the GENERAL RADIO Experimenter

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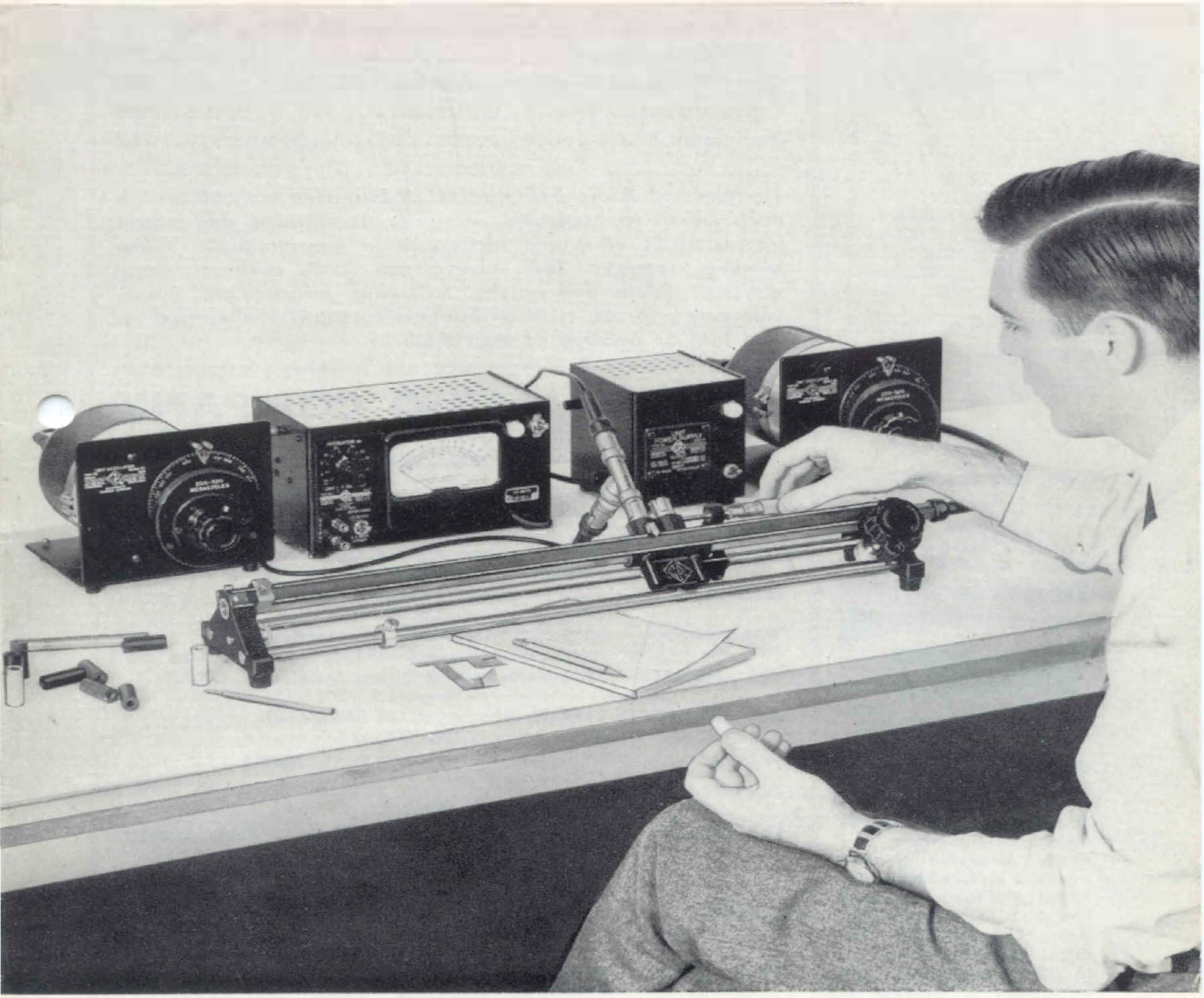

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the GENERAL RADIO Experimenter

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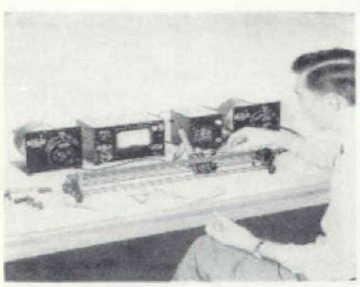


Dielectric constant and dissipation factor of solid-dielectric materials are easily measured at frequencies up to 5000 megacycles with the new slotted line described in this issue. Using easily prepared cylindrical samples, as shown in the photograph, this equipment is capable of measuring very-low-loss materials, such as polystyrene and Teflon.

THE MEASUREMENT OF DIELECTRIC PROPERTIES IN THE 200-5000 MC RANGE

A simplified method and a new slotted line have been developed for the measurement of the dielectric constant and loss of low-loss solid insulating materials in the 200-5000 Mc frequency range. The basic method is a modification of one previously described by Robertson and von Hippel,[1] and Dakin and Works.[2]

Method

If a section of open-circuited transmission line is filled with dielectric as shown in Figure 1, the dielectric constant and dissipation factor can be determined from measurements of the input impedance to the section of line filled with the dielectric and from a knowledge of the frequency and the sample length. The input impedance, Z_i, can be calculated from measurements of the standing-wave pattern present on the air-filled section of line shown in the figure. The actual calculations are complicated by the fact that the equation which has to be solved is complex and transcendental, and they become particularly involved when a low-loss dielectric is being measured, in which case the resistive losses in the line are usually large compared with the dielectric losses in the sample. The whole procedure can be greatly simplified if either the sample length or the frequency is adjusted to make the electrical length of the sample an odd multiple of a quarter-wavelength, so that the voltage minimum on the air-filled section of the line will appear at the front face of the sample. Under these conditions the equations for the dielectric constant and dissipation factor are the following:

$$K = \left(\frac{N\lambda}{4l}\right)^2 \quad (1) \qquad D = \frac{\lambda}{\pi l \rho} - A \quad (2)$$

where
K is the dielectric constant
D is the dissipation factor
λ is the wavelength in free space
l is the physical length of the sample
N is an odd integer which is equal to the number of quarter-wavelengths in the sample
A is a constant which corrects for the resistive losses in the line conductors and
ρ is the VSWR on the air dielectric line.

Since a voltage minimum will appear at the dielectric face at frequencies at which the electrical length of the sample (equals $\frac{l}{\sqrt{K}}$) is ¼, ¾, 5/4, etc., wavelengths, one measurement is not sufficient to give a unique value of the constant. Measurements at two frequencies properly chosen will give a unique solution. In many instances the dielectric constant is approximately known, and, therefore, the proper integer for N can be chosen by inspection.

In practice, however, it is not possible to locate the voltage minimum accurately and to measure the standing-wave ratio when the minimum is directly at the front face of the sample. It has

[1] S. Robertson, A. von Hippel, Journal of Applied Physics, 17, 610 (1946).
[2] A. W. Dakin, C. N. Works, Journal of Applied Physics, 18, 789 (1947).
(For an excellent treatment of dielectric measurements, see also A. von Hippel, *Dielectric Materials and Applications*, John Wiley and Sons, New York, 1954.)

Figure 1.

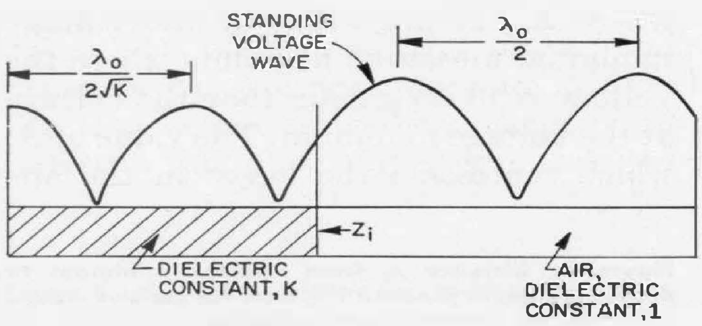
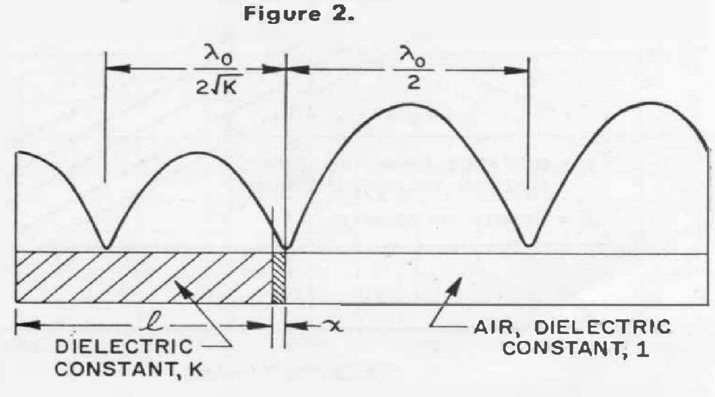


Figure 2.



been determined, however, that, with small modifications of the simple expressions previously presented, one can measure the dielectric properties with the voltage minimum in the vicinity of the sample and yet far enough away to make the selection of the frequency noncritical and to permit the measurement of VSWR by a width-of-minimum method.

Let us assume that the dielectric is exactly an odd multiple of a quarter-wavelength long and that the voltage minimum is directly at the front face of the sample as shown in Figure 2. Under these conditions, K and D can be calculated from Equations (1) and (2). Now suppose that a small amount of the dielectric near the voltage minimum is removed as indicated by the cross-hatched section in the figure, where the length of sample removed is indicated by x. If the sample has low loss, the voltage appearing at the voltage minimum relative to the voltage at other points along the line is very small and, therefore, the effect of dielectric near this point in the line is small compared to the effect at other points along the line. Consequently, the removal of the dielectric in the area near the voltage minimum has very little effect on the position of the minimum on the line. The dielectric constant can, therefore, be measured with the voltage minimum slightly ahead of the dielectric face with a negligibly small error. The modified equation for dielectric constant is:

$$K = \left[\frac{N\lambda}{4(l + x)}\right]^2 \qquad (3)$$

The above equation is based on the following approximation:

$$\frac{1}{\sqrt{K}} \tan(\sqrt{K}\,\beta x) = \tan \beta x \qquad (4)$$

where β is the propagation constant in free space. The error in the determination of K resulting from the use of this approximation is:

$$\frac{8}{3}\left(\frac{K - 1}{l}\right)\left(\frac{\pi}{\lambda}\right)^2 x^3 \qquad (5)$$

The value of x which results in a 1% error is plotted in Figure 3. As indicated in Equation (5), the error varies as the cube of x.

The same condition holds for measurements of the dissipation factor. Near voltage minimum the dielectric loss is low, because of the relatively low voltage and, therefore, the dielectric can be removed near the minimum without a significant change in the over-all dielectric loss. The resistive loss in the conductors in the area where the dielectric is removed is practically unaffected since the current distribution remains practically the same. The equation for dissipation factor becomes:

$$D = \frac{\Delta_{10}}{3(l + x)} - A \qquad (6)$$

where Δ_{10} is the width of the voltage minimum measured at points where the voltage is 10 db greater than the voltage at the voltage minimum. The value of A, which represents the losses in the air-

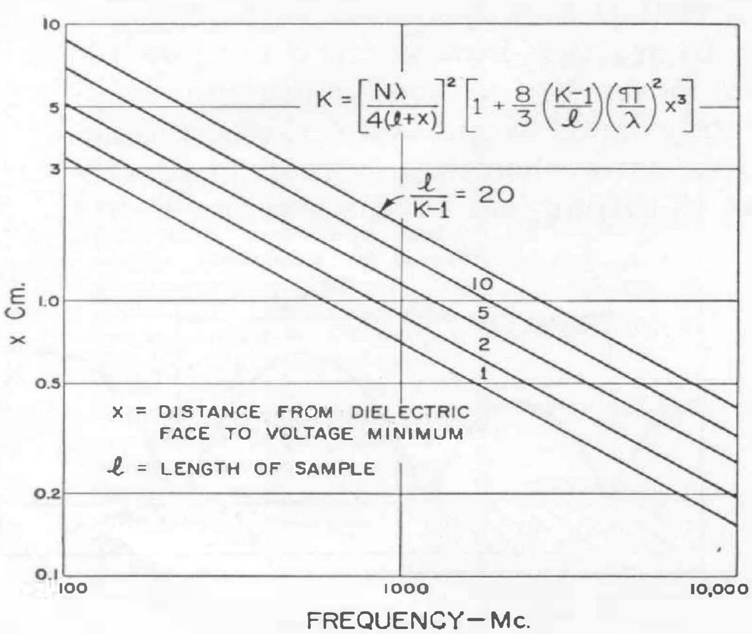


Figure 3. Distance x, from voltage minimum to dielectric face, to produce 1% error for various values of dielectric constant.

filled line, can be obtained from a measurement of the VSWR on the line with the sample removed. The equation for A is:

$$A = \frac{\Delta'_{10}}{3l'} \qquad (7)$$

where the width of the voltage minimum between 10-db points, Δ'_{10}, is measured with the sample removed, and where l' is the distance in centimeters between the voltage minimum at which the VSWR is measured and the open end of the line. For maximum accuracy, the length of line measured should be as long as possible.

THE TYPE 874-LM DIELECTRIC MEASURING LINE

As is obvious from the preceding description, in the proposed measurement method the slotted line and the sample holder must be one integral unit. The instrument designed for this function utilizes a coaxial transmission line which consists of an accurately machined bronze outer tube having an inside diameter of 0.562″ (7/16) with a 0.002″ overlay of silver on its inner surface and an inner conductor 0.250″ in diameter also with a similar overlay. The line is sufficiently long to accommodate samples up to 45 centimeters in length. The minimum frequency at which measurements can be made by the simplified method previously described depends upon the dielectric constant of the material being measured and is approximately $f_{min} = \frac{200}{\sqrt{K}}$ Mc. Of course, measurements can be made at lower frequencies by the more complicated method previously referred to. The actual low-frequency limitation is primarily determined by the sensitivity of the detector.

A movable carriage containing the probe rides on the accurately ground and lapped outer surface of the bronze tube. The position of the probe, and hence of the voltage minimum on the line, can be determined by means of an indicator on the centimeter scale to within ± 0.01 centimeter. A micrometer vernier drive on the carriage is provided for width-of-minimum measurements. The micrometer is capable of measuring the width of a minimum to within 0.0002 centimeter.

SOURCES OF ERROR

Line Losses

As previously mentioned, in measurements on very low-loss materials the line loss can be large compared to the dielectric loss. The effective dissipation of the line itself, A, caused by resistive losses is plotted in Figure 4 as a function of frequency. For purely resistive losses, the effective resistance per unit length increases as the square root of frequency as a result of skin effect and, hence, the effective dissipation factor per unit length decreases as the square root of frequency. Also plotted on Figure 4 is the calculated dissipation factor assum-

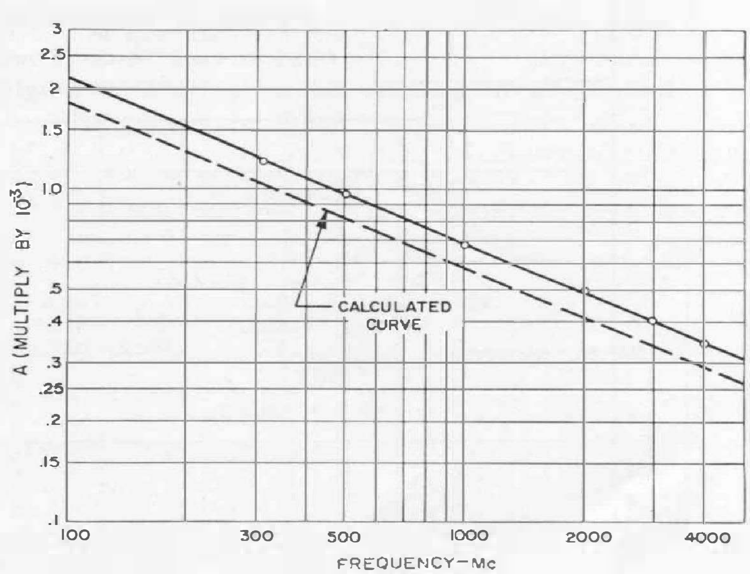


Figure 4. Losses in the slotted line itself, as measured, and as calculated for smooth silver surfaces.

ing smooth, pure-silver, inner and outer conductor surfaces. Note that the agreement is quite good.

The ratio of the dielectric loss to the resistive loss on the line varies with both the dissipation factor of the sample under test and the frequency. It is independent of the length of the sample when the VSWR measurement is made close to the dielectric face. Figure 5 is a plot of this ratio for a normalized dissipation factor 0.0001. In other words, at a frequency of 500 Mc, the ratio for a dielectric material having a dissipation factor of 0.001 would be 1.4. It is obvious that at lower frequencies the ratio becomes smaller, and, hence, an accurate measurement of line losses is very important. Small errors in this measurement can have a large effect on the measured dissipation factor of low-loss materials at low frequencies.

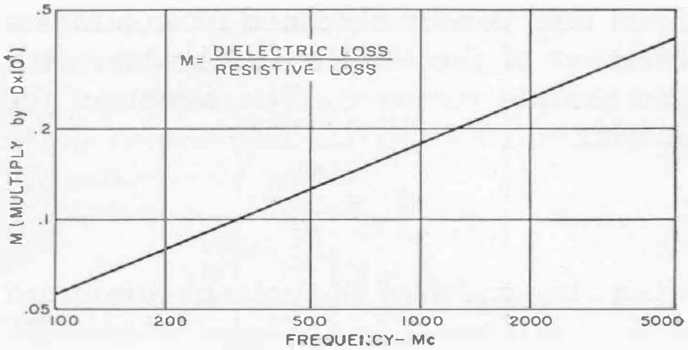


Figure 5. Ratio of loss in sample to loss in line normalized for a *D* of 0.0001.

Fringing

In an open-ended transmission line, fringing capacitance exists at the end of the conductors. This capacitance makes the transmission line appear longer electrically than it is physically. Figure 6 shows the results of measurements made on the fringing capacitance in the coaxial dielectric-measuring line with the dielectric removed. The added electrical length, resulting from the fringing capacitance of $0.15\mu\mu f$, is approximately 0.23 centimeter. When dielectric samples are present, the effective added length decreases approximately proportionally to the dielectric constant of the insulating material. The correction for fringing capacitance can be included in the dielectric-constant equation as indicated below or, if a sufficiently long dielectric sample is used, the error is negligible.

$$K = \left[\frac{N\lambda}{4(l+x)}\right]^2 - \frac{0.46}{l} \qquad (8)$$

Air Gaps

Air gaps between the sample and the dielectric conductors of the transmission

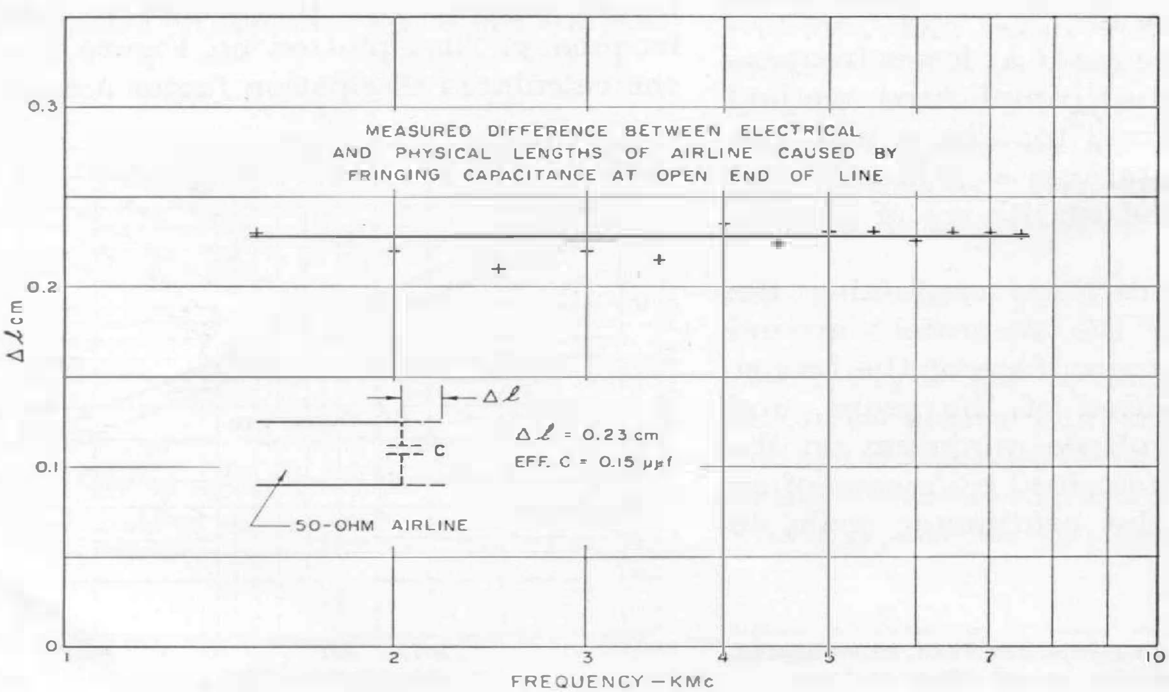


Figure 6. Effective increase in line length caused by fringing.

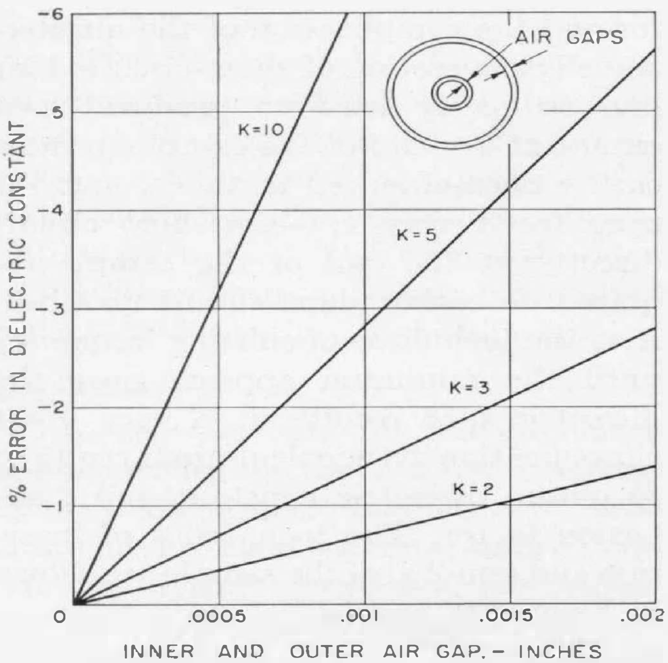


Figure 7. Error in *K* caused by air gaps between dielectric sample and inner and outer conductors.

line cause errors in the measurements. Figure 7 indicates how for a given gap those errors vary with the dielectric constant on the coaxial line described in this article. The minimum practical gap is one of the factors which set a limit on the maximum dielectric constant which can be measured to a given accuracy.

Probe Coupling

As a probe approaches the dielectric sample, its effective coupling to the center conductor will increase as a result of the dielectric effectively increasing the capacitance between the probe and line. The point at which the probe coupling is significantly affected is the minimum distance which can be tolerated between the dielectric face and probe. Figure 8 shows the variation in probe coupling as a function of distance measured in the line described later in this article. Note that, for relatively low-loss dielectric materials with dielectric constants even as large as 9,000, the increase in coupling is very small at distances greater than a millimeter. Therefore, the probe should not be allowed to approach closer than a millimeter when either the position of the minimum or the width of the minimum is measured. When high-loss materials are measured, and the minimum is very broad, an even larger minimum spacing is necessary, because even a slight variation in coupling will shift the apparent center of the broad minimum. Figure 9 shows the results of measurements made on various samples in order to determine the effect on the position of the minimum as a result of added probe coupling. In this figure the position of the voltage minimum with respect to the front face of the dielectric is plotted as a function of wavelength for samples having various dissipation factors. If probe coupling were constant, these curves would be straight lines. Note that, for the two relatively low-loss samples, the variation follows the linear law until a spacing of less than

Figure 8. Variation in probe coupling as a function of distance between probe and dielectric face.

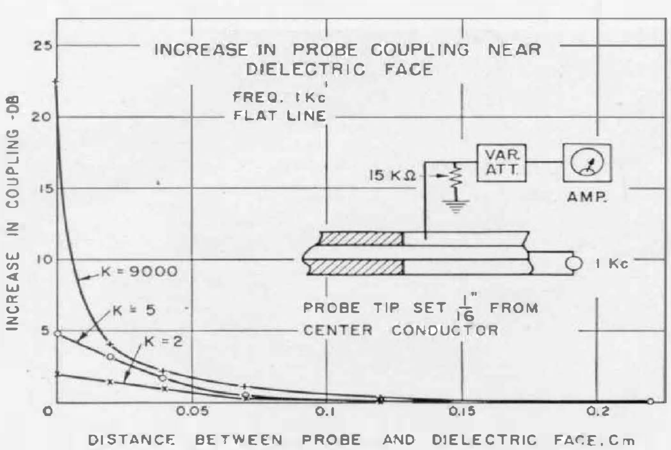
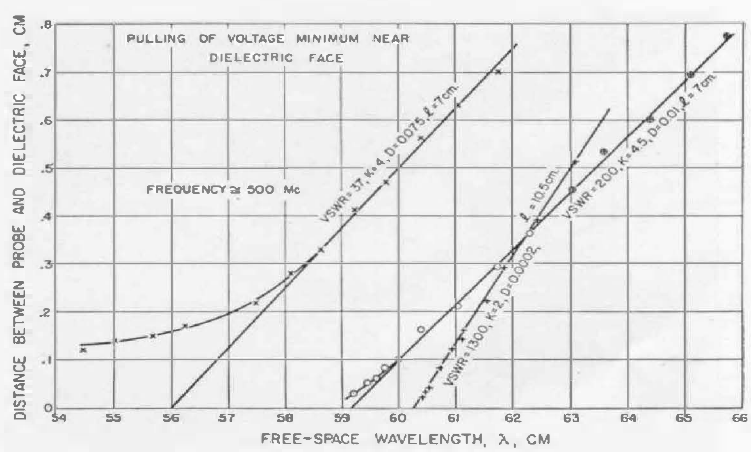


Figure 9. Effect of probe coupling of position of minimum.



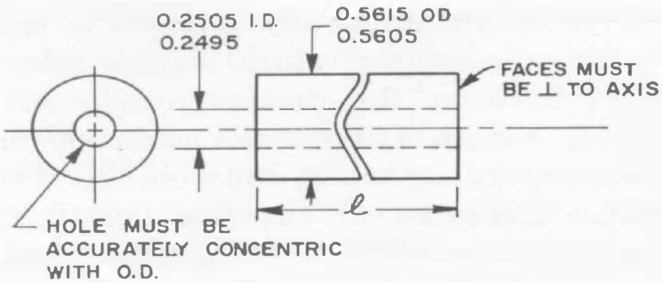


Figure 10. Dimensions of sample.

one millimeter is reached. The sample having a very high dissipation factor, however, shows that the position of the minimum is affected at spacings up to 0.3 centimeter.

The Sample

One limitation of the proposed method is that the samples must be at least a quarter-wavelength long, and at the lower frequencies this length may not be easy to obtain in a single sample. However, the quarter-wavelength section can be made up of a number of shorter lengths, which can be easily machined. Another limitation is that either the frequency or the length of the sample must be trimmed to obtain a voltage minimum within the limits previously described. If the measurements must be made exactly at a specified frequency, some cut-and-try work must be done on the samples themselves. The dimensions of the sample are shown in Figure 10.

The use of an open-ended line greatly simplifies the mechanics of the insertion of the samples and eliminates the need for and the complication of the quarter-wavelength section of short-circuited air line ordinarily used to produce open circuit at the end of the sample in most earlier open-circuited methods, and the need for a very low-loss short circuit directly at the end of the sample required on earlier short-circuit methods. Also the technique of shifting frequency until the minimum appears near the dielectric face results in a very great simplification in the calculations required to obtain dielectric constant and dissipation factor. The techniques of insertion and removal of the sample are shown in Figures 11 and 12.

Detector

The detector which produces the best results in this application is heterodyne type in which the signal from the probe and a signal from a local oscillator are applied to a crystal diode mixer and the difference frequency output is amplified by means of a fixed tuned I-F amplifier. The Type 1216-A Unit I-F Amplifier, Type 874-MR Mixer Rectifier and various Unit Oscillators are well suited to this application. These are available in complete combinations as the Type DNT Detectors. The r-f mixer is accurately linear over a voltage range from about 80 db and, hence, the relative level of the signal picked up by the probe can be easily measured by means of a calibrated step attenuator and calibrated

Figure 11. Sample is easily installed by means of tool furnished.

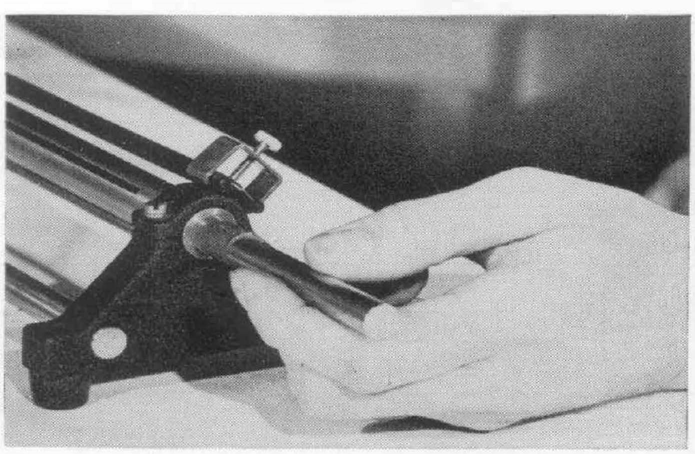
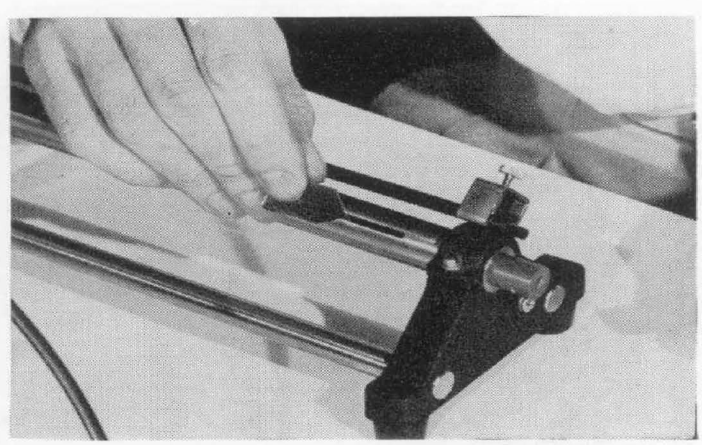


Figure 12. Tool for removing sample is also furnished.



output meter in the TYPE 1216-A I-F Amplifier. With a heterodyne detector, an unmodulated signal can be used to excite the line, thus eliminating errors resulting from incidental frequency modulation produced when the oscillator is amplitude modulated. This type of detector has high sensitivity, good linearity, and excellent discrimination against harmonics.

Oscillator

The requirements for the oscillator used to excite the line are not exacting. Simple, low-power, tunable, c-w oscillators having good stability, such as the GR line of Unit Oscillators, are recommended. Signal generators are also satisfactory sources. Since a high-sensitivity detector is used, the oscillator can be directly coupled to the slotted line, preferably through a resistive pad without the use of tuning elements.

The complete setup, including generator and detector, is shown in the block schematic of Figure 13.

Frequency Limitations

The maximum frequency at which reliable measurements can be made is that at which the first higher-order mode can be propagated in the dielectric under test. In the air-filled line, the first higher-order mode, which is a circumferential mode, has a cutoff frequency of about 9000 Mc. This cutoff frequency decreases as the square root of the dielectric constant and hence the upper frequency limit is $9000/\sqrt{K}$.

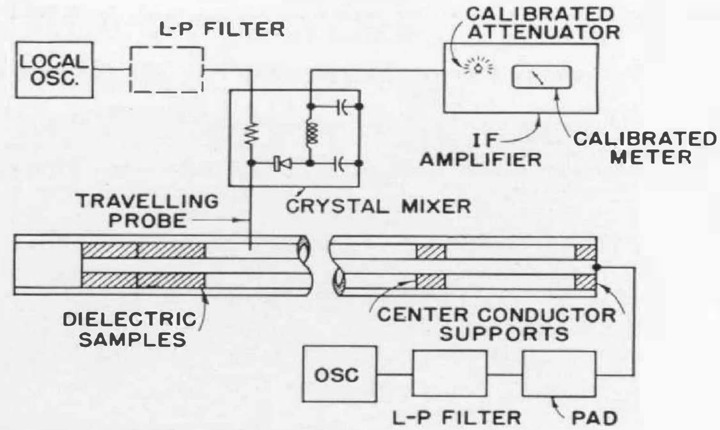


Figure 13. Block diagram of complete dielectric measuring system.

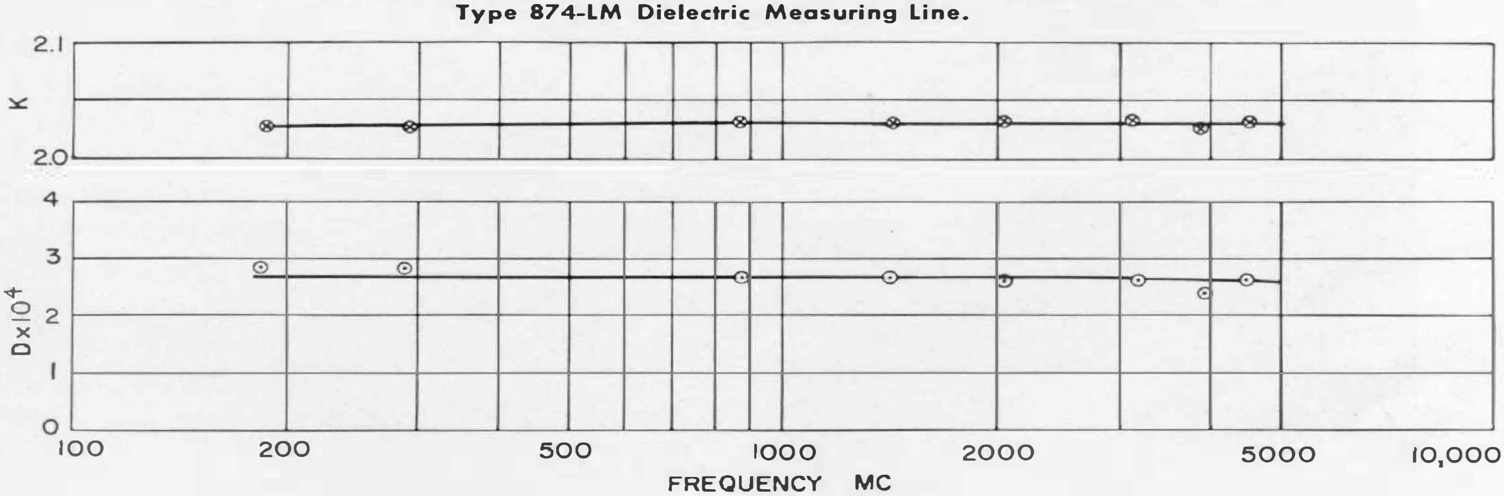
Accuracy

With this instrument, accurate straightforward measurements on materials having dielectric constants between 1 and 10 and dissipation factors between 0.0001 and 0.05 can be made with an accuracy of about ± 2% in dielectric constant and ± (5% + 0.0001) in dissipation factor over a frequency range from about 200 to 5000 Mc. The dielectric-constant accuracy is satisfactory for most applications, and the dissipation-factor resolving power makes possible reasonable measurements on even the lowest loss materials presently available.

Applications

Figure 14 shows the results of measurements made on Teflon over a wide range of frequency. — R. A. SODERMAN

Figure 14. Dielectric constant and dissipation factor of Teflon as measured on the Type 874-LM Dielectric Measuring Line.



SPECIFICATIONS

Frequency Range: Minimum, $\frac{200}{\sqrt{K}}$ Mc; Maximum 5000 Mc or $\frac{9000}{\sqrt{K}}$ Mc, whichever is the smaller.

Measurement Ranges and Accuracies: Dielectric Constant (K) $\pm 2\%$ for values of K between 1 and 10; Dissipation Factor, $\pm$ (5% + 0.0001) for values of dissipation factor between 0 and 0.05.

Sample: Cylindrical; O.D., 0.561 inches; I.D., 0.250 inches; length depends upon dielectric constant and frequency; long samples can be made up of a number of short sections.

Micrometer Scale: Can be read to 0.0002 cm.

Accessories Required: Generator and detector; General Radio Unit Oscillators (with Type 1201-A Unit Regulated Power Supply) and Type DNT Detectors, respectively, are recommended. A complete listing of these will be found in the March, 1958, issue of the *Experimenter*. Also required, one Type 874-G6 6-db Pad and one Type 874-G3 3-db Pad. Appropriate Type 874-F Filters are also recommended.

Dimensions: 26 x 4½ x 3½ inches, over-all.

Net Weight: 9½ pounds.

Type		*Code Word*	*Price*
874-LM	**Dielectric Measuring Line**	COAXFACTOR	**$400.00**

OPEN HOUSE AT NEW CONCORD PLANT

On Friday, June 6, 1958, from 1:00 P.M. until 4:00 P.M. the General Radio Company will hold open house at its newly enlarged plant in West Concord, Mass., located between Massachusetts highways Routes 2 and 62. We invite all of our customers and friends who are interested to attend. Ample parking facilities are located immediately adjacent to the buildings.

Open for inspection:

☆ Many operating displays of the latest GR instruments.

☆ The engineering development laboratories.

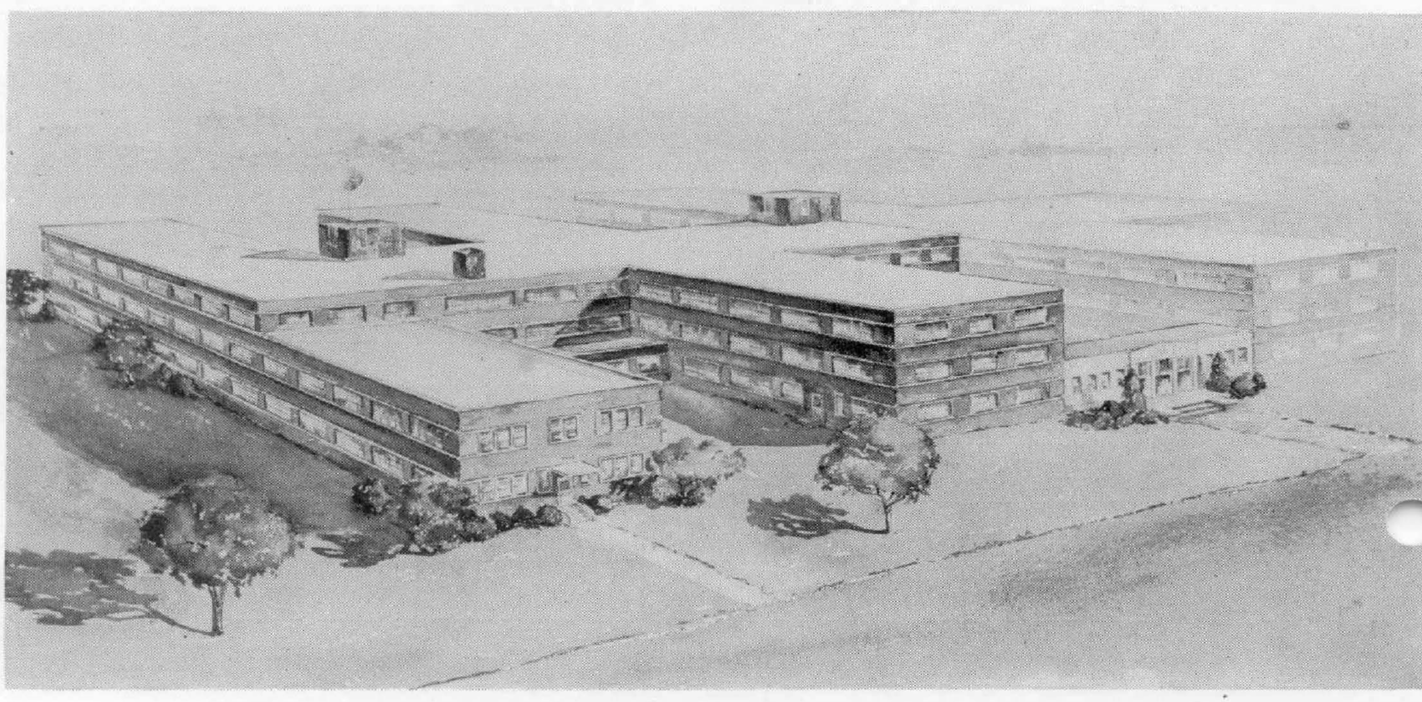
☆ The well-equipped model shop, in which the first models of new items are made.

☆ Standardizing laboratory, where all GR instruments are calibrated, checked and certified prior to shipment.

☆ Instrument- and component-assembly departments.

☆ Variac® winding, assembly and testing department.

☆ Supporting departments, such as production planning, purchasing and shipping.



IMPROVEMENTS IN DECADE INDUCTORS

The TYPE 1490 Decade Inductors and the TYPE 940 Decade Inductance Units have recently been redesigned to use a newer type of switch. As a result, the Q's of the low-inductance units have been improved and the resonant frequencies of the high-inductance units have been raised. These two improvements come about from the lower and more stable contact resistance of the new switch and from a change in the switching method.

The new decade switch has high-quality, ceramic stator-and-rotor members and utilizes a well-defined ball-and-socket detent. All contacts are made of a solid-silver alloy and have a positive wiping action. This switch is inherently reliable in extensive use and should not require bothersome cleaning or adjustment in service.

The d-c resistance at zero setting of a four-decade TYPE 1490 Decade Inductor with the older switch is over 400 milliohms, while with the new switch it is approximately 30 milliohms. The former value is a substantial part of the total resistance in the lowest-inductance decade, where the improvement ranges from 6.2:1 for the 1-mh step to 1.6:1 for the 10-mh step. There is a corresponding improvement in Q at low frequencies, as shown for the 1-mh step in Figure 2.

A different method of switching has lowered the stray capacitance across the active inductors, with a consequent increase in their resonant frequency. This is most important on the high-inductance decades but is also significant for the lower decades of a TYPE 1490 Assembly. Originally, four inductors of unit values 1-2-2-5 were connected in series, and those inductors not required for any setting were shorted out by switches. This added the resistance of

Figure 1. View of the Type 1490-C Decade Inductor.

the closed switches in series with the active inductors and placed the ground capacitance of the unused inductors across the active inductors below them in the series circuit.

With the new switching sequence the number of switch contacts in circuit is minimized, and unused inductors are

Figure 2. Plot of Q versus frequency for the 1-millihenry step in the old and new decade inductors.

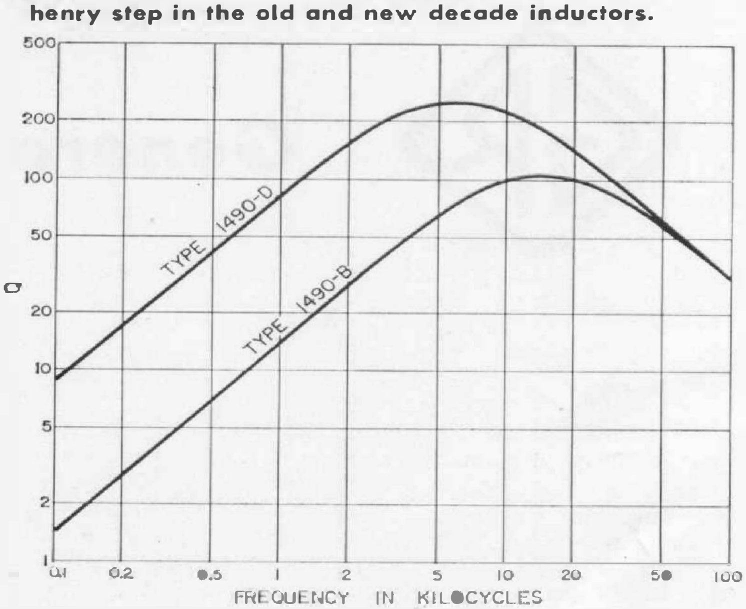


Figure 3. View of the Type 940-H Decade Inductance Unit.

completely disconnected. The resultant increase in resonant frequency for the low setting in each decade runs between 1.5 and 1.9, so that the correction factors for inductance at the high frequencies are reduced by these ratios.

The new switch requires somewhat more space, which increases the length of the TYPE 940 Decade in a direction perpendicular to the switch shaft and likewise the panel width of the TYPE 1490 Cabinets. New type letters have been assigned as follows:

New Type	*Replaces Old*	*Inductance*	*Code Word*	*Price*
940-E	940-A	1 millihenry/step	INDUCTOANT	$100.00
940-F	940-B	10 millihenrys/step	INDUCTOBOY	100.00
940-G	940-C	100 millihenrys/step	INDUCTOCAT	100.00
940-H	940-D	1 henry/step	INDUCTODOG	110.00
1490-C	1490-A	1.11 henry max, 1 mh/step	CLUMP	330.00
1490-D	1490-B	11.11 henry max, 1 mh/step	COACH	440.00

EQUIPMENT LEASING

Some users have found it desirable to lease test equipment rather than to purchase it outright.

We do not have arrangements for direct leasing, but there are a number of concerns which make a business of leasing. We should be glad to suggest to those interested the names of several firms which specialize in the leasing of electronic equipment.

General Radio Company