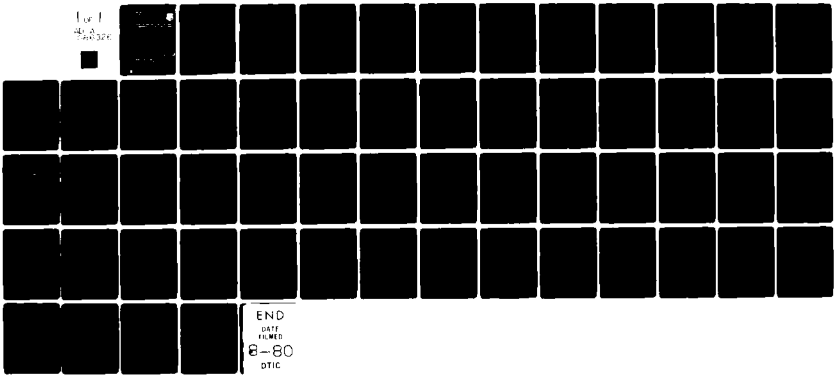
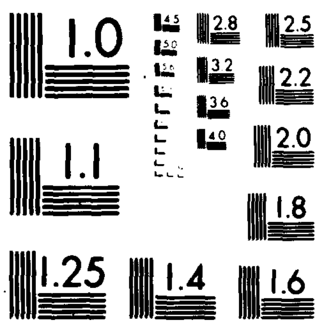
AD-A086 326 GEORGIA INST OF TECH ATLANTA F/G 9/1
ADAPTIVE TIME DELAY CIRCUITRY FOR INTERFERENCE CANCELLATION SYS--ETC(U)
APR 80 D E CLARK, W A HARDELL F30602-78-C-0120
UNCLASSIFIED GIT-A-2287(F) RADC-TR-80-114 NL





MICROCOPY RESOLUTION TEST CHART

LEVEL

ADA086326

ADAPTIVE TIME DELAY CIRCUITRY FOR INTERFERENCE CANCELLATION SYSTEMS

Georgia Institute of Technology

Donald E. Clark
William A. Hardell

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

DTIC
ELECTE
JUL 8 1980
S D
A

ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, New York 13441

80 7 7

This report has been reviewed by the RADC Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be releasable to the general public, including foreign nations.

RADC-TR-[illegible] has been reviewed and is approved for publication.

APPROVED:

[illegible]
Project Engineer

APPROVED:

DAVID C. LUKE, Lt Colonel, USAF
Chief, Reliability & Compatibility Division

FOR THE COMMANDER:

JOHN P. HUSS
Acting Chief, Plans Office

If your address has changed or if you wish to be removed from the RADC mailing list, or if the addressee is no longer employed by your organization, please notify RADC ([illegible]), Griffiss AFB NY 13441. This will assist us in maintaining a current mailing list.

Do not return this copy. Retain or destroy.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

18 19

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: RADC-TR-80-114	2. GOVT ACCESSION NO.: AD-A086329
3. RECIPIENT'S CATALOG NUMBER: 9	
4. TITLE (and Subtitle): 6 ADAPTIVE TIME DELAY CIRCUITRY FOR INTERFERENCE CANCELLATION SYSTEMS	5. TYPE OF REPORT & PERIOD COVERED: Final Technical Report, 30 Oct 78 — 31 Oct 79
	6. PERFORMING ORG. REPORT NUMBER: 14 GIT-A-2287 (F)
7. AUTHOR(s): 10 Donald E. Clark, William A. Hardell	8. CONTRACT OR GRANT NUMBER(s): 15 F30602-78-C-0120
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Georgia Institute of Technology, Atlanta GA 30332	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 62702F, 16 2338 ~~04P0~~ 17 04
11. CONTROLLING OFFICE NAME AND ADDRESS: Rome Air Development Center (RBCT), Griffiss AFB NY 13441	12. REPORT DATE: 11 April 1980
	13. NUMBER OF PAGES: ~~49~~ 12 56
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Same	15. SECURITY CLASS. (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE: N/A

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Same

18. SUPPLEMENTARY NOTES

RADC Project Engineer: Wayne E. Woodward (RBCT)

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Time Delay Lines	Electromagnetic Compatibility
Variable Time Delay	Interference Cancellation
Phase Shifters	Transmission Lines

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The objective of this research program was to study and investigate variable time delay techniques for use in interference cancellation systems so as to improve their performance. A comprehensive survey of past research pertaining to HF, VHF, and UHF variable time delay techniques was undertaken. The survey also included microwave variable time delay techniques that are adaptable to the lower bands. As part of this program, variable delay lines were constructed and experimental — over

DD FORM 1473, 1 JAN 73 — EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

153800

measurements performed. Specifically, two types of delay lines were investigated, one using a coaxial transmission section with a helix surrounding a ferrite rod and the other a powdered ferrite and dielectric loaded coaxial section. The report presents experimental results over the HF, VHF, and UHF bands.

PREFACE

This report was prepared by the Electronics Technology Laboratory of the Engineering Experiment Station of the Georgia Institute of Technology. This work was conducted in response to Task N-9-5069 under Contract No. F30602-78-C-0120 of the RADC Post-Doctoral program. The described work was performed under the general supervision of D. W. Robertson, Director, Electronics Technology Laboratory, and H. W. Denny, Head, Electromagnetic Compatibility Branch. The principal investigator responsible for the project-level direction was Donald E. Clark. William A. Hardell, Student Assistant, assisted in the experimental work.

Accession For
Availability Codes
Dist | Avail and/or special
A

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EVALUATION

The objective of this effort is the investigation of techniques which would be applicable to adaptive time delay circuitry for use in Interference Cancellation System (ICS) to reduce the detrimental effects of multipath propagation over a broad bandwidth. Since the ICS is a balanced bridge arrangement, any movement in the radiated path that is not corrected in the conducted path results in a reduction of the cancellation obtained. On aircraft installations the flexing of the wing antennas results in a varying radiated path that is not compensated for in the conducted path. The basic purpose of the adaptive time delay unit is to provide the compensation required in the conducted path to correct for the varying radiated paths.

The significance of this effort is that it has direct application to C^3I aircraft, reference R4C.

Wayne E. Woodward

WAYNE E. WOODWARD
Project Engineer

1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

Interference cancellation systems have become a viable technique to cope with the high interference environments that degrade communications either at ground stations or on board aircraft. Better performance of interference cancellation systems is thus one method of improving communications from aircraft to aircraft and between aircraft and ground stations. An interference cancellation system is essentially a balanced bridge with one part of the bridge being the transmit-antenna-to-receive-antenna radiated path and the other path being a conducted one between the transmitter and receiver through which a cancellation signal is synthesized. Any movement of either antenna changes the radiated path and momentarily unbalances the system. The result is a lower signal-to-noise ratio at the receiver and a degradation of communications. Present systems are able to contend with some unbalance. However, if one of the antennas experiences large movements, as for example, when it is located on a flexing wing, large path changes result and the bridge cannot adequately balance. To provide the compensation required for path changes, an adaptive time delay device or circuit is needed in the conducted path to correct for the varying radiated path length. The purpose of this program is to study and investigate time delay techniques that lend themselves to adaptive control in HF, VHF, and UHF band interference cancellation systems.

1.2 SUMMARY

The effort of this program was channeled in two directions: the undertaking of a comprehensive survey of existing variable time delay techniques and experimental measurements on several delay line design models. The survey concentrated on past delay line technology for the HF, VHF, and UHF band as well as on technology developed for the lower microwave frequencies, i.e., L-band. Both acoustic and nonacoustic techniques were included in the survey. The experimental effort was directed toward the construction and measurement of helical delay lines and ferrimagnetic loaded delay lines. For the helical delay line, a helix surrounding a ferrite rod was used as the center conductor in a coaxial transmission line. The annular space in the coaxial line was filled with a high-permittivity dielectric material. For the ferrimagnetic loaded line, ferrite powders were mixed with dielectric materials and used as a filler in the annular space of a coaxial line. Adjustments in time delay were achieved by varying a magnetic field which changed the effective permeability of the ferrite materials. The change in the permeability resulted in a change in the electrical length (i.e., propagation time) of the transmission line sections. The delay lines were characterized as to the amount of time delay exhibited and insertion loss as functions of the applied magnetic field and the input frequency.

1.3 CONCLUSIONS

The survey revealed that numerous research efforts to develop time delay techniques have been undertaken and many techniques for achieving variable time delays exist. However, most of these investigations on variable devices have emphasized the microwave frequency bands. There has been considerable research done on UHF phase shifters and on UHF fixed-delay techniques. Many of the techniques appear to be extendible to variable time delays.

Based on the experimental results, the helical delay line appears to be a viable technique for the HF band. The ferrimagnetic loaded delay line unfortunately either did not offer sufficient range of adjustment of time delay or was very lossy, particularly in the UHF band. It is recommended that the helical delay be investigated further to see if different construction and materials can indeed achieve the performance goals needed for use in HF interference cancellation systems. For the VHF and UHF bands, appropriate transmission-line configurations and techniques remain to be identified.

2.0 DESIGN REQUIREMENTS

Interference cancellation techniques offer a method of improving ground station or aircraft communications in the presence of electromagnetic interference. Existing interference cancellation systems are capable of protecting overlapping and adjacent channels in collocated transmitters and receivers over the HF, VHF, and UHF bands. Because of its importance as a method of controlling interference, the interference cancellation system has undergone many improvements and refinements over the last few years. It has been concluded as a further refinement, that adaptive time delay needs to be added to the interference cancellation system control circuitry. The operation of interference cancellation systems is reviewed and the requirements and design goals for inclusion of adaptive time delay circuitry are presented.

2.1 INTERFERENCE CANCELLATION SYSTEMS

Numerous study and investigative reports [1] - [5] on the theory of operation and design of interference cancellation systems are available in the literature. The basic principles of an interference cancellation system may be explained through the use of Figure 1. The interference cancellation system shown is a collocated system where both the transmitter and receiver systems are located in close proximity, such as found on board an aircraft. Full-duplex communications, where it is necessary to simultaneously transmit and receive information, is a necessity for aircraft communication systems. Transmissions from the transmitting antenna are of intense levels which radiate any nearby receiving antenna. Reception of the transmitted energy will degrade and, in some situations, damage the receiving system. The function of an interference cancellation system is to protect the receiving system against such degradation or damage.

Again referring to Figure 1, the interference cancellation system operation may be viewed as a balanced bridge. One branch of the bridge is the radiated path from the transmitter antenna to the receiver antenna. The other branch is the conducted path through the directional coupler and the controller to the summer in the receiver path. The transmitted signal is altered in two ways: the amplitude decreases because of propagation loss

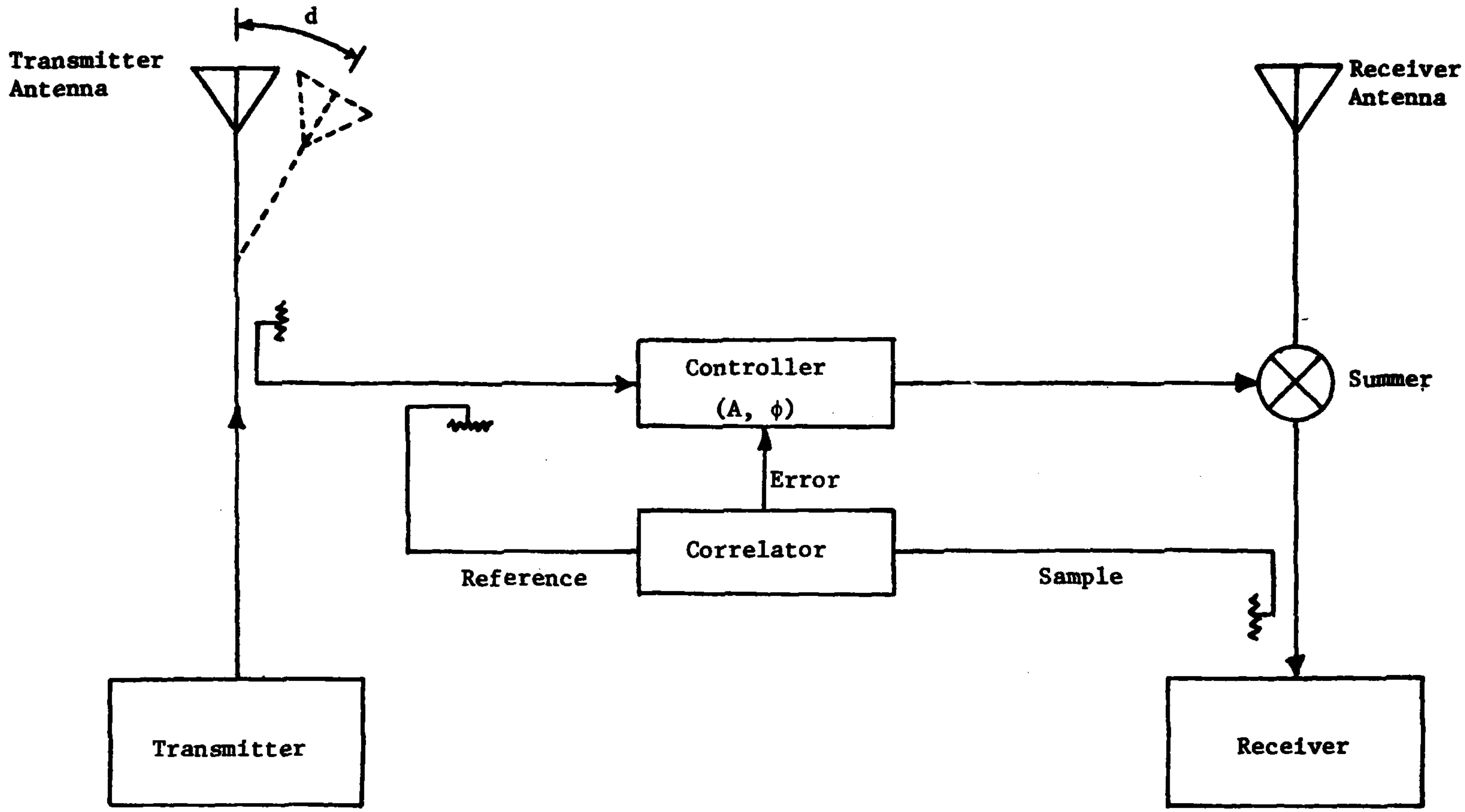


Figure 1 . Collocated Interference Cancellation System.

and is delayed in time because of the physical separation between the transmitter and receiver antennas. Thus the transmitted signal at the receiver antenna is identical to the signal at the transmitter except for a decrease in amplitude and a delay in time. If the conducted path is constructed and controlled so that it has the same time delay and amplitude characteristics as the antenna-to-antenna path, then a cancellation signal is synthesized. Interfering signals from the transmitter traveling through the radiated and conducted paths are identical except for opposite polarities. The signals from both paths are combined in the summer where cancellation occurs, thus preventing the interfering signal from entering the receiver input. Notice that the desired signals will not be cancelled since their propagation paths are different from the radiated path and no desired signals are present in the conducted path.

The conducted path signal is synthesized by first coupling power from the transmitter line through a directional coupler. The coupled power drives a controller which is a network that generates the necessary amplitude and time delay functions. In the controller, the conducted signal is divided into two channels that drive quadrature control mechanisms. One channel controls a sine function signal and the other channel controls a cosine function signal. The sine and cosine components are independently amplitude adjusted and summed to control the amplitude and time delay of the conducted signal. By properly adjusting the sine and cosine functions, a complete 360 degree control function is generated. If the amplitude of two signals is controlled to one-tenth percent with the same time delay, the interference cancellation system is capable of 60 dB cancellation in the receiver input path.

Since the exact parameters of the radiated path are unknown and they vary with time, a closed-loop circuit is added to the conducted path. This circuit is shown in Figure 1 as a correlator. The correlator samples the transmitter power and also samples the undesired power in the receiver path. The correlator uses these two inputs to generate an error signal. The error signal aids the controller in synthesizing the correct signal for cancellation.

Notice that when the transmitter or receiver antennas move with respect to each other, the radiated path parameters (amplitude and time delay) change.

Such movement causes an unbalance in the bridge and, as a result, interference levels increase in the receiver causing communication degradation. For small variations in the radiated or conducted paths, the closed-loop circuit is capable of making the proper adjustments in the amplitude and time delay parameters. However, as presently designed, the interference cancellation system is not capable of making the proper adjustments for large path variations. On large aircraft, such as flying command centers or bombers, one antenna may be mounted on the fuselage and the other on a wing tip. During maneuvering or take-off, the wing tip may move as much as ten feet with respect to the fuselage antenna. A ten-foot increase in the radiated path corresponds to approximately 10 nanoseconds additional time delay. The present controllers are not capable of adjusting for such large time delays. Thus, it is desirable to add an adaptive time delay to the conducted path to further refine the interference cancellation system. Adaptive time delay circuits would automatically make large adjustments during the time when the antenna movement unbalances the interference cancellation system.

2.2 ADAPTIVE TIME DELAY CIRCUITRY

Before establishing the design goals for an adaptive time delay circuit, the desired characteristics for an interference cancellation system will be reviewed. The adaptive time delay circuitry of course must be designed so as not to adversely affect the operation of the interference cancellation system.

The interference cancellation system must be linear and nondispersive. In other words the input signal may be changed in amplitude and delayed in time, but its spectral distribution must not be distorted. Components placed in the transmitter or receiver lines must have low insertion loss so as not to unduly degrade their operation. The signal to noise degradation in the receiver line must be negligible even for weak signals. Furthermore, the receiver performance should not be degraded when the interference cancellation system is inoperative. The interference cancellation system should require only a minimum number of initial setup adjustments. The system should operate over an octave or larger band and, if tuning is necessary, it should be automatic. Interference cancellation should be at least 60 dB or more, or to the receiver noise level.

Some of the mechanical aspects desired in an interference cancellation system are that no moving parts be required and that it be capable of withstanding the shock and vibration typically found in an aircraft. The installation of the interference cancellation system should require no transmitter or receiver modifications. Minimum maintenance should be required to keep the system operative.

Adaptive time delay units are needed in the HF, VHF, and UHF frequency bands. (Initially in this program, emphasis was to be placed on the development of units for the HF and UHF bands.) The time delay circuitry should be capable of handling one watt with higher power capability being desirable. A slow rate of change of the time delay is acceptable and may be on the order of 15-20 cycles per second. The adaptive time delay unit should have a range of 10 nanoseconds and a resolution of 0.01 nanoseconds. In Table I, this desired time delay is converted to the equivalent phase shift degrees for the HF and UHF bands.

Other desirable characteristics for the adaptive time delay units are low insertion loss and low insertion time delay. Insertion losses can be compensated for through amplification, but if the insertion losses become on the order of 40-50 dB, the amplification must be accomplished using tuned amplifiers which require tuning mechanisms. Low insertion time delay is desired since the interference cancellation system is easier to initially balance. In other words, if the conducted path has a time delay greater than the radiated path, additional time delay must be inserted in the receive antenna path to balance the interference cancellation system.

TABLE I

ADAPTIVE TIME DELAY CHARACTERISTICS

Frequency (MHz)	Period (nanosec)	Time Delay (nanosec)	Phase Shift (deg)	Resolution (deg)
2	500.0	10	7.2	.0072
10	100.0	10	36.0	.036
15	66.66	10	54.1	.054
30	33.33	10	108.1	.108
225	4.44	10	810.8	.81
300	3.33	10	1081.1	1.08
350	2.86	10	1258.7	1.26
400	2.50	10	1440.0	1.44

3.0 TIME DELAY TECHNIQUES

A comprehensive survey was made of available reports, published papers, and journal articles on time delay devices and phase shifters. Phase shifters were surveyed since many of the phase shifter techniques are adaptable to time delay. In order to establish the present state-of-the-art, manufacturer's catalogs, engineering data sheets, and bulletins were also reviewed. Some of the more important classes of time delay and phase shifter techniques are reviewed in this section.

3.1 CHARACTERISTICS OF DELAY LINES

Delay lines [6] are a specialized and an important type of transmission line in which the line parameters are adjusted to decrease the velocity of signal transmission. The transmission line may be coaxial, waveguide, strip-line, or parallel wire for electromagnetic waves. In other delay lines, the electromagnetic wave is converted to an acoustic wave and acoustic propagation occurs through a crystal material. Other lines convert an electromagnetic wave to magnetic waves which propagate in a ferrimagnetic material.

In general, delay lines may be of two types: nonacoustic and acoustic. Nonacoustic delay lines are further classified as either lumped-constant or distributed-constant. A lumped-constant delay line is one in which discrete inductors and capacitors are used. Lumped-constant types are used mainly to delay video signals. In the distributed-constant line, the inductance and capacitance are distributed along the line. The distributed-constant line is used for delay at RF or microwave frequencies.

An ideal delay line exhibits a linear phase shift from the input to the output that is proportional to frequency. The attenuation through the line is constant at all frequencies of interest [7]. Ideally the input signal would be transmitted through the delay line without any distortion (variation) in phase or amplitude with frequency. In the ideal delay line, all frequencies are delayed by the same amount t_d.

Omega-k diagrams as shown in Figure 2 illustrate the parameter relationships of concern in delay lines: ω is the radian frequency; k is the

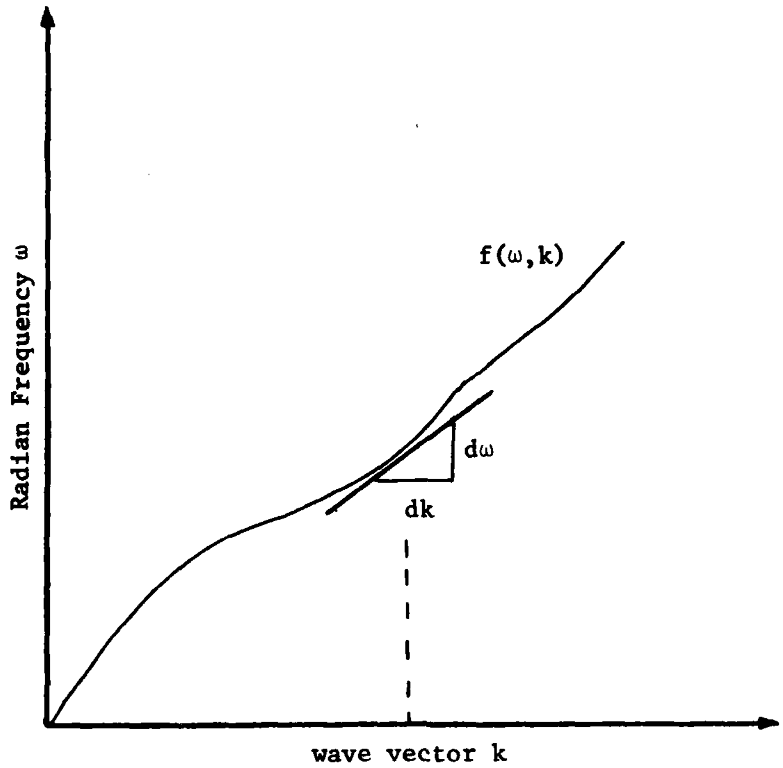


Figure 2 . ω-k Diagram for Delay Line.

wave vector or phase constant of the propagating wave and gives the change in phase per unit length. The phase velocity, V_p, of the delay line is:

$$V_p = \frac{\omega}{k} \text{ meters/second.} \tag{1}$$

The time delay (t_d) per unit length is expressed as:

$$t_d = \frac{1}{V_p} = \frac{k}{\omega} \text{ second.} \tag{2}$$

The total transit time is:

$$t_o = t_d \ell \text{ seconds.} \tag{3}$$

where ℓ is the length of the line in meters.

In Figure 2, an ideal delay line would exhibit a linear ω vs k relationship. If ω vs k is not linear, the delay line distorts (i.e., disperses) the input signal. The slope of the function f (ω, k) is the group delay, which is an equivalent way of measuring deviations from linear phase. Thus, group velocity is equal to:

$$V_g = \frac{\partial \omega}{\partial k} \text{ meters/second.} \tag{4}$$

The corresponding group delay time per unit length is:

$$t_g = \frac{1}{|V_g|} \text{ seconds.} \tag{5}$$

In a nondispersive delay line, the group velocity is equal to a constant. Thus the deviation from constant group delay corresponds to deviation from linear phase; it is these variations that indicate distortion. Where the group velocity is not equal to a constant, the delay line is defined as being dispersive. If the group velocity is equal to a constant over the frequency band of interest, the line is characterized as being nondispersive.

Further insight into group velocity can be gained by expressing the group velocity as a function of the phase velocity [8]:

$$V_g = \frac{V_p}{1 - \frac{\omega}{V_p} \frac{dV_p}{d\omega}} . \tag{6}$$

If $dV_p/d\omega = 0$ (nondispersive), then Equation 6 becomes:

$$V_g = V_p. \tag{7}$$

If $dV_p/d\omega$ is constant in the frequency band of interest, then group velocity expresses approximately the velocity of a signal's composite envelope and may be used as a "signal" velocity. However, if $dV_p/d\omega$ varies rapidly (large dispersions) it may be impossible to give any single velocity describing the propagation of a wave since the signal composite changes shape as it travels through the transmission line.

As previously discussed, an ideal (nondispersive) delay line delays all frequencies by the same amount t_d. Thus, an input frequency component, $\cos \omega t$, appears at the output of the delay line as $\cos \omega(t + t_d)$, since it appears t_d seconds later [9]. But this component can also be written as $\cos(\omega t + \phi)$, where the phase shift ϕ is equal to ωt_d. Thus a phase shift proportional to frequency is equivalent to a pure delay, with the proportionality constant equal to the delay. The difference between a delay line and phase shifter is more in the details of design rather than in their characteristics. Phase shifters are usually designed to produce a total phase shift of 360 degrees or less, while the equivalent phase shift through a delay line may be on the order of thousands of degrees.

3.2 VARIABLE TIME DELAY TECHNIQUES

The review of the technical literature revealed that numerous studies and investigations of variable time delay techniques have been undertaken. Most of these studies and investigations have been for microwave frequencies (1 GHz up) and for delay times greater than one microsecond. It is possible that some of the microwave variable delay techniques can be adapted for use in the VHF and UHF frequency bands. The survey of the microwave techniques was conducted with this objective in mind. Considerable research has been undertaken on UHF phase shifters and UHF fixed-delay techniques. Again some of these techniques may be adaptable to the design goals of this study. Also, several investigations have been completed on HF and VHF distributed-constant delay lines and these techniques are also reviewed.

Kirchner [10] published ten years ago a very good survey of microwave variable delay devices. Kirchner's classification of delay line devices is used in this survey and many of the devices he reviewed are briefly surveyed again. This survey updates Kirchner's and includes phase shifter technology for the HF, VHF and UHF bands. Kirchner classified variable delay lines as two types: nonacoustic and acoustic. Nonacoustic delay lines use either electromagnetic wave or magnetic wave propagation. Acoustic delay lines convert electromagnetic waves to acoustic or vibrational waves which propagate in crystal materials. In some cases, admixture propagation occurs that has properties of both magnetic and acoustic waves (magnetoelastic waves) which can not be classified as either purely nonacoustic or acoustic.

3.2.1 Review of Nonacoustic Variable Delay Techniques

Nonacoustic variable delay techniques employ two basic methods: (1) vary the electrical length of a transmission line by changing the phase velocity, or (2) vary the physical length of a transmission line. Time delay by either of these methods can be controlled either electrically or mechanically.

3.2.1.1 Electrically Controllable Variable Delay with Electrical Length Change

Electrically controllable variable delay with electrical length change may be realized with several devices such as:

(1) Helical delay line,
(2) Ferrimagnetic loaded line,
(3) Ferroelectric loaded line,
(4) Magnetic wave line,
(5) Diode loaded transmission line,
(6) Electron beam transmission.

(1) Helical Delay Line: An indepth study has been done for a low-impedance (50 ohm) helical delay line [11]. The study was done for a fixed delay line, but the technique is adaptable to a variable delay line. The

basic configuration of the line is shown in Figure 3. The line is a coaxial device with a helical center conductor wound on a ferrimagnetic core embedded in a high-permittivity dielectric. This configuration increases both the inductance (L) and capacitance (C) per unit length as compared to typical coaxial lines. The delay, which is proportional to $\sqrt{LC}$, is thus increased. The impedance of the line is equal to $\sqrt{L/C}$ and low-impedance is achieved by using the high-permittivity dielectric to increase the capacitance. Impedance matching [12] is obtainable by tapering the helix spacing at the ends of the ferrite rod.

A variable delay line can be configured by wrapping a wire solenoid around the coaxial line section. By varying the current in the solenoid, a varying magnetic field is set up in the ferrite rod. The permeability of the ferrite rod changes as the magnetic field varies. It appears the helical delay line can be designed for the HF, VHF, and UHF bands assuming that appropriate low-loss dielectric and ferromagnetic materials are available.

Katz [13], [14] investigated a variable helical delay line for the frequency range of 10-30 MHz. These were high-impedance lines designed for phase modulation rather than for variable delay. Nifant'yeva [15] constructed

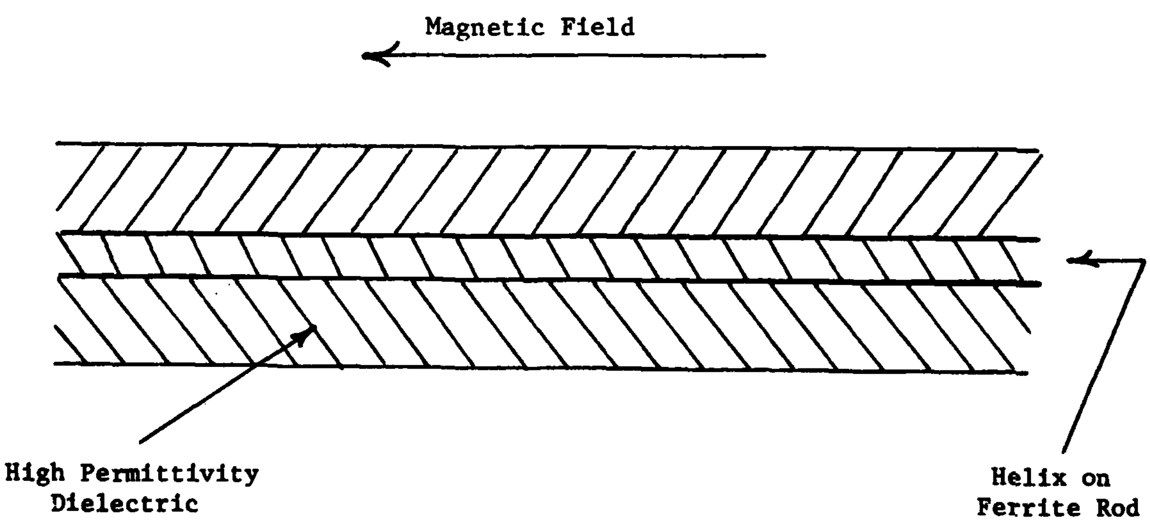


Figure 3. Cross Sectional View of Helical Delay Line.

a UHF phase shifter using a helical line and reported obtaining 360-degree phase shifts by varying the applied magnetic field. The phase shifter had low loss, but required up to 1500 oersteds of magnetic field intensity to vary the phase. Seckelmann [16] and Ivanov [17] investigated the coaxial "inverted" helix for latching ferrite phase shifters. The ferrite surrounds the helix in the "inverted" helix, while for the "normal" one the helix surrounds the ferrite. The latching phase shifter is alterable (but not variable) in phase in that it can be switched to the remanance magnetization. Sakiotis [18] investigated the use of slow-wave transmission lines (helical or meander lines) in the design of UHF phase shifters. He also discusses the different regions of operation for a ferrite material used within a phase shifter. Jones [19] studied the meander transmission line in a stripline configuration. His work was for a latching phase shifter for use at 5 GHz, but the meander line characteristics are useable at lower frequencies.

(2) Ferrimagnetic Loaded Line: This type of line utilizes ferrimagnetic material within the transmission line. In a coaxial line, the annular space is filled with a ferrite material; in stripline, the space between conductors is filled with a ferrite material. Evidently this technique has not been applied directly to variable delay lines, but propagation [19] - [25] in a coaxial or stripline has been researched, and the ferrimagnetic loaded line has been used in phase shifters. Fitzgerald [26] investigated phase shifters for the UHF band (200-400 MHz) using stripline. The ferromagnetic material was biased above resonance and operated below saturation. Phase shifting was accomplished by a change in the effective permeability due to domain-wall rotation. He reported obtaining 360-degrees phase shift with applied magnetic fields on the order of 100 oersteds. Johnson [27] - [29] also investigated the UHF phase shifter. The phase shifter was operated on the high-field side of ferromagnetic resonance and required an applied magnetic field variation of 900 oersteds for 360-degrees change in phase shift. Johnson found that by operating the phase shifter on the high side of resonance low losses were obtainable and high-power operation was possible up to at least 10 kilowatts peak. Boxer [30], [31] studied the characteristic of L-band high-power coaxial ferrite phase shifters. He also operated his phase shifter above resonance and reported good stability at high power levels

with low loss. Boxer pointed out that to obtain the high power stability, the control power and weight must be increased. He also found that the insertion loss changes with the input RF power level if the biasing magnetic field is not sufficiently large (i.e., the device becomes nonlinear).

(3) Ferroelectric Loaded Line: The dielectric constant of ferroelectric materials depends on the electric field applied to the material. The ferroelectric loaded line has been studied as a phase shifter and a delay line. Cohn [32] analyzed and constructed a UHF ferroelectric stripline phase shifter for operation over the 100 to 1000 MHz frequency range. He found that 4 kilovolts of applied voltage were needed to obtain 348 degrees of phase shift. Since the electrical current required to maintain or rapidly shift phase is low, the overall control power requirements are at least one order of magnitude less than those for comparable ferrite phase shifters (as compared to phase shifters available at the time of Cohn's research). Ferroelectric materials investigated by Cohn include barium titanate and mixtures of lead titanate and strontium titanate. Bar-Chaim [33] built and investigated a distributed-constant delay line using ferroelectric ceramics. Variations of the delay time were obtained by applying an external electric field to change the dielectric constant of the ferroelectric material. He reported delays of about 200 nanoseconds (insertion phase) and delay variations of 10 percent. The delay line was capable of operating up to bandwidths of 2 MHz and possibly up to 15 MHz with refinements.

A technique similar to the use of ferroelectric ceramics controlled by electric fields is the use of liquid artificial dielectrics using suspended metallic particles. The physical interaction that causes the suspended particles to exhibit controllable permittivity is similar to the one that occurs between light and the molecules of pure liquids in the Kerr electro-optic effect. Basically, the liquid-solid suspensions are gross models of Kerr liquids scaled from the optical to microwave frequencies. Mikuteit [34] and Bottenberg [35] have both investigated such liquid phase shifters for the Ku-band.

(4) Magnetic Wave Line: In ferrimagnetic materials, both magnetic waves or spin waves can propagate. Magnetic waves [36], [37] are generated

when electromagnetic energy perturbs the magnetic moments within a ferrimagnetic material. Since each magnetic moment is coupled by magnetic forces, adjacent moments will also be perturbed. Thus, magnetic or spin waves are created. There are two main types of magnetic forces that are operative in ferromagnetic material. The relatively long range dipolar forces determine the behavior of magnetic waves at low values of k (i.e., long wavelengths). At higher k's (short wavelengths), the short range exchange forces determine the behavior. The low-k spin waves are often referred to a magnetostatic modes while the high-k waves are called exchange-dominated spin waves. The velocity of propagation of the magnetic waves is controllable by an externally-applied variable magnetic field.

Delay lines using the magnetic wave principle can be built using yttrium iron garnet (YIG) or yttrium aluminum garnet (YAG) material. Figure 4 shows a cross-sectional view of a YIG-YAG-YIG delay line designed for L-band [38] Referring to Figure 4, the electromagnetic wave couples through a cable via the RF input connector. A fine wire coupler guides the electromagnetic wave to the end of a YIG-YAG-YIG rod, where a portion of the electromagnetic wave is converted to magnetic waves within the rod. The magnetic waves propagate through the rod to the other end where another conversion takes place--from magnetic waves to electromagnetic waves. The permanent magnet biases the YIG-YAG-YIG rod and variable delay is achieved by controlling the current through the electromagnet. For this delay line, variable delay times up to 2 microseconds were obtained. The insertion loss of the line was on the order of 60 dB which includes conversion and transmission losses. The conversion efficiency of this type of line has been studied extensively [39]. A similar type of L-band delay line has been studied by Olson [40] Eggers [41] investigated a UHF fixed delay line that operated at 735 MHz and had an insertion loss of about 37 dB for input power levels less than -10 dBm.

(5) Diode Loaded Transmission Line: Diode loaded transmission lines have been used to provide phase shift or to obtain small amounts of delay. Two classes of diode controlled phase shifters exist: the digital or switched-line phase shifter controlled by a PIN diode, and the analog (continuous) phase shifter controlled by a varactor diode. A digital phase shifter makes

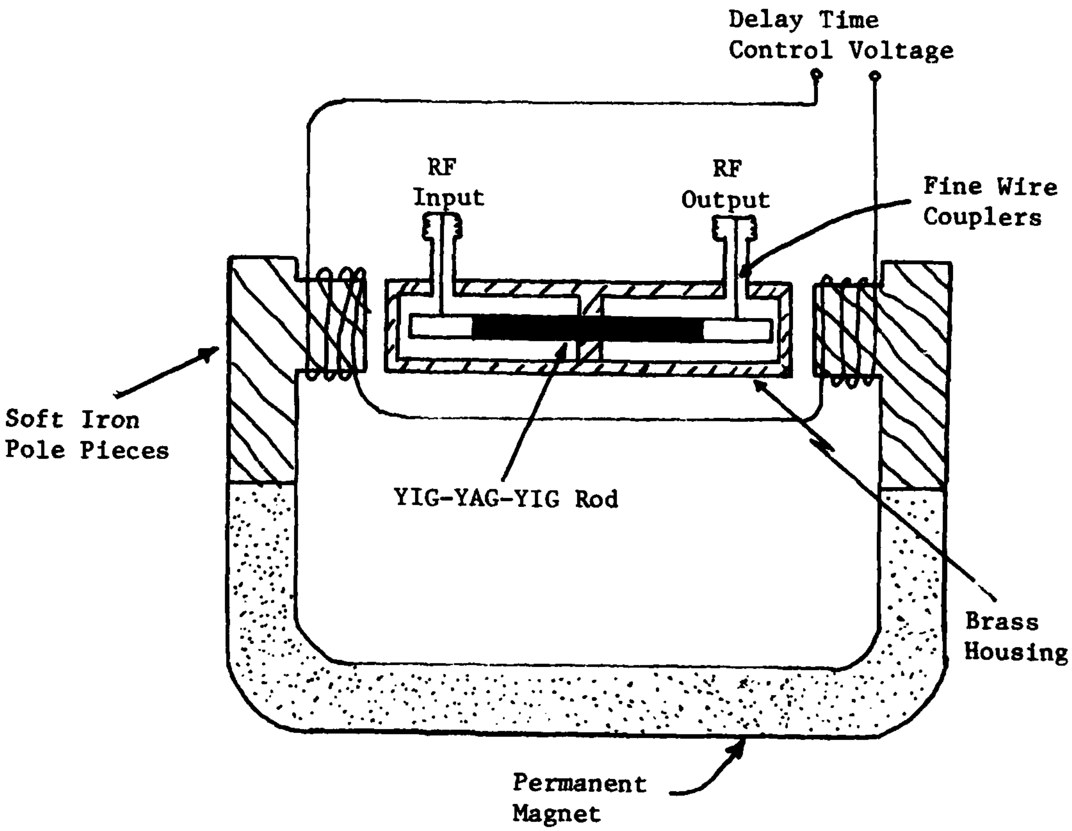


Figure 4 . Cross Sectional View of YIG-YAG-YIG Delay Line.

a predetermined amount of phase shift available by switching one or more of an array of two-position switches. Analog phase shifters may be made by using varactors whose capacitance may be changed continuously by varying the bias. Early diode loaded phase shifters had maximum bandwidths of 10 percent. Garver [42] compared the various types of diode loaded phase shifters and showed that indeed most can operate over an octave bandwidth. Jaffee [43] designed a low-phase velocity, dispersionless, and highly variable delay line for the VHF band with potential for use in the UHF band. He reported phase velocity variations as high as 8:1 from approximately c/50 to c/6, where c is the velocity of light in vacuum. The structure used was a four-layer microstrip line with: (1) a top conductor, (2) a silicon layer, (3) an insulator, and (4) a ground plane. Silicon dioxide was used as the insulator. The line was fabricated using planar integrated circuit techniques. Small diodes were placed along the line and reverse biased. By varying the bias voltage, the depletion layer in the silicon can be changed causing a change in the microstrip line capacitance and the delay time. Jaffe's measurements showed that the line's relative phase change with frequency was linear, showing the nondispersive character of the line.

(6) Electron Beam Transmission Line: By controlling the drift velocity of an electron beam, it is possible to obtain variable delay. The operation of the delay-line tube has many features in common with a traveling wave tube. The signal is coupled to an electron beam by means of a short section of helix and coupled out in a similar manner. Between the two helices, a long drift tube, electrically isolated from other parts of the tube, is inserted. The time delay of the signal is controlled by varying the potential on the drift tube. Harris [44] developed an electron beam line designed to give a variable delay of 500 nanoseconds over the frequency range of 1.1 to 2.3 GHz. Kluver [45] investigated the variable delay mechanism for an electon beam in a crossed field device. He achieved an effective low electron beam velocity in the drift region by using the property of an electron drift in crossed DC electric and magnetic fields. This device had an insertion loss of only 3 dB, but the bandwidth was only 7 MHz. Chorney [46] studied the ion beam delay line which is capable of developing longer delay times than the electron beam delay line.

3.2.1.2 Electrically Controllable Variable Delay with Physical Length Change

The primary method of electrically controlling variable delay with physical length change is through the use of digital delay lines. The recirculating memory is another method of obtaining such delays.

The digital delay line was discussed previously (Section 3.2.1.1) in connection with the diode loaded transmission line. Transmission lines which can be used to provide delay in the digital line include coaxial cable, stripline, special delay line cable, or acoustical devices. Coaxial line provides lowest dispersion. The loss of high quality coaxial can be held to approximately 1.25 dB per 100 nanosecond delay at 1.0 GHz. For long delays, cable lengths have to be long to achieve the necessary delay. For 100 nanosecond delay, approximately 80 to 90 feet of coaxial cable is required.

The power handling capability of switching diodes used in digital lines can be traded off against speed. By utilizing power diodes, switches capable of handling one watt may be built. However, diode switches do have impedance matching problems associated with the series diode reactance and resistance. The matching circuits are necessary to avoid amplitude and phase distortion in complex signals.

3.2.1.3 Mechanically Controllable Variable Delay with Physical Length Change

The adjustable air line, or trombone line stretcher, is the most common type of variable delay line that mechanically varies the physical length. (There are techniques that incorporate acoustic waves and these will be discussed in a later section.)

3.2.1.4 Mechanically Controllable Variable Delay with Electrical Length Change

The electrical length of a transmission line such as a coaxial cable or waveguide can be varied mechanically by moving a dielectric strip from a region of weak electric field to a region of strong electric field. Bleackley [47] constructed a rotary helical coaxial phase shifter based on this principle. The mechanism employs a loosely wound helix with control of phase shift accomplished by both the translation and the rotation of a dielectric worm having the same pitch as the helix. The depth of insertion of the worm into the helix controls the amount of phase change per revolution. The technique is attractive from a mechanical point of view since the phase shift is controllable via rotation and requires no moving electrical contacts.

3.2.2 Review of Acoustic Variable Delay Techniques

In this section, delay line techniques that convert electromagnetic energy to acoustic energy are discussed. Acoustic energy in the form of plane waves propagates through an acoustic delay medium at a velocity four to five orders of magnitude slower than electromagnetic waves (10^6 cm/sec compared with 3×10^{10} cm/sec). At the end of the acoustic medium, the acoustic energy is reconverted to electromagnetic energy. Acoustic delay techniques thus offer long delay times in physically short line lengths. Acoustic variable delay lines may be controlled either electrically or mechanically.

3.2.2.1 Electrically Controllable Acoustic Delay Lines

Electrically controllable acoustic delay can be obtained using: (1) surface acoustic wave (SAW) devices, (2) magnetoelastic wave devices, (3) acoustic delay lines with signal processing, and (4) ferroelectric materials.

(1) Surface Acoustic Wave (SAW) Devices: The operation and design of SAW devices have been tutorially discussed by White [48] and Holland [49] A conventional surface wave acoustic delay line consists of two interdigital transducers (fingers) deposited on a piezoelectric substrate, as shown in Figure 5. The operation of the device can be understood physically by considering that an AC voltage applied to the input transducer causes the substrate between the fingers to distort due to the piezoelectric effect. This periodic strain leads to an acoustic wave propagating away from the input transducer in both directions with a frequency equal to that of the applied signal. In one direction, the acoustic wave is absorbed in a lossy medium. In the other direction, the wave propagates to the output transducer and is detected

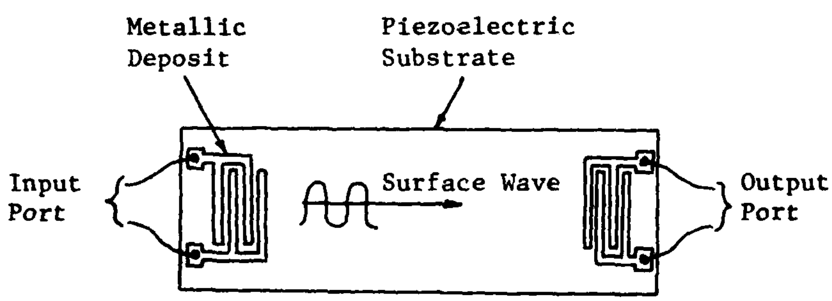


Figure 5. Conventional surface wave delay line configuration.

by the inverse piezoelectric effect. SAW devices usually are operated at frequencies between 1 MHz and 1 GHz. The devices can have high fractional bandwidths (theoretically approaching an octave). They are usually constructed using the same photolithographic processing techniques that are used for metallization of integrated circuits. SAW's are inherently nondispersive devices.

Electrically controlled variable delay is somewhat more difficult to be obtained in SAW devices than in other delay line techniques. However, Hopp [50] invented a variable SAW delay line. His line consists of a fixed interdigital trandsucer formed by metal deposited on a piezoelectric, photoconductive surface. The receiving transducer is formed by illuminati 3 the photoconductive surface through a mask to create the image of a transducer where the signal is to be received. By making the optics movable, a variable path length and, hence, a variable delay time can be achieved. According to Hopp, a variable SAW operating at 1.0 GHz appears to be feasible. Manes [51] also demonstrated a continuously variable delay using a SAW tapped delay line and a digital shift register. By properly timing the shift register clock waveform, the delay time can be controlled. The technique can be viewed as using an electronically programmable delay line whose output is obtained by spatial sampling at the tap points on the delay line.

(2) Magnetoelastic Wave Devices: A single-crystal yttrium iron garnet (YIG) can support a number of modes as shown by the dispersion curves in Figure 6 [52]. The magnetostatic and spin wave modes have been discussed in relation to the magnetic wave delay line. The elastic or acoustic wave was discussed in relation to the SAW devices. In the crossover region between the spin wave and the elastic wave curves, these waves form magnetoelastic waves that take on some of the properties of both magnetic and elastic waves. The distinguishing feature of the magnetoelastic wave is that their velocities of propagation can be varied and controlled by an external magnetic field. Unfortunately, magnetoelastic waves are dispersive as can be seen from the slope of the curves in Figure 6.

By properly shaping the internal magnetic field profile of a YIG rod through the use of magnetic sleeves around the rod and by varying the applied magnetic field, essentially nondispersive variable delay can be obtained

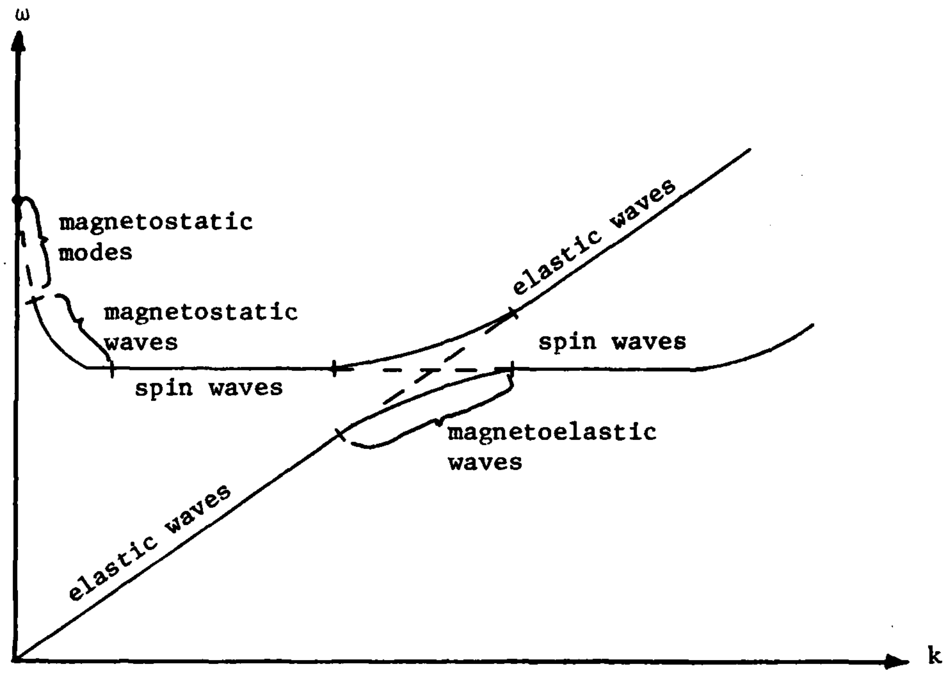


Figure 6 . Dispersion Curves for an Axially Magnetized Rod.

with magnetoelastic waves. Using this technique, Van De Vaart [53] demonstrated dispersionless delay over a 10 percent bandwidth in low L-band with an insertion delay of slightly over 2 microseconds and a delay variation of up to 60 nanoseconds. Insertion loss was greater than 80 dB. Auld [54] has reported on the synthesis procedures to obtain nonuniform magnetic fields needed for nondispersive propagation in a magnetoelastic device. Moore [55] designed a YIG magnetoelastic delay line for L-band which had a bandwidth of 400 MHz and variable delay to 2 microseconds.

(3) Signal-Processing Techniques: Podell [56] reported on a scheme for producing continuously variable time delay using two dispersive delay lines with spectral inversion to achieve dispersionless variable delay. The technique is reported in this section since the dispersive delay lines may be SAW devices [57], [58].

A block diagram of Podell's techniques is shown in Figure 7. Note that two local oscillator signals f_1 and f_2, are mixed and the products are fed

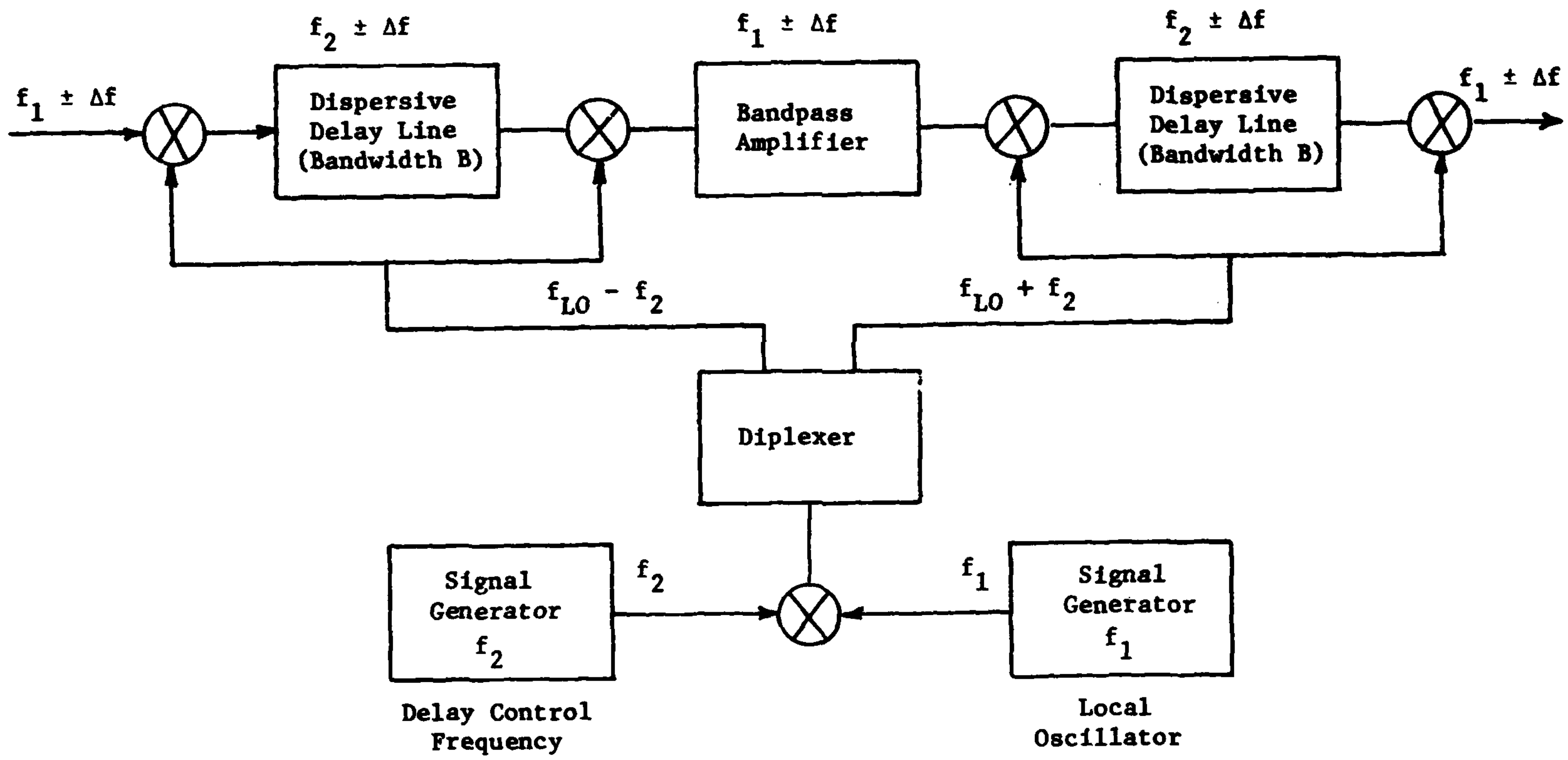


Figure 7 . Nondispersive Delay System Using Dispersive Delay Lines.

to a diplexer. One local oscillator frequency is fixed at the midband frequency, f_1, of the signal band of interest and serves to translate the signal band to the operating band of the dispersive delay lines. The frequency of the other local ocillator, f_2, controls the amount of delay through the system and must lie within the operating band of the dispersive delay lines. From the diplexer, the lower sideband, $f_1 - f_2$, is sent to the mixers preceding and following the first dispersive delay line, and the upper sideband, $f_1 + f_2$, is sent to the mixers preceding and following the second dispersive delay line. The difference between the signal frequency, $f_1 \pm \Delta f$, and the lower sideband produces an IF frequency, $f_2 \pm \Delta f$, in the first dispersive delay line. At the mixer following the first delay line, the sum of the lower sideband and the IF frequency recreates the signal frequency, $f_1 \pm \Delta f$. At the mixer preceding the second delay line, the difference between the upper sideband and the signal frequency again produces an IF frequency that lies within the passband of the dispersive delay line. However, this time the signal spectrum is inverted. The final mixing process at the output of the second delay line produces the difference between the upper sideband and the IF frequency, which again is the signal frequency with its spectrum re-inverted. Podell applied the technique at low L-band and obtained a total variation of time delay of about 45 nanoseconds.

(4) Ferroelectric Materials: Use of ferroelectric materials was discussed in Section 3.2.1 to electrically control the electrical length of a transmission line. Here acoustic propagation in ferroelectric materials is discussed. Investigations of the electromechanical properties of ferroelectric perovskite-type crystals show that the velocity of acoustic waves in these crystals can be varied by changing the strength of an applied electric field. Fedotov [59] has shown that in polarized barium titanate ceramic the velocity of the longitudinal acoustic wave increases with the increasing electric field intensity. He found that one limitation of using barium titanate was that a considerable time lag exists between application of an electric field and the corresponding variation of the velocity. Apparently, it is possible to achieve small delays of up to 10 percent of the insertion phase by using acoustic waves in ferroelectric materials at frequencies below 100 MHz.

3.2.2.2 Mechanically Controllable Acoustic Delay Lines

Acoustic delay lines can be controlled mechanically as well as electrically. For example, Banks [60] developed a continuously variable SAW delay line that had a translatable interdigital transducer of aluminum photo-etched glass substrate. The substrate is moved on the SAW surface to increase decrease the delay time. Translation is accomplished using a micrometer drive. The delay was variable from 1.5 to 5 microseconds with an overall insertion loss of about 17 dB as measured at 109 MHz.

Magnetoelastic mechanically variable delay mechanisms have been investigated by Kirchner [61]. In Kirchner's device, energy is coupled into a YIG rod via a piezoelectric thin-film transducer that produces a shear acoustic wave propagating along the rod axis. The shear acoustic wave propagating along the rod axis is coupled to magnetic modes of the YIG rod by means of the magnetoelastic interaction. Conversion from acoustic energy to magnetic energy takes place within the rod at the point of an applied DC magnetic field. An output loop couples the energy excited magnetic modes to the output. The delay time is the sum of the finite propagation times of the acoustic, magnetoelastic, and magnetic waves. Essentially, nondispersive delay results by minimizing the duration of the signal in the magnetoelastic and magnetic modes. Broadband nondispersive delay is achieved by using a step magnetic field profile which confines magnetoelastic conversion near one physical location for a wide range of frequencies. Variable delay is provided by moving the position of the step magnetic field with respect to the input transducer, thus changing the delay contribution of the nondispersive acoustic wave but leaving the contributions of the magnetoelastic and magnetic waves constant. The net result is a mechanically variable tap on a nondispersive delay line.

Brienza [62] used acousto-optical coupling to achieve a mechanically controllable delay line. Variable delay was obtained by converting an input RF signal into an acoustic wave at one end of a crystal and then removing this signal via elasto-optical coupling at some variable distance from the input transducer. The acousto-optical interaction used to output couple is based on the principle of Bragg diffraction. The output light beam is frequency shifted by the frequency of the input RF signal. Optically heterodyning the output light beam with a portion of the incident light beam provides a means of recovering the delay signal. Variable delay is obtained by mechanically moving the crystal material with respect to a laser beam.

Variable delay can also be achieved by mechanically sliding one acoustic crystal relative to the other to change the acoustic path. Dubrov [63] has constructed a delay line based on this principle.

3.3 EVALUATION OF TECHNIQUES

The evaluation of electrically controllable nonacoustic variable delay line techniques follows:

(1) Helical Delay Line: The feature of the helical delay that is attractive is that low-impedance (50 ohm) can be obtained and impedance matching is possible by appropriate helix design. The line is capable of wide bandwidths and good power-handling capability.

(2) Ferrimagnetic Loaded Line: High losses appear to be the main disadvantage of this line. Its use as a delay line has not been thoroughly investigated.

(3) Ferroelectric Loaded Line: This line has possibilities but more information as to its losses and its obtainable time delay is needed.

(4) Magnetic Wave Line: Efficient coupling methods are needed to minimized conversion losses for this line. Multiple reflections along the YIG rod may occur which would be disruptive to the operation of an interference cancellation system.

(5) Diode-Loaded Transmission Line: Limited time delay variation is the disadvantage of this line. However, the technique of using diodes distributed along a silicon substrate has possibilities but it may be limited in power handling capability. Diodes have nonlinear response regions which may be a source of spurious responses.

(6) Electron Beam Transmission: This technique is capable of producing the desired time delay variation, but it may have rapid changes in the insertion loss. This technique is also fairly complex and may not withstand shock and vibration successfully.

(7) Digital Line: This line is not capable of providing the desired time delay resolution for the HF range. However for the UHF range, it may be possible to use two delay lines in series. The first line would be digitally controlled so as to switch in different transmission-line sections. The second line would be an analog type controlled through a digital-to-analog converter. Both delay

lines could then be controlled digitally. Such a line may be more complex than required, but it would have low loss and be nondispersive.

The disadvantages of using acoustic-type delay lines to achieve the design goals are: (1) high insertion phase, (2) high insertion or conversion losses, and (3) inability to achieve the desired time delay resolution. Again only the electrically controlled lines are evaluated here. The evaluation is as follows:

(1) Surface Acoustic Wave: The SAW devices evidently cannot be easily varied in time delay and the desired time delay resolution would be difficult to achieve.

(2) Magnetoelastic Wave Devices: Nondispersive operation requires a shaped magnetic field which is an added complexity. Insertion loss is high.

(3) Signal-Processing Technique: This is an attractive technique from the control point-of-view since time delay variability is accomplished by changing an oscillator frequency. However, the technique uses several mixers which may be susceptible to spurious responses.

(4) Ferroelectric materials: The technique may have application for the HF band, but needs additional research.

4.0 EXPERIMENTAL RESULTS

Of the various delay techniques discussed in the literature, three were chosen for laboratory evaluations. The three selected were: (1) the ferrite loaded dielectric delay line; (2) the helical delay line; and (3) the ferrofluid dielectric delay line. The selections were motivated primarily by the availability of materials, by the ease of construction, and by the promise of good electrical characteristics. Previous studies under Air Force sponsorship [64] showed ferrite loaded dielectrics could be used to achieve magnetically tunable resonators. It was therefore surmised that such dielectrics could also be used to produce magnetically (i.e., electrically) variable time delays. This past experience with ferrite loaded dielectrics helped motivate the selection of the ferrite loaded dielectric delay line. A factor that contributed to the selection of the helical delay line was its ease of construction and simplicity. Also the literature survey revealed that the helical line had been investigated for fixed delays and these previous studies provide a basis for investigations of variable helical delay lines. The selection of the ferrofluid delay line was influenced by the availability of materials. Also for the ferrofluid, being a fluid with suspended ferrite particles, it was reasoned that ferrofluid's permeability could be easily changed with low magnetic fields and thus minimize the required drive power.

4.1 DESIGN MODELS

The three design models chosen were the helical delay line, a ferrite loaded dielectric delay line, and a ferrofluid dielectric delay line. The latter two delay lines fall within the category of ferrimagnetic loaded lines discussed in Section 3.0.

The magnetic properties of the ferrite rods and powders used in the construction of the delay lines are summarized in Table II. All of the ferrites are off-the-shelf materials obtained from Indiana General, Keasby, New Jersey. The ferrite rods were used in the construction of the helical delay lines, and the ferrite powders were used in the construction of the ferrite loaded dielectric lines.

TABLE II

MAGNETIC PROPERTIES OF FERRITE MATERIALS

Property	Units	T-1	0-3	Q-1	Q-3	H	0-5
Initial Permeability		2000 @ 100 kHz	1500 @ 100 kHz	125	16	850	2200
Maximum Permeability		3600	4000	400	42	4300	5400
Saturation Flux Density	Gauss	4400	4500	3300	2600	3400	4700
Residual Magnetism	Gauss	1000	1600	1800	1470	1470	1100
Coercive Force	Oersted	0.18	0.15	2.1	21	0.18	0.11
Maximum Frequency Range		400 kHz	400 kHz	10 MHz	150 MHz	1 MHz	500 kHz
Curie Point	°C	180	190	350	500	170	215
Loss Factor	PPM	25 @ 100 kHz	33 @ 100 kHz	200 @ 10 MHz	430 @ 100 MHz	300 @ 1 MHz	40 @ 500 kHz

The construction details of the helical delay line are shown in Figure 8. Basically, a coaxial-line section is used with the center conductor replaced with a helix on a ferrite rod and a high-permittivity dielectric material is used to fill the annular space. A 14-turn helix using 27 AWG enamel-insulated copper line was wound on the ferrite rod. The turn spacings were tapered at the rod ends for impedance matching. Powdered titanium dioxide with a dielectric constant of 100 was used in the annular space. The coaxial line dimensions and helix design were based on data in Megla's paper (Reference 11). Three helical delay lines were constructed using identical dimensions, but with different ferrite rods. All the ferrite rods were 0.25 inch in diameter and were H, Q-1, or 0-5 grade ferrites. The helical lines were

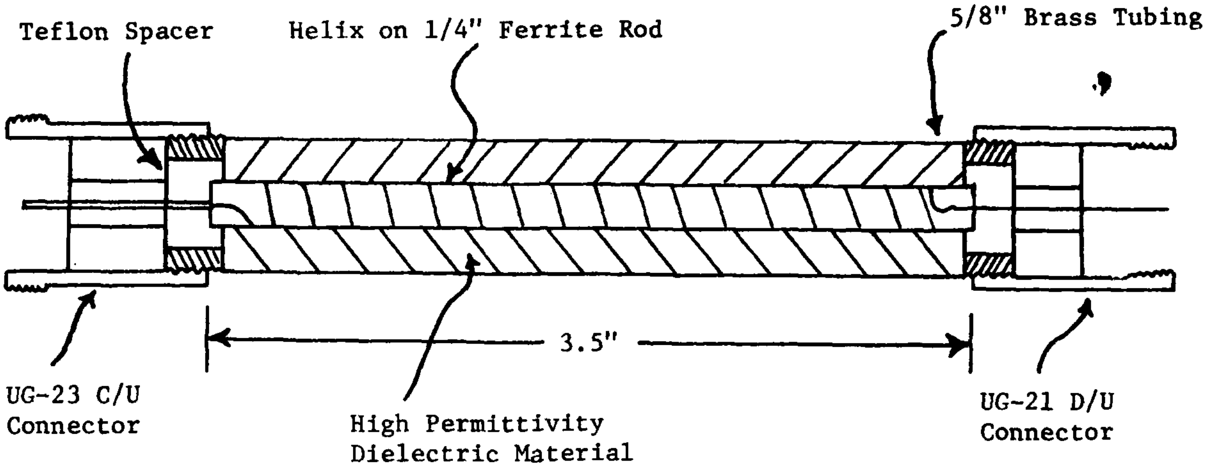


Figure 8. Construction of Helical Delay Line.

magnetized in the longitudinal direction (H-vector parallel to long dimension of line) using a solenoid that surrounded the helical line. The solenoid was 3.5 inches long with an inner diameter of 1.0 inch. The solenoid was constructed with 1500 turns of 22 AWG enamel-coated copper wire.

The ferrite loaded dielectric delay line construction is shown in Figure 9. These coaxial sections used brass center conductors with a ferrite powder and epoxy mixture between the inner and outer conductors. The ferrite powder was mixed with the epoxy in a 4:1 ratio by weight. The epoxy binder is a mixture of epoxy, hardener, and a debubbling agent. Epon Resin 828 manufacturered by Shell Chemical Company was used as the epoxy and the hardener was diethylene triamine marketed by Magnolia Plastics, Inc. The debubbling agent was Plastolein 9051 DNHZ, which was obtained from Emery Industries, Inc. The measured permeability and permittivity of the ferrite loaded dielectric mixtures are given in Table III. The coaxial line sections were designed for 50 ohm impedance using the equation:

$$Z_o = 138\sqrt{\frac{\mu_r}{\varepsilon_r}}\ \log_{10}\frac{r_2}{r_1} \qquad (8)$$

where: Z_o = impedance in ohms

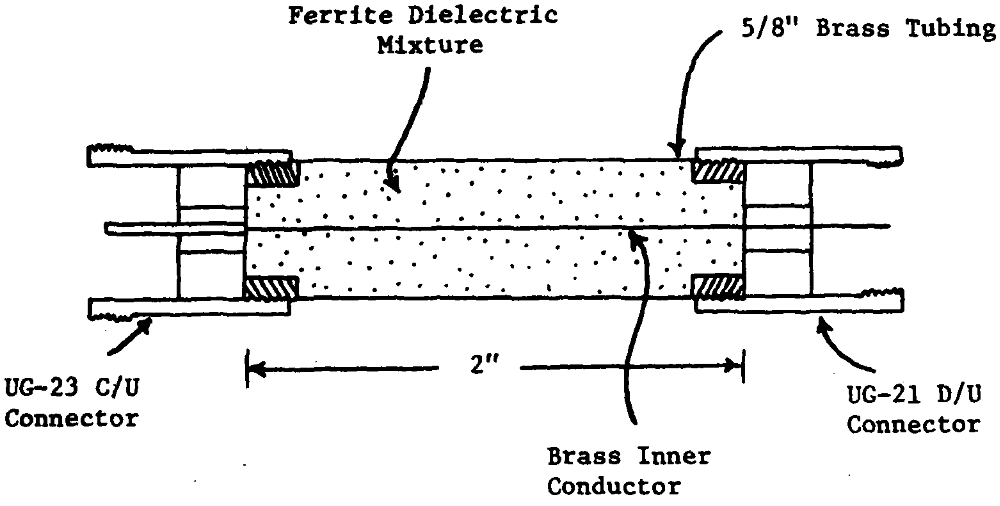


Figure 9. Construction of Ferrite Loaded Dielectric Delay Line.

TABLE III

PERMEABILITY AND PERMITTIVITY OF FERRITE/DIELECTRIC MIXTURES
(4:1 Mixture, Frequency = 400 MHz)

	μ'_r	μ''_r	ε'_r	ε''_r
T-1	4.18	4.01	16.18	1.16
O-3	3.70	1.31	7.97	2.44
Q-1	3.64	1.00	8.17	0.28
Q-3	2.81	0.89	5.93	0.68

μ_r = relative permeability

ϵ_r = relative permittivity

r_2 = radius of outer conductor, inches

r_1 = radius of inner conductors, inches

The ferrite loaded dielectric lines were magnetized in the transverse direction (H vector perpendicular to the long dimension) using a stator from a Barber-Colman shaded-pole motor (part number DYAR 876-118). Use of the stator proved to be an economical method of generating strong magnetic fields. Four different ferrite loaded dielectric lines were constructed using T-1, O-3, Q-1, and Q-3 ferrite grades.

The ferrofluid dielectric delay line was constructed according to the details in Figure 10. The ferrofluid was obtained from Ferrofluidics Corp., Burlington, Massachusetts. H01 hydrocarbon base fluid, which has a magnetic saturation of 200 gauss and a dielectric constant of 20 at 1 kHz, was used between the inner and outer conductor of the delay line. The line was designed using Equation 8 to have 50 ohm input impedance. The center conductor in the coaxial section had a diameter of 0.0625 inches. The stator of the shaded-pole motor was also used as the magnetic field drive for the ferrofluid dielectric delay line.

4.2 TEST INSTRUMENTATION

The instrumentation used to measure the phase shift and loss through the design models is shown in Figure 11. The signal generator was set at a test frequency and the vector voltmeter locked at the frequency. The relative phase shift was observed on the vector voltmeter as the current in the coil surrounding the delay line was varied. The insertion loss was measured by switching between the reference and signal lines of the vector voltmeter. By repeating this procedure, phase shift and insertion loss for each delay line was measured as a function of the applied DC magnetic field. The phase shift at each frequency was converted to time delay using the following equation:

$$\frac{T}{360} = \frac{t_d}{\phi} \tag{9}$$

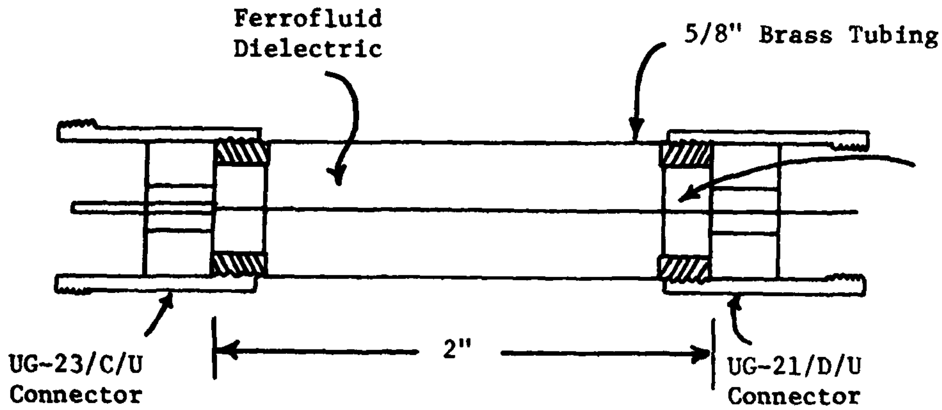


Figure 10. Construction of Ferrofluid Dielectric Delay Line.

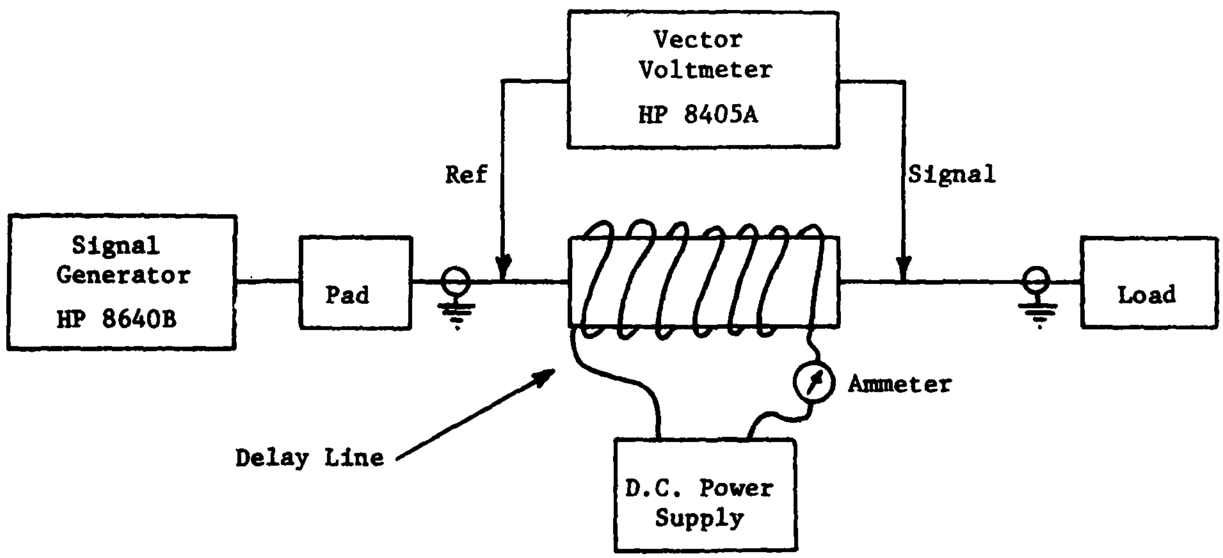


Figure 11. Instrumentation for Measuring Phase Shift and Loss Through Delay Line.

where T = period of the signal, seconds

ϕ = measured phase shift, degrees

t_d = time delay, seconds.

The magnetic fields of the shaded-pole stator and the solenoid were calibrated using a Bell Model 620 gaussmeter with a Hall Effect probe. The current was varied in known quantities and the resulting magnetic field measured using the gaussmeter. The calibration curve for the stator magnetic field is shown in Figure 12.

4.3 TEST RESULTS

The time delay and insertion loss for each of the design models was measured at discrete frequencies over the 2-400 MHz range. Table IV lists the maximum time delays measured for the helical and ferrite loaded dielectric delay lines as a function of frequency for the different grades of ferrites. Of the helical delay lines, the line using the H-grade ferrite rods exhibited the largest time delay in the 2-30 MHz frequency range. However, it was found during the measurements that the H-grade ferrite was temperature sensitive. The material has a Curie temperature of 170 degrees Centigrade which is lowest for the ferrites tested. Of the ferrite loaded dielectric lines, the T-1 ferrite material produced the largest delays across the 2-400 MHz range. Notice that the required applied magnetic field for the helical delay line was 600-800 oersteds while the ferrite loaded dielectric lines requird 1365 oersteds to obtain the maximum delays. Thus, the helical delay line has more attractive control power requirements.

Table V lists the maximum insertion loss measured for the helical and ferrite loaded dielectric lines. Of the helical delay lines, the Q-1 helical delay has the lowest insertion loss over the 2-30 MHz range. Again, for the ferrite loaded dielectric lines, the T-1 ferrite material has the best overall performance over the 2-400 MHz range.

In Figures 13, 14, and 15, time delay and insertion loss are shown for the H grade ferrite helical delay line at 2, 15, and 30 MHz, respectively. Similar graphs are shown in Figures 16, 17, and 18 for the Q-1 grade ferrite helical delay line.

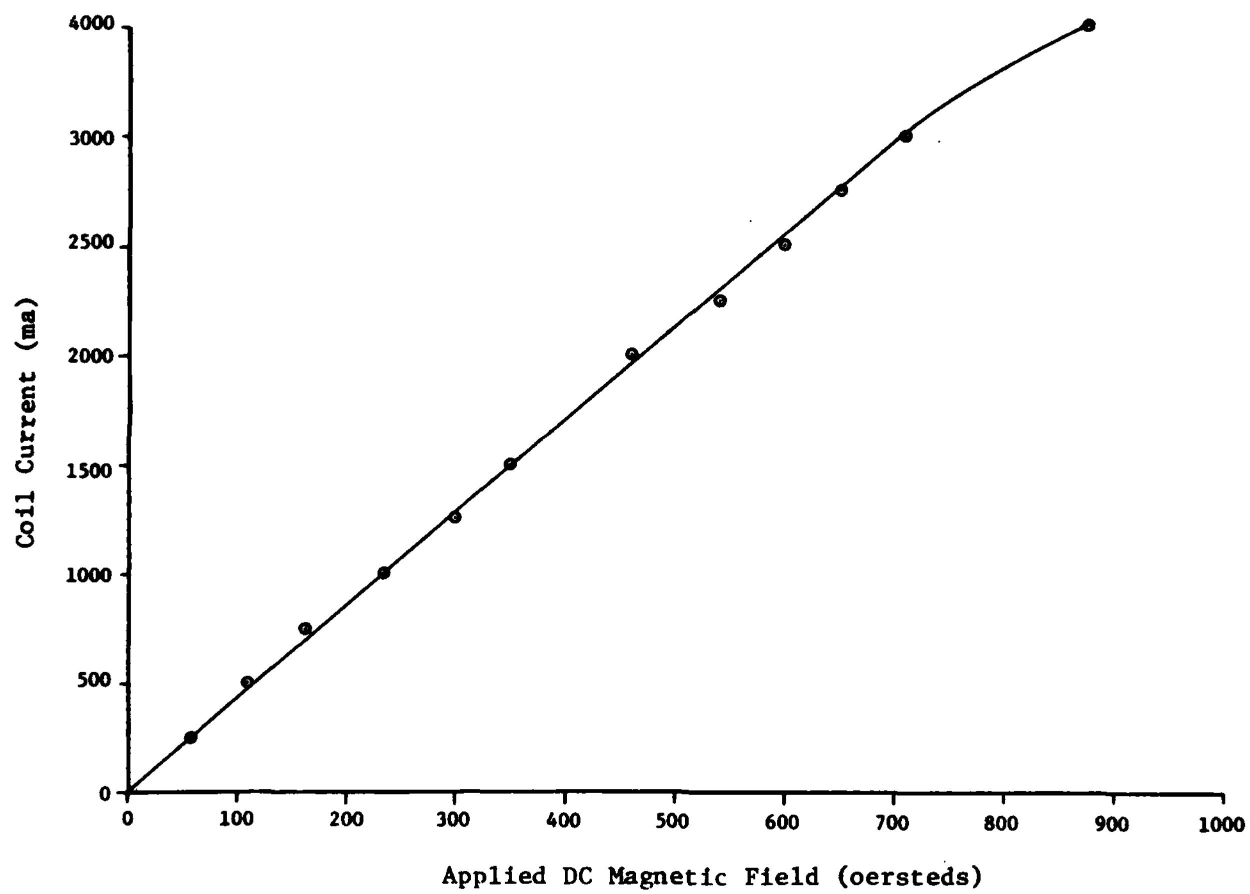


Figure 12. Calibration Curve for Stator Magnetic Field.

TABLE IV

COMPARISON OF MAXIMUM DELAY TIMES VS DELAY LINE TYPE
(Delay Times in Nanoseconds)

Delay Line	Applied Magnetic Field (Oersteds)	Frequency (MHz)									
		2	10	15	25	30	50	100	200	300	400
Q-1 Helical	600-800	6.5	5.0	3.9	2.4	1.9	.8	.2	.8	.6	.6
H Helical	600-800	7.9	5.8	4.4	2.5	2.4		.3	1.3		1.9
O-5 Helical	600-800	7.6	5.4	3.5	1.1	1.6	.1	.3	.02	.03	.04
T-1/Dielectric	1365	2.1	.9	2.0	1.0	2.0	.9	1.0	1.0	.9	.8
O-3/Dielectric	1365		2.5		1.5		1.4	.8	.4	.5	.4
Q-1/Dielectric	1365		1.0		1.0		.7	.4	.1	.2	.3
Q-3/Dielectric	1365		1.0		1.1		.8	.4	.1	.2	.3

Graphs of the time delay and insertion loss for the T-1 ferrite loaded dielectric line are shown in Figures 19, 20, and 21 for 200, 300, and 400 MHz, respectively. Figure 22 is a graph of the dispersion characteristics of the line for frequency variation from 200 and 300 MHz center frequency.

Limited measurements were made on the ferrofluid delay line over the 2-400 MHz frequency range. However, the line exhibited only fractions of a nanosecond time delays. Since its performance in comparison to the helical and ferrite loaded dielectric line was poor, it was decided early that this type of line was not a good candidate. The low variation of time delays measured may be a result of the low concentrations of ferrite material within the H01 ferrofluid.

4.4 CONCLUSIONS - EXPERIMENTAL RESULTS

For the HF frequency range, the helical delay line shows promise of meeting some of the design goals for the desired time delay characteristics. Based on the measured data for the H grade ferrite delay line at 30 MHz, a 15 inch line should be capable of providing the desired 10 nanoseconds variable delay. The insertion loss at 30 MHz for a 15 inch line would be

TABLE V

COMPARISON OF MAXIMUM INSERTION LOSSES VS DELAY LINE TYPE
(Insertion Loss in dB)

Delay Line	Applied Magnetic Field (Oersteds)	Frequency (MHz) 2	10	15	25	30	50	100	200	300	400
Q-1 Helical	0	.1	2.1	3.8	6.7	7.9	11.3	14.1	3.1	12.2	4.8
H Helical	0	.1	2.4	4.2	7.5	8.8		13.0	24.0		19.0
O-5 Helical	0	.1	3.2	5.9	10.3	11.0	9.8	10.1	8.0	7.1	12.0
T-1/Dielectric	0	.1	.1	.1	.2	.2	.8	1.7	4.2	9.0	14.0
O-3/Dielectric	0		.01		.1		1.0	3.1	6.2	9.5	13.0
Q-1/Dielectric	0		.01		.4		1.6	3.5	3.7	2.0	3.8
Q-3/Dielectric	0		.01		.4		1.5	3.4	3.9	2.1	3.4

about 35 dB. However, it may be possible to reduce this loss by using smaller diameter ferrite rods and better high-permittivity dielectric materials. The powdered titanium dioxide was the only dielectric material available at the time of the construction of the helical lines and hence may not be the best choice.

In comparison to the other lines, the T-1 ferrite loaded dielectric line has the best characteristics for the UHF frequency range. However, to obtain the desired 10 nanoseconds delay variation at 400 MHz would require a 25 inch line which would have a prohibitively large insertion loss. For this reason, the ferrite loaded dielectric line does not show promise as a method to obtain the desired time delay characteristics.

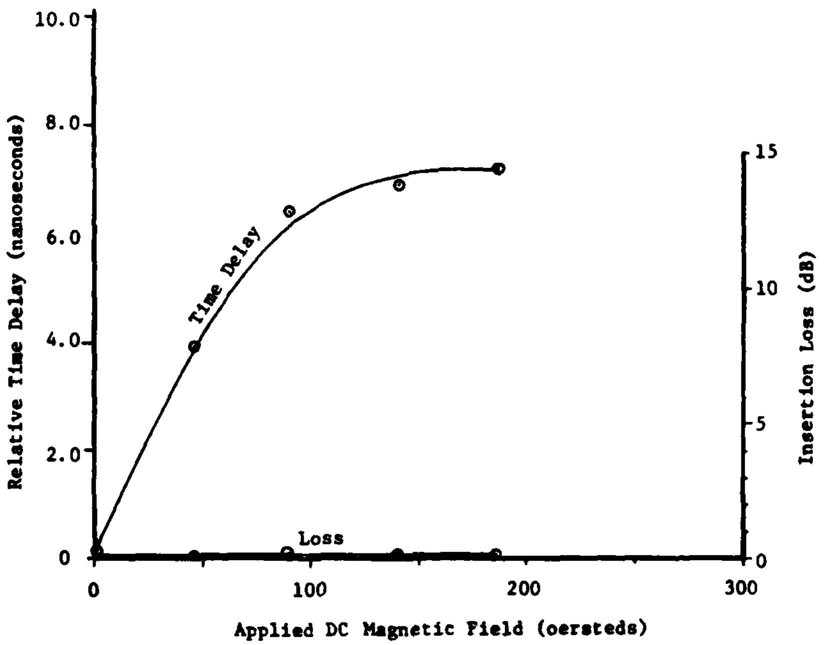


Figure 13. Time Delay Characteristics at 2 MHz of 3.5 Inch Coaxial Line with Helical Inner Conductor Loaded with H Ferrite.

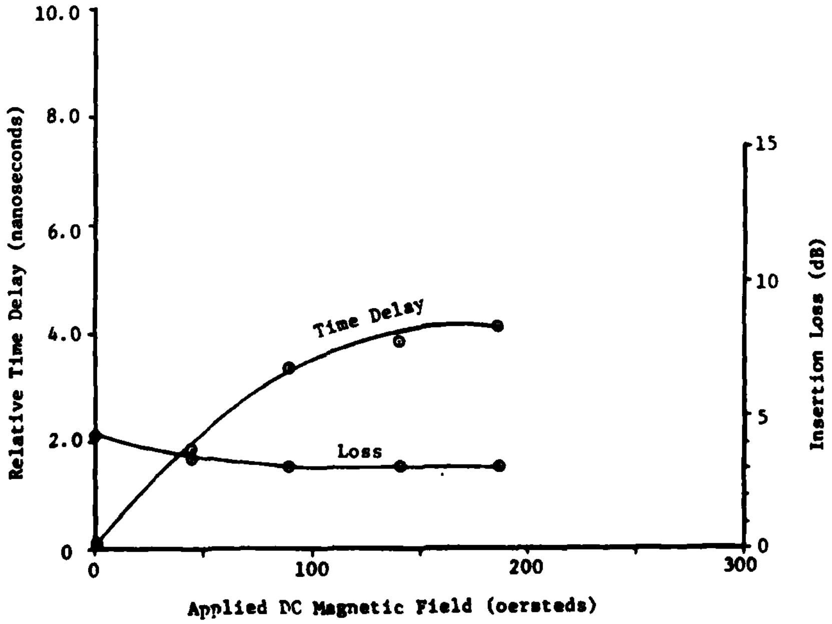


Figure 14. Time Delay Characteristics at 15 MHz of 3.5 Inch Coaxial Line with Helical Inner Conductor Loaded with H Ferrite.

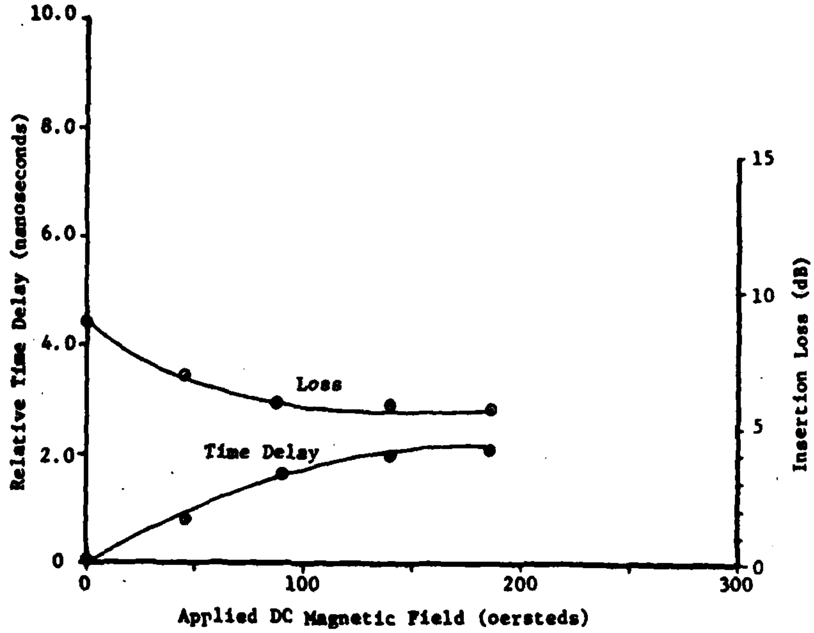


Figure 15. Time Delay Characteristics at 30 MHz of 3.5 Inch Coaxial Line with Helical Inner Conductor Loaded with H Ferrite.

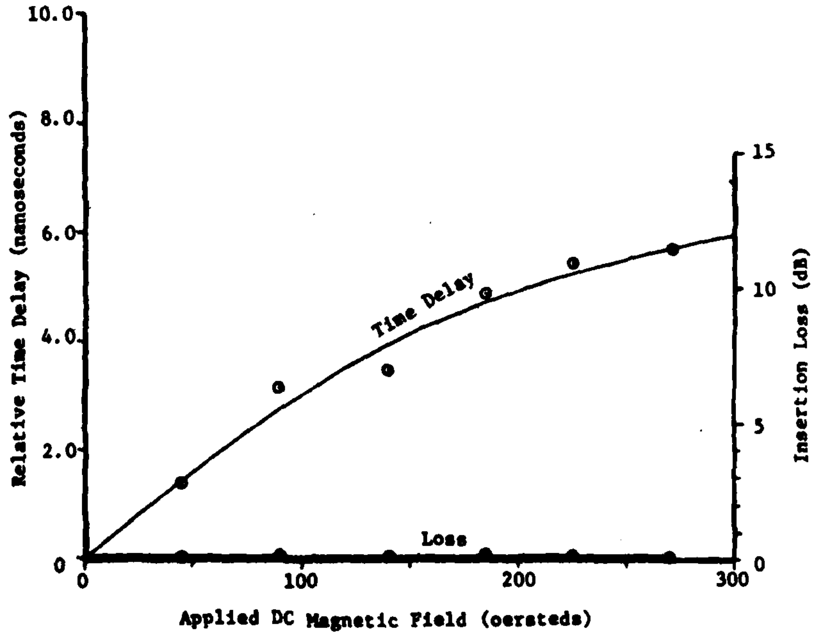


Figure 16. Time Delay Characteristics at 2 MHz of 3.5 Inch Coaxial Line with Helical Inner Conductor Loaded with Q-1 Ferrite.

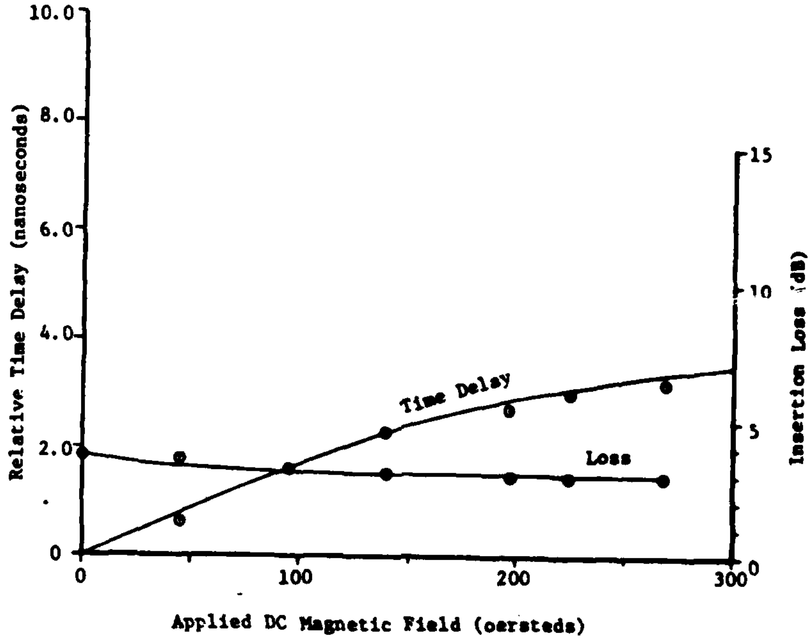


Figure 17. Time Delay Characteristics at 15 MHz of 3.5 Inch Coaxial Line with Helical Inner Conductor Loaded with Q-1 Ferrite.

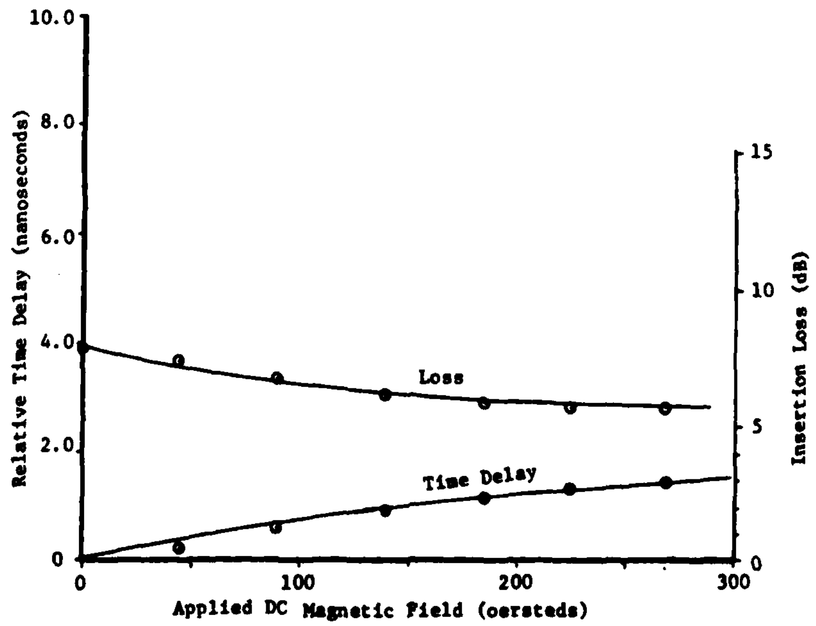


Figure 18. Time Delay Characteristics at 30 MHz of 3.5 Inch Coaxial Line with Helical Inner Conductor Loaded with Q-1 Ferrite.

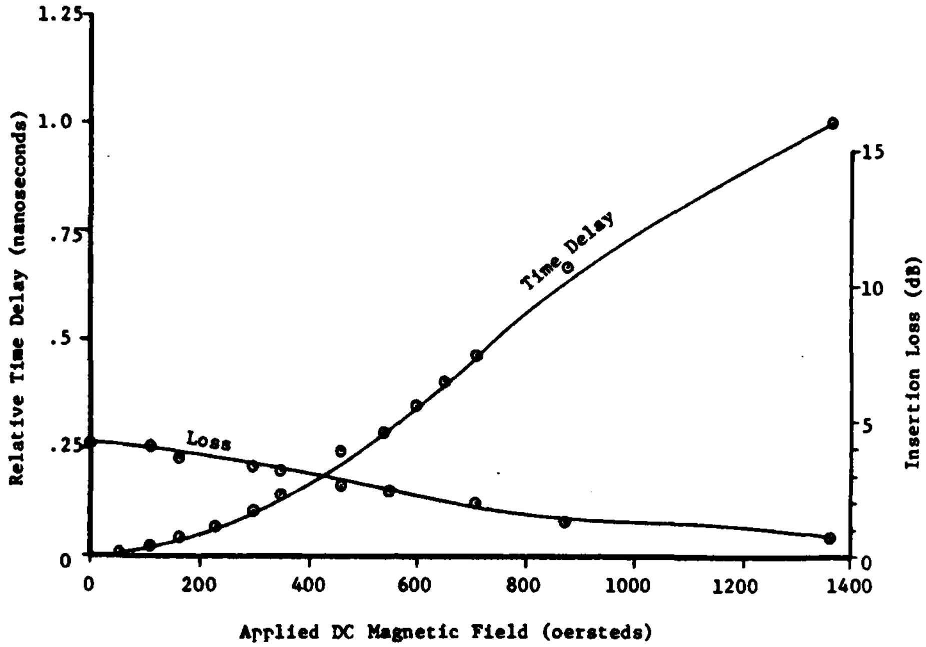


Figure 19. Time Delay Characteristics at 200 MHz of 2.0 Inch Coaxial Line with T-1 Ferrite and Epoxy Mixture in Annular Space.

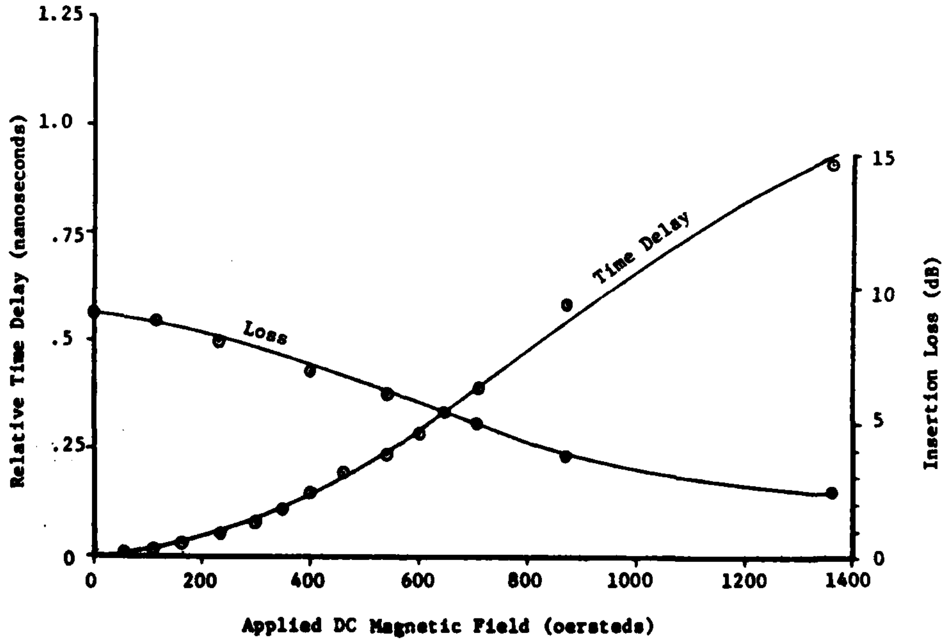


Figure 20. Time Delay Characteristics at 300 MHz of 2.0 Inch Coaxial Line with T-1 Ferrite and Epoxy Mixture in Annular Space.

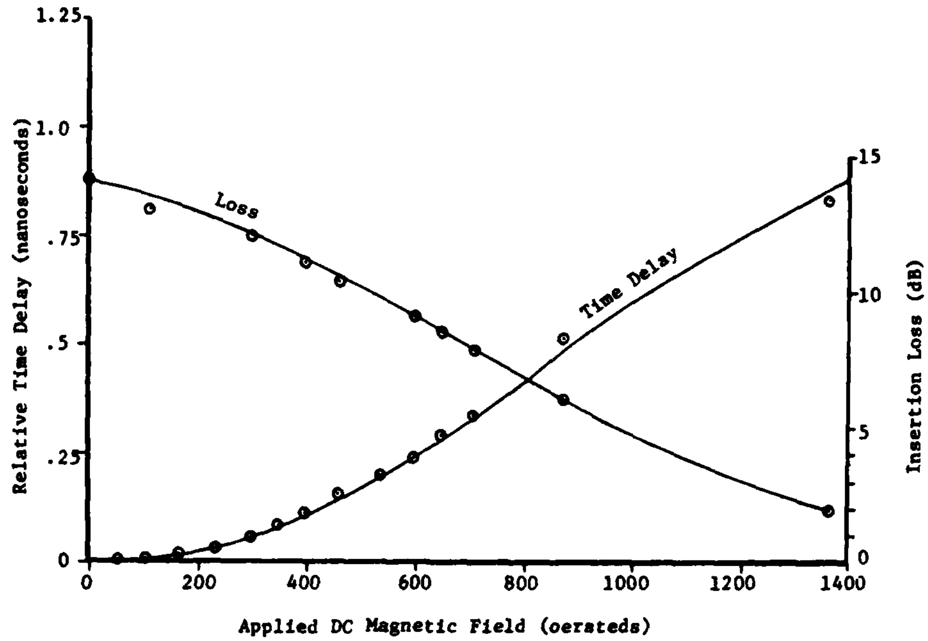


Figure 21. Time Delay Characteristics at 400 MHz of 2.0 Inch Coaxial Line with T-1 Ferrite and Epoxy Mixture in Annular Space.

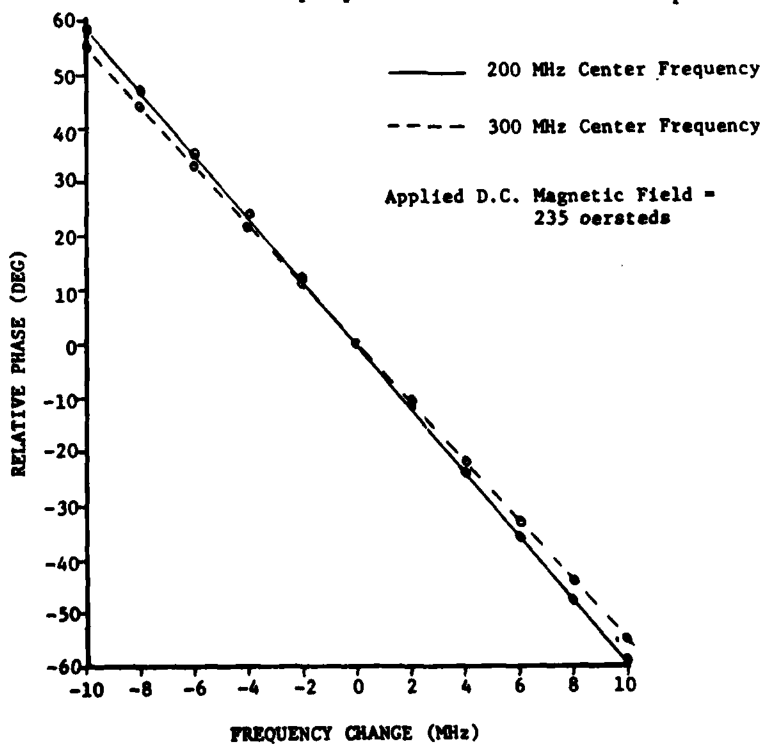


Figure 22. T-1/Dielectric Delay Line Dispersion.

5.0 RECOMMENDATIONS

Based on the techniques surveyed and the experimental results, the helical delay line through improved designs may be capable of achieving the design goals for the HF band. Additional work needs to be completed in the following areas:

(1) Better construction techniques and material selection are needed to further refine the helical delay line.

(2) Longer length helical delay lines need to be constructed. These lines need to be tested as to the obtainable time delay and the required magnetic field drive.

(3) Additional tests are needed to determine the dispersive characteristics of the helical delay line.

(4) Additional tests are needed to characterize the insertion loss of the helical delay line as a function of input power.

For the UHF band, other transmission-line configurations and techniques need to be investigated. Perhaps a ferrite loaded stripline with a meander line center conductor is a good candidate. Additional investigations as to ferrite material selection are needed. The ferrite materials used in this effort are intended primarily for the HF and VHF applications. Perhaps a better approach at UHF would be to use ferrites intended for microwave frequencies. The technique of biasing ferrite materials above ferromagnetic resonance to reduce losses and increase power capability should be investigated, particularly if the stripline with meander line configuration is used. The other alternative is to try a different technique for the UHF band. Possibilities include the YIG delay line, digital delay line, or the magnetoelastic delay line.

6.0 REFERENCES

1. Sauter, Walter A. and Rabindra N. Ghose, "Active Interference Cancellation Systems," American Nucleonics Corp., Glendale, Ca., Final Technical Report, RADC-TR-69-41, April 1969, AD 852 786.

2. Abrams, B. S., et al, "Interference Cancellation: Volume I, Analysis and Breadboard Design, Volume II, Antenna Range and Laboratory Experiments," General Atronics Corporation, Philadelphia, Pa., Final Technical Report, RADC-TR-74-225, September 1974, AD-B000 101L, AD-B000 174L.

3. Harris, Samuel J. and Andrew E. Zeger, "High Power Controller and ICS," General Atronics Corp., Philadelphia, Pa., Final Technical Report, RADC-TR-77-272, August 1977. (A044757)

4. Harris, Samuel, "Nonlinear Interference Cancellation System," General Atronics Corp., Philadelphia, Pa., Final Technical Report, RADC-TR-78-225, November 1978. (B032512L)

5. Sauter, Walter A., "Interference Cancellation Systems," 1979 Interference Technology Engineers Master (ITEM), R&B Enterprises, pp. 166-168.

6. Landee, Robert W., D. C. Davis, and A. P. Albrecht, Electronic Designers' Handbook, McGraw-Hill Book Co., Inc., New York, 1957, pp. 20-59.

7. Nordlin, H. G., "Electromagnetic Delay Lines," 1954 Electronics Components Symposium Proceeding, pp. 153-157.

8. Ramo, Simon, J. R. Whinnery, and T. Van Duzer, Fields and Waves in Communications Electronics, John Wiley & Son, Inc., New York, 1967, pp. 48-51.

9. Lubkin, Yale Jay, Filter Systems and Design: Electrical, Microwave, and Digital, Addison-Wesley Publishing Company, Reading, Massachusetts, 1970, p. 75.

10. Kirchner, Ernst K., "Microwave Variable Delay Devices," IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-17, No. 11, November 1969, pp. 986-997.

11. Megla, G. K., L. C. Gunderson, and J. Singletary, "A Low-Impedance Helical Delay Line," The Micowave Journal, January 1968, pp. 55-59.

12. Lund, C. O., "A Broadband Transition From Coaxial Line to Helix," RCA Review, March 1950, pp. 133-142.

13. Katz, H. W. and R. E. Schultz, "Miniaturized Ferrite Delay Lines," IRE Convention Record, Part 3, 1955, pp. 78-86.

14. Katz, H. W. "High-Frequency Ferrite Delay Line for Phase Modulation," 1957 Electronic Components Symposium Proceedings, May 1957, pp. 55-58.

15. Nifant'yeau, F. P., "A Ferrite UHF Phase-Shifter," Pribory i Tekhnika Eksperiments, No. 1, 1961, pp. 101-102. Translated by Foreign Technology Division, FTD-TT-62-38/1+2+4, AD 272 534.

16. Seckelmann, Robert, "Phase-Shift Characteristics of Helical Phase Shifters," IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-14, No. 1, January 1966, pp. 24-28.

17. Ivanov, K. P. and K. G. Kostov, "Propagation in Helical Line with Latching Ferrite Medium," 5th European Microwave Conference, 1975, pp. 503-507.

18. Sakiotis, N. G. and D. E. Allen, "Slow-Wave UHF Ferrite Phase Shifter," Journal of Applied Physics, Supplement to Vol. 33, No. 3, March 1962, pp. 1265-1266.

19. Brodwin, Morris E., "Propagation in Ferrite-Filled Microstrip," IRE Transactions on Microwave Theory and Techniques, April 1958, pp. 150-155.

20. Fleri, D. and B. J. Duncan, "Reciprocal Ferrite Devices in TEM Mode Transmission Lines," IRE Transactions on Microwave Theory and Techniques, January 1958, pp. 91-96.

21. Brodwin, M. E. and D. A. Miller, "Propagation of the Quasi-TEM Mode in Ferrite-Filled Coaxial Line," IEEE Transactions on Microwave Theory and Techniques, September 1964, pp. 496-503.

22. Weiner, M. M., "Propagation of the Quasi-TEM Mode in Ferrite-Filled Coaxial Line," IEEE Transactions on Microwave Theory and Techniques, (Correspondence), January 1966, pp. 49-50.

23. Lewis, Terry, "Propagation Constant in a Ferrite-Filled Coaxial Waveguide," Proceedings of the IEEE, Feburary 1967, pp. 241-242.

24. Mueller, Ralph S. and Fred J. Rosenbaum, "Propagation in Ferrite-Filled Coaxial Transmission Lines," IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-16, No. 18, October 1968, pp. 835-842.

25. Weiner, Melvin M., "Conditions for Approximating the Limit-TEM Mode by a Quasi-TEM Mode in a Ferrite-Filled Coaxial Line," IEEE Transactions on Microwave Theory and Techniques, (Letters), March 1973, pp. 156-157.

26. Fitzgerald, William D. and Leslie Klein, "UHF Ferromagnetic Phase Shifters (200-400 MHz)", Final Report, Chu Associates, Contracts Nobsr-81386, Nobsr-72586, June 1960, AD 277-361.

27. Johnson, C. M. and G. V. Buehler, "Ferrite Phase Shifter for the UHF Region," Electronic Communications, Inc., Timonium, Md., AFCRC-TN-58-182, Contract AF 19(604)-2407, May 27, 1958, AD 152 430.

28. Johnson, C. M., "Ferrite Phase Shifter for the UHF Region," IRE Transactions on Microwave Theory and Techniques, January 1958, pp. 27-31.

29. Johnson, C. M., "Ferrite Phase Shifter for the UHF Region, Part II," Electronic Communications, Inc., Timonium, Md., AFCRC-TN-60-138, Contract AF 19(604)-2407, October 31, 1959, AD 234 145.

30. Boxer, A. S., S. Hershenov, E. F. Landry, "A High-Power Coaxial Ferrite Phase Shifter," IRE Transactions on Microwave Theory, MTT-19, 1961, p. 577.

31. Boxer, A. S. and R. S. McCarter, "Coaxial Ferrite Phase Shifter for High Power Applications," Journal of Applied Physics, Supplement to Vol. 33, No. 3, March 1962, pp. 1263-1264.

32. Cohn, M. and A. F. Elkenberg, "UHF Ferroelectric Phase Shifter Research," Electronic Communications, Inc., Timonium, Md., AFCRL-62-319, Contract AF 19(604)-8379, April 30, 1962, AD 276 454.

33. Bar-Chaim, H. and M. Brunstein, J. Grunberg, A. Seidman, and M. Birk, "Variable Delay Line Based on the Nonlinear Characteristics of Ferroelectric Ceramics," Proceedings of the IEEE, (Letters) July 1973, pp. 1045-1046.

34. Mikuteit, Siegfried, H. T. Buscher, R. M. McIntyre, "An Artificial Dielectric Liquid Phase Shifter," European Microwave Conference Proceedings, 1971, B10, pp. 4:1-4:4.

35. Bottenberg, W., "Variable Permittivity Liquid Phase Shifters," General Dynamics, Contract F30602-75-C-0202, RADC-TR-76-328, October 1976, AD-A033 396.

36. Smith, A. B., "Microwave Magnetoelectric Devices," Electronic Components Conference Proceedings, May 13-15, 1970, pp. 480-492.

37. Kaufman, I. and R. F. Soohoo, "Magnetic Waves for Microwave Time Delay - Some Observations and Results," IEEE Transactions on Microwave Theory and Techniques, July 1965, pp. 458-467.

38. Smith, A. B., "L-Band Variable-Delay-Time YIG-YAG-YIG and YAG-YIG-YAG Delay Lines," IEEE Transactions on Microwave theory and Techniques, Vol. MTT-17, No. 11, November 1969, pp. 997-1001.

39. Ohta, Tadashi, Naoyuki Ogasawara, Masami Yanagibori and Yoshiaki Kaji, "Conversion Efficiency from Electromagnetic Waves to Magnetostatic Waves," Electronics and Communications in Japan, Vol. 53-B, No. 1, 1970, pp. 73-81.

40. Olson, F. A. and L. D. Buchmiller, "A Two-Port Microwave Variable Delay Line," IEEE Microwave Theory and Techniques Symposium Digest, 1964, pp. 80-83.

41. Eggers, F. G. and Walter Strauss, "A UHF Delay Line Using Single-Crystal Yttrium Iron Garnet," Journal of Aplied Physics, Vol. 34, No. 4 (Part 2) April 1963, pp. 1180-1181.

42. Garver, R. V., "Broadband Diode Phase Shifters," HDL-TR-1562, August 1971, AD-729 302.

43. Jaffe, Jams M., "A High-Frequency Variable Delay Line," IEEE Transactions on Electron Devices, December 1972, pp. 1292-1294.

44. Harris, N. W. and S. F. Palk, "Broad-Band, Voltage-Variable Electron Beam Delay Line," Proceedings of the IEEE, January 1970, pp. 157-159.

45. Kluver, J. W., "An Electronically Variable Delay Line," Proceedings of the IEEE, (Correspondence), Vol. 50, December 1962, p. 2487.

46. Chorney, P., R. J. Briggs, K. K. Chow, and S. F. Palk, "Microwave Electronically Varible Ion Beam Time Delay Device," Technical Report RADC-TR-68-149, July 1968. (837699)

47. Bleackley, W. J., "A Rotary Helical Coaxial Phase Shifter," Microwave Journal, Vol. 9, February 1966, pp. 38-40.

48. White, R. M., "Surface Elastic Waves," Proceedings of the IEEE, Vol. 58, August 1970, pp. 1238-1276.

49. Holland, Melvin, G. and Lewis T. Clairborne, "Practical Surface Acoustic Wave Devices," Proceedings of the IEEE, Vol. 62, May 1974, pp. 582-611.

50. Hopp, Theodore H., "An Investigation of the Frequency Limitations of a Surface Wave Variable Delay Line," Harry Diamond Laboratories, HDL-TM-74-28, December 1974, AD-A008 967.

51. Manes, Gianfranco, "A Novel Surface-Acoustic-Wave Device for Electronically Variable Delay," Proceedings of the IEEE, Vol. 66, No. 4, April 1978, pp. 519-520.

52. Rodrigue, George P., "Magnetoelastic Waves - New Mechanisms for Energy Transport," IEEE Spectrum, June 1965, pp. 81-85.

53. Van De Vaart, H., "A Dispersionless Variable Microwave Delay Line," IEEE Transactions on Microwave Theory and techniques, November 1968, pp. 965-966.

54. Auld, B. A. and W. Strauss, "Internal Mgnetic Field Analysis and Synthesis for Prescribed Magnetoelastic Delay Characteristics," Journal of Applied Physics, Vol. 37, March 1966, pp. 983-987.

55. Moore, R. A. and G. J. Moussally, "Electronically Variable Low-Dispersion YIG Delay Line," IEEE Transactions on Microwave Theory and Techniques, March 1971, pp. 334-337.

56. Podell, A. F., R. E. Lee, and A. J. Bahr, "A Novel Continuously Variable Delay Line," 1972 Microwave Theory and Techniques Symposium Digest, pp. 92-94.

57. Burnsweig, J., W. T. Gosser, and S. H. Arneson, "Electronically Controllable Time Delay," 1973 Microwave Theory and Techniques Symposium Digest, pp. 134-136.

58. Dolat, V. S. and R. C. Williamson, "A Continuously Variable Delay Line System," ESD-TR-76-389, Contract F19628-76-C-0002, 1976, AD-A040 522.

59. Fedotov, I. L. Coll: Applications of Ultrasonics to the Investigation of Matter (In Russian) Vol. 15, 1961, p. 201.

60. Banks, C., Gene Chao, and Dennis Web, "Continuouslly Variable Surface Acoustic Wave Delay Line," Naval Research Laboratory Memorandum Report 2802, May 1974, AD 779 267.

61. Kirchner, E. K., F. A. Olson, and G. E. Bennett, "Magnetoelastic Two-Port Devices: Nondispersive Variable Delay Line," Journal of Applied Physics, Vol. 39, February 1968, p. 489-491.

62. Brienza, M. J. and A. J. DeMaria, "Continuously Variable Laser Acoustic Delay Line," IEEE Journal of Quantum Electronics, Vol. QE-3, November 1967, pp. 567-575.

63. Dubrov, W. I. and G. E. Huling, "Mechanically Variable 1000 MHz Delay Line," IEEE Symposium on Sonics and Ultrasonics, Vancover, Canada, October 1967.

64. Warren, Jr., W. B., J. R. Walsh, Jr., H. W. Denny, and C. S. Wilson, "RFI Applications of Dielectric Materials," RADC-TR-65-466, December 1965, AD 476-392.