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Measurement of Echoes Due to Spurious TE_{0n} Modes in a Long-Distance 60-mm Waveguide Communication System

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To estimate the seriousness of spurious TE_{0n} *mode generation in a long-distance millimeter waveguide communication system requires a measurement of small echoes in the impulse response with delays up to about 500 ns. We report the results of such a measurement made as part of a recent 14-km field test of the WT4 communication system with a novel test set operating near 41 GHz. The results show that the WT4 system can perform satisfactorily without any filters of spurious* TE_{0n} *modes.*

I. INTRODUCTION

The performance of a long-distance millimeter waveguide communication system can be seriously degraded by slowly decaying echo trains in the impulse response. Slowly decaying echo trains are caused by coupling over long distances of the desired signal mode (TE_{01}) with forward traveling spurious TE_{0n} modes. When many echoes in such an echo train act in phase, the resulting peak distortion on a received signal can be quite large, even with relatively small total echo power.

A previous paper[1] described an echo test set (Fig. 1) designed to detect such slowly decaying echo trains. This test set transmits a 20-ns pulse into a 60-mm waveguide line with a shorting plate at the end, samples the signal in 4-ns increments for 1 μs near the returning pulse, transforms the data to loss and delay versus frequency, and overlaps data taken at different center frequencies, f_c, to extend the frequency range of the data. Measurements were made with this test set as part of a recent 14-km field test of the WT4 system[2] between Netcong and Long Valley, New Jersey. These measurements indicated indirectly that the power in slowly decaying echo trains generated in the 60-mm waveguide itself was too small to degrade system performance.[1]

To demonstrate overall system performance, however, we must de-

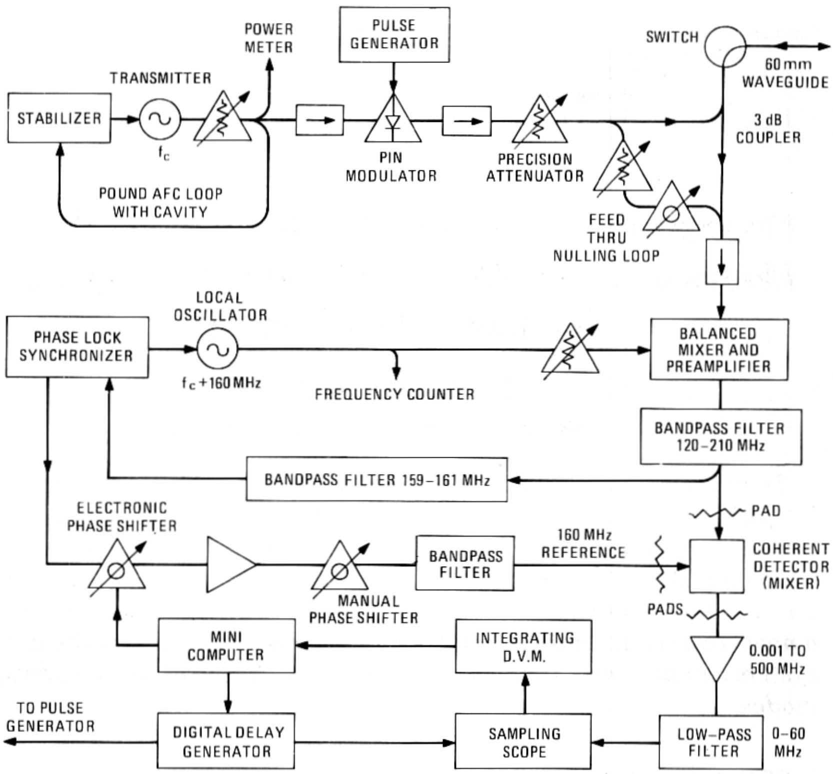


Fig. 1—Block diagram of the echo test set.

termine the impulse response for the entire WT4 system, including the band diplexer trees at each end of the 60-mm waveguide. A band diplexer tree[3] contains several miter elbows and hybrids, each of which converts a relatively large amount of energy to and from spurious TE_{0n} modes.[4] Energy that is converted to TE_{0n} modes in the long-distance 60-mm waveguide medium and then reconverted at the band diplexer tree (or vice versa) can cause echoes much larger than those generated in the waveguide medium alone. Miter elbows used for sharp waveguide bends in an experimental Japanese system caused serious ripples in the measured loss versus frequency[5] and presumably serious echoes in the impulse response also.

In this paper, we evaluate the seriousness of spurious TE_{0n} mode generation in the WT4 system from the levels of echoes in the impulse response. We explain first, in Section II, how to obtain the impulse response from measurements of loss and delay versus frequency. To establish credibility for the results, we consider round-trip loss and delay measurements of the field test without the diplexer tree[1] and show that the level of the large echoes in the impluse response agrees with independent data. Since the echo test set could not conveniently measure through the diplexer tree, we made a discrete TE_{0n} generator to simulate the tree. In Section III, we describe theoretical and experimental characterizations of the mode conversion levels in this TE_{0n} generator and compare the level of TE_{02} with that expected from the diplexer tree. In Section IV, we compare the impulse response of Section II with that obtained from round-trip measurements of the field test with the TE_{0n} generator in place. From the data in Sections III and IV, we also estimate in Section V the level of TE_{02} generated within the waveguide itself and show that this level is consistent with an estimate based on mechanical measurements. We conclude, in Section VI, with a discussion of the implications of all these measurements on the WT4 system design.

II. DETERMINATION OF THE IMPULSE RESPONSE

2.1 Theory

The levels of echoes in the impulse response can be determined from the waveguide forward transfer function. First we write the total waveguide transfer function I_o for the TE_{01} mode (the desired signal mode) as:

$$I_o(f) = P(f)H_o(f), \tag{1}$$

where $P(f)$ is the transfer function for ideal waveguide and contains the effects of dispersion and ohmic losses. For a length z of waveguide, this transfer function is

$$P(f) = e^{-\Gamma_o z} = e^{-\alpha z}e^{-j\beta z}. \tag{2}$$

Here $\alpha(f)$ and $\beta(f)$ are the real and imaginary parts, respectively, of the propagation constant Γ_o for the TE_{01} mode. Reflections and mode conversion cause the normalized transfer function $H_o(f)$ to differ from unity. In the absence of reflections and when there is mode conversion from TE_{01} to only one other mode, $H_o(f)$ is identical to the function $G_o[\Delta\Gamma(f)]$ used in studies of mode conversion.[6,7,8] There, $\Delta\Gamma$ is the differential propagation constant

$$\Delta\alpha + j\Delta\beta = \Delta\Gamma = \Gamma_o - \Gamma_n, \tag{3}$$

where Γ_n is the propagation constant of the spurious mode.

Since we know the ideal transfer function $P(f)$, we consider now only the normalized impulse response $h(t)$, which is the Fourier transform of $H_o(f)$:

$$h(t) = \int_{-\infty}^{+\infty} H_o(f)\exp(j2\pi ft)df. \tag{4}$$

To obtain the normalized transfer function $H_o(f)$, we first remove the characteristics of ideal waveguide from the loss and delay $\tau(f)$ data. We integrate the residual delay data to obtain the residual phase versus frequency $\phi(f)$ and then find $H_o(f)$ by exponentiation of the residual loss $A(f)$ and phase:

$$H_o(f) = \exp(-A(f) + j\phi(f)). \qquad (5)$$

To reduce echo sidelobe levels, we multiply the real and imaginary parts of $H_o(f) - 1$ by a data window and transform the result using an FFT (fast Fourier transform). This procedure produces $h(t)$ minus the delta function at zero delay. Finally, we square and sum the real and imaginary parts of $h(t)$ to obtain the power in each echo as a function of delay. The echo power is corrected for the attenuation introduced by the data window.

2.2 Example

For illustration, we consider round-trip measurements of the 14-km waveguide medium without the TE_{0n} generator. The baseline for these measurements is the round trip to a closed shutter[9] at the manhole (see Fig. 2). Data over a 350-MHz band near 41 GHz are shown in Fig. 3a. These data are the same as reported previously, except that the delay dispersion characteristic of ideal waveguide has been subtracted out.

Most of the features of the data in Fig. 3a exhibit the expected behavior. The decreasing loss versus frequency is characteristic of the ohmic loss in the waveguide wall. The level of the very rapid ripples is about at the level of the test set noise (0.01 dB rms).[1]

The magnitude of the normalized impulse response shown in Fig. 3b reveals a pair of equal magnitude echoes separated from the main impulse by $t_0 = \pm 10$ ns. These echoes correspond to the ripple seen in the delay data with period $1/t_0 = 100$ MHz. Since these echoes produce a ripple in the delay but not in the loss, they must be 180 degrees out of phase.[10]

This pair of echoes is caused by reflections from a pressure window located 1.5 m in front of the shorting end cap in the test station (Fig. 2). This pressure window is a short length of foam with low relative dielectric constant ϵ embedded in the 60-mm waveguide. Some energy is reflected from the pressure window without ever reaching the shorting end cap and returns to the test set 10 ns before the main pulse. Other energy, after being reflected from the end cap, is reflected from the pressure window back to the end cap a second time and finally arrives at the test set 10 ns after the main pulse.

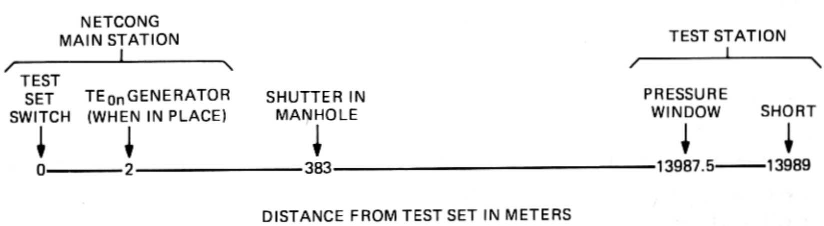


Fig. 2—Distances in the WT4 field test.

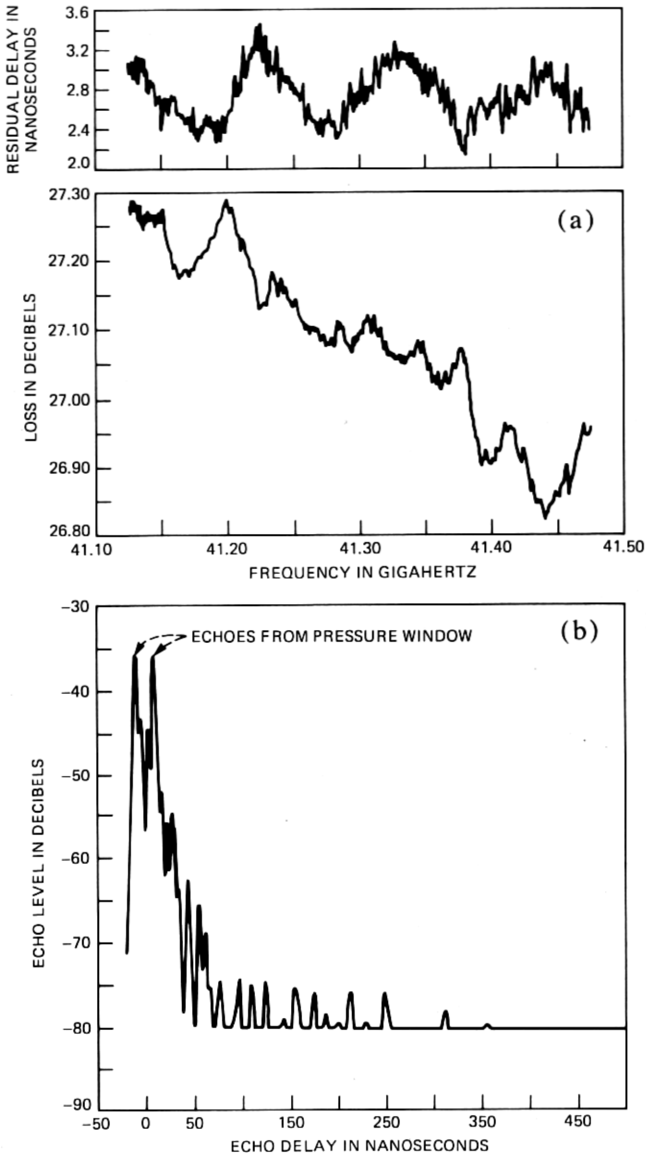


Fig. 3—(a) Measured loss and residual delay for the 27.21-km round trip between the manhole and the test station. (b) Normalized impulse response corresponding to Fig. 3a.

The magnitude of this echo pair seen in Fig. 3b agrees with other measurements. Fault location measurements made at 41.24 GHz with the shorting end cap removed also gave $20 \log_{10}|R| = -37$ dB for the total reflection coefficient R at the location of the pressure window.[11] Furthermore, since the two echoes are 180 degrees out of phase, it is easy to show that the reflection coefficient R_o for each end of the window must satisfy the relation $R_o = |R|/2 = 0.007$. Then we infer that $\sqrt{\epsilon} - 1 \simeq 0.014$, or $\epsilon = 1.03$, which is exactly the dielectric constant specified for the foam.[12]

The remaining echo power in the impulse response shown in Fig 3b is quite small. We conclude that there is negligible power in long echo trains caused by mode conversion and reconversion within the 60-mm waveguide medium itself. Considerably stronger echoes appear, however, when the TE_{0n} generator is inserted to simulate the diplexer tree.

III. TE_{0n} GENERATOR CHARACTERIZATION

The TE_{0n} generator was designed for insertion on the 60-mm side of the circular waveguide taper at the Netcong test set platform (Figs. 2 and 4). The interior of the TE_{0n} generator is a 76-mm (3-in.) length of reduced diameter waveguide. The inside diameter is 54 mm (2.125 in.) over the central 50.8-mm (2 in.) region. To reduce reflections, the diameter is tapered linearly up to 60 mm (2.362 in.) in 12.7-mm (0.5 in.) tapers on each end of the generator.

Perturbation theory[6] applied to the above diameter variation predicts excitation of spurious modes with the levels shown in Table I. We may expect these estimates to be somewhat in error, because the diameter change from 60 to 54 mm is a fairly large fraction of the original diameter and therefore may violate the assumption inherent in the perturbation theory.

We determined experimentally the levels of spurious TE_{0n} modes excited by the generator from the levels of ripples in the round-trip loss from the test set to the shutter in the manhole. We obtained a baseline

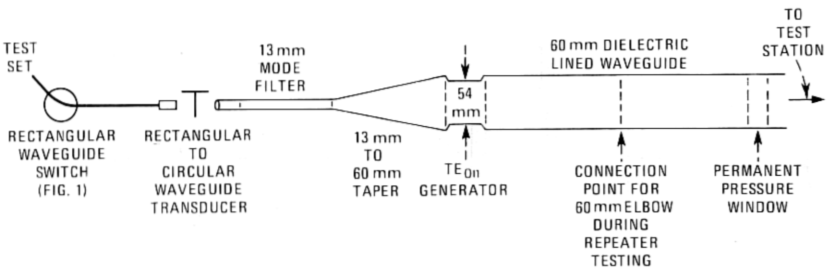


Fig. 4—Layout of test components at Netcong main station including the TE_{0n} generator.

Table I — Mode levels relative to TE_{01} at the TE_{0n} generator output (perturbation theory)

	40 GHz	45 GHz
TE_{02}	−13 dB	−14 dB
TE_{03}	−16 dB	−15 dB
TE_{04}	−24 dB	−34 dB

measurement in this case by closing the rectangular waveguide switch in the test set (see Figs. 1 and 4). The net round-trip measurement sees the effects of two equal discrete mode converters of strength x separated by a distance 2ℓ, where ℓ is 381 m (see Fig. 2). The measured mode conversion loss A due to one spurious TE_{0n} mode is then:[6]

$$A = x^2(1 + e^{-|\Delta\alpha|2\ell} \cos \Delta\beta 2\ell) \text{ nepers.} \tag{6}$$

Here $\Delta\alpha$ and $\Delta\beta$ are the differential attenuation and phase, respectively, of the TE_{0n} mode relative to TE_{01} (see eq. (3)). The first term in eq. (6) is the round-trip insertion loss of the generator. Because $\Delta\beta$ varies with frequency, the second term in eq. (6) represents a loss ripple.

The period of the ripple in eq. (6) corresponds to a change in $\Delta\beta$ of $2\pi/2\ell$. The period δf in frequency is:

$$\delta f = \left(\frac{df}{d\Delta\beta}\right)\left(\frac{2\pi}{2\ell}\right). \tag{7}$$

Equivalently,

$$t_R = \frac{1}{\delta f} = \left(\frac{d\Delta\beta}{d\omega}\right)2\ell, \tag{8}$$

where t_R is clearly the round-trip differential group delay of TE_{0n} relative to TE_{01}.

The theoretical parameters for the lowest order TE_{0n} modes are shown in Table II for 41.3 GHz, which is close to the center frequency of our measurements. We also list for reference the beat wavelengths $2\pi/\Delta\beta$ and wall coupling coefficients Ξ. For TL_{0n} modes, these parameters are not very sensitive to the thickness or properties of the dielectric liner on the wall of the waveguide.

The data in Fig. 5 show clearly that the TE_{0n} generator excites TE_{02}, TE_{03}, and TE_{04}. The loss versus frequency data in Fig. 5a show the 14-MHz ripple period expected from TE_{02} in a 762-m round trip. The presence of TE_{03} and TE_{04} is seen more easily after Fourier transformation of the loss.

With the help of eq. (6), we determined the mode conversion levels plotted in Fig. 5b. Defining $A(k)$ as the N-point discrete Fourier transform of $A(f)$ in eq. (6), we find that the peak magnitudes in $A(k)$ are:

Table II — TE_{0n} parameters at 41.3 GHz in 60-mm waveguide*

	TE_{02}	TE_{03}	TE_{04}	
$\lvert\Delta\alpha\rvert$	0.26	0.70	1.38	nepers/km
$\Delta\beta$	22.73	59.76	113.23	radians/m
$2\pi/\Delta\beta$	0.276	0.105	0.056	m
Ξ	1216	−1804	2447	m^{-2}
$d(\Delta\beta)/d\omega$	−0.092	−0.253	−0.514	ns/m
t_R(in 762 m)	70	193	392	ns
δf(for 762 m)	14.3	5.2	2.6	MHz
$8.686\,\lvert\Delta\alpha\rvert\ell$ (in 381 m)	0.86	2.32	4.57	dB

* Assuming a 179-μm dielectric liner with $\epsilon_r = 2.28$ and $\tan\delta = 1.25 \times 10^{-4}$.

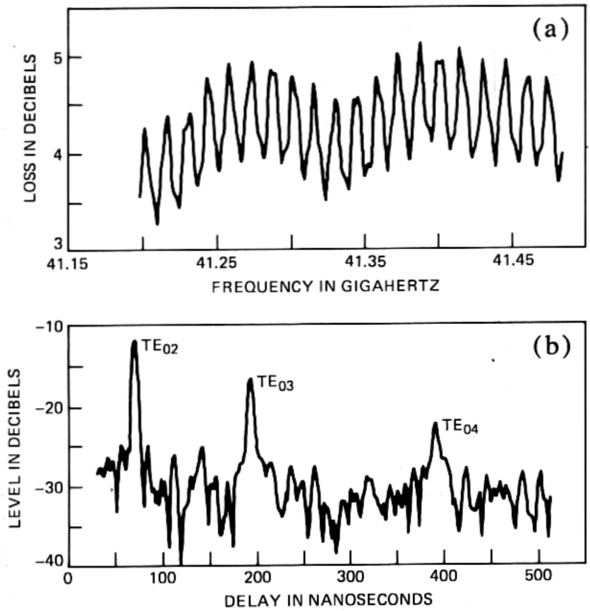


Fig. 5—(a) Measured loss for the 766-m round trip between the test set and the manhole with the TE_{0n} generator in place. (b) Modified Fourier transform of Fig. 5a, showing levels of TE_{0n} modes generated at the TE_{0n} generator.

$$|A(k)| = \frac{N}{2} x^2 e^{-|\Delta\alpha| 2\ell}, \qquad k = N t_R \Delta f, \tag{9}$$

where Δf is the sampling interval in frequency, and t_R is defined in eq. (8). For these data, $\Delta f = 1$ MHz, corresponding to the 1-μs total sampling interval of the original time domain measurements.[1] Inverting eq. (9) to find the mode conversion levels x, we obtain:

$$a_k \equiv 20 \log_{10} x = 10 \log_{10} \left(\frac{2|A(k)|}{N}\right) + 8.686|\Delta\alpha|\ell, \; k = N t_R \Delta f. \tag{10}$$

The ratio of $8.686|\Delta\alpha|\ell$ to round-trip delay t_R is very nearly constant for TE_{0n} modes and is within 3 percent of 0.012 dB/ns for the three modes and conditions of Table II. Using this fact to evaluate the last term in eq. (10), we then plotted eq. (10) in Fig. 5b from the data in Fig. 5a.

The data in Fig. 5b agree quite well with the theoretical expectations for the TE_{0n} generator listed in Table I. The peaks corresponding to TE_{02}, TE_{03}, and TE_{04} occur at delays within 1 ns of those predicted in Table II. The mode levels inferred from Fig. 5b are −12 dB, −17 dB, and −23 dB relative to TE_{01} for TE_{02}, TE_{03}, and TE_{04}, respectively. In particular, the level of TE_{02} generated is roughly equal to the worst possible TE_{02} mode level that could be generated in the band diplexer tree between 40 and 110 GHz.[13]

IV. LONG-DISTANCE ECHO TRAIN MEASUREMENTS WITH THE TE_{0n} GENERATOR

The presence of the TE_{0n} generator causes the round-trip measurements of the 14-km field test to differ significantly from the measurements presented in Section II. In this section, we examine these differences, first in the frequency domain and then in the time domain. The time domain data provide an estimate of the impulse response of the entire waveguide system including the diplexer tree.

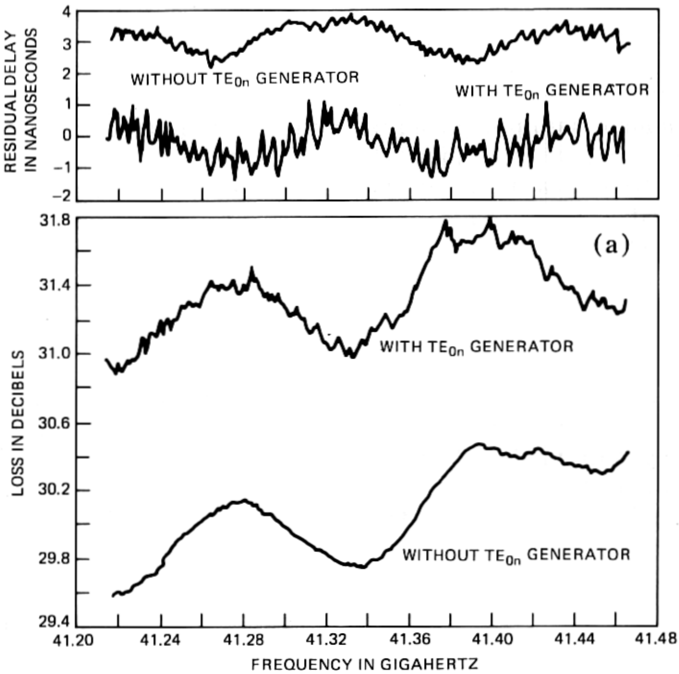
Data from measurements with and without the TE_{0n} generator are displayed together in Fig. 6a. For these measurements, the shorting switch in the echo test set was used to obtain the baseline. The difference in average loss with and without the TE_{0n} generator is due mainly to the mode conversion loss for a round trip through the generator. For the mode conversion levels observed in Fig. 5 for TE_{02}, TE_{03}, and TE_{04}, this loss is theoretically 0.77 dB. The additional discrepancy is consistent with the test set's ±1 percent accuracy in absolute loss.[1] A minor difference in average delay is caused by a slight difference in the pressure of nitrogen filling the waveguide. [We used only the nominal pressure to estimate the effect of the refractive index of nitrogen on the ideal transfer function $P(f)$ of eq. (1).]

The level of the rapidly varying ripples increased substantially after insertion of the TE_{0n} generator. An additional slowly varying loss ripple has also appeared in Fig. 6a that is not present in the measurement made with the baseline in the manhole (Fig. 3a). The origin of these ripples is clarified by the time domain data in Fig. 6b, which was obtained from Fig. 6a by the method described in Section II.

An additional echo at a 10-ns delay is evident in Fig. 6b and is due to a reflection from the precision attenuator in the test set. The echoes leading and lagging the main signal are no longer equal in level, as they were when the baseline was taken at the manhole (see Fig. 3b and Section II). Correspondingly, a loss ripple with a period of about 100 MHz appears in Fig. 6a.

The large echoes in Fig. 6b with delays of 35 and 96 ns may be due to mode conversion at the TE_{0n} generator followed by reconversion near the manhole (and vice versa). The differential delays for the 381 meters between the generator and the manhole are indeed 35 and 96 ns for TE_{02} and TE_{03}, respectively (see Table II).

The power in echoes with long delays generally is substantially greater with the TE_{0n} generator in place than without it. For example, the integrated total power in the echoes shown in Fig. 6b with delays greater than 50 ns, excluding the echo at 96 ns, is 44 dB below the signal. In contrast, the power in such echoes (and test set noise) shown in Fig. 3b is 57 dB below the signal. These levels of echo power are consistent with the expected levels of spurious TE_{0n} modes generated in the waveguide itself, as discussed next.



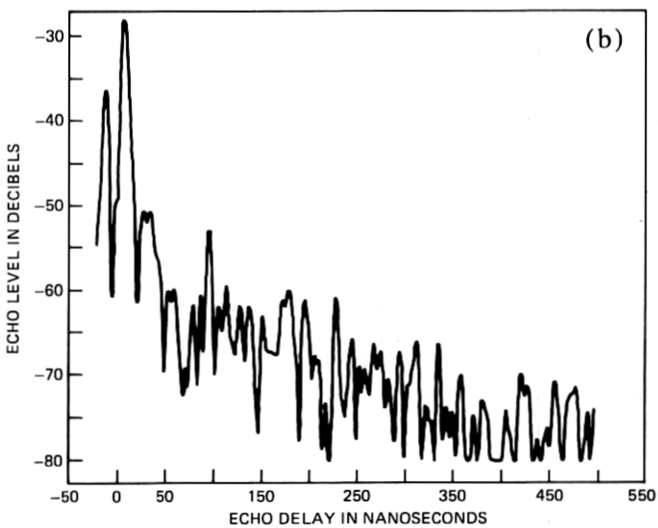


Fig. 6—(a) Measured loss and residual delay for the 27.98-km round trip between the test set and the test station. Measurements with and without the TE_{0n} generator in place are shown. (b) Normalized impulse response corresponding to the data in Fig. 6a for the TE_{0n} generator in place.

V. COUPLING TO TE_{0n} MODES IN THE BURIED 60-mm WAVEGUIDE MEDIUM

5.1 Levels estimated from electrical measurements

From the measurement data presented in Sections III and IV, we can now estimate the amount of spurious TE_{0n} mode power generated in the buried 60-mm waveguide. First, from Section III (Fig. 5 and Table II), there is no evidence that the TE_{0n} generator excites any modes but those in the TE_{0n} family. Therefore, the increase in power in echoes with long delay seen in Fig. 6b is due solely to mode conversion to and from TE_{0n} modes.

For simplicity, let us assume that spurious TE_{0n} energy generated in the buried waveguide is predominantly in the TE_{02} mode. Let us also assume that the level of TE_{02} generated per unit length does not vary greatly with position along the 14-km route. Because TE_{02} has a low differential attenuation per unit length $|\Delta\alpha|$, almost all the TE_{02} energy reconverted at the TE_{0n} generator is then in echoes with delays longer than, say, 50 ns.

To calculate the level of TE_{02} incident on the TE_{0n} generator from the waveguide, we argue in reverse. If the TE_{02} level returning from a round trip in the 60-mm waveguide and incident on the TE_{0n} generator were -38 dB, then the reconverted power seen in TE_{01} would be 12 dB lower, or -50 dB. However, the total reconverted power also contains a contribution from energy converted to TE_{02} at the generator at the beginning of the round trip and then reconverted along the waveguide. Since the coupling is completely reciprocal, the echoes caused by coupling to and from TE_{02} on the forward and reverse legs of the round trip will add in phase. Hence the total reconverted power in echoes would be 6 dB greater, or -44 dB, as was measured (excluding the echo at 96 ns and those with delays less than 50 ns).

Coupling to higher order TE_{0n} modes probably causes a smaller fraction of the total echo power than does coupling to TE_{02}, because those modes have a higher differential attenuation and also less coupling at the TE_{0n} generator (see Tables I and II). The level of TE_{02} generated through continuous coupling in a one-way trip through the buried waveguide is therefore roughly 40 dB below the level of TE_{01}.

5.2 Levels estimated from mechanical measurements

From independent measurements, we can estimate the level of TE_{02} that is generated by various coupling mechanisms. These mechanisms include continuous coupling at diameter distortions in helix and dielectric-lined waveguide and coupling at localized diameter distortions at the waveguide flanges.

The average TE_{02} spurious mode level generated by continuous coupling in dielectric-lined waveguide can be calculated from the spectrum of waveguide diameter variation with distance.[6] At the mechanical frequency $\Delta\beta/2\pi$ appropriate for coupling to TE_{02} near 41 GHz, the average spectrum measured on individual waveguide sections corresponds to an average TE_{01} mode conversion loss in 14 km of about 5×10^{-5} neper (0.0004 dB). According to the coupled power equations,[14] the average random spurious mode power P builds up to a steady state independent of the length L of waveguide, when the total differential attenuation $|\Delta\alpha|L$ is large. This steady-state level is

$$P = \frac{\langle A \rangle}{|\Delta\alpha|}, \tag{11}$$

when $\langle A \rangle$ is the average TE_{01} loss per unit distance. Taking $|\Delta\alpha|$ from Table II, we find $10 \log_{10} P$ to be about -48 dB for continuous conversion in dielectric-lined waveguide.

Analysis of diameter data for some helix mode filters in the field test showed that TE_{02} levels of about -51 dB could be generated in some of these filters near 50 GHz.[15] If we assume every mode filter generates that much TE_{02} and take into account the effect of differential attenuation, we find that the steady-state level P after 14 km is about 3 dB higher, or $P = -48$ dB.

The TE_{02} level generated at the flanges can be very serious, but the randomized waveguide length scheme used in the field test reduces this level considerably.[16] Without randomization of lengths, the steady-state TE_{02} power after a long distance would be only 16 dB below the power in TE_{01}. (This level was calculated from measured diameter distortions near flanges.) Randomization of the waveguide lengths destroys the coherent build-up of spurious mode power and thus keeps the average random TE_{02} mode power P at a steady state 45 dB below the power in TE_{01}.

The sum of the calculated TE_{02} mode power generated by the above three sources of coupling is -42 dB, which is close to the value of -40 dB inferred above from the electrical measurements. While the levels calculated from the mechanical and electrical measurements are only rough estimates, the agreement between them is reasonable.

Reconversion of TE_{02} mode power at strong couplers such as the TE_{0n} generator or the diplexer tree is evidently always more serious than continual conversion and reconversion along the waveguide alone. The calculated reconverted power caused by the above three sources of mode coupling without the TE_{0n} generator in place is less than -80 dB and thus is completely invisible in Fig. 3. For the case without randomized lengths, the total power reconverted from TE_{02} with and without the TE_{0n} generator would be -22 dB and -50 dB, respectively.

VI. CONCLUSIONS

The power in long echo trains caused by coupling between TE_{01} and spurious TE_{0n} modes is too small to affect the performance of the WT4 system. In the two- and four-phase WT4 systems, the designed thermal noise levels are 22 and 28 dB below the carrier, respectively.[17] By comparison, the estimated maximum power in long echo trains in the WT4 field test is about 44 dB below the signal power after a 28-km round trip including the diplexer tree. The system thermal noise will therefore certainly swamp out the power in long echo trains.

Assuming the waveguide lengths are randomized as in the field test, the power in long echo trains should be no greater in a 50-km or 60-km repeater hop than in the field test. After a certain distance in 60-mm waveguide, the average random power in any spurious TE_{0n} mode reaches a steady state independent of the length of the waveguide. Echo power generated by continuous mode conversion and reconversion in the 60-mm waveguide alone does increase indefinitely with the length of the waveguide. The level of this echo power, however, is generally much smaller than the echo power caused by reconversion at the band diplexer tree of spurious TE_{0n} mode power generated in the 60-mm waveguide.

Filters of spurious TE_{0n} modes are therefore not necessary in the WT4 system. Such filters are difficult to fabricate without introducing significant TE_{01} insertion loss, and they also require obstructions within the waveguide[18] that may interfere with waveguide maintenance.

VII. ACKNOWLEDGMENTS

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REFERENCES

1. J. L. Doane, "Measurement of the Transfer Function of Long Lengths of 60-mm Waveguide with 1-MHz Resolution and High Dynamic Range," Digest of the Conference on Precision Electromagnetic Measurements, Boulder, Colorado, June 28 to July 1, 1976, IEEE Publication No. 76, CH1099-1 IM, pp. 153–155.
2. D. A. Alsberg, J. C. Bankert, and P. T. Hutchison, "The WT4/WT4A Millimeter-Wave Transmission System," B.S.T.J., *56,* No. 10 (December 1977), pp. 1829–1848.
3. E. T. Harkless, A. J. Nardi, and H. C. Wang, "Channelization," B.S.T.J., *56,* No. 10 (December 1977), pp. 2089–2101.
4. E. A. Marcatili, "Miter Elbow for Circular Electric Mode," Proc. Symp. on Quasi-Optics, Polytechnic Institute of Brooklyn, June 1964, p. 535.
5. K. Yamaguchi, K. Kondoh, F. Nihei, and M. Kikushima, "Transmission Characteristics of an Experimental Millimeter-Waveguide Line including Miter Elbows," Rev. Elec. Commun. Lab., *20,* Nos. 11-12 (November–December 1972), pp. 1114–1118.
6. H. E. Rowe and W. D. Warters, "Transmission in Multimode Waveguide with Random Imperfections," B.S.T.J., *41,* No. 5 (May 1962), pp. 1031–1170.
7. H.E. Rowe and D. T. Young, "Transmission Distortion in Multimode Random Waveguides," IEEE Trans. Microwave Theory and Techniques, *MTT-20,* No. 6 (June 1972), pp. 349–365.
8. H. E. Rowe and D. T. Young, "Minimum Phase Behavior of Random Media," IEEE Trans. Microwave Theory and Techniques, *MTT-23,* No. 5 (May 1975), pp. 411–416.

9. M. A. Gerdine, L. W. Hinderks, S. D. Williams, and D. T. Young," Electrical Transmission Measurement System," B.S.T.J., *56,* No. 10 (December 1977), pp. 2025–2034.
10. H. A. Wheeler, "The Interpretation of Amplitude and Phase Distortion in Terms of Paired Echoes," Proc. IRE, *27,* No. 6 (June 1939), pp. 359–384.
11. J. L. Doane, unpublished work.
12. S. Shapiro, private communication.
13. J. L. Doane and D. N. Zuckerman, unpublished work.
14. S. E. Miller, "The Nature of and System Inferences of Delay Distortion Due to Mode Conversion in Multimode Transmission Systems," B.S.T.J., *42,* No. 9 (November 1963), pp. 2741–2760.
15. S. C. Moorthy, unpublished work.
16. J. L. Doane, unpublished work.
17. S. Cheng, unpublished work.
18. K. Hashimoto, "Circular TE_{0n} Mode Filters for Guided Millimeter-Wave Transmission," IEEE Trans. Microwave Theory and Techniques, *MTT-24,* No. 1 (January 1976), pp. 25–31, and references cited therein.