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WT4 Millimeter Waveguide System:

Channelization

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Waveguide networks operating in the millimeter wave region to separate the 62 transmitter and 62 receiver frequency spectra at each end of every waveguide transmission line are described. The overall loss of these networks for the various channels has been designed to complement the shape of the transmission medium loss in order to yield maximum repeater spacing. General descriptions of the design and performance of all filters used in the complete channelization array are given.

I. NETWORK LAYOUT

The main factors controlling the repeater spacing in the WT4 system are the available gain, the transmission medium loss, and the channelizing network loss. For each of the 124 channels, the available gain must exceed the sum of the transmission medium plus channelizing network losses. Both the transmission medium loss and the available gain are strong functions of frequency over the 40 to 110 GHz band. To obtain maximum repeater spacing and reduce systems costs, it is therefore necessary to plan the channelizing networks such that they will have minimum loss at the frequencies where the transmission medium loss is high and/or the available gain is low. Figure 1 plots the moderate terrain transmission medium loss and the projection of available gain for four-phase repeater development. (It is planned to set the repeater spacing such that four-phase repeaters can be introduced at some future date without change in repeater spacing or channelizing networks.) The plot clearly shows that the channelizing networks should be designed to minimize the loss at the edges of the band. In the early development of the system, it was projected that the medium loss at 40 GHz would be considerably higher than the loss at 110 GHz. Therefore, the chan-

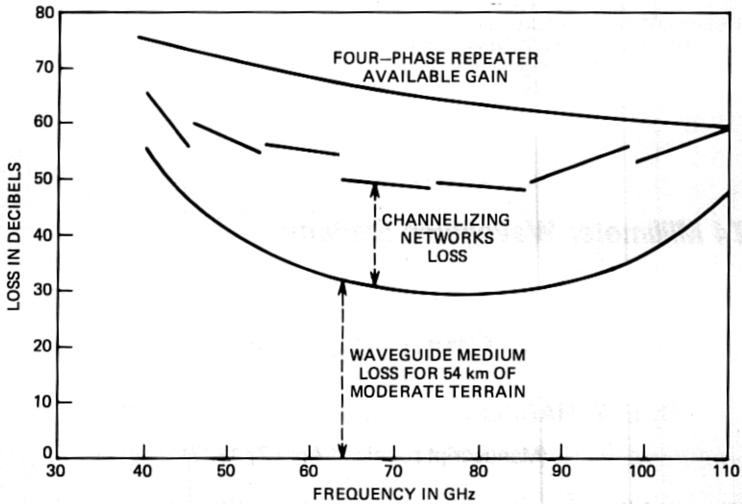

Fig. 1—Moderate-terrain transmission medium loss and projection of available gain.

nelization was laid out so that the lowest frequencies would be dropped first. A filter configuration to accomplish this and to separate all 124 mm-wave channels into individual ports is shown on Fig. 2. There are three types of filters used in this network; bandsplitting filters, channel dropping filters, and low-pass filters. The portion of the array closest to the transmission medium contains the six band-splitting filters and separates the 40 to 110 GHz frequency spectrum into seven subbands each about 15 percent wide. This portion of the array maintains the signals in the circular electric mode in 2-inch diameter waveguide so the losses are quite low. Each of the seven subband signals then goes through a taper transition to small semicircular waveguide. The semicircular waveguide runs have from 12 to 21 tandem connected channel-dropping filters. Each filter separates out one 475-MHz-wide channel via resonant cavities which couple from the flat wall of the semicircular waveguide to a dominant mode rectangular waveguide. When the band above 75 GHz is used for transmitters and the one below is used for reception, the low-pass filters prevent leakage of high-frequency transmitter signals into low-frequency receivers. The frequency assignments of the 124 channels are given in Table I.

The 40.2-GHz channel-dropping filter is connected closest to the band splitter so the 40.2-GHz signal passes through only one band splitter, one low-pass, and one channel-dropping filter. The other channel-dropping filters in subband 1 are connected in order of ascending frequency so that, as frequency increases, so does the number of filters traversed. In subband 7, the 109.8-GHz channel is dropped first in the string of channel-dropping filters so the loss and number of filters tra-

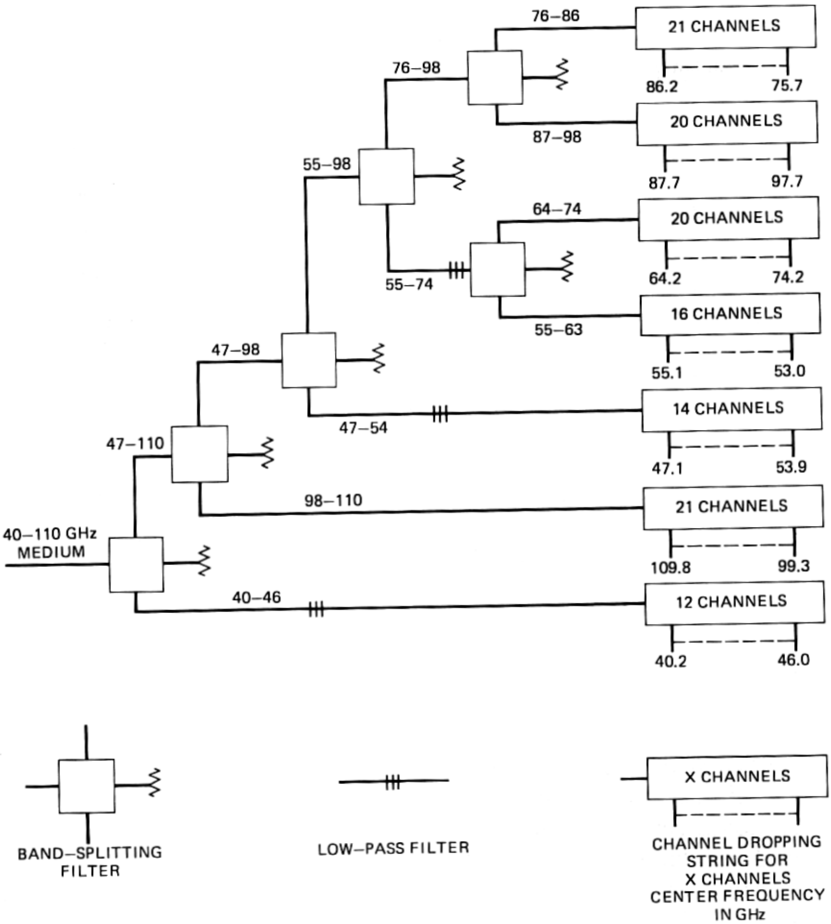

Fig. 2—Channelizing array.

versed increases as the frequency is lowered. The 109.8-GHz channel passes through two band splitters and one channel-dropping filter. This channelizing network layout, therefore, gives the lowest possible loss to the 40.2-GHz channel with slightly higher loss to the 109.8-GHz channel and increasing loss as frequency is moved toward the band center. This, of course, complements the shape of the transmission medium loss so as to obtain maximum repeater spacing.

The design of the individual filters will now be described.

II. BAND DIPLEXER

The band diplexer filters must separate subbands with low loss (at least near the band edges), and they also provide the means for physical

Table I — WT4 channel center frequencies

Subband	Channel	Frequency
1	1 (12 channels) 12	40.235 46.010
2	13 (14 channels) 26	47.085 53.910
3	27 (16 channels) 42	55.085 62.960
4	43 (20 channels) 62	64.235 74.210
5	63 (21 channels) 83	75.740 86.240
6	84 (20 channels) 103	87.715 97.690
7	104 (21 channels) 124	99.265 109.765

All channels spaced 525 MHz within one subband.

separation of the groups of repeaters in the different subbands. In order to minimize loss both in the filters and the interconnecting waveguide it is advantageous to retain the low-loss circular-electric mode in oversized circular waveguide for the band diplexers. Figure 3 shows the Michelson interferometer diplexer[1] consisting of two hybrid junctions, two high-pass filters, four tapers, and two elbows. The function of the hybrid junction is to split the input signal equally between two output ports with no coupling to the fourth port. The high-pass filters provide the frequency separation with unit reflection below cutoff and very small reflection above cutoff. The tapers provide low reflection and low-mode conversion transitions between different diameters and the elbows are necessary to physically complete the structure.

2.1 Hybrid junction

The hybrid junctions used in the field evaluation test consist of the four port networks formed by the right-angle intersection of two oversized circular waveguides with a thin sheet of dielectric material with dielectric constant ϵ and thickness τ inclined at 45 deg across the junction. An ideal hybrid must (*i*) be lossless, (*ii*) have all ports matched, (*iii*) divide an input signal equally between two output ports, and (*iv*) have

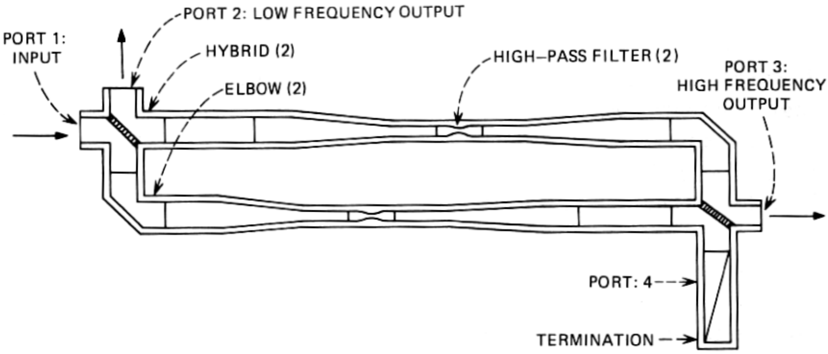

Fig. 3—Band-splitting filter.

phase quadrature between the output ports and have the fourth port decoupled. Since the waveguide is highly oversized, this structure can be analyzed as a quasioptical device, and properties (*ii*) and (*iv*) can be attained rather easily. The choice of ϵ and τ for each hybrid junction must be made to meet requirement (*iii*). If ϵ and τ are kept fixed across the junction for ease in manufacture, then there is a small (¼ dB) loss penalty associated with conversion of energy to other modes. Each band diplexer operates over a different frequency band depending on its position in the array, and the hybrids on each end of a band diplexer also operate over different frequency bands. The dielectric sheet (ϵ and τ) for each hybrid junction is chosen to optimize the return loss and insertion loss for each band diplexer. For the field evaluation test, the values of ϵ ranged from 6.5 to 8.7 and the thickness varied from 0.013 inches to 0.017 inches.

2.2 High-pass filters

The high-pass filter is a section of smoothly tapered waveguide whose diameter varies from 0.375 inch at both ends down to a diameter corresponding to the cutoff of the TE^0_{01} mode at a subband edge frequency. The overall length is 6 inches. Six guard bands ranging from 600 MHz to 1100 MHz were allocated to separate the seven subbands. The filter must have an insertion loss greater than 25 dB for frequencies below the guard band and a return loss greater than 25 dB for frequencies above the guard band. In addition, the tapers must not exceed −40 dB mode conversion to the TE^0_{02} mode over their operating band. In addition to the steep cutoff and low mode conversion, the design should be easily programmable to permit machining of the contour on a numerically controlled machine. Consequently, a satisfactory solution is one where analytical expression can be used to describe a contour and in which a good compromise can be made between the filter cutoff shape and mode conversion. Literature[2] has established the theory of high-pass filter designs having a sharp cutoff and a good return loss in the pass band. However, this filter synthesis technique is strictly applicable to only single mode waveguide. Over portions of the WT4 band, the 0.375 inch diameter waveguide can propagate TE_{02}^{0} and TE_{03}^{0} and other higher-order modes. To include mode conversion coupling in a rigorous method of filter design would be very difficult. However, an adequate approximation can be obtained by the following procedure.

Several simple functions to describe impedance variation along the axis have been studied in the literature.[3] Among these the exponential function raised to the cosine nth power is of special interest. For $n = 2$, combined with proper parameters, the filter was shown to have an optimum return loss cutoff characteristic. However, the contour of this filter design has rather steep slope which in turn causes severe mode conversion. A larger value of n deviates from optimum cutoff but yields a design with better mode conversion. (Mode conversion was computed using an analysis program for a given contour.) By successive iterations, it is possible to determine a proper value of n to meet the requirement. The six pairs of high-pass filter design have their n value varying between 3 for the low-frequency band and 6 for the high-frequency band.

2.3 Tapers

The taper changes a 2-inch diameter waveguide to a 0.375-inch diameter and is designed to have less than −40 dB mode conversion to the TE_{02}^{0} mode and 40 dB return loss over the 40 to 110 GHz band.[3] It has an inner layer of helically wound insulated wire and a lossy jacket on the outside. This suppresses all noncircular electric modes generated in the hybrid junction. The overall length is about 21 inches.

III. LOW-PASS FILTER

The low-pass filter structure used in the WT4 system consists of a parallel array of transverse dielectric disks in a section of circular TE_{01}^{0} mode waveguide. If the material of each dielectric disk is homogeneous and isotropic there will be no mode conversion from TE_{01}^{0} to any other modes, either propagating or nonpropagating. This yields the particularly simple equivalent circuit for the disk of simply a change in characteristic impedance for the TE_{01}^{0} mode with no coupling to other modes and no discontinuity reactance at the disk boundaries. In addition, because the waveguide is highly oversized for most of the modes concerned in the design, the waveguide can be regarded as nondispersive. The stop band of the filter rejects not only the TE_{01}^{0} mode but also most of the other modes which might exist in the system. This is a very desirable feature for components used in overmoded applications.

A detailed exact design procedure based on these simple transverse disks has been published elsewhere.[4] All known filter synthesis techniques are applicable. The image method will produce a simple structure if the desired pass band is far away from the cutoff frequency of the stop band. This design results in an array of uniformly spaced dielectric disks of identical thickness and, therefore, is economical for fabrication. In the case where the pass band is very close to the cutoff frequency, the image method may not yield sufficiently steep cutoff. Modern filter synthesis technique should then be used. However, the thickness of dielectric disks and their spacing will have more variations and the fabrication cost may be higher.

There are two codes of low-pass filters in the system. The first one has a pass band from 40 to 54 GHz and an insertion loss requirement of 80 dB from 76 to 110 GHz. The second code has a pass band from 55 to 74.5 GHz and a stop band from 76 to 110 GHz. The choice of dielectric material is mainly determined by the bandwidth of the stop band. In our cases, fused quartz was chosen. The first code uses 30 disks for the filter section and two 3-disk matching sections at the ends. The second code uses a 22-disk Chebyshev design. Excellent agreement between the theory and measurement was observed. The filter is constructed with two diameters of metallic rings (2.000 and 2.010 inch ID) stacked up alternately. Quartz disks of 2.010 inch diameter were inserted between rings. Although all parts require high precision on their thickness, they are readily manufactured due to their simple geometry. The pass band insertion loss was measured to be about 0.1 dB and pass band return loss was about 25 dB.

IV. CHANNEL DIPLEXER

Design of a millimeter-wave channel-dropping filter is, in principle, no different from the design of conventional waveguide filters except for an emphasis on low loss. At millimeter wave frequencies, filter structures designed in single mode rectangular waveguide have high loss for both the through channels and the dropped channel. Oversized semicircular waveguide has one-third the loss of single-mode rectangular waveguide, but mode cutoffs must be avoided in the passband. With an 18 percent bandwidth located between cutoffs of the TE_{12}^{0} and TM_{31}^{0} modes, seven sizes of semicircular waveguide are required to cover the 40 to 110 GHz band. Because of the nonzero longitudinal magnetic field along the axis of semicircular waveguide, circular electric modes (TE_{0n}^{0}) can be discriminated from all other modes. Narrow rectangular apertures along the center axis provide convenient and practical couplings between the main guide and the resonant cavities (see Fig. 4). With the diameter chosen so that TE_{02}^{0} is below cutoff, theoretically, there is no moding problem at all.

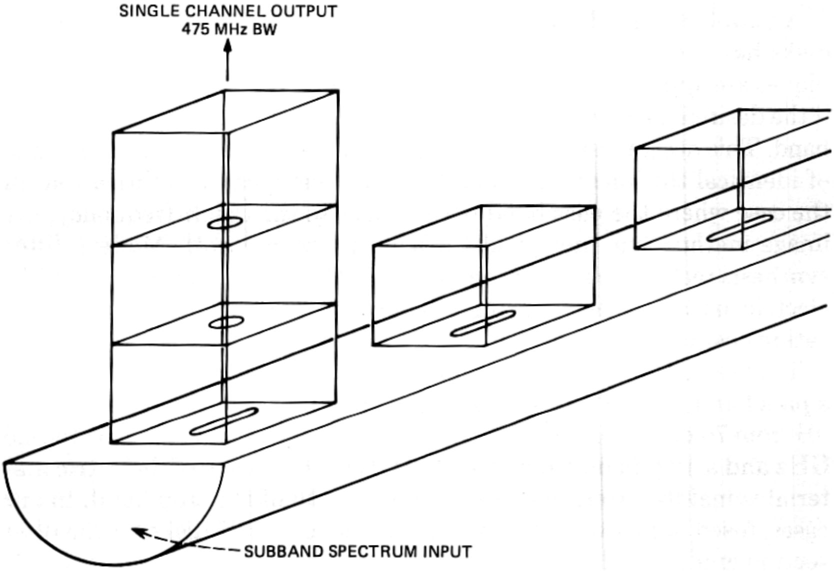

Fig. 4—Channel-dropping filter.

The channel diplexer used in WT4 is a two-pole design[5] with a 3-dB bandwidth of 475 MHz. There are seven sizes of semicircular waveguide, one for each subband. The dropped channel port is in rectangular waveguide. Only three sizes are used: WR22 covers 40 to 50 GHz, WR15 covers 50 to 75 GHz, and WR10 covers 75 to 110 GHz. For easy construction, the channel diplexer is divided into three main parts. A main guide block contains the semicircular channel. The coupling plate provides the top wall of the semicircular guide, three coupling holes and half of the four cavities. The tuning plate contains the other half of the four cavities and slots for tuning elements. There is a transducer block at the output port to provide a transition to the correct waveguide size. A sealing gasket, a protective cover and connecting hardware complete a channel diplexer. The coupling plate, the tuning plate, and the transducer block, which require a high degree of dimensional precision, are obtained by electroforming copper on permanent mandrels. The remaining parts are obtained by conventional machining. The mandrels are produced by high-precision, two-dimensional profile grinding operations. The use of permanent mandrels is a key to the manufacture of channel diplexers at a reasonable cost.

Thirty channel diplexers were built and tested for the field evaluation test. The input port return loss is about 20 dB over each subband. The dropped channel loss of the field evaluation test model at 108.7 GHz was about 0.8 dB above our objective of 2.8 dB.

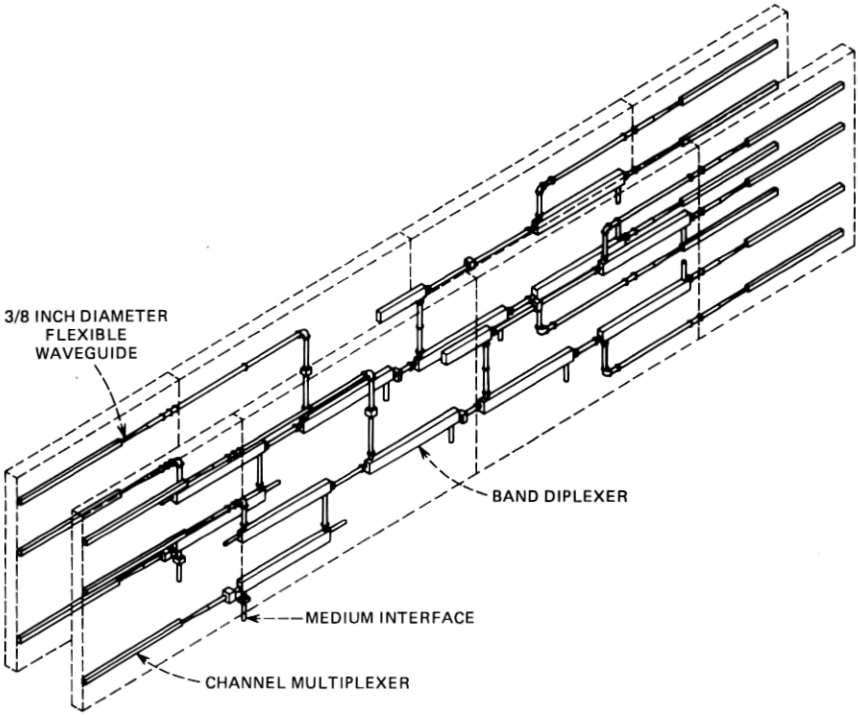

Fig. 5—WT4 channelizing networks.

V. CHANNELIZATION NETWORK PHYSICAL DESIGN

The band diplexers and channel filters that constitute the WT4 channelization networks are contained within two large frameworks each 43 feet long, 7.9 feet high and 1 foot deep (Fig. 5). Band-splitting elements and low-pass filters are mounted in the two center frames while the outer-frames contain the channel multiplexer assemblies and provide the mountings for repeaters and water-cooled channels. One network is provided at a repeater station for each waveguide medium direction. For each channel a receiver and line equalizer is mounted on one network framework while the associated transmitter is mounted on the second framework opposite the receiver (Fig. 6). Connections between the two are made at baseband frequencies via a coaxial cable. Figure 7 is a photograph of the field evaluation test band diplexer network.

5.1 Band diplexer assembly

The band diplexer assembly consists of the filters and interconnection sections of mode suppressing helix waveguide that split the waveguide bandwidth into seven subbands. The network components are mounted

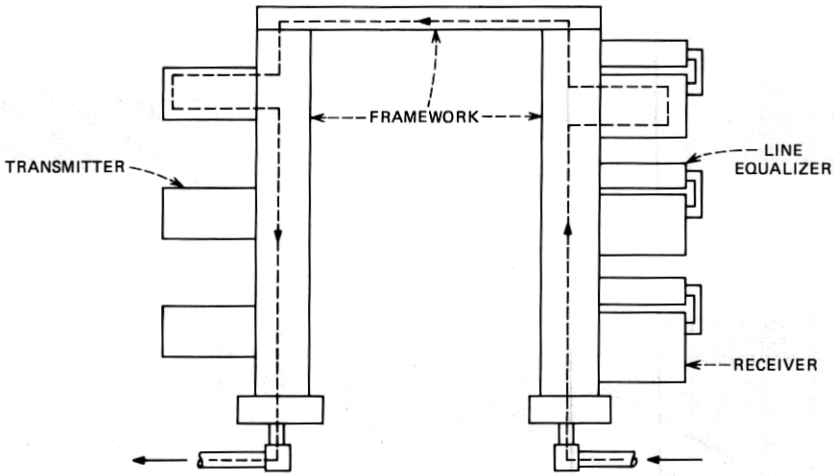

Fig. 6—End view of repeater mounting on channelization network frame.

on the frame starting with the component that interfaces with the medium. The band diplexer components are somewhat sensitive to mechanical stress so every effort is made to provide all connections as stress-free as possible. A large series of helix waveguide spacers are available to insure that the subband outputs are in the prescribed po-

Fig. 7—Band diplexer assembly.

sitions and that there is not an excessive tolerance buildup. Six-degree-of-freedom mounting brackets have been designed to simplify this process.

For shipping, the band diplexer assembly can be disassembled into four sections. As an option, the entire network can also be shipped as one unit. During the field evaluation test, the reassembly of the four sections in the Netcong station took less than one day.

5.2 Channel diplexer and repeater frames

The repeater and channel diplexer frames are installed in the repeater station at the same time as the band diplexer assembly. These frames include the fuse panels, patch panels, water-cooling channels, connectorized cables, and all mounting hardware for the individual channel multiplexers as well as the repeaters. The repeaters and channel multiplexers are installed as the system grows.

To take up the residual mechanical tolerances between the channel multiplexer and band diplexer subband port, a specially developed $3/8$-inch-diameter flexible waveguide section is provided. It consists of helix waveguide supported in a lossy flexible epoxy which allows offsets up to $1/4$ inch.

5.3 Channelization network environmental control

The entire channelization network is pressurized to $1/6$ psig with dry nitrogen. The gas is provided via a manifold mounted in the diplexer array. A waveguide window placed at the input to the network isolates the network from the higher pressure of the medium. The nitrogen supply system was designed to maintain the desired pressure relative to the local atmospheric situation. This was necessary because the low-pass filters are quite fragile and sudden changes in pressure across the quartz plates could cause a failure.

The water-cooling channels consist of rectangular extruded aluminum channels with two circular passages. Only one passage is required; the second is provided in the unlikely event that the first becomes clogged. Temperature monitors are mounted on the cooling channels, which are tied into the chilled water control and alarm system. The system has worked for over two years at Netcong without any malfunctions.

VI. CONCLUSION

Two channelization arrays have been constructed and one installed at each end of the field evaluation test waveguide run in northern New Jersey. Each end has a complete array of band-splitting filters to divide the 40 to 110 GHz spectrum into seven subbands. There were 18 channel-dropping filters installed at one end and 12 at the other end. The

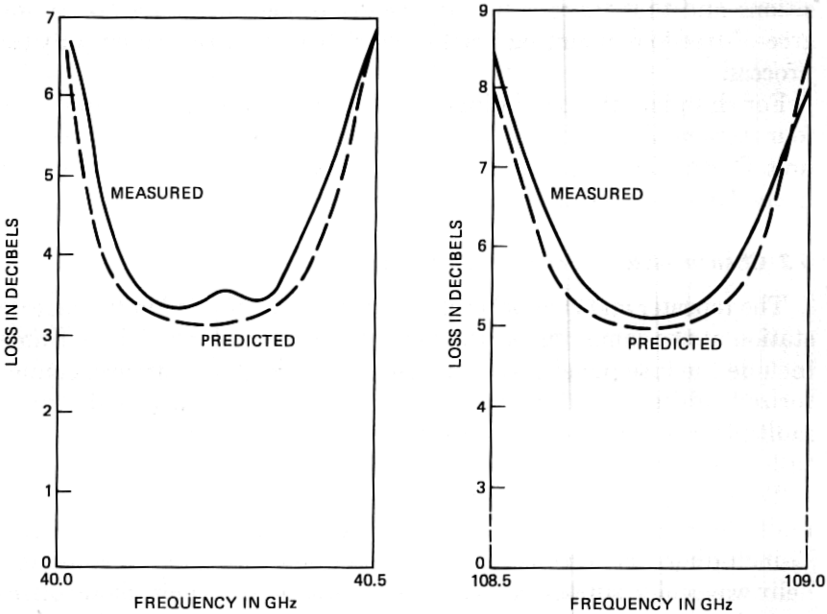

Fig. 8—Experimental measurement and prediction of channelizing network loss for channels at low end and near high end of spectrum.

transfer functions were measured for all 30 channels from the circular waveguide input port to each rectangular waveguide output port. Various leakages and return losses were also measured. The measured data agreed quite well with what would be expected from summing the performance of the individual filters. (See Fig. 8.) The performance of the two trial models indicated that a complete array for 124 channels would meet the performance requirements for either a two-phase or four-phase WT4 system.

The channelization filters described for the field evaluation trial operate in the 40 to 110 GHz range. However, measurements of the transmission medium[6] show that severe loss peaks could be avoided by shifting the highest WT4 channel to below 105 GHz. Simultaneous lowering of the bottom channel to 35 GHz would result in greatly increased medium loss for this lowest channel. If the number of millimeter-wave channels (124) is to be held fixed, then the only way to lower the top and not the bottom frequency is to move the channels closer together by reducing the guard bands. The field evaluation test measurements confirmed that 525-MHz spacing between adjacent channels was more than adequate to avoid appreciable adjacent channel interference. Studies have been made of the effect of changing the frequency assignments of Table I to a 500-MHz channel separation and also reducing the spacing between subbands slightly. The recommendation resulting from these studies is to provide 124 WT4 channels in the frequency range of 38 to 104.5 GHz. The penalty associated with the reduced channel spacing is less than 1 dB in the repeater available gain.

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