October 1984

Multi-Access Fiber

Optic Data Bus Using

FDM/FSK

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Summary Review

The development of an efficient T coupler that comprises the major portion of this research effort (this year) is a precursor to the development of a complete multiaccess data bus using FDM.

The original use of FDM was motivated by two specific applications in:

1. A distributed fault tolerant realtime microprocessing system.

2. A fiber optic replacement of existing interbuilding communication lines.

The major thrust was to develop a T coupler with very low (0.1 0.2dB) in-line loss. This is essential to any multiaccess bus structure where the word multi implies fifteen or more nodes on the bus, and it is tacitly assumed to be a passive bus. (Reliability considerations tend to exclude the use of active nodes - repeater nodes.)

The basic structure of the T coupler is shown in fig. 1. The use of different refractives indicies for the side arm and bus is designed to allow the angle θ to be "reasonable" compared to the numerical apperture of the bus which when expressed in degrees is in the order of $10^\circ - 15^\circ$. The additional section with index n_3 provides some prefocusing of the light energy.

The structure shown in fig. 1 has been modified to include an indentation in the bus fiber to allow a more efficient and structurally easier construction of the coupler. (Fig. 2.)

Sample Structures

Two methods were originally used in producing the crevice in the bus fiber. Laser machining and chemical etching. The use of Lasers resulted in poorly controlled crevice dimensions, as a result all experiments relied on chemical etching. After numerous attempts, the use of this technique finally produced relatively clean crevices which allowed construction of a number of sample couplers. It should be noted that so far crevices have been produced only near the end of the bus fiber (a special acid bath must be used if the crevice is to be located somewhere midway in a long fiber.) In addition, the masking used in the etching process is at the present time somewhat primitive (melted Beeswax with a "cut" where the crevice is to be etched.)

Three methods of joining the side arm and the bus fiber were tried.

First, direct fusion using the Arc fusion system (Orionic Model 301). The major problems with this approach is the fact that the two fibers have different melting points and vary in their diameter. Both of these facts tend to cause the side arm fiber (the smaller one and the one with the lower melting point) to "burn" before the bus fiber is soft enough to allow the fusion to take place. Some remedies are the careful location of the two fibers relative to the arc center and the search for fibers more compatible in terms of their melting point. The latter may be inherently difficult to obtain since most fiber manufacturers contacted have indicated a strong relationship between melting point and refractive index. Fibers with higher refractive index tend to have a lower melting point.

Second, a two part epoxy (Epoxy Technology Inc. EPOTEK 302-3) was used as the bonding agent. So far this method has not yielded couplers which are structurally stable to allow their use in the various power measurements entailed in evaluating the couplers. It may be necessary to produce a supporting structure to hold the coupler fibers in place while and after bonding.

The third method, and the most successful one, involves the use of a high temperature bonding agent (Cargille Meltmount #5870) in conjunction with the arc fusion system. The arc was used to melt the epoxy over the junction and serve as an optically matched bonding agent. This method yielded a number of couplers for which power measurements were made.

Power Losses in Couplers

The couplers that were constructed had a number of basic flaws that affected both the accuracy of measurements as well as the coupler performance. First and foremost the fiber edges were improperly polished (suitable equipment was not available). This results in measuring error, since the variation in loss due to edge dispersion, rather large in unpolished fibers, directly affect the measurements. In addition the coupling loss (from side arm to bus) is to a large extent a function of the edge surface finish. Second, the crevice size and finish were poorly controlled leading to large in-line and coupling loss. Third, the surface end match between the crevice exit angle and the side arm fiber edge was very poor, increasing further the coupling loss. (See fig. 3)

Table 1 gives the measurements of the various losses in the couplers that were constructed. The terms are defined in fig.4. The fibers used were:

Bus fiber - 500 μM , n_{core}= 1.581

Side fiber - 100 μM , n_{core}= 1.81

The bonding agent was the high temperature Meltmount 5870 made by Cargille Inc. with n= 1.582.

Coupler number	Coupling loss	Inline loss	Reverse coupling	Tapping ratio	Angle
1	-5 dB	-3 dB	-29 dB	-26 dB	16^{o}
2	-12 dB	-12 dB	-----	-26 dB	15^{o}
3	-9 dB	-----	30 dB	------	15^{o}
4	-11 dB	-----	47 dB	------	16.5^{o}

Coupler Structure Reevaluation

The basic coupler structure as originally envisioned is shown in fig. 1. It is redrawn in fig. 5 for the purpose of reexamining the ray tracing from side arm to bus. The two rays shown propagate at the critical side arm fiber angle (θ_{SA}) and represent the extreme angle of incidence in the bus fiber, θ_{min} and θ_{max} where

1a) $\theta_{min} = \theta - \theta_{sa}$

1b) $\theta_{max} = \theta + \theta_{sa}$

In order to assure efficient coupling into the bus, these angles must be large enough to avoid complete reflection. The condition for complete reflection at an interface is shown in fig. 6.

The relation between θ_{refr} and θ_{in} is given by Snell's law

2) $\sin \theta_{in} / \sin \theta_{refr} = n_2 / n_1$

To avoid full reflection

3) $\sin \theta_{in} < n_2/n_1$

The critical incident angle is given by

$$\theta_{cr} = \sin^{-1} (n_2/n_1)$$

As an example for $n_1 = 1.81$ $n_2 = 1.51$

$$\sin \theta_{in} < 1.51/1.81$$

$$\theta_{in} < 56^\circ 32'$$

In terms of the angles θ_{min}, θ_{max} in the coupler structure (note the shift in the reference for the angles, the perpendicular to the interface line in Snell's law and the interface itself in fig. 1 and fig. 5) this means that $\theta_{min} > 33^\circ 28'$. This angle is well outside the effective acceptance (N.A) angle of the bus fiber. Thus to avoid full reflection the angle θ must be made relatively large, however in order to effect efficient coupling the angle must be kept relatively small ($\sim 20^\circ$).

<u>A Modified Structure</u>

The structure shown in fig. 7 is designed to eliminate the problem of full reflection while providing efficient coupling between side arm and bus. The notations used are as follows:

θ_{sa} – critical angle of side arm. (Rays propagating at this angle are used in the computations since they represent the extremes of the incident angles).

θ_{en1}, θ_{en2} – The angles between the bus axis and the incident rays.

Min θ_{inc}, Max θ_{inc} – The angles of incident measured with respect to a perpendicular to the interface surface.

α - The exit angle of the crevice.

θ - The angle between the bus and the side arm.

β - The angle at which the end of the side arm is cut.

The match between the side arm edge and the crevice exit surface is established by setting

4) $\beta = 90 - (\alpha + \theta)$.

From the geometry we have

5a) $\theta_{en1} = \theta_{SA} - \theta$

5b) $\theta_{en2} = \theta_{SA} + \theta$

and

6a) Max $\theta_{inc} = 90 - (\alpha + \theta_{en1})$

6b) Min $\theta_{inc} = 90 - (\alpha - \theta_{en2})$

So that

7a) Max $\theta_{inc} = 90 - [\alpha - (\theta_{SA} - \theta)]$

7b) Min $\theta_{inc} = 90 - (\alpha + \theta_{SA} + \theta)$

For the refracted angle θ_{eff} with respect to the perpendicular to the interface

8) $\sin \theta_{inc} / \sin \theta_{eff} = n_B/n_{SA}$; $\theta_{eff} = \sin^{-1}[(n_B/n_{SA}) \sin \theta_{inc}]$

The same angle when measured with respect to the bus axis is

9) $\theta'_{eff} = 90 - \alpha - \theta_{eff}$

The condition for no reflections requires that

10) $\sin(\text{Max } \theta_{inc}) < n_B/n_{SA}$

The condition for propagation in the bus calls for

11) $\theta'_{eff} < \sin^{-1} N.A_B$

Sample Computations

Given $n_B = 1.52$ $n_{SA} = 1.62$

$\alpha = 30^o$ $\theta = 15^o$ $\theta_{Sa} = 10^o$

Min $\theta_{inc} = 90 - 30 - 10 - 15 = 35^o$

Max $\theta_{inc} = 90 - 30 - 5 = 55^o$

For no reflections:

$\sin 55^o < n_B/n_{SA} = 1.52/1.82 = .84$ - satisfied

For Max θ_{inc} we get θ'_{eff}

$\sin \theta_{eff} = \sin 55/.84 = .975$ $\theta_{eff} = 77.2^o$ $\theta'_{eff} = 17.2^o$

For Min θ_{inc}

$\sin \theta_{eff} = \sin 35/.84 = .683$, $\theta_{eff} = 43.06^o$ $\theta'_{eff} = 17^o$

Fig. 8 shows this example. It is apparent that reducing θ_{SA} by prefocusing the light beam in the side arm will improve coupling.

As eq. 11 indicates, in order to obtain 100% (or near that) coupling the effective angle θ'_{eff} must be within the acceptance angle of the bus fiber. The $\theta'_{eff} = 17^o$ implies a $N.A_B = .29$

which is somewhat high for the standard communications fibers.

Further Research

Future work in the development of the fiber optic coupler must concentrate on:

1. The selection of the geometeric parameters α, β as they relate to the refractive indices of the bus and side arm;
2. Develop techniques of bonding the fibers, while maintaining a good refractive index match.
3. Further improve and control the bus crevice.
4. Set up a method to produce quality fiber ends with the appropriate angle (β).
5. Experiment with and measure performance characteristics of the couplers.

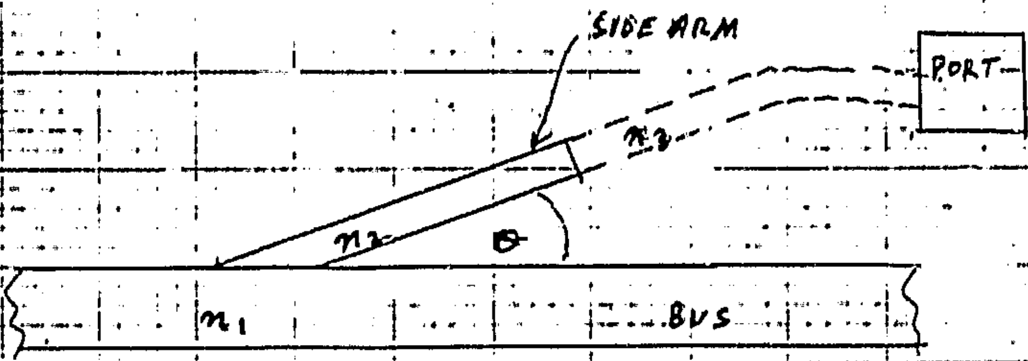

FIG. 1 GENERAL STRUCTURE

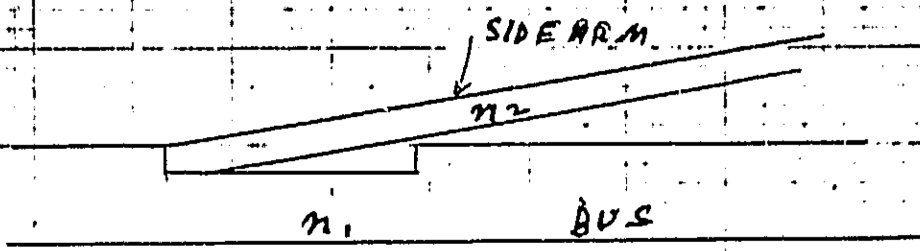

FIG. 2 INDENTED BUS FIBER

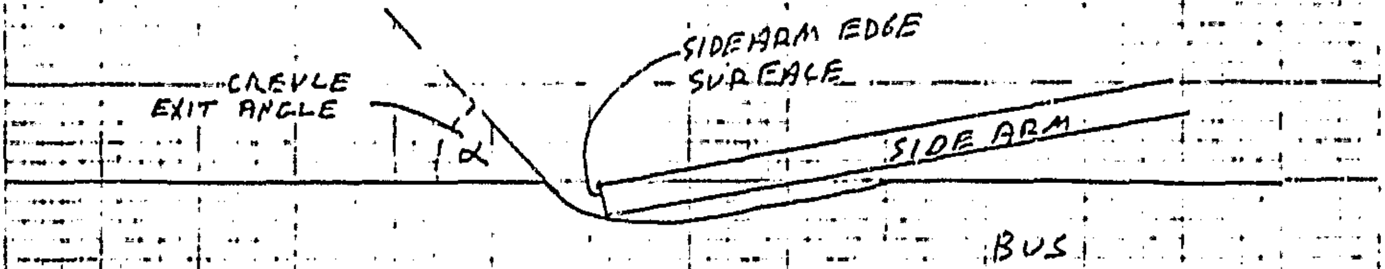

FIG. 3 ACTUAL STRUCTURE

$\frac{P_o}{P_{in}}$ – COUPLING LOSS

$\frac{P_F}{P_{in}-P_o} \approx$ IN LINE LOSS.

$\frac{P_R}{P_{in}}$ – REVERSE COUPLING

$\frac{P_o}{P_{in}}$ – TAPPING RATIO

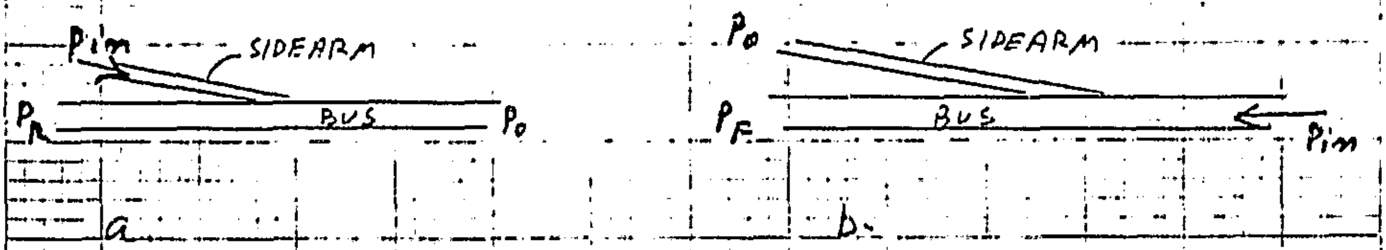

FIG. 4 DEFINIG LOSS PARAMETER

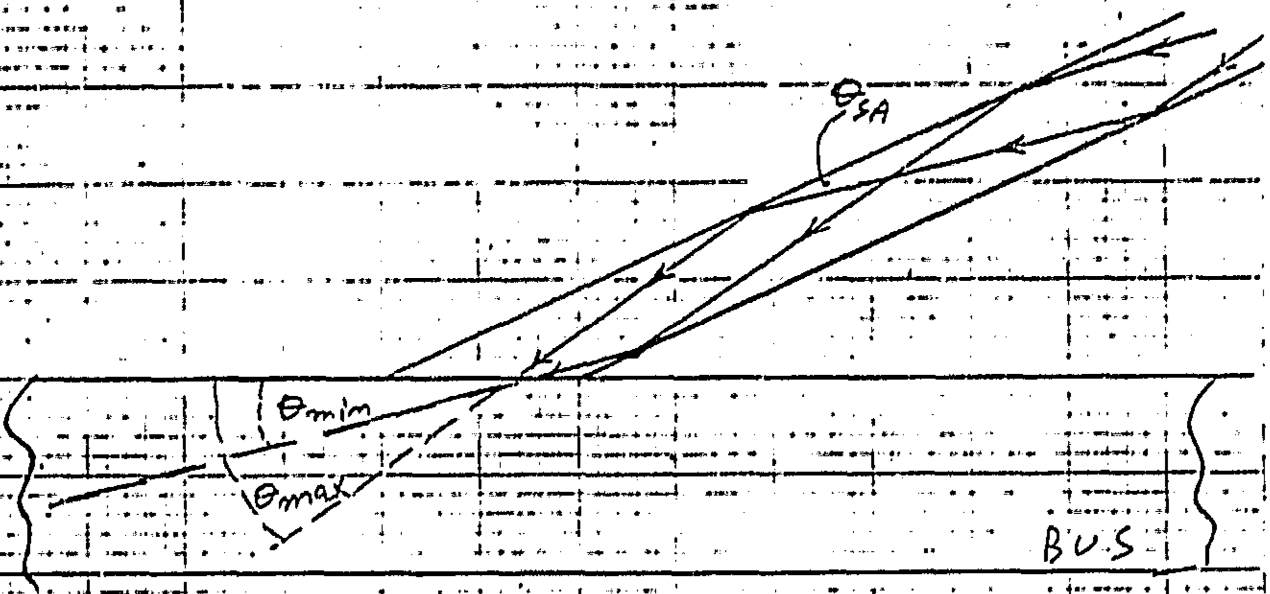

FIG. 5 RAY TRACE IN COUPLER

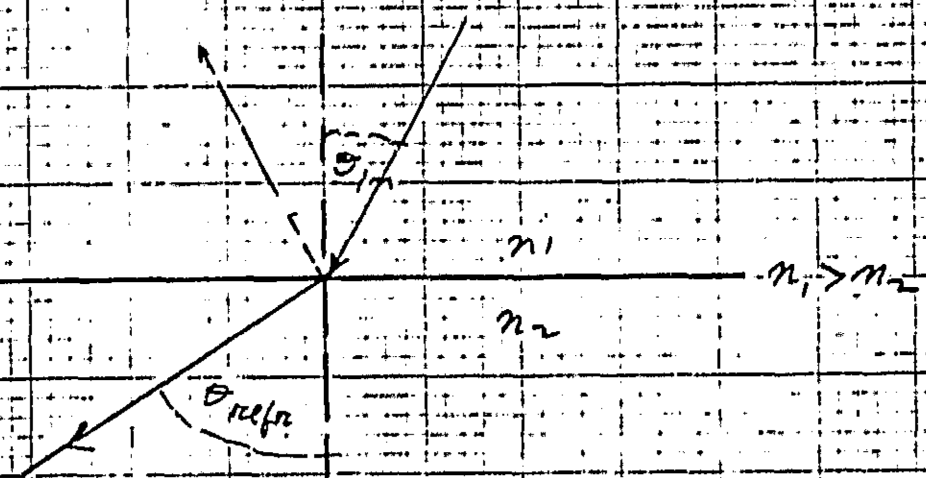

FIG. 6 REFRACTION

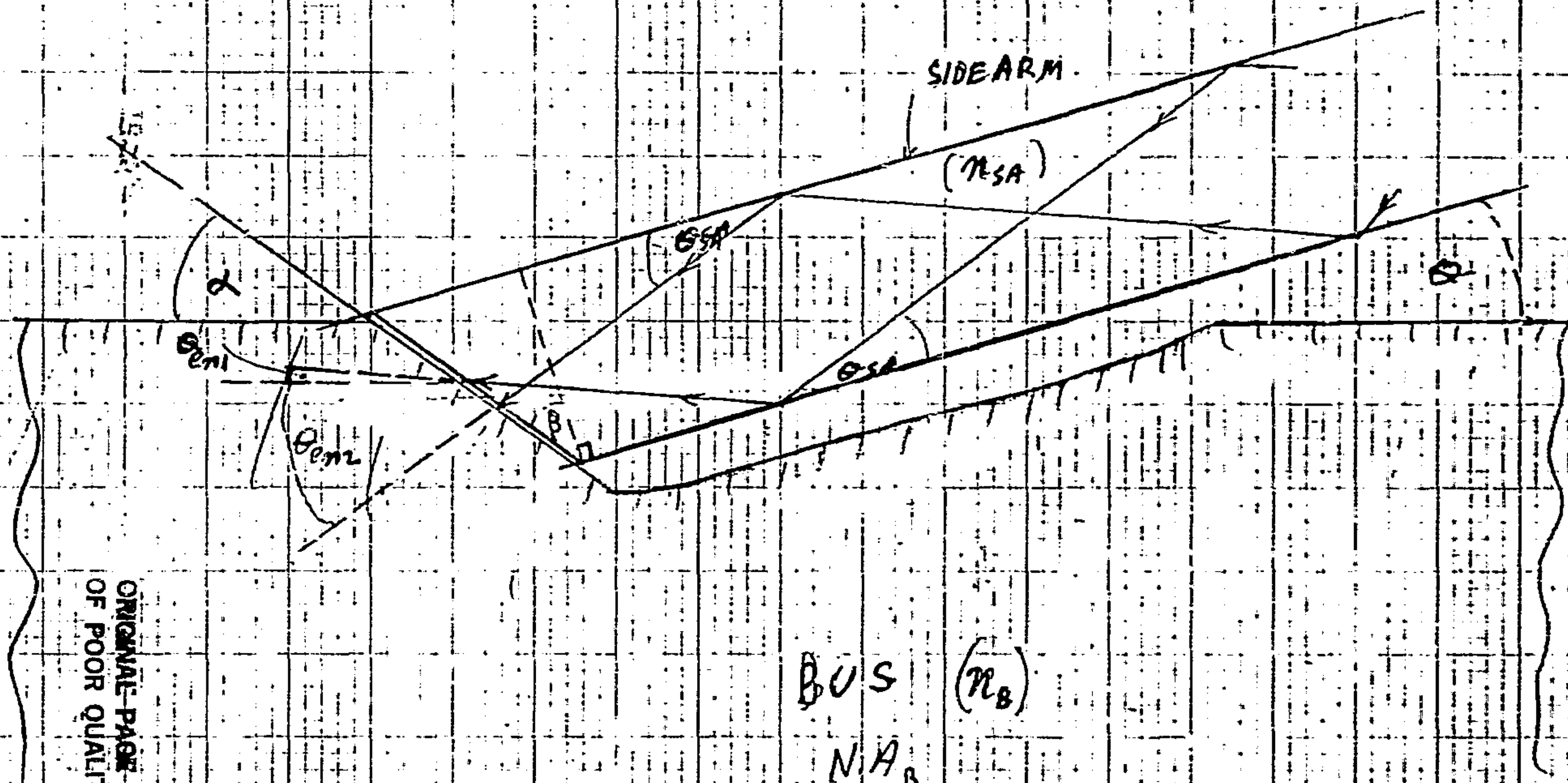

FIG. 7 RAY TRACE IN MODIFIED STRUCTURE

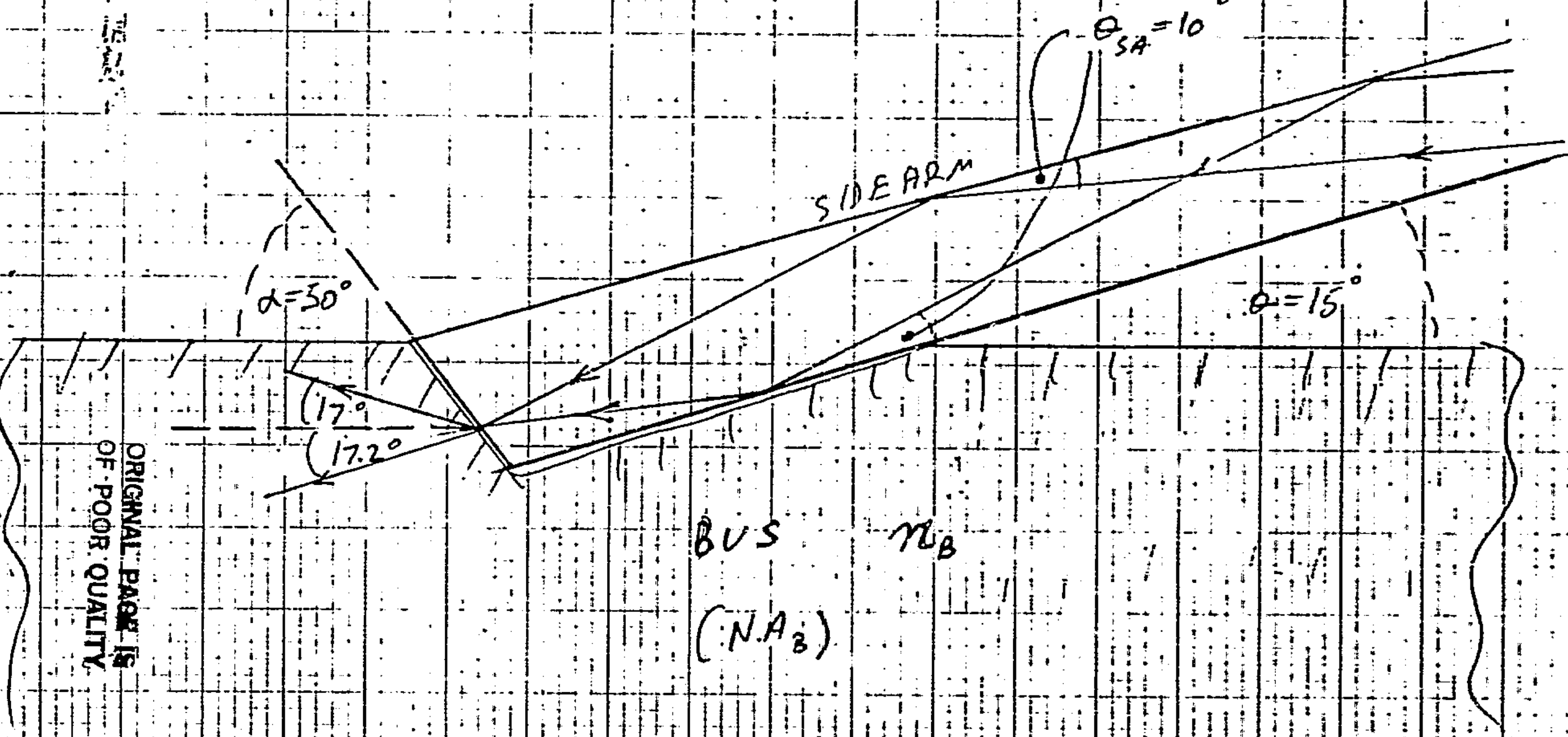

FIG 8 SAMPLE TRACE