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Atlanta Fiber System Experiment:

Optical Crosstalk Evaluation for Two End-to-End Lightguide System Installations

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A visual photometric method of measuring lightguide cross-coupling is described. Cross-coupling losses up to 100 dB can be measured with a resolution of ±1 dB. The end-to-end cross-coupling losses were measured for the Bell System's 1976 Atlanta Fiber System Experiment and 1977 Chicago Lightwave Communications Project installations. In the Atlanta experiment, the crosstalk was also measured for the unconnectorized lightguide cable and fanout ribbons, separately. Worst-case cross-coupling losses were measured to be 55 dB for far-end output-to-output and 70 dB for near-end. Results presented here confirm that properly designed parallel lightguides have negligibly small levels of optical crosstalk. However, it is shown that future optical interconnection devices that involve high-fiber packing densities will have to take crosstalk considerations into account.

I. INTRODUCTION

The Bell System uses many types of transmission media to carry telephone calls, computer data, and television signals. One of the newest telecommunications medium under development is the glass fiber lightguide medium.[1] The first telephone plant application of lightwave systems will probably be between central offices in metropolitan areas—where duct and manhole space are at a premium, the volume of traffic is high, and central offices are close enough so that manhole repeaters are not needed.

In 1976 Bell Laboratories successfully demonstrated an experimental lightwave communications system at its facility shared with Western Electric in Atlanta.[2] This system, designated FT3, which uses solid-state lasers as light sources, could carry the equivalent of nearly 50,000 telephone calls through a one-half-in. diameter cable containing 144 fiber lightguides. Following this successful experiment, the Bell System's first lightwave system to be evaluated under actual service traffic conditions was installed in Chicago (Illinois Bell Telephone Company) in early 1977.[3]

Advantages of optical fibers over conventional copper links include small size, freedom from interference, immunity to ground-loop problems, large information capacity, and potential economy. Data available thus far on early lightwave systems have, for the most part, been limited to optical loss and signal distortion (pulse spreading),[4] which can be related directly to economic viability. However, for telecommunication applications in congested metropolitan areas, the trend is toward higher fiber packing density. Therefore, as the lightguides are packed closer together and as the connectorization schemes become more miniaturized, the effects of lightguide cross-coupling will be enhanced. As a result, lightguide crosstalk could directly influence system applications and engineering rules, as well as system immunity to outside intrusion.

Although the theory of optical crosstalk for parallel lightguides has been studied by others,[5–9] a search of the literature turned up no actual measurements for a complete optical fiber transmission system. This paper presents the in-depth optical crosstalk data measured for the Bell System's lightwave systems in Atlanta and Chicago. These results show, as others have predicted,[5–9] that crosstalk levels in parallel lightguides arranged in our cable geometry are extremely low. Moreover, it is seen that there are measurable levels of system end-to-end optical crosstalk; however, the source of this crosstalk is believed to be the interconnection hardware. The laser measurement technique and equipment used for these optical crosstalk evaluations are described in the next section.

II. CROSS-COUPLING MEASUREMENT TECHNIQUE

It is well known that the human eye is incapable of making an absolute measurement of the amount of light entering it; we can look at two sources and estimate that one appears "brighter" than the other if there is sufficient difference between them, but we cannot form a reliable judgment as to how much they differ.[10] However, the eye can decide with very good accuracy whether two adjacent surfaces appear equally bright; this was the basic premise used for our visual photometric measurement of lightguide cross-coupling.

According to the law of Weber,[10] the smallest perceptible difference of apparent brightness or luminosity is a constant fraction of the luminosity ($\Delta L/L$ = constant). This fraction, known as Fechner's fraction, is, over a large range of luminosities, about 1 percent. The eye can therefore distinguish between two adjacent surfaces that differ in luminance by this amount.[10]

The measurement setup for photometrically measuring the cross-coupling between optical fibers is shown in Fig. 1. The optical excitation source used for these measurements was a 2.5-mW helium-neon laser having an approximately Gaussian distribution of light in the TEM_{00} mode. This laser output beam is expanded, collimated, and focused to a numerical aperture of 0.23 to match the average numerical aperture of the optical fibers to be tested. The procedural steps of optically measuring the cross-coupling between optical fibers are as follows:

(*i*) Only one of the fibers is illuminated in the packaged fiber structure to be tested.

(*ii*) The end of the fiber being energized is covered at the far end of the structure being tested.

(*iii*) The far-end observer uses a loupe to observe the He-Ne luminance in a cross-coupled-to fiber.

(*iv*) The near-end observer (and source operator) now places a neutral density filter in the laser beam path.

(*v*) The far-end observer uncovers the far end of the energized fiber and observes the He-Ne luminance with the loupe.

(*vi*) The far-end observer covers the energized fiber and the near-end observer removes the neutral density filter.

(*vii*) Steps (*iii*), (*iv*), and (*v*) are repeated in rapid succession with different amounts of neutral density filtering until the far-end observer notes that the energized fiber with filter has the same luminance as the cross-coupled-to fiber.

The amount of neutral density filtering required to equalize these luminances is the same as the equal-level far-end output-to-output cross-coupling for that fiber pair. This is essentially a null-comparison type measurement process in that it attempts to maintain a balance by suitably applying an effect balancing that which is generated by the cross-coupling.[11] All the cross-coupling experiments were performed

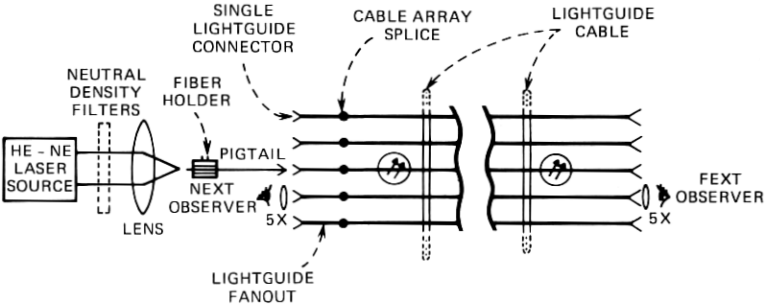


Fig. 1—Cross-coupling measurement setup.

under darkened ambient conditions. For these conditions, it was found that input-to-input or output-to-output cross-coupling losses of up to 100 dB could be detected.

With parallel lightguides, not only is there far-end crosstalk (FEXT) due to parallel interference, but there can also be near-end crosstalk (NEXT) caused by antiparallel interference. The procedures for measuring the near-end optical cross-coupling are essentially the same as those stated above for FEXT. For near-end cross-coupling, neutral density filters are inserted into the laser beam path until the energized fiber pigtail output luminance equals the luminance of the near end of the cross-coupled-to fiber. Using this visual photometric method of measuring lightguide cross-coupling, the optical crosstalk was measured for the Bell System's end-to-end lightguide installations in Atlanta and Chicago.

III. CROSSTALK MEASUREMENTS FOR THE ATLANTA FIBER SYSTEM EXPERIMENT

In the past several years, many fundamental advances have been made at Bell Laboratories in lightwave communications technology. Low-loss optical fibers have been fabricated, cabling and splicing techniques devised, long-lived laser transmitter packages constructed, and optical repeater technology advanced. The 1976 Atlanta Fiber System Experiment brought all these components together into a working system to evaluate system performance in an environment approximating field conditions. The experimental system contained all the elements of an operational 44.7-Mb/s digital transmission system. Plastic underground ducts, typical of those used in metropolitan areas, provided the outside plant environment for the lightguide cable (see Fig. 2).

The 658-m cable is 12 mm in outer diameter and has 144 optical fibers arranged in 12 fiber ribbons—each encapsulating 12 graded-index optical fibers manufactured by the Western Electric Company at Atlanta.[12] The 12 ribbons are stacked and twisted together as shown in Fig. 3. The stacked ribbon structure permits simple interconnection of cables via array splice "butt" joints.[13] An important part of the central office environment is the transition (fanout) from the cable end to the individual fiber connectors on a fiberguide distributing frame. This fanout is composed of 12 laminated fiber ribbons,[14] each containing 12 fibers, where one end has a single 12 × 12 array connector[13] for splicing to the cable end and the other end has 144 individual fiber connectors[15] for interconnection at the fiberguide distributing frame. This complete Atlanta end-to-end installation of 658-m 144-fiber cable, two array splices, and 24 fanout ribbons was measured for optical crosstalk.

Because of the large number of fibers in this installation and the tedious nature of these measurements, the 144-fiber cross section was first

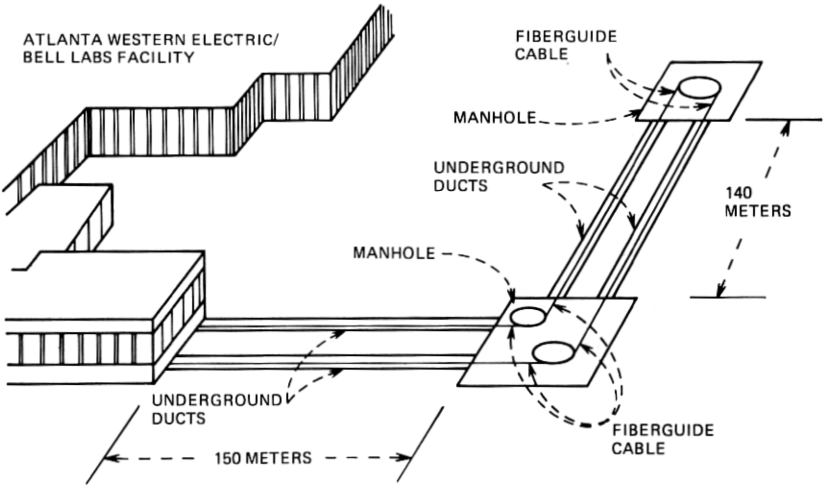


Fig. 2—Atlanta installation route.

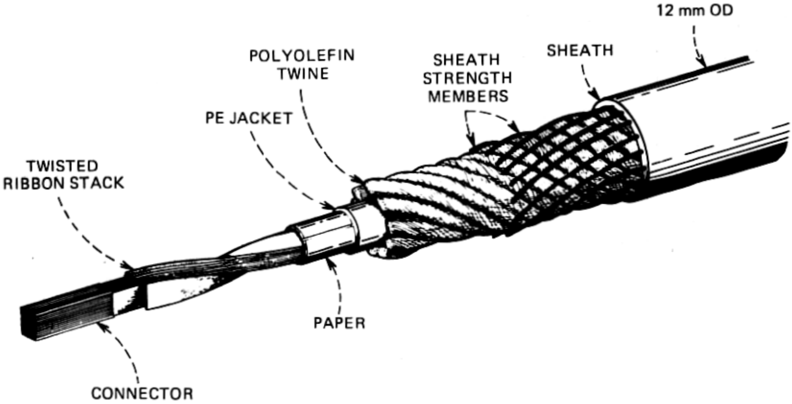


Fig. 3—Lightguide cable design.

quickly searched for fibers exhibiting abnormal amounts of cross-coupling. Only one energized fiber caused significant crosstalk at the far end. In this case, the output-to-output cross-coupling loss to the two adjacent fibers in that ribbon was 55 dB. Using an interfering digital signal and error rate analyses with computer simulations, Wolaver[16] has obtained exactly the same result for these two fiber pairs. It should be noted that, with present technologies, the digital receiver sensitivities are such that cross-coupling losses of greater than $\simeq$65 dB cannot be detected using these error rate analysis techniques, but at least this single comparison has given additional credence to the photometric method of measuring cross-coupling losses.

Once all the fibers were scanned, six energized fibers showing the largest far-end cross-coupling were selected and their measurable cross-coupled-to near neighbors (14 in this case) were measured for cross-coupling loss (to the nearest decibel). Output-to-output far-end crosstalk was converted to input-to-output far-end crosstalk by increasing the numerical value in decibels by the cable, array splice, and fanout ribbon attenuation. The far-end cross-coupling losses in decibels are presented in the format:

mean output-to-output, mean input-to-output
worst case output-to-output

Figure 4 shows the results for the far-end cross-coupling losses measured for the end-to-end Atlanta lightguide installation. Since ribbons are horizontal in Fig. 4, the primary far-end cross-coupling mechanism appears to be intra-ribbon induced, while secondary effects seem to be associated with inter-ribbon mechanisms. For the complete Atlanta end-to-end installation, there was no measurable near-end cross-coupling. To try to isolate the system components causing the cross-coupling mechanisms, further tests were performed for the various segments of the end-to-end transmission medium.

Crosstalk measurements on a second 144-fiber cable fabricated for the Atlanta Experiment, which were without connectors or a ribbon fanout and which contained both Western Electric and Corning fibers, showed that there was not a single case of measurable cross-coupling in the cable. In fact, a different He-Ne laser source of 17-mW output was used in the measurement setup of Fig. 1 and still no measurable crosstalk was observed. Crosstalk was also measured for a 3-m long unconnectorized laminated fiber ribbon like those used for the fanouts from the connectorized cable. For this laminated fiber ribbon, the mean far-end output-to-output cross-coupling loss was 83 dB for adjacent fibers and

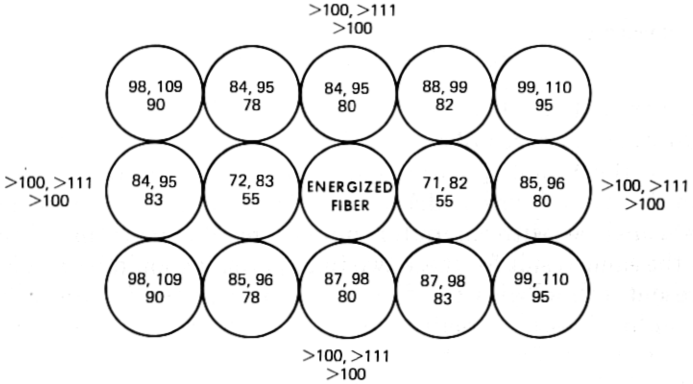


Fig. 4—Far-end cross-coupling losses in decibels for the Atlanta Experiment installation.

98 dB for fibers two positions apart. These data, along with the data of Fig. 4, indicate that for the Atlanta end-to-end installation, the primary far-end crosstalk inducing mechanism was the 12 × 12 array splices with the secondary contributor being the laminated fiber fanout ribbons. It should be pointed out that the measured crosstalk levels were sufficiently small that their effect on system performance was negligible. No near-end cross-coupling was found for the unconnectorized cable or the fanout ribbons separately. This is not surprising, since the end-to-end installation had no measurable NEXT even for the connectorized case.

IV. CROSSTALK MEASUREMENTS FOR THE CHICAGO LIGHTWAVE COMMUNICATIONS PROJECT

Upon the completion of the 1976 Atlanta Experiment, the Bell System's first lightwave system to be evaluated under actual field conditions was installed in Chicago in early 1977. A total of 10 lightguide cable segments, each having the same make-up (except for the core) as those in Fig. 3, were successfully installed in conventional ducts and manholes along a 2.65-km route in downtown Chicago (see Fig. 5). There are 12 cable array splices on this route—five in manholes and seven in the three buildings involved. In the Chicago project, the cable core consists of two 12-fiber ribbons stacked and twisted as in Fig. 3 (all other cable parameters are the same as those of the Atlanta Experiment cables). Thus, the cable segments are joined together with 2 × 12 cable array splices. The central office fanout from the cable end to the fiberguide distributing frame is accomplished this time with unribboned fibers, where one end has a single 2 × 12 array connector and the other end has 24 individual fiber connectors.

Crosstalk for the Chicago Lightwave Communications Project was measured from distributing frame to distributing frame for the Franklin-to-Wabash 1.62-km route and for the Franklin-to-Brunswick 0.94-km route. The characteristics of each route are listed below:

Route	Length	Number of Cable Segments	Number of Array Splices
Franklin-Wabash	1.62 km	6	7
Franklin-Brunswick	0.94 km	4	5

Each route also has two fanouts—one at each end location. To reduce the measurement time per fiber so that all of the fibers could be measured, the crosstalk was measured to the nearest 5 dB instead of to the nearest decibel.

Figure 6 shows the cross-coupling losses measured, both far-end and near-end, for the Franklin-to-Wabash route. The format for the far-end cross-coupling losses (shown in Fig. 6a) is the same as in Fig. 4. The near-end cross-coupling losses shown in Fig. 6b are in the format:

mean input-to-input, worst case input-to-input

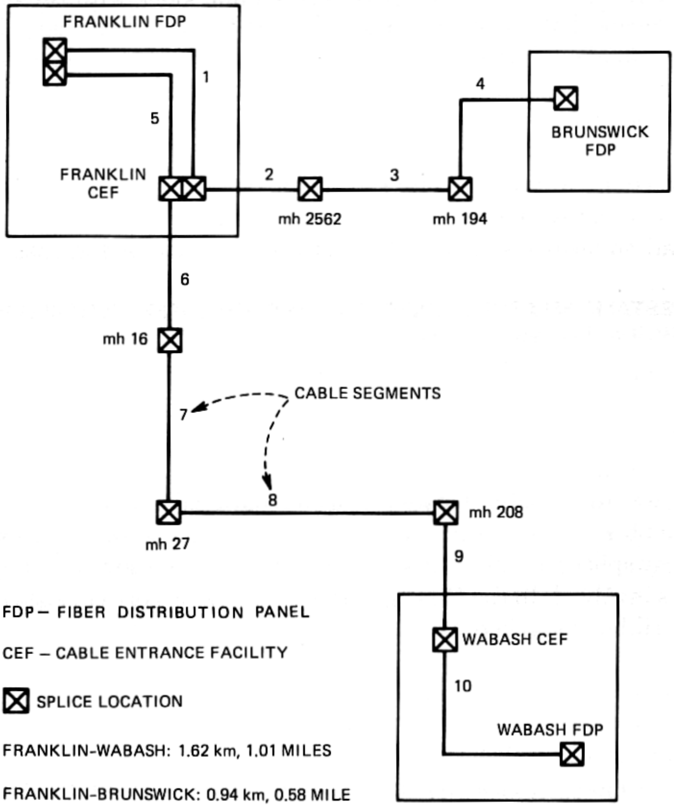
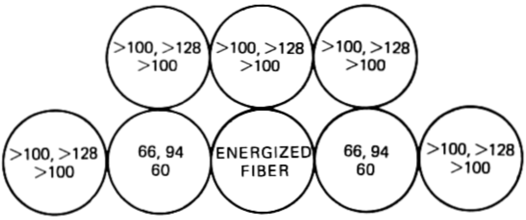
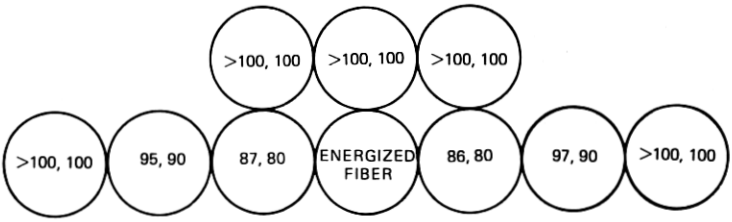


Fig. 5—Chicago route plan.

Figure 7 shows the cross-coupling losses for the Franklin-to-Brunswick route. As can be seen from Figs. 6 and 7, far-end cross-coupling is almost totally intra-ribbon effects most probably induced by the numerous array splices. Unlike the Atlanta Experiment, the Chicago Project installation had near-end cross-coupling. The data of Figs. 6 and 7 show that the primary mechanism for near-end cross-coupling is also intra-ribbon effects, with a secondary mechanism of inter-ribbon effects (both are probably array splice effects). In fact, in the Atlanta array connectors, the intra-ribbon fiber spacing was 9 mils with inter-ribbon fiber spacing of 11 mils, whereas for the Chicago array connectors the intra-ribbon fiber spacing was 9 mils, with inter-ribbon fiber spacing of 21 mils. The major differences between the Atlanta and Chicago end-to-end installations are the number and size of the array splices, the presence of fanout ribbons for Atlanta, and the installed length of the lightguide medium. The numerous cable array splices with their inherent mirror-like end-face cavity construction is most probably the cause of the Chicago near-end cross-coupling. The Atlanta installation had only a single

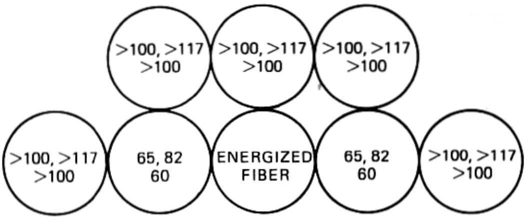


a) FAR-END CROSS-COUPLING LOSSES (dB)

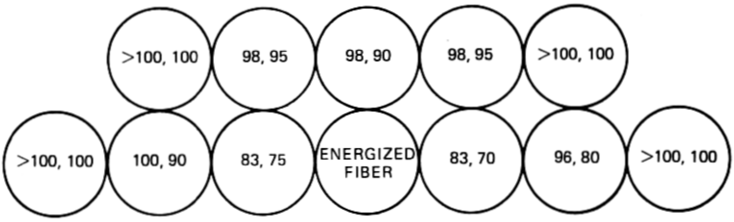


b) NEAR-END CROSS-COUPLING LOSSES (dB)

Fig. 6—Cross-coupling losses in decibels for the Franklin-to-Wabash Chicago route.



a) FAR-END CROSS-COUPLING LOSSES (dB)



b) NEAR-END CROSS-COUPLING LOSSES (dB)

Fig. 7—Cross-coupling losses in decibels for the Franklin-to-Brunswick Chicago route.

array splice at each end, thus possibly explaining why no near-end cross-coupling was observed there.

V. SUMMARY AND CONCLUSIONS

A visual photometric method of measuring lightguide cross-coupling has been described. Cross-coupling losses up to 100 dB can be measured with a resolution of ±1 dB. These concepts could be used to build cross-coupling measurement instrumentation using sensitive optical detection devices, such as a photomultiplier tube.

The end-to-end cross-coupling losses were measured for the Bell System's 1976 Atlanta Fiber System Experiment and 1977 Chicago Lightwave Communications Project installations. In the Atlanta Experiment, the crosstalk was also measured for the unconnectorized lightguide cable and fanout ribbons separately. For the Atlanta Experiment, it was found that the primary far-end crosstalk-inducing mechanism was the cable array splices, with the fanout ribbons having a secondary effect. There was no measurable near-end cross-coupling. For the Chicago project, both far-end and near-end cross-coupling were measured and the primary mechanism was intra-ribbon effects that are probably associated with the array connectors.

The worst case cross-coupling losses measured were 55 dB (far-end output-to-output) for the Atlanta installation, and 70 dB (near-end) for the Chicago installation. These results confirm one of the important advantages of optical fiber transmission; namely, that crosstalk is not a serious fundamental problem. However, it has been shown that, even though parallel lightguides can be designed to produce little crosstalk, optical components that are desirable for system operation introduce measurable amounts of crosstalk. Future optical cable and interconnection devices that involve high fiber packing densities will have to take crosstalk considerations into account.

VI. ACKNOWLEDGMENT

W. B. Gardner shared the burden of the many crosstalk measurements made for the Chicago project, and his efforts are very gratefully acknowledged.

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