July 15, 1966

A STANDING-WAVE METHOD FOR THE MICROWAVE EVALUATION OF DIELECTRIC AND MAGNETIC MATERIALS

by

Jerald A. Weiss
and
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Prepared by
Worcester Polytechnic Institute
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Lincoln Laboratory

Report No. 2
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ABSTRACT

This report presents results of an investigation into the standing-wave method for evaluation of microwave loss and effective dielectric constant of low-loss ceramic materials. The objective of the study was primarily to devise a sensitive method for determination of the dependence of loss on the magnetic state of ferrites and ferrimagnetic garnets in various conditions of remanence. Design of a special coaxial slotted line and specimen holder is described. Preparation of specimens, including metallization of surfaces, is discussed. Data taken at S-band ($\sim$3 GHz) on a dielectric and a garnet material are presented. They show that the sensitivity of the method in its present form is marginal for the purpose, although within an order of magnitude of that of conventional resonant-cavity methods. A means for accurately determining a correction for distributed loss in the slotted line is presented. The report includes graphs of the theoretical voltage ratio (1/VSWR) versus electrical length of the specimen, for low-loss material having dielectric constants in the range 8 -- 16, together with the computer program used to calculate these graphs.

A Standing-Wave Method for the Microwave Evaluation of Dielectric and Magnetic Materials

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A Standing-Wave Method for the Microwave Evaluation of Dielectric and Magnetic Materials

1. Introduction.

This report presents a summary of the work performed under Subcontract No. 302 during the period September 15, 1965 -- June 15, 1966, on the development of a reflection method for determination of the effective dielectric constant and loss tangent of microwave dielectric and ferrite materials. The measurements were performed in S-band (about 3 GHz) by a standing-wave method, using a coaxial slotted transmission line especially designed for this project. Toroidal specimens, dimensioned to fill a section of the line, were used. The specimen surfaces were partly metallized so as to provide intimate contact with the conducting walls of the line. The report reviews the theory of the measurement and describes the experimental apparatus and procedure. Data are presented on two materials which illustrate the capabilities and limitations of the method. The materials are a polycrystalline ferromagnetic garnet and a ceramic aluminum oxide.

One of the objectives of this investigation was to develop a sensitive method for observation of loss in microwave magnetic materials in various states of remanent magnetization. The toroidal geometry employed in this coaxial-line method lends itself to precise control over the magnetic state of the specimen. Data obtained during this period indicate, however, that the method in its present form does not offer sufficient sensitivity to permit accurate determination of the small variations in loss which occur in the low-loss materials of interest for microwave device applications.

The method is capable of yielding accurate values of effective[1] dielectric constant ϵ and loss tangent $\tan \delta$, for ϵ in the range 9 -- 16 and $\tan \delta$ down to the order of 10^{-2}. For values of $\tan \delta$ less than this the accuracy is degraded, becoming poor around $\tan \delta \sim 10^{-3}$. Limiting factors are: conduction loss in the slotted line, radiation from the slot, imperfect contact of the specimen with the walls of the transmission line, and ultimately, inaccuracy in the mechanical measurement of high standing-wave ratios.

2. Theory of the Measurement.

The experimental arrangement is essentially that of a standard standing-wave method. A specimen of the material under investigation is prepared in the form of a toroid of radii equal to those of standard coaxial 50-ohm transmission line, namely 0.5625 inch OD and 0.2442 inch ID. The specimen is placed in the line with its load-end face in contact with a short circuit. Axial lengths of the specimens were chosen so as to be 1/4 and 3/4 wavelengths at approximately 3 GHz.

The positions of standing-wave minima, and the voltage ratio Λ, are measured. By voltage ratio we mean the reciprocal of the customary voltage standing-wave ratio (VSWR), namely

$$\Lambda = \frac{|E_{min}|}{|E_{max}|} \qquad (1)$$

Let β_2 denote the propagation constant in the specimen, d the length of the specimen, ϵ_2 the real part of the dielectric constant, and tan δ the loss tangent. Thus, the complex effective dielectric constant is $\epsilon_2(1 - i \tan \delta)$. Let ϵ_1 denote the dielectric constant of the medium (air) filling the remainder of the line. Then, as shown for example by Westphal[2], for small values of tan δ the voltage ratio is

$$\Lambda = \frac{1}{2} (\tan \delta) \sqrt{\frac{\epsilon_1}{\epsilon_2}} \, \frac{\beta_2 d(1 + \tan^2 \beta_2 d) - \tan \beta_2 d}{1 + (\epsilon_1/\epsilon_2) \tan^2 \beta_2 d} \qquad (2)$$

As a part of this investigation, the expression (2) for the voltage ratio was evaluated numerically for values of ϵ_2/ϵ_1 in the range from 8 to 16 and for the parameter $\beta_2 d/2\pi = d/\lambda_2$ in the range from zero to two. These data are presented graphically in the Appendix, as graphs of $\log_{10} (\Lambda/\tan \delta)$ versus d/λ_2, together with the Fortran program used in the computation.

The graphs show that for values of ϵ_2/ϵ_1 substantially greater than one Λ passes through a more or less sharp maximum when the resonance condition $d/\lambda_2 = (2n + 1)/4$ or

$$\beta_2 d = (2n + 1) \frac{\pi}{2} \qquad (3)$$

is fulfilled. This characteristic resonance of the specimen is useful in several ways in the performance of this experiment. First, it provides an enhancement of the loss effect, thereby improving sensitivity in rather the same way as in resonant cavity methods. In comparison with the cavity perturbation method, we accept a relatively low Q in return for higher filling fraction (namely, 100 % filling of the resonant section). Second, condition (3) provides a means for measuring the dielectric constant ϵ_2 of the specimen, by observing the frequencies ω of the resonances and the physical length d of the specimen, since for small losses β_2 is given by

$$\beta_2 \cong \frac{\omega}{c} \frac{1}{\sqrt{\epsilon_2}} \tag{4}$$

where c is the velocity of propagation in the empty coaxial line. Third, condition (3) furnishes a means for detecting errors, by observing whether the measured values of the intrinsic material constants ϵ_2 and tan δ for specimens of electrical length $\beta_2 d = 3\pi/2$ agree with those for length $\pi/2$. Under the best conditions of sample preparation and mounting, data on the low-loss ferrite fulfilled this condition approximately.

According to (2), the maximum values of Λ under the condition (3) are

$$\Lambda_{max,\, n} = \frac{\pi}{4}(2n + 1) \sqrt{\frac{\epsilon_2}{\epsilon_1}} \tan \delta \tag{5}$$

Thus, with ϵ_2 determined as indicated above (from the length of the specimen and the frequency at which $\Lambda_{max,n}$ occurs) the value of tan δ can be determined from (5).

Formula (2) connecting the voltage ratio Λ with the loss tangent of the specimen is derived on the assumption that there are no other causes of loss. When tan δ is extremely small, the errors due to conduction and radiation losses become appreciable. A correction for these effects can be determined experimentally, however, so as to permit accurate measurements of specimen loss in the presence of these competing effects. The correction procedure is discussed in Sec. 5.

3. Experimental Apparatus.

A block diagram of the microwave circuit is shown in Fig. 1. The source is a signal generator tunable over the range 1.8 -- 4.0 GHz. Square-wave modulation at 1 KHz was provided externally. The standing-wave detector is a low-noise tunnel diode; the signal is presented on a standing-wave indicator. Observations of voltage ratio Λ are made by the method appropriate for low Λ (high VSWR), namely by observing the distance between 3-db points at the standing-wave minimum, according to

$$\Lambda \cong \pi \frac{\Delta z}{\lambda_1} \qquad (6)$$

where Δz is the distance and λ_1 is the empty-line wavelength. The slotted line is the General Radio model 874-LBA, modified to improve the electrical quality of the specimen mounting, as described below. The position of the probe carriage is observed with the aid of a dial indicator which furnishes precision such that the uncertainty in the probe position is less than 0.001 cm. This degree of precision in the measurement of Δz (eq. 6) is required for determination of tan $\delta \sim 10^{-2}$, corresponding to $\Lambda \sim 3 \times 10^{-2}$ and therefore, at 3GHz, $\Delta z \sim 0.09$ cm, which are typical values for the ferrite specimen.

As the result of various difficulties encountered in establishing correct and reproducible mounting of the specimens and the short-circuit termination, a special slotted line was made and installed in place of the one furnished in the commercial instrument. Drawings of the center and outer conductors are shown in Figs. 2 and 3. The pieces were made of brass and were finished with an electroplated coating of silver. The slot extends continuously to the end of the outer conductor. Over the central portion, 5.5 inches long, it is 0.110 inch wide to accept the probe, while over the remaining length, 5 inches to the end, it is made narrower, namely 0.010 inch wide, to minimize radiation loss while permitting the outer conductor to act as a spring holder for the specimen. The end portion of the center conductor, 1.6 inches long, is split into quarters and sprung open slightly to provide good contact with the hole in the toroidal specimen. A pin making a press fit into the 0.241-inch diameter hole in the end of the center conductor is inserted after the specimen has been mounted, so as to provide positive contact.

To allow for the thickness of the metal coatings on the inner and outer surfaces of the specimens (see below), the diameters of the inner and outer conductor were modified by 0.004 inch as shown in the Figures.

The specimens themselves were metallized to provide complete contact with the conducting surfaces of the transmission line and with the short-circuit termination. The metallization[4] was composed of electroless-deposition of copper, followed by copper electroplating to a thickness of 0.002 inch. This was covered with a thin (50 μ inch) protective coating of electroplated gold.

The materials which were used to establish the capability of the method were[5,6] the polycrystalline ferromagnetic yttrium-iron garnet TT-G-1005 and the ceramic alumina "Lucalox." The specimens were toroids, centerless-ground to OD 0.561 inch, ID 0.243 inch; lengths, 0.250 and 0.500 inch for the garnet, and 0.328 and 0.656 inch for the alumina. Tolerances on these dimensions were ± 0.0005 inch.

4. Experimental Data.

Measurements performed on the TT-G-1005 illustrate the procedure and results. A specimen 0.250 inch long, prepared as described in Sec. 3, was used to obtain the resonance corresponding to $n = 0$ (one quarter-wavelength -- see eq. 3). To obtain the resonance for $n = 1$ (three quarter-wavelengths), a second specimen 0.500 inch long and metallized on its curved surfaces only, was placed in the line in contact with the first specimen. Except for the slight discontinuity in the medium and in the metallized surfaces, this combination is equivalent to a single specimen three quarter-wavelengths long.

Since propagation in the garnet is influenced by the magnetic state of the material, each specimen was magnetized to its remanent state just before the measurement. A current pulse of approximately 36 amp was passed through the hole in each toroid. This produces a circumferential field ranging from about 24 oersteds at the inner radius to about 10 oersteds at the outer -- sufficient to yield a reproducible, maximum remanent magnetization. The coercive field of this material is 2 oersteds.

Graphs of Λ versus $\beta_2 d$ (obtained by varying the frequency) for these two values of n are shown in Fig. 4. In both cases the peak occurred at 3.11 GHz, corresponding to an effective dielectric constant $\epsilon_2 = 14.5$, as determined from eqs. (3) and (4). The peak values of Λ are not in the ratio three to one; hence the resulting calculated values of tan δ disagree: tan $\delta = 1.05 \times 10^{-2}$ for the short specimen and tan $\delta = 1.58 \times 10^{-2}$ for the long. The correction for loss in the empty portion of the slotted line (discussed in Sec. 5) is about 10% of these values, in the direction such as to increase the discrepancy slightly.

The manufacturer's value for dielectric constant of this material is 15.5. The difference between this and the value of effective dielectric constant measured by the present methods is in the right direction and, qualitatively, at least, of a reasonable magnitude, considering the effect of magnetic disorder on the permeability and therefore on the propagation constant. "Low-field" depression of the permeability becomes appreciable as the ratio $4\pi M_s \gamma/\omega$ approaches one. For this material, with $4\pi M_s = 725$ gauss, this magnetization ratio is 0.65 at 3 GHz.

Regarding the loss tangent, we may conclude that for TT-G-1005 it is close to 1×10^{-2}. The discrepancy between the results for the $\lambda/4$ and the $3\lambda/4$ specimens may result from contact difficulties, which would be particularly troublesome if the diameters or concentricities of the two pieces were slightly different. Although the specimens passed a good mechanical inspection showing that such defects must have been smaller than 0.0005 inch, it is nevertheless conceivable that they might manifest themselves in the low range $\Lambda \sim 10^{-2}$.

Observations on the "Lucalox" specimens showed that the peak in the voltage ratio Λ was barely discernible. Repeated series of measurements appeared to indicate a maximum near 2.8 GHz, which would correspond to $\epsilon_2 = 9.6$ -- near the expected value for aluminum oxide. (The manufacturer's value for "Lucalox" is $\epsilon_2 = 9.9$.) The value of Λ was, however, very low: 4.4×10^{-3}, which exceeds only slightly the contribution due to losses in the length of empty transmission line between the specimen and the detector probe -- $\Lambda_l = 2.8 \times 10^{-3}$; see Sec. 5. Although the results are of no use for evaluation of tan δ for this material, they are at least roughly consistent with the expected value: assuming tan $\delta \sim 10^{-3}$, the contribution of the specimen loss to Λ would be about 2.5×10^{-3}. We must conclude that the method in its present form is not capable of yielding meaningful values of tan δ of such low-loss materials. It is worth noting, however, that this limit is higher by a factor of only 4 or 5 than that for standard cavity-perturbation methods.

5. Loss in the Slotted Line.

The observed voltage ratio Λ used to determine the loss tangent of the dielectric specimen includes also a contribution due to the radiation and conduction losses in the slotted line. The accuracy of the measurement can be improved by subtracting this contribution. At the same time, determination of the line losses serves to assess the quality of the slotted line and to indicate the order of magnitude of the minimum measurable loss tangent.

With no specimen in the line, the reflection coefficient of the short-circuit termination may still not be of unit magnitude, due to slight imperfections in electrical contact. We denote the magnitude of this reflection coefficient by $e^{-\rho}$, where $\rho \ll 1$; also, denote the loss tangent of the empty line by $\tan \delta_l$. Then the value of the voltage ratio Λ_l, as determined[7] by observing the width of the standing-wave minimum (eq. 6) at distance z in front of the short circuit, can be readily shown to be

$$\Lambda_l = \sinh \frac{1}{2} (\beta z \tan \delta_l + \rho) \qquad (7)$$

which, for small ρ and $\tan \delta_l$ is very nearly

$$\Lambda_l \cong \frac{1}{2} (\beta z \tan \delta_l + \rho) \qquad (8)$$

To determine $\tan \delta_l$ and ρ, we observe Λ_l at each of the minima occurring within the range of z accessible to the probe. A graph of $2\Lambda_l/\beta z$ versus $1/\beta z$ yields a straight line according to

$$\frac{2\Lambda_l}{\beta z} = \rho \left(\frac{1}{\beta z}\right) + \tan \delta_l \qquad (9)$$

on which the intercept at $1/\beta z = 0$ yields the desired value of tan δ_l. The slope of the line yields ρ, from which the reflection coefficient $e^{-\rho}$ of the short-circuit termination can also be determined.

The graph of $2\Lambda_l/\beta z$ versus $1/\beta z$ for the slotted section used in this project is shown in Fig. 5, as determined at 3 GHz. It yields

$$\tan \delta_l = (3.65 \pm 0.05) \times 10^{-4} \tag{10}$$

and $$\rho = 1.077 \times 10^{-3}$$

from which $$e^{-\rho} \cong 1 - 1.077 \times 10^{-3}$$

As a measure of merit of the slotted line, this value of tan δ_l may be compared to the theoretical value[8] for empty coaxial line, taking account of conduction loss in the silver walls:

$$\alpha = \beta \tan \delta_l = \sqrt{\frac{\epsilon}{\mu}} \sqrt{\frac{\omega\mu}{2\sigma}} \left(\frac{1}{a} + \frac{1}{b}\right) \Big/ 2 \ln \frac{b}{a}$$

$$= 0.972 \times 10^{-4} \text{ cm}^{-1}$$

at 3 GHz. Then

$$\tan \delta_l = 3.09 \times 10^{-4}$$

The excess in the observed value of tan δ_l may be attributed to radiation loss and surface roughness.

With the aid of the value (10) thus determined, we can make the correction for line loss as follows. On insertion of the specimen, the reflection coefficient as represented by $\frac{1}{2}\rho$ in (7) becomes

$$\frac{1}{2}\rho \longrightarrow \tanh^{-1} \Lambda_s$$

where Λ_s is the voltage ratio due to the specimen alone. From (7), the observed width Δz of the standing-wave minimum is given by

$$\frac{\beta \Delta z}{2} = \sinh \left(\frac{\beta z}{2} \tan \delta_l + \tanh^{-1} \Lambda_s\right)$$

whence

$$\Lambda_s = \tanh \left(\sinh^{-1} \frac{\beta \Delta z}{2} - \frac{\beta z}{2} \tan \delta_l \right)$$

For low losses this is very nearly

$$\Lambda_s \cong \frac{\beta \Delta z}{2} - \frac{\beta z}{2} \tan \delta_l$$

Thus, for low losses the contributions to Δz due to absorption by the specimen and distributed line loss are additive.

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We wish to thank D. H. Temme of Lincoln Laboratory for suggesting this investigation and for continuous exchange of ideas. For loan of equipment and technical assistance, we are grateful to the Array Radars Group and to a number of its members.

FOOTNOTES

1. The term "effective" used in this connection refers to the fact that the present experimental method does not distinguish between dielectric and magnetic loss mechanisms. The method can, however, be extended so as to determine the two contributions separately. See Footnote 3.

2. A. von Hippel, ed.: Dielectric Materials and Applications; Technology Press (M.I.T.), 1954. Sec. II A 2, "Distributed Circuits," by William B. Westphal; page 67.

3. Ibid., Sec. II B, "Permeability," by David J. Epstein; page 133.

4. The metallizing was performed by American Electroplating Company, Cambridge, Massachusetts.

5. The magnetic material TT-G-1005 is an yttrium-iron garnet gadolinium-substituted for temperature stability; manufactured by Trans-Tech, Inc., Gaithersburg, Maryland.

6. "Lucalox" is the trade name for a dense aluminum oxide ceramic manufactured by General Electric Co., Cleveland, Ohio.

7. In the presence of distributed losses in the slotted line, the definition of Λ as $|E_{min}|/|E_{max}|$ is inappropriate in that it refers to fields at two different positions on the line. In this circumstance the definition of Λ through its relation to reflection coefficient may be used: $|E_-/E_+| = (1 - \Lambda)/(1 + \Lambda)$ defined at position z.

8. N. Marcuvitz: Waveguide Handbook; M.I.T. Radiation Laboratory Series, Vol. 10; McGraw-Hill, 1951; Sec. 2.4, "Coaxial Waveguides," page 73.

Figure 6. Appendix

Computer Program for Calculation of Voltage Ratio Λ

```
C REFLECTION FROM LOSSY DIELECTRIC IN COAX
C
C  REFERENCE.. VON HIPPEL, DIELECTRIC MATERIALS, P. 68
C  THIS PROGRAM COMPUTES THE VOLTAGE RATIO (1/VSWR) DUE TO A SECTION OF
C   COAX FILLED WITH DIELECTRIC AND TERMINATED IN A SHORT CIRCUIT, WHEN
C   DIELECTRIC CONSTANT, LOSS TANGENT, AND LENGTH IN UNITS OF WAVELENGTH
C   ARE GIVEN. APPROXIMATION POOR FOR LOSS TANGENT GREATER THAN 0.1
C
C        1         2         3         4         5         6         7
C234567890123456789012345678901234567890123456789012345678901234567890l2
C
      PI=3.1415926536
C   VALUE OF TAN DELTA.. 0.001
      TDEL=0.001
C   RANGE OF EPSILON.. 8 TO 16 IN STEPS OF 2
      EPST=7.0
      JFI=9
C   RANGE OF LENGTH.. ZERO TO 2 WAVELENGTHS IN STEPS OF 0.025
      RST=0.025
      KFI=80
      DO 1 J=1,JFI,2
      AJ=J
      EP=EPST&AJ
      SQEP=SQRT(EP)
      WRITE(6,10) TDEL,EP
      WRITE(6,11)
      DO 2 K=1,KFI
      AK=K
      R=RST*AK
      RD=2.0*R
      RP=PI*RD
      TST=ABS(RD-AINT(RD)-0.5)
      IF(TST .LT. 0.001) GO TO 4
      T=TAN(RP)
      DEN=1.0&(T**2)/EP
      CO=0.5*TDEL/SQEP
      ANUM=RP*(1.0&T**2)-T
      VRAT=CO*ANUM/DEN
      GO TO 3
    4 VRAT=0.5*TDEL*SQEP*RP
    3 ALVR=ALOG10(VRAT)
      IF(ALVR) 5,6,6
    5 BLVR=ALVR&10.0
      IF(BLVR) 7,8,8
    7 WRITE(6,14) R,VRAT,BLVR
   14 FORMAT (6X,E11.4,4X,E12.5,4X,F8.5,5H - 10,2X,12HV.R. IS LESS,1X,
     C12HTHAN 0.1E-09)
      GO TO 2
    8 WRITE(6,13) R,VRAT,BLVR
   13 FORMAT (6X,E11.4,4X,E12.5,4X,F8.5,5H - 10)
      GO TO 2
    6 WRITE(6,12) R,VRAT,ALVR
   12 FORMAT (6X,E11.4,4X,E12.5,4X,F8.5,7X,19HAPPROXIMATION FAILS)
    2 CONTINUE
    1 CONTINUE
   10 FORMAT (1H1,11HTAN DELTA =,E10.3,3X,9HEPSILON =,E10.3//)
   11 FORMAT(1H ,8X,6HLENGTH,6X,13HVOLTAGE RATIO,6X,8HLOG V.R.//)
      WRITE(6,15)
   15 FORMAT (1H0,14HEND OF PROGRAM)
      STOP
```

Figure 1. Block Diagram of the Circuit

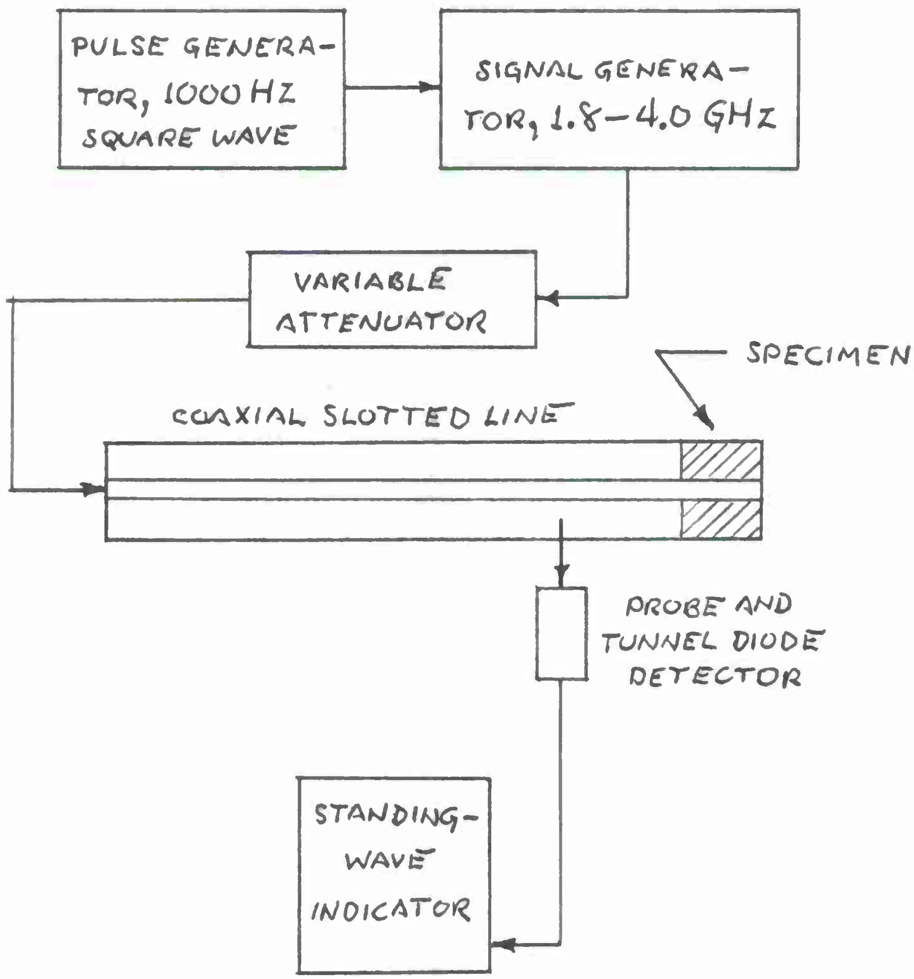


Figure 2. Slotted Line -- Outer Conductor

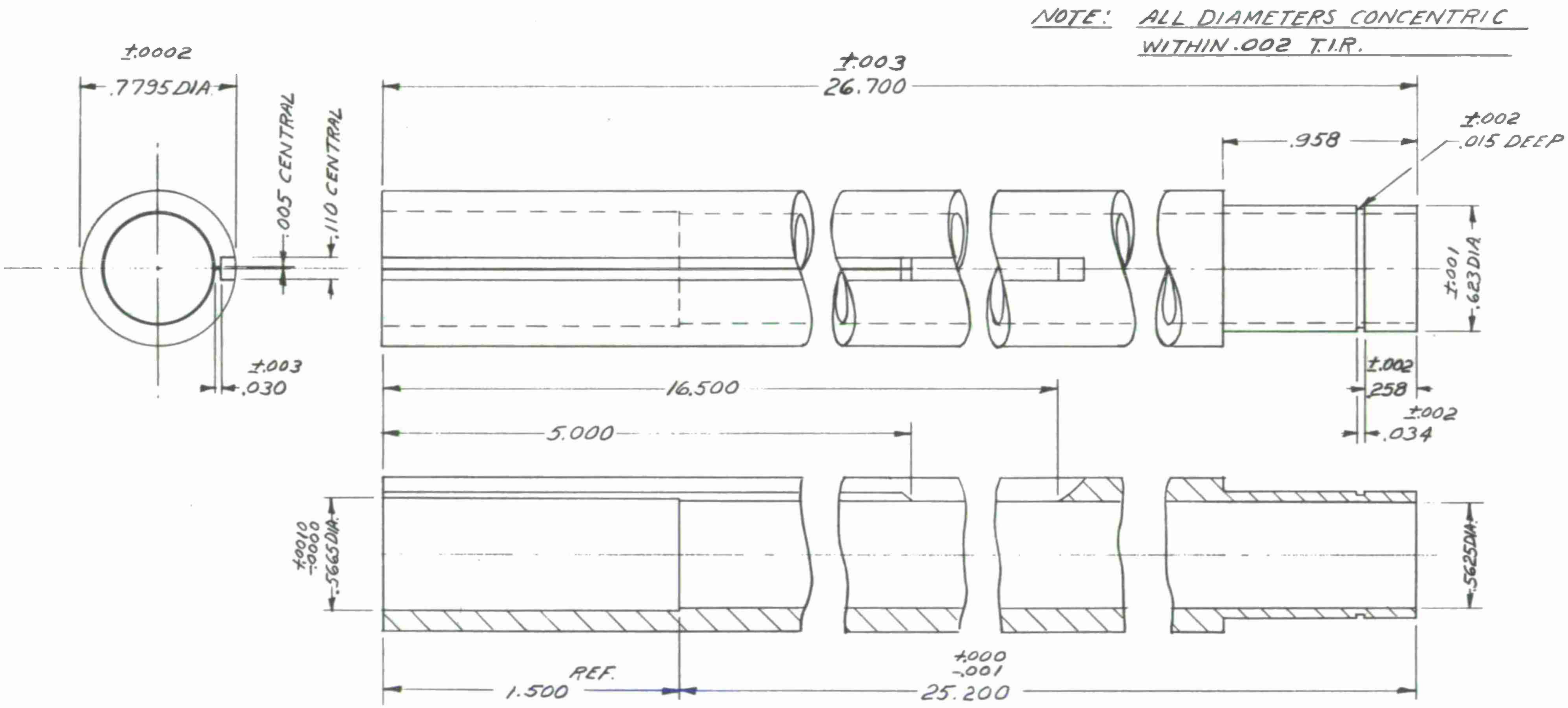


Figure 3. Slotted Line -- Center Conductor

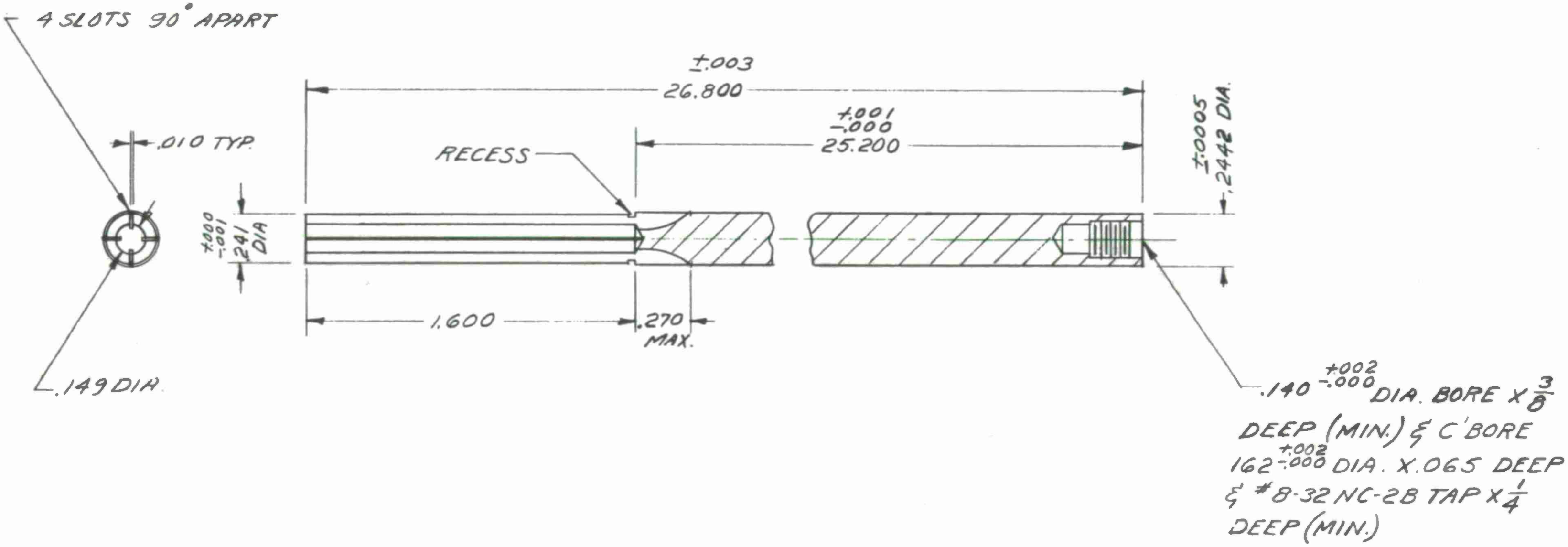


Figure 4. Λ versus $\beta_2 d$ for TT-G-1005 (observed)

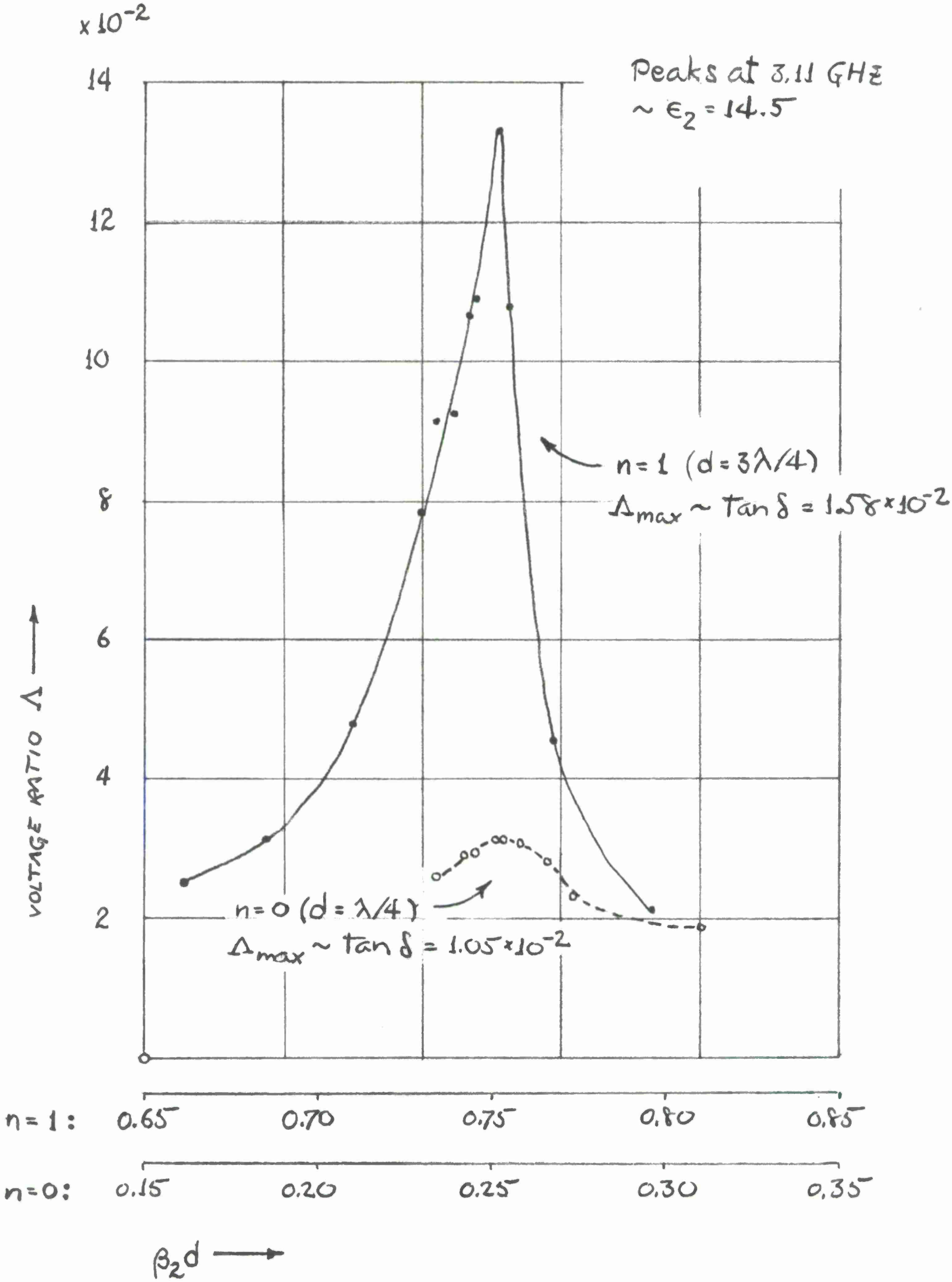
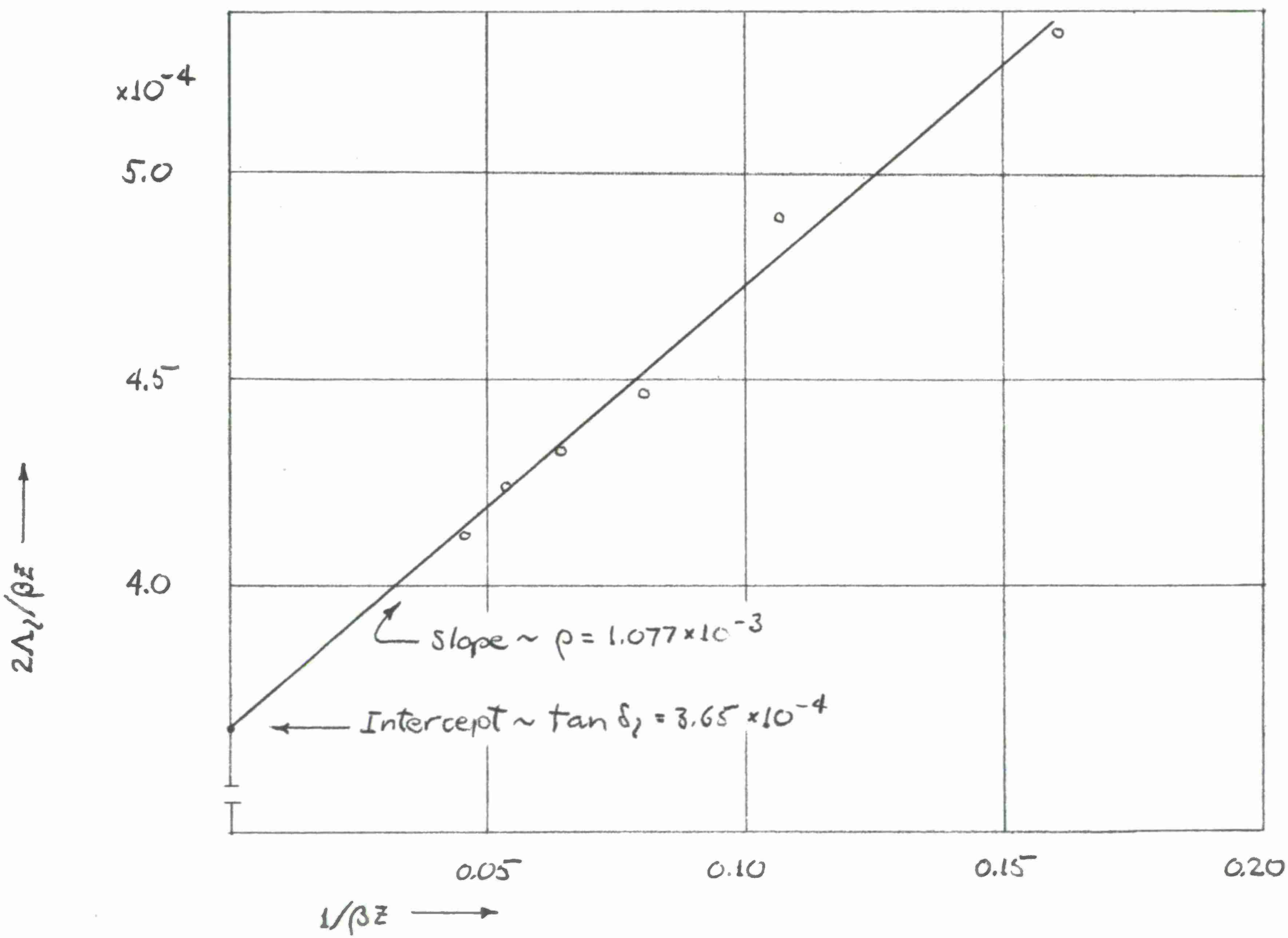
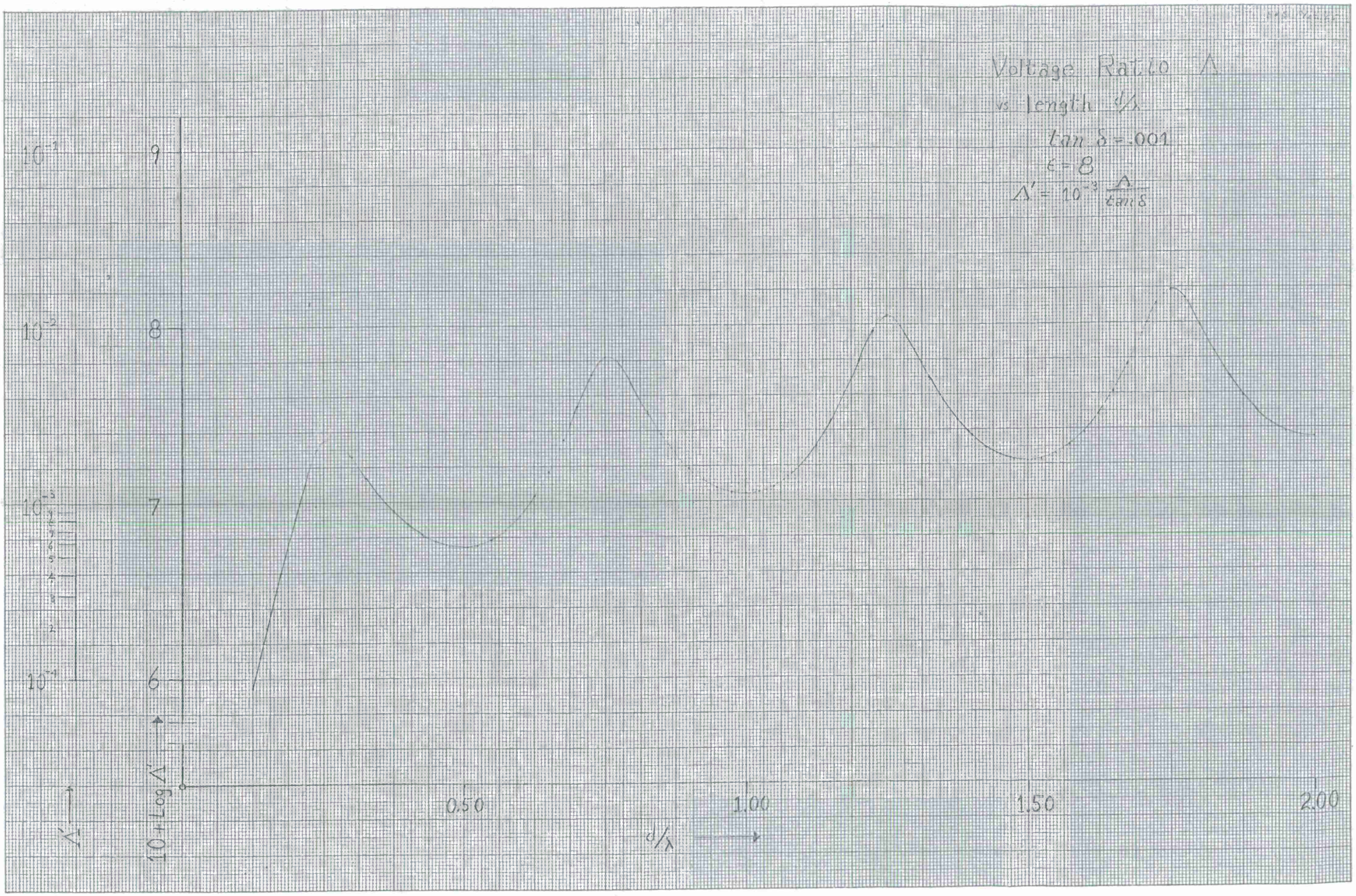
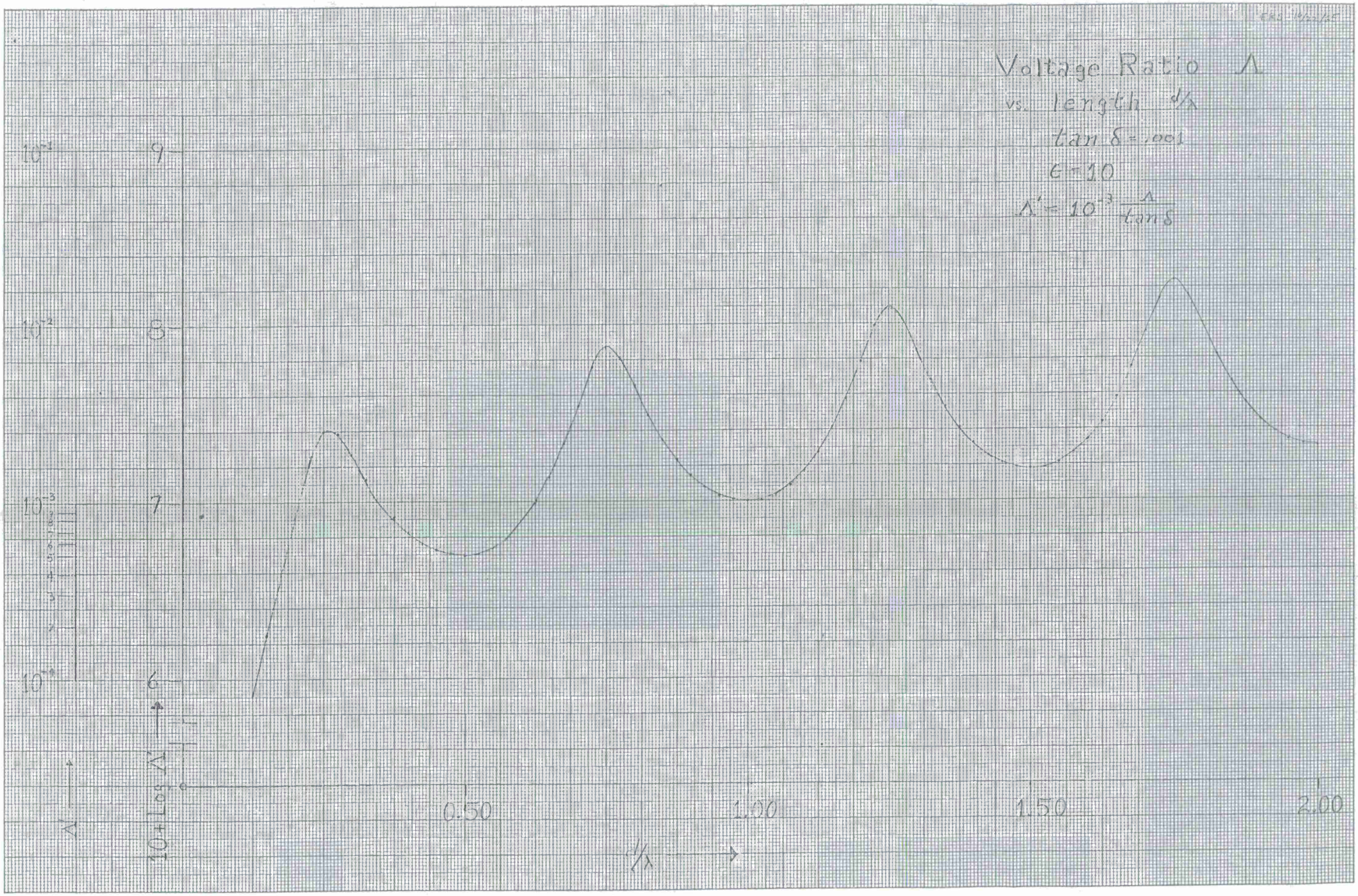


Figure 5. Graph for Determination of Line Loss

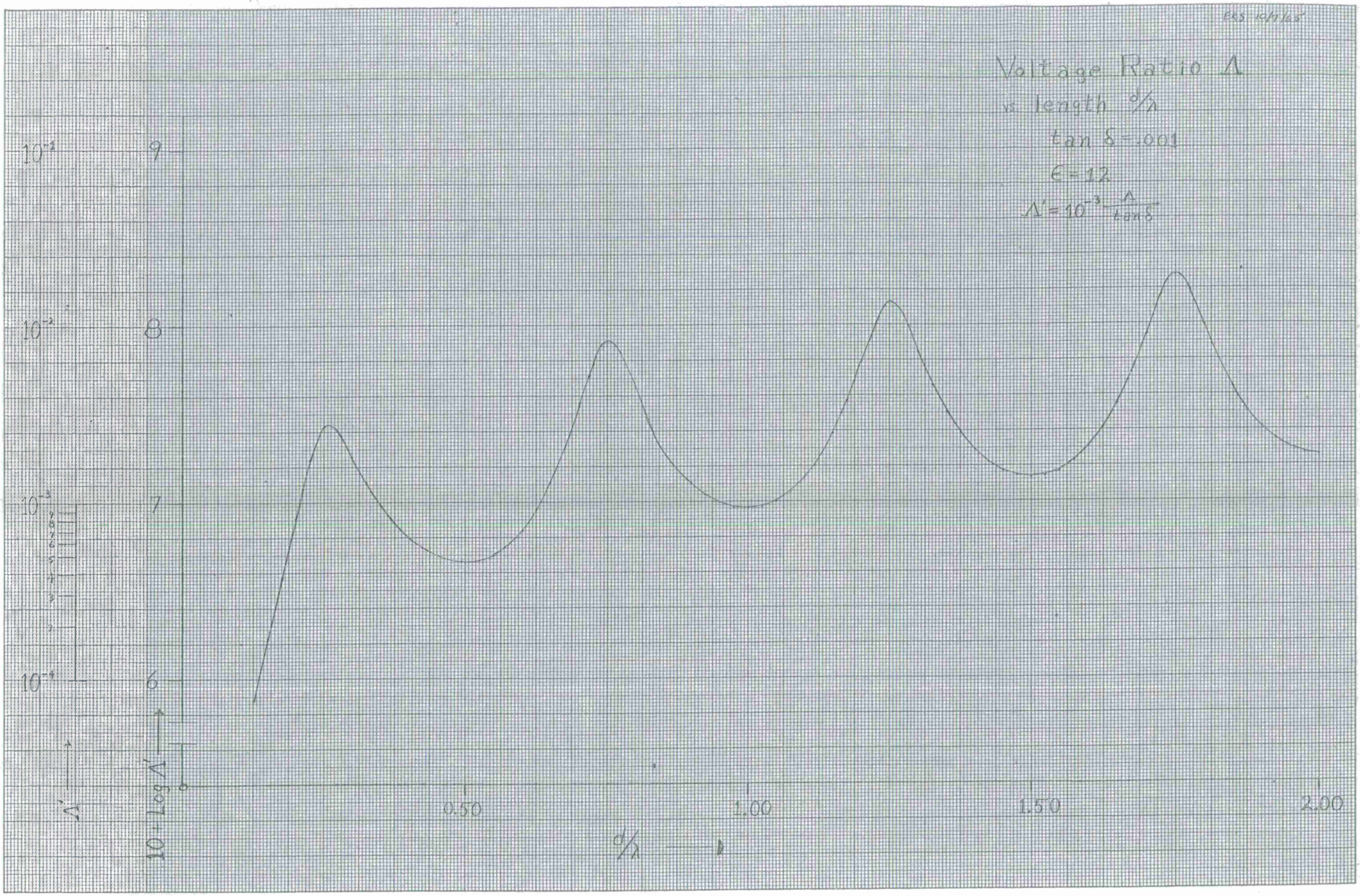




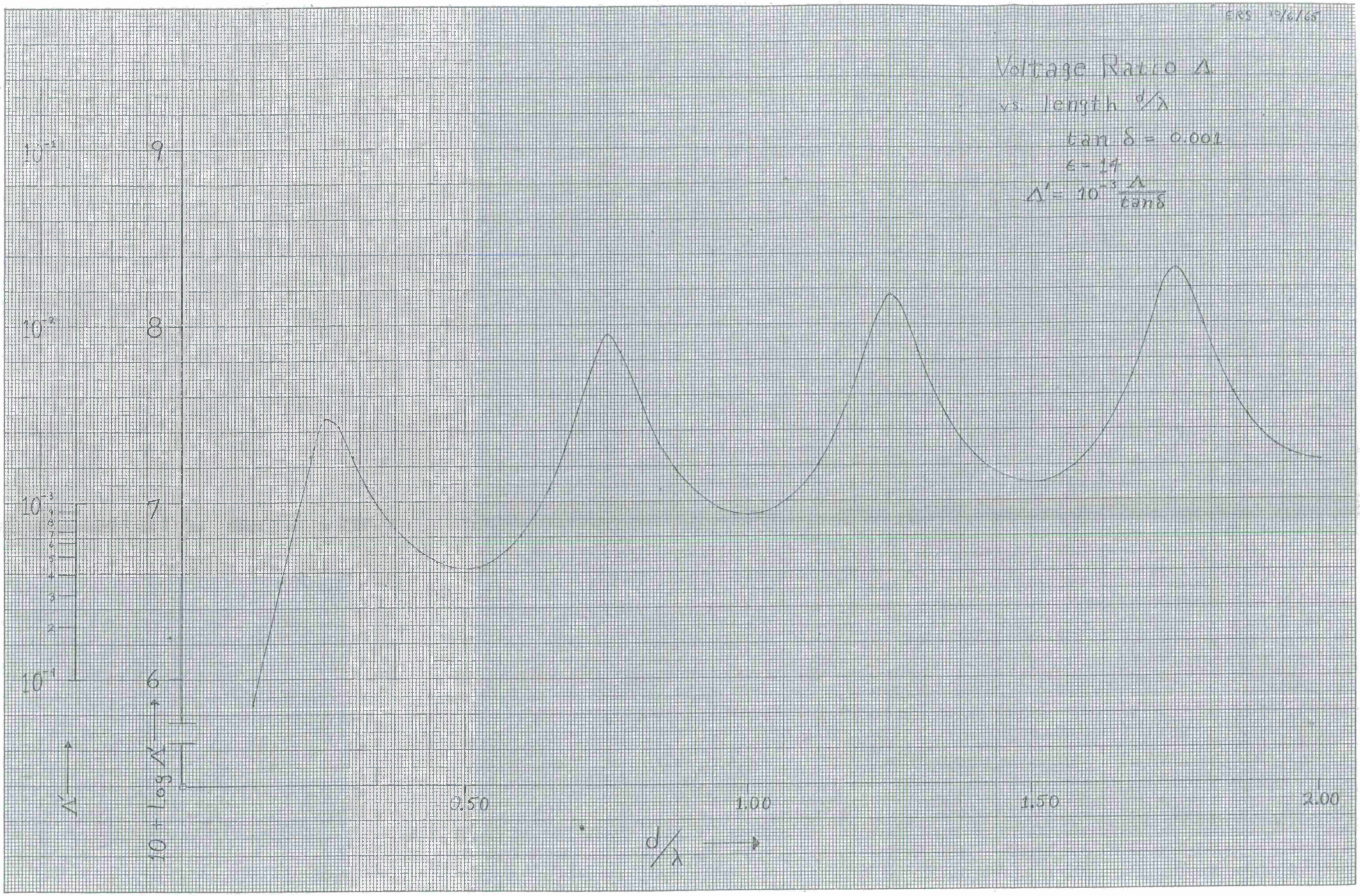
Voltage Ratio Δ
vs Length d/λ
tan δ = .001
ε = 8
Λ' = 10⁻³ Δ/tan δ
9
8
7
6
10 + Log Λ'
Λ'
0.50
1.00
1.50
2.00
d/λ

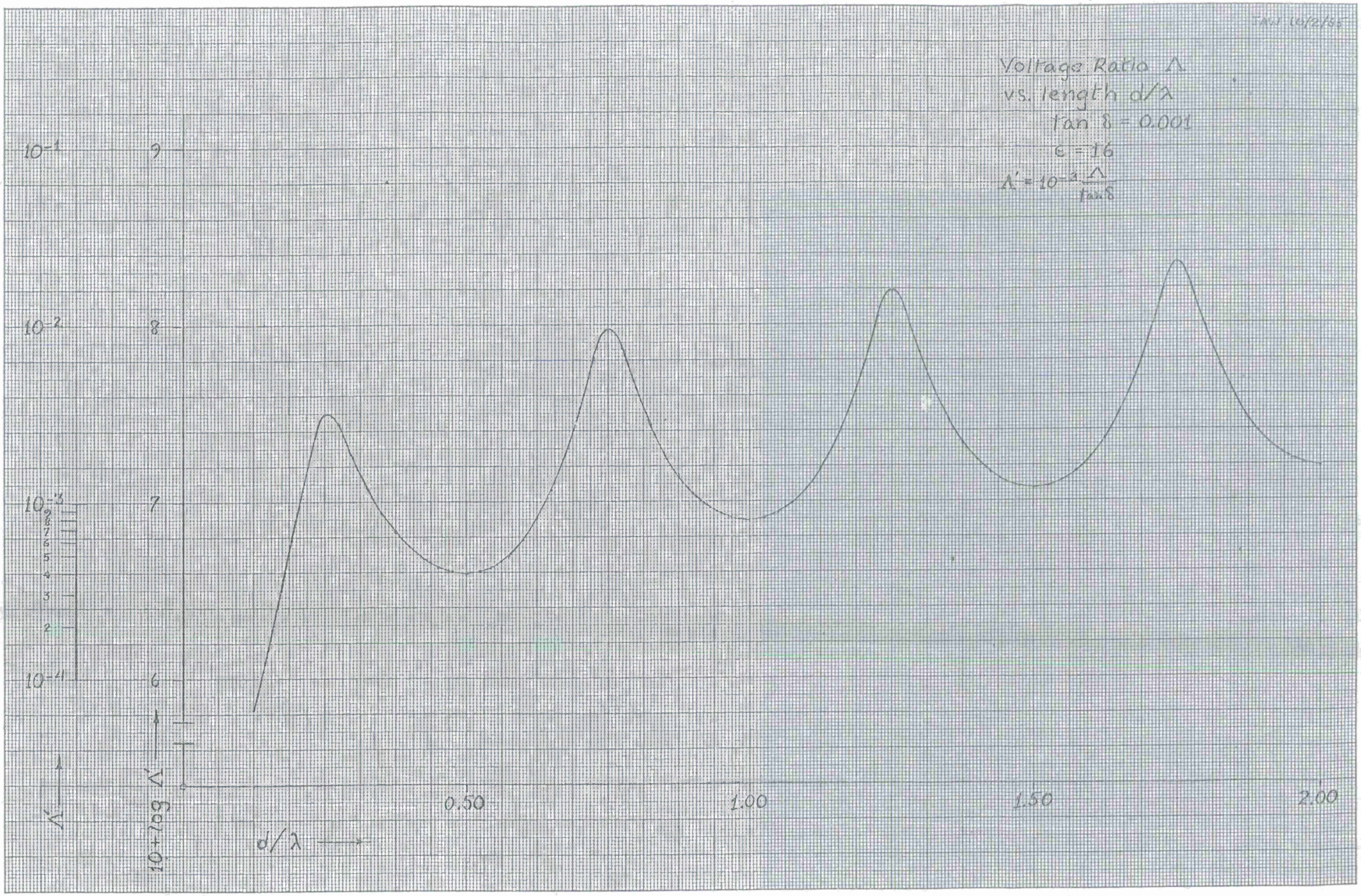


Voltage Ratio Λ
vs. length d/λ
$\tan\delta = .001$
$\epsilon = 10$
$\Lambda' = 10^{-3}\frac{\Lambda}{\tan\delta}$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
9
8
7
6
Λ'
$10 + \log\Lambda'$
0.50
1.00
1.50
2.00
d/λ



EKS 10/11/65
Voltage Ratio Λ
vs length d/λ
tan δ = .001
ε = 12
Λ' = 10^-3 Λ/tan δ
10^-1
10^-2
10^-3
10^-4
9
8
7
6
Λ'
10 + Log Λ'
0.50
1.00
1.50
2.00
d/λ


ERS 10/6/65
Voltage Ratio Δ
vs. length d/λ
tan δ = 0.001
ε = 14
Δ' = 10⁻³ Δ/tan δ
9
8
7
6
10 + Log Δ'
10⁻¹
10⁻²
10⁻³
10⁻⁴
Δ'
0.50
1.00
1.50
2.00
d/λ


TAN 10/2/55
Voltage Ratio Λ
vs. length d/λ
tan δ = 0.001
ε = 16
Λ' = 10^-3 Λ/tan δ
10^-1
10^-2
10^-3
10^-4
9
8
7
6
Λ'
10 + log Λ'
0.50
1.00
1.50
2.00
d/λ

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13. ABSTRACT

This report presents results of an investigation into the standing-wave method for evaluation of microwave loss and effective dielectric constant of low-loss ceramic materials. The objective of the study was primarily to devise a sensitive method for determination of the dependence of loss on the magnetic state of ferrites and ferrimagnetic garnets in various conditions of remanence. Design of a special coaxial slotted line and specimen holder is described. Preparation of specimens, including metallization of surfaces, is discussed. Data taken at S-band ($\sim$ 3 GHz) on a dielectric and garnet material are presented. They show that the sensitivity of the method in its present form is marginal for the purpose, although within an order of magnitude of that of conventional resonant-cavity methods. A means for accurately determining a correction for distributed loss in the slotted line is presented. The report includes graphs of the theoretical voltage ratio (1/VSWR) versus electrical length of the specimen, for low-loss material having dielectric constants in the range 8 -- 16, together with the computer program used to calculate these graphs.

14. KEY WORDS

microwave dielectrics
microwave ferrites
dielectric-magnetic loss

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