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WT4 Millimeter Waveguide System:

Electrical Transmission Measurement System

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An electrical transmission measurement system which measures the TE_{01} loss characteristics of the millimeter waveguide medium is described in this paper. This computer-controlled system operates from 33 to 117 GHz with fully automated measurements over 10-GHz frequency intervals after several preparatory manual adjustments. The measurement signal is a pulse which is reflected from the end of the test waveguide line and detected in a calibrated receiver. The transmitter and receiver are both located at one end of the test line. The measuring range is 50 dB and the systematic error and random uncertainty are less than ±0.3 dB and ±0.1 dB respectively for any test line longer than 100 meters. The minimum line length is determined by the spatial duration of the signal pulse. The system can also be used to measure the reflected signal from a piston moving in the waveguide. This technique is useful for measuring loss and mode conversion effects in a local region of the transmission medium.

I. INTRODUCTION

During 1975 and 1976 a field evaluation test of the WT4 millimeter waveguide transmission system was conducted jointly by AT&T Long Lines, Western Electric, and Bell Laboratories. A major component of this test was the installation and evaluation of 14 km of the buried waveguide transmission medium. This paper describes an electrical transmission measurement system which measures the TE_{01} circular mode transmission loss in the installed waveguide medium throughout the 33 to 117 GHz frequency band under consideration. This system has been used for evaluation of waveguide lines ranging from 0.1 to 14 km in length at frequency spacings as small as 50 MHz. The field evaluation

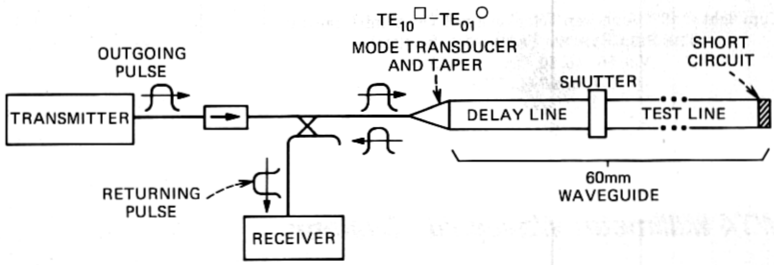

Fig. 1—Pulse reflection loss measurement arrangement.

test measuring system is the culmination of a test set development program which included systems for laboratory evaluation of dielectric and helix waveguide prototypes and final inspection of Western Electric waveguide product. Typically the loss is measured at as many as 1000 frequencies over the entire WT4 transmission band. A computer-controlled test set is required to make this number of measurements on a repeated basis with high accuracy. The computer system provides capability for automating the test set operation, fast signal averaging of the measured levels for more accurate and repeatable measurements, immediate Fourier transforms for data spectral analysis, and permanent data storage. These data can be displayed on a CRT moniter or plotted on hard copy for immediate evaluation. The performance capabilities of the measurement system are listed in Table I.

The electrical transmission measurements are made by a single-pulse reflection technique. The experimental arrangement is shown in Fig. 1. The transmitter sends a pulse down the delay line which is initially terminated by a closed short-circuiting shutter. This pulse is reflected back to the receiver where its amplitude is measured. Next, the shutter is opened and the pulse is reflected from a short circuit at the far end of the test line. The logarithmic amplitude difference between these pulses is the round-trip attenuation of the test line at the transmitter frequency.

Two manholes were installed in the test route for placing a short-circuiting shutter in the waveguide line. The delay line is 370 m in length to the first shutter location. Loss vs. frequency measurements were made on all the waveguide sections which were installed after this delay line. These sections were installed by the methods which are described by Baxter et al.[1] A detailed report on the electrical transmission data is given in Anderson, et al.[2]

Since the delay line and test line scatter energy from the TE_{01} signal mode into unwanted spurious modes, both lines should be terminated by ideal mode filters which cause infinite attenuation of the unwanted modes. This insures that: (*i*) the reference baseline obtained from the round-trip pulse in the delay line is due solely to the TE_{01} mode incident on the test line when the shutter is opened and (*ii*) the one-way loss of the test line is one-half the measured round-trip attenuation. In practice, 9-meter lengths of helix mode filters, which were manufactured for the field evaluation test, were used to terminate the reference delay line and the test line.

The transmission measurement system is also used for measureing the signal pulse reflected from a short-circuiting piston moving in the test waveguide. The shape of the received signal power plotted as a function of piston position is described by three main effects:

(*i*) The signal having propagated through a different length of guide for each piston position undergoes the TE_{01} mode round-trip attenuation of the traversed portion of the waveguide.

(*ii*) If the waveguide does not possess the ideal geometry of a right circular cylinder, some power in the TE_{01} mode is converted to power in unwanted spurious propagation modes. Power in the spurious modes is lost to the receiver since it only recovers the power in the TE_{01} mode.

(*iii*) If the waveguide attenuation for the converted spurious modes is not extremely large compared to the attenuation for the TE_{01} mode, some of the power in these spurious modes is reconverted into the TE_{01} mode by the same coupling mechanism which generated them initially, because the signal must propagate through the same waveguide geometry after being reflected from the piston. Since, in general, different modes have different phase propagation constants, this reconversion occurs in a manner varying from completely constructive to completely destructive, depending on the distance traveled and the difference in the phase propagation constants of the interfering modes.

The preceding discussion implies that increasing the test line length with a moving piston does not necessarily cause a monotonically decreasing signal level. In general, there is an average decrease due to the attenuation properties of the waveguide with superposed fluctuations caused by mode conversion and reconversion effects. The slope of the power level change versus test waveguide position is the average TE_{01} mode attenuation coefficient. The Fourier transform of the fluctuations over some section of the test waveguide is used to identify and obtain the average relative level of the spurious modes coupled in this section.[2]

In the following sections, we describe the important circuit and computer features and discuss the performance of the measurement system.

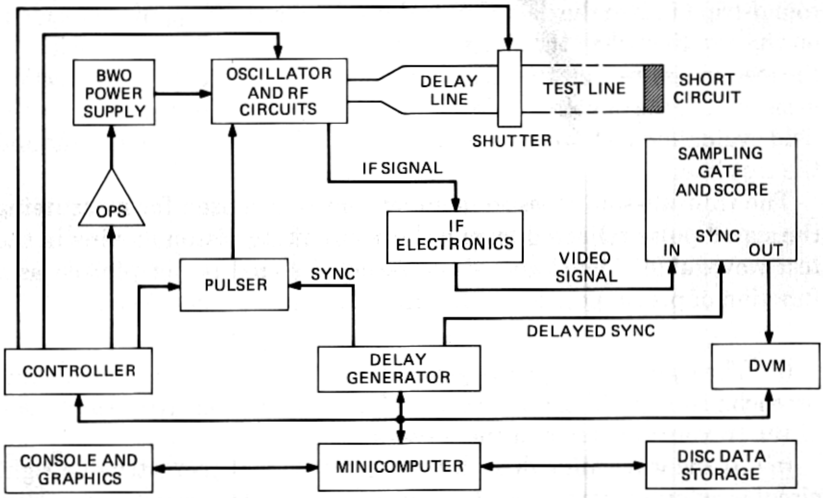

Fig. 2—Millimeter waveguide transmission measurement system.

II. CIRCUIT FEATURES

Figure 2 is a block diagram of the transmission loss set. The RF circuit consists of a single Backward-Wave Oscillator tube (BWO), which serves as the source of both the measurement signal and the Local Oscillator (LO), and rectangular waveguide components which operate in the dominant mode over the same frequency range as the BWO. The measurement signal is derived by shifting the BWO away from its quiescent operating frequency by 160 MHz for a short time (700 nsec). When this shifted frequency pulse returns from the test line, the BWO has returned to its quiescent frequency. The RF circuit (Fig. 3) directs a part of the transmitter signal to the test line and part, which serves as the LO, to the mixer diode. Signals returning from the test line are also directed to the mixer diode where they are down-converted to a fixed intermediate frequency of 160 MHz. Since the level of the LO signal remains constant regardless of the loss in the test line, the IF pulse amplitude is a measure of the signal returning from the test line. The level of the signal pulse is always maintained at least 20 dB below the LO. Therefore over the RF range of the set, the change in amplitude of the IF pulse is linearly related to the change in power of the RF signal. The calibrated IF substitution method is used to measure the signal level change. To provide measurement capability over the entire WT4 frequency band, three interchangeable RF circuits, each with its own BWO, are required. The three measurement bands are 33 to 50 GHz, 50 to 75 GHz, and 75 to 117 GHz.

BWO frequency control (Fig. 4) is accomplished using a high voltage (1000 volt) Operational Power Supply (OPS) inserted in series with the

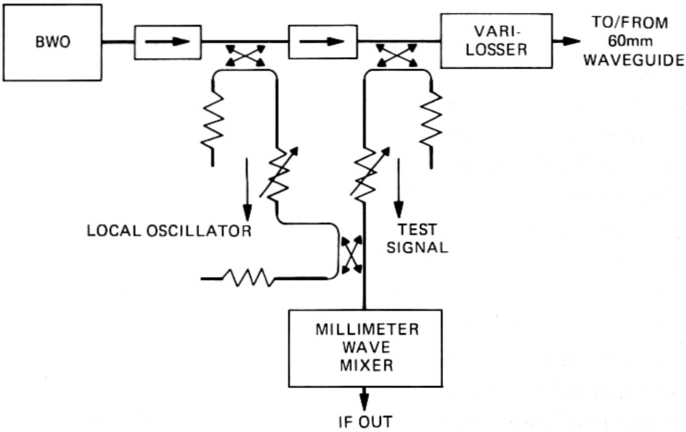

Fig. 3—RF millimeter-wave circuit arrangement.

output of a standard BWO power supply.[3] The combined voltage is applied to the cathode of the BWO, setting its quiescent operating frequency. The input to the OPS comes from a programmable 12-bit D/A converter located in the test set controller. Pulsed frequency modulation of the BWO is performed by superposing the output of a pulser on the anode of the BWO causing a momentary 160 MHz shift in the BWO output frequency. This burst of offset frequency provides the test signal in the waveguide line. The pulser is programmable because the amplitude of the pulse required to cause a 160 MHz offset is a rapidly varying function of the operating frequency of the BWO. Since the dynamic range of the

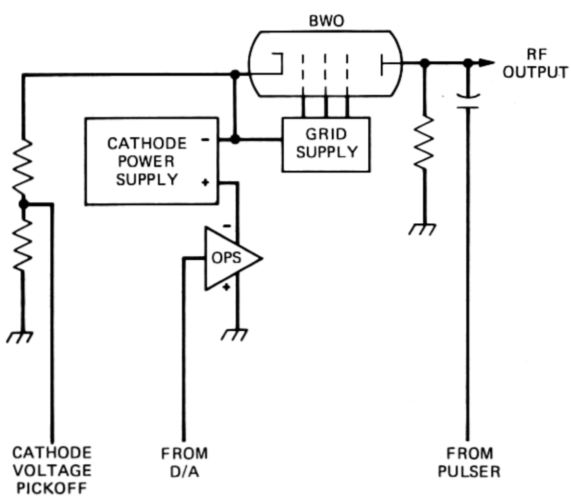

Fig. 4—BWO frequency-control circuit arrangement.

OPS and the programming range of the pulser are limited, the cathode voltage from the BWO power supply and the pulser voltage amplitude are manually adjusted 2 or 3 times for each RF circuit.

The IF electronics consist of a combined 160 MHz amplifier and video detector preceded by a calibrated precision step attenuator. The IF signal pulse is amplified and converted to a video pulse which is the input to the video instrumentation. The electronics and all succeeding measurement equipment are calibrated as a unit over a 25 dB range, by recording the output values as a function of 1 dB incremental settings of the attenuator. The IF calibration is restricted to 25 dB to assure an adequate signal-to-noise ratio that does not require time-consuming signal averaging to recover low-level video signals. In the measurement mode, measured values are converted to a relative dB value by exponential interpolation between the calibration points. Exponential interpolation is used since the video detector operates as a "square law" device.

All measurement data are obtained from video pulses. A sampling oscilloscope displays the pulse and provides a means for sampling the video signal at any point on the pulse and at some point outside of the pulse to serve as a base line reference for the pulse. The amplified output of the sampling gate is measured with a digital voltmeter, converted to a relative dB value and stored in memory. The delay generator controls the measurement cycle. This generator triggers the pulser causing a signal pulse from the BWO and after a programmable time interval, triggers the sampling gate enabling a measurement on the video representation of the returning delay line or test line pulse.

For long test lines the loss can be greater than the calibrated dynamic range (25 dB) of the IF signal. In this case, either the delay line pulse or the test line pulse will not be measurable. The range is extended by using the varilosser as a programmable precision RF attenuator over the full dominant mode waveguide bandwidth.[5] With the varilosser, a known amount of attenuation is automatically inserted when measuring the shutter pulse and removed when measuring the test line pulse. This added loss is accounted for in calculating the test line loss. A table of loss versus frequency for each of several fixed drive currents controlling the varilosser is generated by calibration with the precision IF attenuator. The currents are chosen to give nominal losses in 5-dB increments. This technique gives a repeatable varilosser calibration which is within 0.1 percent of the attenuation standard over a 25-dB range.

The test set controller operates the BWO frequency control circuit, varilosser, and shutter. A programmable current source is located in the controller for setting the varilosser attenuation. Relays in the controller operate the shutter which is located in a manhole where it intercepts a short span of the test installation.

III. COMPUTER FEATURES

The transmission loss set is almost completely automated. This automation is achieved by interfacing the programmable instrumentation to a minicomputer. The minicomputer system acquires, processes, displays, and stores the measurement data.

The computer's central processing unit (CPU) is equipped with 32k words of 16-bit memory. The real-time operating system, supplied by the computer manufacturer, requires 14k words of memory which leaves a user space of 18k. The system area of memory contains the operating system as well as the hardware interface drivers. These input-output (I/O) software routines are in part supplied by the computer manufacturer for use with their hardware. Other I/O drivers were designed especially for the test set. The CPU is equipped with special firmware for high-speed execution of many floating point operations. This increased computational speed allows almost all data reduction to be done in the CPU. The computer is equipped with two disk drives. The larger disk is capable of storing 5.0 megabytes of data, 2.5 megabytes on a fixed platter, and 2.5 megabytes on a removable cartridge. The fixed platter contains the absolute system programs and absolute user programs. The removable cartridge of the larger disk drive stores user source programs. The smaller drive has a 2.5-megabyte removable cartridge and stores measurement data files. As the removable pack of the small drive fills, an empty pack is easily inserted without disrupting the measurements if the operator does not want to halt the program. Additionally, the system has several terminals, a CRT display and hard-copy unit, and a line-printer.

Program development represented a large part of system development. To increase programmer efficiency a special software system, LOGON, was devised.[4] LOGON is a monitor system which provides an interface between the user and the computer vendor's operating system. The LOGON command structure is designed so that the user can perform the most often needed tasks of program development with relative ease. It allows for easy editing, high-level language programming and mass data storage such that software design modification is greatly simplified compared to previous minicomputer operating systems. LOGON can handle multiple users and time-share the CPU when multiple requests are made for the processor. Thus, LOGON enhances the real-time operating system to a multiprogramming time-sharing level.

The software development included I/O drivers; data acquisition programs; and data storage, manipulation, and display programs. The program space necessary to perform a complete task was generally too large for the limited CPU memory. Therefore, program modules, which performed individual functions, were chained together to accomplish the complete task. Each module performs its function, writes the results

Table 1 — Measurement system performance*

Frequency bands	33–50 GHz	50–75 GHz	75–117 GHz
Frequency uncertainty	±50 MHz	±50 MHz	±50 MHz
Frequency repeatability	±5 MHz	±5 MHz	±5 MHz
Reflection piston location uncertainty	±0.3 meters	±0.3 meters	±0.3 meters
Average measurement speed in 10-GHz subband	100 measurements/hour	100 measurements/hour	100 measurements/hour
Measuring range	50 dB	50 dB	50 dB
Relative error	±0.020 dB	±0.07 dB	±0.3 dB
Random error	±0.005 dB	±0.02 dB	±0.1 dB

* All experimental estimates are maximum values except the measuring range which is a minimum value.

on disk, and schedules the succeeding module from the user programs on the disk. The modules communicate with each other from a common CPU memory block.

IV. PERFORMANCE

With proper attention to details, the time domain technique of this measurement system virtually eliminates any sources of error due to millimeter wave component mismatches. The minimum length of reference delay line (370 meters) was chosen to allow reasonable transition times to obtain a well-defined signal pulse. Since this pulse is obtained by frequency offset of the single BWO source, it is extremely important that sufficient time (1 microsecond) is allowed for the BWO to stabilize at its quiescent point, which is the LO source, before the reflected signal arrives at the receiver. Since the shutter is rapidly operated, any errors due to amplitude fluctuations are also minimized. The signal levels in the calibrated IF section are chosen to minimize any errors from nonlinearities and noise.

If the mode filter at the end of the delay line does not provide sufficient attenuation of the unwanted modes which are converted from the forward TE_{01} signal pulse, there is a complex interaction between the forward and return trips of the pulse. This interaction leads to an error in the baseline measurement. The detailed base-line characteristic is a function of the round-trip length between mode conversion points on the forward trip and mode reconversion points on the return trip. This line length changes when the shutter opens, therefore the baseline reference at each measurement frequency can change from the measured value.

Since the transmission characteristics of the helix mode filters are strongly dependent on their installed axial curvature,[2] we performed an experiment which gave a worst-case estimate of the maximum baseline error. The loss characteristic was measured for a 710 m waveguide test line which was not terminated with a mode filter. The maximum

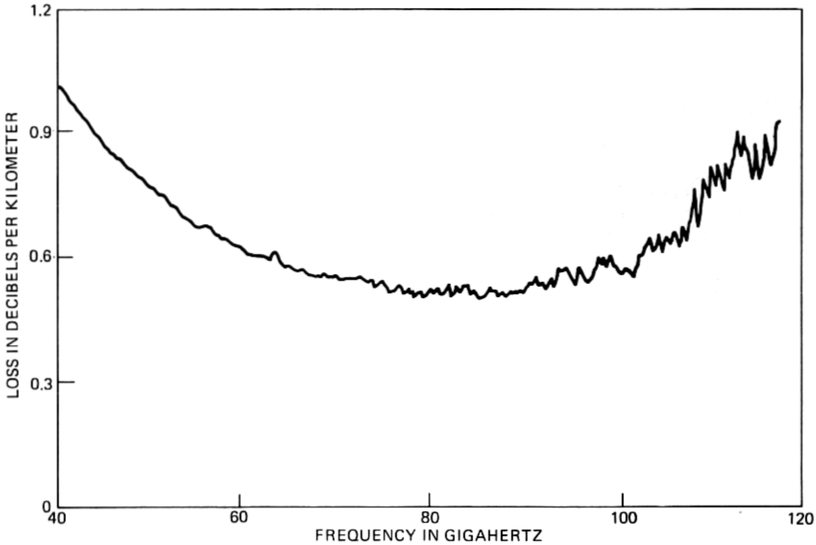

Fig. 5—Field evaluation test waveguide measured loss.

value of the peak-to-peak deviations from the average loss in each of the three RF circuit bands was scaled linearly to the 370 m length of the actual delay line. These estimates are given as the relative error in Table I. The random error (repeatability) values in Table I were obtained from continual experimental measurements on the buried field evaluation test waveguide line.

The measured loss for the 14 km field evaluation test route is shown in Fig. 5. The loss characteristic was measured at 250 MHz intervals from 40 to 75 GHz and at 100 MHz intervals from 75 to 117 GHz.

V. CONCLUSION

The computer-controlled system was developed to make TE_{01} circular mode transmission loss versus frequency and moving piston experiments on the field evaluation test waveguide medium. Accurate measurements are obtained for transmission loss up to 50 dB in the frequency range from 33 to 117 GHz.

VI. ACKNOWLEDGMENT

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