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Fiber-Optic Array Splicing with Etched Silicon Chips

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The two-dimensional array splicing concept using aluminum chips was reported earlier as a technique that is potentially suitable for field-splicing an optical cable containing linear arrays of optical fibers. Two arrays are stacked, epoxied, polished, and positioned to form a butt-joint splice. This paper reports the use of preferentially etched silicon chips to fabricate higher precision arrays which deviate from perfect uniformity by only 2.5 μm (0.0001 inch) on the average. Average losses for splices assembled with these arrays have been in the range 0.16 dB to 0.32 dB with a yield of 98.8 percent. These average losses are close to the anticipated values based on the measured mean offset between corresponding fiber axes in the spliced arrays. After several combinations of arrays were assembled and loss measurements made, the original array configuration was measured to test for array deterioration, loss measurement repeatability and final alignment repeatability. Only one fiber position showed evidence of contamination, and the mean splice loss was repeatable to within 0.02 dB.

I. INTRODUCTION

A two-dimensional array splicing approach for connecting fiber optic cable has been reported previously.[1] This mass splicing technique has given encouraging results and was used in the Atlanta Fiberguide System Experiment. The method of fabrication of the connector halves involves the following operations:[1,2]

(*i*) Ribbons containing linear arrays of fibers are prepared by removing all ribbon and coating material from the fibers at the end of the ribbons.
(*ii*) A stack is formed by interleaving chips and layers of fibers to form a two-dimensional array (see Fig. 1).
(*iii*) The array is potted to maintain the geometry.

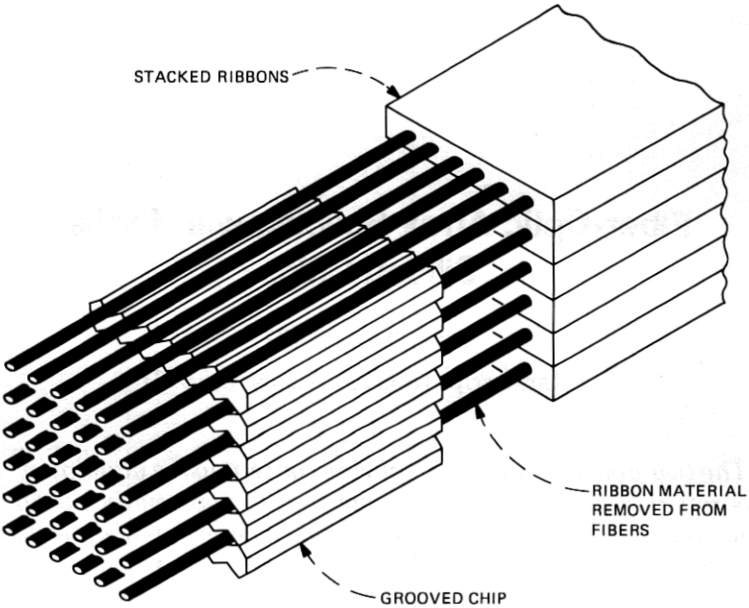

Fig. 1—Stacking fiber ribbons.

(*iv*) "Good ends" on all fibers in the array are obtained by grinding and polishing the array.

(*v*) An array splice is made by butting two arrays, prepared as previously described; the arrays are held in position using the unoccupied grooves on top and bottom of the array for final alignment.

The purpose of this paper is to give a progress report on the array splicing method for connecting groups of optical fibers. Improvements in the chips and in the fabrication of the arrays are described. A method is given for determining a "figure of merit" for a two-dimensional array. Four array-splice loss tests are described and correlation of loss and offset is presented.

II. IMPROVEMENTS

Several improvements have been incorporated in the process for fabrication of two-dimensional arrays. These include improved tools and fixtures for assembly and end preparation. A stack of 12 prepared ribbons interleaved between 13 chips can be assembled without microscopes or micromanipulators in approximately 10 minutes. An improved, simplified polishing fixture has replaced the previous version.[2] This fixture uses a negative chip mounted to the inside wall of the holding fixture to accurately position the array.

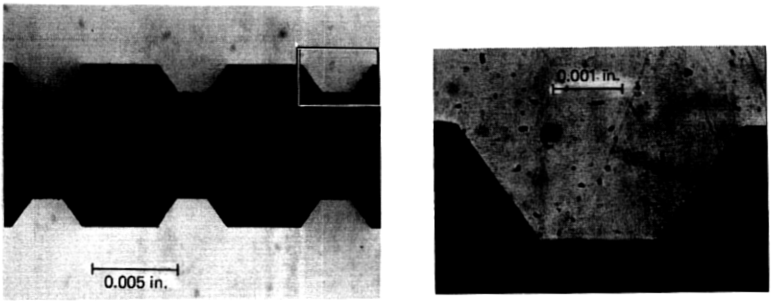

Fig. 2—Silicon chip cross section.

The most significant improvement in the array splicing technique has been the introduction of preferentially etched silicon chips.[3] These chips were developed and produced by C. M. Schroeder[6] at Western Electric Engineering Research Center using photolithographic techniques applied to (100) oriented silicon wafers. Oxide masks are generated on both surfaces of the silicon wafer and the wafer is submerged in a basic solution such as potassium hydroxide. The etch rate in the unmasked region in the (100) direction is much greater than in the (111) direction. Groove angles are dependent only on the accuracy of slicing the wafer relative to the crystal axis, which is on the order of 1°. Groove opening is dependent only on the mask accuracy which is approximately ±1 micron. Alignment between top and bottom grooves is accomplished by using a dual exposure channel with near collimated ultraviolet light. Finished wafers are laser scribed and broken into individual chips. Figure 2 consists of two photographs of the cross section of a typical silicon chip. A companion paper[6] describes the chip fabrication process in greater detail. Occasionally groove bridges occur (perhaps in 1 percent of the chips) which must be detected by visual inspection and discarded. Figure 3 shows a bridged groove on a silicon chip.

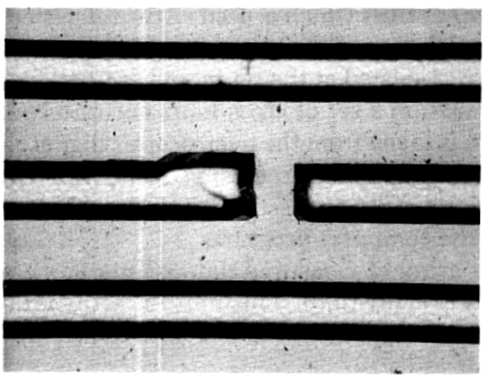

Fig. 3—Bridged groove on a silicon chip.

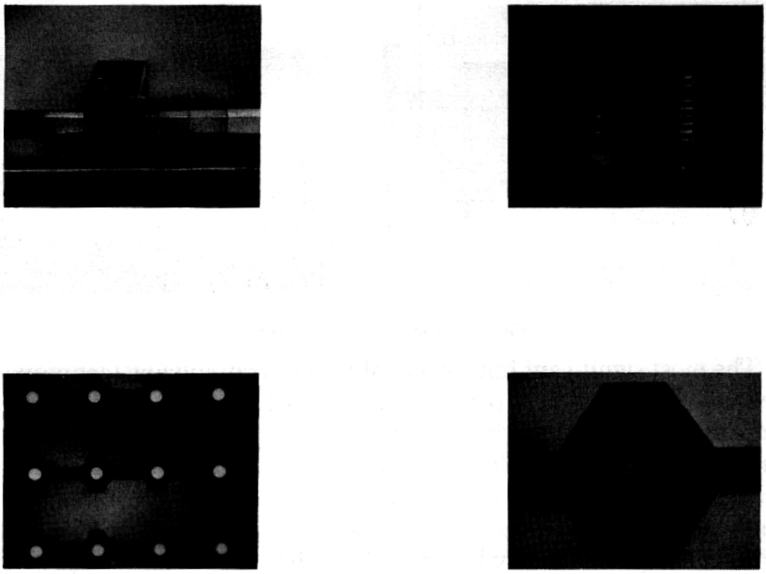

Fig. 4—Array splicing.

Connectors assembled with silicon chips have given greatly improved array alignment. Figure 4 shows three views of a connector end at different magnifications. The completed splice shown in Fig. 4 is one of the splices used in the Atlanta Fiberguide System Experiment.

III. ARRAY ALIGNMENT MEASUREMENTS

An accurate method has been developed for determining an alignment "figure of merit" which characterizes the degree of uniformity of a two-dimensional array. A Leitz-Leica Microscope with a micrometer stage is used to measure the coordinates (x,y) of each fiber in the array relative to a corner fiber which is used as the reference origin (0,0). The accuracy and resolution of these measurement is ±1.25 micron. A small dark spot which is located at the center of the fiber core* (as seen in Fig. 4) is used to position a set of cross-hairs accurately and quickly. The coordinate data is taken from the microscope's digital readout and typed into a computer data file for processing. Iterative programs are used to generate a uniform array of "best fit." The flow chart of Fig. 5 maps the main loops in the computer programs.

Consider an array of measured data points (x,y) as compared to a perfectly uniform array (u,v). The uniform array is defined by a value for the uniform spacing of points along both coordinate axes (x_s,y_s), the

* The dark spot is thought to be due to loss of germania or the inside surface of the preform which produces a dip in the index of refraction.

origin relative to the origin of the measured data (x_o,y_o) and the angle between the u-axis of the uniform array and the x-axis of the measured data (θ).

The measured data is transformed by translation and rotation into the coordinate system of the uniform array by the following transformations.

$$x_t = a_{11}x + a_{12}y + b_1$$

$$y_t = a_{21}x + a_{22} + b_2$$

where

$$a_{11} = a_{22} = \cos\theta$$

$$a_{12} = \cos\left(\frac{\pi}{2} - \theta\right)$$

$$a_{21} = \cos\left(\frac{\pi}{2} + \theta\right)$$

and

$$b_1 = -x_o \cos\theta - y_o \sin\theta$$

$$b_2 = x_o \sin\theta - y_o \cos\theta.$$

The magnitude and angle of the vector, q_i, joining the ith point of the uniform array with the corresponding ith transformed data point is calculated as simply

$$|q_i| = (x_{t_i} - u_i)^2 + (y_{t_i} - v_i)^2$$

and

$$\angle q_i = \arc\tan\frac{y_{t_i} - v_i}{x_{t_i} - u_i}$$

The parameters of the uniform array, θ, x_o, y_o, x_s and y_s are now changed systematically according to the flow charts in Fig. 5 by using two separate computer programs. When this "number-crunching" is finished, the output gives the values of θ, x_o, y_o, x_s and y_s that define a uniform array of "best fit." That is, the mean value of $|q_i|$ is a minimum for this uniform array. This minimum mean value of $|q_i|$ is used as a "figure of merit" for the connector being characterized. The x and y components of q_i (the offsets) are calculated and printed out along with the standard deviation of the minimum $|q_i|$ and the standard deviation of the x and y components of q_i.

Several additional calculations are made as a check on the measured data to eliminate gross errors. A histogram is calculated which gives the number of offsets, $|q_i|$, between o to σ, σ to 2σ, 2σ to 3σ, and greater than

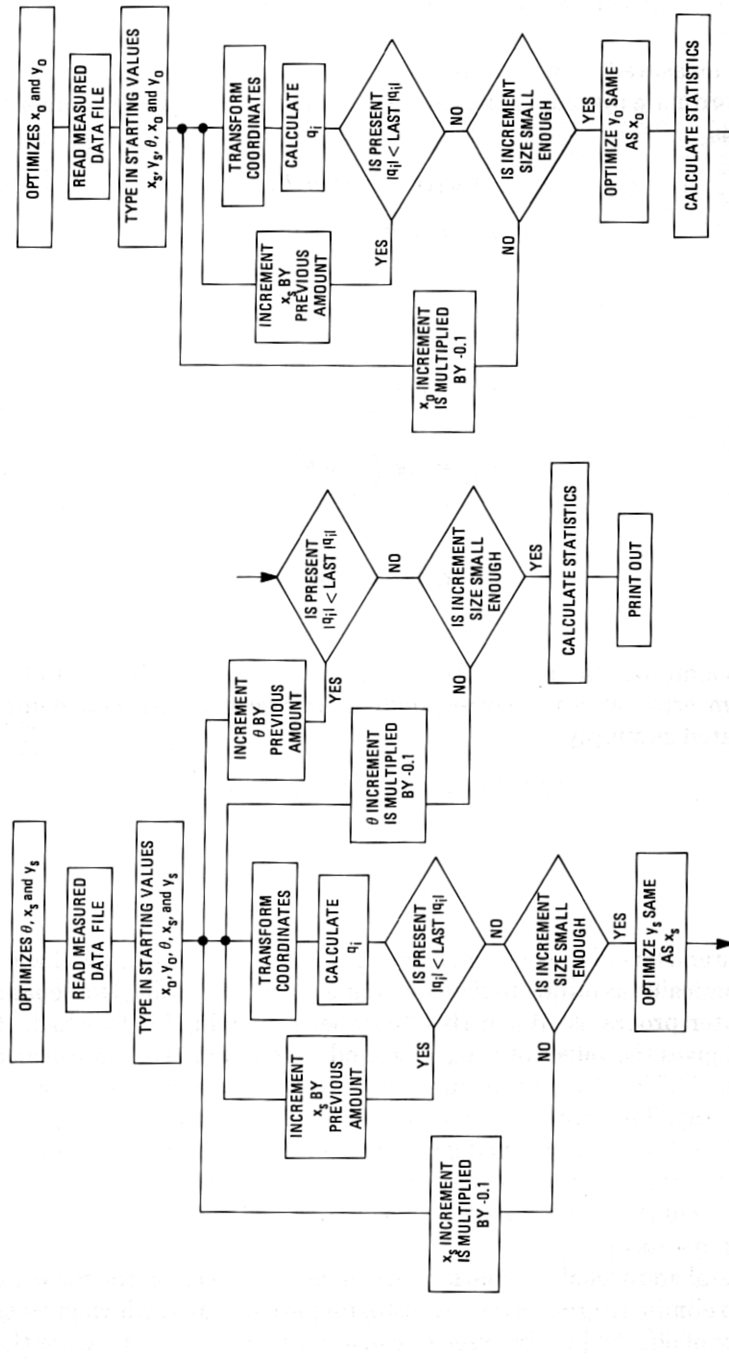

Fig. 5—Flow charts for optimizing θ, x_s, y_s, x_o, and y_o.

3σ. Typically, a few offsets will be in the 2σ to 3σ interval and seldom any greater than 3σ. Also the angle of the offset, $\angle q_i$, places it in one of four quadrants. The distribution of offsets among the four quadrants is printed out as a check to see if the offset vectors are more or less uniformly distributed among the four quadrants.

The primary use of these alignment calculations is for use as a "figure of merit" for an individual connector half. From the outset, it was realized that assembly and measurement of splice loss for a 144-fiber array splice would be tedious and time-consuming. This method of alignment characterization provides a basis for alignment comparison of connector halves, while requiring only one connector half to be assembled and without requiring splices to be assembled or losses to be measured.

IV. ARRAY ALIGNMENT RESULTS

Table I lists the alignment results for selected connector halves. A further description of these connector halves is needed. Connectors 34 and 35 were the last 12 × 12 aluminum chip arrays[1] assembled. The 0.3 mil to 0.4 mil value for the minimum mean offset is typical for 12 × 12 aluminum arrays. (All offset data are in mils, 0.001 inch.)

Silicon chip arrays have from the outset exhibited greatly reduced minimum mean offsets. Connectors 38 through 41 had mean offset values close to 0.1 mil. Connectors 40 and 41 were the input and output fanout connectors for the Atlanta Fiberguide System Experiment. Connectors 45 and 46 were the connector halves on the fiberguide experiment cable. These connectors mated with fanout connectors 40 and 41 to provide access to the cable, and performed satisfactorily. Splice loss data for these specific splices are unavailable due to the fact that they appeared in series with other splices in the system configuration.

V. SPLICE LOSS TEST CONNECTORS

Connectors 47 through 50 were fabricated on the ends of two 0.8 meter long ribbon stacks for the purpose of measuring splice loss for these improved silicon chip arrays. Fiber diameter variations were measured to be approximately ±2.5 percent for the fiber used in these connectors. Connectors 47 and 49 were epoxied at the same time in the holding vise. The stack height for connector 47 was less than that for connector 49 by 0.4 mils and this "slop" may account for the slightly higher minimum mean offset. Connectors 48 and 50 were fabricated separately and gave improved offset characteristics.

VI. LOSS MEASUREMENT PROCEDURE

Array splice losses were measured using the setup shown in Fig. 6. The beam from a Spectra Physics He-Ne laser was expanded and focused with

Table I — Connector data

Connector number	Array size	Material	Min. mean offset, mils	Var. of offset, mils	x_s, mils	y_s, mils	x_o, mils	y_o, mils	θ, millirads
34	12 × 12	Al	0.33	0.20	9.03	9.51	0	−0.19	−1.4
35	12 × 12	Al	0.39	0.18	9.02	9.80	−0.05	−0.17	−2.5
38	12 × 12	Si	0.094	0.05	9.02	11.40	0.01	−0.06	−0.62
39	12 × 12	Si	0.104	0.07	9.015	11.33	−0.01	−0.04	−0.53
40	12 × 12	Si	0.105	0.08	9.011	11.87	0.03	0.03	1.55
41	12 × 12	Si	0.104	0.05	9.021	11.85	0.09	0.04	0.70
45	12 × 12	Si	0.129	0.06	9.021	11.75	0.05	−0.14	0.44
46	12 × 12	Si	0.114	0.075	9.018	11.804	−0.06	0.024	1.79
47	12 × 12	Si	0.179	0.072	9.001	11.604	−0.13	−0.05	−1.39
48	12 × 12	Si	0.135	0.061	9.019	11.658	0.03	−0.03	−1.12
49	12 × 12	Si	0.106	0.051	9.017	11.667	−0.01	−0.13	1.89
50	12 × 12	Si	0.095	0.052	9.012	11.591	0.02	−0.01	0.68

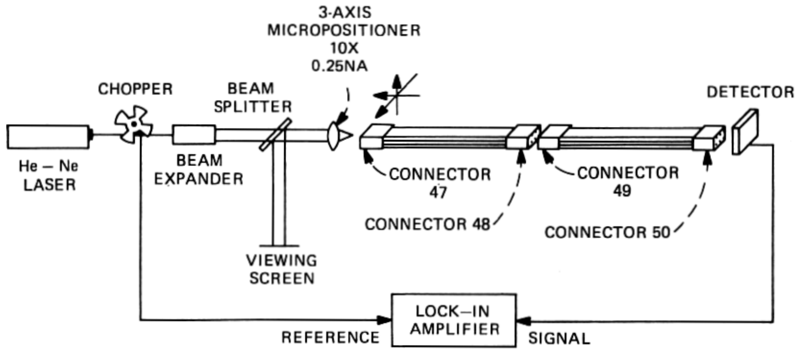

Fig. 6—Loss measurement setup.

a 10×, 0.25 NA, lens onto the core of a fiber in the array. The reflected image from the fiber core was observed on the viewing screen (Fig. 6) and the laser spot positioned above the center of the core approximately midway to the core-clad boundary. The exact spot in this region was not critical since input power to the splice was found to be close to maximum as long as the spot was about midway between core center and cladding.

Input power measurements were obtained by exciting each fiber of connector 47 and measuring the power exiting connector 48. The splice was then assembled by placing connector 49 (or connector 50) in position against connector 48. Again, each fiber of connector 47 was excited by positioning the spot as previously described and the power exiting connector 50 (or connector 49) was measured. Once again the same vicinity on the fiber core almost always corresponded to maximum transmission through the splices. This technique, by contrast with the technique of maximizing input and output power, allowed a larger time constant (1 or 3 seconds) to be used on the lock-in amplifier, thereby reducing noise fluctuations. The time required for a full 12 × 12 array loss measurement was reduced from 4 hours with the previous technique to less than 2 hours with the new technique. The fact that only two negative losses occurred (−0.03 dB and −0.06 dB) compared to 130 positive losses between 0 and +0.1 dB is indicative of measurement accuracy and repeatability substantially better than 0.1 dB.

VII. LOSS MEASUREMENT RESULTS

7.1 Case 1—Connector 48 to connector 49

Figure 9 is a splice loss histogram for case 1. In this case, the ribbons were organized so that a particular fiber was spliced to its mating section. This splicing of "identical" fibers was done to minimize the effect of mismatch due to core diameter variations.

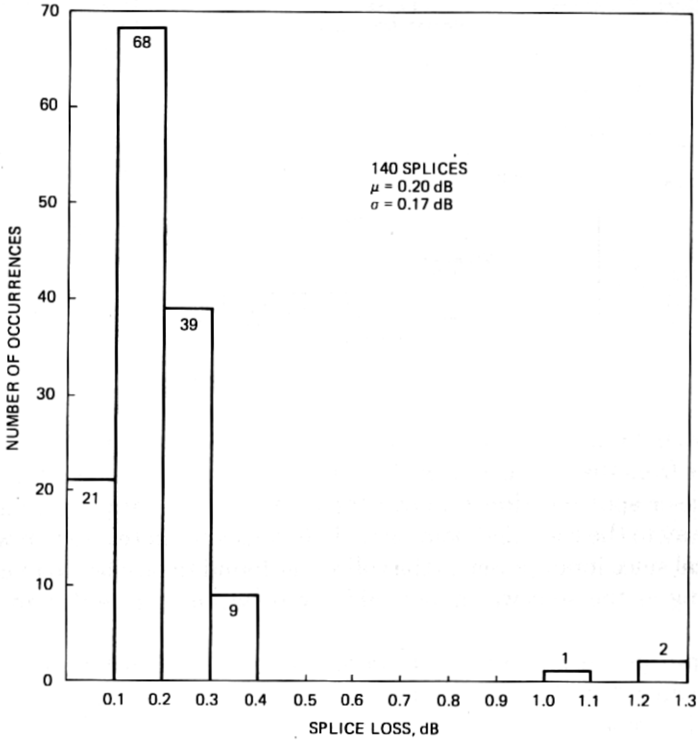

Fig. 7—12 × 12 array splice, connector 48 to connector 49.

Three fibers were broken within connectors 47 or 48 as indicated by a low input power to the splice and one fiber was broken in connector 49 or 50 as indicated by a large loss. These four fibers were not included in Fig. 7 due to definite scattering, indicating breaks. Two fibers also had low input power indicating a break in connector 47 or 48 although the losses for these splices were 1.05 dB and 1.29 dB respectively. It is suspected that another break occurred (1.26 dB loss) in either connector 49 or 50 as this was the only other loss above 0.4 dB.

These seven high losses are due to breaks and if they are excluded from the data, a mean loss of 0.18 dB results with a variance of 0.09 dB. Seven breaks in fabricating four connectors involving 576 fibers corresponds to 98.8 percent yield, and, although this is high, it is believed that improvements in the yield can be made.

7.2 Case 2—Connector 48 to rotated connector 49

Figure 8 is a splice loss histogram for the case of rotating connector 49 by 180° before joining it with connector 48. Fiber diameter mismatches occur in this case and have contributed to the higher mean loss

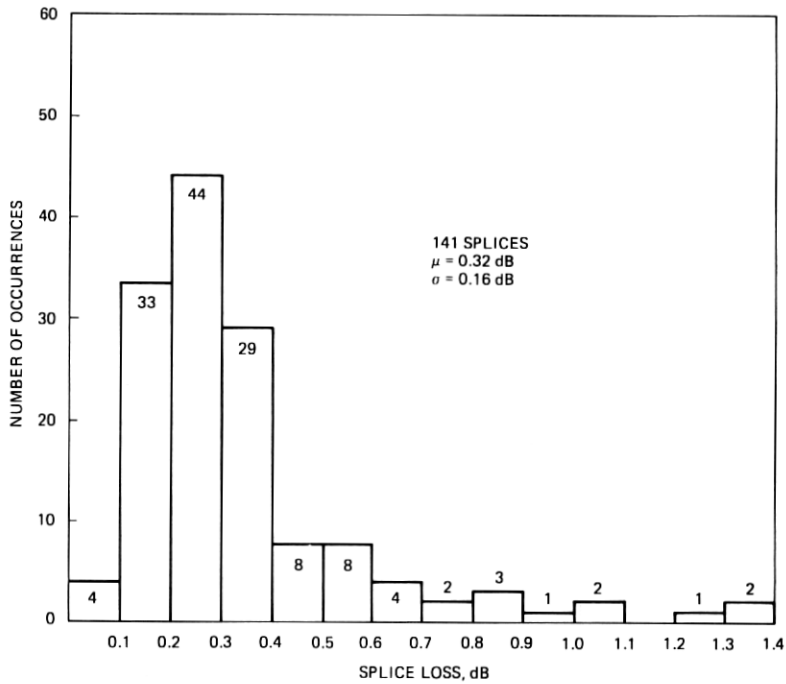

Fig. 8—12 × 12 array splice, connector 48 to inverted connector 49.

and variance. Of the five losses above 1 dB in Fig. 8, three can be attributed to breaks in fibers, leaving two losses over 1 dB unexplained thus far.

Considering the possible effects of ±2.5 percent core diameter variation—if splice loss increases with the square of the ratio of the core diameters when the transmitting core is larger,[4] then a worst-case effect would be 0.42 dB. This worst-case effect may account for the two losses over 1 dB mentioned earlier. Since no core diameter mismatch effect occurs when the transmitting core is the smaller, the mean effect is probably less than half the worst case or perhaps on the order of 0.1 dB. Thus the core diameter mismatch could account for most of the increased mean loss.

7.3 Case 3—Connector 48 to connector 50

Figure 9 is the splice loss histogram for this case. All losses greater than 1 dB have been previously identified as breaks. In this case, improved alignment accuracy appears to be present, since a significant portion of the mean loss could be due to diameter mismatch effects. It is unclear, at this time, how mismatch losses and alignment losses combine. From Table I it is seen that connector 50 has the least value of minimum mean offset and the least θ; therefore, improved splice loss is expected.

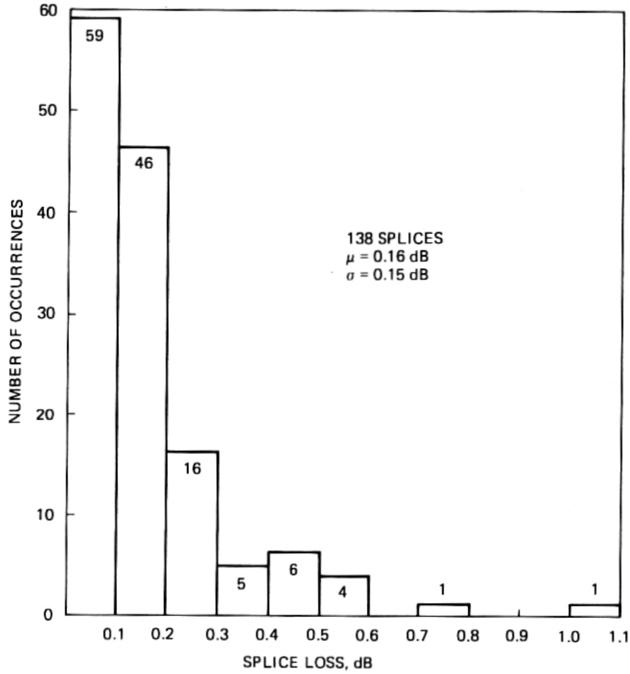

Fig. 9—12 × 12 array splice, connector 48 to connector 50.

It is also seen in Table I that y_s for connector 50 is significantly less than y_s for connector 48. This difference accumulates throughout the array and a connector height measurement shows that connector 48 is 0.52 mils larger than connector 50. When the connectors are placed in the final alignment fixture, a greater force is applied to the thicker connector; however, it was unclear how much deformation occurred and to what extent connector height differences affect array splice losses. This case shows that 0.52 mils can be accommodated with little or no degradation in the splice.

7.4 Case 4—Connector 48 to connector 49

This case is a repeat of case 1. The connectors had been handled, assembled and disassembled several times since the first set of measurements. This test was to see if any noticeable deterioration had taken place and to check the repeatability of the final alignment procedure.

Figure 10 shows that the mean loss is reduced slightly from case 1. All losses greater than 0.9 dB occur in positions which have been identified as broken fibers. It is interesting to note that the three losses between 1 dB and 1.3 dB in case 1 are between 0.7 dB and 1.0 dB in this case. One fiber position measured 0.15 dB in case 1 and increased to 0.89 dB in case 4 possibly due to contamination or end damage.

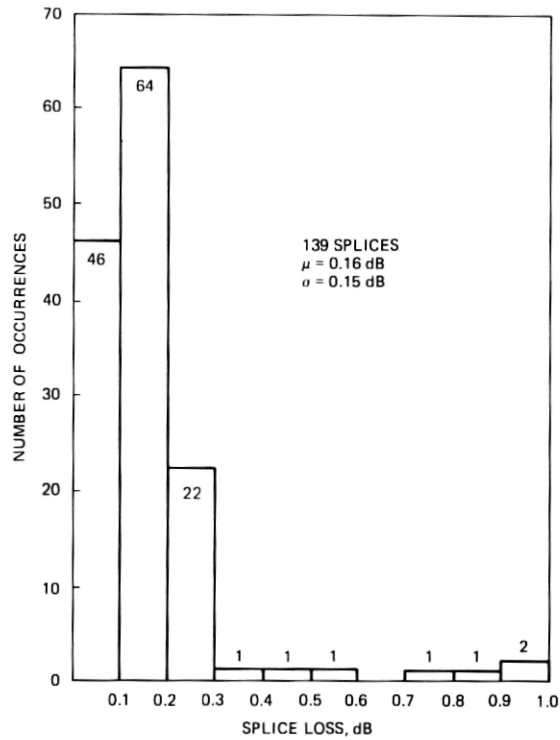

Fig. 10—12 × 12 array splice, connector 48 to connector 49.

VIII. CORRELATION OF LOSS AND OFFSET

A computer program has been written that calculates this mean value of offset between two sets of fiber position data. Two fiber positions that are well separated within the array are selected on the basis of low splice loss at these points. One position is used as the origin, the other is used to fix the position of the x-axis. This operation defines a coordinate system common to both arrays. Each set of fiber position data is transformed by the previously described set of transformations, and the mean offset is calculated as before. After generation of a computer data file containing the measured splice loss data, a correlation coefficient, ρ, is calculated.

$$\rho = \frac{\sum_{i=1}^{n} |q_i| \cdot l_i - n|\overline{q_i}| \cdot \bar{l}_i}{\left(\sum_{i=1}^{n} |q_i|^2 - n|\overline{q_i}|^2\right)\left(\sum_{i=1}^{n} l_i^2 - n\bar{l}_i^2\right)}$$

where l_i = splice loss data and $\bar{l}_i$ = mean splice loss.

Table II — Splice data

Splices	Probable $\lvert\overline{q}_i\rvert$, mils	$\bar{l}_i$, dB	ρ	Loss limit, dB
1. 48 to 49	0.16–0.18	0.18	<0.2	0.5
2. 48 to inv (49)	0.18–0.20	0.32	<0.15	1.0
3. 48 to 50	0.32	0.16	0	0.5
4. 48 to 49	0.16–0.18	0.16	<0.2	0.5

To eliminate the predominating effect of high-loss fibers, a loss limit is set to exclude high losses caused by fiber breaks. Table II lists the results of the mean offset and correlation coefficient calculation. It is seen in Table II that the correlation coefficients are small, indicating little or no correlation between offset and loss on a fiber-by-fiber basis. This had not been the case with aluminum chip splices which exhibited correlation coefficients of typically 0.7. The reduced correlation coefficient for silicon chip arrays indicates that alignment accuracies and the resulting splice losses are approaching the limit of measurement resolution as applied on a fiber-by-fiber basis.

Another approach is to compare the mean offset to the mean loss. Figure 11 is a measured loss versus offset curve[5] for a single fiber similar in index profile and diameter to the fibers used in these arrays. Normalizing a mean offset of 0.17 mils (from Table II for connector 48 spliced to 49) with respect to fiber core radius yields a mean offset of approximately 0.16 core radius. From Fig. 11, this corresponds to a transmission of 96 percent or 0.18 dB loss. The measured mean loss was 0.18 dB (excluding fiber breaks), in agreement with the value predicted from the measured mean offset.

For connector 48 spliced to inverted connector 49, the mean offset was 0.19 mils (0.176 core radius) which corresponds to 95 percent transmission or 0.28 dB. The 0.04 dB by which the mean measured loss exceeded 0.28 dB is probably attributable to core diameter mismatch.

Connector 48 spliced to 50 does not follow the same trends as the previous two splices, due to the 0.52 mil overall connector height difference and the supposed unequal deformation during final alignment. The 0.32 mil (0.30 core radius) mean offset should cause a 0.75 dB mean splice loss, from Fig. 11. The measured mean loss of 0.16 dB suggests that significantly unequal array deformation is taking place in this splice as previously supposed.

IX. CONCLUSIONS

Etched silicon chips have enabled uniform arrays to be fabricated with an average error of 0.1 mil without complex tools or microscopes. Exceptionally low mean splice loss data have been obtained which correlated well with mean offset.

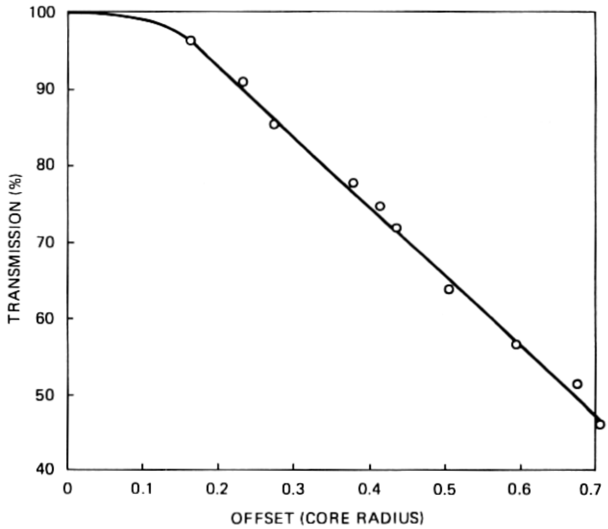

Fig. 11—Measured transmission vs. transverse offset.

Fiber diameter variations of ±2.5 percent caused an increase in the mean loss on the order of 0.1 dB; however, it is not known to what extent array uniformity was affected by these fiber diameter variations. Two arrays with an overall height difference of 0.52 mil had very low mean splice loss, indicating that this height difference was equalized within the splice holding fixture. After several combinations of arrays were assembled and loss measurements made, the original array configuration was measured to test for array deterioration, loss measurement repeatability and final alignment repeatability. Only one fiber position showed evidence of contamination, and repeatability was within 0.02 dB for the mean.

X. ACKNOWLEDGMENTS

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