THE MAGNETIC FIELD DEPENDENCE OF THE MICROWAVE DIELECTRIC CONSTANT OF A LIQUID CRYSTAL AT 3 KMC.

Thesis for the Degree of M. S.

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Robert W. Lee

1954

This is to certify that the

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Robert W. Lee

has been accepted towards fulfillment of the requirements for

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R. D. Spence
Major professor

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by

Robert W. Lee

A THESIS

Submitted to the School of Graduate Studies of Michigan
State College of Agriculture and Applied Science
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Physics

1954

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Robt. W. Lee

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AN ABSTRACT

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This work discusses the determination of the real and imaginary parts of the microwave dielectric constant of the liquid crystal, para-azoxyanisole, by transmission methods. A ten-centimeter wave guide apparatus was employed to yield results at a frequency of three kilo-megacycles.

The magnetic field dependence of the dielectric constant is discussed, supplemented by a graph indicating the order of variation in power absorption with and without an externally applied magnetic field.

Experimentally, transmitted power was plotted against sample column height with and without an applied magnetic field. Theoretical curves were then fitted to the experimental curves thus yielding values of the propagation constant of which the dielectric constant is a function.

A derivation of the theoretical curves is made as is a comparison between the dielectric constant values thus found and values obtained from various other experiments at higher and lower frequencies.

Photographs and schematic drawings of the wave guide apparatus are included along with a detailed discussion of procedures used.

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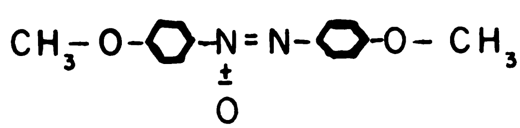
INTRODUCTION

Liquid crystals, as first observed by F. Reinitzer in 1888, are substances that act much like liquids but exhibit properties generally associated with anisotropic crystals.[1] These liquid crystals have no crystalline lattice as we ordinarily think of associated with crystals. They do, however, give interference patterns in polarized light, and often exhibit mobile thread-like structures when observed between Nicol prisms.

Para-azoxyanisole is one compound exhibiting these characteristics and falls in the nematic class of liquid crystals. This class is one of the three; smectic, nematic, and cholesteric, and is characterized by long, thin organic molecules. The smectic phase is characterized by a soap-like layer which does not flow like a liquid but "glides". The nematic phase, however, does flow like a true liquid with the exception that it exhibits more than one viscosity when under the influence of a magnetic field. That is, the viscosity when observed upon a plate which has been dipped into a nematic liquid crystal perpendicular to the magnetic field is different from that observed when the plate is dipped parallel. The cholesteric phase is less clear cut, having characteristics of both of the former classes.

The swarm theory suggests these long, nematic molecules are arranged in parallel bundles called "swarms". The swarms themselves, however, have no order. It is thought also that the application of an external magnetic field will align the swarms such that each swarm lies with its molecules parallel not only to each other but to the lines of force of the applied field. Furthermore, there is associated with this class of liquid crystals not only an induced electric moment parallel to each molecule but a separate electric moment either perpendicular or parallel to the molecule. In para-azoxyanisole this electric moment is perpendicular due to the ionic bond between the central nitrogen and oxygen atoms as shown in the molecular formula below. Thus, the aligning of the molecules as brought about by the application of a magnetic field causes the addition of these electric moments. The above phenomena supports the difference in the dielectric constant of the liquid crystal as measured in and out of magnetic fields.[2]

The compound used in this experiment was para-azoxyanisole whose molecular formula is:



and whose liquid crystal range is (118°C.-135.8°C.).

PROCEDURE

It is the purpose of this experiment to investigate the temperature and magnetic field dependence of the dielectric constant of para-azoxyanisole by microwave transmission methods at a frequency of 3 Kmc. This particular frequency was chosen to bridge the gap between dielectric constant measurements that have been made at higher and lower frequencies.

Low frequency, long wave length (of the order of meters) determinations of the real part of the dielectric constant (ϵ') for para-azoxyanisole were made by Abegg and Seitz[3] in 1894, yielding (4.0-4.3 c.g.s.). In further low frequency work by Eichwald in 1904[4] an ϵ' of approximately

6 was found. Buhmer[5] repeated Eichwald's experiment and found an value of 4.9. In 1924 Jezewski[6] made dielectric constant measurements at 0.42 Mc (λ = 720 meters) and found a value of 6.9 for ϵ' . In the same year Kast[7] independently made measurements at a wave length of 200 meters and found a comparable ϵ' value. Further support was given to Kast's work by Ornstein[8] when the latter developed his crystal aggregation theory of liquid crystals. His theoretical results compared favorably to Kast.

At the other end of the frequency scale, E. F. Carr[9] in 1954 determined both the real and imaginary parts of the dielectric constant of para-azoxyanisole at frequencies of the order of 15 Kmc. He used both reflection and transmission techniques with a 2 centimeter wave guide apparatus and found values of approximately 3.8 and 0.45 for the real and imaginary parts respectively.

Carr's method requires a column height of sample several wave lengths long and an electromagnet of sufficient size to maintain the entire sample in a magnetic field. This enabled him to experimentally determine the wave length in the sample, and, subsequently, the variables of which the dielectric constant is a function. However, with a 10 centimeter wave guide apparatus as used in this experiment, the Carr technique is impractical due to the comparatively long wave length (λ_g = 14.56 centimeters). The wave length in the dielectric is of the order of one-half the guide wave length, λ_g ; hence, several wave lengths would require a approximately 20 centimeter column height of sample. And since the wave guide cross-sectional dimensions are 7.2 X 3.4 centimeters, this would require approximately 2000 grams of para-azoxyanisole. Also since a magnetic-field dependence of dielectric constant is one objective of this study, the pole faces of the electromagnet must have the dimensions: 7.2 centimeters X the maximum column height. Furthermore, since the magnet must be immersed in an oil bath, its size must be kept to a minimum to keep the oil tank size reasonable. These two factors, the limited supply of sample and the magnet size, forced the use of methods other than those employed by Carr.

The method selected consisted of measuring the power transmitted through the sample as a function of column height. The real and imaginary parts of the dielectric constant were then obtained by fitting the experimental curve with the theoretical curve for this quantity.

THEORETICAL CURVE

The real and imaginary parts of the microwave dielectric constant of para-azoxyanisole are ϵ' and ϵ'' respectively and are written:

$$\epsilon = \epsilon' - i\epsilon'' \tag{1}$$

where ϵ' is represented by the ratio:

$$\epsilon' = \frac{c^2}{\upsilon^2} \tag{2}$$

$\underline{c}$ being the velocity of light and $\underline{\upsilon}$ the velocity of the electromagnetic wave in the sample. The imaginary part ϵ'' is a measure of the power absorption.

Carr's method[9] uses the relationships:

$$\epsilon'' = \frac{\lambda^2}{\pi \lambda_d} \beta'' \tag{3}$$

$$\epsilon' = \left(\frac{\lambda}{\lambda_d}\right)^2 + \left(\frac{\lambda}{2a}\right)^2 \tag{4}$$

where λ is the wave length in free space which is related to the measurable wave length in the wave guide, λ_g (done by measuring the distance along the guide between successive maxima as indicated on the tuned amplifier with infinite standing wave ratio) by the expression:

$$\frac{1}{\lambda^2} = \frac{1}{\lambda_g^2} + \frac{1}{(2a)^2} \tag{5}$$

$\underline{a}$ is the larger cross-sectional dimension of the rectangular guide and λ_d is the wave length in the sample dielectric. β'' is the imaginary part of the propagation constant:

$$\beta = \beta' - i\beta'' \tag{6}$$

which is also expressed as:

$$\beta = \frac{\omega}{v} \tag{7}$$

where $\underline{\omega}$ is the usual angular frequency and $\underline{v}$ is the wave velocity in the sample.

The unknowns of these relationships are not all obtainable from curves with so few maxima and minima as those obtained from this experiment; hence, the necessity of determining a theoretical curve. This curve must be a function of variables from which the dielectric constant can be derived. As shown by equations (3) and (4) along with the relationship,

$$\beta' = \frac{2\pi}{\lambda_d} \qquad (8)$$

the β' and β'' are these variables. The derivation of the theoretical expression for power as a function of sample column height and of the propagation constant β is as follows:

Consider a sample column height X and an incident wave of unit magnitude. This we can do since we are dealing with relative power. Fig. 1 shows the transmitted and reflected waves.

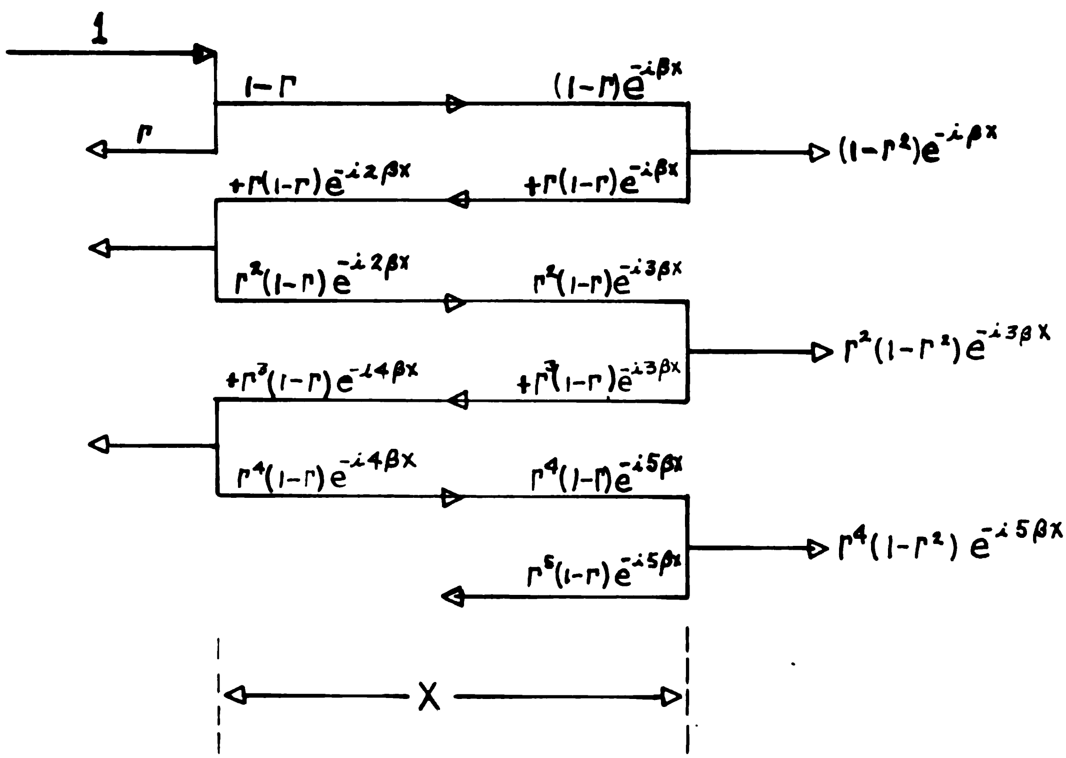


FIG. 1: Relative Power Transmitted Through Sample Column Height X.
Key: Γ = reflection coefficient
β = propagation constant

The reflection portion is of no interest, since it was matched out as explained earlier. The transmitted waves, on the other hand, are what we want so we add the successive terms to yield T, the total transmitted energy. This sum yields:

$$T = (1-r^2)\, e^{-i\beta x} \sum_{n=0}^{\infty} [(r e^{-i\beta x})^2]^n \tag{9}$$

To simplify this expression let $(r e^{-i\beta x})^2 = a$. Then $\sum_{n=0}^{N} [(r e^{-i\beta x})^2]^n$ becomes:

$$\sum_{n=0}^{N} a^n = 1 + a + a^2 + \cdots\cdots + a^N \tag{10}$$

Now, if $a \sum_{n=0}^{N} a^n$ is subtracted from (10) the following results:

$$\sum_{n=0}^{N} a^n - a \sum_{n=0}^{N} a^n = 1 - a^{N+1} \tag{11}$$

Or,

$$\left[\sum_{n=0}^{N} a^n\right](1-a) = 1 - a^{N+1} \tag{12}$$

And, since $a < 1$, it follows that in the limit as N approaches infinity:

$$\left[\sum_{n=0}^{\infty} a^n\right](1-a) = 1 \tag{13}$$

Or,

$$\sum_{n=0}^{\infty} a^n = \frac{1}{1-a} \tag{14}$$

Now substitution for a yields:

$$\sum_{n=0}^{\infty}[(\Gamma e^{-i\beta x})^2]^n = \frac{1}{1-(\Gamma e^{-i\beta x})^2} \tag{15}$$

Substitution of this expression into equation (9) gives:

$$T = (1-\Gamma^2)\, e^{-i\beta x} \frac{1}{1-\Gamma^2 e^{-i2\beta x}} \tag{16}$$

Furthermore, since power is proportional to $|T|^2$

$$p = |T|^2 = TT^* = \frac{|1-\Gamma^2|^2\, e^{-2\beta'' x}}{|1-\Gamma^2 e^{-i2\beta x}|^2} \tag{17}$$

And since $|1-\Gamma^2|^2$ is a constant, i.e., it merely causes a shift up or down of the p values, we can divide it out. Therefore, if we call P relative power, we can write:

$$P = \frac{e^{-2\beta'' x}}{|1-\Gamma^2 e^{-i2\beta x}|^2} \tag{18}$$

Now to determine the reflection coefficient squared, use the following expression:

$$\Gamma = \frac{Z_d - Z_o}{Z_d + Z_o} \tag{19}$$

where Z_d and Z_o are the dielectric impedance and air impedance respectively given by:

$$Z_d = \frac{\omega\mu}{\beta} = \frac{\omega\mu}{\beta' - i\beta''} \tag{20}$$

$$Z_o = \frac{\omega\mu}{\beta_o} \tag{21}$$

Here ω and μ are the angular frequency and magnetic permeability respectively, but they cancel and therefore are of no interest. However, β_o does not cancel but is a constant:

$$\beta_o = \frac{2\pi}{\lambda_g} = \frac{2\pi}{14.56} = 0.432 \ 1/cm. \tag{22}$$

Substitution of expressions (20) and (21) into (19) gives:

$$\Gamma = \frac{\frac{1}{\beta' - i\beta''} - \frac{1}{\beta_o}}{\frac{1}{\beta' - i\beta''} + \frac{1}{\beta_o}} = \frac{\beta_o - \beta' + i\beta''}{\beta_o + \beta' - i\beta''} \tag{23}$$

Hence,

$$\Gamma = \frac{\sqrt{(\beta_o - \beta')^2 + (\beta'')^2}}{\sqrt{(\beta_o + \beta')^2 + (\beta'')^2}} \cdot \frac{e^{i\theta}}{e^{i\phi}} \tag{24}$$

Or,

$$\Gamma^2 = \frac{(\beta_o - \beta')^2 + (\beta'')^2}{(\beta_o + \beta')^2 + (\beta'')^2} \cdot e^{i2(\theta - \phi)}$$

$$= |\Gamma|^2 e^{i2(\theta - \phi)} \tag{25}$$

The angles θ and ϕ are given by: (from 23)

$$\theta = \tan^{-1}\left(\frac{+\beta''}{\beta_o - \beta'}\right) \tag{26}$$

$$\phi = \tan^{-1}\left(\frac{-\beta''}{\beta_o + \beta'}\right) \tag{27}$$

Let $\alpha = (\theta - \phi)$. Then the expression for power becomes:

$$P = \frac{e^{-2\beta''x}}{|1 - |\Gamma|^2 e^{i2\alpha} \cdot e^{-i2\beta x}|^2} = \frac{e^{-2\beta''x}}{R} \tag{28}$$

Rewrite R:

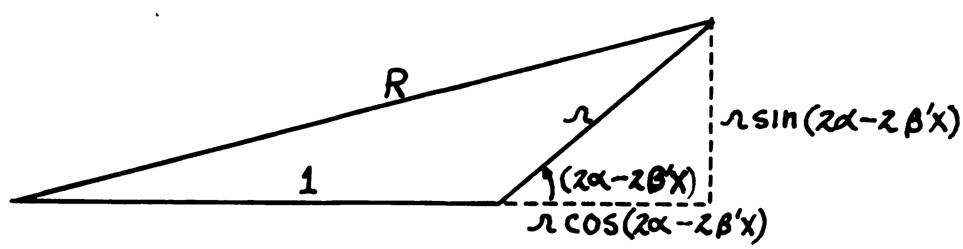
$$R^2 = |1 - |\Gamma|^2 e^{i2\alpha} \cdot e^{-i2x(\beta' - i\beta'')}|^2$$

$$= |1 - |\Gamma|^2 e^{-2\beta''x} \cdot e^{i2(\alpha - \beta'x)}|^2 \tag{29}$$

Let $(-|\Gamma|^2 e^{-2\beta''x}) = \rho$. Then $\underline{R}^2$ becomes:

$$R^2 = |1 + \rho e^{i2(\alpha - \beta'x)}|^2 \tag{30}$$

The graphical representation of this is as follows:



From the above picture we see that

$$R^2 = [1 + \rho \cos(2\alpha - 2\beta' X)]^2 + [\rho \sin(2\alpha - 2\beta' X)]^2 \qquad (31)$$

Squaring and expanding this expression yields:

$$R^2 = 1 + 2\rho \cos(2\alpha - 2\beta' X) + \rho^2 \qquad (32)$$

Substitution of $\underline{r}$ into (32) and (32) into (28) gives:

$$P = \frac{e^{-2\beta'' X}}{1 - 2|r|^2 e^{-2\beta'' X} \cos(2\alpha - 2\beta' X) + |r|^4 e^{-4\beta'' X}} \qquad (33)$$

Divide numerator and denominator by $e^{-2\beta'' X}$ to obtain the final expression for power:

$$P = \frac{1}{e^{2\beta'' X} - 2|r|^2 \cos(2\alpha - 2\beta' X) + \frac{|r|^4}{e^{2\beta'' X}}} \qquad (34)$$

In this expression given a β' and β'' all quantities are known except $\underline{X}$. Therefore $\underline{P}$, relative power, is given as a function of $\underline{X}$ after assuming β' and β'' .

This is precisely what was done. Various combinations of β' and β'' were chosen and some twenty-three curves were drawn until the best possible fit between the curves thus calculated and the experimental curves was obtained. These curves and the associated $\beta'_{\perp}$ and $\beta''_{\perp}$ are shown in dotted lines in Fig. 2.

The real and imaginary parts of the dielectric constant are derived from these $\beta_{\perp}$ by equations (3) and (4) respectively.

EXPERIMENTAL CURVE

The set-up used to determine the experimental curve is shown in Figs. 3 and 4. The sample holder section of the apparatus as shown in Fig. 3 was attached to the bottom plate of the oil tank by a flange in which was sealed a thin sheet of mica. A small hole was drilled into the upper half of this flange to enclose a thermocouple (Fig. 5) so as to bring its tip as close as possible to the sample. This hole was then plugged and sealed as was the entire flange with clear glyptal to prevent oil leakage into the sample.

Another view of this sample holder section with the magnet in operating position is shown in Fig. 6. The magnet produces a maximum field strength of 1300 gauss and has pole faces of dimensions 6.5 x 8 centimeters with a 3.5 centimeter separation.

Peanut oil was found to be satisfactory in maintaining a uniform temperature bath. The oil was kept in circulation by a fin-disk type stirrer whose motor was supported by a corner of the tank. The heating elements used were two independent coils of nichrome wire wrapped between layers of asbestos paper which in turn were wrapped around the oil tank.

In order to make even relative power measurements accurately,

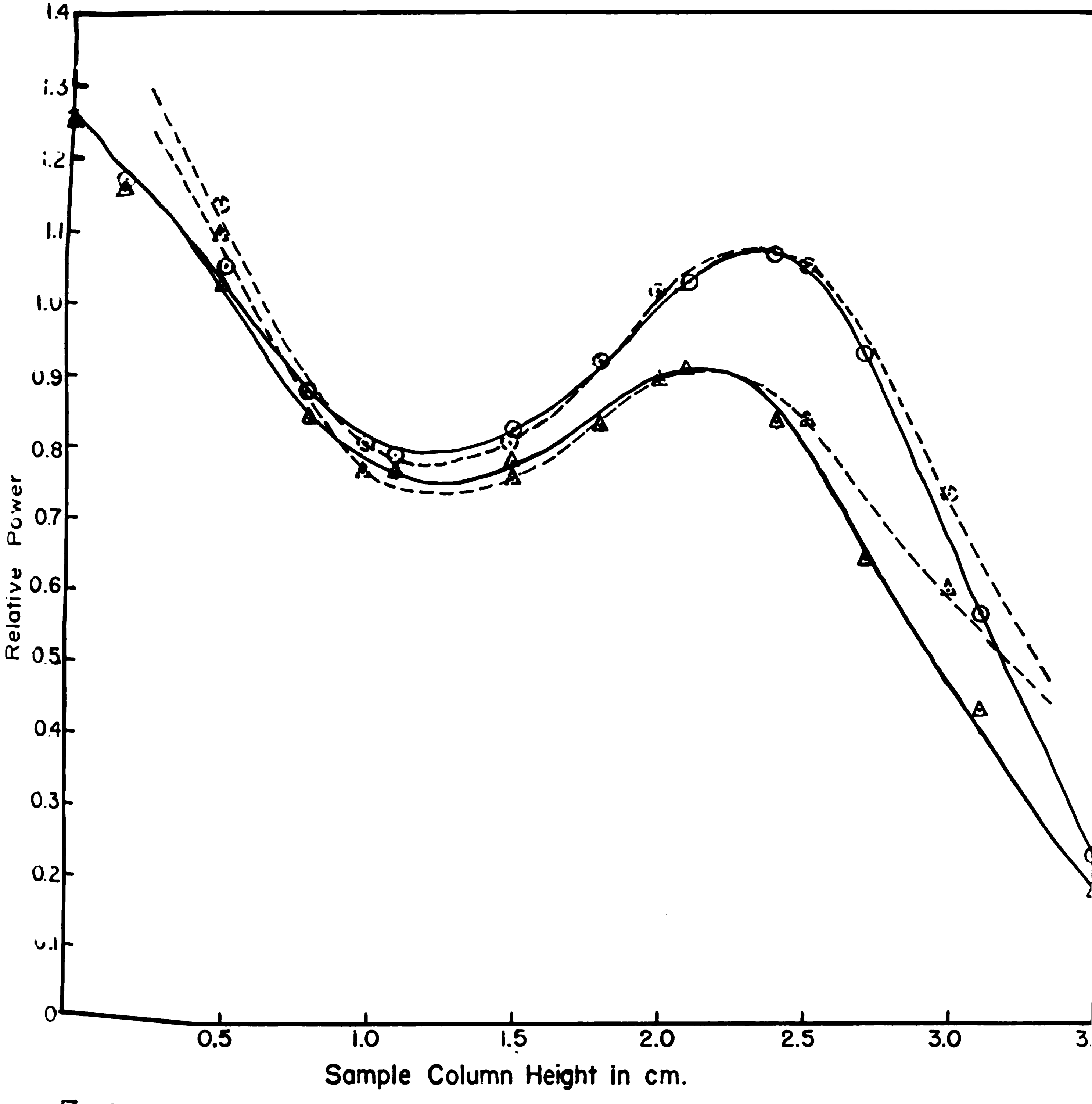


Fig. 2. EXPERIMENTAL and THEORETICAL POWER versus SAMPLE COLUMN HEIGHT

Key: Upper solid curve – Experimental $H \neq 0$

Upper broken curve – Theoretical associated with $\beta' = 1.30$, $\beta'' = 0.10$

Lower solid curve – Experimental $H = 0$

Lower broken curve – Theoretical associated with $\beta' = 1.30$, $\beta'' = 0.14$

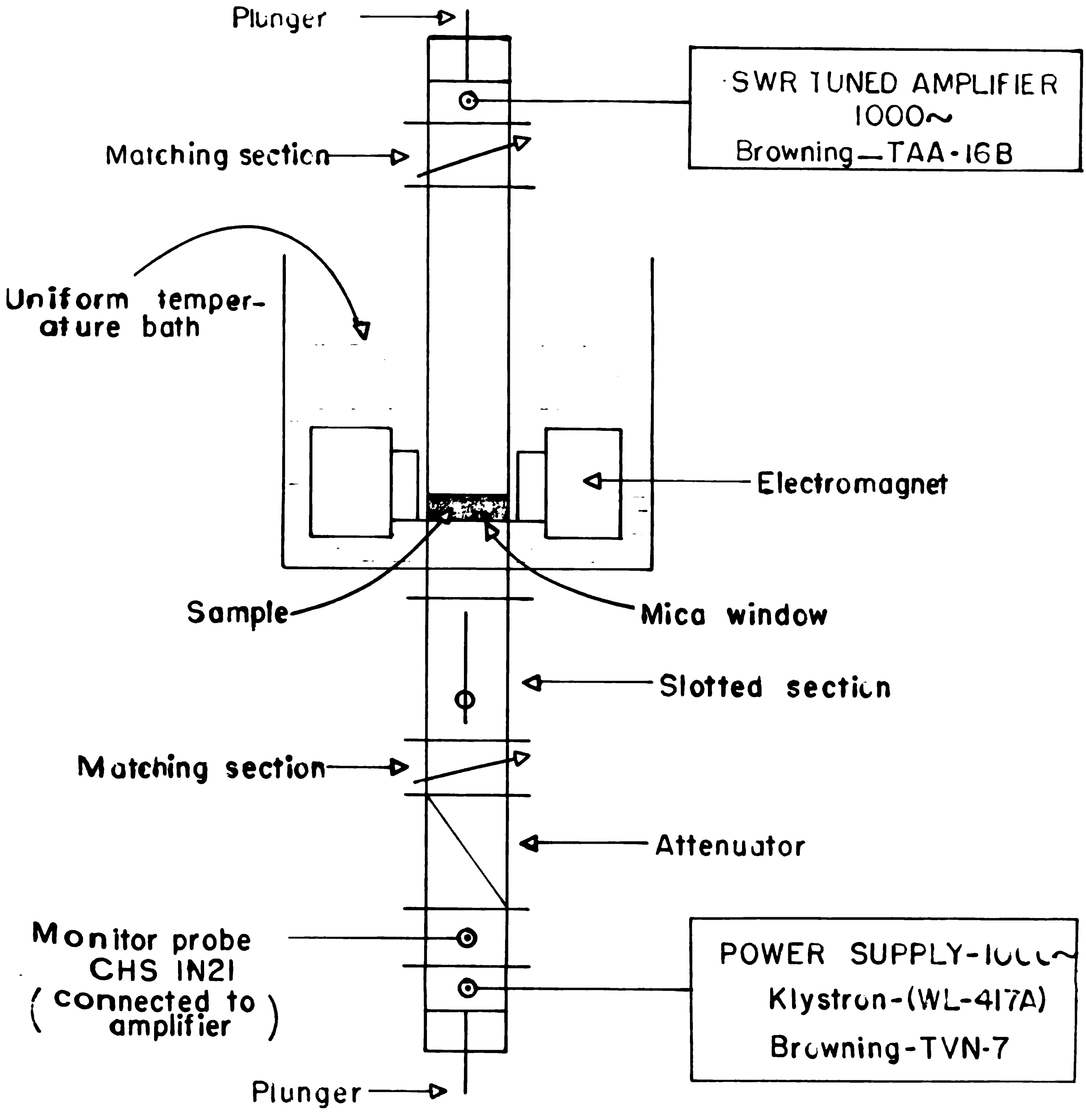


Fig. 3. BLOCK DIAGRAM of EXPERIMENTAL SET-UP

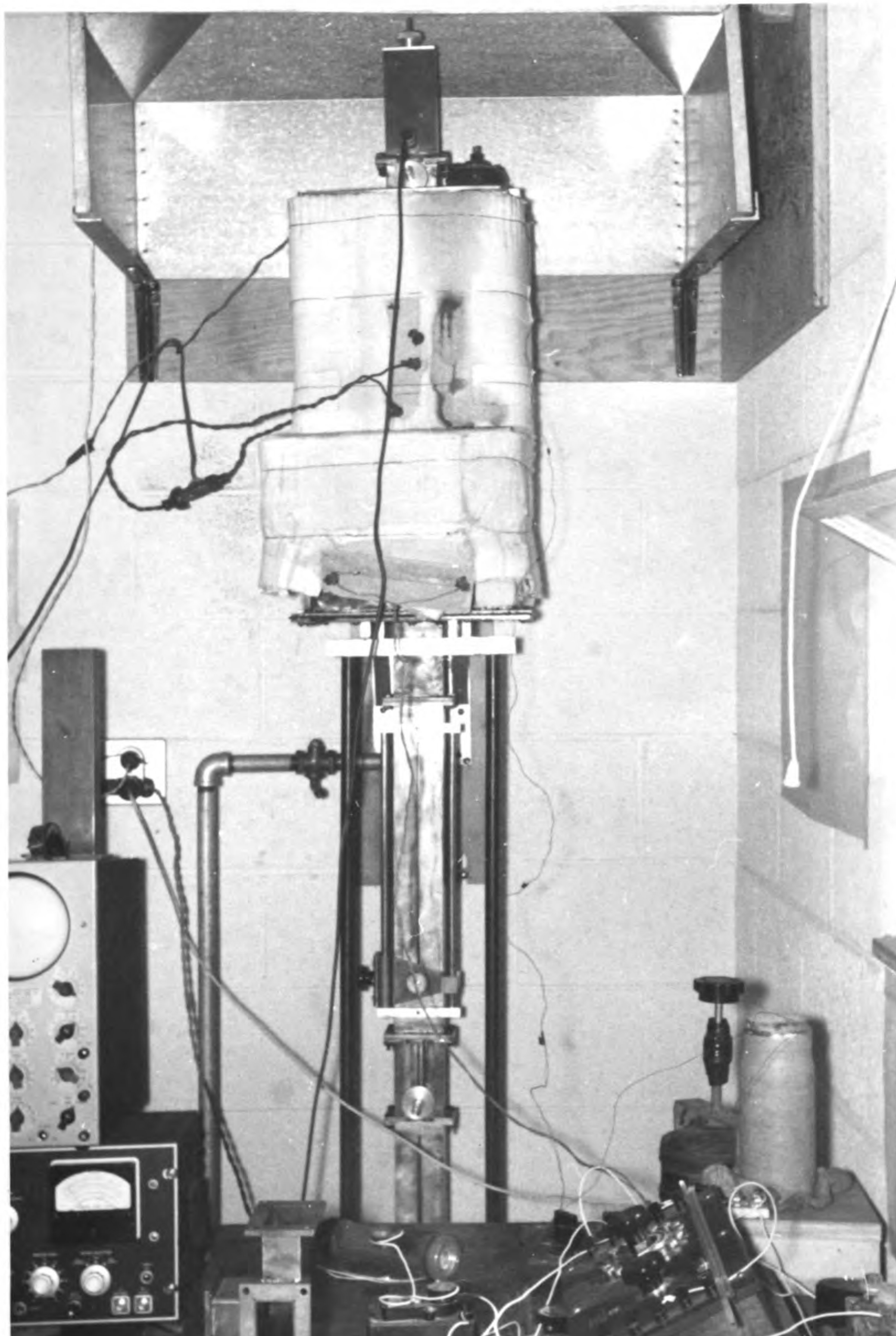


Fig. 4. Experimental Set-up

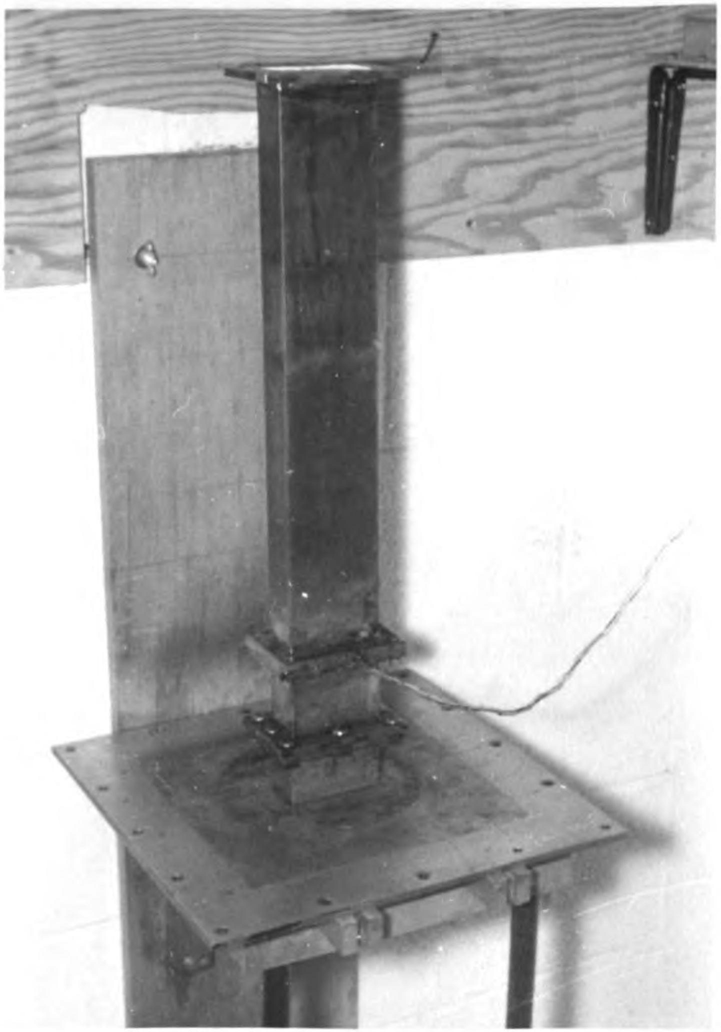


Fig. 5. Sample Holder Section

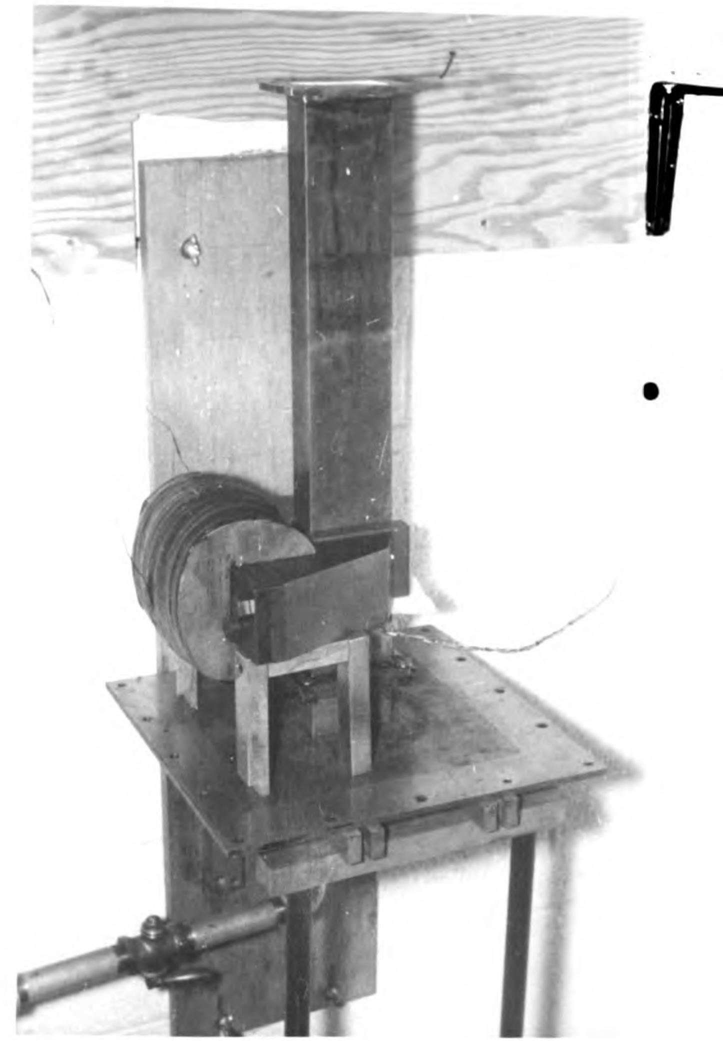


Fig. 6. Sample Holder Section and Magnet

the reflected energy must be matched out. This was done in the following manner. A preliminary adjustment of the reflector and modulation voltages of the power supply and the klystron cavity using the set-up shown in Fig. 7 was made to insure $T.E._{10}$ mode propagation as characterized by the appearance of a square wave on the C.R.O. In this adjustment the amplifier was replaced by the C.R.O., and the plungers at either end of the guide were used to yield a maximum square wave amplitude and thus maximum transmitted power.

Then the upper end (output) of the wave guide was matched using the set-up of Fig. 7 (also shown in block form in Fig. 8a). In this match the tuner was used almost exclusively to obtain a standing wave ratio of 1.08, since even the slightest adjustment of the plungers (the only other tuning mechanisms) diminished the power appreciably. This value of the standing wave ratio is approximate since there was a drift in the readings toward either end of the slotted section due to reflections from the rather blunt ends of the slot. However, the ratio was definitely less than 1.1.

During this matching procedure the sample section including the mica window was not in the system, thus a second matching was required to do away with any reflections arising from the sample section and mica window. This "back" match was accomplished by using the set-up in Fig. 8b. In this case the power supply was connected to the output end of the guide and a cold klystron to the input end. The klystron connection was to insure approximately the same impedance that would be "seen" by the multiple reflections from the mica window and sample. Again the best

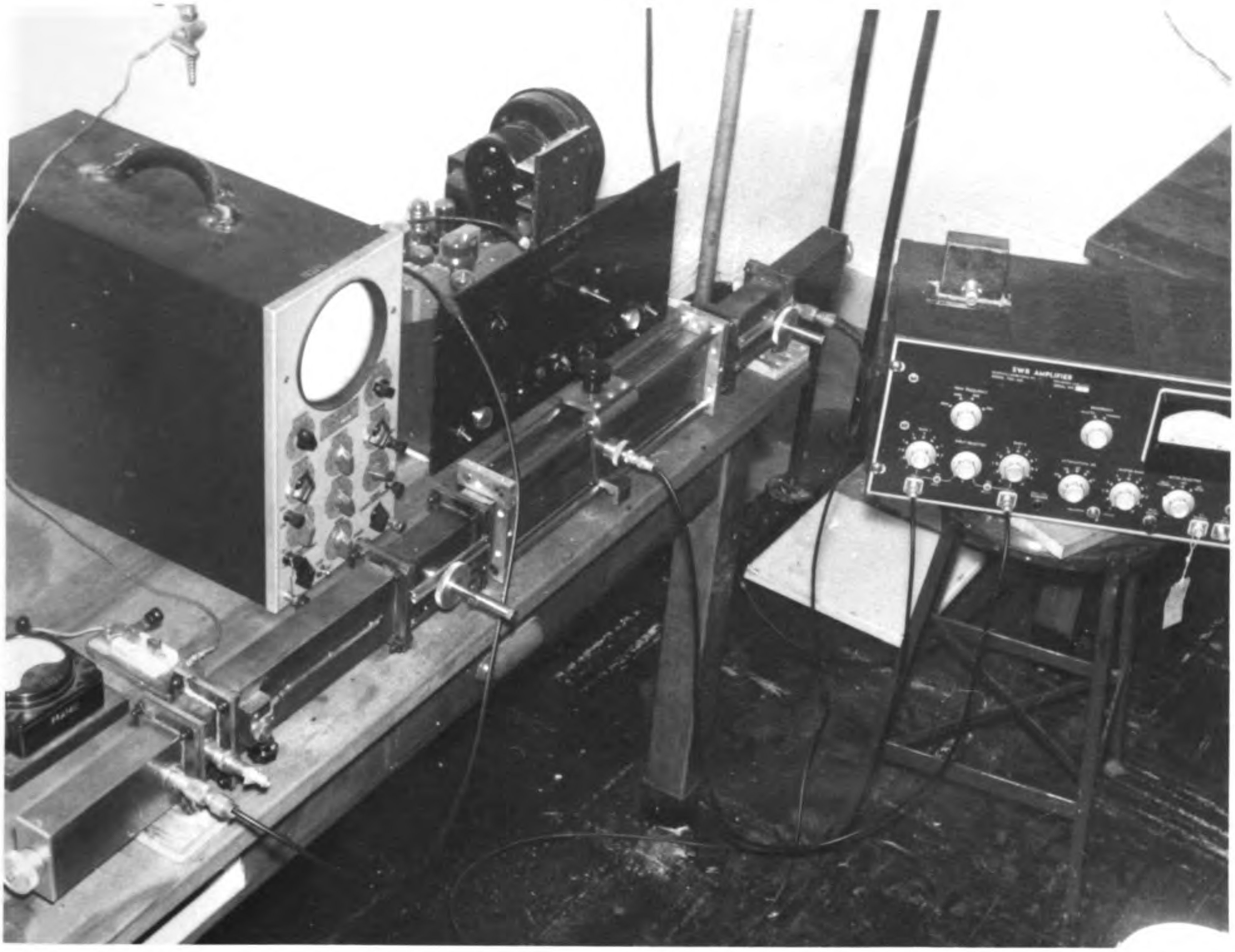
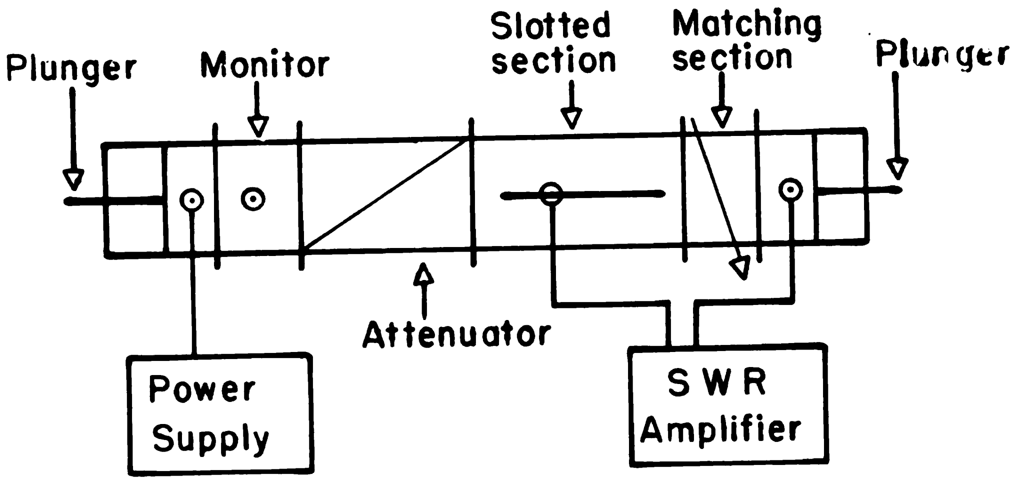


Fig. 7. Matching Set-up

a) Forward match.



b) Back match.

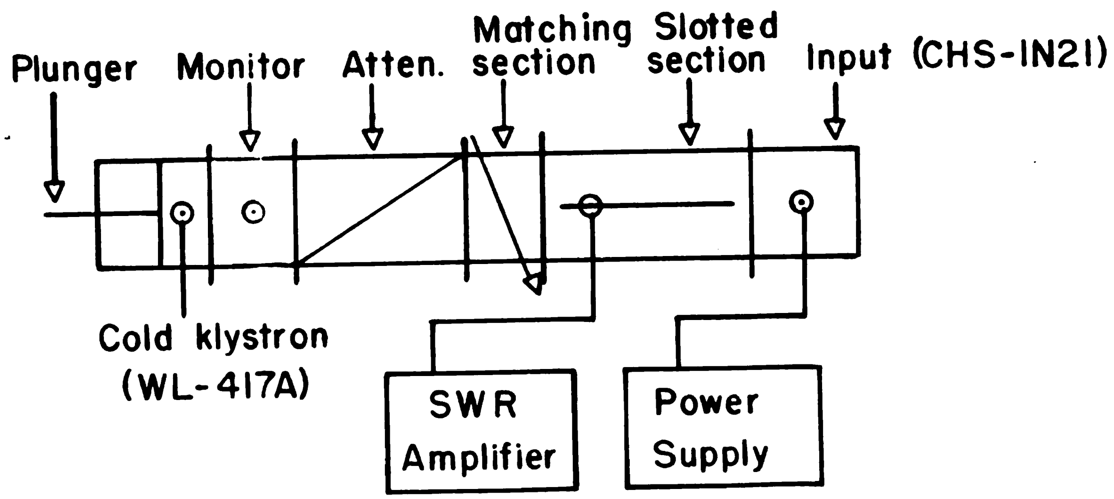


Fig. 8. BLOCK DIAGRAM of MATCHING SET-UP

standing wave ratio obtainable was less than 1.1.

In both of the above matching procedures as in the experiment proper, the wave guide attenuator was adjusted for maximum attenuation. This was done so that any power that was not matched out would upon reflection be in comparison only a small percentage of the power output of the klystron.

The guide was next connected in its vertical position as shown in Fig. 4. The same set-up pictured schematically in Fig. 3 shows the two connections to the amplifier, one being the monitor probe and the other the output power. With no sample in the guide, the amplifier gains of both the monitored and transmitted power were set so as to yield convenient scale readings. Henceforth only slight changes in the master gain were made so as to keep the monitored (input) power constant throughout the experiment. Even if it had been necessary to make appreciable master gain adjustments the final output power readings would still have been valid since relative power and not absolute power was all it was necessary to measure. Furthermore, the individual gain controls were left fixed so as to insure a constant ratio between input and output power.

With the oil bath slightly above 136° centigrade, a small amount of sample (approximately 2 millimeters column height) was placed in the guide by removing the top two sections of the guide and spooning into the guide atop the mica window a few grams of the powdered para-azoxyanisole. A thin, stiff wire was then held vertically in the melted sample and withdrawn, retaining a very thin coating of para-azoxyanisole. The height of the sample in the guide was then obtained by measuring the length of this coating. The top two sections of guide (connected as a unit) were then carefully rejoined in the same position as they had occupied to the sample section of guide.

The heating coils were then turned off allowing the circulating oil bath to cool slowly. The progress of the cooling was followed by keeping the thermocouple balanced at all times. As the temperature dropped, readings of the transmitted power were recorded while maintaining a constant input (monitor) power reading; first, with no external field and then immediately thereafter with a 1300 gauss magnetic field parallel to the electric field of the propagated wave. These readings were made every two degrees throughout the liquid crystal range allowing time between successive "magnet on" and "magnet off" readings for the sample to return to its unmagnetized state.

When the entire temperature range (135.8°C.-118°C.) was covered, the heating coils were turned on, more sample was added and measured, and the procedure was repeated.

Table I shows the data associated with one column height of sample taken in the above manner:

TABLE I: Experimental data associated with a column height of 0.8 centimeters

Thermocouple	Temperature	Power Field Off	Power Field On	Monitor	Room Temperature
6.08 μ volts	136°C.	7.9±0.2	7.9±0.2	2.5	31.5°C.
5.98	134	8.3	8.4	"	"
5.88	132	8.4	8.6	"	"
5.77	130	9.0	9.4	"	"
5.67	128	8.3	8.7	"	"
5.57	126	8.4	8.8	2.5	31.5
5.47	124	8.4	8.9	"	"
5.37	122	8.4	8.9	"	"
5.26	120	9.1	9.6	"	"
5.16	118	8.5	9.2	"	"
5.06	116	9.3	9.8	2.5	31.5
4.96	114	9.0	9.5	"	"

EXPERIMENTAL RESULTS

Theoretically a curve of transmitted power versus column height of sample can be drawn for each temperature at which readings were taken. However, these curves then overlap and tend to confuse the picture. Hence, a plot of the three general ranges of the liquid crystal temperature range, i.e., lower, middle and upper ranges were plotted against sample column height for the two cases...magnet off and magnet on. Even in this attempt to clarify the picture there appeared a certain degree of overlapping with each of the curves of either of the two groups of three being separated from its neighbor (e.g., middle range magnet off and lower range magnet off) by roughly 0.2 on the relative power scale. And since, as shown in Table I the accuracy of the power readings were only within ± (0.1-0.2) due to fluctuations of the S.W.R. amplifier indicator needle, each of the curves is within the experimental error of its adjacent curve.

In spite of this overlapping there appears to be a shift toward greater power loss with a decrease in temperature. That is, in both magnet off and magnet on cases, the upper range curve lies for the most part slightly above the middle range curve and likewise the middle lies above the lower.

Due to the fact that the curves nearly overlap and that the middle temperature range curve is the central curve of each group, only two curves are plotted, one for no external field and one for the applied parallel magnetic field of 1300 gauss. These two curves indicating the power absorption with height of sample appear in Fig. 2 as the solid lines.

The β values of which the theoretical curves (dotted lines, Fig. 2) are a function and the corresponding ϵ values are listed in Table II.

TABLE II: Experimental Results

Temperature Range	Magnetic Field	β'	β''	ϵ'	ϵ''
medium	off	1.30	0.14	5.0	0.97
medium	on	1.30	0.10	5.0	0.69

Key: β' = real part of propagation constant
β'' = imaginary part of propagation constant
ϵ' = real part of dielectric constant
ϵ'' = imaginary part of dielectric constant

DISCUSSION

A reference to Fig. 2 raises several questions. The most obvious one is with respect to the poor fit between the experimental and theoretical curves at either end, i.e., between (0-0.5 cm.) column height and (3.0-3.5 cm.) column height. It is noted that the experimental curves fall below the theoretical at these points. The discrepancy at the small column height end is believed to be due to the existing standing wave ratio (1.1). That is to say, the bending down of the curves appear as a false representation of power absorption which is actually a distortion due to reflected energy rather than absorbed energy. The other end of the curves represent more of a problem and is still rather vague. However, since this falling off of power occurs at approximately the half-wave length height of sample, it is reasonable to assume that the imperfect match (1.1 rather than 1.0) becomes more predominant in causing error at perhaps every half-wave length of column height. Or more generally, there may be a connection between the magnitude of error and the wave length in some other fashion. Again the low frequency -- long wave length aspect of the problem prevents the answering of this question. The use of one or two wave lengths of sample may well have clarified this issue.

An attempt was made to bring about a better fit in these two areas, but to no avail. It was found that a steeper theoretical curve could be obtained in the 3-centimeter column height range by the choice of a larger β' ; but this in effect shortens the wave length by the relation:

$$\beta' = \frac{2\pi}{\lambda_d}$$

This causes a shortening of the distance between the minima and maxima of the curve and thus affords a very bad fit in the central region. Other such attempts with varying β' and/or β'' were also unsuccessful.

There would appear to be a shortening of wave length λ_d for the "field off" as compared to the "field on" curve indicating a larger β' associated with the former curve. However, $\beta' = 1.30$ offers a better fit than $\beta' = 1.35$ and any choices intermediate are certainly not warranted by the accuracy of the experiment. Hence, it is believed that the β and ϵ values listed in Table II are the best to be obtained by this method.

The values listed in the introduction for the real part of the dielectric constant of para-azoxyanisole range from 3.5 to 6.9, thus the 5.0 determined in this experiment is of comparable magnitude. Also a comparison between Carr's[9] β'' values, 0.45 and 0.80 for "field on" and "field off" respectively and the 0.69 and 0.97 determined in this experiment, is noteworthy.

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