.

APPENDIX

**Bimonthly Activity Reports
No. 1 through No. 16**

Bimonthly Activity Report No. 1

Optical Fiber for Acoustic Sensor Applications

Prepared by
James R. Onstott
Principal Investigator

Prepared for the
Naval Research Laboratory
Contract No. N00014-89-C-2455

February, 1990

3M Fiber Optics Laboratory
3M Center
St. Paul, Minnesota 55144



APPENDIX

1.0 INTRODUCTION

This bimonthly activity report summarizes the research and development efforts performed to date by 3M on the development of optical fiber for acoustic sensor applications under Naval Research Contract Number N00014-89-C-2455.

2.0 PROGRAM OBJECTIVE

The objectives of this program are to develop long lengths of both acoustically sensitive and insensitive optical fibers that are environmentally stable, and to develop a fiber which is optimized for fused coupler fabrication. During the first phase of this program, the development of optical fibers and organic fiber coatings specifically optimized for acoustic sensing applications will be pursued.

3.0 PROGRAM ACTIVITIES

Fiber Design- Task One of the program statement of work requires the design and fabrication of two single mode fibers. Initial work has concentrated on the completion of this task. Current results for the two fiber designs are described below.

3.1 Sensor Fiber Design. Design of the fiber for sensor coating experiments has been completed. The design approach taken for the fiber is a high numerical aperture "depressed well" structure, where a low index fluorosilicate well surrounds a lightly doped germanium oxide core. This design approach allows the simultaneous minimization of intrinsic attenuation (Rayleigh scattering) and extrinsic attenuation (macro and micro bending). Target design specifications and measured results are listed in Table 1.

Table 1. Sensor Fiber Design Specifications and Results

| | Target Specifications | Measured Results |
|--------------------|-----------------------|------------------|
| Cladding Diameter | 80um | 80um |
| Numerical Aperture | 0.16 | 0.160 |
| Cutoff Wavelength | 1250nm | 1229nm |
| Attenuation | 0.5 db/km | 1.88 db/km |

Measured results for this fiber (attenuation, mode field diameter, cutoff wavelength, ESI parameters, and concentricity) are shown in Figures 1 through 5 and Tables 3 and 4. All target specifications have been met with the exception of fiber attenuation. The unusually high attenuation is due to a 20 db -OH absorption peak at 1.38um. The -OH impurity level will be reduced in future preforms which will reduce the 1300nm attenuation to acceptable levels.

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3.2 Coupler Fiber Design. This fiber is a high numerical aperture "matched index" structure which trades slightly higher attenuation for ease of coupler fabrication. Target design specifications and measured results are listed in Table 2.

Table 2. Coupler Fiber Design Specifications and Results

| | Target Specifications | Measured Results |
|--------------------|-----------------------|------------------|
| Cladding Diameter | 80um | 80um |
| Numerical Aperture | 0.16 | 0.178 |
| Cutoff Wavelength | 1250nm | 1249nm |
| Attenuation | 2.0db | 2.01db/km |

Measured results for this fiber (attenuation, mode field diameter, cutoff wavelength, ESI parameters and concentricity) are shown in Figures 6 through 10 and Tables 5 and 6. All target specifications have been met with the exception of numerical aperture. One additional design iteration is needed to bring this parameter into specification.

4.0 DISCUSSION

Design of the two fibers is essentially complete. A major goal has been to match the mode field diameters so that splice loss would be minimized. Mode field diameter mismatch between the two fibers described above is 9%. Future design iterations will result in MFD mismatches of <5%. Refracted near field scans of the fibers are shown in Figures 5 and 10. The excellent concentricity of these fibers will result in low-loss splicing and connectorization.

5.0 FUTURE WORK

5.1 Completion of Fiber Design. Fiber design activities will be completed by the end of February, 1990. Two kilometers of coupler fiber will be delivered at this time. In addition, a sample of sensor fiber (acrylate coatings) will be delivered to NRL.

5.2 Coating Development. Subtask 2.0 of the program statement of work calls for the fabrication of silicone/Hytrel coated sensor fiber as the first stage of sensor fiber development. Delivery of this fiber to NRL is scheduled for March, 1990.

3M is currently evaluating the feasibility of thin (< 15um thickness), high adhesion fluoropolymer coatings as a primary buffer for sensor fiber applications. Preliminary results indicate that these coatings improve fiber strength in adverse environmental conditions. Delivery of sample fibers coated with these materials is scheduled for April, 1990. Further coating developments will occur after consultation with NRL personnel.

APPENDIX

Table 3. Sensor Fiber Attenuation versus Wavelength

Spectral Attenuation

Fiber ID: 900131 SMDTN D434 8-Feb-90 08:49:28

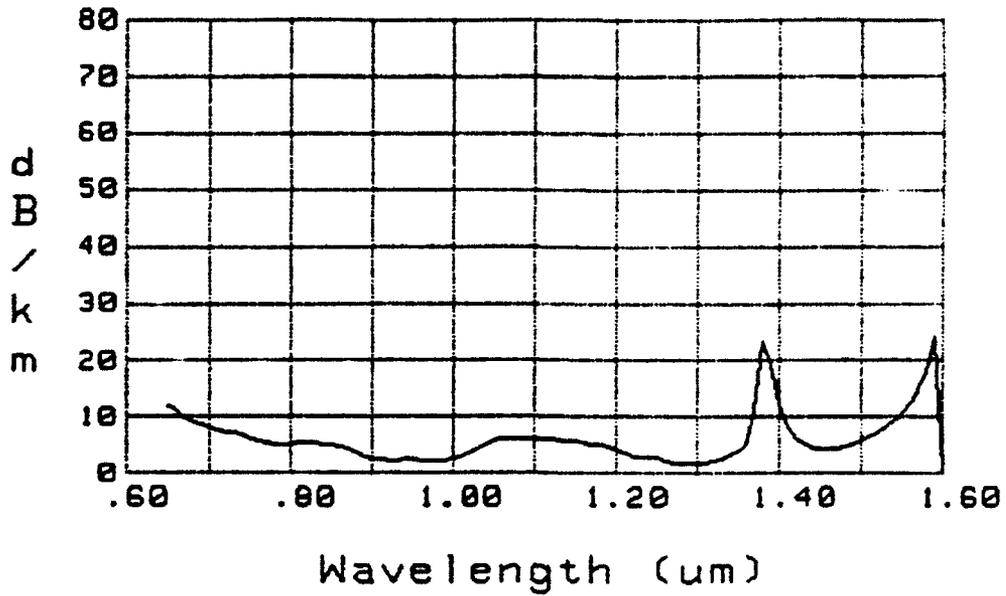
Length: 1 km

File: 2424

| Wavelength | Attenuation (dB/Km) | Wavelength | Attenuation (dB/Km) |
|------------|---------------------|------------|---------------------|
| 650 | 11.89 | 1130 | 6.00 |
| 660 | 11.13 | 1140 | 5.90 |
| 670 | 9.93 | 1150 | 5.72 |
| 680 | 9.00 | 1160 | 5.54 |
| 690 | 8.60 | 1170 | 5.27 |
| 700 | 8.11 | 1180 | 5.04 |
| 710 | 7.62 | 1190 | 4.61 |
| 720 | 7.34 | 1200 | 4.19 |
| 730 | 7.22 | 1210 | 3.72 |
| 740 | 6.88 | 1220 | 3.14 |
| 750 | 6.26 | 1230 | 2.94 |
| 760 | 5.83 | 1240 | 3.13 |
| 770 | 5.48 | 1250 | 2.81 |
| 780 | 5.17 | 1260 | 2.14 |
| 790 | 5.04 | 1270 | 1.86 |
| 800 | 5.19 | 1280 | 1.79 |
| 810 | 5.50 | 1290 | 1.80 |
| 820 | 5.53 | 1300 | 1.88 |
| 830 | 5.40 | 1310 | 2.03 |
| 840 | 5.24 | 1320 | 2.31 |
| 850 | 5.04 | 1330 | 2.79 |
| 860 | 4.76 | 1340 | 3.42 |
| 870 | 4.26 | 1350 | 4.05 |
| 880 | 3.53 | 1360 | 5.03 |
| 890 | 2.81 | 1370 | 10.94 |
| 900 | 2.57 | 1380 | 23.29 |
| 910 | 2.49 | 1390 | 19.44 |
| 920 | 2.43 | 1400 | 12.38 |
| 930 | 2.42 | 1410 | 8.48 |
| 940 | 2.76 | 1420 | 6.24 |
| 950 | 2.61 | 1430 | 5.07 |
| 960 | 2.39 | 1440 | 4.51 |
| 970 | 2.28 | 1450 | 4.30 |
| 980 | 2.27 | 1460 | 4.32 |
| 990 | 2.39 | 1470 | 4.48 |
| 1000 | 2.64 | 1480 | 4.80 |
| 1010 | 3.03 | 1490 | 5.29 |
| 1020 | 3.65 | 1500 | 5.83 |
| 1030 | 4.43 | 1510 | 6.48 |
| 1040 | 5.26 | 1520 | 7.31 |
| 1050 | 5.84 | 1530 | 8.25 |
| 1060 | 6.15 | 1540 | 9.29 |
| 1070 | 6.23 | 1550 | 10.91 |
| 1080 | 6.25 | 1560 | 12.81 |
| 1090 | 6.21 | 1570 | 14.75 |
| 1100 | 6.16 | 1580 | 17.95 |
| 1110 | 6.11 | 1590 | 24.04 |
| 1120 | 6.08 | 1600 | 0.00 |

APPENDIX

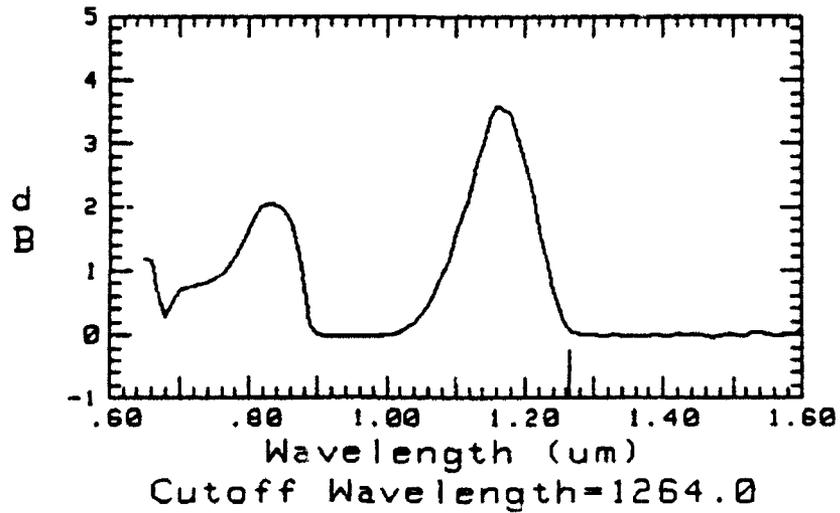
SPECTRAL ATTENUATION LENGTH: 1.0000 km
ID: 900131 SMDTN D434 8-FEB-90 08:49:28



File: 2424

Figure 1
Sensor Fiber Attenuation versus Wavelength

CUTOFF PLOT TYPE: BEND
ID: 900131 SMDTN D434 TIP OF 1000M 8-FEB-90



File: 2425

Figure 2
Sensor Fiber Cutoff Plot

APPENDIX

VARIABLE APERTURE PATTERN AT 1300 nm
 ID: 900131 SMDTN D434 TIP OF 1000M 8-FEB-92

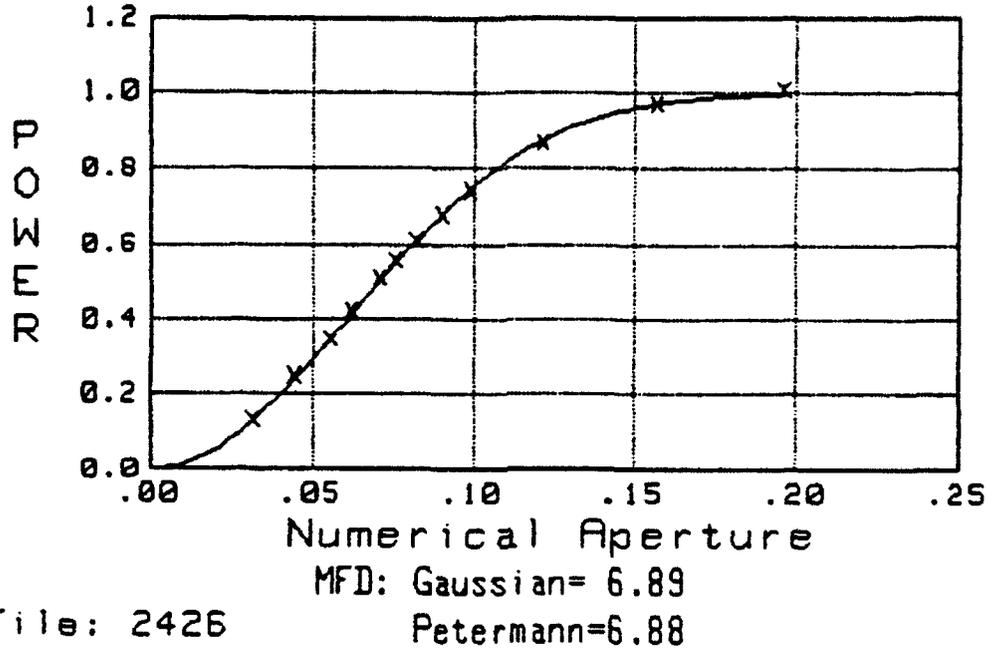


Figure 3
Sensor Fiber Numerical Aperture

Table 4. Sensor Fiber ESI Parameters

| | | |
|--------------------------|----------|-----------|
| File: | 2426 | |
| Measuremer., Wavelength: | 1300 nm | |
| Cutoff Wavelength: | 1264 nm | |
| Conversion Factor: | 1.120 | |
| | Gaussian | Petermann |
| Spot Radius: | 3.4229 | 3.4410 um |
| ESI Core Radius: | 3.0731 | 3.0715 um |
| ESI Delta: | .0058 | .0058 |
| Nc-Ncl: | .0085 | .0085 |
| Numerical Aperture: | .1574 | .1575 |

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Profile Name 988131 SMDTN 6/100/D 1633 D434 at 28.4 deg C

Cladding Level Index : 1.4522

Cladding Diameter : 81.24 μm

ESI : 0.0000

Core Peak Index : 1.4629

Core Diameter : 7.91 μm

ESR : 3.52 μm

Handle of 1000 μm

λ_{co} : 1.45 μm

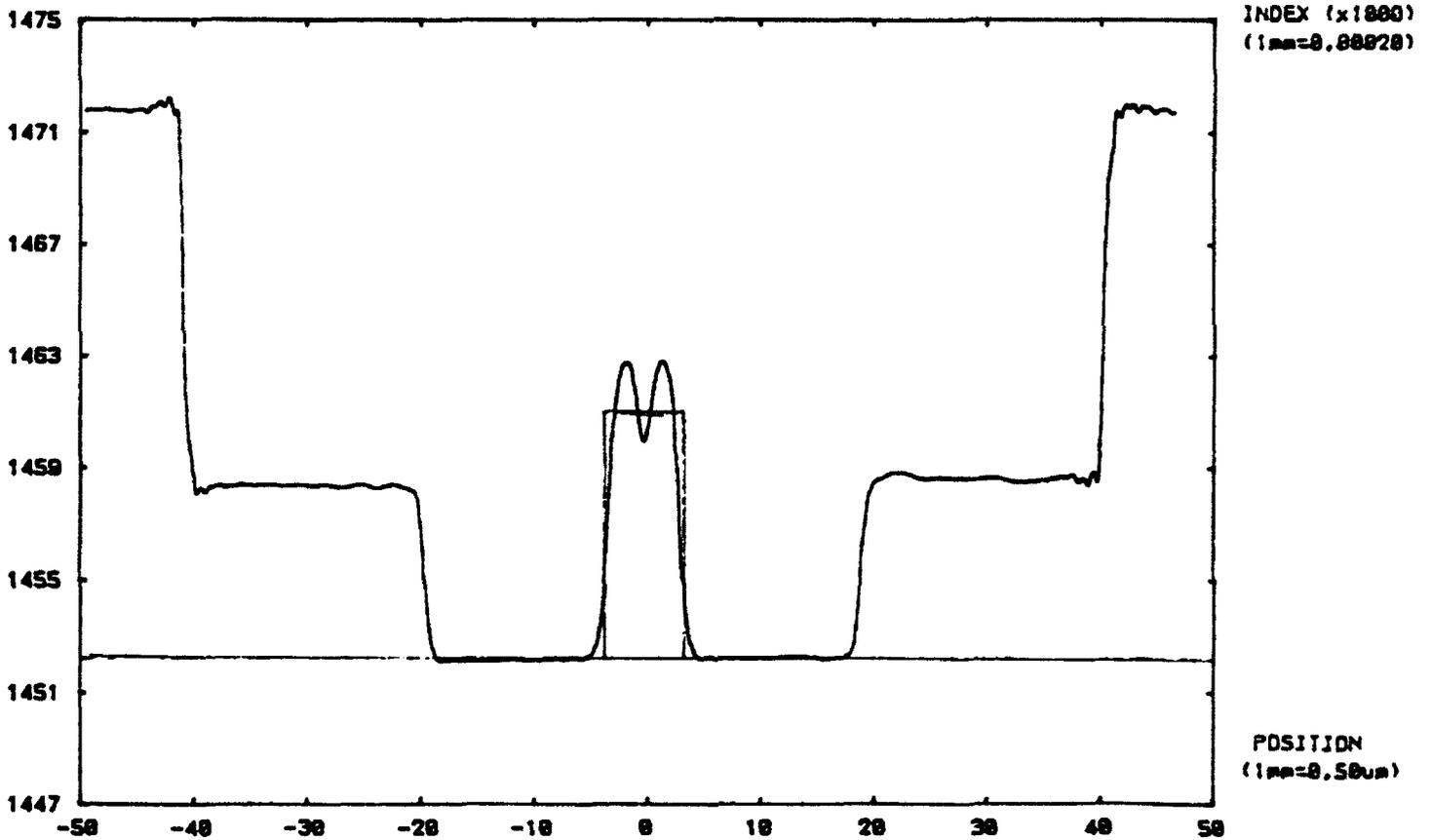
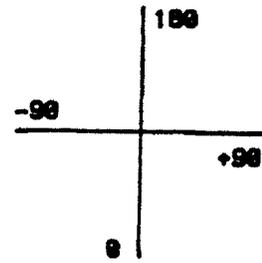
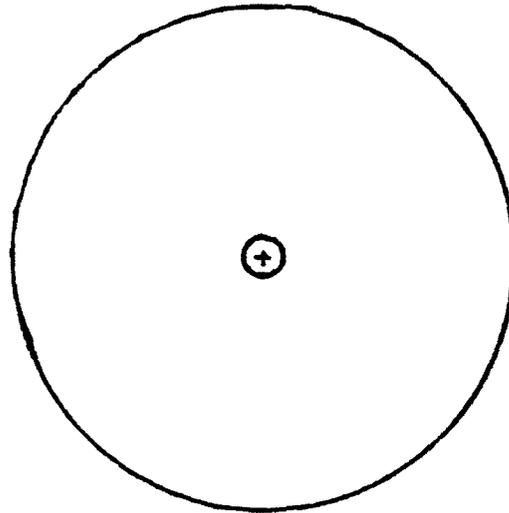


Figure 4
Sensor Fiber Refracted Near Field Scan

APPENDIX



| | Cladding | Core |
|------------------------|----------|-------|
| Mean Diameter (um) | 81.28 | 6.44 |
| Maximum " (um) | 81.58 | 6.56 |
| Minimum " (um) | 80.44 | 6.27 |
| Non-Circularity (%) | 1.4 | 4.6 |
| Eccentricity | 0.167 % | 0.297 |
| Major Axis Angle (deg) | 6.8 | 77.7 |
| Threshold Level (%) | 50.0 | 50.0 |

Cladding Centre to Core Centre Distance 0.18 um

Concentricity Error 1.6 %

Figure 5
Sensor Fiber Geometry Report

APPENDIX

Table 5. Coupler Fibers Attenuation versus Wavelength

Spectral Attenuation

Fiber ID: 900201 SMTN D435 As Drawn 8-Feb-90 12:42:29

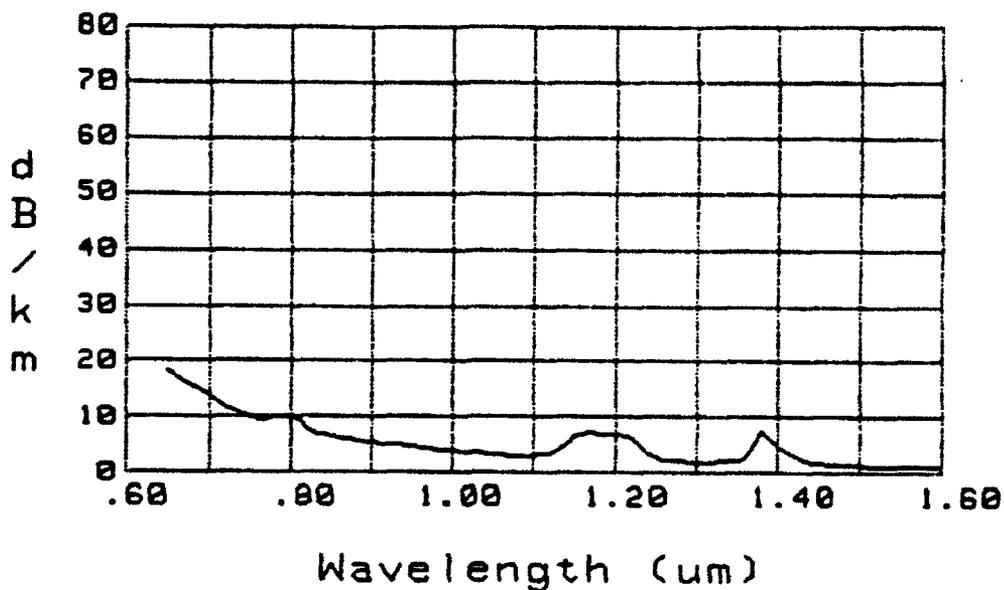
Length: 1 km

File: 2429

| Wavelength | Attenuation (dB/Km) | Wavelength | Attenuation (dB/Km) |
|------------|---------------------|------------|---------------------|
| 650 | 18.49 | 1130 | 4.02 |
| 660 | 17.17 | 1140 | 5.13 |
| 670 | 16.29 | 1150 | 6.44 |
| 680 | 15.57 | 1160 | 7.03 |
| 690 | 14.75 | 1170 | 7.11 |
| 700 | 13.77 | 1180 | 7.06 |
| 710 | 12.58 | 1190 | 6.98 |
| 720 | 11.69 | 1200 | 6.97 |
| 730 | 11.06 | 1210 | 6.55 |
| 740 | 10.51 | 1220 | 6.03 |
| 750 | 10.00 | 1230 | 4.94 |
| 760 | 9.57 | 1240 | 3.36 |
| 770 | 9.51 | 1250 | 2.58 |
| 780 | 10.16 | 1260 | 2.31 |
| 790 | 10.24 | 1270 | 2.17 |
| 800 | 9.95 | 1280 | 2.11 |
| 810 | 9.27 | 1290 | 2.03 |
| 820 | 7.63 | 1300 | 2.01 |
| 830 | 7.08 | 1310 | 1.99 |
| 840 | 6.78 | 1320 | 2.03 |
| 850 | 6.53 | 1330 | 2.08 |
| 860 | 6.28 | 1340 | 2.18 |
| 870 | 6.04 | 1350 | 2.29 |
| 880 | 5.83 | 1360 | 2.51 |
| 890 | 5.61 | 1370 | 4.30 |
| 900 | 5.42 | 1380 | 7.51 |
| 910 | 5.25 | 1390 | 6.14 |
| 920 | 5.09 | 1400 | 4.76 |
| 930 | 4.95 | 1410 | 3.75 |
| 940 | 4.87 | 1420 | 2.83 |
| 950 | 4.69 | 1430 | 2.28 |
| 960 | 4.49 | 1440 | 1.97 |
| 970 | 4.31 | 1450 | 1.79 |
| 980 | 4.16 | 1460 | 1.63 |
| 990 | 4.02 | 1470 | 1.53 |
| 1000 | 3.89 | 1480 | 1.45 |
| 1010 | 3.75 | 1490 | 1.38 |
| 1020 | 3.63 | 1500 | 1.37 |
| 1030 | 3.51 | 1510 | 1.30 |
| 1040 | 3.41 | 1520 | 1.25 |
| 1050 | 3.31 | 1530 | 1.21 |
| 1060 | 3.22 | 1540 | 1.23 |
| 1070 | 3.13 | 1550 | 1.21 |
| 1080 | 3.08 | 1560 | 1.23 |
| 1090 | 3.04 | 1570 | 1.21 |
| 1100 | 3.05 | 1580 | 1.17 |
| 1110 | 3.15 | 1590 | 1.13 |
| 1120 | 3.42 | 1600 | 1.09 |

APPENDIX

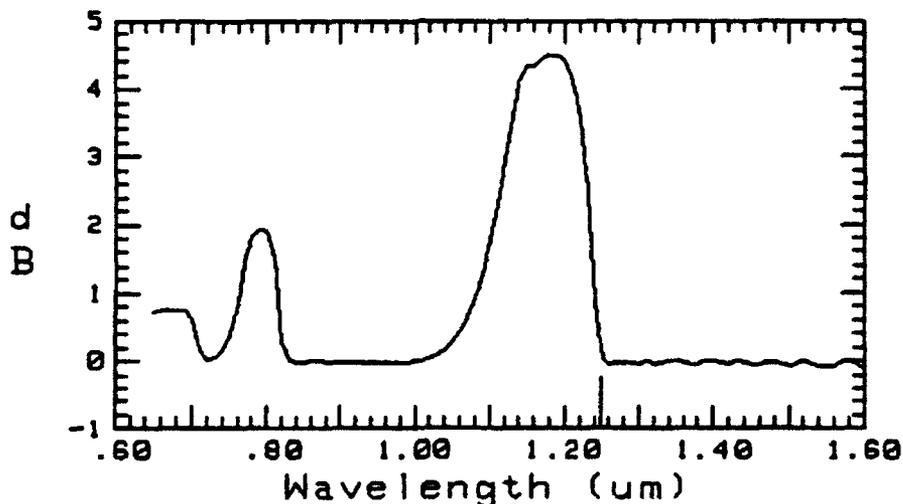
SPECTRAL ATTENUATION LENGTH: 1.0000 km
ID: 900201 SMTN D435 AS DRAWN 8-FEB-90 12:42:25



File: 2429

Figure 6
Coupler Fiber Attenuation versus Wavelength

CUTOFF PLOT TYPE: BEND
ID:900201 SMTN D435 TIP OF 1000M 8-FEB-90 1



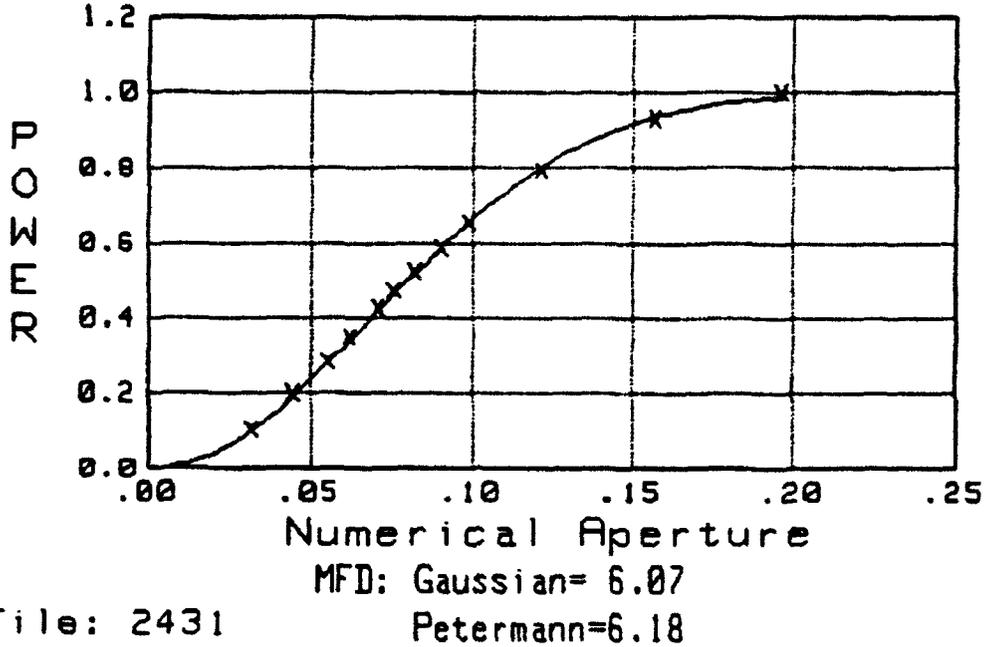
Cutoff Wavelength=1249.2

File: 2430

Figure 7
Coupler Fiber Cutoff

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VARIABLE APERTURE PATTERN AT 1300 nm
 ID: 900201 SMTN D435 TIP OF 1000M 8-FEB-90



File: 2431

Figure 8
Coupler Fiber Numerical Aperture

Table 6. Coupler Fiber ESI Parameters

| | | |
|-------------------------|----------|-----------|
| File: | 2431 | |
| Measurement Wavelength: | 1300 nm | |
| Cutoff Wavelength: | 1249 nm | |
| Conversion Factor: | 1.130 | |
| Spot Radius: | Gaussian | Petermann |
| ESI Core Radius: | 3.0355 | 3.0901 um |
| ESI Delta: | 2.6868 | 2.7351 um |
| Nc-Ncl: | .0074 | .0072 |
| Numerical Aperture: | .0109 | .0105 |
| | .1780 | .1748 |

APPENDIX

Profile Name 900201 SMTN 6/100/D 1624 D435 at 28.2 deg C

Cladding Level Index : 1.4527

Cladding Diameter : 81.71 μm

ESI : 0.0179

Core Peak Index : 1.4755

Core Diameter : 6.26 μm

ESR : 2.65 μm

Tip of 1800 μm

λ_{co} : 1.70 μm

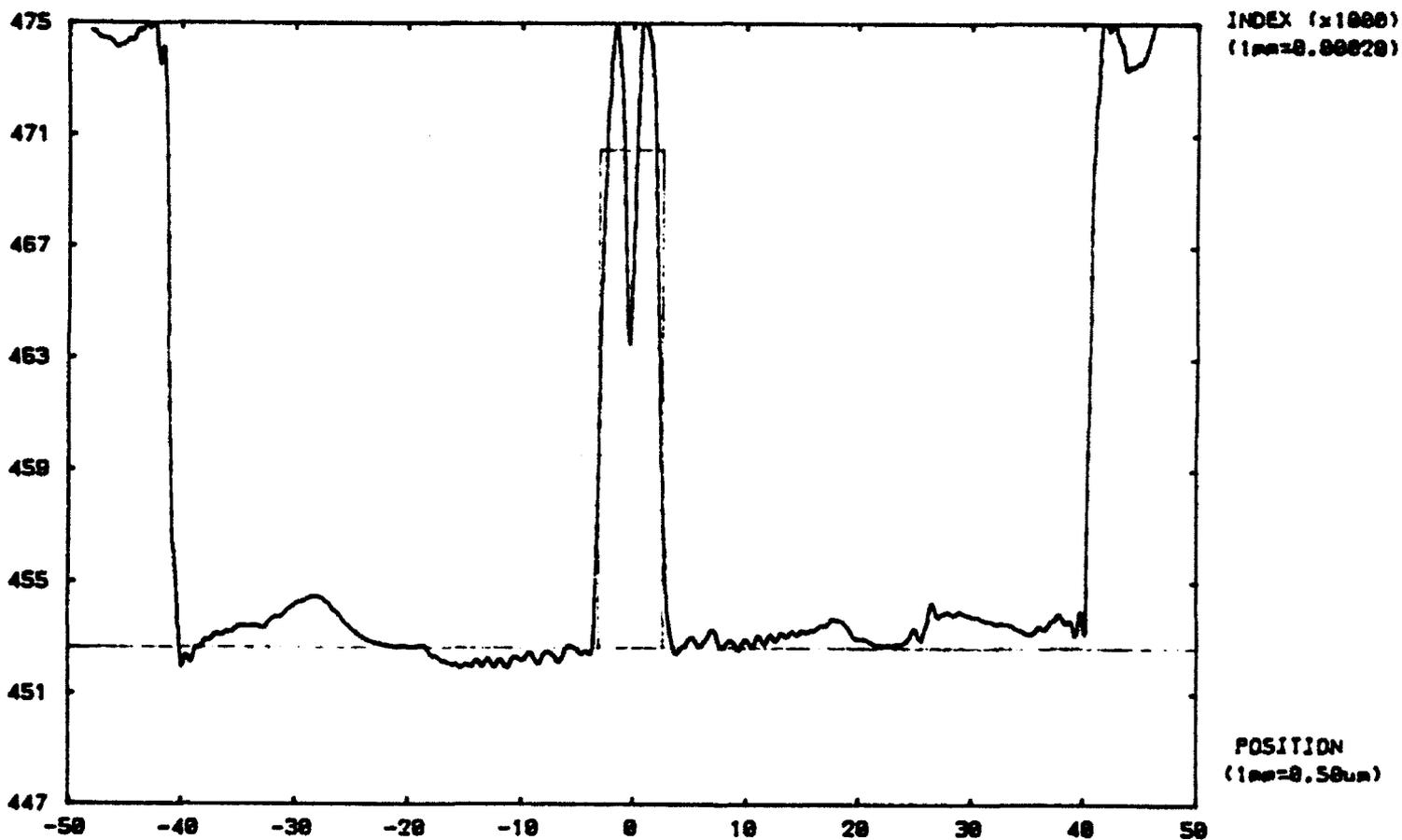
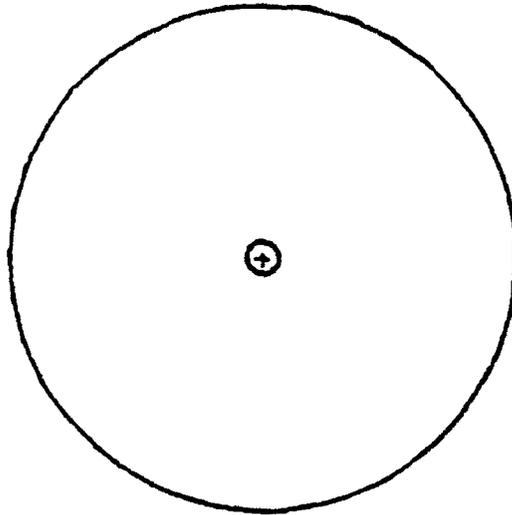
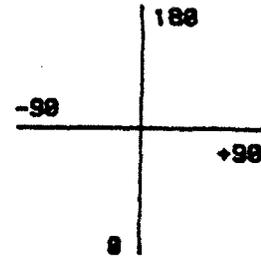


Figure 9
Coupler Fiber Refracted Near Field Scan

APPENDIX

Fibre Name 988201 SMTN /BDET/ 1625 D435



| | Cladding | Core |
|------------------------|----------|---------|
| Mean Diameter (um) | 81.93 | 5.27 |
| Maximum " (um) | 82.21 | 5.41 |
| Minimum " (um) | 81.40 | 5.17 |
| Non-Circularity (%) | 1.0 | 4.6 |
| Eccentricity | 0.140 | 0.295 * |
| Major Axis Angle (deg) | -28.3 | 58.3 |
| Threshold Level (%) | 50.0 | 50.0 |

Cladding Centre to Core Centre Distance 0.15 um

Concentricity Error 3.0 %

Figure 10
Coupler Fiber Geometry Report

Bimonthly Activity Report No. 2

Optical Fiber for Acoustic Sensor Applications

Prepared by
James R. Onstott
Principal Investigator

Prepared for the
Naval Research Laboratory
Contract No. N00014-89-C-2455

December, 1990

3M Fiber Optics Laboratory
3M Center
St. Paul, Minnesota 55144



APPENDIX

1.0 INTRODUCTION

This interim report summarizes the research and development efforts performed during the bimonthly reporting period of February-March, 1990 by 3M on the development of optical fiber for acoustic sensor applications under Naval Research Contract Number N00014-89-C-2455.

2.0 PROGRAM OBJECTIVE

The objectives of this program are to develop long lengths of both acoustically sensitive and insensitive optical fibers that are environmentally stable, and to develop a fiber which is optimized for fused coupler fabrication. During the first phase of this program, the development of optical fibers and organic fiber coatings specifically optimized for acoustic sensing applications is being pursued.

3.0 PROGRAM ACTIVITIES

Fiber Design - Task One of the program statement of work requires the design and fabrication of two single mode fibers. We report the completion of this task in this interim report. Results for the two fiber designs are described below.

3.1 Sensor Fiber Design - Design of the fiber for sensor coating experiments was completed during the last reporting period. The design approach taken for the fiber was a high numerical aperture "depressed well" structure, with a low index fluorosilicate well surrounding a lightly doped germanium oxide core. This design approach allowed the simultaneous minimization of intrinsic attenuation (Rayleigh scattering) and extrinsic attenuation (macro and micro bending). Final fiber fabrication was completed during this reporting period. Target design specifications and measured results are listed in Table 1.

Table 1. Fiber Number 900320 SMDTN

| | Target Specifications | Measured Results |
|--------------------|-----------------------|------------------|
| Cladding Diameter | 80um | 80um |
| Numerical Aperture | 0.16 | 0.160 |
| Cutoff Wavelength | 1250nm | 1300nm |
| Attenuation | 0.5 db/km | 1.9 db/km |

APPENDIX

Measured results for this fiber (attenuation, mode field diameter, cutoff wavelength, ESI parameters, and concentricity) are shown in Figures 1 through 5 and Tables 2 through 4. The unusually high water absorption peak at 1.38 μm which was reported in the previous interim report has been reduced to normal levels during this reporting period.

3.2 Coupler Fiber Design.- This fiber is a high numerical aperture "matched index" structure which trades slightly higher attenuation for ease of coupler fabrication. Final fiber fabrication of this design was completed during the previous reporting period.

4.0 DISCUSSION

Design and fabrication of the two fibers is complete. A major goal has been to match the mode field diameters so that splice loss would be minimized. Mode field diameter mismatch between the two fibers described above is 3%. Attenuation of the sensor fiber design is somewhat higher than the coupler fiber. This discrepancy is under investigation.

5.0 FUTURE WORK

Upon completion of fiber characterization activities, samples of the two fibers described above will be delivered to NRL for evaluation. Development of extrusion technology is continuing and fabrication of preliminary samples of sensor fibers with extruded coatings are in preparation.

APPENDIX

Table 2. Fiber - Summary of Properties

3M Specialty Fiber
NRL Contract N00014-89-C-2455

Sample: 900320 SMDTN, d472, T+0m

Length: 200m

Cladding OD: $80 \pm 1\mu\text{m}$

Coating: Dual Acrylate

Outer Coating OD: $200 \pm 5\mu\text{m}$

Optical Characteristics

Attenuation: 1.9dB/km at 1310nm

Cutoff: 1300nm

Mode Field Diameter: $6.8\mu\text{m}$ at 1300nm

Attenuation Change, 10 Turns on $\frac{1}{8}$ " Mandrel: $< 0.1\text{dB}$

Effective Step Index (ESI) Parameters

ESI Core Diameter: $6.1\mu\text{m}$

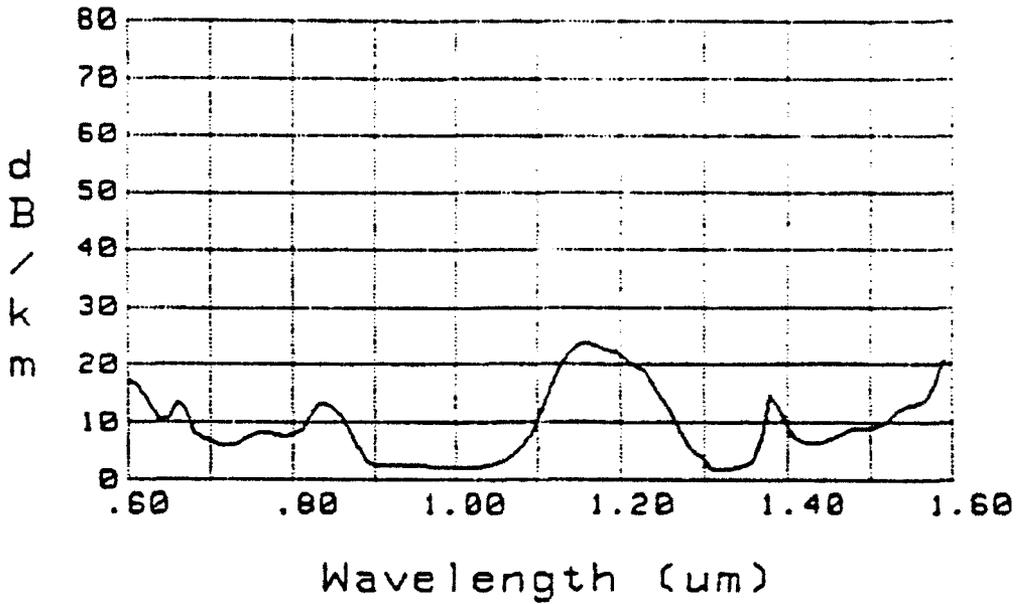
ESI Δ : 0.60%

N.A.: 0.16

4/25/90

APPENDIX

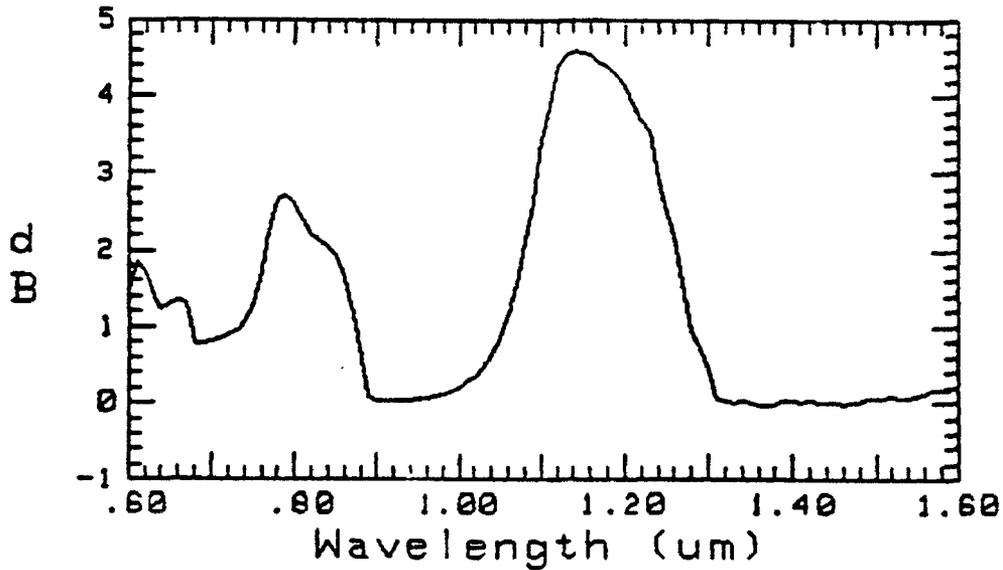
SPECTRAL ATTENUATION LENGTH: .2000 km
ID: 900320 SMDTN D472 T+0 24-APR-90 07:54:33



File: 2656

Figure 1
Fiber Attenuation versus Wavelength

CUTOFF PLOT TYPE: BEND
ID: 900320 SMDTN D472 T+0 10 TURNS 1/2 IN 24



Cutoff Wavelength not found

File: 2657

Figure 2
Fiber Cutoff Plot

APPENDIX

Table 3. Fiber Attenuation versus Wavelength

Spectral Attenuation

Fiber ID: 900320 SMDTN D472 T+0 24-Apr-90 07:54:33

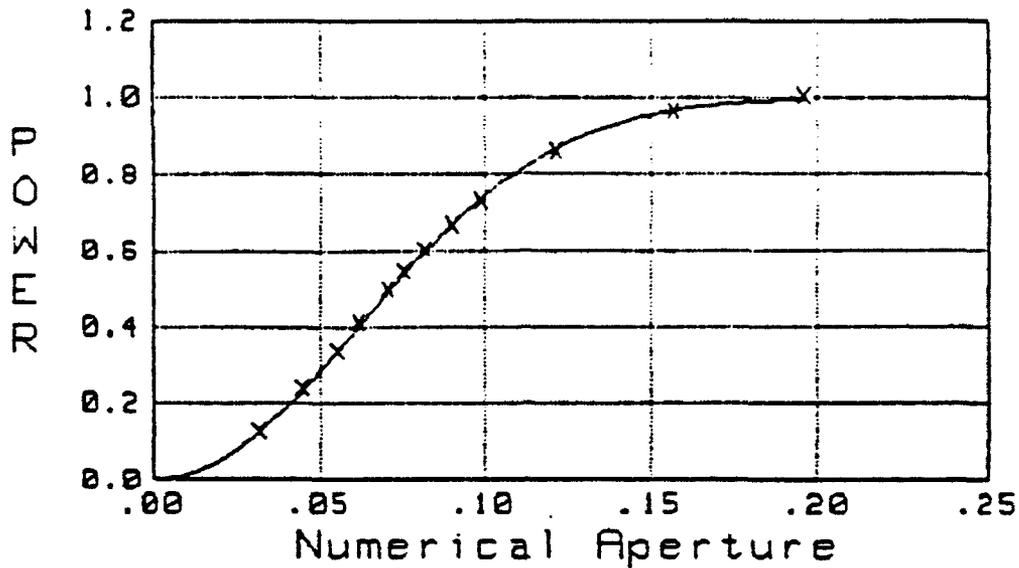
Length: 3.0 km

File: 2656

| Wavelength | Attenuation (dB/Km) | Wavelength | Attenuation (dB/Km) |
|------------|---------------------|------------|---------------------|
| 600 | 17.29 | 1100 | 10.42 |
| 610 | 16.74 | 1110 | 13.62 |
| 620 | 14.72 | 1120 | 17.42 |
| 630 | 12.12 | 1130 | 20.48 |
| 640 | 10.37 | 1140 | 22.40 |
| 650 | 10.92 | 1150 | 23.48 |
| 660 | 13.54 | 1160 | 23.59 |
| 670 | 12.55 | 1170 | 23.24 |
| 680 | 8.21 | 1180 | 22.75 |
| 690 | 7.24 | 1190 | 22.36 |
| 700 | 6.77 | 1200 | 21.79 |
| 710 | 6.33 | 1210 | 20.44 |
| 720 | 6.17 | 1220 | 19.58 |
| 730 | 6.35 | 1230 | 18.91 |
| 740 | 6.92 | 1240 | 16.32 |
| 750 | 7.76 | 1250 | 14.05 |
| 760 | 8.26 | 1260 | 12.37 |
| 770 | 8.18 | 1270 | 9.34 |
| 780 | 7.97 | 1280 | 6.06 |
| 790 | 7.79 | 1290 | 4.81 |
| 800 | 7.90 | 1300 | 3.53 |
| 810 | 8.78 | 1310 | 1.84 |
| 820 | 11.20 | 1320 | 1.91 |
| 830 | 13.25 | 1330 | 1.91 |
| 840 | 13.40 | 1340 | 2.31 |
| 850 | 12.78 | 1350 | 2.75 |
| 860 | 11.31 | 1360 | 3.42 |
| 870 | 8.75 | 1370 | 7.16 |
| 880 | 5.87 | 1380 | 14.89 |
| 890 | 3.29 | 1390 | 12.81 |
| 900 | 2.79 | 1400 | 9.04 |
| 910 | 2.69 | 1410 | 7.35 |
| 920 | 2.61 | 1420 | 6.63 |
| 930 | 2.59 | 1430 | 6.40 |
| 940 | 2.74 | 1440 | 6.67 |
| 950 | 2.60 | 1450 | 7.23 |
| 960 | 2.44 | 1460 | 7.66 |
| 970 | 2.31 | 1470 | 8.29 |
| 980 | 2.20 | 1480 | 8.89 |
| 990 | 2.18 | 1490 | 9.03 |
| 1000 | 2.09 | 1500 | 9.20 |
| 1010 | 2.14 | 1510 | 9.47 |
| 1020 | 2.16 | 1520 | 10.28 |
| 1030 | 2.36 | 1530 | 11.54 |
| 1040 | 2.54 | 1540 | 12.73 |
| 1050 | 2.97 | 1550 | 13.10 |
| 1060 | 3.50 | 1560 | 13.35 |
| 1070 | 4.42 | 1570 | 13.97 |
| 1080 | 5.82 | 1580 | 16.76 |
| 1090 | 7.65 | 1590 | 20.75 |

APPENDIX

VARIABLE APERTURE PATTERN AT 1300 nm
 ID: 900320 SMDTN D472 HANDLE OF 1000m 18-AF



MFD: Gaussian= 6.78

Petermann=6.8

File: 2626

Figure 3
Fiber Mode Field Diameter

Table 4. Fiber ESI Parameters

| | | |
|-------------------------|----------|-----------|
| File: | 2626 | |
| Measurement Wavelength: | 1300 nm | |
| Cutoff Wavelength: | 1282 nm | |
| Conversion Factor: | 1.109 | |
| | Gaussian | Petermann |
| Spot Radius: | 3.3906 | 3.3992 μm |
| ESI Core Radius: | 3.0564 | 3.0640 μm |
| ESI Delta: | .0061 | .0060 |
| Nc-Ncl: | .0088 | .0088 |
| Numerical Aperture: | .1606 | .1602 |

APPENDIX

Profile Name 999328 SHD1N C/120/S 1708 D472 et 27.8 deg C

Cladding Level Index : 1.4586

Core Peak Index : 1.4618

Cladding Diameter : 81.66 um

Core Diameter : 7.54 um

ESI : 0.0095

ESR : 3.37 um

λ_{co} : 1.47 um

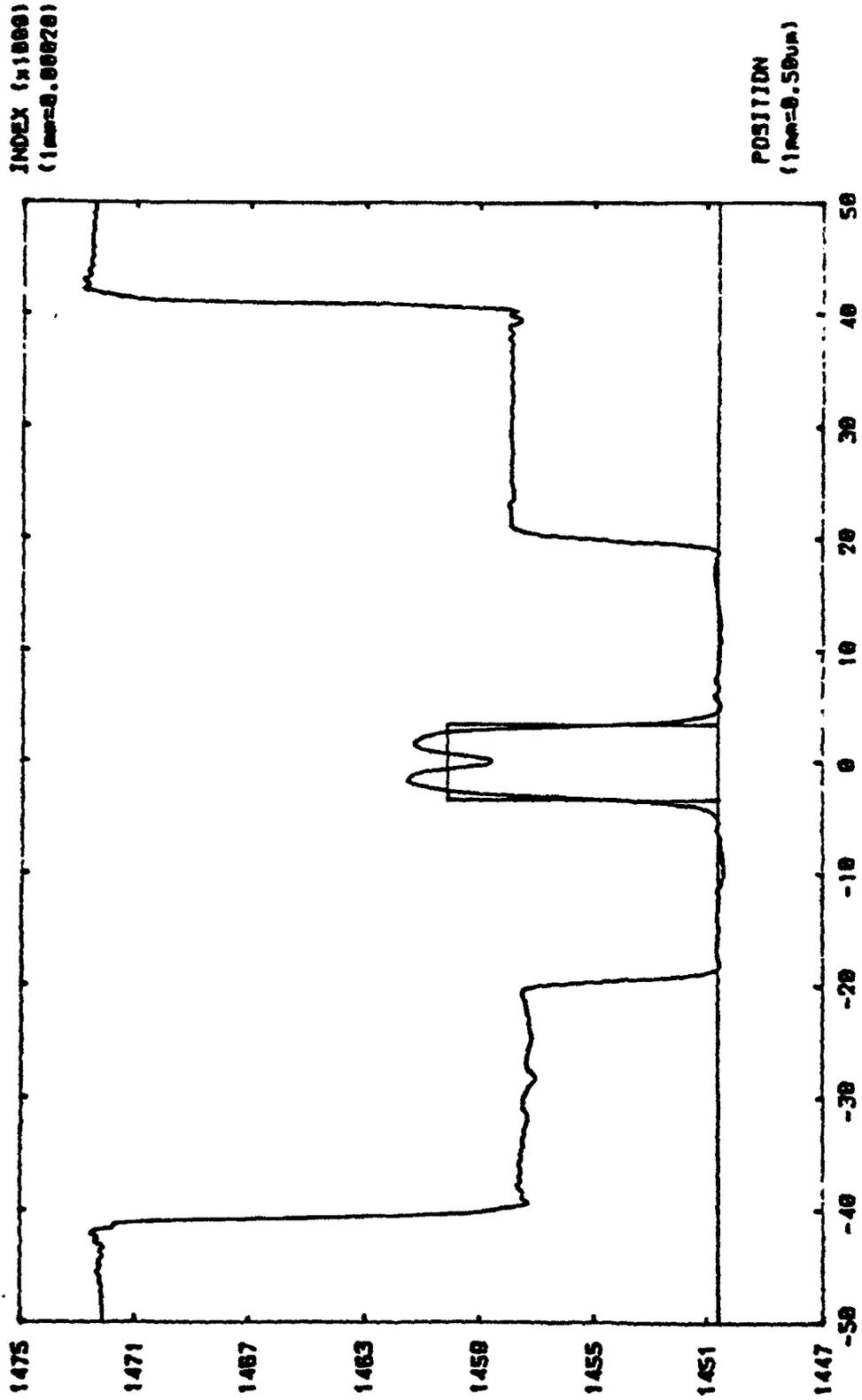
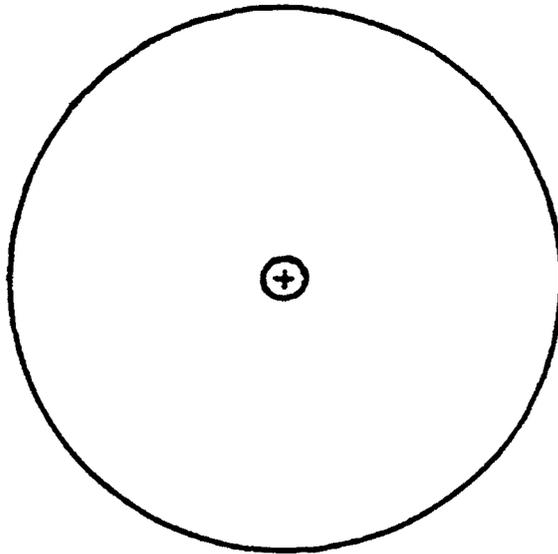
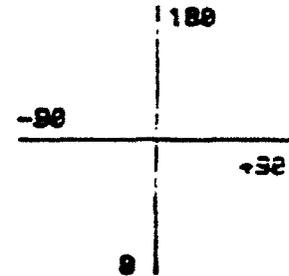


Figure 4
Fiber Refractive Index Profile

APPENDIX

Fibre Name 988328 SMDTN /BDET/ 1706 D472



| | Cladding | Core |
|------------------------|----------|-------|
| Mean Diameter (um) | 81.60 | 6.19 |
| Maximum " (um) | 81.80 | 6.43 |
| Minimum " (um) | 81.40 | 5.93 |
| Non-Circularity (%) | 0.5 | 8.0 |
| Eccentricity | 0.099 | 0.384 |
| Major Axis Angle (deg) | 65.1 | -65.8 |
| Threshold Level (%) | 50.0 | 50.0 |

Cladding Centre to Core Centre Distance 0.18 um

Concentricity Error 1.7 %

Figure 5
Fiber Geometry Characterization

Bimonthly Activity Report No. 3

Optical Fiber for Acoustic Sensor Applications

Prepared by
James R. Onstott
Principal Investigator

Prepared for the
Naval Research Laboratory
Contract No. N00014-89-C-2455

March, 1991

3M Fiber Optics Laboratory
3M Center
St. Paul, Minnesota 55144



APPENDIX

1.0 INTRODUCTION

This interim report summarizes the research and development efforts performed during the bimonthly reporting period of April-May, 1990 by 3M on the development of optical fiber for acoustic sensor applications under Naval Research Laboratory (NRL) Contract Number N00014-89-C-2455.

2.0 PROGRAM OBJECTIVE

The objectives of this program are to develop long lengths of both acoustically sensitive and insensitive optical fibers that are environmentally stable, and to develop a fiber which is optimized for fused coupler fabrication. During the first phase of this program, the development of optical fibers and organic fiber coatings specifically optimized for acoustic sensing applications is being pursued.

3.0 PROGRAM ACTIVITIES

As noted in Bi monthly Report No. 2, design of the fiber for sensor coating experiments has been completed. Fiber sample number 9000220SMDTN was completed to satisfy the milestone requirement for fused coupler applications. In addition, fiber sample number 900320SMTN for acoustic sensor applications was developed. These samples were forwarded on April 25, 1990 for NRL analysis. Target design measurement results were included with the samples.

4.0 DISCUSSION

Design and fabrication of the two fibers are complete. 3M is awaiting NRL evaluation results and guidance for further development activity.

5.0 FUTURE WORK

Development of extrusion technology is continuing and the fabrication of preliminary samples of sensor fibers with extruded coatings will be continued after receipt of NRL evaluation results and guidance.

Bimonthly Activity Report No. 4

Optical Fiber for Acoustic Sensor Applications

Prepared by
James R. Onstott
Principal Investigator

Prepared for the
Naval Research Laboratory
Contract No. N00014-89-C-2455

March, 1991

3M Fiber Optics Laboratory
3M Center
St. Paul, Minnesota 55144



APPENDIX

1.0 INTRODUCTION

This interim report summarizes the research and development efforts performed during the bimonthly reporting period of June-July, 1990 by 3M on the development of optical fiber for acoustic sensor applications under Naval Research Laboratory (NRL) Contract Number N00014-89-C-2455.

2.0 PROGRAM OBJECTIVE

The objectives of this program are to develop long lengths of both acoustically sensitive and insensitive optical fibers that are environmentally stable, and to develop a fiber which is optimized for fused coupler fabrication. During the first phase of this program, the development of optical fibers and organic fiber coatings specifically optimized for acoustic sensing applications is being pursued.

3.0 PROGRAM ACTIVITIES

As noted in Bi monthly Report No. 3, design of the fiber for sensor coating experiments has been completed. The milestone coupler and acoustic sensing fiber samples were forwarded April 25, 1990 for NRL analysis. Measurement results were included with the samples.

4.0 DISCUSSION

The design and fabrication under this portion of the program is complete. 3M is awaiting NRL evaluation results and guidance for further development activity.

5.0 FUTURE WORK

Development of fiber coating technology is continuing and the fabrication of preliminary samples of sensor fibers with extruded coatings will be continued after receipt of NRL evaluation results and guidance.

Bimonthly Activity Report No. 5

Optical Fiber for Acoustic Sensor Applications

Prepared by
James R. Onstott
Principal Investigator

Prepared for the
Naval Research Laboratory
Contract No. N00014-89-C-2455

March, 1991

3M Fiber Optics Laboratory
3M Center
St. Paul, Minnesota 55144



APPENDIX

1.0 INTRODUCTION

This interim report summarizes the research and development efforts performed during the bimonthly reporting period of August–September, 1990 by 3M on the development of optical fiber for acoustic sensor applications under Naval Research Laboratory (NRL) Contract Number N00014-89-C-2455.

2.0 PROGRAM OBJECTIVE

The objectives of this program are to develop long lengths of both acoustically sensitive and insensitive optical fibers that are environmentally stable, and to develop a fiber which is optimized for fused coupler fabrication. During the first phase of this program, the development of optical fibers and organic fiber coatings specifically optimized for acoustic sensing applications is being pursued.

3.0 PROGRAM ACTIVITIES

As noted in Bi monthly Report No. 3, design of the fiber for sensor coating experiments has been completed. The milestone coupler and acoustic sensing fiber samples were forwarded April 25, 1990 for NRL analysis. Measurement results were included with the samples.

4.0 DISCUSSION

The design and fabrication under this portion of the program is complete. 3M is awaiting NRL evaluation results and guidance for further development activity. Technical discussions during the month of September addressed the need to update the program statement of work, and extend the contract for continued development activity. A request for extension was provided by 3M.

5.0 FUTURE WORK

Development of fiber coating technology is continuing and the fabrication of preliminary samples of sensor fibers with extruded coatings will be continued after receipt of NRL evaluation results and guidance.

Bimonthly Activity Report No. 6

Optical Fiber for Acoustic Sensor Applications

Prepared by
James R. Onstott
Principal Investigator

Prepared for the
Naval Research Laboratory
Contract No. N00014-89-C-2455

March, 1991

3M Fiber Optics Laboratory
3M Center
St. Paul, Minnesota 55144



APPENDIX

1.0 INTRODUCTION

This interim report summarizes the research and development efforts performed during the bimonthly reporting period of October–November, 1990 by 3M on the development of optical fiber for acoustic sensor applications under Naval Research Laboratory (NRL) Contract Number N00014-89-C-2455.

2.0 PROGRAM OBJECTIVE

The objectives of this program are to develop long lengths of both acoustically sensitive and insensitive optical fibers that are environmentally stable, and to develop a fiber which is optimized for fused coupler fabrication. During the first phase of this program, the development of optical fibers and organic fiber coatings specifically optimized for acoustic sensing applications is being pursued.

3.0 PROGRAM ACTIVITIES

The design of the fiber for sensor coating experiments has been completed. The milestone coupler and acoustic sensing fiber samples have been forwarded to NRL analysis. Measurement results were included with the samples.

4.0 DISCUSSION

In response to 3M's letter of September 21, 1990, action was initiated to extend the contract so that technical interchange and feedback might be obtained from NRL on the technical concepts necessary to start Task 2.0, Fiber Coating Development. The modification action in process will carry the schedule out to March 31, 1991.

Several technical discussions, with NRL, reviewed program progress and shifted the focus of the research effort on the development of long lengths of optical fiber with small diameter polymeric coatings. To reflect this emphasis, limited changes to update the Statement of Work were identified. Attached is a draft which reflects the technical revisions, and renumbers the tasks for clarification. Pending NRL's agreement with the changes, 3M will limit activity on Task 2.0 in order that the fiber coating characteristics and goals for the program may be optimized.

APPENDIX

5.0 FUTURE WORK

Development of extrusion technology is continuing and the fabrication of preliminary samples of sensor fibers with extruded coatings will be continued after receipt of NRL evaluation results and guidance.

APPENDIX Attachment

3.0 MODIFIED STATEMENT OF WORK

Reference Contractor's Proposal No. IE0525.441-NAV-89, Dated June, 1989
Sections 3.0 to 3.2

3.1 PROGRAM OBJECTIVES

At the request of NRL, the overall objectives of this program have been modified from the development of acoustically sensitive and insensitive optical fiber to the development of long lengths of optical fiber with small diameter polymeric coatings.

Task 1.0 Fiber Design

Fiber to be used in this program shall be based on the design previously developed during the performance of this contract under phase 1, task 1.0. Target specifications for the fiber are: Cladding diameter - 80um, numerical aperture-0.16, cutoff wavelength 1250nm, attenuation<0.5db/km.

Task 2.0 Fiber Coating Development

Task 2.1 125um Fiber

Single layer ultraviolet polymerizable coatings of conventional acrylate composition shall be applied to the fiber. Technology required to fabricate these coatings with a total diameter of <125um shall be developed.

Task 2.2 100um Fiber

Technology and materials required to fabricate coated fiber with a total diameter of <100um will be investigated.

Task 3.0 Fiber Drawing and Coating

Optical preforms fabricated in task 1.0 will be drawn into fiber and coated with materials and techniques developed in task 2.

Task 4.0 Physical and Optical Measurements

Optical and mechanical properties of fibers drawn in Task 3.0 will be measured. Optical properties to be measured include attenuation, cutoff wavelength, equivalent step index parameters (core radius, delta, numerical aperture) and fiber refractive index profile. Mechanical properties of the fiber include clad diameter, core diameter and core/cladding concentricity. In addition, mechanical characteristics and composition of coating materials will be reported.

Task 5.0 Analysis

The data obtained from Tasks 1 through 4 will be correlated and interpreted by 3M. This information, in addition to any feedback from NRL's analyses of fiber samples, will be used to guide further experiments.

APPENDIX
Attachment (Continued)

Modified Statement of Work
Page Two

Task 6.0 Technical Liaison with NRL

Technical liaison will be maintained with the Optical Techniques Branch of NRL. Reports generated in Tasks 1 through 4 will be sufficiently complete to permit technical participation by the NRL Optical Techniques Branch in the analyses described in subtask 5. Joint interaction between 3M and NRL is critical to the successful achievement of the goals described in this program.

Task 7.0 Deliverables and Reporting

3M will submit fiber and data produced in Tasks 1-4 to NRL. 20-30km of fiber with coatings developed in Task 2.1 will be produced and delivered to NRL. 3M will also submit fiber samples and data with coatings produced in Task 2.2. These samples will be approximately 100 meters in length.

Milestones

*125um coated fiber- 20-30km of fiber suitable for single mode operation at 1300nm and with a total coated diameter of less than 125um will be fabricated and delivered to NRL for evaluation.

* 100um coated fiber- Short samples of fiber suitable for single mode operation at 1300nm and with a total coated diameter of <100um will be fabricated and submitted to NRL for evaluation. 3M will select the best materials and coating technology for this fiber. Additional samples may be prepared after evaluation by and consultation with NRL.

Bimonthly Activity Report No. 7

Optical Fiber for Acoustic Sensor Applications

Prepared by
James R. Onstott
Principal Investigator

Prepared for the
Naval Research Laboratory
Contract No. N00014-89-C-2455

April, 1991

3M Fiber Optics Laboratory
3M Center
St. Paul, Minnesota 55144



APPENDIX

1.0 INTRODUCTION

This interim report summarizes the research and development efforts performed during the bimonthly reporting period of December 1990–January 1991 by 3M on the development of optical fiber for acoustic sensor applications under Naval Research Laboratory (NRL) Contract Number N00014-89-C-2455.

2.0 PROGRAM OBJECTIVE

At the request of NRL, the overall objectives of this program have been modified from the development of acoustically sensitive and insensitive optical fiber to the development of long lengths of optical fiber with small diameter polymeric coatings.

3.0 PROGRAM ACTIVITIES

3.1 Task 1.0: Fiber Design

A fiber design previously developed during the performance of this contract under Phase I, Subtask 1.0 was used in this task. This design is a "matched clad" high numerical aperture structure which is suitable for use in both sensing and fused fiber coupler applications. We report the fabrication of an evaluation sample of this fiber design in this interim report. Target design specifications and measured results are listed in Table 1.

Table 1. Fiber Number 910128 SMTNP

| | Target Specifications | Measured Results |
|--------------------|------------------------------|-------------------------|
| Cladding Diameter | 80 μm | 80 μm |
| Numerical Aperture | 0.16 | 0.160 |
| Cutoff Wavelength | 1250 nm | 1300 nm |
| Attenuation | 0.5 dB/km | 1.5 dB/km |

APPENDIX

3.2 Task 2.1: 125 μm Fiber Coating Development

Technology required to apply single layer ultraviolet polymerizable coatings with a total diameter of $\sim 125 \mu\text{m}$ was developed. We have found that conventional "pressurized die" coaters with appropriately sized coating dies may be used to perform this task.

3.3 Task 2.2: 100 μm Fiber Coating Fiber Development

Preliminary screening of coating materials and coating application technology for this task has begun. Experiments to produce this fiber will begin in the next reporting period.

3.3 Task 3.0: Fiber Drawing and Coating

One optical test preform was fabricated as part of Task 1.0 and drawn into a continuous 6.0 km length of $80 \mu\text{m}$ fiber. The fiber was coated with a $23 \mu\text{m}$ thickness ($126 \mu\text{m}$ total OD) single UV polymerized coating which was developed in Task 2.1.

3.4 Task 4.0: Physical and Optical Measurements

A complete set of physical and optical measurements were performed on this fiber. Table 2 summarizes these results. Detailed measurement data are shown in Figures 1 through 6 and Tables 3 and 4. Figure 1 and Table 3 show fiber attenuation versus wavelength. Figure 2 shows the fiber cutoff wavelength results, while Figure 3 and Table 4 show the fiber mode field diameter and Equivalent Step Index parameters (ESI) respectively. Mechanical characteristics (fiber diameter, ovality, core diameter, core ovality and core/clad concentricity) are shown in Figures 4 and 5. The refractive index profile for the fiber is shown in Figure 6.

APPENDIX

Table 2. Fiber - Summary of Properties
3M SOF
1300 nm Coil Fiber

Contract: N00014-89-C-2455
Lot: 910128 SMTNP, D600, T+500 - T+6500
Length: 6000 m

Mechanical Characteristics

Cladding OD: $80 \pm 1 \mu\text{m}$
Coating: Single Acrylate
Coating OD: $125 \pm 5 \mu\text{m}$
Core/Cladding Concentricity: $0.1 \mu\text{m}$

Optical Characteristics

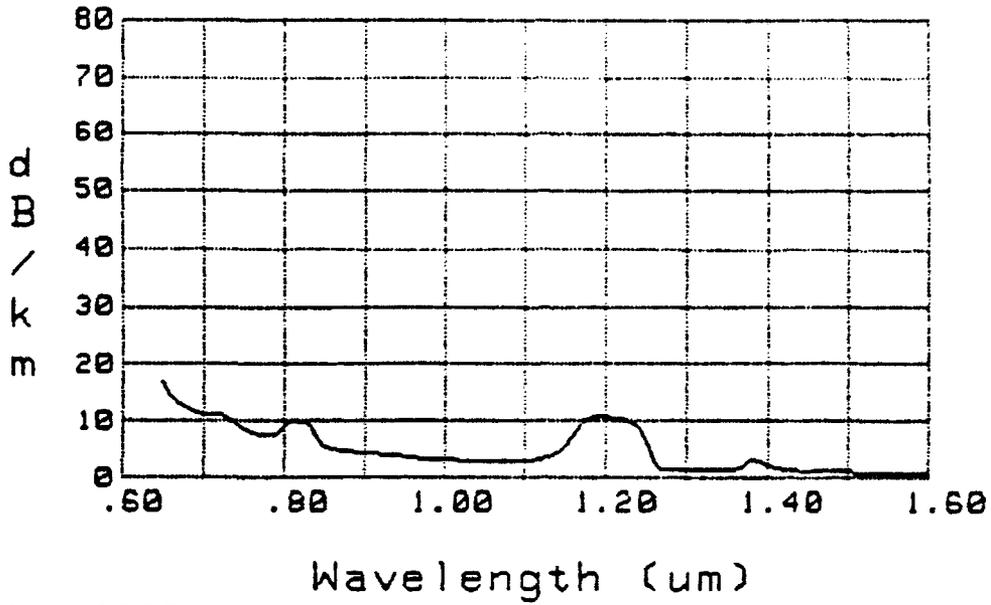
Attenuation : 1.6 dB/km at 1300 nm
Cutoff: 1270 nm
Mode Field Diameter: $6.5 \mu\text{m}$ at 1300 nm

Effective Step Index (ESI) Parameters

ESI Core Diameter: $5.8 \mu\text{m}$
ESI Δ : 0.65%
N.A.: 0.17

APPENDIX

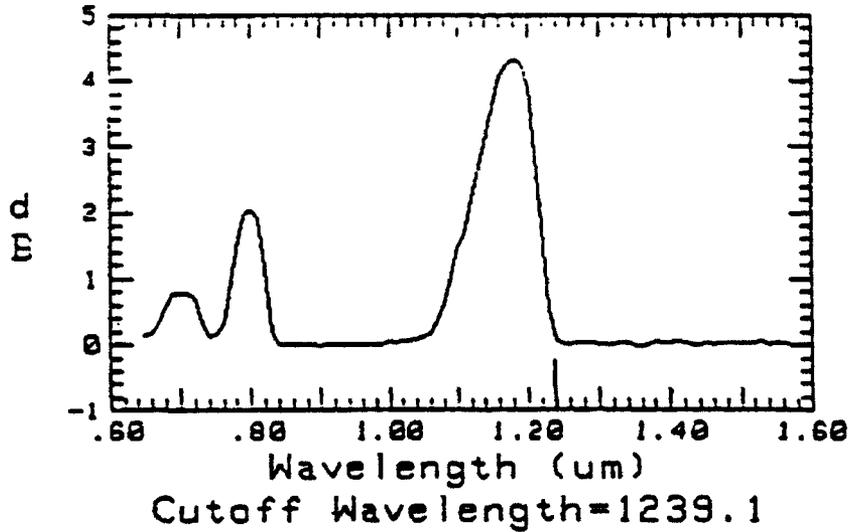
SPECTRAL ATTENUATION LENGTH: .5000 km
ID: 910128 SMTNP 0600 T+6500M-T+7000M 11-FEB-91



File: 3380

Figure 1
Fiber Attenuation versus Wavelength

CUTOFF PLOT TYPE: BEND
ID: 910128 SMTNP 0600 T+7000M 11-FEB-91 16:09



File: 3371

Figure 2
Fiber Cutoff Plot

APPENDIX

Table 3. Fiber Attenuation versus Wavelength

SPECTRAL ATTENUATION

FIBER ID: 910128 SMTNP D600 T+6500M-T+7000M 11-FEB-91 11:52:12

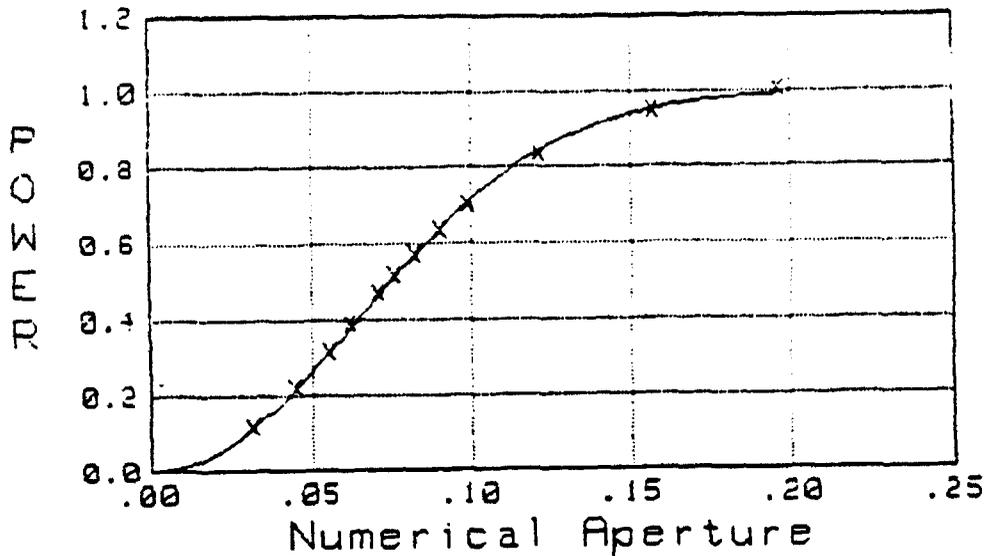
LENGTH: .5 km

FILE: 3380

| Wavelength | Attenuation (dB/km) | Wavelength | Attenuation (dB/km) |
|------------|---------------------|------------|---------------------|
| 650 | 16.80 | 1130 | 3.67 |
| 660 | 14.28 | 1140 | 4.38 |
| 670 | 13.03 | 1150 | 5.44 |
| 680 | 12.29 | 1160 | 7.26 |
| 690 | 11.61 | 1170 | 9.30 |
| 700 | 11.24 | 1180 | 10.52 |
| 710 | 11.24 | 1190 | 10.85 |
| 720 | 11.03 | 1200 | 10.85 |
| 730 | 10.59 | 1210 | 10.66 |
| 740 | 9.69 | 1220 | 10.36 |
| 750 | 8.60 | 1230 | 9.93 |
| 760 | 8.05 | 1240 | 9.01 |
| 770 | 7.76 | 1250 | 6.53 |
| 780 | 7.55 | 1260 | 3.26 |
| 790 | 7.65 | 1270 | 1.68 |
| 800 | 8.98 | 1280 | 1.46 |
| 810 | 10.02 | 1290 | 1.43 |
| 820 | 9.90 | 1300 | 1.52 |
| 830 | 9.37 | 1310 | 1.44 |
| 840 | 7.49 | 1320 | 1.47 |
| 850 | 5.49 | 1330 | 1.45 |
| 860 | 5.03 | 1340 | 1.38 |
| 870 | 4.85 | 1350 | 1.44 |
| 880 | 4.68 | 1360 | 1.42 |
| 890 | 4.56 | 1370 | 2.01 |
| 900 | 4.41 | 1380 | 3.25 |
| 910 | 4.25 | 1390 | 2.95 |
| 920 | 4.14 | 1400 | 2.28 |
| 930 | 4.01 | 1410 | 1.87 |
| 940 | 3.92 | 1420 | 1.58 |
| 950 | 3.78 | 1430 | 1.40 |
| 960 | 3.64 | 1440 | 1.28 |
| 970 | 3.49 | 1450 | 1.20 |
| 980 | 3.40 | 1460 | 1.06 |
| 990 | 3.29 | 1470 | 1.02 |
| 1000 | 3.21 | 1480 | 1.01 |
| 1010 | 3.17 | 1490 | 1.03 |
| 1020 | 3.09 | 1500 | 1.05 |
| 1030 | 2.94 | 1510 | .90 |
| 1040 | 2.95 | 1520 | .95 |
| 1050 | 2.88 | 1530 | .87 |
| 1060 | 2.85 | 1540 | .93 |
| 1070 | 2.85 | 1550 | .98 |
| 1080 | 2.81 | 1560 | .93 |
| 1090 | 2.86 | 1570 | .97 |
| 1100 | 2.89 | 1580 | .96 |
| 1110 | 3.03 | 1590 | .93 |
| 1120 | 3.29 | 1600 | .96 |

APPENDIX

VARIABLE APERTURE PATTERN AT 1300 nm
 ID: 910128 SMTNP D600 T-7000M 1-FEB-91 17:1



File: 3372
 MFD: Gaussian=6.51
 Petermann=6.52

Figure 3
Fiber Mode Field Diameter

Table 4. Fiber ESI Parameters

File: 3372
 Measurement Wavelength: 1300 nm
 Cutoff Wavelength: 1239 nm
 Conversion Factor: 1.136

| | Gaussian | Petermann |
|---------------------|-----------|-----------|
| Spot Radius: | 3.2531 μm | 3.2586 μm |
| ESI Core Radius: | 2.8628 μm | 2.8677 μm |
| ESI Delta: | .0064 | .0064 |
| Nc-Ncl: | .0094 | .0094 |
| Numerical Aperture: | .1657 | .1654 |

APPENDIX

geometry
Drum Number:600
Fiber ID:910128 SMTNP T+7000m
Length=0.0020 km
Time of Test: 1-FEB-91 16:55:22

=====
clad: (101.35,77.55) diam=80.20 non_circ=0.063 (40.11,40.09) at 79.12
core: (101.54,78.03) diam=6.52 non_circ=0.866 (3.27, 3.25) at -31.03
Concentricity of clad to core=0.144 microns (119.14 degrees)

Phase Plot of clad 1-FEB-91 16:55:22 Model: ELLIPSE
Fiber ID:910128 SMTNP T+7000m
Drum Number:600

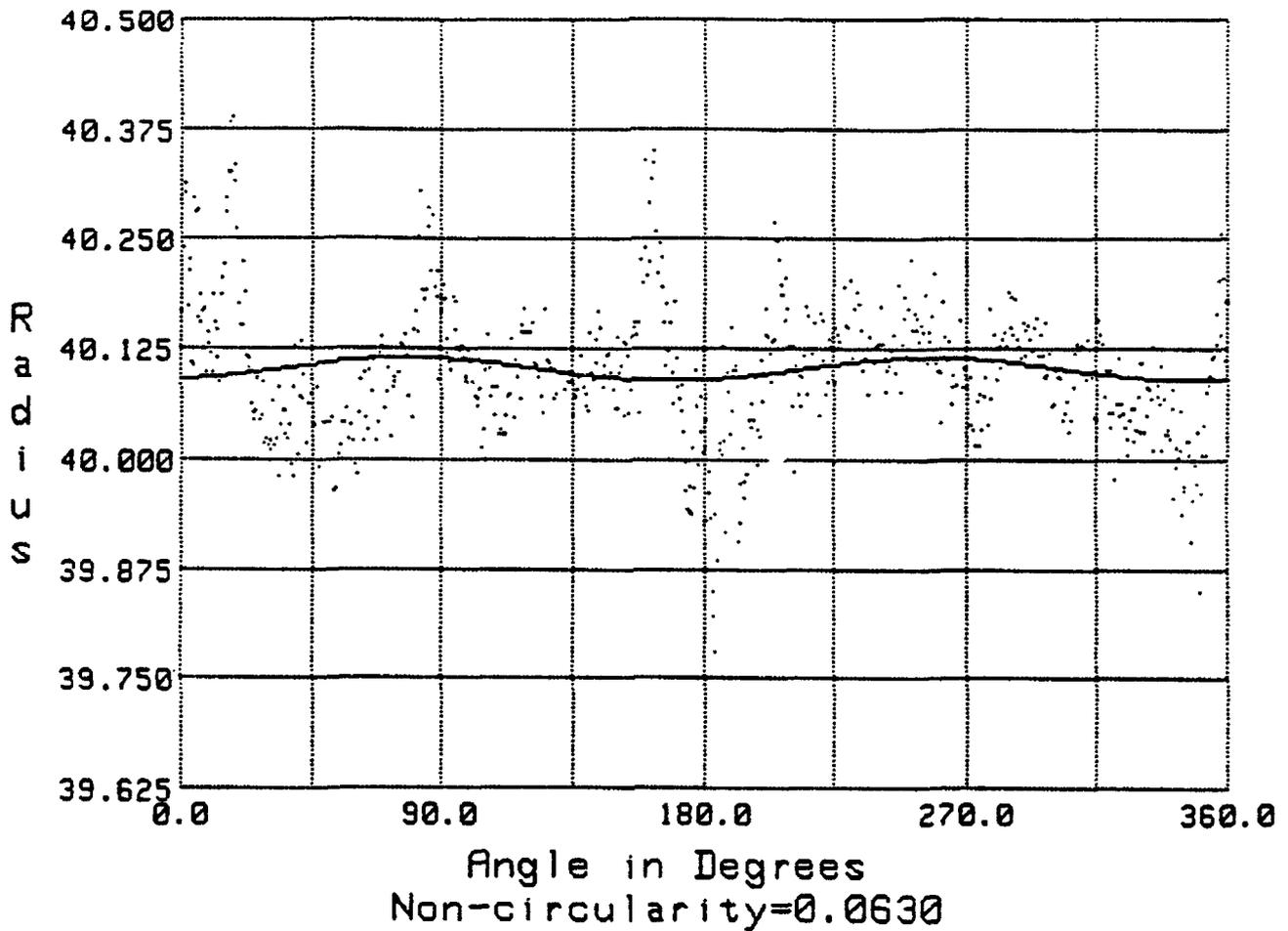
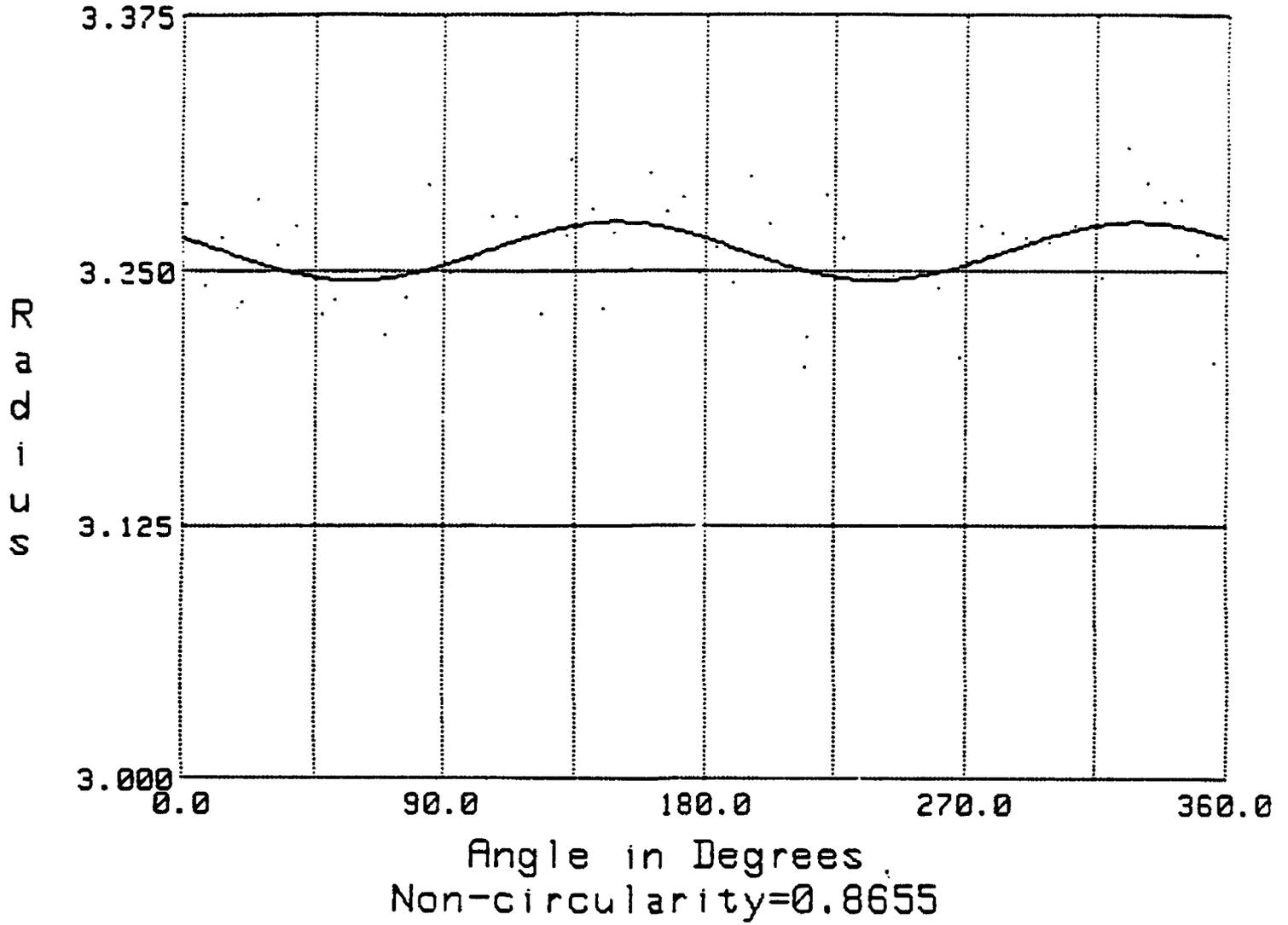


Figure 4
Fiber Geometry Report

APPENDIX

Phase Plot of core 1-FEB-91 16:55:22 Model: ELLIPSE
 Fiber ID:910128 SMTNP T+7000m
 Drum Number:600



END ANGLE MEASUREMENT

Diameter used to compute = 80.45

| angle | position | end angle | angle | position | end angle |
|-------|----------|-----------|-------|----------|-----------|
| 0 | -0.3114 | -0.4436 | 180 | 1.1664 | 1.6611 * |
| 45 | -0.2827 | -0.4026 | 225 | 0.3082 | 0.4390 |
| 90 | 0.0250 | 0.0356 | 270 | 0.4181 | 0.5956 |
| 135 | -0.1267 | -0.1805 | 315 | -0.0305 | -0.0435 |

* - rejected orientation

Figure 5
 Fiber Core Geometry Report

APPENDIX

Cladding Level Index : 1.4562
Core Peak Index : 1.4691
T=6580m
Left circular polarization

Cladding Diameter : 79.21 μm
Core Diameter : 7.09 μm

ESI : 0.0096
ESR : 3.36 μm
 λ_{co} : 1.47 μm

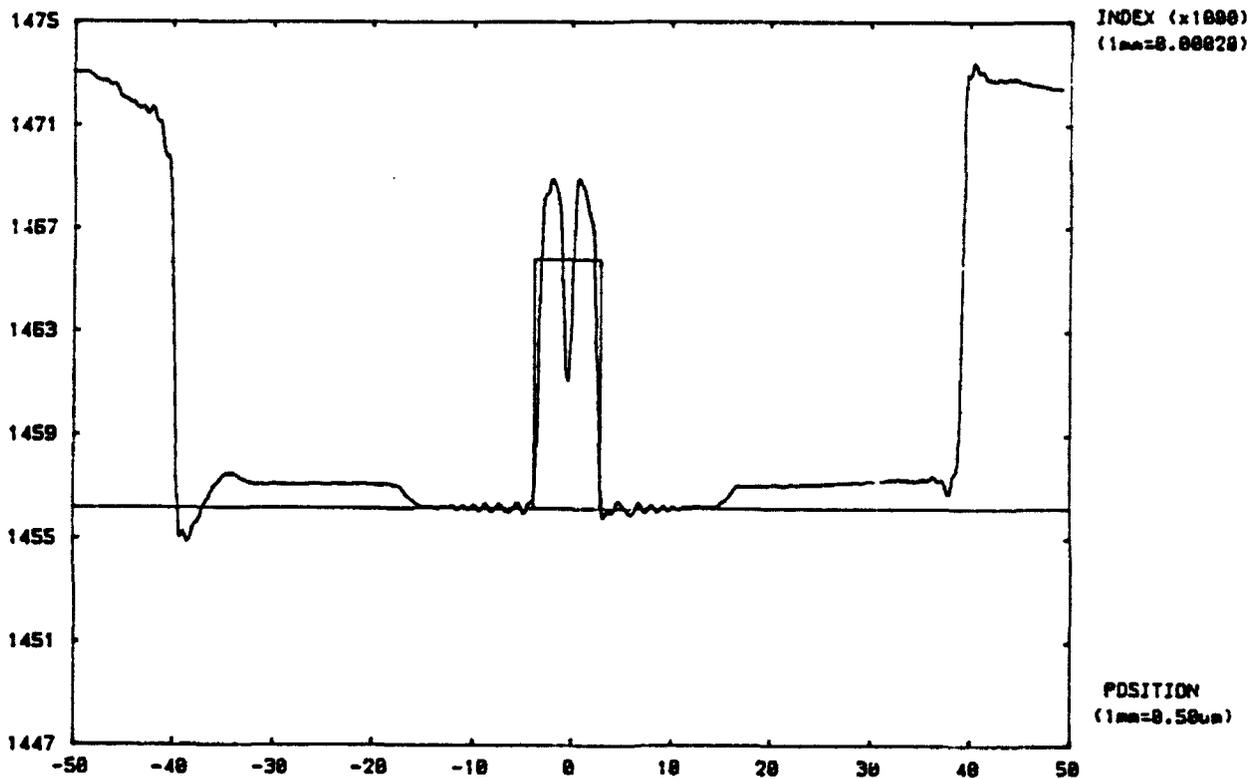


Figure 6
Fiber Refractive Index Profile

4.0 DISCUSSION AND FUTURE WORK

Design and fabrication of an evaluation sample of a reduced coating diameter single mode fiber is complete. This sample will be delivered to NRL for evaluation. Upon approval by NRL personnel, and additional 35 km of this fiber will be fabricated and delivered to NRL. Work will continue to develop fiber coatings with target coating thickness of $\sim 5 \mu\text{m}$.

Bimonthly Activity Report No. 8

Optical Fiber for Acoustic Sensor Applications

Prepared by
James R. Onstott
Principal Investigator

Prepared for the
Naval Research Laboratory
Contract No. N00014-89-C-2455

April, 1991

3M Fiber Optics Laboratory
3M Center
St. Paul, Minnesota 55144



APPENDIX

1.0 INTRODUCTION

This interim report summarizes the research and development efforts performed during the bimonthly reporting period of February 1991 - March 1991 by 3M on the development of optical fiber for acoustic sensor applications under Naval Research Laboratory (NRL) Contract Number N00014-89-C-2455.

2.0 PROGRAM OBJECTIVE

At the request of NRL, the overall objectives of this program have been modified from the development of acoustically sensitive and insensitive optical fiber to the development of long lengths of optical fiber with small diameter polymeric coatings.

3.0 PROGRAM ACTIVITIES

3.1 Task 1.0: Fiber Design

A fiber design previously developed during the performance of this contract under Phase I, Subtask 1.0 was used in this task. This design is a "matched clad" high numerical aperture structure which is suitable for use in both sensing and fused fiber coupler applications. We report the fabrication of an evaluation sample of this fiber design in this interim report. Target design specifications and measured results are listed in Table 1.

Table 1. Fiber Number 910128 SMTNP

| | Target Specifications | Measured Results |
|--------------------|------------------------------|-------------------------|
| Cladding Diameter | 80 μm | 80 μm |
| Numerical Aperture | 0.16 | 0.160 |
| Cutoff Wavelength | 1250 nm | 1300 nm |
| Attenuation | 0.5 dB/km | 1.5 dB/km |

APPENDIX

3.2 Task 2.1: 125 μm Fiber Coating Development

Technology required to apply single layer ultraviolet polymerizable coatings with a total diameter of $\sim 125 \mu\text{m}$ was developed. We have found that conventional "pressurized die" coaters with appropriately sized coating dies may be used to perform this task.

3.3 Task 2.2: 100 μm Fiber Coating Fiber Development

Preliminary screening of coating materials and coating application technology for this task has begun. Experiments to produce this fiber will begin in the next reporting period.

3.3 Task 3.0: Fiber Drawing and Coating

One optical test preform was fabricated as part of Task 1.0 and drawn into a continuous 6.0 km length of $80 \mu\text{m}$ fiber. The fiber was coated with a $23 \mu\text{m}$ thickness ($126 \mu\text{m}$ total OD) single UV polymerized coating which was developed in Task 2.1.

3.4 Task 4.0: Physical and Optical Measurements

A complete set of physical and optical measurements were performed on this fiber. Table 2 summarizes these results. Detailed measurement data were provided in Bimonthly Report No. 7.

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Table 2. Fiber - Summary of Properties
3M SOF
1300 nm Coil Fiber

Contract: N00014-89-C-2455
Lot: 910128 SMTNP, D600, T+500 - T+6500
Length: 6000 m

Mechanical Characteristics

Cladding OD: $80 \pm 1 \mu\text{m}$
Coating: Single Acrylate
Coating OD: $125 \pm 5 \mu\text{m}$
Core/Cladding Concentricity: $0.1 \mu\text{m}$

Optical Characteristics

Attenuation : 1.6 dB/km at 1300 nm
Cutoff: 1270 nm
Mode Field Diameter: $6.5 \mu\text{m}$ at 1300 nm

Effective Step Index (ESI) Parameters

ESI Core Diameter: $5.8 \mu\text{m}$
ESI Δ : 0.65%
N.A.: 0.17

4.0 DISCUSSION AND FUTURE WORK

Design and fabrication of an evaluation sample of a reduced coating diameter single mode fiber is complete. This sample will be delivered to NRL for evaluation. Upon approval by NRL personnel, and additional 35 km of this fiber will be fabricated and delivered to NRL. Work will continue to develop fiber coatings with target coating thickness of $\sim 5 \mu\text{m}$.

Bimonthly Activity Report No. 9

Optical Fiber for Acoustic Sensor Applications

Prepared by
James R. Onstott
Principal Investigator

Prepared for the
Naval Research Laboratory
Contract No. N00014-89-C-2455

June, 1991

3M Fiber Optics Laboratory
3M Center
St. Paul, Minnesota 55144



APPENDIX

1.0 INTRODUCTION

This interim report summarizes the research and development efforts performed during the bimonthly reporting period of April 1991 - May 1991 by 3M on the development of optical fiber for acoustic sensor applications under Naval Research Laboratory (NRL) Contract Number N00014-89-C-2455.

2.0 PROGRAM OBJECTIVE

At the request of NRL, the overall objectives of this program have been modified from the development of acoustically sensitive and insensitive optical fiber to the development of long lengths of optical fiber with small diameter polymeric coatings.

3.0 PROGRAM ACTIVITIES

3.1 Task 1.0: Fiber Design

A fiber design previously developed during the performance of this contract under Phase I, Subtask 1.0 was used in this task. This design was a "matched clad" high numerical aperture structure which is suitable for use in both sensing and fused fiber coupler applications. In the previous reporting period, a sample of this fiber was delivered to NRL personnel for evaluation. Additional fiber fabrication activities await satisfactory tests results from NRL.

3.2 Task 2.1: 125 μm Fiber Coating Development

Technology required to apply single layer ultraviolet polymerizable coatings with a total diameter of $\sim 125 \mu\text{m}$ was developed during previous reporting periods. Additional fabrication activities await satisfactory tests results from NRL personnel.

3.3 Task 2.2: 100 μm Fiber Coating Fiber Development

Coating application technology to produce 10 μm thick ultraviolet polymerizable coatings on 80 μm diameter optical fiber has been acquired and is currently

APPENDIX

undergoing test and evaluation. Additional fabrication activities await satisfactory test results of the existing fiber from NRL personnel.

3.4 3.0: Fiber Drawing and Coating

New fiber drawing activities await satisfactory test results from NRL personnel.

3.5 Task 4.0: Physical and Optical Measurements

Toward the end of the current reporting period, test results of the macrobend performance of the fiber sample were received from Dr. Aileen Yurek at NRL. These results are reproduced in Figure 1, which shows the fiber loss in db/meter when 3 meters of the fiber sample were coiled around mandrels of various diameters. This data shows that the loss induced by macrobending is negligible for mandrel diameters > 1 cm.

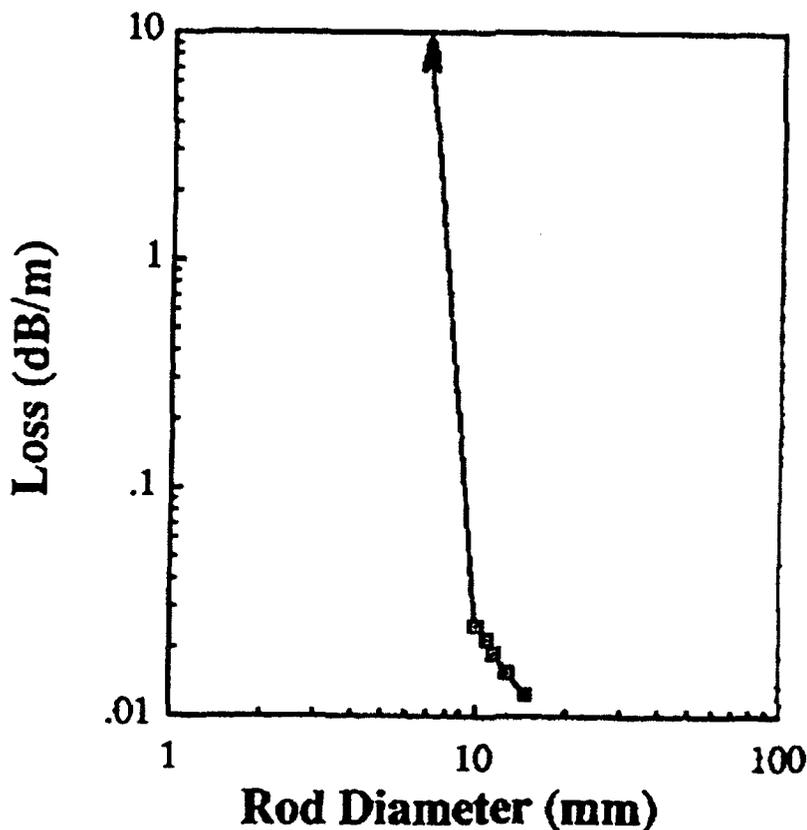


Figure 1
Fiber Bend Loss for 3M Single Mode Fiber

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4.0 DISCUSSION AND FUTURE WORK

Based on satisfactory experimental results of fiber macrobending performance shown in Figure 1 and verbal approval from Dr. Weller, activities to fabricate additional quantities of the fiber described in paragraph 3.1 (above) have begun. Completion and delivery to NRL of an additional 30 - 40 km of this fiber is anticipated in the next reporting period.

Bimonthly Activity Report No. 10

Optical Fiber for Acoustic Sensor Applications

Prepared by
James R. Onstott
Principal Investigator

Prepared for the
Naval Research Laboratory
Contract No. N00014-89-C-2455

August, 1991

3M Fiber Optics Laboratory
3M Center
St. Paul, Minnesota 55144



APPENDIX

1.0 INTRODUCTION

This interim report summarizes the research and development efforts performed during the bimonthly reporting period of June 1991 - July 1991 by 3M on the development of optical fiber for acoustic sensor applications under Naval Research Laboratory (NRL) Contract Number N00014-89-C-2455.

2.0 PROGRAM OBJECTIVE

At the request of NRL, the overall objectives of this program have been modified from the development of acoustically sensitive and insensitive optical fiber to the development of long lengths of optical fiber with small diameter polymeric coatings.

3.0 PROGRAM ACTIVITIES

3.1 Task 1.0: Fiber Design

A fiber design previously developed during the performance of this contract under Phase 1, Subtask 1.0, was used in this task. This design was a "matched clad" high numerical aperture structure which is suitable for use in both sensing and fused fiber coupler applications. Delivery of 5.6 km of this fiber during the current period is reported.

3.2 Task 2.1: 125 μm Fiber Coating Development

Technology required to apply single layer ultraviolet polymerizable coatings with a total diameter of $\sim 125 \mu\text{m}$ was developed during previous reporting periods. Deliverables described in this report have been coated to this diameter. Implications of this unusually thin coating on the mechanical strength of this fiber are reported in Sections 3.5. and 5.0.

APPENDIX

3.3 Task 2.2: 100 μm Fiber Coating Development

Coating application technology to produce 10 μm thick ultraviolet polymerizable coatings on 80 μm diameter optical fiber is currently undergoing test and evaluation.

3.4 Task 3.0: Fiber Drawing and Coating

Fiber was drawn to 80 μm and coated with a single coating of UV polymerizable acrylate material manufactured by Desoto, Inc. (coating #133). Measurement results for the fiber diameter and fiber coating diameter are reported in Section 3.5.

3.5 Task 4.0: Physical and Optical Measurements

3.5.1 FIBER ATTENUATION - Fiber attenuation versus wavelength is plotted in Figure 1 and listed in Table 1. Attenuation at the fiber operating wavelength of 1300 nm is <1.15 dB/km.

SPECTRAL ATTENUATION LENGTH: 1.1200 km
ID: 910617 SMNT D695 T+1620-2740M ON SHIP SPOOL

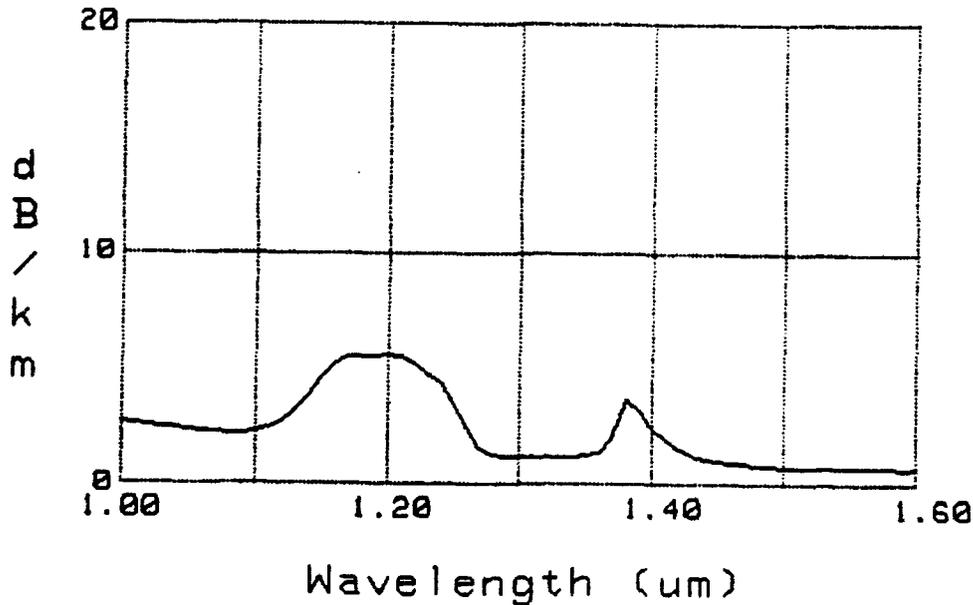


Figure 1
Attenuation versus Wavelength

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Table 1. Attenuation versus Wavelength

Spectral Attenuation

Fiber ID: 910617 SMNT D695 T+1620-2740M on ship spool 14-Aug-91 09:38:26

Length: 1.12 km

File: 4084

| Wavelength | Attenuation (dB/km) | Wavelength | Attenuation (dB/km) |
|------------|---------------------|------------|---------------------|
| 1000 | 2.68 | 1310 | 1.17 |
| 1010 | 2.62 | 1320 | 1.17 |
| 1020 | 2.54 | 1330 | 1.18 |
| 1030 | 2.48 | 1340 | 1.21 |
| 1040 | 2.41 | 1350 | 1.26 |
| 1050 | 2.35 | 1360 | 1.35 |
| 1060 | 2.29 | 1370 | 2.02 |
| 1070 | 2.23 | 1380 | 3.66 |
| 1080 | 2.21 | 1390 | 3.29 |
| 1090 | 2.22 | 1400 | 2.49 |
| 1100 | 2.30 | 1410 | 1.98 |
| 1110 | 2.42 | 1420 | 1.54 |
| 1120 | 2.69 | 1430 | 1.24 |
| 1130 | 3.16 | 1440 | 1.09 |
| 1140 | 3.80 | 1450 | 1.01 |
| 1150 | 4.53 | 1460 | 0.95 |
| 1160 | 5.12 | 1470 | 0.90 |
| 1170 | 5.46 | 1480 | 0.86 |
| 1180 | 5.52 | 1490 | 0.81 |
| 1190 | 5.52 | 1500 | 0.77 |
| 1200 | 5.56 | 1510 | 0.78 |
| 1210 | 5.52 | 1520 | 0.79 |
| 1220 | 5.26 | 1530 | 0.74 |
| 1230 | 4.78 | 1540 | 0.76 |
| 1240 | 4.44 | 1550 | 0.74 |
| 1250 | 3.55 | 1560 | 0.72 |
| 1260 | 2.44 | 1570 | 0.71 |
| 1270 | 1.57 | 1580 | 0.71 |
| 1280 | 1.26 | 1590 | 0.69 |
| 1290 | 1.22 | 1600 | 0.70 |
| 1300 | 1.17 | | |

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3.5.2 FIBER CUTOFF WAVELENGTH - Fiber cutoff wavelength is shown in Figure 2. Single mode operation is achieved for wavelengths beyond 1246 nm. For 1300 nm operation, this corresponds to an operating "V number" of ~2.3. Operation close to the cutoff wavelength ($V=2.4$) is necessary to achieve good macrobending performance.

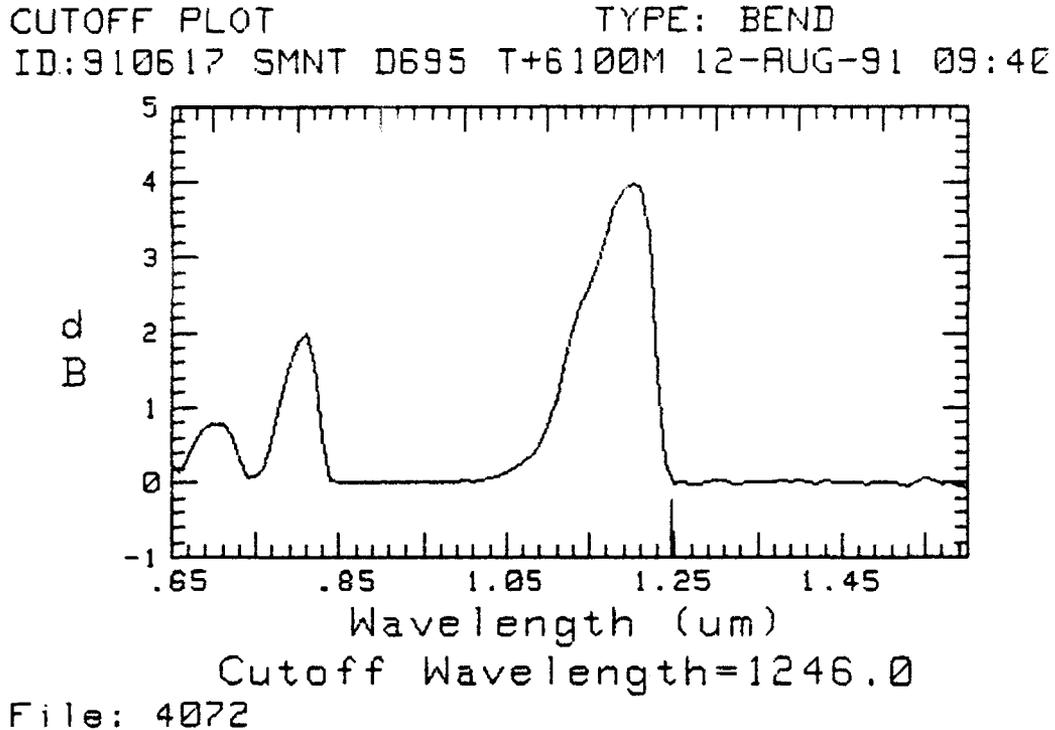
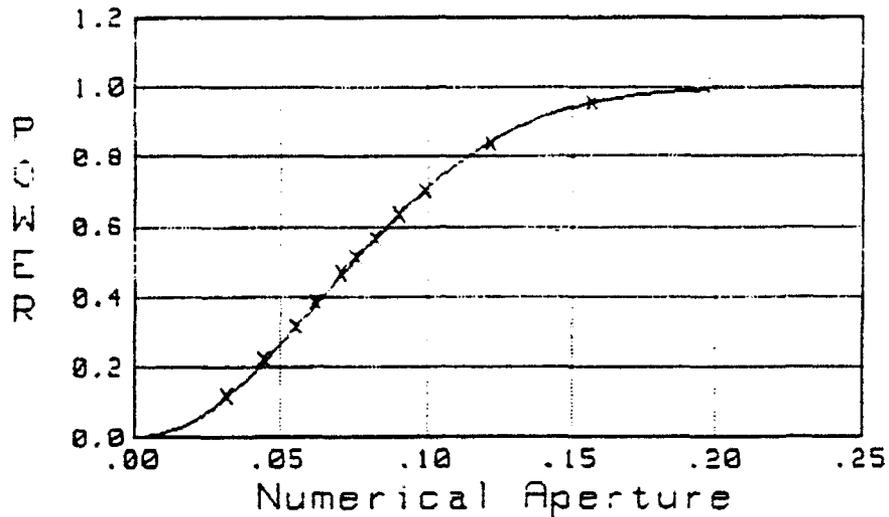


Figure 2
Fiber Cutoff Wavelength

3.5.3 FIBER MODE FIELD DIAMETER/ESI PARAMETERS - Fiber mode field diameter at 1300 nm design operating wavelength is shown in Figure 3. Calculated equivalent step index parameters (ESI) are shown in Table 2. The fiber numerical aperture of ~0.16 is required for good macrobending performance.

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VARIABLE APERTURE PATTERN AT 1300 nm
 ID: 910617 SMNT D695 T+6100M 12-AUG-91 10:2



MFD: Gaussian= 6.43

File: 4073

Petermann=6.53

Figure 3
Fiber Mode Field Diameter

Table 2. Fiber ESI Parameters

| | | |
|-------------------------|----------|----------------------|
| File: | 4073 | |
| Measurement Wavelength: | 1300 nm | |
| Cutoff Wavelength: | 1246 nm | |
| Conversion Factor: | 1.132 | |
| | Gaussian | Petermann |
| Spot Radius: | 3.2446 | 3.2632 μm |
| ESI Core Radius: | 2.8669 | 2.8834 μm |
| ESI Delta: | 0.0065 | 0.0064 |
| Nc-Ncl: | 0.0095 | 0.0094 |
| Numerical Aperture: | 0.1664 | 0.1654 |

3.5.4 FIBER MECHANICAL CHARACTERISTICS - Typical fiber geometry results are shown in Figures 4 and 5. These results show excellent core and cladding circularity and low core/cladding concentricity error ($<0.1 \mu\text{m}$). Fiber cladding diameter results are shown in Figures 6 and 7. Figure 6 shows a typical fiber diameter versus fiber length measurement taken during the fiber draw. The "start-up" transient at a draw length of ~ 100 meters is typical and is not included in the fiber delivered to NRL. Figure 7 shows the results of a statistical analysis of this fiber. Average diameter for the draw data shown in Figure 1 is $79.97 \mu\text{m}$ and standard deviation is $0.43 \mu\text{m}$.

APPENDIX

geometry

Drum Number:695

Fiber ID:910617 SMNT T+6100m

Length=0.0020 km

Time of Test:12-AUG-91 09:38:33

=====
clad: (101.18,77.40) diam=80.66 non_circ=0.008 (40.33,40.33) at 28.11
core: (101.49,77.71) diam=6.42 non_circ=1.233 (3.23, 3.19) at -68.60
Concentricity of clad to core=0.071 microns (-44.17 degrees)

Phase Plot of clad 12-AUG-91 09:38:33 Model: ELLIPSE

Fiber ID:910617 SMNT T+6100m

Drum Number:695

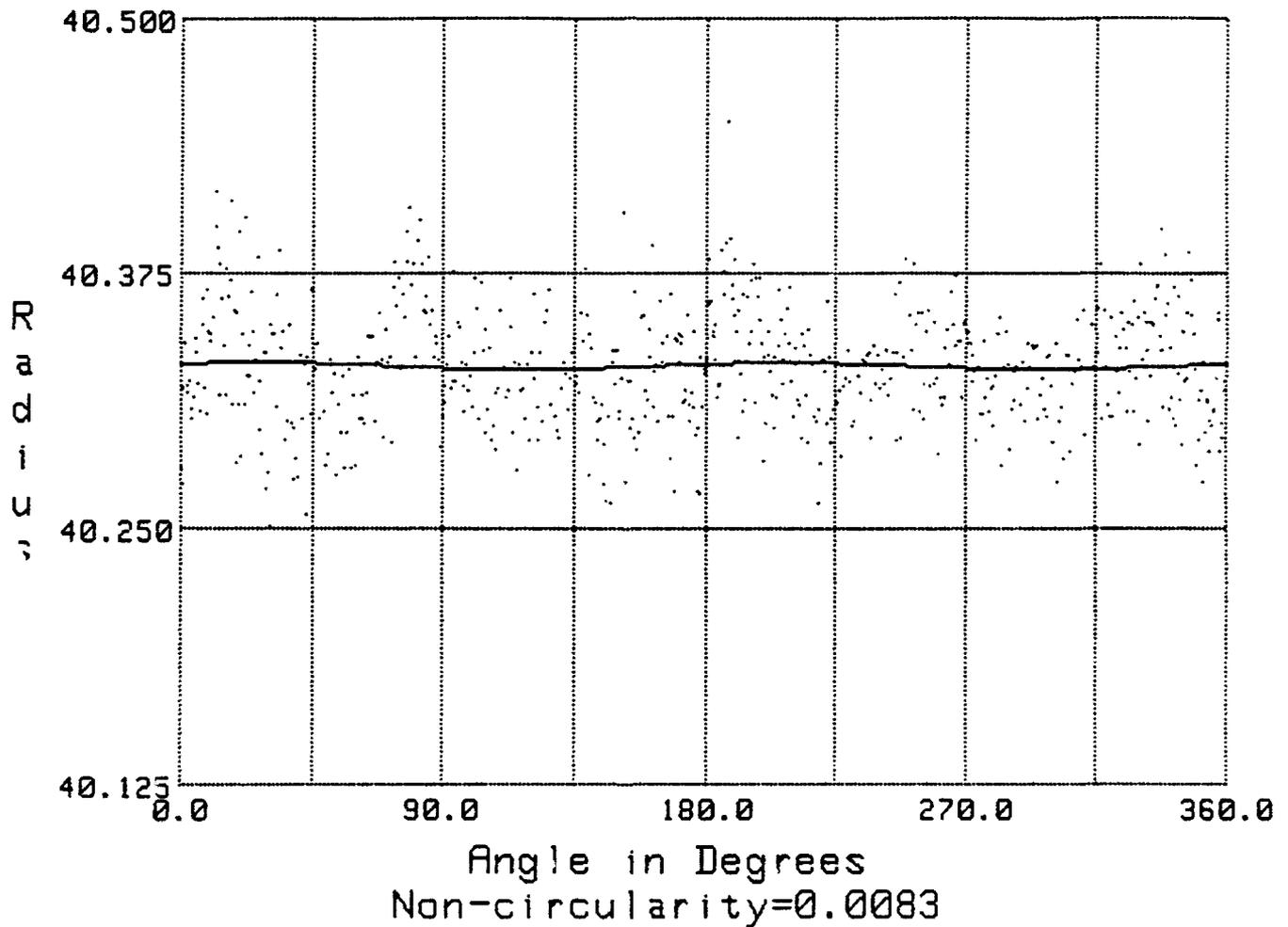
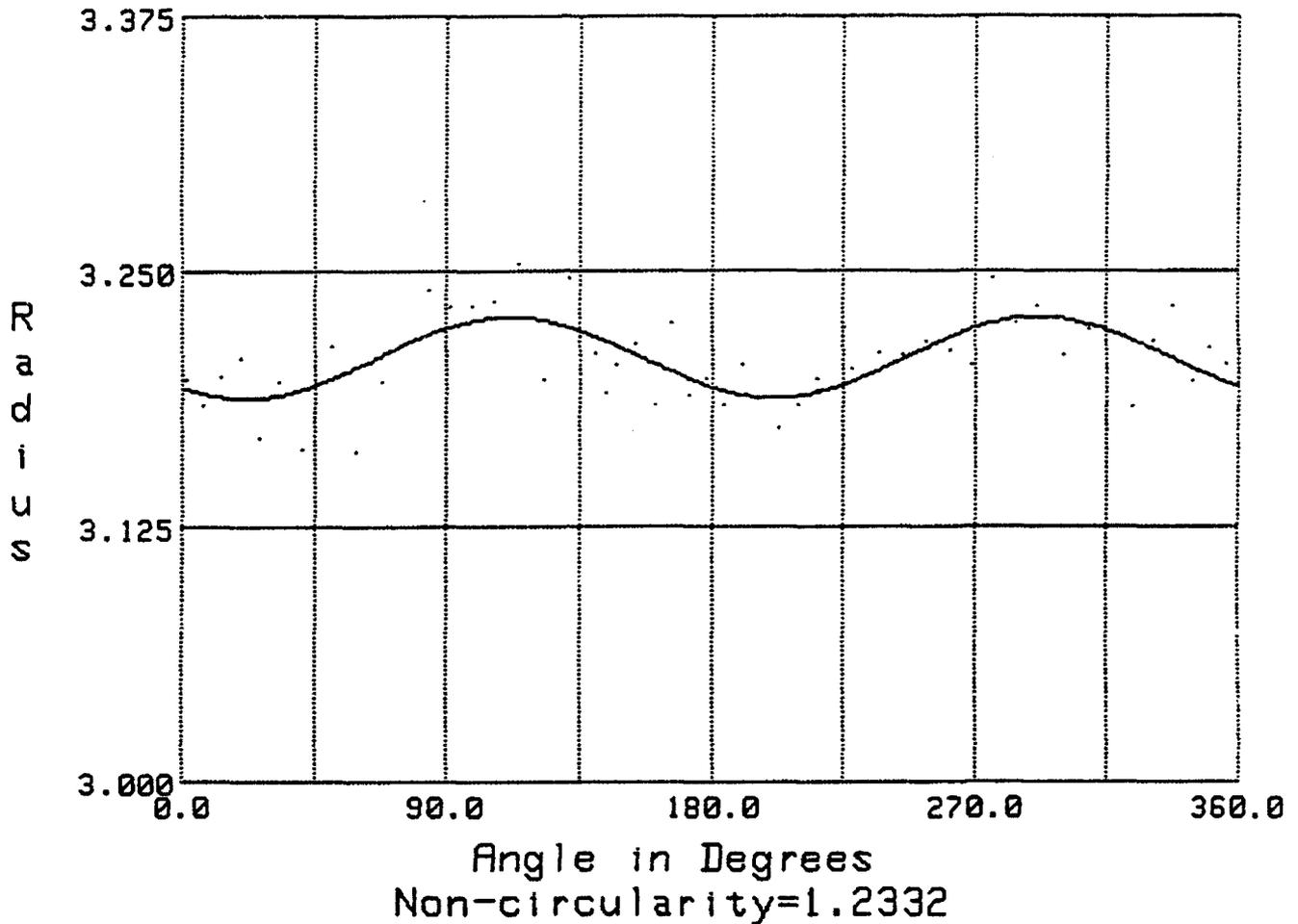


Figure 4
Fiber Geometry, Cladding Diameter, and Core/Clad Concentricity

APPENDIX

Phase Plot of core 12-AUG-91 09:38:33 Model: ELLIPSE
 Fiber ID:910617 SMNT T+6100m
 Drum Number:695



END ANGLE MEASUREMENT
 =====

Diameter used to compute=80.82

| angle | position | end angle |
|-------|----------|-----------|
| ===== | ===== | ===== |
| 0 | -0.1429 | -0.2025 |
| 45 | 0.1314 | 0.1863 |
| 90 | -0.0631 | -0.0895 |
| 135 | -0.3620 | -0.5132 |
| 180 | -0.7410 | -1.0505 * |
| 225 | -0.0246 | -0.0349 |
| 270 | 0.2483 | 0.3521 |
| 315 | 0.2128 | 0.3017 |

'*' - rejected orientation

Figure 5
Fiber Geometry, Core Non-circularity

APPENDIX

Variable Shewhart Control Charts
D695 G441 Acquired Data

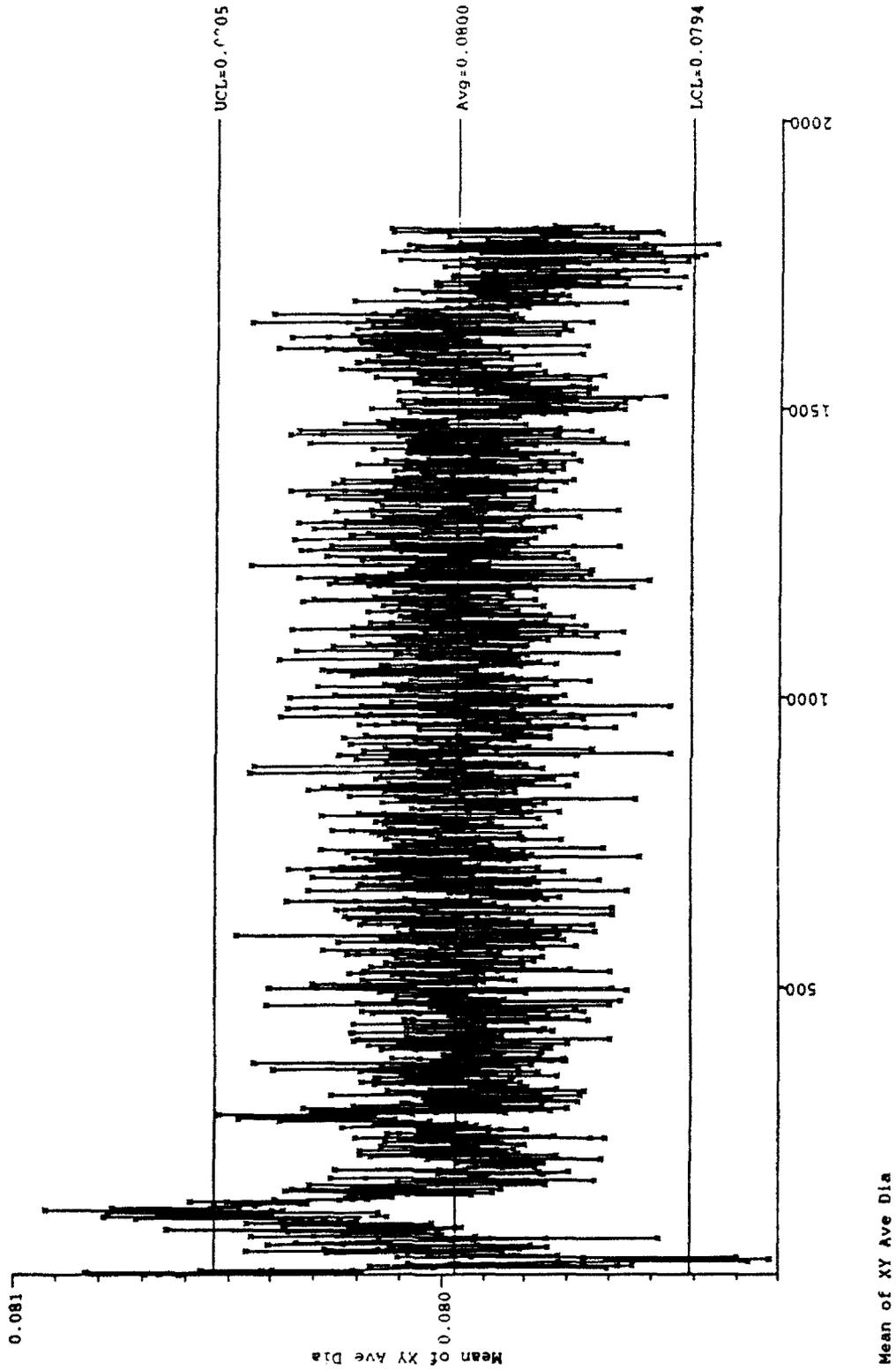


Figure 6
Fiber Diameter versus Fiber Length

APPENDIX

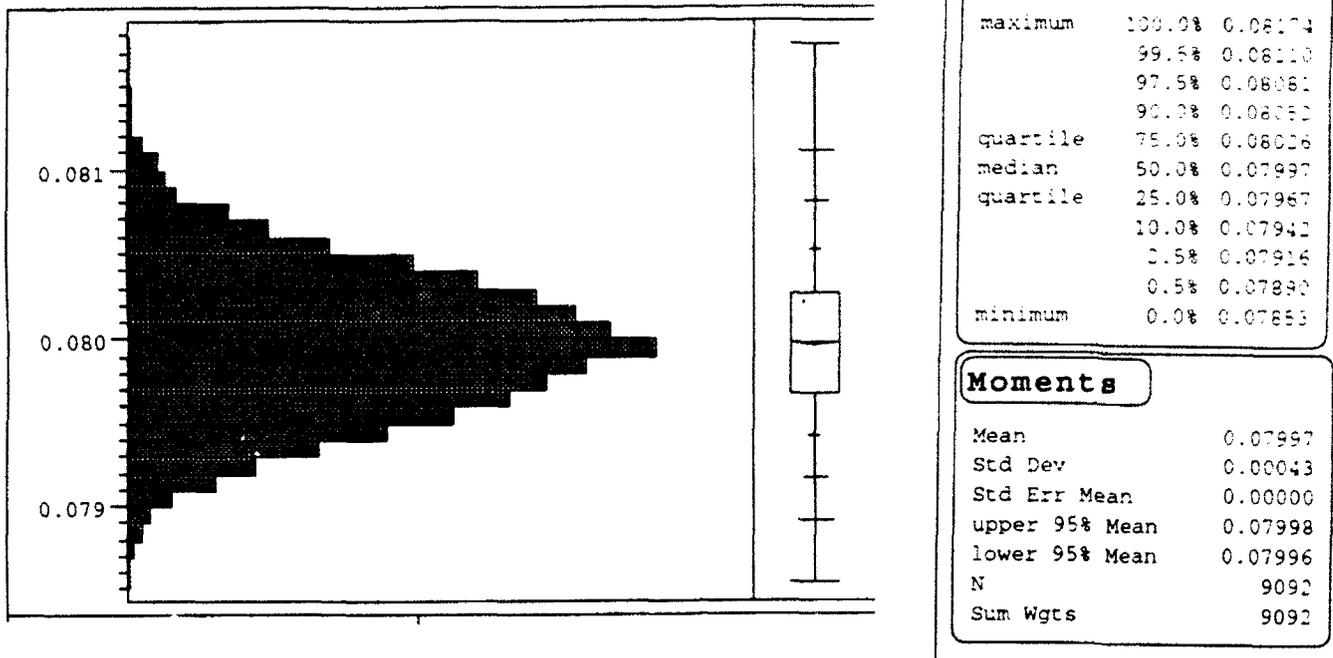


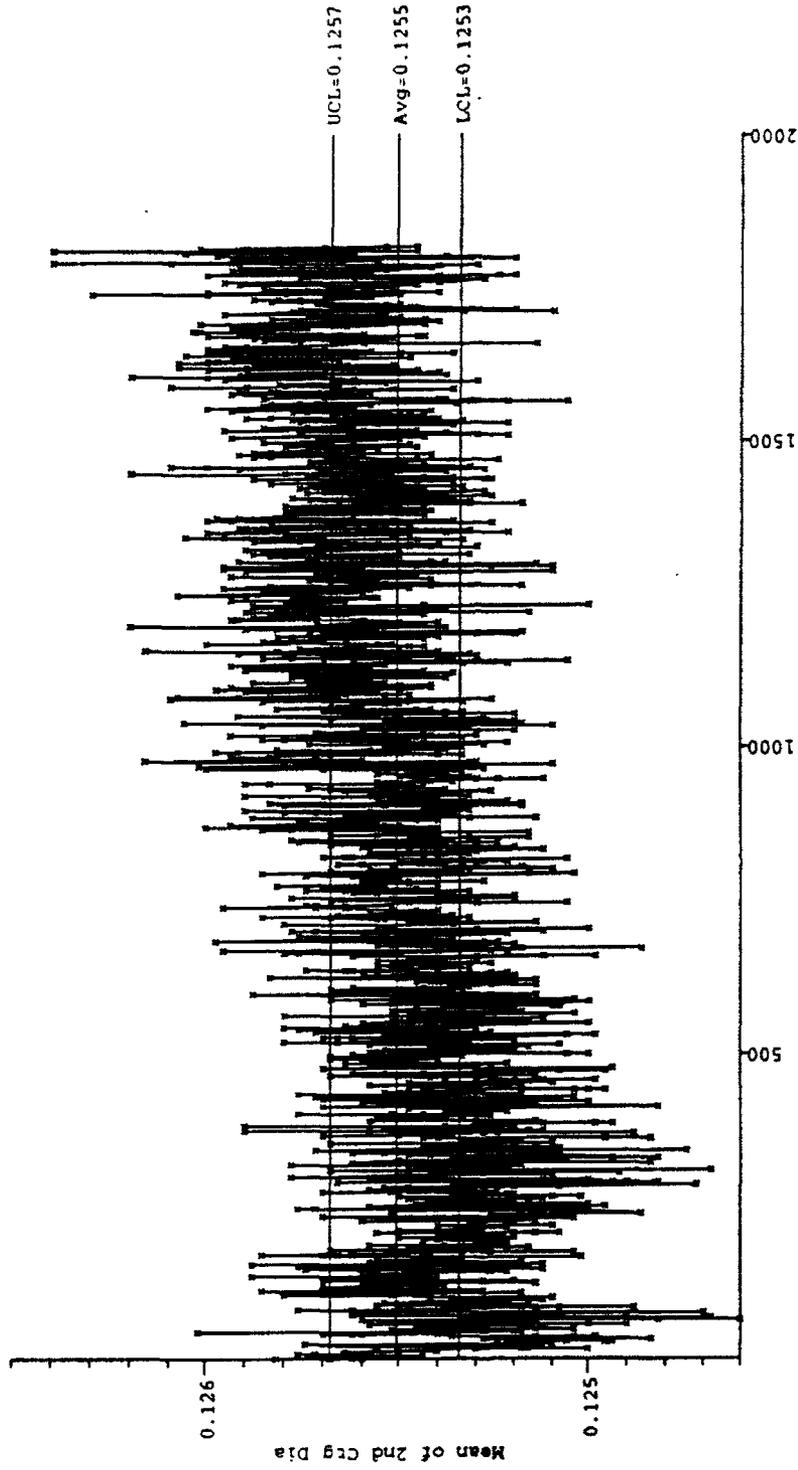
Figure 7
Fiber Diameter - Statistical Analysis

3.5.5 COATING CHARACTERISTICS - Coating diameter results are shown in Figures 8 and 9. Figure 8 shows a typical coating diameter versus fiber length measurement. This data show a slight trend toward an increase in fiber diameter at the beginning of the fiber draw; however, as shown in the statistical analysis (Figure 8), this effect is relatively small. Coating average diameter is 125.5 μm and standard deviation is 0.3 μm . Target coating diameter is 125.0 μm .

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Variable Shewhart Control Charts

D695 G441 Acquired Data



Mean of 2nd Ctg Dia

Note : Limits are based on 3 sigma.

Figure 8
Coating Diameter versus Fiber Length

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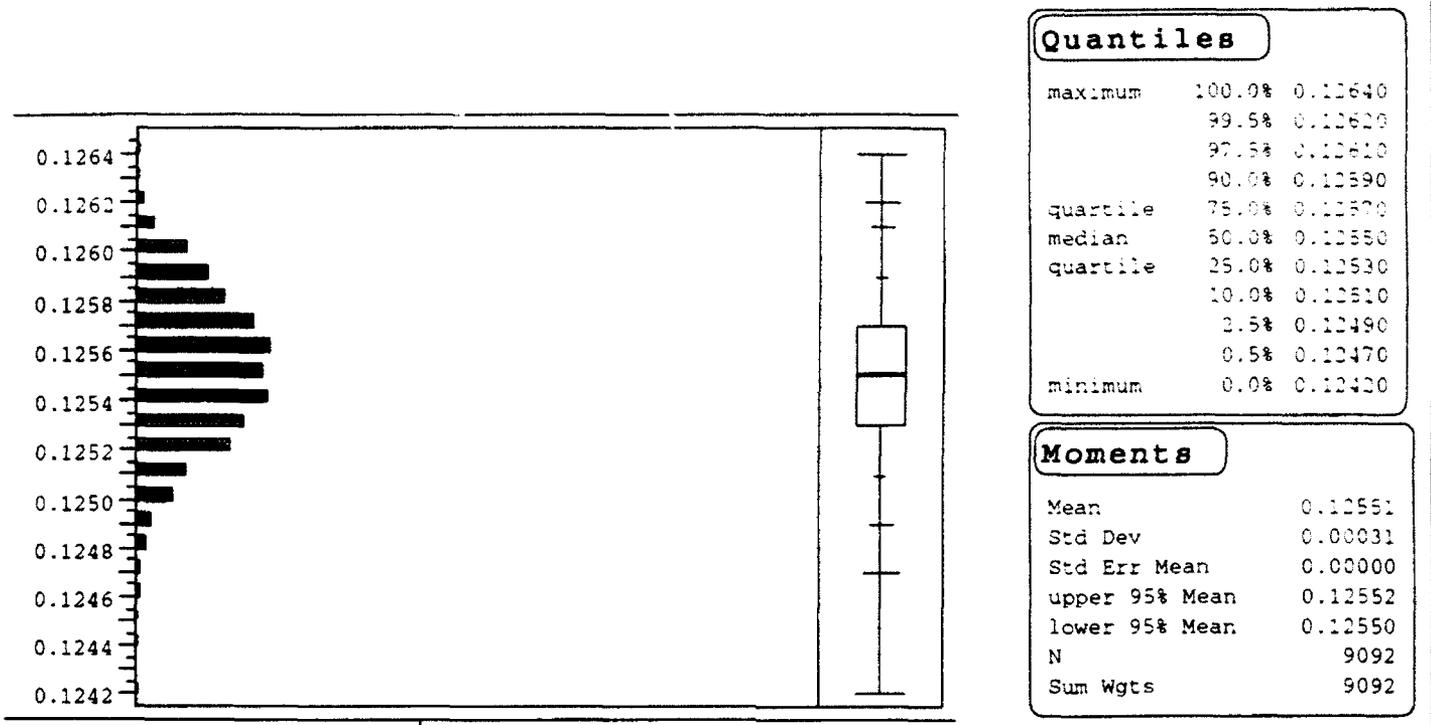


Figure 9
Coating Diameter - Statistical Analysis

3.5.6 FIBER STRENGTH CHARACTERISTICS - Figure 1 shows a typical Weibull strength plot for the fiber before prooftesting at 50 ksi. Strain rate for these measurements was 9%/minute and fiber gauge length was 3.9 meters. This plot shows a typical high strength distribution; however there is some evidence of a "low strength tail" in the distribution. This feature is attributed to the unusually thin fiber coating (see Section 4.0). Figure 11 shows a Weibull distribution for fiber after a 50 ksi prooftest. This result shows a significant increase in the number of low strength breaks in the fiber and is attributed to damage to the coating from the fiber prooftest procedure.

APPENDIX

DYNAMIC FATIGUE TEST #SM-695AT

PREFORM #910617SMNT

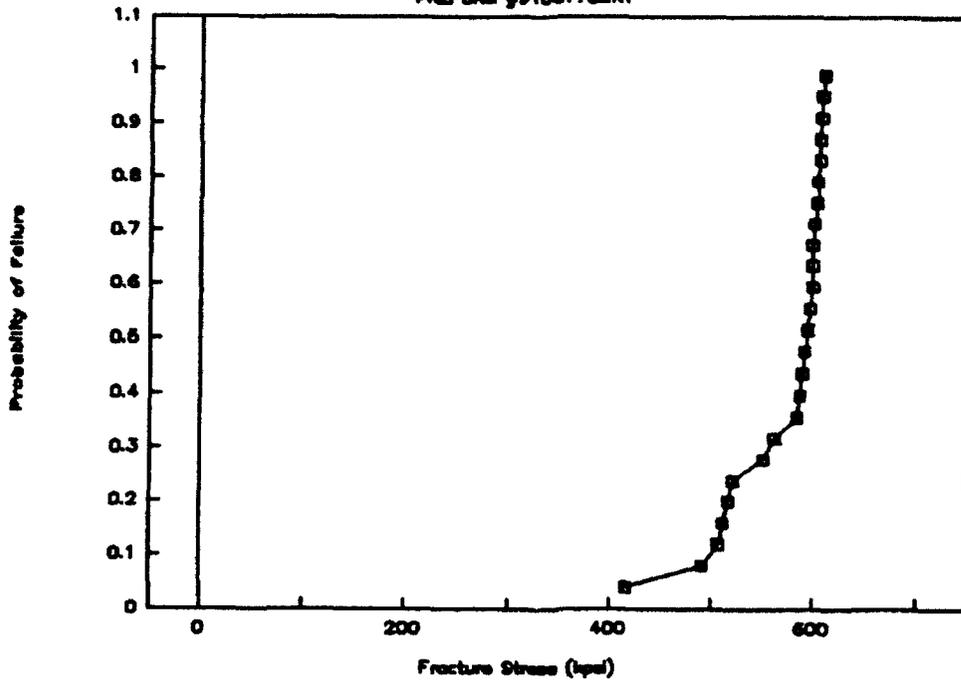


Figure 10

Dynamic Fatigue Test Results for Fiber Before 50 ksi Proof Test

DYNAMIC FATIGUE TEST #SM-695E

PREFORM #910617SMNT

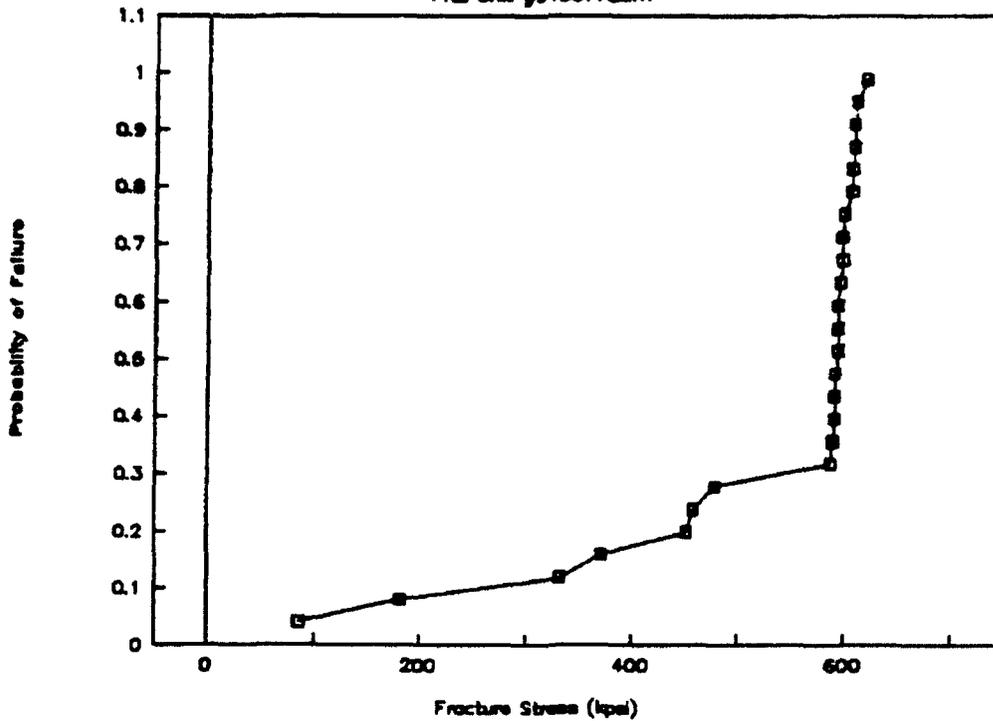


Figure 11

Dynamic Fatigue Test Results for Fiber After 50 ksi Proof Test

APPENDIX

4.0 DELIVERABLES

Five lengths of optical fiber with a total length 5.6 km is being delivered to NRL in this reporting period. A summary of the fiber identification codes is as follows:

| Spool # | Lot# | Fiber Length |
|---------|---------------------------|--------------|
| 1 | 910617 D695 T+500-T+1620 | 1105 m |
| 2 | 910617 D695 T+1620-T+2740 | 1120 m |
| 3 | 910617 D695 T+2740-T+3860 | 1120 m |
| 4 | 910617 D695 T+3860-T+4980 | 1120 m |
| 5 | 910617 D695 T+4980-T+6100 | 1120 m |

5.0 DISCUSSION AND FUTURE WORK

Target optical and mechanical specifications for the fiber were met. The studies of fiber mechanical strength, however, show that the unusually thin coating on the fiber is subject to damage during normal handling of the fiber. Improvement in the strength of the fiber should be realized by application of a harder coating. We will consult with NRL personnel concerning fiber strength/coating issues before any additional fiber draw/coating runs are made.

One draw additional coating run has been completed. This fiber is currently undergoing measurement and analysis. Delivery to NRL is anticipated for mid-August. Due to the unexpected issue of fiber strength, completion of this contract by October 1 will be difficult. A three-month extension may be required to complete the fabrication and delivery of the remaining ~30 km of fiber

Bimonthly Activity Report No. 11

Optical Fiber for Acoustic Sensor Applications

Prepared by
James R. Onstott
Principal Investigator

Prepared for the
Naval Research Laboratory
Contract No. N00014-89-C-2455

October, 1991

3M Fiber Optics Laboratory
3M Center
St. Paul, Minnesota 55144



APPENDIX

1.0 INTRODUCTION

This interim report summarizes the research and development efforts performed during the bimonthly reporting period of August 1991 - September 1991 by 3M on the development of optical fiber for acoustic sensor applications under Naval Research Laboratory (NRL) Contract Number N00014-89-C-2455.

2.0 PROGRAM OBJECTIVE

At the request of NRL, the overall objectives of this program have been modified from the development of acoustically sensitive and insensitive optical fiber to the development of long lengths of optical fiber with small diameter polymeric coatings.

3.0 PROGRAM ACTIVITIES

3.1 Task 1.0: Fiber Design

A fiber design previously developed during the performance of this contract under Phase 1, Subtask 1.0, was used in this task. This design was a "matched clad" high numerical aperture structure which is suitable for use in both sensing and fused fiber coupler applications. Delivery of 6.65 km of this fiber during the current period is reported.

3.2 Task 2.1: 125 μm Fiber Coating Development

Technology required to apply single layer ultraviolet polymerizable coatings with a total diameter of $\sim 125 \mu\text{m}$ was developed during previous reporting periods. Deliverables described in this report have been coated to this diameter. Implications of this unusually thin coating on the mechanical strength of this fiber were reported in the previous (June-July) bimonthly activity report.

APPENDIX

3.3 Task 2.2: 100 μm Fiber Coating Development

Coating application technology to produce 10 μm thick ultraviolet polymerizable coatings on 80 μm diameter optical fiber has been acquired and is currently undergoing test and evaluation.

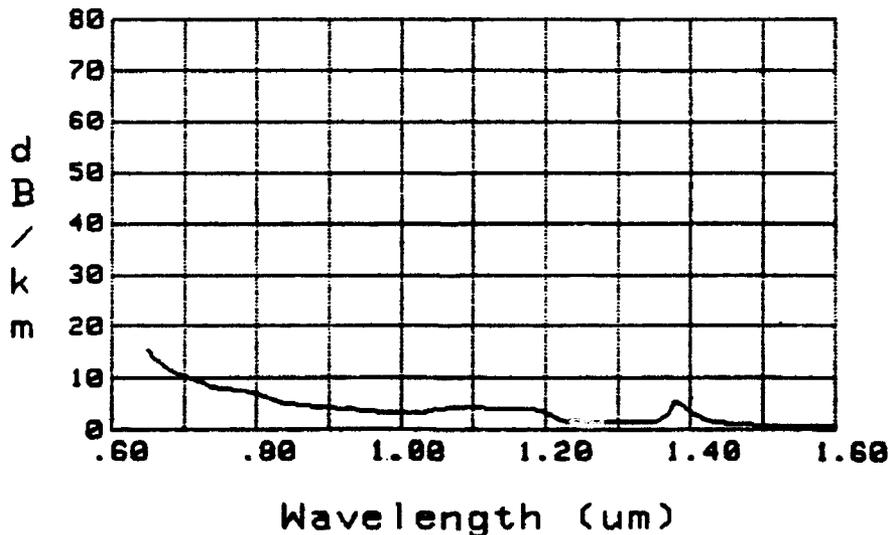
3.4 Task 3.0: Fiber Drawing and Coating

Fiber was drawn to 80 μm and coated with a single coating of UV polymerizable acrylate material manufactured by Desoto, Inc. (coating #133). Measurement results for the fiber diameter and fiber coating diameter are reported in Section 3.5.

3.5 Task 4.0: Physical and Optical Measurements

3.5.1 FIBER ATTENUATION - Fiber attenuation versus wavelength is plotted in Figure 1 and listed in Table 1. Attenuation at the fiber operating wavelength of 1300 nm is <1.5 dB/km.

SPECTRAL ATTENUATION LENGTH: 2.0540 km
ID: 910603 SMTN D678 T+5807-T+7861 ON SHIP SPOC



File: 4158

Figure 1
Fiber Attenuation versus Wavelength

APPENDIX

Table 1. Fiber Attenuation versus Wavelength

Spectral Attenuation

Fiber ID: 910603 SMTN D678 T+5807-T+7861 ON SHIP SPOOL 5-Sep-91 90:27:22

Length: 2.054 km

File: 4158

| Wavelength | Attenuation (dB/km) | Wavelength | Attenuation (dB/km) |
|------------|---------------------|------------|---------------------|
| 650 | 15.42 | 1130 | 4.16 |
| 660 | 13.78 | 1140 | 4.14 |
| 670 | 12.49 | 1150 | 4.11 |
| 680 | 11.72 | 1160 | 4.09 |
| 690 | 10.98 | 1170 | 4.03 |
| 700 | 10.47 | 1180 | 3.91 |
| 710 | 9.89 | 1190 | 3.63 |
| 720 | 9.24 | 1200 | 3.36 |
| 730 | 8.69 | 1210 | 2.64 |
| 740 | 8.34 | 1220 | 1.80 |
| 750 | 8.12 | 1230 | 1.63 |
| 760 | 7.93 | 1240 | 1.73 |
| 770 | 7.71 | 1250 | 1.72 |
| 780 | 7.51 | 1260 | 1.59 |
| 790 | 7.32 | 1270 | 1.51 |
| 800 | 7.06 | 1280 | 1.45 |
| 810 | 6.63 | 1290 | 1.42 |
| 820 | 5.86 | 1300 | 1.39 |
| 830 | 5.45 | 1310 | 1.38 |
| 840 | 5.22 | 1320 | 1.40 |
| 850 | 5.03 | 1330 | 1.46 |
| 860 | 4.86 | 1340 | 1.54 |
| 870 | 4.70 | 1350 | 1.63 |
| 880 | 4.52 | 1360 | 1.78 |
| 890 | 4.37 | 1370 | 2.99 |
| 900 | 4.23 | 1380 | 5.51 |
| 910 | 4.10 | 1390 | 4.74 |
| 920 | 3.98 | 1400 | 3.45 |
| 930 | 3.87 | 1410 | 2.75 |
| 940 | 3.82 | 1420 | 2.07 |
| 950 | 3.68 | 1430 | 1.66 |
| 960 | 3.54 | 1440 | 1.41 |
| 970 | 3.42 | 1450 | 1.27 |
| 980 | 3.31 | 1460 | 1.18 |
| 990 | 3.24 | 1470 | 1.08 |
| 1000 | 3.20 | 1480 | 1.04 |
| 1010 | 3.20 | 1490 | .99 |
| 1020 | 3.27 | 1500 | .95 |
| 1030 | 3.39 | 1510 | .95 |
| 1040 | 3.63 | 1520 | .89 |
| 1050 | 3.93 | 1530 | .89 |
| 1060 | 4.21 | 1540 | .87 |
| 1070 | 4.35 | 1550 | .88 |
| 1080 | 4.36 | 1560 | .85 |
| 1090 | 4.32 | 1570 | .87 |
| 1100 | 4.28 | 1580 | .88 |
| 1110 | 4.24 | 1590 | .89 |
| 1120 | 4.19 | 1600 | .89 |

APPENDIX

3.5.2 FIBER CUTOFF WAVELENGTH - Fiber cutoff wavelength is shown in Figure 2. Single mode operation is achieved for wavelengths beyond 1280 nm. For 1310 nm operation, this corresponds to an operating "V number" of ~2.3. Operation close to the cutoff wavelength ($V=2.4$) is necessary to achieve good macrobending performance.

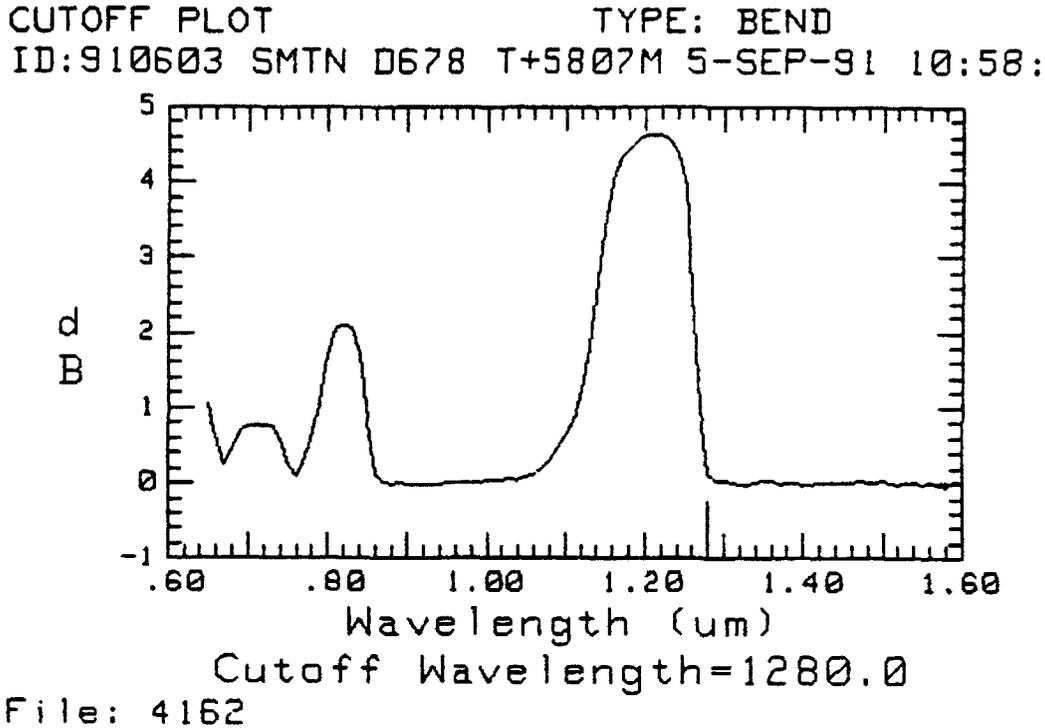
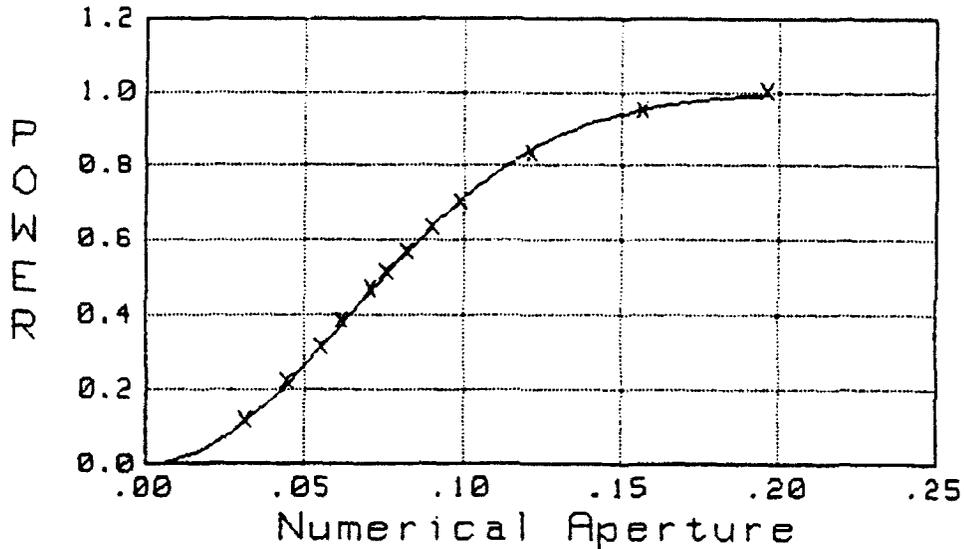


Figure 2
Fiber Cutoff Wavelength

3.5.3 FIBER MODE FIELD DIAMETER/ESI PARAMETERS - Fiber mode field diameter at 1300 nm design operating wavelength is shown in Figure 3. Calculated equivalent step index parameters (ESI) are shown in Table 2. The fiber numerical aperture of ~0.16 is required for good macrobending performance.

APPENDIX

VARIABLE APERTURE PATTERN AT 1320 nm
 ID: 910603 SMTN D678 T+5807M 5-SEP-91 11:58



MFD: Gaussian= 6.58

Petermann=6.63

File: 4163

Figure 3
Fiber Mode Field Diameter

Table 2. Fiber ESI Parameters

| | |
|-------------------------|---------|
| File: | 4163 |
| Measurement Wavelength: | 1320 nm |
| Cutoff Wavelength: | 1280 nm |
| Conversion Factor: | 1.122 |

| | Gaussian | Petermann |
|---------------------|----------|----------------------|
| Spot Radius: | 3.2918 | 3.3132 μm |
| ESI Core Radius: | 2.9327 | 2.9518 μm |
| ESI Delta: | 0.0066 | 0.0065 |
| Nc-Ncl: | 0.0096 | 0.0094 |
| Numerical Aperture: | 0.1671 | 0.1660 |

3.5.4 FIBER MECHANICAL CHARACTERISTICS - Typical fiber geometry results are shown in Figures 4 and 5. These results show excellent core and cladding circularity and low core/cladding concentricity error (<0.1 μm). The fiber was coated with a 125 μm OD single acrylate material.

APPENDIX

geometry
Drum Number:678
Fiber ID:910603 SMTN T+5807m
Length=0.0020 km
Time of Test: 5-SEP-91 11:19:31

clad: (101.56,77.86) diam=81.30 non_circ=0.067 (40.67,40.64) at -16.25
core: (101.76,78.17) diam=6.89 non_circ=1.916 (3.48, 3.41) at -31.15
Concentricity of clad to core=0.079 microns (-138.07 degrees)

Phase Plot of clad 5-SEP-91 11:19:31 Model: ELLIPSE
Fiber ID:910603 SMTN T+5807m
Drum Number:678

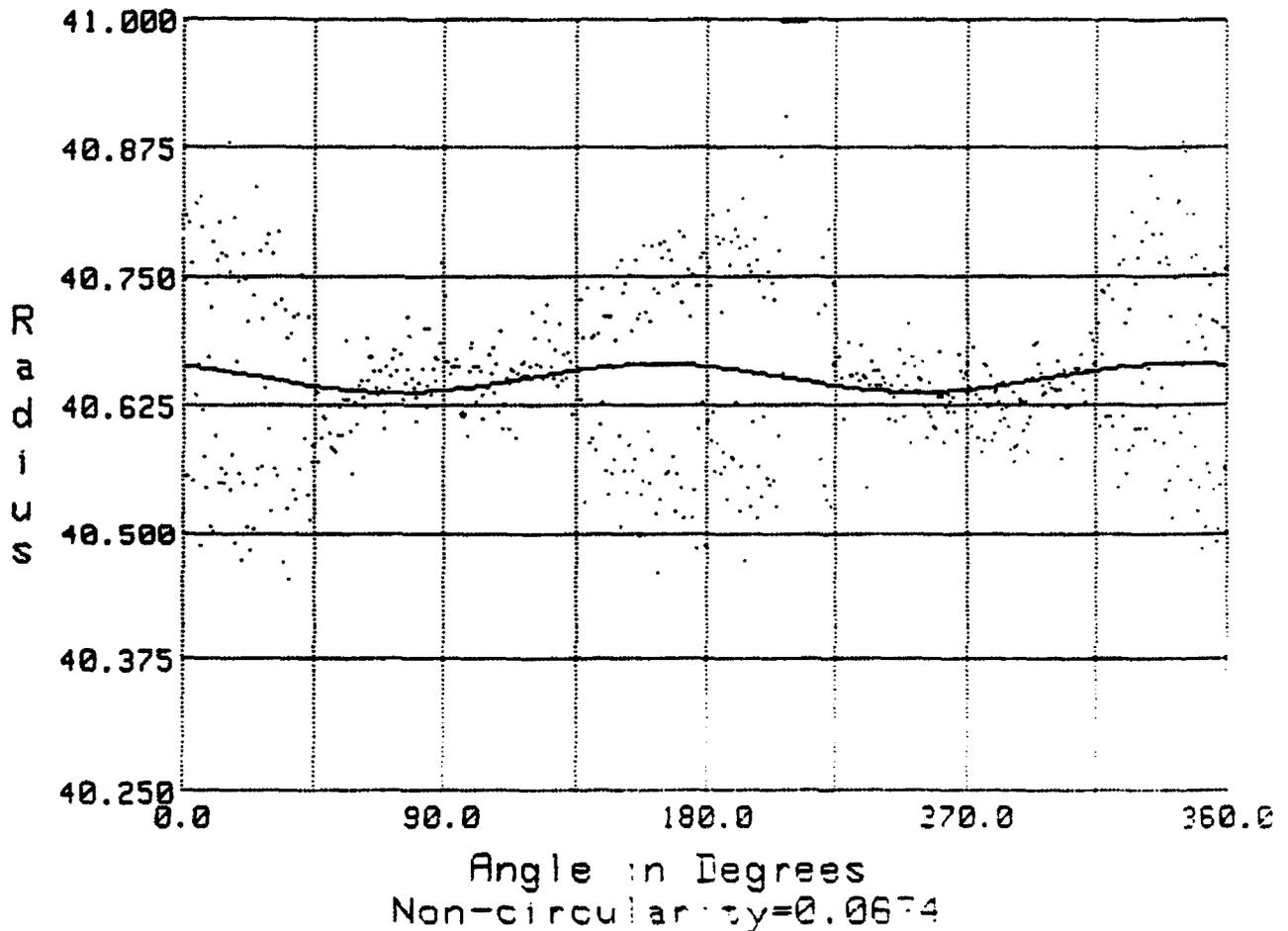
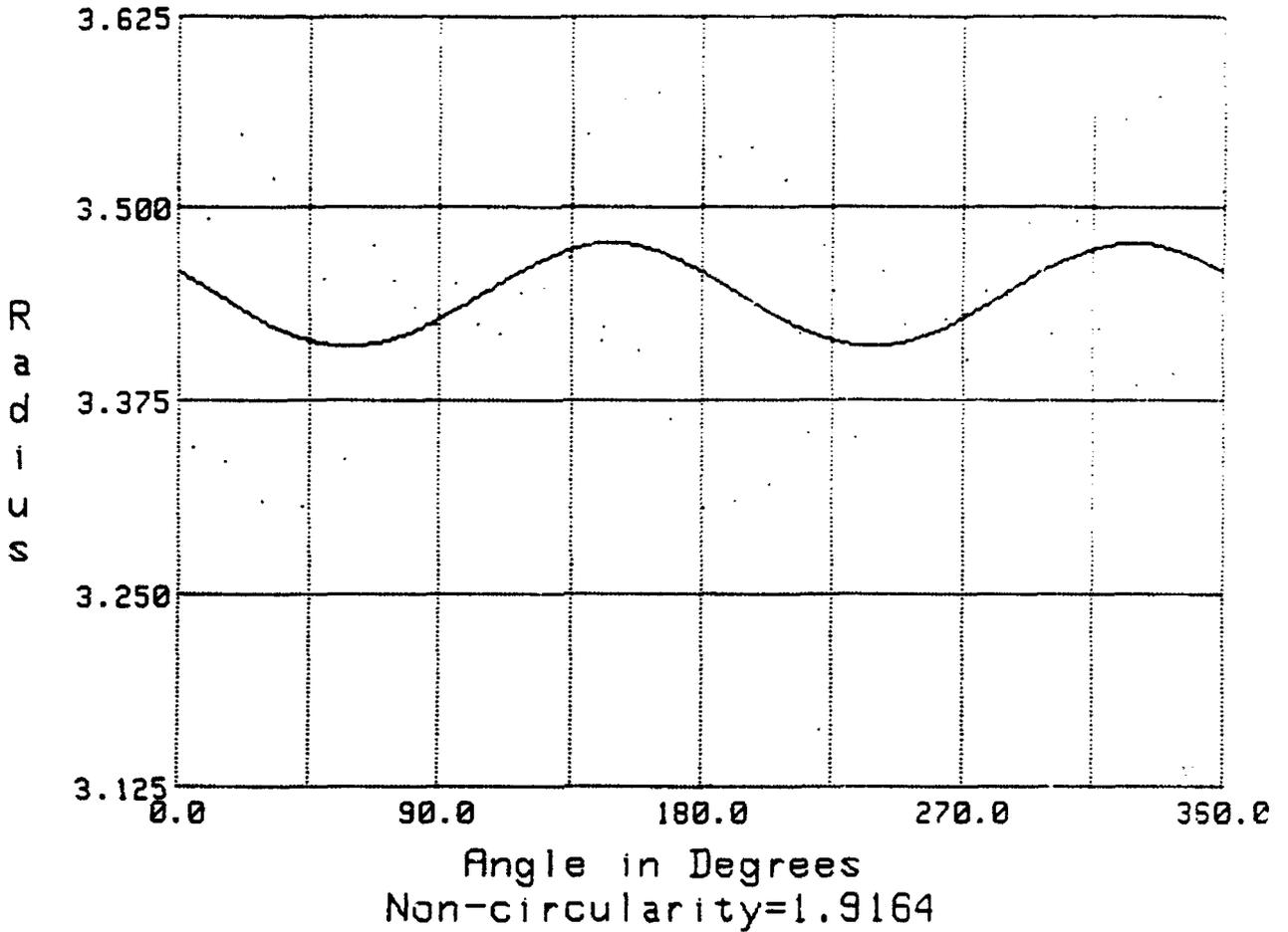


Figure 4
Fiber Geometry Report

APPENDIX

Phase Plot of core 5-SEP-91 11:19:31 Model: ELLIPSE
 Fiber ID:910603 SMTN T+5007m
 Drum Number:678



END ANGLE MEASUREMENT
 =====

Diameter used to compute=01.36

| angle | position | end angle |
|-------|----------|-----------|
| ===== | ===== | ===== |
| 0 | -0.2766 | -0.3896 |
| 45 | -0.2150 | -0.3028 |
| 90 | 0.0158 | 1.1489 * |
| 135 | 0.4894 | 0.6893 |
| 180 | 0.1753 | 0.2470 |
| 225 | 0.2032 | 0.2863 |
| 270 | -0.0456 | -0.0642 |
| 315 | -0.3308 | -0.4659 |

* - rejected orientation

Figure 5
Fiber Geometry Report

APPENDIX

4.0 DELIVERABLES

Three lengths of optical fiber with a total length 6.65 km has been delivered to NRL in this reporting period. A summary of the fiber identification codes is shown below.

| <u>Spool #</u> | <u>Lot#</u> | <u>Fiber Length</u> |
|----------------|---------------------------|---------------------|
| 1 | 910603 D678 T+1207-T+3507 | 2300 m |
| 2 | 910603 D678 T+3507-T+5807 | 2300 m |
| 3 | 910603 D678 T+5807-T+7861 | 2050 m |

5.0 DISCUSSION AND FUTURE WORK

Target optical and mechanical specifications for the fiber were met. Previously reported studies of fiber mechanical strength, however, show that the unusually thin coating on the fiber is subject to damage during normal handling of the fiber. We have consulted with NRL personnel and with their concurrence we will apply a harder acrylate coating formulation in future fiber draw/coating runs in an attempt to improve fiber strength.

Bimonthly Activity Report No. 12

Optical Fiber for Acoustic Sensor Applications

Prepared by
James R. Onstott
Principal Investigator

Prepared for the
Naval Research Laboratory
Contract No. N00014-89-C-2455

January, 1992

3M Fiber Optics Laboratory
3M Center
St. Paul, Minnesota 55144



APPENDIX

1.0 INTRODUCTION

This interim report summarizes the research and development efforts performed during the bimonthly reporting period of October 1991 - November 1991 by 3M on the development of optical fiber for acoustic sensor applications under Naval Research Laboratory (NRL) Contract Number N00014-89-C-2455.

2.0 PROGRAM OBJECTIVE

At the request of NRL, the overall objectives of this program have been modified from the development of acoustically sensitive and insensitive optical fiber to the development of long lengths of optical fiber with small diameter polymeric coatings.

3.0 PROGRAM ACTIVITIES

3.1 Task 1.0: Fiber Design

A fiber design previously developed during the performance of this contract under Phase 1, Subtask 1.0, was used in this task. This design was a "matched clad" high numerical aperture structure which is suitable for use in both sensing and fused fiber coupler applications. Delivery of 3.0 km of this fiber during the current period is reported.

3.2 Task 2.1: 125 μm Fiber Coating Development

Technology required to apply single layer ultraviolet polymerizable coatings with a total diameter of $\sim 125 \mu\text{m}$ was developed during previous reporting periods. Deliverables described in this report have been coated to this diameter.

Previous reports have discussed the poor mechanical strength of fibers with very thin coatings. These results are attributed to damage during normal handling of the fiber due to the thin coatings. Progress in the development of thin, high strength coatings is reported in Section 3.5.5.

APPENDIX

3.3 Task 2.2: 100 μm Fiber Coating Development

Coating application technology to produce 10 μm thick ultraviolet polymerizable coatings on 80 μm diameter optical fiber has been acquired and is currently undergoing test and evaluation. It is expected that samples will be supplied to NRL for evaluation in the next reporting period.

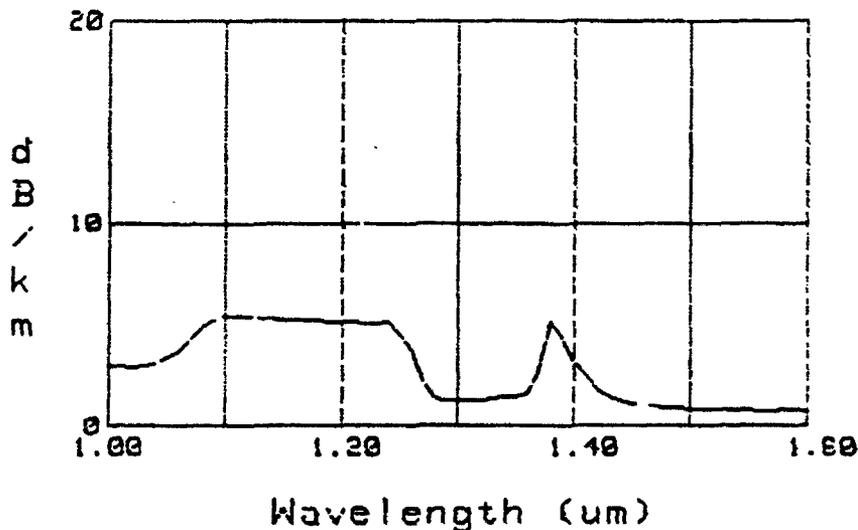
3.4 Task 3.0: Fiber Drawing and Coating

Fiber was drawn to 80 μm and coated with a single coating of UV polymerizable acrylate material manufactured by Desoto, Inc. (Coating #103). This material is normally used as a "hard" secondary buffer coating in optical fiber applications. Previous fibers delivered have been coated with a "softer" UV polymerizable acrylate (Desoto #133).

3.5 Task 4.0: Physical and Optical Measurements

3.5.1 FIBER ATTENUATION - Fiber attenuation versus wavelength is plotted in Figure 1 and listed in Table 1. Attenuation at the fiber operating wavelength of 1320 nm is <1.5 dB/km.

SPECTRAL ATTENUATION LENGTH: 1.2810 km
ID: 910909 SMTN, D742, T+1901-T+3182 30-DEC-91



File: 4428

Figure 1
Fiber Attenuation versus Wavelength

APPENDIX

Table 1. Fiber Attenuation versus Wavelength

Spectral Attenuation

Fiber ID: 910909 SMTN, D742, T+1901-T+3162 30-Dec-91 14:17:39

Length: 1.281 km

File: 4428

| Wavelength | Attenuation (dB/km) | Wavelength | Attenuation (dB/km) |
|------------|---------------------|------------|---------------------|
| 1000 | 2.98 | 1300 | 1.30 |
| 1010 | 2.94 | 1310 | 1.30 |
| 1020 | 2.93 | 1320 | 1.30 |
| 1030 | 2.98 | 1330 | 1.34 |
| 1040 | 3.10 | 1340 | 1.43 |
| 1050 | 3.33 | 1350 | 1.50 |
| 1060 | 3.72 | 1360 | 1.66 |
| 1070 | 4.26 | 1370 | 2.79 |
| 1080 | 4.84 | 1380 | 5.12 |
| 1090 | 5.25 | 1390 | 4.28 |
| 1100 | 5.40 | 1400 | 3.19 |
| 1110 | 5.38 | 1410 | 2.46 |
| 1120 | 5.37 | 1420 | 1.85 |
| 1130 | 5.35 | 1430 | 1.49 |
| 1140 | 5.30 | 1440 | 1.26 |
| 1150 | 5.26 | 1450 | 1.14 |
| 1160 | 5.24 | 1460 | 1.04 |
| 1170 | 5.22 | 1470 | .98 |
| 1180 | 5.20 | 1480 | .93 |
| 1190 | 5.16 | 1490 | .89 |
| 1200 | 5.13 | 1500 | .87 |
| 1210 | 5.11 | 1510 | .81 |
| 1220 | 5.08 | 1520 | .81 |
| 1230 | 5.06 | 1530 | .81 |
| 1240 | 5.09 | 1540 | .80 |
| 1250 | 4.50 | 1550 | .82 |
| 1260 | 3.73 | 1560 | .76 |
| 1270 | 2.19 | 1570 | .76 |
| 1280 | 1.37 | 1580 | .80 |
| 1290 | 1.32 | 1590 | .80 |
| | | 1600 | .76 |

APPENDIX

3.5.2 FIBER CUTOFF WAVELENGTH - Fiber cutoff wavelength is shown in Figure 2. Single mode operation is achieved for wavelengths beyond 1300 nm. For 1310 nm operation, this corresponds to an operating "V number" of ~2.35. Operation close to the cutoff wavelength ($V=2.4$) is necessary to achieve good macrobending performance.

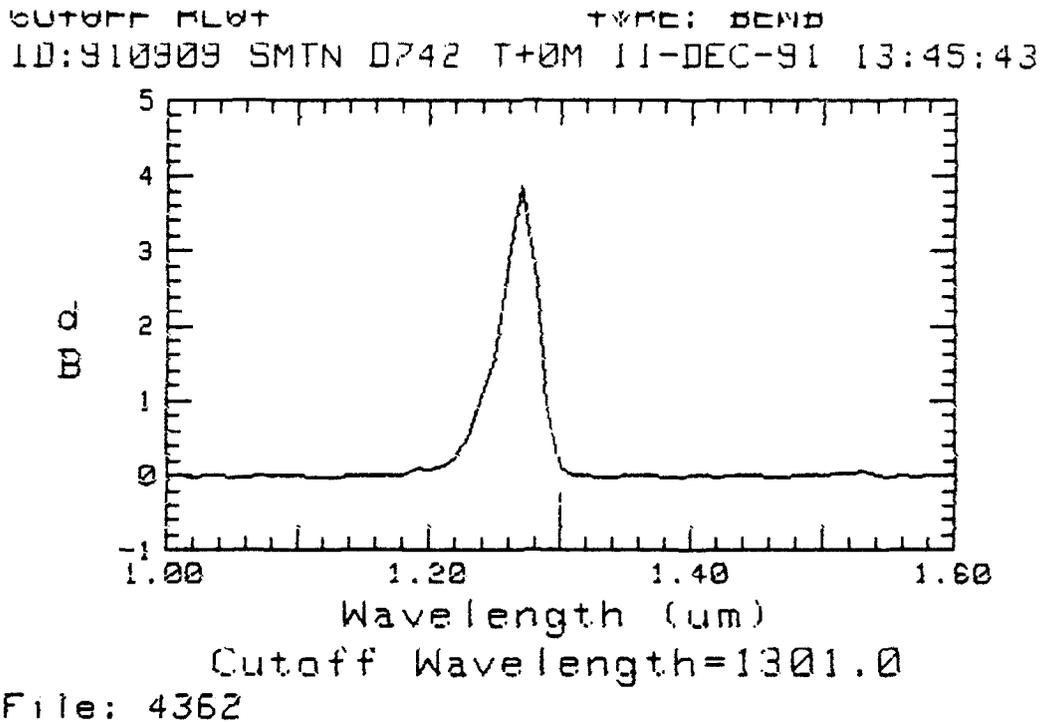
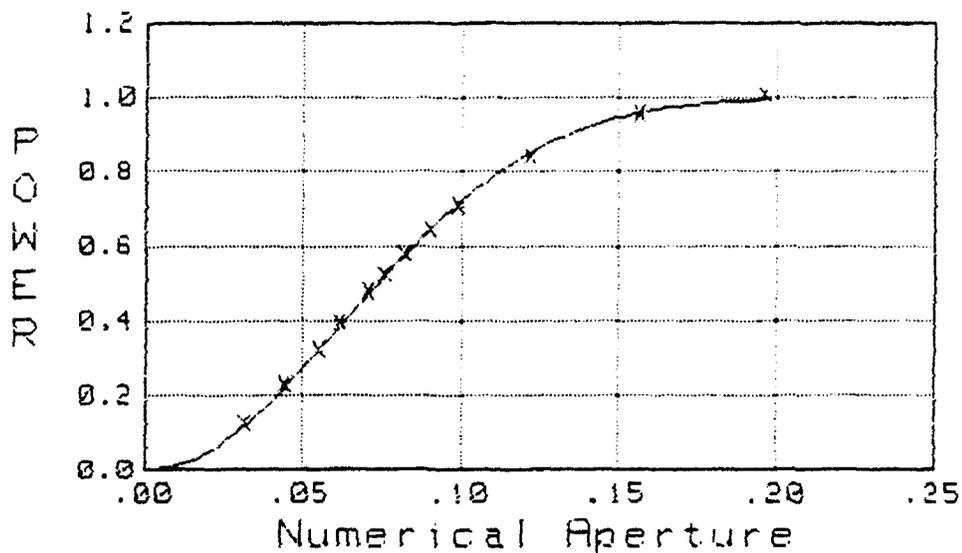


Figure 2
Fiber Cutoff Wavelength

3.5.3 FIBER MODE FIELD DIAMETER/ESI PARAMETERS - Fiber mode field diameter at the 1320 nm design operating wavelength is shown in Figure 3. Calculated equivalent step index parameters (ESI) are shown in Table 2. The fiber numerical aperture of ~0.16 is required for good macrobending performance.

APPENDIX

VARIABLE APERTURE PATTERN AT 1300 nm
 ID: 910909 SMTN D742 T+0M 11-DEC-91 14:05:1



MFD: Gaussian=6.58

Petermann=6.59

File: 4363

Figure 3
Fiber Mode Field Diameter

Table 2. Fiber ESI Parameters

| | | |
|-------------------------|-----------------|------------------|
| File: | 4363 | |
| Measurement Wavelength: | 1300 nm | |
| Cutoff Wavelength: | 1300 nm | |
| Conversion Factor: | 1.099 | |
| | Gaussian | Petermann |
| Spot Radius: | 3.2917 | 3.2975 μm |
| ESI Core Radius: | 2.9954 | 3.0007 μm |
| ESI Delta: | 0.0065 | 0.0065 |
| Nc-Ncl: | 0.0095 | 0.0094 |
| Numerical Aperture: | 0.1661 | 0.1658 |

3.5.4 FIBER MECHANICAL CHARACTERISTICS - Typical fiber geometry results are shown in Figure 4. These results show excellent core and cladding circularity and low core/cladding concentricity error (<0.1 μm).

APPENDIX

geometry

Drum Number:742

Fiber ID:910909 SMTN T+0m

Length=0.0010 km

Time of Test:11-DEC-91 16:46:01

=====
clad: (102.16,77.74) diam=80.51 non_circ=0.185 (40.29,40.22) at -66.44
core: (102.47,78.06) diam=6.85 non_circ=0.588 (3.43, 3.41) at -51.59
Concentricity of clad to core=0.019 microns (-114.54 degrees)

Phase Plot of clad 11-DEC-91 16:46:01 Model: ELLIPSE

Fiber ID:910909 SMTN T+0m

Drum Number:742

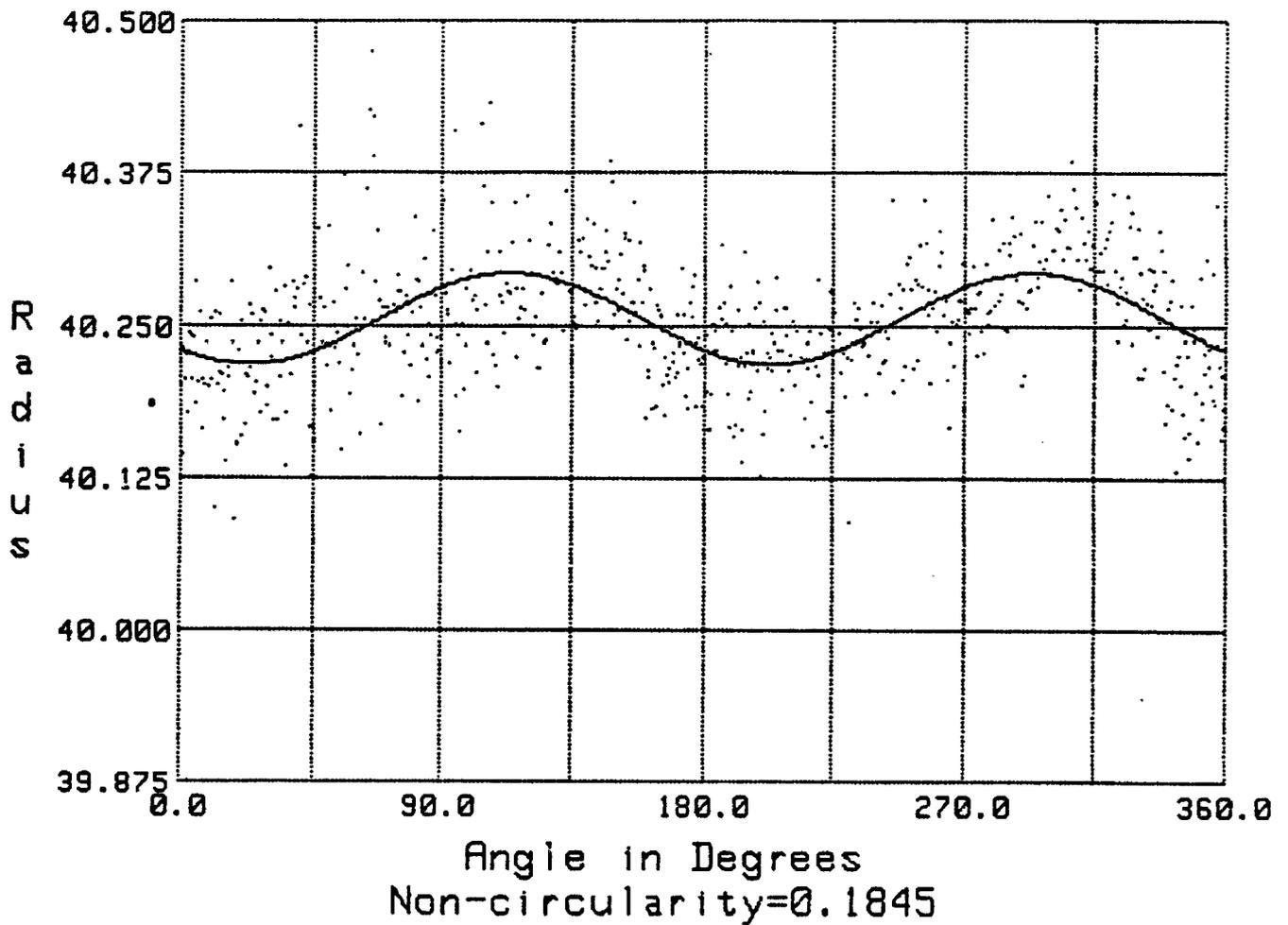


Figure 4
Fiber Geometry Report

APPENDIX

3.5.5 FIBER STRENGTH CHARACTERISTICS - Figure 5 shows Weibull strength plots for fiber lot-910909 ("Hard Coating") and for previously reported fiber lot-910617 ("Soft Coating"). Strain rate for both measurements was 9%/minute and fiber gauge length was 3.9 meters. Comparison of the two strength curves clearly shows the improvement in fiber strength obtained by use of the harder coating. Average breaking strength increased by 17% (from 570 ksi to 665 ksi) and the low strength "tail" observed in the soft coating data was not present in the hard coating data.

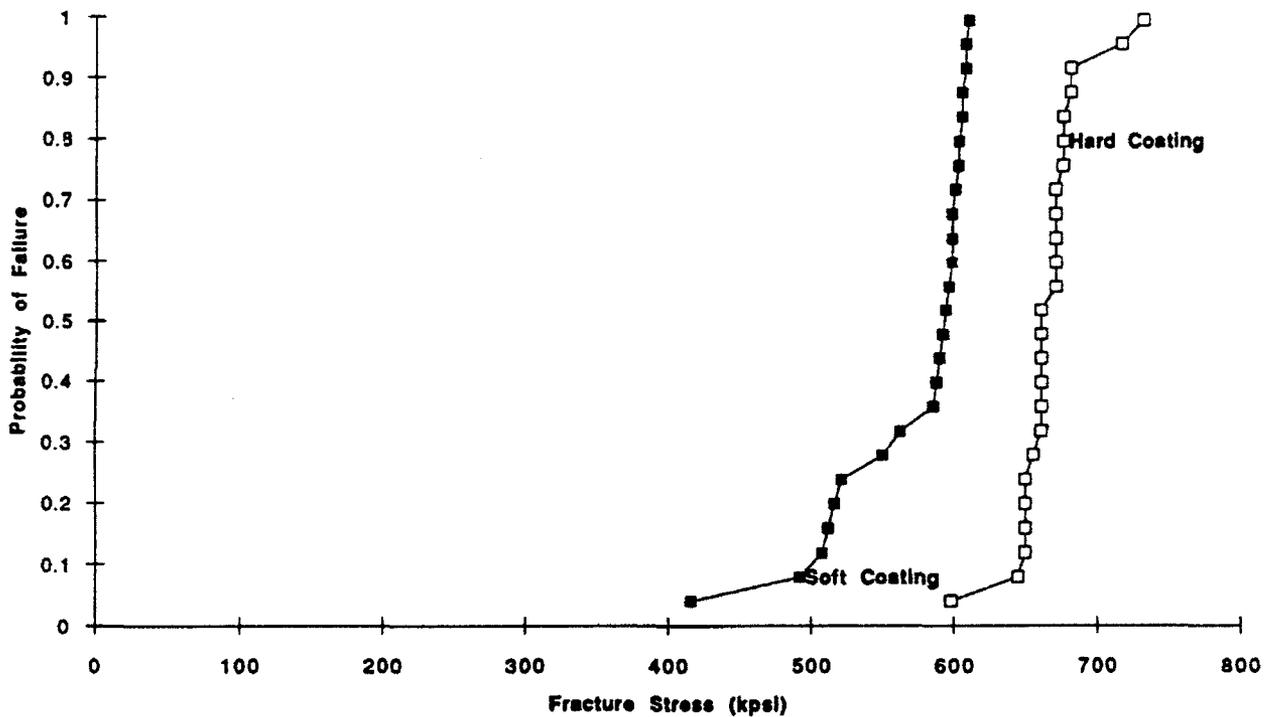


Figure 5
Fiber Strength Distribution

4.0 DELIVERABLES

Two lengths of optical fiber with a total length 3.0 km has been delivered to NRL in this reporting period. A summary of the fiber identification codes is shown below:

| <u>Spool #</u> | <u>Lot#</u> | <u>Fiber Length</u> |
|----------------|---------------------------|---------------------|
| 1 | 910909 D742 T+0-T+1717 | 1717 m |
| 2 | 910909 D742 T+1901-T+3182 | 1281 m |

5.0 DISCUSSION AND FUTURE WORK

Target optical and mechanical specifications for the fiber were met. Previously reported studies of fiber mechanical strength have shown that the unusually thin coating on the fiber is subject to damage during normal handling of the fiber. We have consulted with NRL personnel and with their concurrence we have applied a harder acrylate coating formulation on the fiber draw/coating runs described in this report. The test data clearly shows an improvement in the fiber strength when a harder coating is used.

We have identified a new coating material with which we believe may further improve fiber strength. This material will be evaluated and results will be described in the next report.

Bimonthly Activity Report No. 13

Optical Fiber for Acoustic Sensor Applications

Prepared by
James R. Onstott
Principal Investigator

Prepared for the
Naval Research Laboratory
Contract No. N00014-89-C-2455

February, 1992

3M Fiber Optics Laboratory
3M Center
St. Paul, Minnesota 55144



APPENDIX

1.0 INTRODUCTION

This interim report summarizes the research and development efforts performed during the bimonthly reporting period of December 1991 - January 1992 by 3M on the development of optical fiber for acoustic sensor applications under Naval Research Laboratory (NRL) Contract Number N00014-89-C-2455.

2.0 PROGRAM OBJECTIVE

At the request of NRL, the overall objectives of this program have been modified from the development of acoustically sensitive and insensitive optical fiber to the development of long lengths of optical fiber with small diameter polymeric coatings.

3.0 PROGRAM ACTIVITIES

3.1 Task 1.0: Fiber Design

A fiber design previously developed during the performance of this contract under Phase 1, Subtask 1.0, was used in this task. This design was a "matched clad" high numerical aperture structure which is suitable for use in both sensing and fused fiber coupler applications.

3.2 Task 2.1: 125 μm Fiber Coating Development

Technology required to apply single layer ultraviolet polymerizable coatings with a total diameter of $\sim 125 \mu\text{m}$ was developed during previous reporting periods.

Previous reports have discussed the poor mechanical strength of fibers with very thin coatings. These results are attributed to damage during normal handling of the fiber due to the thin coatings. Although previously delivered fiber samples are performing satisfactorily in NRL development activities, we are continuing development of fiber coating technology. We have identified a new coating material candidate with mechanical characteristics that are superior to previously applied coating materials. Evaluation of this material is in progress and samples will be delivered to NRL in the next reporting period.

APPENDIX

3.3 Task 2.2: 100 μm Fiber Coating Development

Coating application technology to produce 10 μm thick ultraviolet polymerizable coatings on 80 μm diameter optical fiber has been acquired and is currently undergoing test and evaluation. The new coating material discussed in Section 3.2 is also being evaluated for this task. Samples will be supplied to NRL for evaluation in the next reporting period. Based on discussions with Dr. A. Dandridge of NRL, attempts will be made to fabricate coated fiber with total diameters of 90 μm and 80 μm . If successful, samples of this fiber will be supplied in the next reporting period.

4.0 DISCUSSION AND FUTURE WORK

Previously reported studies of fiber mechanical strength have shown that the unusually thin coating on the fiber is subject to damage during normal handling of the fiber. We have consulted with NRL personnel and with their concurrence, we are investigating harder acrylate coating formulations as a means of improving fiber strength. Previous test data clearly shows an improvement in the fiber strength when a harder coating is used.

We have identified a new coating material with which we believe may further improve fiber strength. This material will be evaluated and results will be described in the next report. In addition, we will attempt to fabricate fiber with unusually small coated diameters of 80 μm and 90 μm .

Bimonthly Activity Report No. 14

Optical Fiber for Acoustic Sensor Applications

Prepared by
James R. Onstott
Principal Investigator

Prepared for the
Naval Research Laboratory
Contract No. N00014-89-C-2455

May, 1992

3M Fiber Optics Laboratory
3M Center
St. Paul, Minnesota 55144



APPENDIX

1.0 INTRODUCTION

This interim report summarizes the research and development efforts performed during the bimonthly reporting period of February 1992 - March 1992 by 3M on the development of optical fiber for acoustic sensor applications under Naval Research Laboratory (NRL) Contract Number N00014-89-C-2455.

2.0 PROGRAM OBJECTIVE

At the request of NRL, the overall objectives of this program have been modified from the development of acoustically sensitive and insensitive optical fiber to the development of long lengths of optical fiber with small diameter polymeric coatings.

3.0 PROGRAM ACTIVITIES

3.1 Task 1.0: Fiber Design

A fiber design previously developed during the performance of this contract under Phase 1, Subtask 1.0, was used in this task. This design was a "matched clad" high numerical aperture structure which is suitable for use in both sensing and fused fiber coupler applications.

3.2 Task 2.1: 125 μm Fiber Coating Development

Technology required to apply single layer ultraviolet polymerizable coatings with a total diameter of $\sim 125 \mu\text{m}$ was developed during previous reporting periods.

Previous reports have discussed the poor mechanical strength of fibers with very thin coatings. These results are attributed to damage during normal handling of the fiber due to the thin coatings. Although previously delivered fiber samples are performing satisfactorily in NRL development activities, we are continuing development of fiber coating technology. We have identified a new coating material candidate with mechanical characteristics that are superior to previously applied coating materials. Evaluation of this material is in progress and samples will be delivered to NRL in the next reporting period.

APPENDIX

3.3 Task 2.2: 100 μm Fiber Coating Development

Coating application technology to produce 10 μm thick ultraviolet polymerizable coatings on 80 μm diameter optical fiber has been acquired and is currently undergoing test and evaluation. The new coating material discussed in Section 3.2 is also being evaluated for this task. Samples will be supplied to NRL for evaluation in the next reporting period. Based on discussions with Dr. A. Dandridge of NRL, attempts will be made to fabricate coated fiber with total diameters of 90 μm and 80 μm . In addition to thin coatings, this fiber will require a reduction in the draw diameter. Draw diameters of 75 μm and 70 μm will be initially attempted. If successful, samples of this fiber will be supplied in the next reporting period.

4.0 DISCUSSION AND FUTURE WORK

Based on discussions with Dr. Dandridge, a modification to the standard fiber design used in previously delivered samples will be made. Dr. Dandridge has requested that the fiber cutoff wavelength be reduced to <1230 nm for future fiber experiments. Fiber fabricated with this design modification will be delivered in the next reporting period.

One preform which was made this reporting period with a 1300 nm cutoff wavelength (at 80 μm) will be used for reduced fiber diameter experiments. For fiber diameters of 75 μm and 70 μm , the cutoff wavelengths will be <1230 nm. Samples of this fiber will be delivered in the next reporting period.

Bimonthly Activity Report No. 15

Optical Fiber for Acoustic Sensor Applications

Prepared by
James R. Onstott
Principal Investigator

Prepared for the
Naval Research Laboratory
Contract No. N00014-89-C-2455

July, 1992

3M Fiber Optics Laboratory
3M Center
St. Paul, Minnesota 55144



APPENDIX

1.0 INTRODUCTION

This interim report summarizes the research and development efforts performed during the bimonthly reporting period of April 1992 - May 1992 by 3M on the development of optical fiber for acoustic sensor applications under Naval Research Laboratory (NRL) Contract Number N00014-89-C-2455.

2.0 PROGRAM OBJECTIVE

At the request of NRL, the overall objectives of this program have been modified from the development of acoustically sensitive and insensitive optical fiber to the development of long lengths of optical fiber with small diameter polymeric coatings.

3.0 PROGRAM ACTIVITIES

3.1 Task 1.0: Fiber Design

A fiber design previously developed during the performance of this contract under Phase 1, Subtask 1.0, was used in this task. This design was a "matched clad" high numerical aperture structure which is suitable for use in both sensing and fused fiber coupler applications. At the request of NRL personnel, the design of the fiber was modified during this reporting period to reduce the second mode cutoff to <1230 nm. Delivery of 6620 meters of fiber during the current period is reported.

3.2 Task 2.1: 125 μ m Fiber Coating Development

Technology required to apply single layer ultraviolet polymerizable coatings with a total diameter of ~ 125 μ m was developed during previous reporting periods.

Previous reports have discussed the poor mechanical strength of fibers with very thin coatings. These results are attributed to damage during normal handling of the fiber due to the thin coatings. Although previously delivered fiber samples are performing satisfactorily in NRL development activities, we are continuing development of fiber coating technology. We have identified a new coating material candidate with mechanical characteristics that are superior to previously applied coating materials. Evaluation of this material is in progress and samples will be delivered to NRL in the next reporting period.

APPENDIX

3.3 Task 2.2: 100 μm Fiber Coating Development

Coating application technology to produce 10 μm thick ultraviolet polymerizable coatings on 80 μm diameter optical fiber has been acquired and is currently undergoing test and evaluation. The new coating material discussed in Section 3.2 is also being evaluated for this task. Samples will be supplied to NRL for evaluation in the next reporting period. Based on discussions with Dr. A. Dandridge of NRL, attempts will be made to fabricate coated fiber with total diameters of 90 μm and 80 μm . In addition to thin coatings, this fiber will require a reduction in the draw diameter. Draw diameters of 75 μm and 70 μm will be initially attempted. If successful, samples of this fiber will be supplied in the next reporting period.

3.4 Task 3.0: Fiber Drawing and Coating

Fiber was drawn to 80 μm and coated with a single coating of UV polymerized acrylate material manufactured by Desoto Inc. (coating #103). This material is normally used as a "hard secondary" buffer coating in optical fiber applications. Previous work has shown that the harder coating increases the mechanical strength of the fiber.

3.5 Task 4.0: Physical and Optical Measurements

3.5.1 FIBER ATTENUATION – Fiber attenuation versus wavelength is plotted in Figure 1 and listed in Table 1. Attenuation at the fiber operating wavelength of 1320 nm is <1.2 dB/km.

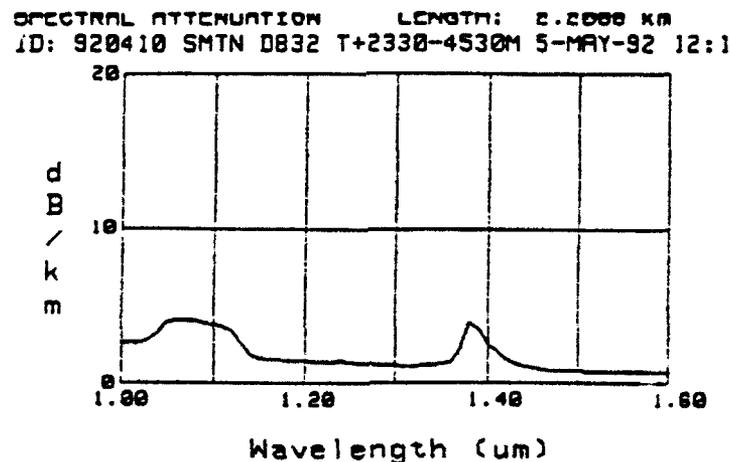


Figure 1
Fiber Attenuation versus Wavelength

APPENDIX

Table 1. Fiber Attenuation versus Wavelength

File: 5413

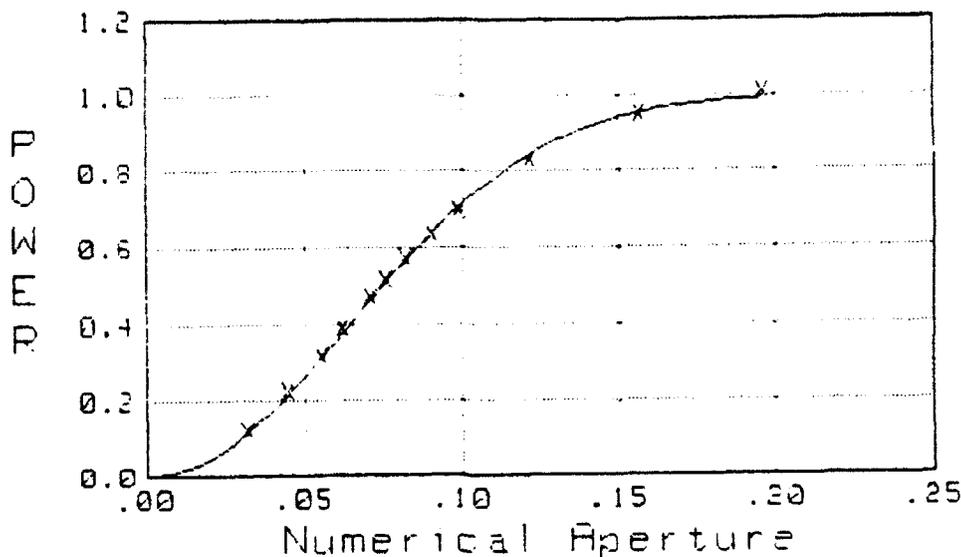
SPECTRAL ATTENUATION

 FIBER ID: 920410 SMTN D832 T+2330-4530M 5-MAY-92 12:11:18
 LENGTH: 2.2 km
 FILE: 5413

| WAVELENGTH | ATTENUATION (dB/Km) | WAVELENGTH | ATTENUATION (dB/Km) |
|------------|---------------------|------------|---------------------|
| 1000 | 2.62 | 1310 | 1.14 |
| 1010 | 2.59 | 1320 | 1.14 |
| 1020 | 2.63 | 1330 | 1.17 |
| 1030 | 2.83 | 1340 | 1.23 |
| 1040 | 3.31 | 1350 | 1.29 |
| 1050 | 3.94 | 1360 | 1.39 |
| 1060 | 4.08 | 1370 | 2.15 |
| 1070 | 4.06 | 1380 | 3.98 |
| 1080 | 4.03 | 1390 | 3.45 |
| 1090 | 3.91 | 1400 | 2.51 |
| 1100 | 3.82 | 1410 | 2.02 |
| 1110 | 3.66 | 1420 | 1.57 |
| 1120 | 3.33 | 1430 | 1.28 |
| 1130 | 2.65 | 1440 | 1.13 |
| 1140 | 1.86 | 1450 | 1.00 |
| 1150 | 1.62 | 1460 | .95 |
| 1160 | 1.56 | 1470 | .87 |
| 1170 | 1.52 | 1480 | .84 |
| 1180 | 1.49 | 1490 | .83 |
| 1190 | 1.45 | 1500 | .80 |
| 1200 | 1.42 | 1510 | .78 |
| 1210 | 1.40 | 1520 | .77 |
| 1220 | 1.38 | 1530 | .77 |
| 1230 | 1.37 | 1540 | .77 |
| 1240 | 1.44 | 1550 | .75 |
| 1250 | 1.41 | 1560 | .74 |
| 1260 | 1.31 | 1570 | .73 |
| 1270 | 1.25 | 1580 | .72 |
| 1280 | 1.21 | 1590 | .73 |
| 1290 | 1.19 | 1600 | .73 |
| 1300 | 1.16 | | |

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VARIABLE APERTURE PATTERN AT 1320 nm
 ID: 920410 SMTN D832 T+2255M 30-APR-92 15:2



MFD: Gaussian=6.6

Petermann=6.56

File: 5409

Figure 3
Fiber Mode Field Diameter

Table 2. ESI Parameters

| | | |
|-------------------------|----------|----------------------|
| File: | 5409 | |
| Measurement Wavelength: | 1320 nm | |
| Cutoff Wavelength: | 1136 nm | |
| Conversion Factor: | 1.230 | |
| | Gaussian | Petermann |
| Spot Radius: | 3.3019 | 3.2813 μm |
| ESI Core Radius: | 2.6838 | 2.6671 μm |
| ESI Delta: | 0.0062 | 0.0062 |
| Nc-Ncl: | 0.0090 | 0.0091 |
| Numerical Aperture: | 0.1620 | 0.1630 |

3.5.4 FIBER STRENGTH CHARACTERISTICS – Figure 4 shows a Weibull strength plot for the fiber described in this report. Strain rate for this measurement was 9%/minute and fiber gauge length was 3.9 meters. As has been demonstrated in previous reports, the harder coating used for this fiber improved the fiber strength.

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DYNAMIC FATIGUE TEST #df0022

PREFORM #920410 SMTN

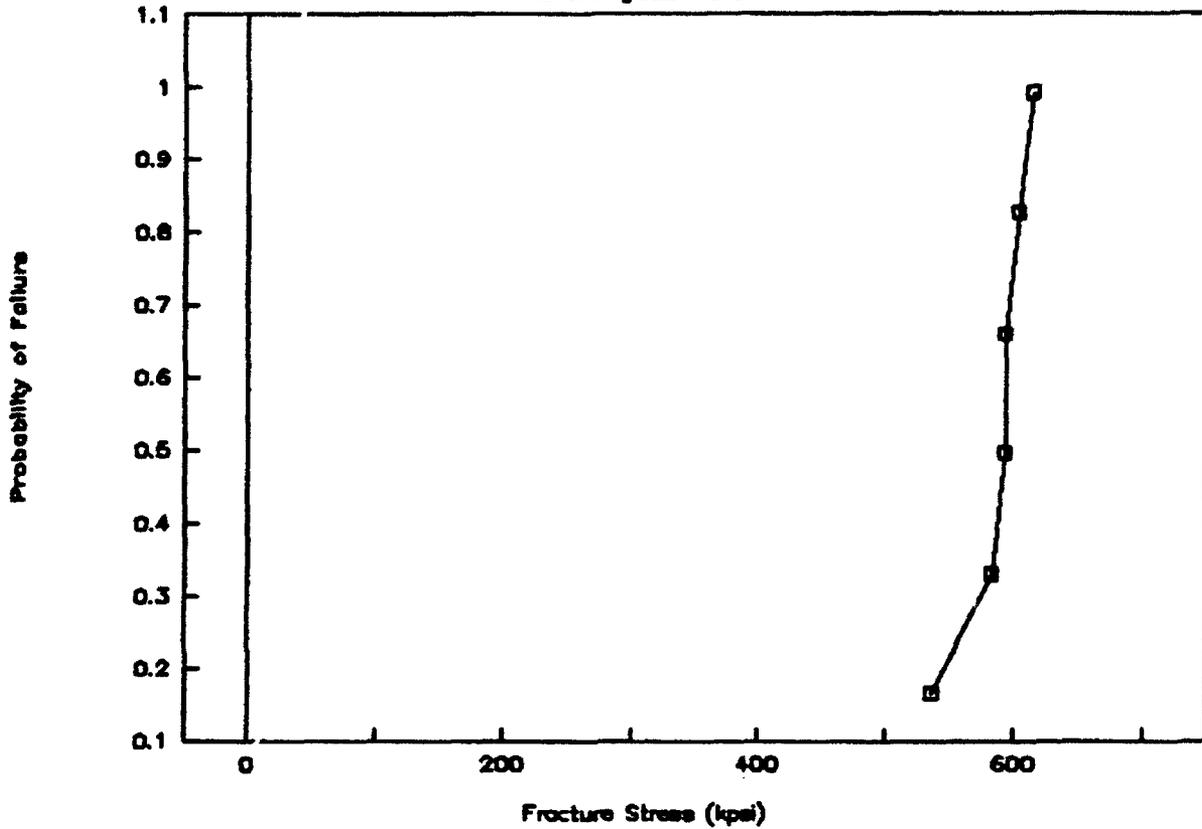


Figure 4
Fiber Strength

4.0 DELIVERABLES

Three spools of fiber with a total length 6.620 km has been delivered to NRL in this reporting period. A summary of the fiber identification codes is as follows:

| <u>Spool #</u> | <u>Lot#</u> | <u>Fiber Length</u> |
|----------------|----------------------------|---------------------|
| 2115575 | 920410.832, T+45, T+2295 | 2250 m |
| 2115585 | 920410.832, T+2330, T+4530 | 2200 m |
| 2115595 | 920410.832, T+4530, T+6700 | 2170 m |

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5.0 DISCUSSION AND FUTURE WORK

A modification to the standard fiber design to reduce the fiber cutoff wavelength has been successfully completed. Future fiber samples will also use this modification. To date, 28.354 km of fiber has been fabricated and delivered to NRL under this contract. Additional fiber samples are in preparation and include reduced fiber clad and coated diameter samples.

Bimonthly Activity Report No. 16

Optical Fiber for Acoustic Sensor Applications

Prepared by
James R. Onstott
Principal Investigator

Prepared for the
Naval Research Laboratory
Contract No. N00014-89-C-2455

October, 1992

3M Fiber Optics Laboratory
3M Center
St. Paul, Minnesota 55144



APPENDIX

1.0 INTRODUCTION

This interim report summarizes the research and development efforts performed during the bimonthly reporting period of June 1992 - July 1992 by 3M on the development of optical fiber for acoustic sensor applications under Naval Research Laboratory (NRL) Contract Number N00014-89-C-2455.

2.0 PROGRAM OBJECTIVE

At the request of NRL, the overall objectives of this program have been modified from the development of acoustically sensitive and insensitive optical fiber to the development of long lengths of optical fiber with small diameter polymeric coatings.

3.0 PROGRAM ACTIVITIES

3.1 Task 1.0: Fiber Design

A fiber design previously developed during the performance of this contract under Phase 1, Subtask 1.0, was used in this task. This design was a "matched clad" high numerical aperture structure which was suitable for use in both sensing and fused fiber coupler applications. At the request of NRL personnel, the design of the fiber was modified in a previous reporting period to reduce the second mode cutoff to <1230 nm. Delivery of 7520 meters of fiber during the current period is reported.

3.2 Task 2.1: 125 μm Fiber Coating Development

Technology required to apply single layer ultraviolet polymerizable coatings with a total diameter of $\sim 125 \mu\text{m}$ was developed during previous reporting periods. Delivery of 5520 meters of single mode fiber developed in Task 1 and coated with this coating was delivered to NRL during this reporting period.

3.3 Task 2.2: 100 μm Fiber Coating Development

Coating application technology to produce 10 μm thick ultraviolet polymerizable coatings on 80 μm diameter optical fiber was acquired during previous reporting periods. Based on conversations with Dr. A. Dandridge of NRL, attempts were made to fabricate coated fibers with coated diameters of 90 μm and 80 μm . In addition to thin

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coatings, this task required a reduction in fiber draw diameter. On an experimental basis, the following fiber/coating diameters were attempted:

| <u>Fiber Diameter</u> | <u>Coating Diameter</u> |
|-----------------------|-------------------------|
| 70 μm | 100 μm |
| 70 μm | 80 μm |
| 60 μm | 90 μm |

1000 meter lengths of 70 μm /100 μm and 60 μm /90 μm fiber were successfully fabricated and delivered to NRL during this reporting period. The fiber 70 μm /80 μm samples were extremely fragile and could not be supplied for evaluation.

3.4 Task 3.0: Fiber Drawing and Coating

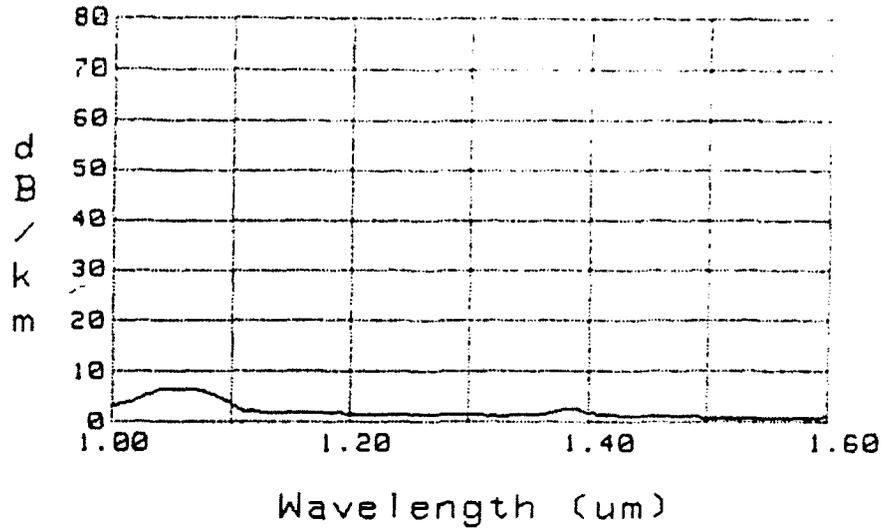
All of the experiments described above were drawn and coated with a single coating of UV polymerizable Acrylate material manufactured by Desoto Inc. (Coating #103). This coating material is normally used as a "hard" secondary buffer coating in optical fiber applications. Previous work has shown that the harder coating increases the mechanical strength of the fiber.

3.5 Task 4.0: Physical and Optical Measurements

3.5.1 FIBER ATTENUATION – Typical fiber attenuation versus wavelength for fibers with a clad diameter of 80 μm (Lot #920520.876) is plotted in Figure 1 and listed in Table 1. Attenuation at the fiber operating wavelength of 1300 nm is <1.5 dB/km. Figure 2 and Table 2 show the attenuation characteristics for fiber drawn to a clad diameter of 70 μm (Spool #2223407). At the operating wavelength of 1300 nm, the attenuation has increased to ~2.5 dB/km. Figure 3 and Table 3 show the attenuation characteristics for fiber drawn to a clad diameter of 60 μm (Spool #2222497). At the operating wavelength of 1300 nm, the attenuation has increased significantly to a level of ~11 dB/km.

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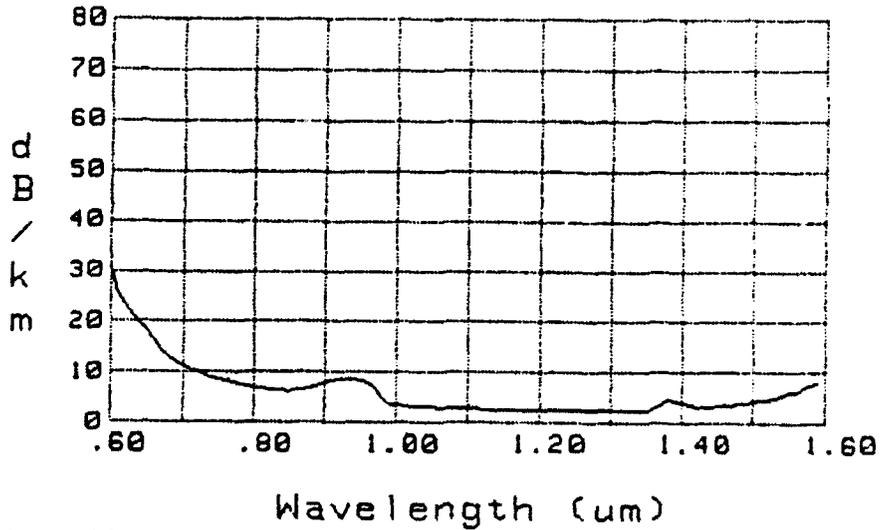
SPECTRAL ATTENUATION LENGTH: 1.1000 km
ID: 920520 SMTN D876 T+1280-2380M 15-JUL-92 14:



File: 5773

Figure 1
Fiber Attenuation versus Wavelength (80 μm Diameter)

SPECTRAL ATTENUATION LENGTH: 1.0000 km
ID: 920206 SMTN D881.1 T+0-1000M 70U/100U 29-JL



File: 5816

Figure 2
Fiber Attenuation versus Wavelength (70 μm Diameter)

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Table 1. Fiber Attenuation versus Wavelength (80 μ m Diameter)

SPECTRAL ATTENUATION

FIBER ID: S20520 SMTN 0876 T-1280-2380M 15-JUL-92 14:17:06
 LENGTH: 1.1 km
 FILE: 5773

| WAVELENGTH | ATTENUATION (dB/Km) | WAVELENGTH | ATTENUATION (dB/Km) |
|------------|---------------------|------------|---------------------|
| 1000 | 3.43 | 1500 | .95 |
| 1010 | 3.66 | 1510 | .97 |
| 1020 | 4.26 | 1520 | .99 |
| 1030 | 5.46 | 1530 | .94 |
| 1040 | 6.43 | 1540 | .96 |
| 1050 | 6.64 | 1550 | .97 |
| 1060 | 6.61 | 1560 | .98 |
| 1070 | 6.40 | 1570 | .93 |
| 1080 | 5.95 | 1580 | .94 |
| 1090 | 4.94 | 1590 | .97 |
| 1100 | 3.55 | 1600 | 1.02 |
| 1110 | 2.41 | | |
| 1120 | 2.14 | | |
| 1130 | 2.00 | | |
| 1140 | 1.99 | | |
| 1150 | 1.92 | | |
| 1160 | 1.85 | | |
| 1170 | 1.81 | | |
| 1180 | 1.79 | | |
| 1190 | 1.73 | | |
| 1200 | 1.70 | | |
| 1210 | 1.66 | | |
| 1220 | 1.63 | | |
| 1230 | 1.62 | | |
| 1240 | 1.61 | | |
| 1250 | 1.58 | | |
| 1260 | 1.53 | | |
| 1270 | 1.49 | | |
| 1280 | 1.43 | | |
| 1290 | 1.40 | | |
| 1300 | 1.39 | | |
| 1310 | 1.37 | | |
| 1320 | 1.35 | | |
| 1330 | 1.34 | | |
| 1340 | 1.38 | | |
| 1350 | 1.40 | | |
| 1360 | 1.41 | | |
| 1370 | 1.76 | | |
| 1380 | 2.64 | | |
| 1390 | 2.47 | | |
| 1400 | 1.99 | | |
| 1410 | 1.70 | | |
| 1420 | 1.45 | | |
| 1430 | 1.29 | | |
| 1440 | 1.18 | | |
| 1450 | 1.12 | | |
| 1460 | 1.08 | | |
| 1470 | 1.04 | | |
| 1480 | 1.01 | | |
| 1490 | 1.00 | | |

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Table 2. Fiber Attenuation versus Wavelength (70 μ m Diameter)

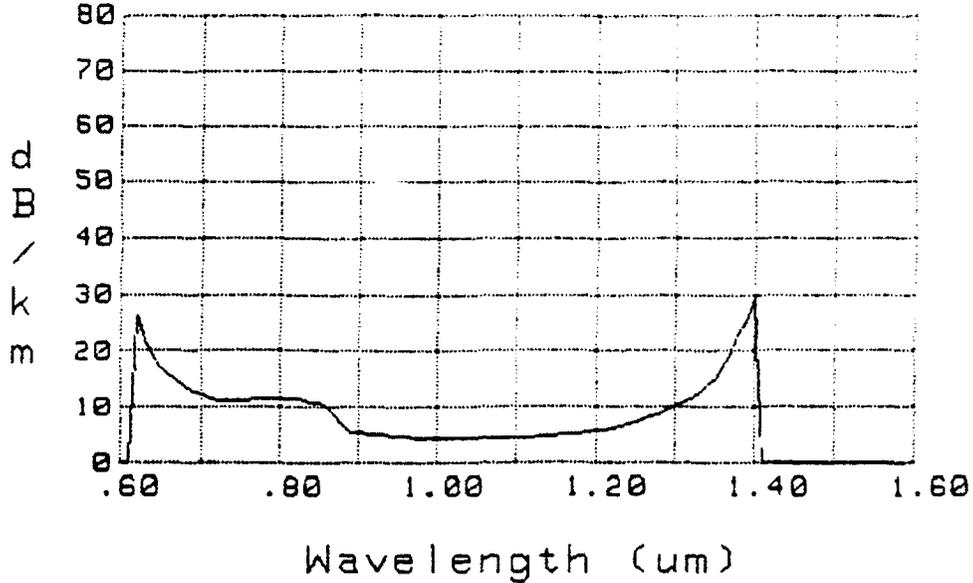
SPECTRAL ATTENUATION

FIBER ID: 920206 SMTN 0881.1 T+0-1000M 70U/100U 29-JUL-92 09:31:56
 LENGTH: 1 km
 FILE: 5816

| WAVELENGTH | ATTENUATION (dB/Km) | WAVELENGTH | ATTENUATION (dB/Km) |
|------------|---------------------|------------|---------------------|
| 600 | 30.39 | 1100 | 2.82 |
| 610 | 25.67 | 1110 | 2.80 |
| 620 | 23.38 | 1120 | 2.73 |
| 630 | 21.18 | 1130 | 2.68 |
| 640 | 19.81 | 1140 | 2.63 |
| 650 | 18.35 | 1150 | 2.61 |
| 660 | 16.60 | 1160 | 2.58 |
| 670 | 14.45 | 1170 | 2.55 |
| 680 | 12.90 | 1180 | 2.52 |
| 690 | 11.99 | 1190 | 2.50 |
| 700 | 11.25 | 1200 | 2.47 |
| 710 | 10.62 | 1210 | 2.45 |
| 720 | 10.06 | 1220 | 2.44 |
| 730 | 9.56 | 1230 | 2.44 |
| 740 | 9.09 | 1240 | 2.51 |
| 750 | 8.68 | 1250 | 2.50 |
| 760 | 8.29 | 1260 | 2.45 |
| 770 | 7.94 | 1270 | 2.44 |
| 780 | 7.59 | 1280 | 2.44 |
| 790 | 7.28 | 1290 | 2.45 |
| 800 | 7.07 | 1300 | 2.47 |
| 810 | 6.82 | 1310 | 2.48 |
| 820 | 6.61 | 1320 | 2.52 |
| 830 | 6.47 | 1330 | 2.58 |
| 840 | 6.39 | 1340 | 2.68 |
| 850 | 6.37 | 1350 | 2.76 |
| 860 | 6.44 | 1360 | 2.90 |
| 870 | 6.60 | 1370 | 3.57 |
| 880 | 6.92 | 1380 | 4.87 |
| 890 | 7.39 | 1390 | 4.48 |
| 900 | 8.04 | 1400 | 3.97 |
| 910 | 8.48 | 1410 | 3.69 |
| 920 | 8.68 | 1420 | 3.50 |
| 930 | 8.69 | 1430 | 3.45 |
| 940 | 8.62 | 1440 | 3.47 |
| 950 | 8.38 | 1450 | 3.55 |
| 960 | 8.02 | 1460 | 3.66 |
| 970 | 6.90 | 1470 | 3.80 |
| 980 | 5.06 | 1480 | 3.96 |
| 990 | 3.76 | 1490 | 4.17 |
| 1000 | 3.58 | 1500 | 4.39 |
| 1010 | 3.48 | 1510 | 4.63 |
| 1020 | 3.41 | 1520 | 4.92 |
| 1030 | 3.33 | 1530 | 5.23 |
| 1040 | 3.25 | 1540 | 5.62 |
| 1050 | 3.19 | 1550 | 6.08 |
| 1060 | 3.09 | 1560 | 6.31 |
| 1070 | 3.02 | 1570 | 6.84 |
| 1080 | 2.96 | 1580 | 7.46 |
| 1090 | 2.92 | 1590 | 8.08 |

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SPECTRAL ATTENUATION LENGTH: 1.0000 km
 ID: 920206 SMTN D882.1 T+0-1000M 60U/90U 28-JUL



File: 5807

Figure 3
Fiber Attenuation versus Wavelength (60 μm Diameter)

3.5.2 FIBER CUTOFF WAVELENGTH – Fiber cutoff wavelength measurements for the three fiber diameters are shown in Figures 4 through 6. The following is a summary of these results:

| <u>Fiber Diameter</u> | <u>Fiber ID #</u> | <u>Cutoff Wavelength</u> |
|-----------------------|-------------------|--------------------------|
| 80 μm | 920520.876 | 1112 nm |
| 70 μm | 2223407 | 992 nm |
| 60 μm | 2222497 | 873 nm |

3.5.3 FIBER MODE FIELD DIAMETER/ESI PARAMETERS – Fiber mode field diameters for the three fiber diameters are shown in Figures 7 through 9. Calculated Equivalent Step Index (ESI) parameters are shown in Tables 4 through 6.

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Table 3. Fiber Attenuation versus Wavelength (60 μm Diameter)

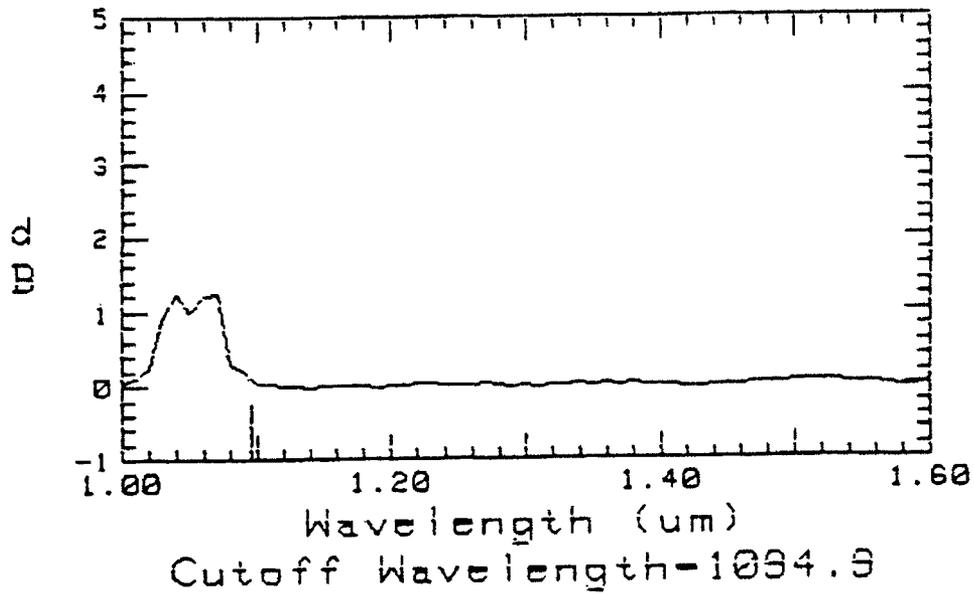
SPECTRAL ATTENUATION

FIBER ID: 920206 SMTN 0882.1 T+0-1000M 60U/90U 28-JUL-92 10:49:24
 LENGTH: 1 km
 FILE: 5807

| WAVELENGTH | ATTENUATION (dB/KM) | WAVELENGTH | ATTENUATION (dB/KM) |
|------------|---------------------|------------|---------------------|
| 600 | 0.00 | 1100 | 4.41 |
| 610 | 0.00 | 1110 | 4.48 |
| 620 | 26.25 | 1120 | 4.52 |
| 630 | 21.85 | 1130 | 4.59 |
| 640 | 19.42 | 1140 | 4.57 |
| 650 | 17.47 | 1150 | 4.85 |
| 660 | 15.93 | 1160 | 4.97 |
| 670 | 14.71 | 1170 | 5.09 |
| 680 | 13.68 | 1180 | 5.26 |
| 690 | 12.81 | 1190 | 5.47 |
| 700 | 12.20 | 1200 | 5.70 |
| 710 | 11.70 | 1210 | 5.99 |
| 720 | 11.27 | 1220 | 6.26 |
| 730 | 11.09 | 1230 | 6.57 |
| 740 | 11.03 | 1240 | 6.96 |
| 750 | 11.09 | 1250 | 7.42 |
| 760 | 11.28 | 1260 | 7.83 |
| 770 | 11.50 | 1270 | 8.36 |
| 780 | 11.68 | 1280 | 8.76 |
| 790 | 11.71 | 1290 | 9.40 |
| 800 | 11.71 | 1300 | 10.10 |
| 810 | 11.62 | 1310 | 10.86 |
| 820 | 11.40 | 1320 | 11.73 |
| 830 | 11.16 | 1330 | 12.76 |
| 840 | 10.93 | 1340 | 13.95 |
| 850 | 10.68 | 1350 | 15.24 |
| 860 | 10.08 | 1360 | 16.87 |
| 870 | 8.82 | 1370 | 19.08 |
| 880 | 6.74 | 1380 | 23.15 |
| 890 | 5.53 | 1390 | 25.15 |
| 900 | 5.30 | 1400 | 29.54 |
| 910 | 5.17 | 1410 | 0.00 |
| 920 | 5.06 | 1420 | 0.00 |
| 930 | 4.96 | 1430 | 0.00 |
| 940 | 4.89 | 1440 | 0.00 |
| 950 | 4.78 | 1450 | 0.00 |
| 960 | 4.66 | 1460 | 0.00 |
| 970 | 4.57 | 1470 | 0.00 |
| 980 | 4.50 | 1480 | 0.00 |
| 990 | 4.43 | 1490 | 0.00 |
| 1000 | 4.47 | 1500 | 0.00 |
| 1010 | 4.42 | 1510 | 0.00 |
| 1020 | 4.37 | 1520 | 0.00 |
| 1030 | 4.33 | 1530 | 0.00 |
| 1040 | 4.36 | 1540 | 0.00 |
| 1050 | 4.33 | 1550 | 0.00 |
| 1060 | 4.32 | 1560 | 0.00 |
| 1070 | 4.30 | 1570 | 0.00 |
| 1080 | 4.29 | 1580 | 0.00 |
| 1090 | 4.35 | 1590 | 0.00 |

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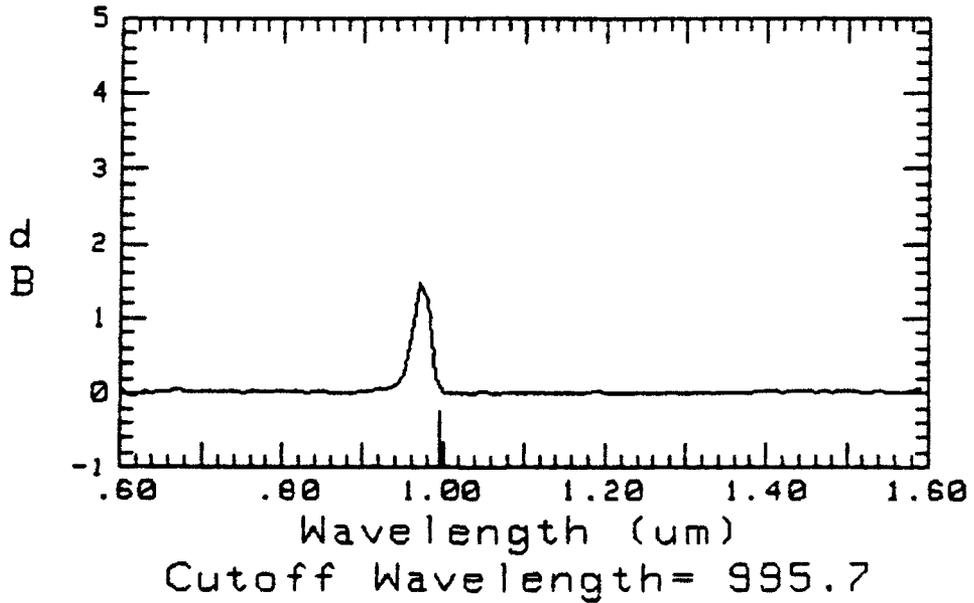
ID:920520 SMTN 0876 T+1280M 14-JUL-92 09:15



File: 5752

Figure 4
Fiber Cutoff Wavelength (80 μm Diameter)

ID:920206 SMTN 0881.1 T+1000M 70U/100U 29-J

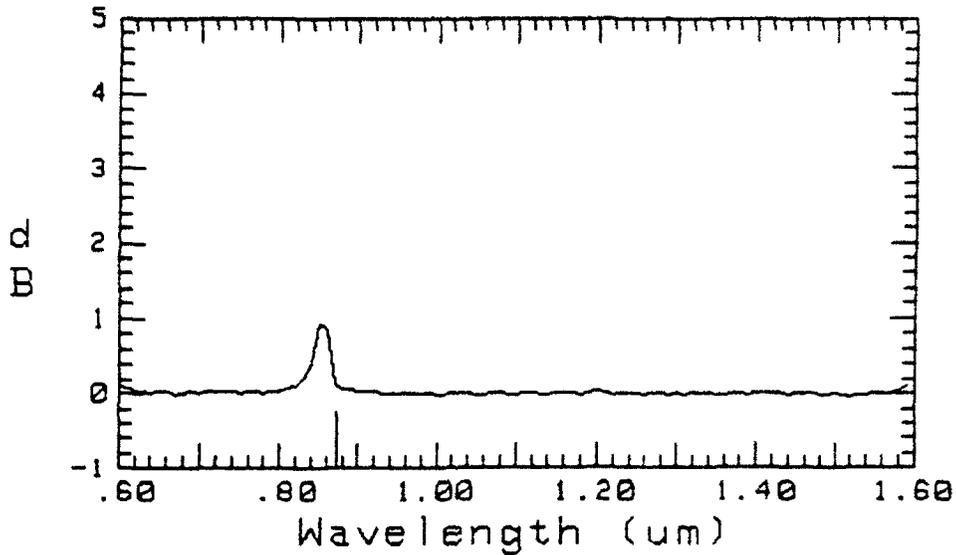


File: 5819

Figure 5
Fiber Cutoff Wavelength (70 μm Diameter)

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CUTOFF PLOT TYPE: BEND
 ID: 920206 SMTN D882.1 T+1000M 60U/90U 28-JL



Cutoff Wavelength = 873.9

File: 5809

Figure 6
Fiber Cutoff Wavelength (60 μm Diameter)

4.0 DELIVERABLES

Seven spools of fiber with a total length of 7520 meters were delivered to NRL in this reporting period. A summary of the fiber identification codes is as follows:

| Spool # | Lot # | Fiber Diameter/ Coating Diameter | Fiber Length |
|---------|---------------------------|-------------------------------------|--------------|
| 2222425 | 920520.876, T+5595,T+6800 | 80 μm /137 μm | 1205 m |
| 2222415 | 920520.876, T+4580,T+5595 | 80 μm /137 μm | 1015 m |
| 2222405 | 920520.876, T+4580,T+3480 | 80 μm /137 μm | 1100 m |
| 2221495 | 920520.876, T+3480,T+2380 | 80 μm /137 μm | 1100 m |
| 2221485 | 920520.876, T+2380,T+1280 | 80 μm /137 μm | 1100 m |
| 2222497 | 920206.882, T+0,T+1000 | 60 μm /90 μm | 1000 m |
| 2223407 | 920206.881, T+0,T+1000 | 70 μm /100 μm | 1000 m |

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VARIABLE APERTURE PATTERN AT 1320 nm
 ID: 920520 SMTN D876 T+1280M 14-JUL-92 09:3

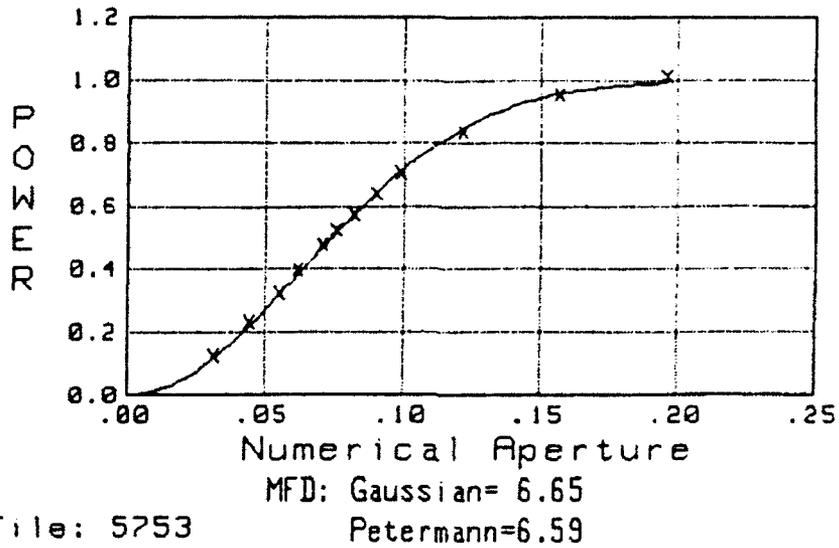


Figure 7
Mode Field Diameter (80 μ m Diameter)

Table 4. Fiber ESI Parameters (80 μ m Diameter)

| | | |
|-------------------------|----------|----------------|
| File: | 5753 | |
| Measurement Wavelength: | 1320 nm | |
| Cutoff Wavelength: | 1095 nm | |
| Conversion Factor: | 1.270 | |
| | Gaussian | Petermann |
| Spot Radius: | 3.3271 | 3.2974 μ m |
| ESI Core Radius: | 2.6195 | 2.5961 μ m |
| ESI Delta: | .0060 | .0061 |
| Nc-Ncl: | .0088 | .0089 |
| Numerical Aperture: | .1600 | .1615 |

APPENDIX

VARIABLE APERTURE PATTERN AT 1280 nm
 ID: 920206 SMTN 0881.1 T+1000M 70U/100U 29-

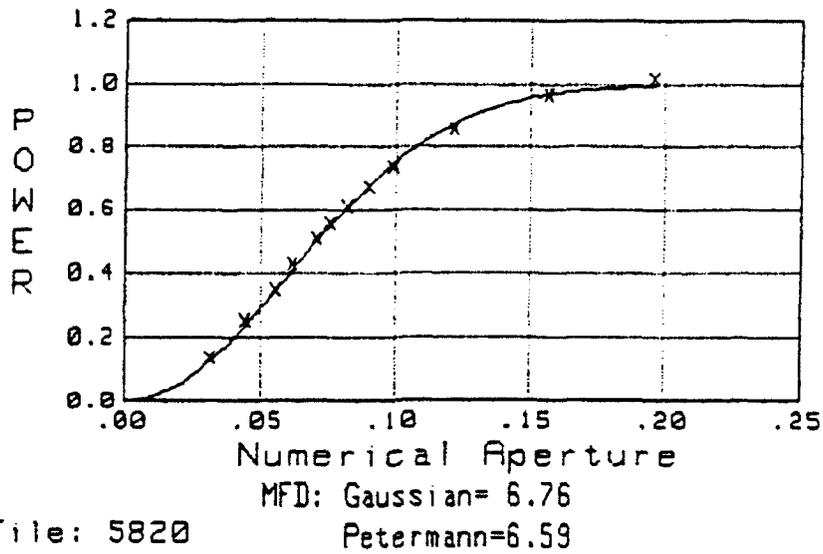


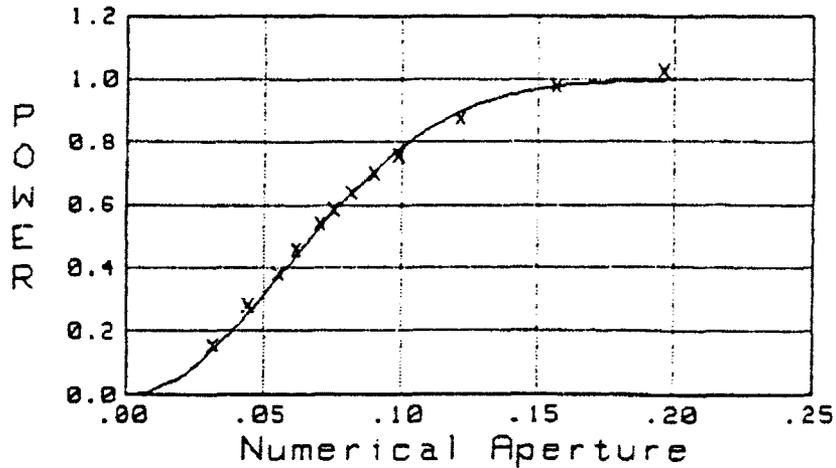
Figure 8
Mode Field Diameter (70 μ m Diameter)

Table 5. Fiber ESI Parameters (70 μ m Diameter)

| | | |
|-------------------------|----------|----------------|
| File: | 5820 | |
| Measurement Wavelength: | 1280 nm | |
| Cutoff Wavelength: | 996 nm | |
| Conversion Factor: | 1.349 | |
| | Gaussian | Petermann |
| Spot Radius: | 3.3791 | 3.2944 μ m |
| ESI Core Radius: | 2.5041 | 2.4413 μ m |
| ESI Delta: | .0054 | .0057 |
| Nc-Ncl: | .0079 | .0084 |
| Numerical Aperture: | .1523 | .1562 |

APPENDIX

VARIABLE APERTURE PATTERN AT 1280 nm
 ID: 920206 SMTN D882.1 T+1000M 60U/90U 28-J



MFD: Gaussian= 7.07

File: 5811

Petermann=6.74

Figure 9
Mode Field Diameter (60 μm Diameter)

Table 6. Fiber ESI Parameters (60 μm Diameter)

File: 5811
 Measurement Wavelength: 1280 nm
 Cutoff Wavelength: 874 nm
 Conversion Factor: 1.566

| | Gaussian | Petermann | |
|---------------------|----------|-----------|----|
| Spot Radius: | 3.5327 | 3.3685 | um |
| ESI Core Radius: | 2.2556 | 2.1507 | um |
| ESI Delta: | .0052 | .0057 | |
| Nc-Ncl: | .0075 | .0083 | |
| Numerical Aperture: | .1483 | .1556 | |

APPENDIX

5.0 DISCUSSION AND FUTURE WORK

Approximately 5500 meters of 80 μm /137 μm fiber was successfully fabricated and delivered to NRL. This fiber met all target optical and mechanical specifications.

For the first time, experiments to produce fiber with reduced diameter claddings and coatings were attempted. Fibers with cladding/coating diameters of 60 μm /90 μm and 70 μm /100 μm were successfully fabricated. Fiber with a coating thickness of 5 μm was attempted, but proved to be extremely fragile.

The fiber sample with a 70 μm cladding diameter met most target specifications; however, some increase in optical attenuation was noted. The fiber sample with a 60 μm cladding diameter showed a significant increase in attenuation at 1320 nm. This effect is probably the result of the short cutoff wavelength (873 nm) of the fiber and to the reduced cladding diameter. Fiber designs which operate at low V numbers ($V \sim 1.6$ for this sample) are very sensitive to increases in macro and microbending induced attenuation. The reduced cladding diameter also increases the fiber sensitivity to microbending effects. Other possible causes for this attenuation increase include spreading of the optical mode into the higher loss substrate tube and UV induced radiation damage to the GeO_2 doped fiber core.

Detailed investigation of these effects has not been performed due to the limited time remaining to complete the contract requirements. Additional fiber samples are in preparation and will be delivered to NRL in the final contract reporting period.