A SIMPLE REFLEX KLYSTRON STABILIZATION SYSTEM FOR MEASURING DIELECTRIC CONSTANT CHANGES

By

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PREFACE

Precision measurement of the dielectric constant of many materials is possible at microwave frequencies. The limiting factor in the precision of frequency resolution is generally the frequency stability of the microwave sources. For this reason, many types of automatic frequency control circuits have been devised. However, all present precision control systems are quite complicated.

I have presented a stabilization system for reflex klystrons which is much simpler to assemble and to operate than are other precision control systems. However, this system is less stable by one order of magnitude than some precision systems. I have combined two of these stabilized systems with a low frequency counter to measure the dielectric constant of helium and nitrogen. The results are discussed and compared with other reported data.

I wish to express my appreciation to Dr. Ken Cook for his advice and guidance in the preparation of this work, and to Mr. Norman Conger, Continental Oil Co., for his counsel and advice in the early stages of this work.

Especially, I wish to thank my wife, Shirley, for her patience and encouragement during this work and for her assistance in the preparation of this thesis.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

CHAPTER I

INTRODUCTION

The use of microwaves to make precision measurements has long been known due to the precision of frequency resolution at microwave frequencies. The measurement of polarization of materials at microwave frequencies is also established because the microwave frequency range lies generally above the relaxation time and below the molecular spectral resonances of these materials, thereby allowing greater resolution of their dielectric and dipole measurements. Of particular importance is the measurement of the dielectric constant of gases or changes in the dielectric constant of solids, liquids, or gases in the microwave region.

Many systems have been proposed to make the necessary frequency measurements. One class of systems uses swept frequency techniques and radio frequency beat markers to determine frequency differences, as done by Magnuson (1). Others, notably Crain (2), Birnbaum (3), and Gabriel (4), have developed a class of systems which use automatic frequency controlled sources. In the latter case, the frequencies are determined either by comparison with a known standard or by measuring the frequency difference of two controlled sources, one controlled source being a reference.

The accuracy of these systems depends upon the stabilization of the microwave sources. The method of klystron stabilization proposed by Pound (5), capable of a short term stability of 1 part in 10^8, was long recognized as the most accurate of the methods of source stabilization. However, this system must be critically adjusted and its tuning is very sensitive to environmental and frequency changes. Tuller, Galloway, and Zaffarano (6) improved on Pound's system by rearranging the components in a manner less sensitive to frequency. Frequency control to 1 part in 10^8 over long periods is now possible by using methods of phase locking, but the systems become very complex. To avoid the complexities of Pound's system and of phase locking, numerous simple automatic frequency control (AFC) systems have been proposed. A simplified method of resonant circuit sensing employed by Tyson (7) results in a stability of 1 part in 10^5. A servomechanism circuit described by Rideout (8) showed a stability of 1 part in 50,000 was obtainable. A transistorized reflex klystron frequency stabilizer using frequency modulation discussed by Jung (9) is said to reduce the effect of power supply ripple and drift by a factor of 1000. Of the many types of AFC studied, the method of frequency modulation appears capable of realizing the greatest stability to equipment simplicity ratio for stabilizing reflex klystrons.

A need exists for an AFC system for stabilizing reflex klystrons to about 1 part in 10^7 with equipment that is either inexpensive, available off-the-shelf, or easily and cheaply fabricated. This thesis presents a simple reflex klystron stabilization system that can be put together with off-the-shelf equipment which is generally available in microwave laboratories along with a minimum of fabricated circuitry. The principle of the stabilizer employed is similar to that used by Jung (9), except that a passive detector is used in place of active detector elements. Two of these stabilization systems are then combined with a mixer and a frequency counter to form an apparatus for measuring small changes in dielectric constants. It is an objective of this thesis to determine the overall stability of this system and to demonstrate its usefulness by measuring the dielectric constant of two gases. The design, construction, and operation of the stabilization system is discussed in Chapter II. Chapter III is a discussion of the design, equipment used, and operation of the system for measuring dielectric constant changes. The experimental method and results are given in Chapter IV along with a discussion of the results and sources of error.

CHAPTER II

THE STABILIZATION SYSTEM

The purpose in this chapter is to discuss the design, construction, and operation of the stabilization system employed in this work. Electronic details and circuit operation are confined to the discussion on construction wherever possible.

Design

The stabilization system employed here is one which uses frequency modulation of the microwave source. A block diagram of the stabilization system is shown in Figure 1. A 2K25 X-band reflex klystron is used as the microwave source. This klystron, which is readily available, operates at fairly low power supply voltages, thereby simplifying power supply requirements. The beam, filament, and manual repeller power supplies are part of a commercial power supply. The AFC repeller power supply consists of a variable battery voltage which can be switched into the system to help provide AFC action. A commercial variable oscillator tuned to 1 kc is used to modulate either the manual or AFC repeller power supplies with an adjustable amplitude. When frequency modulated on its repeller, the klystron will

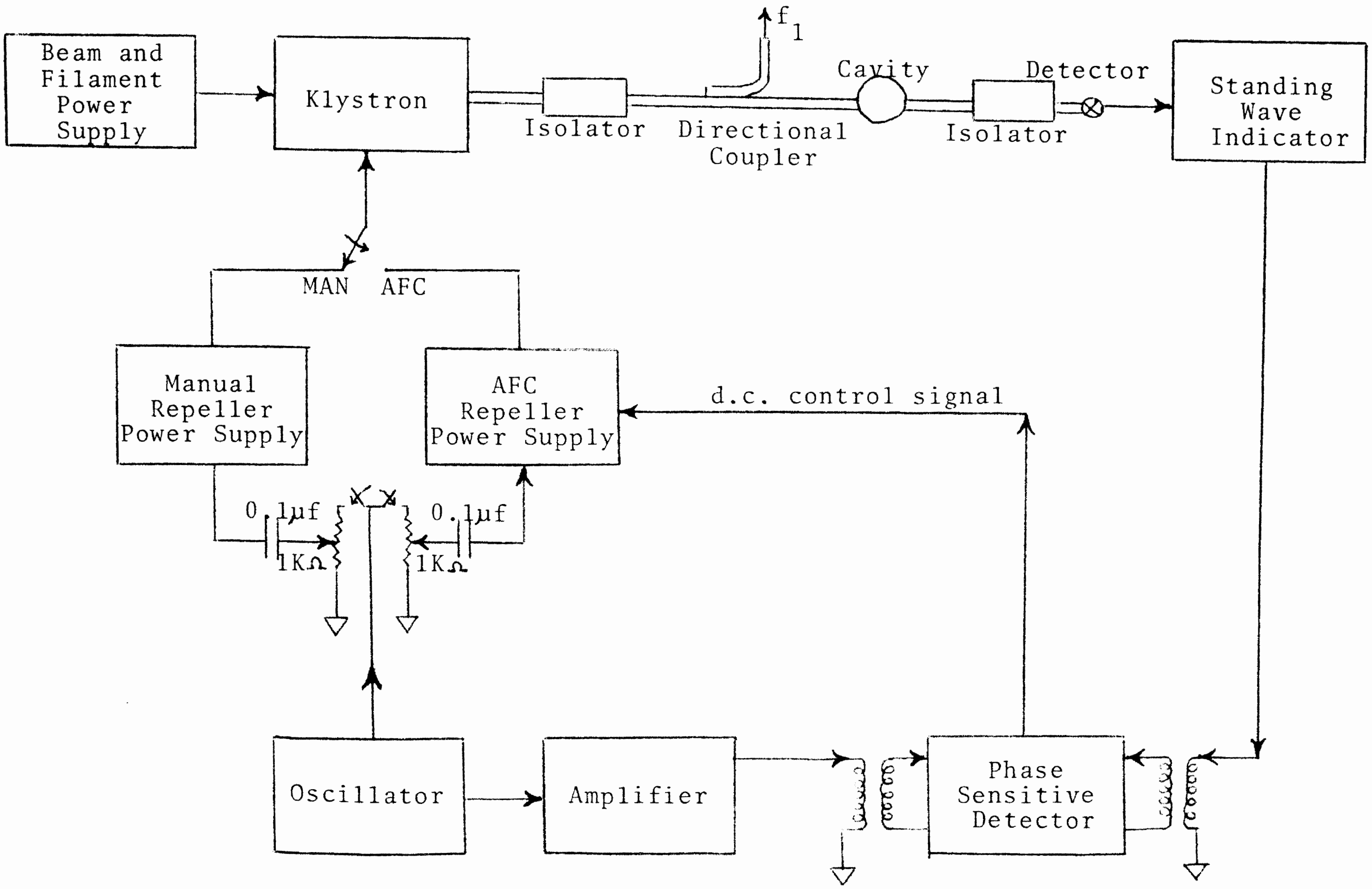

Figure 1. Block Diagram of the Stabilization System

oscillate with a sinusoidal frequency variation, the range of which is determined by the amplitude of the modulating voltage. The oscillator must be stable to within ± 5 cps over a period of several hours. This requirement is necessary to keep the frequency within the tuned amplifier bandwidth as will be explained later. The microwave power from the klystron is fed through a ferrite isolator to a TM_{012} transmission type microwave cavity. The ferrite isolator contains a ferrite material which is, at least macroscopically, ferromagnetic. This device prevents energy transmission toward the klystron and effectively eliminates any klystron detuning effects due to reflected waves. A directional coupler, inserted between the isolator and the cavity, decouples microwave energy for use in the frequency difference measuring section of the system for measuring dielectric constant changes.

The microwave cavity is a high-frequency filter (10). Being a tuned resonant element, the cavity exhibits a 180° phase shift of any modulation at resonance (11). This phase shift can be utilized to determine within ± 10 kc the exact center frequency of the cavity and also to generate an error signal for AFC loop action. To achieve this, microwave energy entering the cavity is frequency modulated at 1 kc. If the resonant frequency of the cavity falls within the band of frequencies entering the cavity, then the 180° phase information at resonance will be contained in the microwave signal leaving the cavity. This signal is then fed through a second ferrite isolator to be detected by a silicon crystal rectifier. This second isolator prevents the varying impedance of the detector crystal from reflecting back into the cavity and causing cavity "pulling". The voltage across the crystal varies at 1 kc. For maximum gain, this signal is amplified in a tuned amplifier and then fed to the phase sensitive detector.

The phase sensitive detector is a bridge diode arrangement which compares the phase of the signal arriving through the tuned amplifier with the phase of a reference signal derived from the 1 kc oscillator. The reference signal is amplified in an ordinary amplifier to provide a large reference signal so that maximum phase sensitive detector efficiency may be obtained.

In order to get AFC action, it is necessary that a control signal be generated to drive the klystron in a direction opposite to what it is tending to go and to maintain the klystron at one particular frequency, i.e. cavity resonance. This can be accomplished if, for more negative repeller voltages, a positive voltage is generated, and vice versa.

The phase comparison in the phase sensitive detector is such that, as the klystron frequency is varied through cavity resonance, a discriminator curve is generated at the output of the phase sensitive detector. The zero d.c. level of the discriminator corresponds to the resonant frequency of the cavity. When the reference and input signals are properly phased, the slope of the discriminator voltage opposes the normal repeller voltage variation. The phase sensitive detector is operated at the negative repeller potential so the discriminator voltage may be applied directly to the klystron repeller for AFC action. This necessitates d.c. isolation of the phase sensitive detector from both the tuned amplifier and the oscillator.

The stabilization system is designed so that AFC operation may be easily effected. The proper phasing in the phase sensitive detector may be ascertained with an oscilloscope when the repeller power supply is in the manual position. This procedure will be discussed in the section on operation. After proper phasing, the repeller power supply is switched from manual to AFC. When the repeller voltage is such that the klystron oscillates at cavity resonance, AFC will be initiated. If for any reason the AFC is subsequently unlocked, retuning of the klystron to cavity resonance will automatically re-initiate AFC. This is one of the prime advantages of frequency modulated AFC systems.

Construction

The stabilization system herein presented can be assembled from generally available off-the-shelf items with a minimum of extra fabrication. The klystron used is a Raytheon 2K25 X-band klystron. The beam, filament, and manual repeller power supplies are furnished from a commercial klystron power supply (Narda 438). The AFC repeller power supply is shown in Figure 2. It consists of two 90 v.

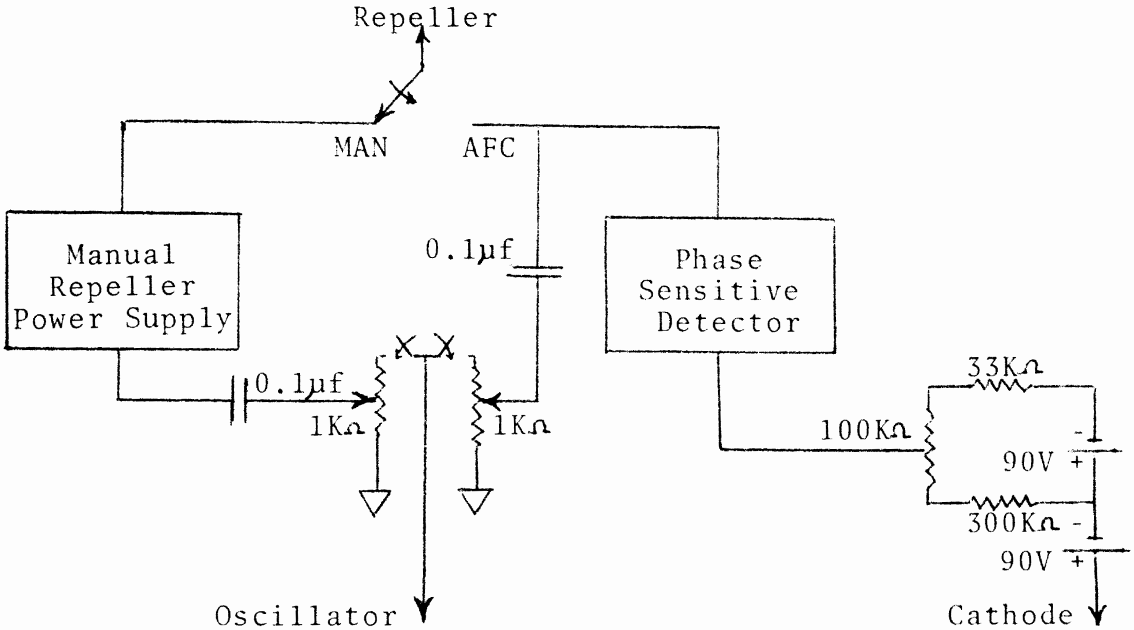

Figure 2. Repeller Power Supply Schematic Diagram

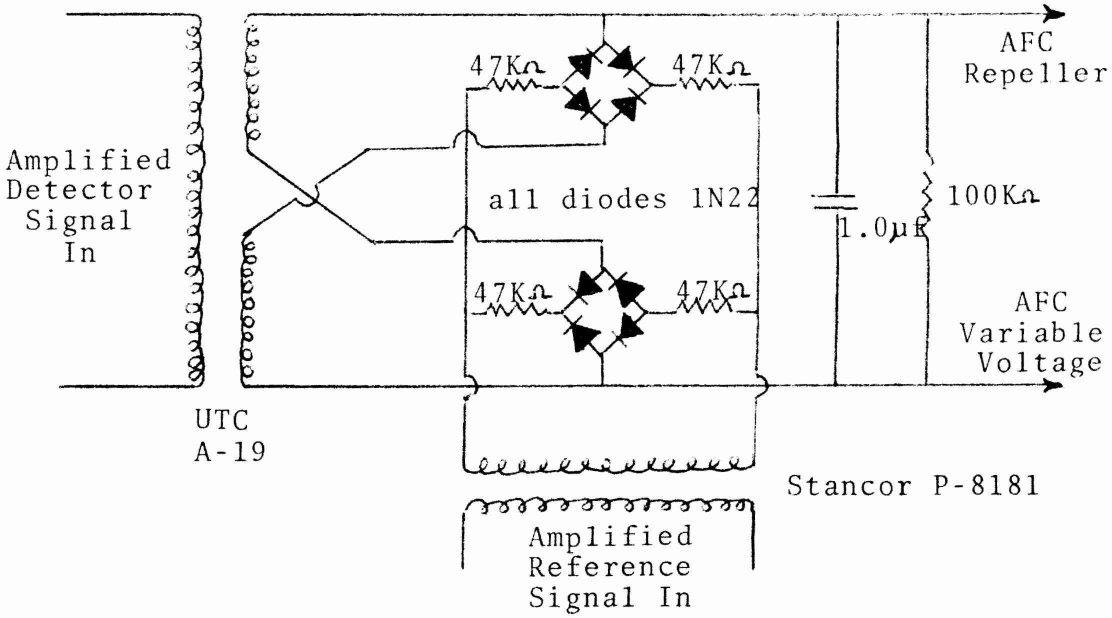

Figure 3. Phase Sensitive Detector Schematic Diagram

batteries in a voltage variable arrangement that is referenced to the cathode voltage. The cathode reference is essential to ensure that the repeller is always more negative than the cathode and beam. If the repeller were to become positive, an increased repeller current would flow which would either permanently damage or ruin the klystron. The phase sensitive detector is placed in series with the repeller voltage to provide AFC action as explained later. A 0.1 μf capacitor introduces the 1 kc modulation onto the repeller. The amplitude is controlled by varying a 1 kΩ potentiometer, and the signal may be conveniently applied or disconnected through a switch. A second switch provides for the use of either the manual or AFC repeller power supplies, depending upon the mode of operation desired.

The waveguide isolators used were FXR (X157A) and Narda (1210) units. The directional coupler was manufactured by Hewlett Packard (X752C) and the crystal detector mount was made by DeMornay-Bonardi (DBG-313). Similar units are made by various manufacturers and may be directly interchanged with the above units. Crystals of the 1N23 family were used in the detector mount.

The microwave cavity is a cylindrical type transmission cavity resonant in the TM_{012} mode. The inner height of the cavity is 2.0 inches and its inner diameter is 1.3 inches. Coupling into and out of the cavity is by small circular apertures located symmetrically on either side of the cavity. Samples may be introduced into the cavity through a 0.25

inch diameter hole in one end of the cavity. This type of cavity, when made of copper, has a Q typically greater than 10,000.

Amplification of the detected signal is done in a voltage standing wave indicator (Hewlett Packard 415B). This unit contains a tuned amplifier for 1 kc amplification. Its bandwidth of 10 cps at 1 kc provides for maximum 1 kc amplification with a minimum of noise. The gain of this unit is directly adjustable from 0 db to 60 db.

The oscillator used to modulate the repeller and for a reference signal was a Hewlett Packard 650A. This oscillator meets the necessary stability requirements. The reference signal to the phase sensitive detector from the oscillator was amplified to 50 v. rms in a Textronix amplifier (132) containing a Type 53/54B module.

The phase sensitive detector and AFC repeller power supply construction constituted a bulk of the necessary fabrication. A schematic diagram of the phase sensitive detector is shown in Figure 3. Phase comparison is accomplished in the two diode bridge networks. The detected and reference signals are both transformer coupled into the phase comparator since it is operated at the negative repeller potential. The necessary windings for introducing the detected signal are available in an interstage transformer (UTC A-19), and a small power transformer (Stancor P-8181) was used to transform the reference signal into the phase comparator. The phase comparator was constructed to be similar to a commercial unit available from Sanders Associates (Model 2). The diode bridges are arranged in a configuration that will yield either a positive or a negative d.c. output depending upon the relative phasing of the two input signals (12). Care is taken in the selection of the diodes and resistors in the phase comparator to yield a balanced output that is free of any 1 kc ripple, thereby preventing feedback modulation of the klystron. With no reference signal present, the output of the phase sensitive detector is zero and the klystron repeller voltage is determined by the manual battery adjustment. However, under AFC conditions and with a reference signal present, the phase sensitive detector generates a d.c. signal directly on the repeller voltage such that stabilized klystron frequency control is maintained. For a given detected signal, the output of this unit is proportional to the amplitude of the reference signal up to 125 v. rms. This is the justification for amplifying the reference signal input from the oscillator.

Operation

This section, concerning the operation and adjustment of the stabilization system, will present the necessary details of operation to allow proper system operation by anyone reasonably familiar with the separate pieces of equipment.

When applying power to the separate units, only the klystron power supplies require special attention. The klystron filament should be energized at least one full minute prior to applying the beam potential. During this time all other units except the klystron beam supply may be switched on. After filament warm-up, both the manual and AFC repeller voltages should be observed on a high resistance voltmeter. The repeller voltages must be negative with respect to both the cathode and beam. Proper voltage ranges are from -150 v. to -180 v. Since the repeller voltage is referenced to the cathode connection, a negative voltage on the repeller before the beam voltage is applied ensures proper voltage relations on the klystron when the beam voltage is supplied. The cathode is similarly referenced to the beam voltage, and, since the beam voltage when applied is at system ground potential, the cathode and repeller voltages are both forced more negative when the beam voltage is switched on.

The beam voltage may now be turned on and set for 250 volts. Proper pressure tuning of the 2K25 klystron should result in klystron oscillation. If a large amplitude 60 cps sine wave modulation is applied to the manual repeller voltage, the klystron frequency should be swept across the resonant frequency of the cavity. Observation of the detector crystal output on an oscilloscope will show the cavity frequency response curve (a Gaussian shaped curve) under these conditions. Some adjustment of the manual repeller voltage and klystron pressure tuning may be necessary to obtain and optimize this display. Optimum klystron pressure tuning ensures that when the 60 cps modulation is removed, klystron oscillation will still occur at cavity resonance for some available repeller voltage. Upon removal of the 60 cps modulation, adjustment of the manual repeller voltage is made to tune the klystron to cavity resonance as indicated by maximum d.c. signal at the detector crystal. About 30 minutes is required for the klystron to reach a temperature equilibrium. During this time, minor manual repeller voltage adjustments are necessary to keep the klystron frequency on cavity resonance. Also during this warm-up period, the phasing of the control signal can be checked.

As mentioned previously, the control signal voltage must be of opposite polarity from the normal voltage change. To check the necessary phasing, apply the full 1 kc frequency modulation to the manual repeller voltage and adjust the tuned amplifier for about 30 db of amplification. As the manual repeller voltage is slowly made more negative, a positive control signal should be present at the output of the phase sensitive detector in the region of cavity resonance. If a negative output is present, it indicates a 180° phase error at the phase sensitive detector. When it is ascertained that the phasing is correct, the repeller voltage may be switched from manual to AFC. When the AFC repeller voltage is adjusted so the klystron frequency is near resonance, AFC action will be automatically initiated. This action is easily identifiable by observing the crystal detector output on an oscilloscope. When locked-in, a "double-frequency" modulation appears at the detector crystal as shown in

Figure 4b. This is due to the 180° phase shift at resonance (13). The tuned amplifier, however, is oblivious to the double-frequency and only amplifies the 1 kc signal. The amplitude of the 1 kc signal ideally goes to zero at resonance, and thus will be unobservable even with a very sensitive oscilloscope. To minimize the developed error signal, and hence, control signal, the AFC repeller is further adjusted so the amplitude of the double-frequency is balanced as in Figure 4b. An unbalanced double-frequency shown in Figure 4c is indicative of a frequency error larger than the system can compensate for entirely. Tuning to cavity resonance can also be determined by adjusting the AFC repeller voltage for a minimum 1 kc signal as indicated on the face of the tuned amplifier used (voltage standing wave indicator).

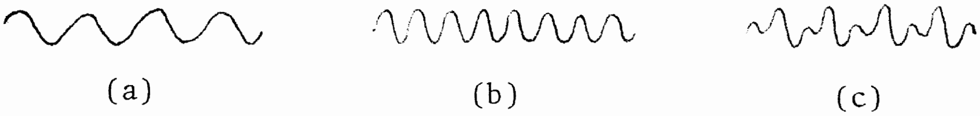
(a) (b) (c)

Figure 4. Detector Crystal Modulation Frequency Relations. (a) Modulation frequency. (b) Balanced double-frequency at resonance. (c) Unbalanced double-frequency slightly above or below resonance.

The modulation amplitude is now decreased and the tuned amplifier gain increased until the tuned amplifier oscillates from 1 kc noise. The amplification is then backed off for stable operation. The stabilization system is now controlling the klystron center frequency to the cavity resonance frequency.

CHAPTER III

THE SYSTEM FOR MEASURING DIELECTRIC CONSTANT CHANGES

This chapter will constitute a discussion of the design, equipment used, and operation of the system presented herein for measuring dielectric constant changes. The discussion in this chapter will assume a knowledge of Chapter II regarding operation of the stabilization systems involved.

Design

The system for measuring dielectric constant changes is composed of three major sections. These are:

1. The reference arm,
2. The measuring arm,
3. The frequency difference measuring section.

A simplified block diagram of the system is shown in Figure 5. Each arm of the system is a stabilization system identical to that described in Chapter II. The reference arm is set and maintained at any suitable frequency for use as a frequency reference point. The measuring arm is then set to follow any frequency shift within its resonant cavity due to a change in dielectric constant. The stabilization systems, as explained previously, stabilize the frequency of each klystron to that of its respective resonant cavity.

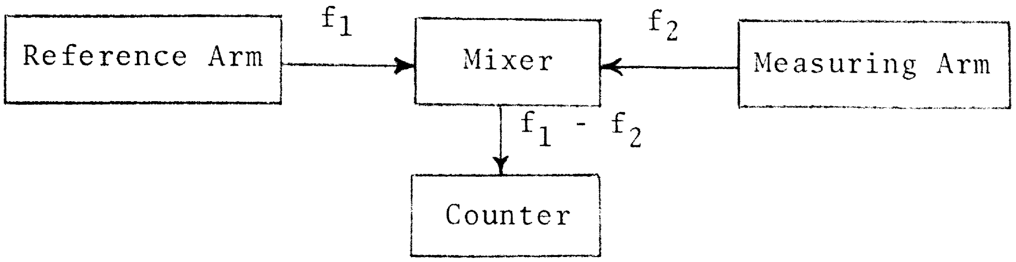

Figure 5. Block Diagram of the System for Measuring Dielectric Constant Changes.

Part of the power from each arm of the system is decoupled and fed into the frequency difference measuring section. This section consists of a balanced magic tee crystal mixer and an electronic counter. The microwave energy decoupled from one stabilized arm is then fed into the E-arm of the balanced mixer and the energy decoupled from the other stabilized arm is fed into the H-arm of the mixer. The signal in the colinear side arms of the balanced mixer contains the difference frequency between the two modulated, stabilized frequencies (13). The mixer crystal output is then connected to the input of an electronic counter. Since both klystrons are frequency modulated at 1 kc, the output of the mixer will also be frequency modulated at 1 kc. However, by triggering the counter to sample the mixer output for at least one second intervals, these frequency variations are averaged over one thousand cycles so the electronic counter readout is independent of the respective klystron frequency variations due to modulation. The visual counter readout is then the true frequency difference between the two arms of the system. The electronic counter must be capable of counting the largest frequency difference expected. The equipment used here was capable of measuring up to 100 Mc differences to an accuracy of ± 10 cps. The resonant frequency of the measuring arm was determined to four significant figures by inserting a wavemeter between the second isolator and the detector. In addition to the electronic items described, a vacuum pump and connecting hoses were used to obtain some of the data presented in this report.

Equipment

The equipment used for the stabilization systems has been previously described. The frequency difference measuring equipment consisted of a DeMornay-Bonardi balanced crystal mixer (DBG-665) and a Hewlett Packard electronic counter (524C). The resonant frequency was determined with a Hewlett Packard wavemeter (X532B). A complete list of the commercial equipment used in the measuring system is given in Table I. This list includes commercial substitutes for the phase comparators which were constructed.

Operation

The operation of the measuring system is basically the operation of each of the two arms. The reference arm is set up at some resonant frequency as a reference. The measuring arm is then set up to follow its respective cavity resonance. This resonance will change if the dielectric

TABLE I

EQUIPMENT USED IN THE MEASURING SYSTEM

Equipment	Quantity	Manufacturer	Model
Amplifier	1	Textronix	132
Amplifier Plug-in	1	Textronix	53/54B
Balanced Crystal Mixer	1	DeMornay-Bonardi	DBG-665
Detector Crystal Mount	2	DeMornay-Bonardi	DBG-313
Directional Coupler	2	Hewlett Packard	X752C
Electronic Counter	1	Hewlett Packard	524C
Ferrite Isolator	2	FXR	X157A
	2	Narda	1210
Klystron Power Supply	2	Narda	438
Oscillator	1	Hewlett Packard	650A
Phase Comparator	2	Sanders	2
Reflex Klystron	2	Raytheon	2K25
TM_{012} Transmission Cavity	2	-	-
Transformer	2	Stancor	P-8181
	2	UTC	A-19
Vacuum Pump	1	Welch	-
Voltage Standing Wave Indicator	2	Hewlett Packard	415B
Wavemeter	1	Hewlett Packard	X532B

constant of the material in the cavity changes. Consider, for example, the situation where the reference and measuring arms are locked-in, the reference cavity being filled with air and the measuring cavity evacuated to near 1 micron of pressure. A certain frequency difference, f_i, which is the frequency difference between the reference and measuring arms, will be read on the electronic counter. If some gas is now allowed to fill the measuring cavity, its resonant frequency will change. The necessary adjustments must be made in the AFC repeller voltage to retune the measuring arm as discussed in Chapter II. The new frequency difference will be f_f. The change in resonant frequency of the measuring cavity due to the gas is then $\Delta f = f_f - f_i$.

CHAPTER IV

EXPERIMENTAL METHOD AND RESULTS

The details of the methods and procedure used in this work to obtain data will be discussed. As this work studies the accuracy of resonance determination and stability of the measuring system previously described as well as shows its usefulness and accuracy in measuring the dielectric constant of gases, these topics will be discussed and the data obtained will be presented.

Accuracy of Resonance Determination

The accuracy of the data obtained with this system can be no more accurate than the system accuracy in determining resonance. The accuracy in resonance determination as used here is the ability to retune the system to cavity resonance after it has been displaced. This was determined by changing the AFC repeller voltage of one arm of the system so as to cause that arm not to be controlled and then retuning it as accurately as possible. Detection of resonance was by the scope method discussed in Chapter II. The results of a series of 60 of these measurements are given in Table II. The Δf reported is the counter readout, and the frequency of occurrence is the number of times that value occurred in 60 trials. The data shows a random variation in accuracy of resetting within deviation limits of ± 5 kc. The ± 5 kc variation represents an error in $(\epsilon - 1)\text{x}10^6$ of ± 2.1 at 9.414 kMc if additive errors in the determination of both the evacuated cavity and the cavity filled with sample are considered.

TABLE II

ACCURACY DATA FOR RESONANCE DETERMINATION

f (kc)	frequency of occurrence
7398	0
7399	1
7400	3
7401	8
7402	6
7403	7
7404	5
7405	9
7406	7
7407	9
7408	5
7409	0

Stability

The absolute accuracy of the measuring system can also be no better than its stability. Since no crystal controlled reference signal was available at X-band microwave frequencies, it was not possible to check the stability of only one arm of the system. It was deemed important, however, to determine the overall frequency stability of the system. Since the AFC circuits stabilize the klystron frequencies to their respective cavity resonances, any change in cavity resonance will appear as a system drift. Because cavities of two different materials, brass and copper, were used, their temperature coefficients of expansion, and hence, their resonant frequency changes with temperature, were different. It was, therefore, important that the cavity temperatures be held constant. This was achieved to ± 0.1° C by wrapping the cavities with several layers of fiberglass insulating tape. Figure 6 shows a stability run of 26 hours duration in which an overall system frequency stability of better than ± 4 kc about the mean was achieved. The ambient temperature variation during this test was less than ± 0.1° C. For periods up to ten hours, a stability of ± 1 kc was achieved. A ± 1 kc change represents an error in $(\epsilon - 1)\times 10^6$ of ± 0.2.

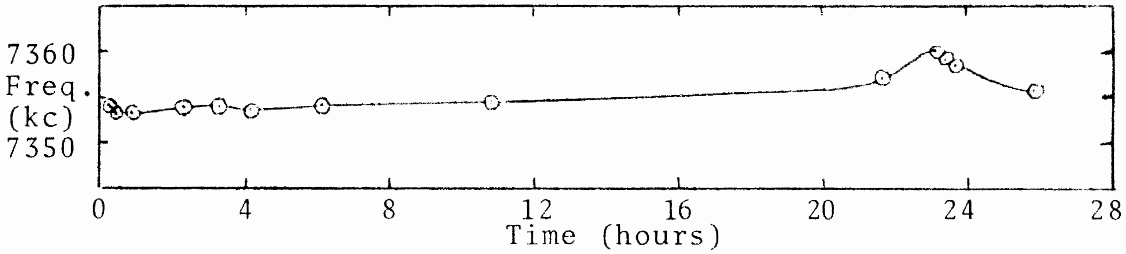

Figure 6. Stability Test of the System.

Gas Dielectric Constant Measurements

The purpose of the system described in this work is to be able to measure changes in dielectric constant. For small cylindrical rods of dielectrics centered axially in a TM_{01} cavity, Bethe and Schwinger (14) have shown the dielectric constant to be given by

$$\epsilon = \left(\frac{\Delta f}{fG} + 1 \right)^2$$

where G is a constant depending on the sample geometry. This equipment is designed to measure small changes in the dielectric constant of such a cylindrical rod whenever such changes might occur. However, the state of the art for repositioning the described rods in TM_{012} cavities is not adequate to allow an evaluation of the accuracy of this system. Therefore, a more satisfactory test must be presented.

For gases or liquids filling a resonant cavity, Slater (15) has shown the dielectric constant to be given by

$$\epsilon = \frac{f_0{}^2}{f_1{}^2}$$

where f_0 is the resonant frequency of the cavity under vacuum and f_1 is the resonant frequency of the cavity when filled with the dielectric. It is easily shown that this dielectric constant can be approximated by

$$\epsilon \doteq 1 + \frac{2\Delta f}{f_1}$$

where $\Delta f = f_0 - f_1$ (see Appendix A). The values of dielectric constants for typical gases ($65 < [\epsilon - 1]\text{x}10^6 < 650$) will cause a Δf change in resonance of 300 kc to 3000 kc at $f_0 = 9.414$ kMc. These values should prove sufficient for testing the accuracy of the system. The gases selected to evaluate the system were helium ($[\epsilon - 1]\text{x}10^6 \doteq 65$) and nitrogen ($[\epsilon - 1]\text{x}10^6 \doteq 540$). Both were obtained directly from bottled cylinders of laboratory grade gas.

The method used for measuring the dielectric constants of the gases was to measure Δf between the evacuated measuring cavity and the measuring cavity filled with the gas under test. The counter readout, f_e, was first obtained for the evacuated cavity. The gas was then admitted to the cavity and the system was electronically balanced as described in Chapter II. The counter readout with the gas in the cavity was f_g. The cavity was then again evacuated and a second f_e was obtained. The Δf due to the gas is then $\Delta f = f_e - f_g$. The method used resulted in two values of Δf for each sample. These are designated as Δf_{in} for the frequency shift associated with introducing the sample into the cavity, and Δf_{out} for the frequency shift when the gas was evacuated from the cavity. The readings were taken at room temperature (about 24° C). The length of time necessary for measuring one sample was typically one minute.

The data obtained from measuring the dielectric constant of helium is given in Table III and the data for nitrogen is given in Table IV. The value of Δf_{in} obtained when a sample of gas was admitted to the cavity is recorded, as is the value of Δf_{out} obtained when that sample was evacuated. The average Δf for each sample is then also recorded. A series of measurements on ten samples of helium resulted in a $\Delta f_{He_2} = 310 \pm 6$ kc. This corresponds to an $(\epsilon - 1)\text{x}10^6$ of 65.9 ± 1.3. The series of ten samples of nitrogen yielded a $\Delta f_{N_2} = 2397 \pm 8$ kc. This corresponds to an $(\epsilon - 1)\text{x}10^6$ of 509.2 ± 1.7. These values are compared with those obtained by Birnbaum, Kryder, and Lyons (16) and Zieman (17) in Table V. The reported values have been corrected from 0° C

TABLE III

DIELECTRIC CONSTANT DATA FOR HELIUM

Sample	Δf_{in} (kc)	Δf_{out} (kc)	Δf_{avg} (kc)
1	303	310	307
2	314	312	313
3	314	309	312
4	311	311	311
5	309	298	304
6	310	312	311
7	308	312	310
8	304	315	310
9	315	303	309
10	314	306	310

TABLE IV

DIELECTRIC CONSTANT DATA FOR NITROGEN

Sample	Δf_{in} (kc)	Δf_{out} (kc)	Δf_{avg} (kc)
1	2403	2398	2401
2	2403	2407	2405
3	2391	2401	2396
4	2392	2400	2396
5	2400	2401	2401
6	2394	2393	2394
7	2392	2387	2390
8	2389	2396	2393
9	2390	2394	2392
10	2399	2400	2400

to 24° C by an empirical formula in which

$$\frac{(\epsilon - 1)_t}{(\epsilon - 1)_{20^\circ C}} = \frac{1}{1 + 0.003411(t - 20)} \quad .$$

This formula was developed by the National Bureau of Standards and is claimed to have less than 0.1% error (18). The value for the helium dielectric constant expressed as $(\epsilon - 1)\mathrm{x}10^6$ obtained in this work agrees within about 1% with the values of Birnbaum, Kryder, and Lyons and falls within their experimental accuracy. The value reported herein for the nitrogen dielectric constant, however, differs from other reported data by 6%. It is important to note that the variation of the nitrogen dielectric constant data obtained in this work was less than ± 10 kc which corresponds to a dielectric constant variance of ± 0.3%. Therefore, it is felt that the dielectric constant of the particular specimen of gas under study was very nearly 509. It is to be emphasized that this study is concerned with the electronic system and its usefulness and is not an attempt to improve on the measurement of the stated dielectric constants. However, this system is very much less complex than the Pound stabilization systems used to obtain the other reported data.

Sources of Error

The sources of error dealing with stability and accuracy of resonance determination have been discussed previously. However, additional sources of error were present in the dielectric constant measurements. As the cavity was evacuated, the atmospheric pressure on its exterior must have caused some cavity deformation. This rather constant source of error could not be measured and, based on the accuracy attained in the helium data, was estimated to produce a negligible effect. Not so negligible, however, was the effect of some random source of error. This effect was clearly noticeable as it produced a step change in the data invalidating the particular segment of data being obtained (see Appendix B). It is proposed that this effect could be due to changing contact pressure on the connecting surfaces of the two pieces which compose the cavity. Contact pressure changes could cause changes in the surface conductivity of the cavity, and hence, could produce changes in the resonant frequency of the cavity.

TABLE V

DIELECTRIC CONSTANTS OF HELIUM AND NITROGEN

values corrected to 24° C

Results by	Frequency (Gc/s)	$(\epsilon - 1)\times10^6$	
		He_2	N_2
Birnbaum, Kryder, and Lyons	9.28	65.2 ± 1.1	
	9.0		542.5 ± 2.9
Zieman	9.47		542.6 ± 2.0
This Work	9.414	65.9 ± 2.1	509.2 ± 2.1

Another source of error was involved in the vacuum system used. A perfect vacuum, naturally, was unattainable. Therefore, some gas remained in the cavity during the evacuated readings. The attained evacuation pressure of 5 mm Hg contained about 1% of the atmospheric gas content of the cavity. This would allow slightly less than 100% of the total volume of the cavity to be filled by the gas being inserted and would cause a smaller dielectric constant than would be expected. This could explain part of the deviation of the data reported here from other reported data.

Summary

A careful study has been made of the stability and accuracy of the system presented for measuring dielectric constant changes. The design, construction, and operation of the reflex klystron stabilization system was discussed. A system for measuring dielectric constant changes by utilizing two of the mentioned stabilization systems and a frequency measuring scheme was described.

The stability of the overall system was determined and factors affecting this stability were enumerated. The accuracy with which the resonant frequency of each cavity could be determined was studied. Two methods of making this determination were discussed.

To illustrate the usefulness of the system, the dielectric constants of helium and nitrogen were measured. The results of these measurements were compared with other reported data. The helium data agreed within 1% of reported values, while the nitrogen data obtained here was nearly 6% below the reported values. Possible sources of error which contributed

to the overall system operation and accuracy, and which account for part of the deviation between this data and other reported data, were also discussed.

It is concluded that the system presented is capable of measuring frequency changes to within ± 10 kc over the frequency spectrum of its klystron. This corresponds to changes in $(\epsilon - 1)x10^6$ of ± 2.1 for $f_0 = 9.4$ kMc. As the errors involved here are of a rather constant nature, the percentage error of larger measurements should be much better. It is believed that this system has sufficient accuracy and simplicity to find much use as a routine measuring device for determining the dielectric constant, or changes in the dielectric constant, of applicable materials.

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APPENDIX A

EQUATIONS FOR DIELECTRIC CONSTANT MEASUREMENT FROM FREQUENCY SHIFT

Slater (15) has shown the dielectric constant of a material with $\mu = 1$ filling a resonant cavity to be given by

$$\epsilon = \frac{f_0^2}{f_1^2}$$

where ϵ is the dielectric constant, f_0 is the resonant frequency of the cavity containing a vacuum, and f_1 is the resonant frequency of the cavity filled with the dielectric. If we now express f_0 in terms of f_1 and a frequency shift, Δf, from f_1 to f_0, we get

$$f_0 = f_1 + \Delta f$$

where the + sign indicates a choice of $\Delta f = f_0 - f_1$. Substituting this form of f_0 into Slater's equation and expanding yields

$$\epsilon = \frac{f_1^2 + 2\Delta f f_1 + \Delta f^2}{f_1^2} .$$

This simplifies to

$$\epsilon = 1 + \frac{2\Delta f}{f_1} + \frac{\Delta f^2}{f_1^2} .$$

The last term is typically three orders of magnitude smaller than the second term and is therefore negligible. This yields the approximation

$$\epsilon \doteq 1 + \frac{2\Delta f}{f_1}$$

which is valid for $\Delta f << f_1$. This relation holds for microwave frequencies.

APPENDIX B

DIELECTRIC CONSTANT MEASUREMENT DATA

HELIUM

Sample Number	f_e(before) (kc)	f_g (kc)	f_e(after) (kc)	Δf_{in} (kc)	Δf_{out} (kc)	Δf_{avg} (kc)
1	7815	7512	7822	303	310	307
2	7822	7508	7820	314	312	313
3	7820	7506	7815	314	309	312
4	7815	7504	7815	311	311	311
5	7815	7506	7804	309	298	304
6	7213	6903	7215	310	312	311
7	7215	6907	7219	308	312	310
8	7219	6915	7230	304	315	310
9	7230	6915	7218	315	303	309
10	7218	6904	7210	314	306	310

NITROGEN

Sample Number	f_e(before) (kc)	f_g (kc)	f_e(after) (kc)	Δf_{in} (kc)	Δf_{out} (kc)	Δf_{avg} (kc)
1	7738	5335	7733	2403	2398	2401
2	7733	5330	7737	2403	2407	2405
3	7737	5346	7747	2391	2401	2396
4	7247	4855	7255	2392	2400	2396
5	7255	4855	7256	2400	2401	2401
6	7256	4862	7255	2394	2393	2394
7	7255	4864	7250	2392	2387	2390
8	7250	4861	7257	2389	2396	2393
9	7257	4867	7261	2390	2394	2392
10	7261	4862	7262	2399	2400	2400

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