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WT4 Millimeter Waveguide System:

Line and Repeater Equalization

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The WT4 millimeter waveguide system requires equalization of the loss and delay of the line, which is made up of both the waveguide itself and the diplexer (waveguide channelizing filter) arrays. In the lower portion of the band (40 to 60 GHz) there is considerable linear delay (as much as 30.5 nsec per 400 MHz at 40 GHz), which is equalized by using a folded tape meander line delay equalizer. The remaining delay and amplitude deviation from the desired transfer characteristic is further reduced by field-adjustable trim equalizers. In this paper, we describe the equalization and measurement philosophy for the WT4 system and also the technologies used in achieving the resulting degree of equalization. We put special emphasis on the description of trim equalization because line equalization has been described in detail in a previous publication.[1]

I. INTRODUCTION

The WT4 millimeter waveguide system requires equalization of the loss and delay of the line which is made up of both the waveguide itself and the diplexer (waveguide channelizing filter) arrays.[2] Furthermore, the RF and IF portions of the WT4 receiver require equalization for optimum performance. In Fig. 1, we show a simplified block diagram of a repeater hop. In the WT4 system all equalization is performed about the IF of 1371 MHz. Theoretically, a single equalizer package could be designed to equalize simultaneously the line and the repeater. However, as a maintenance philosophy[3] evolved, it became desirable to separate the line equalizer and the repeater equalizer. The repeater equalizer equalizes only the RF and IF portions of the repeater and resides in the repeater package while the line equalizer is designed to equalize only the

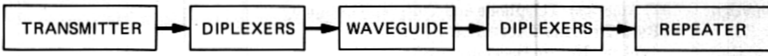

Fig. 1—Repeater hop.

line and is mounted in a separate package apart from the repeater. The line equalizer is made up of a major delay equalizer and mop-up trim delay and amplitude equalizers. The repeater requires only trim equalization. Because passive devices are used for equalization, a very high degree of reliability as well as transfer function stability was obtained compared to the reliability and stability obtainable from active devices.

In order to determine the required characteristics for the various line equalizers, a line measurement is performed. A computer-controlled measurement of the line with utilization of time domain techniques is both feasible and attractive. Accuracy to within 0.1 dB rms for loss and 0.1 nsec rms for delay can be achieved using this method.

In this paper, we describe the equalization and measurement philosophy for the WT4 system and also the technologies used in achieving the resulting degree of equalization. We put special emphasis on the description of trim equalization because line equalization has been described previously.[1]

II. MAJOR DELAY EQUALIZATION OF THE WAVEGUIDE

The circular waveguide in the WT4 system has an inside diameter of 60 mm,[4] which corresponds to a cutoff frequency of 6.09 GHz. It can be shown that the waveguide introduces considerable dispersion in the WT4 signal. Although the dispersion introduced by the waveguide is an order of magnitude less harmful at the higher portion of the band than at 40 GHz, due to WT4's high transmission rate (274 Mb/s), long repeater spacing (up to 60 km) and tight performance requirement (error rate less than 10^{-9} per repeater hop), equalization over the entire WT4 band is essential. This may be seen by noting that a bit period is 3.6 ns and the linear delay distortion at the high end of the band is 1.5 ns per 400 Mhz which would cause considerable intersymbol interference if unequalized.

Part of the task in developing the major delay equalizer for the waveguide was the definition of the equalizer itself. This was especially important in the early stage of the repeater development, for the type of equalizer chosen could well influence the overall repeater configuration. For example, delay equalization could be carried out at the RF frequency band in the form of frequency frogging. This method, if adopted, would require that every other repeater be a linear repeater, as opposed to a regenerative repeater. The tight specifications that would

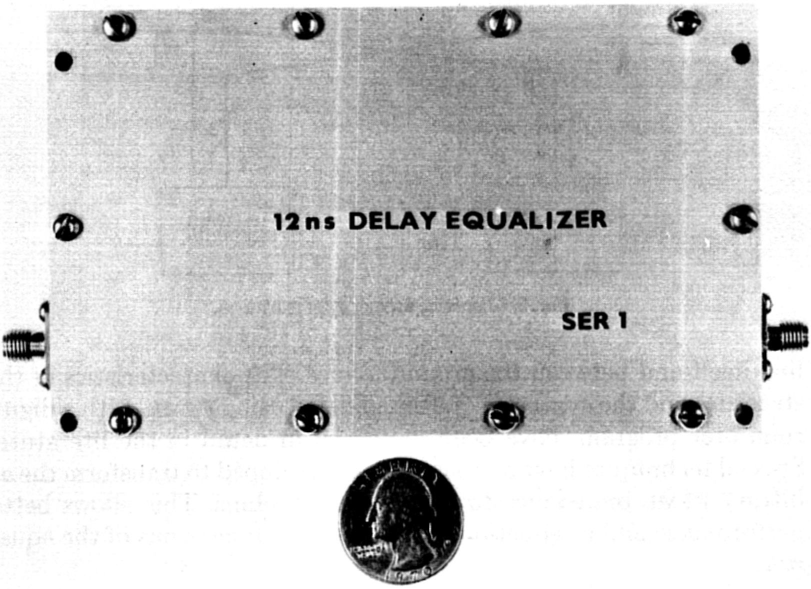

Fig. 2—FTML equalizer.

be required of the linear repeater design and the restrictions to be placed on adjacent repeater spacings, however, made this method undesirable.

Subsequent studies showed that it is best to equalize at IF frequency. Basically the reasons for this conclusion are that RF equalizers would be too costly, require more manufacturing codes (because of the numerous RF frequencies) and probably not perform as well as IF equalizers. In the IF equalization approach, the center frequency and the bandwidth of the equalizer are fixed for all channels. The IF band had been chosen to be from 1.15 to 1.57 GHz. The early objective, therefore, was to develop an L-band delay equalizer with 400 to 500 MHz of bandwidth.

The delay distortion of the waveguide, when measured in a 400 MHz window, is essentially linear. The magnitude of this linear delay varies from 30 ns at 40 GHz to 1.5 ns at 100 GHz. The amount of equalization required at each channel is different. The final configuration consists of seven codes of folded-tape meander-line (FTML) equalizers of fixed design to equalize the bulk of the waveguide delay.

2.1 Folded-tape meander-line equalizers

The FTML is a periodic structure, consisting of a conducting tape, perpendicular to two ground planes, folded back and forth to form a meander pattern. Dielectric material fills the space between the meander

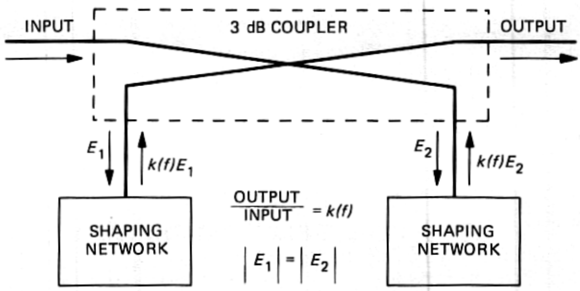

Fig. 3—Basic equalizer configuration.

line itself and between the ground planes. The characteristics of this structure and the synthesis of desired delay using FTML, with a digital computer program, have been described in detail in the literature.[1] Special techniques have also since been developed to transform the arbitrary FTML impedance to the desired 50 ohms. This allows better performance and a reduction in the physical dimensions of the equalizer.

In the final design, the FTML equalizer has an overall dimension of 5 by 3 by 0.5 inches. (See Fig. 2.) It provides linear delays at 4 ns (per bit rate frequency) increments up to a total of 20 ns. Above 20 ns, the increment is reduced to 3 ns. Typical insertion loss of the equalizer is approximately 0.15 dB per 1.0 ns of delay. The average return loss of the equalizer is better than 20 dB.

III. TRIM EQUALIZATION OF THE LINE AND REPEATER

The repeater and line trim equalizers are designed to compensate for relatively small amplitude and delay variations. The repeater equalizer compensates for distortions introduced between the input of the down-converter and the output of the final IF amplifier. The line trim equalizer is used to mop up after the meander line has removed the bulk of the transmission delay distortion. It also has an amplitude section which compensates more for amplitude distortions in the delay equalizers than for anything else.

3.1 Basic configuration

All equalization is accomplished in the IF band. Since the equalizer is in the transmission path it should present a good impedance match to connecting networks while at the same time shape the amplitude and delay characteristic of the signal. Consideration of these requirements along with other factors such as component availability and space limitation led to the selection of the network configuration shown in Fig. 3. The figure shows two identical shaping networks connected to the

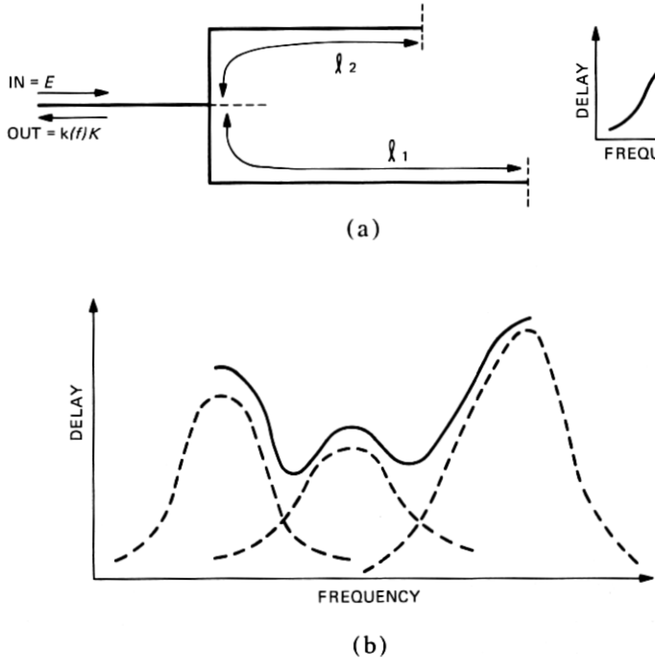

Fig. 4—(a) Delay reflection network. (b) Typical delay shape.

transmission ports of a 3 dB coupler. The input energy is divided evenly but 90 deg out of phase and sent to each network where the signal phase-frequency or loss-frequency characteristic is altered, and the energy is reflected back to the coupler. An additional 90 deg phase shift is introduced by the coupler, resulting in a cancellation of the reflected signals at the input port and the addition of signals at the output. The overall transfer characteristic is given by $k(f)$, the complex reflection coefficient of the shaping network.

3.2 Trim delay Equalization

The final version of the delay reflection network is shown in Fig. 4a. This network consists of two open circuit stubs forming a resonant circuit. The expression for delay, τ, is found by taking the derivative of the phase function of $k(f)$, and it is given by

$$\tau = \frac{1}{2f_0} \frac{(1-\delta)\cos^2\frac{\pi}{2}\frac{f}{f_0}(1+\delta) + (1+\delta)\cos^2\frac{\pi}{2}\frac{f}{f_0}(1-\delta)}{\cos^2\frac{\pi}{2}\frac{f}{f_0}(1-\delta)\cos^2\frac{\pi}{2}\frac{f}{f_0}(1+\delta) + \sin^2\pi\frac{f}{f_0}} \quad \text{nsec} \tag{1}$$

where ℓ_1 and ℓ_2 are the lengths of the open circuit stubs, f_0 is the frequency which makes $\ell_1 + \ell_2$ a half-wavelength long and $\delta = (\ell_1 - \ell_2)/(\ell_1 + \ell_2)$. When $f = f_0$ the delay expression reduces to

$$\tau\big|_{f=f_0} = \frac{2}{f_0} \frac{1}{(1 - \cos \pi\delta)} \tag{2}$$

Equation (2) is a very good approximation for the maximum delay given a value of δ. The expression is exact in the limit a $\delta \rightarrow 0$.

One complete network is fabricated on a 1 inch by 2 inch ceramic substrate, and it is configured as shown in Fig. 3 with two identical delay reflection networks. When a delay bump of a particular magnitude and center frequency is desired the stubs are laser-cut with δ proportional to $(\ell_1 - \ell_2)/(\ell_1 + \ell_2)$ and f_0 proportional to $\ell_1 + \ell_2$. Using this universal substrate a delay bump of any magnitude may be centered at any frequency between 1 GHz and 2 GHz. Fig. 4b indicates how three such delay bumps may be combined to yield a particular delay shape.

The synthesis procedure may be reduced to two major operations. The first is the specification of the delay requirement, after which the theoretical snythesis is performed using a computerized curve-fitting routine. The degree of accuracy for this procedure is completely dependent on the complexity of the delay requirement and the number of delay sections or bumps allowed to do the job. For the WT4 system three bumps have been used for all equalizers. Apart from this, the attractiveness of using the bump equalizer is that it allows the designer to estimate the closeness of fit and the location of bumps before any detailed synthesis is attempted. This cuts down on computation time since a trial-and-error technique is not required. Assuming that this first operation has provided a satisfactory curve fit, the second step is to specify the physical stub lengths on each of the substrates. The relationship between the electrical and physical length of the line is given as

$$\ell = \frac{c}{f\sqrt{\epsilon_e}} \tag{3}$$

where c is the free-space velocity of light, f is the frequency and ϵ_e is the effective dielectric constant of the microstrip line. Obviously the critical parameter is ϵ_e since c is a constant and f is specified by the synthesis. The value of the effective dielectric constant may be obtained from a theoretical analysis or it may be determined from a measurement made on the substrate. The latter approach has been used throughout the development due to the difficulty in determining the relative dielectric constant of the ceramic. The measurement technique will also compensate for junction effects and fringing capacitance which are an integral part of the network. The constant so determined is a function of the network layout; therefore it is not the value of effective dielectric

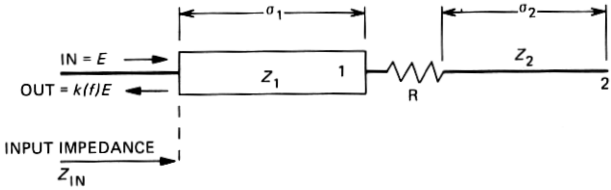

Fig. 5—Amplitude reflection network.

constant. In a mass-production environment, this characterization may be necessary only when a new batch of substrates is produced.

3.3 Trim amplitude equalization

The amplitude reflection network is shown in Fig. 5. This network consists of a low-impedance line, 1, a resistor R and a high impedance open circuit stub 2. As with the delay network, a bump loss shape is generated. The expression for the input impedance, z_{IN}, is easily derived and is given as

$$z_{IN} = z_1 \frac{(r + jz_2 ctn\sigma_2) + jz_1 \tan \sigma_1}{z_1 + j(r - jz_2 ctn\sigma_2) \tan \sigma_1} \tag{4}$$

where z_1, z_2 are the normalized impedances of the transmission lines, σ_1, σ_2 are the electrical lengths of the lines, r is the normalized resistance and z_{in} is the normalized input impedance. For the special case of $\sigma_1 = \sigma_2$, and the particular frequency, f_0, such that $\tan \sigma_1 = \tan \sigma_2 = \infty$, the input impedance is given as

$$|z_{IN}|_{f=f_0} = \frac{z_1^2}{r}. \tag{5}$$

The magnitude of the reflection coefficient for this case is

$$|k(f)|_{f=f_0} = \frac{1 - \frac{z_1^2}{r}}{1 + \frac{z_1^2}{r}} \qquad z_1^2 < r \tag{6}$$

and peak loss is given as

$$\text{Peak loss} = -20 \log |k(f)|_{f=f_0} \tag{7}$$

A maximum amplitude bump of 8 dB was deemed sufficient for amplitude equalization. Assuming also that the smallest practical resistor value available with thin-film technology is 10 ohms, the solution of eq. (6) leads to a value of $z_1 = 0.293$. For a 50 ohm system the line impedance is $z_1 \times 50 = 14.7$ ohms. To keep the flat loss to a minimum the skirts of the amplitude shape should drop off as rapidly as possible. To achieve this, a very high impedance line is used to terminate the resistor. This line is 2 mils wide with an impedance $z_2 = 2.2343$. For the 50-ohm system, the 2-mil line has an impedance of $z_2 \times 50 = 112$ ohms.

One complete amplitude network is fabricated on a 1 inch by 2 inch ceramic substrate, and it is configured as shown in Fig. 3 with two identical amplitude reflection networks. The length ℓ_1 of the high-impedance line determines the center frequency and the resistance R determines the magnitude of the bump. As with the delay equalizer the bump shape may be moved across the IF band by laser trimming the high-impedance line and the magnitude adjusted by laser trimming the resistor. The bumps may be added to produce a general shape.

3.4 Equalizer synthesis

The amplitude and delay shape requirements are synthesized by adding three delay bump equalizers and three amplitude bump equalizers. To achieve the best possible fit, a least squares curve-fitting program is used to determine the equalizer parameters.

As indicated earlier, there is an interaction between the amplitude and delay equalizers. The amplitude equalizer has delay shape and the delay equalizer has loss.

An efficient technique was developed to determine the equalizer requirements and is illustrated in Figs. 6a and b. Fig. 6a shows the delay requirement plotted on the negative frequency axis and the amplitude requirement plotted for positive frequencies. The interaction components are plotted in Fig. 6b. The program is designed to optimize both amplitude and delay as though they were a single requirement. When the negative frequency region is used the program adds the delay of the delay equalizer to the delay of the amplitude equalizer. The positive frequency region computes and adds the loss of the amplitude equalizer to the loss of the delay equalizer. In this way the optimization procedure can fit the total equalizer requirement with all interaction components accounted for.

3.5 Equalizer fabrication

The individual networks are assembled in a single housing. The substrates may be connected in any order, with the equalizer normally consisting of three delay bumps and three amplitude bumps. However, any combination of amplitude and delay substrates totaling six may be used, depending on the equalizer desired. The substrates are bonded together with gold ribbon and the input and output ports are brought out through OSM-type connectors.

The line trim equalizer is designed to permit field equalization adjustments in conjunction with the equalization test set. Laser trimming

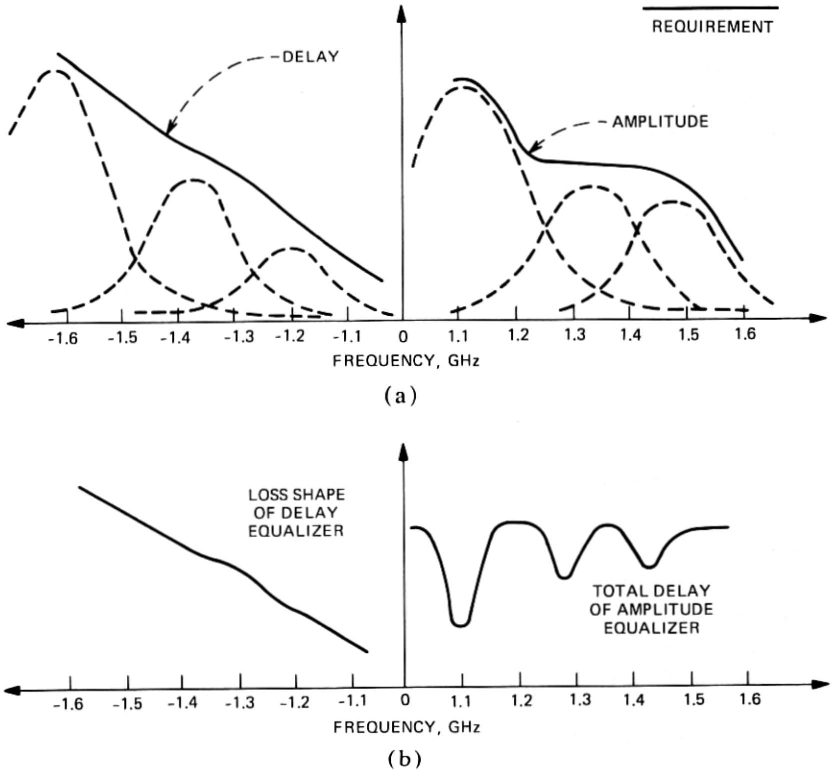

Fig. 6—(a) Delay and amplitude curve fitting. (b) Parasitic delay and loss.

was ruled out for field use so the repeater equalizer networks were modified to provide an acceptable tuning structure. The two basic reflection networks are shown in Fig. 7. The delay section is shown at the

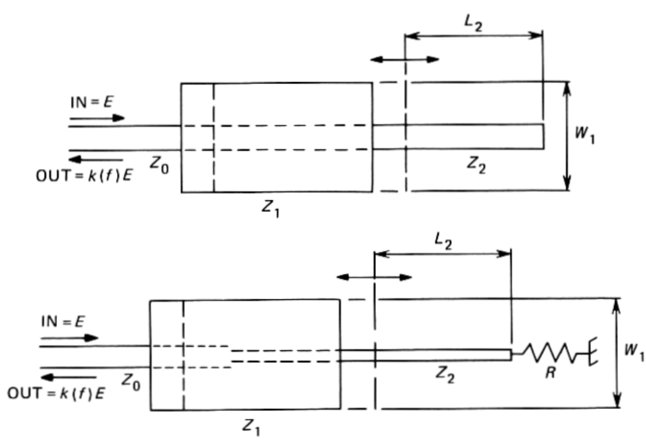

Fig. 7—Line trim equalizers.

top and the amplitude section below it. For each network the variable parameters are W_1, the width of the low impedance line, and L_2, the stub length from the open circuit or resistive termination. The magnitude of the delay (amplitude) bump is proportional to Z_2/Z_1 and the frequency at which the peak occurs is determined by L_2.

The tuning of this structure is accomplished by first selecting a preformed block which has the low-impedance line plated on and then positioning the block to set the center frequency. The blocks are fabricated to provide 0.5 nsec delay increments and 0.5 dB magnitude increments from 8 nsec (dB) down to 1 nsec (dB). When the adjustment is completed, the block is held in position by a spring-loaded cover and positioning bracket. The completed equalizer consists of six sections, three delay and three amplitude, housed in a metal case with miniature coaxial connectors to the outside.

IV. EQUALIZATION MEASUREMENT

In order to determine the transfer function of the required line and repeater equalizers some type of measurement must be performed. For the repeater equalizers it is simple to perform a swept-frequency measurement of the RF and IF portions of the repeater in the factory. The situation is quite different for the line equalizer, however.

It is clear that the required characteristics of the various line equalizers are not known in detail until the specific channel has been measured. Accurate measurement of loss and delay by well-established swept-frequency techniques requires that a suitable reference signal be supplied from the transmitter to the receiver while the measurements are being performed. For the waveguide system this is difficult to do because the two ends of any section to be measured up to 40 km apart. The total frequency range to be covered is also very wide (40 to 110 GHz). To provide full coverage would require at least three sets of wide-sweep millimeter-wave transmitters and receivers. Such test set bulk is of concern because the test set has to be transported from repeater station to repeater station throughout the country. These factors led to consideration of time domain measurement techniques. The basic procedure has been described in Ref. 5 and consists of digitally phase modulating the WT4 transmitter for a particular band and linearly detecting the pulse train received in the receiver IF. By using fast Fourier transform processing of the detected waveforms with the transmitter and receiver connected back-to-back and with transmission through the line, an accurate determination of the line transfer function can be made. This information is then used to synthesize and appropriate channel equalizer for the waveguide system. The above procedure is repeated each time a channel in the WT4 system is put into service for the first time. The complete operation is controlled by a PDP-11/05 minicomputer.

Table I — Typical equalization results

Frequency, GHz	Repeater delay, nsec	Equalizer delay, nsec	Total delay, nsec
1.21	1.01	−0.95	+0.05
1.25	0.55	−0.61	−0.06
1.29	0.14	−0.17	−0.03
1.33	−0.09	−0.01	−0.10
1.37	0.	0.	0.
1.41	0.23	−0.16	+0.07
1.45	0.67	−0.46	+0.21
1.49	1.23	−0.95	+0.28
1.53	1.82	−1.73	+0.09

Note: Delay figures are normalized to give 0 delay of 1.37 GHz.

V. EQUALIZATION RESULTS

5.1 Repeater equalization results

In Table I, we list the delay characteristic versus frequency of a typical repeater along with the corresponding delay characteristic of the repeater equalizer. Also included is the resultant delay of the repeater after equalization. Typically we have experienced ±0.2 ns in delay deviation after equalization and ±0.3 dB in amplitude deviation.

5.2 Line equalization results

The transfer characteristics of each broadband channel were measured using the equalization test set described in Section IV. Figure 8 shows the measured characteristics of a typical channel (solid curve) and the desired characteristics. For the line, the desired characteristic is the ideal shape of the waveguide channelizing filter which is shown with a dashed line in Fig. 8. The fast ripples in the transfer function are due mainly to the channelizing filters; the waveguide medium contributes small ripples. The equalizer is designed as described in previous sections to make up

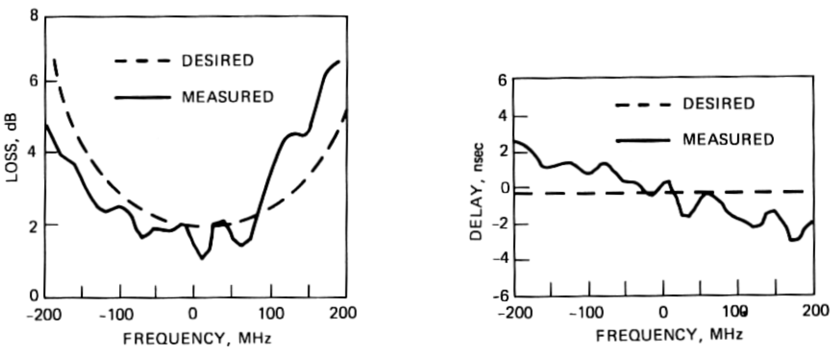

Fig. 8—Loss and delay in unequalized line.

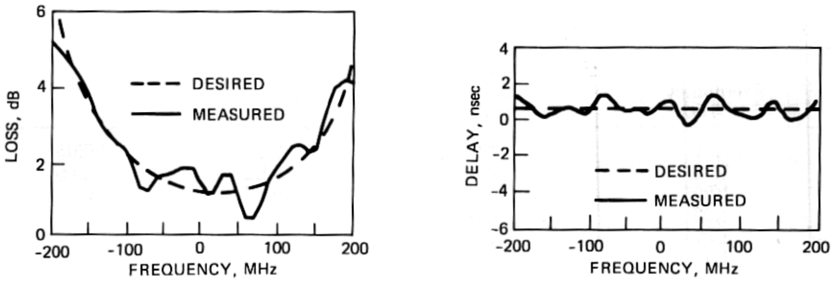

Fig. 9—Loss and delay in equalized line.

the difference between the curves. Our line equalizer is only capable of compensating for three "bumps" in amplitude and delay in addition to linear delay in the pass band; therefore, we are only attempting to equalize the slowly varying portion of the difference. The results of equalization are shown in Fig. 9. Note that the peak-to-peak variations in amplitude and delay after equalization are about ±0.5 dB and ±1.0 nsec and that essentially all of the slowly varying distortion has been removed.

VI. CONCLUSIONS

Line and repeater equalization techniques which have proved to be successful for the WT4 waveguide system have been described. The residual amplitude and delay shapes of the waveguide system transfer function after equalization is quite acceptable. Furthermore, an extension and modification of previous time-domain techniques to cover the millimeter-wave frequencies has been found to be both a feasible and attractive method for characterization of the waveguide line.

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