hp JOURNAL
TECHNICAL INFORMATION FROM THE HEWLETT-PACKARD LABORATORIES
VOL. 1 No. 5
PUBLISHED BY THE HEWLETT-PACKARD COMPANY, 395 PAGE MILL ROAD, PALO ALTO, CALIFORNIA JANUARY, 1950

Greater Reliability in UHF Impedance Measurements

An accurate slotted line section is a very effective aid in the determination of impedance or investigation of impedance mismatch and power wastage at ultra-high frequencies. Although other methods for measuring the impedance of UHF components and devices are available, the engineer usually turns to the slotted section when reliable quantitative measurements are desired[1,2].

Conventional slotted lines consist of a section of rigid coaxial transmission line that has a longitudinal slot in the outer conductor to permit penetration of a capacitive probe into the line for voltage sampling purposes. Coaxial slotted sections have certain inherent sources of error, some of which are attributable to the slot. A relatively large slot introduces slope error—error characterized by different values of standing-wave ratio along the line owing to radiated energy losses—and in addition permits error caused by external fields. A narrow slot permits slight variations in the centering of the probe within the slot to cause large error in readings. Finally, variations in the probe penetration depth cause errors because of the change of coupling to the fields in the line.

The novel slotted line section shown in Figure 1 is an improved type of the slotted line device. Basically this new section consists of two separated parallel conducting semi-planes between which is located a rod-like center conductor. The parallel-plane configuration is obtained from that of the coaxial by use of the conformal transformation $w = \tan z$. A cross-section of the line is compared with the cross-section of a conventional slotted line in Figure 2. The equi-potential lines, drawn lightly in Figure 2, show that each of the semi-planes of the new type section is equivalent to one-half of the outer conductor of a coaxial section. Strict application of the above transformation requires that the center conductor have an elliptically-shaped cross section, but for practical purposes this shape can be modified to a circular cross section. Because of the type of field configur-

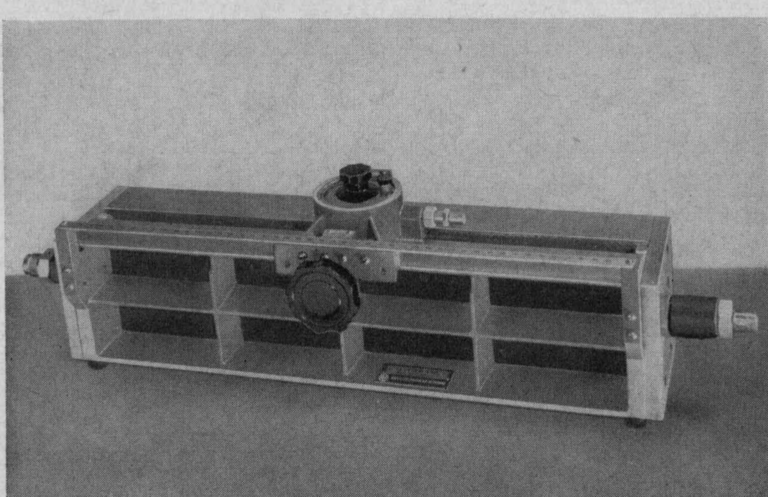

Figure 1. *-hp- Model 805A Slotted Line*

[1]F. E. Terman, *Radio Engineering,* 3rd ed., p. 109, McGraw-Hill Book Co., 1947.

[2]C. G. Montgomery, *Technique of Microwave Measurements,* Radiation Laboratory Series, pp. 478-480, McGraw-Hill Book Co., 1947.

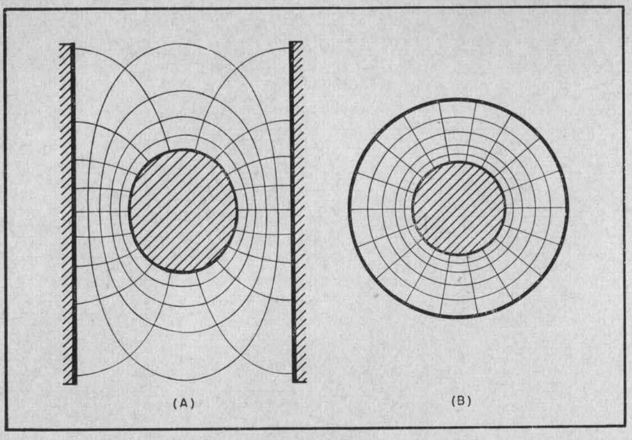

Figure 2. *Cross Section of (a) Parallel-Plane Line and (b) Coaxial Line*

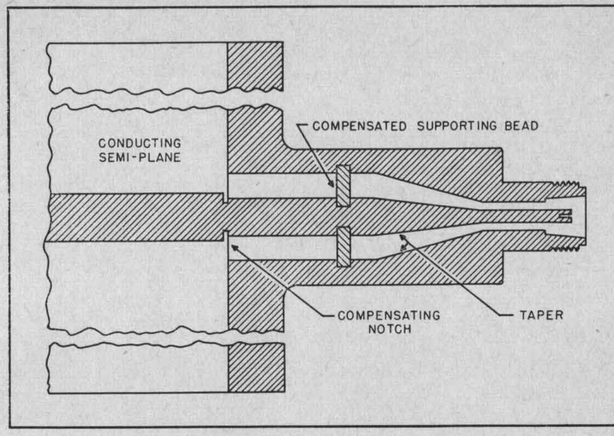

Figure 3. *Cross Section of Basic Transition Section*

ation in the parallel-plane line, a given variation in probe depth or probe centering causes less error than in the coaxial line.

The parallel semi-planes are separated by a space approximately $\frac{3}{4}''$ wide, and the slot thus formed is equivalent to a slot width of less than 0.002 radian in a coaxial section. This effective slot width is so small that no radiation effects are discernible.

To reduce sagging, the center conductor of the new type line is made of $\frac{15}{32}''$ diameter brass rod and is supported at both ends by insulating beads compensated to minimize reflection. Each end of the line is terminated by a transition section that permits conventional flexible cables and constant-impedance coaxial connectors to be connected to the line. The transition sections change the field configuration within the slotted section to that in a coaxial cable without the reflections that ordinarily arise from the capacitive discontinuity associated with a sharp change in configuration.

The change in configuration is accomplished with a conventional step, a compensated bead support, and a taper (Figure 3). The transition from the parallel-plane line to the large size coaxial line is compensated by notching the center conductor at the transition. This notch appears inductive to the main line and in conjunction with the discontinuity capacities forms a low-pass filter section having a very high cut-off frequency. The cut-off frequency is sufficiently high that the variation of image impedance throughout the desired frequency band is small. The bead support is compensated in a similar manner.

The transition from the large size coaxial line in the transition section to the small is accomplished with a taper section in which the change from one physical size to another occurs gradually. Thus the effect of discontinuities is minimized

The carriage for the sampling probe rides on the two semi-planes which are milled from two large cast aluminum slabs. The entire line section is therefore very rugged so that the usual errors arising from mechanical deficiencies are minimized. The depth of penetration of the probe into the slot is adjustable, and an adjustable shorted-stub tuner, which resonates the probe circuit, is built into the probe carriage. This carriage provides for the mounting either of a silicon crystal unit or a bolometer element to act as the rf detector. Along the top of the line is mounted a metric scale and the probe carriage contains a matching vernier so that standing-wave patterns can be measured accurately.

IMPEDANCE CONSIDERATIONS

Two factors enter into the selection of a specific impedance for the slotted line section. One is that the most satisfactory series of high-frequency connectors, the type N, has an impedance of 49 ohms. The second is that the current trend is towards a standard of 50 ohms for UHF components. Accordingly, the line itself has been designed to have an impedance of 50 ohms, and this value is transformed by the transition sections to slightly less than 50 ohms at the input connector. The actual input impedance varies a little with frequency and from one production unit to another. A representative value of input impedance is 49.5 ohms, although this value may vary with frequency from approximately 49.0 to 50.0 ohms. A typical curve of residual VSWR of the complete line section is shown in Figure 4. The data for Figure 4 were obtained by comparing production units with a 49-ohm load by a procedure that is described below.

The above impedance variations are considerably less than those of standard cables and type N connectors. For example, the cables nearest 50 ohms in impedance are RG-9/U (51 ohms) and RG-8/U (52 ohms).

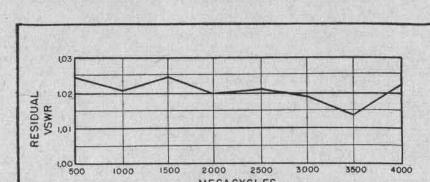

Figure 4. *Residual VSWR of Typical 805A Slotted Line*

Moreover, the impedance of such cables varies appreciably with frequency. Cables and connectors therefore become the limiting factor with respect to accuracy in most measurements, and calculations can be made on a 50-ohm basis with little sacrifice in accuracy. The most accurate measurements can be made with a load of 49 ohms, the ideal impedance of a type N connector and the impedance against which the sections are tested. Such measurements should be made with a carefully-assembled type N connector or without a connector and with a special 49-ohm transmission line (0.271" O.D., 0.120" I.D.). Calculations can then be made on a 49-ohm basis.

A second slotted line section has been designed to be used with RG-44/U stub-supported rigid coaxial cable. The impedance of the second type line is approximately the same as RG-44/U cable, 46.3 ohms.

FREQUENCY CONSIDERATIONS

The lowest useable frequency for the line is determined primarily by the distance the probe can travel in the slot formed by the two semi-planes. This distance has been designed to be somewhat more than one-half wavelength at 500 megacycles. Thus, at this, the lower frequency limit, the probe can always be set to a standing-wave maximum as well as a minimum.

The high frequency limit is determined by the cut-off frequency in the line for modes of an order higher than the principal mode. This cut-off point is a little higher than 4000 megacycles, leading to the selection of this frequency as the nominal high-frequency limit for the line. However, models that operate satisfactorily over the range from 4000 to 10,000 megacycles have been constructed.

VERIFICATION TESTS

In the development of the parallel-plane slotted section it was necessary to determine accurately the magnitude of the voltage reflections

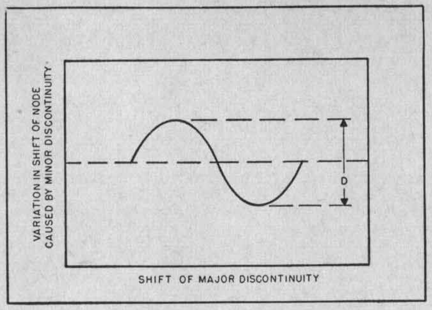

Figure 5. *Curve Obtained When Plotting Very Small Standing-Wave Shifts*

caused by the transition sections. Such reflections were in the order of 0.5% and corresponded to standing-wave ratios of 1.01. These reflections were measured by means of the null-shift method. This method is based on the fact that, in a system having a major discontinuity in the form of an open or short at one end and having a minor discontinuity between the generator and the major discontinuity, nodal positions on one side of the minor discontinuity shift a different amount physically than do nodal positions on the other side when the position of the major discontinuity is changed.

When the percentage reflection is very small, the difference in the magnitude of these shifts follows a smooth, cyclical curve resembling a sinusoidal curve. It has been shown[3] that the peak-to-peak amplitude of this cyclical curve is proportional to the magnitude of the voltage reflected by the minor discontinuity.

Applying these facts to the testing of the parallel-plane slotted line, a variable-length coaxial line is connected to one end of the slotted section and a signal generator to the other. The free end of the variable-length coaxial line is left open, thus constituting a major discontinuity in the form of an open-ended line. The actual measurement consists of adjusting the length of the variable line by known amounts and meanwhile noting the movement of a nodal position on the opposite side of the minor discontinuity. These data, when plotted, generate a curve such as that shown in Figure 5. The VSWR arising from the reflection caused by the minor discontinuity can then be calculated from the expression VSWR $= 1 + 2\pi D/\lambda$ when the amplitude of the reflection is very small compared to the incident wave.

The above method can be used to determine the residual reflections caused by the transition sections at the ends of the slotted line. These transition sections can be made to cause less than 2% reflection over the entire frequency band from 500 to 4000 megacycles.

SWR MEASUREMENTS

A tpyical test set-up for making standing-wave measurements is shown in block form in Figure 6. A signal generator such as the -hp- Model 610A, 614A, or 616A drives the system containing the slotted line and the load to be measured. The detector circuit on the slotted section connects to a standing-wave indicator such as the -hp- Model 415A which, in combination with a square-law detector, indicates the magnitude of the voltage standing-wave ratio directly.

Standing-wave ratios can be measured with either cw or amplitude-modulated power flowing in the transmission system under test. However, such measurements are almost

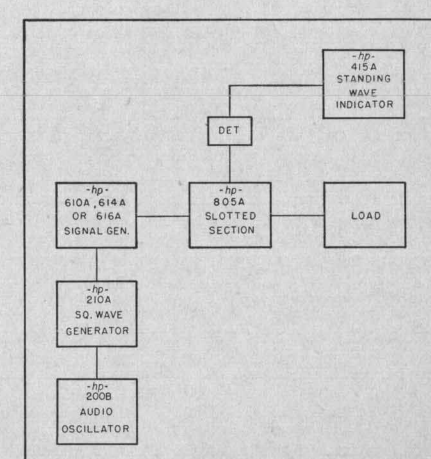

Figure 6. *Block Diagram of Measurement Set-Up*

[3]E. Feenberg, *The Relation Between Nodal Positions and Standing Wave Ratio in a Composite Transmission System*, Jour. App. Physics, Vol. 17, No. 6, p. 530, June, 1946.

always made with a-m power rather than cw because of the vast increase in sensitivity obtainable with a standing-wave indicator that responds to the ac modulation rather than the rectified cw (dc). Since UHF oscillator circuits for the most part use reflex klystrons (which are incapable of sinusoidal amplitude-modulation without serious frequency modulation), it is common practice to key the modulating electrode of the klystron from a square-wave generator to obtain 100% square-wave modulation of the signal source. This arrangement is indicated by the square-wave generator and audio oscillator in Figure 6. The frequency of the audio oscillator is tuned to the acceptance frequency of the standing-wave indicator, which is frequency-selective to provide highest sensitivity.

When making measurements with a slotted line of the quality of the parallel-plane line, certain precautions are necessary in order to obtain the full accuracy of the system. Chief among these are precautions concerning detector elements and especially silicon crystal units. Silicon crystals have a characteristic that is relatively square-law only over small ranges at quite low levels. Consequently silicon crystals should not be used for measurements in excess of about a 3:1 VSWR range if maximum accuracy is required, and the coupling to the crystal should be as loose as the sensitivity of the standing-wave indicator will permit. In applications where VSWR ranges in excess of 3:1 are to be measured using a crystal detector, the output attenuator on the signal generator should be used to reduce the amplitude of the standing-wave maxima or peaks so that the same reading is obtained on the indicator at a standing-wave maximum with attenuation as at a minimum without attenuation. The standing-wave ratio is then determined from the difference in the two settings of the output attenuator. This method offers the advantage that the crystal is operated at the same power level for the two measurements and crystal error is therefore minimized.

Bolometer elements maintain a rather accurate square-law response over a much wider range than crystals, but are not as sensitive as crystals and require a small biasing current to reach the threshold of square-law operation. This current is supplied automatically by the 415A.

Signal sources used for standing-wave measurements should have relatively low harmonic content in their output, because the standing-wave ratio at a harmonic frequency often is considerably higher than at the fundamental. When a signal source of questionable harmonic content is used, low-pass filters such as the -hp- Model 360A-D filters can be inserted to prevent transmission of harmonics. Spurious frequency modulation in the signal source is also undesirable, for, unless very slight, it obscures the minimum points at high VSWR values.

It has been shown[4] that tight coupling between the probe and the fields within the line will give rise to shifts in the standing-wave pattern, particularly with respect to maximums. Tight coupling also reduces the amplitude of the maximums, thus modifying the standing-wave ratio. The effects of probe coupling are somewhat more pronounced if the probe circuit appears reactive to the slotted line. Consequently, the input impedance of the probe should be peaked by tuning the stub on the probe circuit for maximum output as read on the standing-wave indicator and the coupling should be as loose as possible.

In critical measurements it is usually desirable to determine the magnitude of the errors introduced by the slight residual standing-wave ratio of the slotted line itself. The measured VSWR can be shown to be not larger than $\sigma_t\ \sigma_r$ nor less than σ_t/σ_r, where σ_t is the true standing-wave ratio of the load and σ_r the residual standing-wave ratio of the slotted line. Since the residual standing-wave ratio of the slotted line is less than 1.04, the error caused in the worst case can not be greater than approximately ±4%. This error will introduce an error of the same magnitude into the subsequent impedance calculations.

—*W. B. Wholey.*

[4]W. Altar et al, "Probe Error in Standing-Wave Detectors," Proc. I.R.E., Vol. 34, No. 1, p. 33P-44P, Jan., 1946.

SPECIFICATIONS FOR MODEL 805A SLOTTED LINE

FREQUENCY RANGE: 500 to 4000 megacycles.

CHARACTERISTIC IMPEDANCE: 50 ohms nominal (for use with type N connectors and cables such as RG-8/U, RG-9/U, etc.)

CONNECTORS: Type N, one male, one female. Either end can be connected to load. Male and female shorting connector also included for making phase measurements.

RESIDUAL VSWR: Less than 1.04.

SLOPE: Negligible.

CALIBRATION: Metric, calibrated in cm and mm. Vernier permits readings to 0.1 mm.

DETECTOR: Circuit tunable; 1N21B or 1N23B silicon crystal or bolometer element such as 1/100 ampere instrument fuse.

SIZE: 27" long, 8" high, 6" wide. 18 lbs. Supplied with 28" long, 9¼" high, 9¾" wide metal carrying case. 33 lbs. net weight. 75 lbs. total shipping weight.

PRICE: $475.00 f.o.b. Palo Alto, California.

MODEL 805B SLOTTED LINE

CHARACTERISTIC IMPEDANCE: 46.3 ohms. For use with RG-44/U stub-supported rigid coaxial line.

CONNECTORS: UG-45/U male and UG-46/U female. Male and female shorting connectors also supplied.

RESIDUAL VSWR: Less than 1.02.

PRICE: $475.00 f.o.b. Palo Alto, California. Other specifications same as 805A

MODEL 415A STANDING-WAVE INDICATOR

FREQUENCY: 1000 cps ±2%. Plug-in units for other frequencies from 300 to 2000 cps available at $7.50 each. Request unit 41A-42 and specify frequency. Amplifier "Q" is 20 ± 5.

SENSITIVITY: 0.3 microvolt gives full-scale deflection. Equivalent noise level referred to input less than 0.04 microvolt.

CALIBRATION: For use with square-law detector such as silicon crystal or bolometer element. 60 db range covered in 7 ranges. Relative accuracy ±0.1 db per 10 db step.

GAIN CONTROL: Adjusts meter to convenient level. Approx. 30 db range.

INPUT: Connects to crystal or bolometer. Supplies a bias of approx. 8.75 ma to 200-ohm bolometer element. Bridge null measurements can be made with special 75,000-ohm input. One terminal grounded.

SIZE: 12" long, 9" wide, 9" high. 17 lbs. Shipping weight 30 lbs.

PRICE: $200.00 f.o.b. Palo Alto, California. Data subject to change without notice