Fabrication, Measurement, and Alignment Uniformity Analysis of Linear Arrays of Optical Fibers

Federal Manufacturing & Technologies

P. E. Klingsporn

KCP-613-5317

Published June 1997

Topical Report

C. E. Watterson, Project Leader

Approved for public release; distribution is unlimited.

Prepared Under Contract Number DE-ACO4-76-DP00613 for the
United States Department of Energy

MASTER
AlliedSignal
AEROSPACE

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

**Portions of this document may be illegible
in electronic image products. Images are
produced from the best available original
document.**

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

All data prepared, analyzed and presented has been developed in a specific context of work and was prepared for internal evaluation and use pursuant to that work authorized under the referenced contract. Reference herein to any specific commercial product, process or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof or AlliedSignal Inc.

Printed in the United States of America.

This report has been reproduced from the best available copy.

Available to DOE and DOE contractors from the Office of Scientific and Technical Information, P. O. Box 62, Oak Ridge, Tennessee 37831; prices available from (615) 576-8401, FTS 626-8401.

Available to the public from the National Technical Information Service, U. S. Department of Commerce, 5285 Port Royal Rd., Springfield, Virginia 22161.

A prime contractor with the United States
Department of Energy under Contract Number
DE-ACO4-76-DP00613.

AlliedSignal Inc.
Federal Manufacturing & Technologies
P. O. Box 419159
Kansas City, Missouri
64141-6159

KCP-613-5317
Distribution Category UC-706

Approved for public release; distribution is unlimited.

FABRICATION, MEASUREMENT, AND ALIGNMENT UNIFORMITY ANALYSIS OF LINEAR ARRAYS OF OPTICAL FIBERS

P. E. Klingsporn

Published June 1997

Topical Report
C. E. Watterson, Project Leader

Project Team:
P. M. Mizik
D. N. Moore
M. W. Moore
J. H. Williams

Contents

<i>Section</i>	<i>Page</i>
Abstract	9
Summary	9
Discussion	11
Scope and Purpose	11
Activity	11
Background	11
Factors Affecting Alignment Uniformity	15
Measured Geometry of V-Grooves	21
Preparation of a Linear Array Assembly	22
Measurement of Fiber Cross-Section Geometry	23
Measured Uniformity of Linear Fiber Array	25
Analysis of the Linear Array Fiber Uniformity	26
Accomplishments	28
Future Work	29
References	31

Illustrations

<i>Figure</i>	<i>Page</i>
1 (a) Three Major Crystallographic Planes and the Corresponding Crystallographic Directions; (b) Geometry of the Etched V-Grooves in the Silicon Plates Used in This Study	12
2 Geometry Used in Determining the Half-Angle, θ , Between the Groove Faces, in a Plane Mutually Perpendicular to the Faces, for the Silicon Plate Geometry Shown in Figure 1b	13
3 Cross-Section View of Two Schemes for Capturing Optical Fibers in a Linear Array: in (a), One V-Groove Plate and a Flat Plate, and in (b), Two V-Groove Plates Placed in Opposition to One Another Around the Fibers	14
4 Geometry Used in Deriving Equation 5 of the Text	16
5 Geometry Used in Deriving Equation 8 of the Text	18
6 Change in Elevation of Fiber Center as a Function of Fiber Diameter Variation (δd) at Constant Groove Width and as a Function of Groove Width Variation (δw) at Constant Fiber Diameter	19
7 Geometry Used in Deriving Equations 10, 13, and 14 of the Text	20
8 Cross Section of a Silicon Plate Showing Location of a Line aa' Parallel to Plate Top Surface for Measurement of Groove Separation	22
9 Fixture for Holding Linear Array Assembly in Place During Polishing in a Plane Perpendicular to the Fiber Axis	24
10 (a) Fiber Cross Section Showing Definition of Coordinates for Concentricity Measurements; (b) Straight Line AA' Defined by the Measured Coordinates of Centers of Mode Fields of the First and Last Fibers in the Linear Array	27

Tables

<i>Number</i>		<i>Page</i>
1	Measured Separation of Adjacent V-Grooves in Silicon Plates	23
2	Measured Concentricity of Outer Fiber Diameter Relative to Mode Field Center	25
3	Alignment Uniformity Measurements of the Mode Field Centers of the Optical Fibers in the Linear Arrays	26
4	Comparison of Max/Min Variation in Groove Separation, Fiber Outer/Inner Concentricity, and Average Max/Min Fiber Spacing Variation in Array	28

Abstract

Techniques were developed for assembling a linear array of optical fibers between two silicon plates and polishing the fiber ends in a plane perpendicular to the fiber axis. The silicon plates contained etched V-grooves for capturing the fibers. Optical fibers from two sources were evaluated, along with silicon plates supplied by two sources. Most of the arrays were assembled by epoxy bonding, but some effort was made to form a eutectic bond using gold metallized fibers with gold-coated silicon plates. Measurements were made of the uniformity of spacing of the fiber mode field centers in the linear array. The work was performed to develop a multi-fiber linear array connector to couple optical signals to and from optoelectronic devices.

Summary

Linear arrays of optical fibers were formed by bonding the end portions of fibers between two silicon plates and polishing the fibers in a transverse plane. The uniformity of spacing of fiber mode field centers in the array was measured by laser interferometry. The work was done to provide a precision multifiber connector array for coupling optical energy to and from optoelectronic devices.

The silicon plates contained etched V-grooves for capture of the fibers. Silicon plates from two sources were evaluated. Prior to assembly of the array, the uniformity of spacing of the V-grooves was measured. The grooves in plates provided by one vendor had an average spacing of $250.17 \mu\text{m} \pm 1.38 \mu\text{m}$. Plates supplied by the other vendor had a groove spacing of $250.17 \mu\text{m} \pm 0.76 \mu\text{m}$. All assemblies were formed with plates from the first vendor because the depth of etched grooves in the plates of the other vendor was too deep for capture of the fibers between two opposing plates.

Two types of fused silica optical fiber were evaluated. All fibers were $125 \mu\text{m}$ outer diameter and had mode field diameter of

$8\text{-}8.5 \mu\text{m}$. One fiber was a polarization-maintaining single-mode optical fiber, and the other was a single-mode step-index fiber. Laser interferometry measurements under controlled temperature and humidity conditions showed that the degree of concentricity of the polarization-maintaining fiber mode field relative to the outer diameter was $0.85 \mu\text{m} \pm 0.76 \mu\text{m}$ among 18 fibers measured. The step-index fibers had a higher degree of concentricity with a value of $0.49 \mu\text{m} \pm 0.37 \mu\text{m}$ among 50 fibers measured.

Epoxy was used to bond the silicon V-groove plates in intimate contact with the fibers, and a device was built to hold the linear array for polishing in a plane perpendicular to the fiber axis. Laser interferometry was also used to measure the uniformity of the mode field centers of the fibers forming the array. One plate contained 12 step-index fibers in the array with a measured average separation of $249.87 \mu\text{m} \pm 0.68 \mu\text{m}$. A linear array assembled with the polarization-maintaining fibers had a measured spacing uniformity of $249.92 \mu\text{m} \pm 3.63 \mu\text{m}$.

Two assemblies were fabricated in which a eutectic bond was used to secure step-index fibers in place between the silicon plates. The measured spacing uniformity of fibers in these assemblies, $\pm 1.78 \mu\text{m}$ and $\pm 1.50 \mu\text{m}$, were not nearly as good as the spacing in the epoxy-bonded assemblies.

An analysis was made of the effects of variations of fiber outer diameter and V-groove width on the position of fiber centers in the linear array. The effect of variation in registration of grooves of the two plates was analyzed with respect to the effect on fiber uniformity spacing in the array.

Discussion

Scope and Purpose

Techniques were developed for assembling linear arrays of optical fibers and polishing the fibers in a transverse section, and measurements were made of the fiber uniformity of spacing in the transverse plane. The development work was done to provide a capability for coupling optical signals to and from optoelectronic devices using a precise multi-fiber connector.

Activity

Background

Silicon plates containing etched V-grooves to align an array of optical fibers have been used earlier.¹ (A novel fiber coupling scheme was recently reported concerning a put-in arrangement with an integral planar microlens substrate, but the accuracy, $\pm 8 \mu\text{m}$, is not nearly as good as that achieved with V-grooves.)² Silicon is an appropriate choice because of its availability and because grooves can be formed accurately in it through a process of photomasking and etching. The way in which accurate V-grooves are formed in silicon can be understood with reference to Figure 1a, which shows three major crystallographic directions and their corresponding planes. A plane parallel to the x-y plane and intersecting the z-axis at unit distance is the (100) plane and, by definition, the z-axis is the "100 direction," denoted by $\langle 100 \rangle$. Similarly, a (110) plane is a plane parallel to the z-axis,

intersecting the x- and y-axes at unit distances from the origin; the direction perpendicular to the plane is the $\langle 110 \rangle$ crystallographic direction. The (111) plane is the plane that intersects the x-, y-, and z-axes at unit distance; a perpendicular to this plane defines the $\langle 111 \rangle$ crystallographic direction.

It is known experimentally that silicon exposed to a basic solution will etch at a greater rate in the $\langle 100 \rangle$ direction than in the $\langle 111 \rangle$ direction. Therefore, when a silicon block is prepared with a (100) face and an oxide mask is applied to the face, submersion of the masked block in the etchant will result in the formation of "V-grooves," with (111) faces exposed. The etching process proceeds until the exposed (111) faces intersect, forming the vertex of the groove as shown in Figure 1b. The included angle between the V-groove faces, in a plane mutually perpendicular to the faces, can be calculated with the aid of the geometry in Figure 2. Each face of the groove makes an angle of 54.736° with the horizontal, and hence the angle between the two intersecting faces is twice the complement of 54.736° , or 70.528° .

Two possible schemes for using the silicon V-groove plates to capture optical fibers for alignment purposes are shown schematically in Figure 3. In Figure 3a, the fibers are placed in the grooves and a flat plate is positioned over the fibers to hold them in the grooves. A somewhat better arrangement is shown in Figure 3b in which two silicon plates with identical groove geometry are positioned with the

(a)

(b)

Figure 1. (a) Three Major Crystallographic Planes and the Corresponding Crystallographic Directions; (b) Geometry of the Etched V-Grooves in the Silicon Plates Used in This Study

Figure 2. Geometry Used in Determining the Half-Angle, θ , Between the Groove Faces, in a Plane Mutually Perpendicular to the Faces, for the Silicon Plate Geometry Shown in Figure 1b

V-groove faces in opposition, to capture the fibers symmetrically.

It can be argued that it is advantageous for the fiber to make contact with the (111)

faces of the groove in contrast with the case in which the fiber contacts the plate only at the groove entrance. This implies, for a given fiber diameter, that the groove width must be equal to or greater than a

Figure 3. Cross-Section View of Two Schemes for Capturing Optical Fibers in a Linear Array: in (a), One V-Groove Plate and a Flat Plate, and in (b), Two V-Groove Plates Placed in Opposition to One Another Around the Fibers

certain value. If d is the fiber diameter, it can be seen from Figure 3 that the groove width, for which the fiber will contact the (111) groove faces, must be equal to or greater than the value

$$w \geq d \cos 35.264^\circ$$

$$= 0.8165 d. \quad (1)$$

However, when the fibers are captured by two plates with opposing grooves as in Figure 3b, the groove width must not exceed a certain value, or else the fiber will not make simultaneous line contact with both groove faces. From the geometry of Figure 3b, this limiting value of width is

$$w \leq \frac{d}{\cos 35.264^\circ}$$

$$= 1.2247 d. \quad (2)$$

It follows that the groove width at the surface must lie within the bounds given by

$$0.8165d < w < 1.2247d, \quad (3)$$

if a fiber of diameter d is to be captured in intimate contact with the (111) faces of both V-groove plates in the geometry of Figure 3b.

When the geometry of Figure 3a is employed, the groove width must not be too wide for a given fiber diameter, or else the flat plate will not contact the fibers for the purpose of maintaining the fibers in contact with the (111) faces of the V-groove plate. The limit on groove width for a given

fiber diameter can be determined from Figure 3a, which yields the relation

$$\tan \theta = \frac{w}{d \left(1 + \frac{1}{\sin \theta} \right)}, \quad (4)$$

where $\theta = 35.264^\circ$. Solving the latter for w gives

$$w \leq 1.9318 d.$$

Factors Affecting Alignment Uniformity

Fiber Outer Diameter

For a V-groove of fixed geometry, that is, constant groove width and constant included angle between the groove faces, the elevation of the center of a fiber lying in the groove is dependent on the radius of the fiber. The relationship between the fiber elevation and fiber radius can be obtained with reference to Figure 4, in which it is assumed that the fiber is in contact with the groove faces as discussed earlier in relation to the condition given by Equation 1. Let θ be half the included angle between the faces. Then from Figure 4, it can be seen that the elevation of the fiber center relative to the vertex of the groove is

$$H = \frac{d}{2 \sin \theta}. \quad (5)$$

From Equation 5, it can be seen that the variation in fiber elevation as a result of

Figure 4. Geometry Used in Deriving Equation 5 of the Text

fiber size variation is

$$\delta H = \frac{\delta d}{2 \sin \theta} \quad (6)$$

For silicon V-grooves of the type shown in Figure 1b, the angle θ is 35.264° and hence Equation 6 yields

$$\delta H = 0.866 \delta d. \quad (7)$$

V-Groove Width

Consider the case in which fibers of constant diameter lie in V-grooves characterized by constant included angle between the faces, but slightly varying width. The way in which groove width variation affects the elevation of the fiber center relative to the groove can be determined with the aid of Figure 5, where it is assumed again that the condition of Equation 1 holds so that the fiber contacts the groove faces at some point below the groove entrance. Referring to Figure 5, the change in fiber center elevation relative to the top of the plate, for a groove width variation δw , is

$$\delta H = \frac{\delta w}{2 \tan \theta}, \quad (8)$$

where w is the groove width. Taking into account the fact that the angle θ is 35.264° for silicon, the variation in fiber elevation caused by a variation in groove width is

$$\delta H = 0.707 \delta w. \quad (9)$$

The results of Equations 7 and 9 are displayed graphically in Figure 6. For grooves of constant included angle, a given variation in fiber diameter for constant groove width causes variation in fiber elevation (in absolute value) 22.4% higher than that caused by the same variation in groove width for constant fiber diameter.

Registration of Grooves in One Plate Relative to Those in Opposing Plate

When variations in fiber outer diameter and shifting of grooves in one plate relative to the capturing grooves in the opposing plate are considered, the geometry assumes many complexities. An understanding can be obtained, however, through the following analysis. It is assumed that the grooves in both plates are all of the same width. (The effect of groove width variation can be accounted for later by applying the results of the analysis associated with Figure 5 to the present analysis). Consider two fibers of the same diameter captured in an array and separated by a number of intervening fibers. Let these two fibers fit the pairs of capturing grooves perfectly. It follows that all the intervening fibers are of diameter equal to or less than the two separated fibers; if this were not so, the two outer fibers would not contact their capturing grooves intimately because a larger intermediate fiber would lift the plate off one of the two fibers. With these conditions in mind, the following questions can be asked.

If the intervening fibers vary as much as ΔD in outer diameter, what shift in groove registration between the two opposing plates can be tolerated while still maintaining the two extreme fibers in intimate contact with their capturing grooves? Furthermore, what is the shift in location of an intermediate fiber in the

Figure 5. Geometry Used in Deriving Equation 8 of the Text

array if its diameter varies by ΔD from that of the two outer fiber diameters? The questions can be answered with the aid of Figure 7 in which the two capturing

grooves are of the same width, but the upper is shifted to the right by the distance ϵ . For no shift, the fiber diameter for perfect capture is $D = 2R$. In the shifted

Figure 6. Change in Elevation of Fiber Center as a Function of Fiber Diameter Variation (δd) at Constant Groove Width and as a Function of Groove Width Variation (δw) at Constant Fiber Diameter

location, the fiber of smaller diameter ($D - \Delta D$) can contact the upper shifted groove on both faces at the extreme position shown, and hence $\cos \theta = (\Delta D)/\epsilon$, which gives

$$\epsilon = \frac{\Delta D}{\cos \theta} \quad (10)$$

Figure 7. Geometry Used in Deriving Equations 10, 13, and 14 of the Text

Now, $\theta = 35.264^\circ$ for the (111) faces of silicon and it follows that a shift in registration of upper and lower capturing grooves in the amount

$$\varepsilon = \frac{\Delta D}{\cos \theta} = 1.2247 \Delta D \quad (11)$$

can be tolerated and still allow perfect capturing of the two outer fibers of diameter D .

From the extreme possible location of the fiber of diameter $D-\Delta D$, it follows from Figure 7 that the x coordinate shift in location of the fiber center in the array is

$$\Delta x = \varepsilon. \quad (12)$$

In the transverse direction, the shift in coordinate of the fiber center is $\Delta y = H - h$. But, from the figure, $H = D/(2 \sin \theta)$ and $h = (D-\Delta D)/2 \sin \theta$, and combining these results with Equation 10 gives

$$\begin{aligned} \Delta y &= H - h \\ &= \frac{\Delta D}{2 \sin \theta} \\ &= \frac{1}{2} \varepsilon \cot \theta = 0.707 \varepsilon. \end{aligned} \quad (13)$$

From Equations 12 and 13, the shift in hypotenuse of the fiber center is

$$\begin{aligned} \Delta_{Hypot.} &= \varepsilon \left(1 + \frac{1}{4} \cot^2 \theta \right)^{\frac{1}{2}} \\ &= 1.2247 \varepsilon. \end{aligned} \quad (14)$$

Measured Geometry of V-Grooves

Two sources of silicon V-groove plates were evaluated, and two sources of optical fiber were included in the study. The silicon plates available from one source contained grooves that were too wide and too deep for the particular fiber diameter ($125 \mu\text{m}$) used and hence linear array assemblies were not made with these plates. The silicon plates available from the other source contained appropriate groove geometry for capture of the $125 \mu\text{m}$ -diameter fibers and therefore assemblies of the type shown in Figure 3b were made with two opposing V-groove plates.

Laser interferometry in a controlled environment of temperature and humidity was used to measure the spacing of adjacent V-grooves in the silicon plates obtained from both sources. The plates were potted in epoxy and sectioned and polished in a plane perpendicular to the length of the grooves. Figure 8 shows a plate cross section and the location for measurement of adjacent groove separation. Results of measurements on five samples from each source of plates are given in Table 1. The intended separation of adjacent grooves was $250 \mu\text{m}$, and it can be seen that both sources meet this requirement very closely. The variation in adjacent groove separation for the plates used, ± 0.80 to $\pm 1.38 \mu\text{m}$ among the samples, is greater than that for the unused plates, ± 0.22 to $\pm 0.76 \mu\text{m}$.

Figure 8. Cross Section of a Silicon Plate Showing Location of a Line aa' Parallel to Plate Top Surface for Measurement of Groove Separation. (The coordinates of the intersections of aa' with the groove face boundaries served as the basis for determining adjacent groove separation, S .)

Preparation of a Linear Array Assembly

To assemble a linear array of fibers, the buffer coating was stripped from a section of the end of each fiber, and the fiber end sections were placed together parallel on a plane surface and secured with a piece of tape, allowing the stripped end sections to be exposed. The fiber end sections were then placed as a unit in the grooves on one silicon plate. Epoxy (Epo Tech 353ND) was applied sparingly over the fiber end sections, and the second silicon plate was placed over the fiber end sections and slid along until the grooves captured the upper portions of the fiber ends. A small weight was applied on the top plate to force the epoxy into a very thin film. The epoxy was

then cured at an elevated temperature near 100°C for 30 minutes.

On the ends to be polished, the fibers were allowed to extend slightly beyond the ends of the silicon plates, and a small amount of epoxy, squeezed out between the plates before curing, surrounded the fiber ends and served to support them later during the initial steps of coarse lapping. A fixture in the form of a stainless steel plate 2 inches in diameter and 0.25-inch thick was used to hold the assembly during lapping and polishing, as shown in schematic cross section in Figure 9. The plate contained a rectangular opening to hold the fiber axis perpendicular to the polishing face of the plate. The sides of the rectangular opening contained a wedge-shaped piece that was forced against the plates as the

Table 1. Measured Separation of Adjacent V-Grooves in Silicon Plates

Plate Source	Sample	Number of Adjacent Grooves	Measured Separation (μm)
Vendor 1	1	22	250.18 $\pm$ 1.04
	2	22	250.17 $\pm$ 1.38
	3	22	250.22 $\pm$ 1.26
	4	22	250.18 $\pm$ 0.80
	5	18	250.10 $\pm$ 1.23
Vendor 2	1	12	250.00 $\pm$ 0.23
	2	12	250.16 $\pm$ 0.69
	3	12	250.39 $\pm$ 0.76
	4	12	249.99 $\pm$ 0.22
	5	12	250.32 $\pm$ 0.50

surrounding nut was tightened, thereby holding the silicon plate assembly firmly in the rectangular aperture and maintaining its axis perpendicular to the polishing surface.

A standard lapping and polishing procedure was used that involved the use of successively finer grit-size aluminum oxide polishing media, with a final polishing step using aluminum oxide and cloth.

Measurement of Fiber Cross-Section Geometry

The first array that was fabricated contained polarization-maintaining single-mode optical fiber. As a first step in the overall evaluation of the alignment accuracy, laser interferometry measurements under controlled conditions of temperature and

humidity were made to determine the degree of concentricity of the fiber outer diameter relative to the center of the central mode field. This was done by measuring the x-y coordinates of each of a number of points on the fiber outer diameter and using this data to obtain the equation of a best-fit circle. The coordinates of the center of the circle represented the center of the fiber outer diameter in the polished plane. Next, the measurement system was used to determine the coordinates of the center of the fiber mode field. The degree of concentricity was then obtained by calculating the distance between the two points, as indicated in Figure 10a. The result for an average of 18 fibers is given in Table 2. Among the 18 fibers, the concentricity ranged from 0.09 μm to 1.61 μm , which is 0.85 μm $\pm$ 0.76 μm .

Figure 9. Fixture for Holding Linear Array Assembly in Place During Polishing in a Plane Perpendicular to the Fiber Axis

Additional assemblies were fabricated, all of which contained single-mode step-index optical fibers. The number of fibers contained in a given assembly varied from

eleven to fifteen. The foregoing procedure was followed in measuring the concentricity of the fibers in the polished plane, and the results are given in Table 2, along with

Table 2. Measured Concentricity of Outer Fiber Diameter Relative to Mode Field Center

Fiber Source	Number of Fibers	Outer Diameter* (μm)	Measured Concentricity (μm)
Polarization-Maintaining	18	+/- 4.3	0.85 +/- 0.76
Step-Index	15	+/- 0.9	0.44 +/- 0.37
Step Index	11	+/- 1.05	0.43 +/- 0.26
Step-Index	12	+/- 0.67	0.68 +/- 0.53
Step Index	12	+/- 1.06	0.42 +/- 0.35

*Nominal: 125 μm

those for the other fibers. From these results, it can be seen that the step-index fibers possess a much higher degree of concentricity than the other fibers. The eccentricity of the step-index fibers is approximately half that of the other fibers. Also, the outer diameters of the step-index fibers are much more uniform.

Measured Uniformity of Linear Fiber Array

The coordinates of the center of the mode field diameter measured for each fiber in the array provided a data base for determining the uniformity of spacing of the fibers in the array. The first column of Table 3 gives the average separation of adjacent fibers in the array, measured along the x-axis of the array, as indicated in Figure 10b.

The second column in Table 3 gives the uniformity of alignment of the fibers in the direction (y-axis) perpendicular to the axis of the array. The data in the second column were obtained as follows. The coordinates of the centers of the first and last fibers in the array were used to define a straight line; the perpendicular distance of the center of each fiber from the straight

line so defined was then calculated, and the results constitute the second column of Table 3.

The data in the first row of Table 3 show that the linear array with the polarization-maintaining fibers is not nearly as uniform as those arrays fabricated with the step-index fibers. This is to be expected based on the fiber diameter and concentricity measurements of Table 2, which show that the polarization-maintaining fibers are not as precise as the step-index fibers. Hence, the former linear array would not be expected to be as uniform as the step-index linear arrays.

The polarization-maintaining linear fiber array and the first three step-index fiber linear arrays listed in Table 3 were bonded with epoxy, as described earlier. The data given in the last two rows of Table 3 are for eutectic-bonded linear arrays in which the step-index fibers had been coated with 2 to 3 μm of gold on a radius and the silicon plates had been metallized with 6 μm of gold. The fiber mode field centers in the eutectic-bonded arrays are not nearly as uniform as those in the epoxy-bonded linear arrays with step-index fibers. This may be due to variability of the gold coatings and a slight

Table 3. Alignment Uniformity Measurements of the Mode Field Centers of the Optical Fibers in the Linear Arrays

Assembly	Number of Fibers	Measured Alignment Uniformity	
		Δx , Adjacent Fiber Separation* (μm)	Δy , in Direction Transverse to Array Axis* (μm)
Polarization-Maintaining	18	249.92 +/- 3.63	0.46 +/- 1.41
Step-Index	15	250.13 +/- 0.96	0.25 +/- 0.48
Step Index	12	249.65 +/- 0.99	0.71 +/- 1.03
Step-Index	12	249.87 +/- 0.68	0.35 +/- 0.35
Step Index**	12	250.47 +/- 1.78	0.90 +/- 1.16
Step Index**	13	249.95 +/- 1.50	0.51 +/- 0.80

* Refer to Figure 10.

** Eutectic-bonded assembly. Fiber end portions contained gold coating approximately 2.5 μm thick on radius, and the silicon plates were gold-metallized to approximate thickness of 6 μm , prior to assembly.

loss of groove boundary uniformity as the gold-silicon eutectic is formed.

Analysis of the Linear Array Fiber Uniformity

A reasonable assumption is that the variation in measured uniformity of spacing in the fiber mode centers of the array is a combination of the variation of groove spacing and lack of concentricity of the fiber outer diameter with respect to the fiber mode center. Based on this, the variation in the array would be expected to be greater than either the groove uniformity or the degree of concentricity of the fibers themselves. In approximate terms, the variation in the array assembly might be expected to be equal to the variation in fiber uniformity plus the variation in groove spacing. However, the data of Tables 1, 2,

and 3 do not show this trend. This can be seen through the comparison of data presented in Table 4 which lists the average max/min variation in groove spacing (obtained from Table 1), the average fiber concentricity (obtained from Table 2), and the average max/min spacing of all measurements in Table 3. The fiber outer diameter uniformity data of Table 2 is not included in this analysis of adjacent fiber spacing uniformity because fiber outer diameter variations would influence only the uniformity in the direction perpendicular to the linear array axis.

Note from Table 4 that, although the max/min variation in spacing in the linear array assembly is nearly twice the eccentricity of the fibers, the variation in the array assembly is actually 23% less than the variation in V-groove spacing. If the component variations of groove spacings

Figure 10. (a) Fiber Cross Section Showing Definition of Coordinates for Concentricity Measurements; (b) Straight Line AA' Defined by the Measured Coordinates of Centers of Mode Fields of the First and Last Fibers in the Linear Array. (Adjacent fiber spacings (Δx) measured along AA', and transverse uniformity (Δy) measured in direction perpendicular to AA'.)

Table 4. Comparison of Max/Min Variation in Groove Separation, Fiber Outer/Inner Concentricity, and Average Max/Min Fiber Spacing Variation in Array*

Entity	Average Max/Min Variation (μm)
Silicon Plate V-Grooves	+/- 1.14
Fiber Concentricity	+/- 0.49
Fibers in Array Assembly	+/- 0.88

*Step index fibers and epoxy-bonded assemblies

and fiber eccentricity were simply added, then a variation of $\pm 1.63 \mu\text{m}$ might be expected, but the measured variation in the array is only 54% of this value.

A possible explanation for this is as follows. Measurements of the groove spacing are made in a plane perpendicular to the length of the groove. Any given groove may meander slightly by a few tenths of a micron, along its length, relative to its neighboring adjacent groove. However, when a fiber is placed in a groove, its resting position represents a smoothing of the micron-size variations that may occur along the length of the groove. The final fiber location, therefore, represents a mathematical best-fit of a cylinder in the groove, and likewise for each fiber. Consequently, the spacing between adjacent fibers can be expected to be more uniform than the adjacent groove spacing measurement representing only one transverse plane of the grooves.

Accomplishments

Techniques were developed for assembling linear arrays of optical fibers between two silicon plates and polishing the fiber ends in a plane perpendicular to the fiber axis. The silicon plates contained etched V-grooves

for capture and alignment of the fibers, and epoxy was used to bond most of the assemblies that were fabricated. Eutectic bonding was used to bond two assemblies.

The primary goal of the work was to obtain precisely aligned linear arrays of optical fibers for coupling of energy from optoelectronic devices. To this end, laser interferometry under controlled conditions of temperature and humidity was used to measure the uniformity of the grooves in the silicon plates, the degree of concentricity of the fiber outer diameter with regard to the fiber mode field center, and, ultimately, the uniformity of spacing of the fiber centers in the polished linear arrays.

The V-groove silicon plates were obtained from two sources. The nominal spacing of the grooves was $250.0 \mu\text{m}$. One vendor's silicon plates had a uniformity in spacing of $\pm 0.76 \mu\text{m}$ whereas plates obtained from the other vendor were not quite as good, showing a variation of $\pm 1.38 \mu\text{m}$. A single-mode polarization-maintaining optical fiber of diameter $125 \mu\text{m}$ showed a concentricity of $0.85 \mu\text{m} \pm 0.76 \mu\text{m}$. The other fiber investigated was single-mode step-index, and the concentricity was measured as $0.49 \mu\text{m} \pm 0.37 \mu\text{m}$.

Although the one set of plates possessed more uniformly spaced grooves, the groove depth and width were slightly too large for capture of the particular fiber diameter, 125 μm . Therefore, the second vendor's plates which had proper groove geometry for the fiber were used in all assemblies. Laser interferometric measurements of the polished fiber mode field centers in a linear array fabricated with step-index fibers showed spacing of 249.87 μm $\pm$ 0.68 μm . The variation in spacing in the finished array, $\pm$ 0.68 μm , is considerably less than the average variation of the grooves alone, $\pm$ 1.14 μm , and, of course, less than the worst case sum of the average individual fiber concentricity ($\pm$ 0.49 μm) plus the groove separation variation ($\pm$ 1.14 μm). The reason for this, it is believed, is that the adjacent groove spacing measurements in one transverse plane of the silicon plates do not adequately reflect the uniformity of spacing of the adjacent grooves when considered along the entire length of the groove. The end portion of a given fiber actually assumes a best-fit location along the groove length and hence the actual positions of any two adjacent fibers are expected to be more uniform than adjacent groove separation measured only in one transverse plane.

Analytic expressions were derived giving the dependence of fiber center location as a function of groove width variation and fiber outer diameter variation. Also, the effect of varying registration of the grooves in one plate relative to those in the opposing plate was treated analytically in relation to fiber center location.

Future Work

The techniques developed for the linear array will be extended to the fabrication and measurement of two-dimensional arrays of optical fibers. This may include silicon plates with V-grooves on both sides of each plate and/or other configurations for holding the fibers in precise alignment.

References

¹C. M. Schroeder, "Accurate Silicon Spacer Chips for an Optical-Fiber Cable Connector," *The Bell System Technical Journal*, January 1978, pp 91-97.

²A. Sasaki, T. Baba, and K. Iga, "Put-In Microconnectors for Alignment-Free Coupling of Optical Fiber Arrays," *IEEE Photonics Technology Letters*, Vol. 4, No. 8, 1992, pp 908-911.