Microwave Variable Delay Devices

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Abstract—Needs for nondispersive microwave variable delay devices exist in radar, communication, ECM, and test systems. Methods which have been investigated to satisfy these needs are reviewed in this paper. Techniques that employ solid-state microwave acoustic interactions and that have promise of satisfying some of the microwave variable delay requirements are described in detail, and their present capabilities and potential capabilities are discussed. One technique employing magnetoelastic waves is particularly promising and the state of the art of this technique is analyzed thoroughly.

I. INTRODUCTION

The need for nondispersive microwave delay lines is readily apparent in such applications as radars, fuses, repeaters, altimeters, and similar electronic systems. Many of the needs can be, and have been met, by devices providing fixed delay. One very successful development providing fixed microwave delay is the solid-state broadband nondispersive microwave acoustic delay line. However, other applications exist in which the delay must be variable. Utilizing the interaction of a microwave acoustic wave with the magnetic spin of a ferrimagnetic material, or the interaction of a microwave acoustic wave with a laser beam, provides a technique for obtaining variable delay at microwave frequencies. Nondispersive microwave variable delay using acoustic waves can also be obtained by utilizing an acoustic delay device in a repetitive pulse memory system, using sliding acoustic crystals, or employing acoustic waves in ferroelectric materials.

In this paper, a brief review of several of the applications of microwave variable delay devices is presented and techniques that have been or that are being investigated are briefly analyzed in relation to the stated applications. Techniques employing microwave acoustic waves are considered in detail and the technique employing magnetoelastic waves is shown to have great promise of satisfying some of the microwave variable delay application requirements.

II. VARIABLE DELAY APPLICATIONS

To understand their value and to estimate the usefulness of different variable delay techniques, it is necessary to know the characteristics of variable delay devices that would meet present application requirements. In this section, therefore, we briefly review some of the application requirements of microwave variable delay devices. The review is by no means complete, but the applications mentioned do give a general idea of the characteristics that are desirable in a microwave variable delay device.

One application of microwave variable delay devices is in array antennas. For many years, array antennas have been used both in the communications field and in radar applications. Until recently, the requirements placed on the array antenna have included handling only narrow-band signals. Since scanning of the array antenna beam was accomplished...
by using phase shifters, the antenna system was referred to as a phased array. It is now desired to utilize the greater power-handling capability and the rapid single or multiple beam scanning from a stationary structure property of the array antenna in order to meet the increased demands placed on modern radar and communication technology. With the requirements of greater range resolution using narrow pulses or chirp pulses and with the need for higher data rates, the bandwidth of the array system must be increased. As the bandwidth of a phased array system is increased, there is a loss in the signal-to-noise ratio. This deterioration in system performance of a phased array is due to the finite propagation time across the array aperture for off-broadside beam positions. For a narrow pulse, this effect produces a finite buildup and decay of the signal. For example, when the pulse length is equal to the array transient time, the signal-to-noise ratio will decrease 3 dB. For certain types of pulse compression, this finite transit time prevents coherent element-to-element summation off broadside. This loss can be overcome by the insertion of real time delay devices in each element signal path. Variable time delay is necessary to provide beam steering. To realize the use of array antennas for broad-band signals, a wide-band compact lossless nondispersive microwave electronically variable time delay device is necessary. Typical characteristics desired of such a delay device include a delay variation of up to 100 ns with an instantaneous bandwidth of 500 MHz having a center frequency between 500 MHz and 10 GHz.

Variable microwave delay devices also have an application in simulating a moving-target return for testing radar equipment. For this requirement, it is desirable to have a variable delay range of 1 to 150 μs in order to simulate ranges of roughly 500 feet to 14 miles. Since a target return is simulated, attenuation is not important and can be 80 to 100 dB. Reference signals for pulsed Doppler radars and range gates in moving target indication can also be provided by microwave variable delay devices. For this last requirement, the variable delay must be continuous rather than in discrete steps.

Finally, in electronic countermeasure (ECM) systems, microwave variable delay lines produce false range and speed information. Most of the characteristics desired for ECM uses are classified and cannot be discussed further in this paper. In general, however, broad bandwidth, low loss, and nondispersive properties are desirable.

Therefore, for the applications above, we would look to mechanisms that would have the following characteristics: 1) provide variable delay at microwave frequencies; 2) are nondispersive broad-band, and preferably low loss; 3) in some instances require short delays (zero to 100 ns) and in other cases require longer delays (1 μs to hundreds of μs). With the present state of the art, no one mechanism is capable of satisfying all microwave variable delay needs, nor does any one mechanism have the ability to satisfy all requirements of one need. However, several of the techniques described below do meet some of the application requirements.

III. REVIEW OF NONACOUSTIC MICROWAVE VARIABLE DELAY TECHNIQUE

A. Introduction

In this section, microwave variable delay techniques are briefly reviewed. Techniques that employ acoustic waves are not included, since acoustic techniques are described in detail in the next section. Present approaches for realizing the required variable delay are encompassed by either of two basic methods—changing the physical length of a transmission line, or holding the physical length constant but varying the electrical length (i.e., changing the energy propagation velocity). Both of these techniques can be controlled either by electrical or by mechanical means as described below.

B. Electrically Controlled Variable Delay with Physical Length Change

Microwave variable delay lines that achieve variable delay via physical length change (which is controlled electrically) include digital delay lines, recirculating memory loops, and repetitive pulse memory systems. The first two types of delay lines are discussed below. The repetitive pulse memory system utilizing acoustic delay lines is discussed in Section IV.

1) Digital Delay Lines: Microwave variable delay may be obtained by changing the transmission line length through which the energy propagates. This may be accomplished by utilizing switches to direct the signal through or around delay increments. Such a technique forms a digital line since changes in delay are discrete rather than continuous. Since switches can be controlled electrically, the digital delay line is essentially an electrically controlled microwave variable delay line.

One can use p-i-n diodes for high-speed (subnanosecond) broad-band microwave switches. Switching times as short as one nanosecond can be obtained with thin p-i-n diodes. By controlling the size of the diode, one can exchange power-handling capabilities for speed, with the speed-power product remaining approximately constant. One-nanosecond one-watt X-band switches have been built with p-i-n diodes [1]. In addition, switches operating over a double octave (1 to 4.5 GHz) have been built [2]. However, a disadvantage of the diode switches is the matching problems associated with the series diode reactance and resistance. Matching circuits are necessary to avoid amplitude and phase distortion in complex signals.

Transistor amplifiers having several hundred megahertz bandwidths have also been used as switches [3], [4]. These amplifiers can be gated on or off with very low power. Each incremental delay line can be properly terminated and each delay line increment can be isolated from the next because of the presence of the amplifiers. Selecting the gain of the amplifier allows the overall loss of the digital delay line to be controlled; it can be made equal to zero or with net gain. Fast switching times of less than a nanosecond are available.

1 "Length" here is the transmission line length through which the energy propagates.
Complexity and cost, however, are disadvantages if many delay increments are necessary.

Delay lines which can be used to provide the signal delay in the digital delay line include coaxial cable, waveguide, strip lines and acoustical devices. Coaxial line provides low dispersion. The loss of high-quality coaxial cable can be held to approximately 1.25 dB per 100 ns delay at one GHz. This loss increases approximately as the square root of the frequency. The real disadvantage of coaxial line is the relatively large size needed for each delay increment. For 100 ns delay, approximately 80 to 90 feet of coaxial cable is required. Waveguide loss at 1 GHz is about 0.5 dB per foot and increases roughly as the three-halves power of frequency when the dimensions are reduced in the typical fashion as frequency is increased. Size and dispersion are distinct disadvantages of waveguide. Strip lines have low loss, low dispersion, and are easier to integrate with switches. Although strip line can be made more compact than coaxial line, size is still a problem. Acoustical delay devices overcome the size problems but they are relatively lossy for a delay increment, which is due to the rather large transducer insertion loss of 4 to 30 dB—depending on the bandwidth and material. Also, elimination of multiple reflections (both internal to the acoustic device and external due to impedance mismatches) becomes a problem when using acoustic delay increments.

Hence, size and complexity are disadvantages of digital delay lines; however, in applications where not too many discrete delay steps are required, a digital delay line providing either short or long delays with relatively broad-band response might be attractive for satisfying some of the microwave variable delay requirements.

2) Recirculating Memory Loop: A recirculating memory loop can also be used to provide electrically variable delay at microwave frequencies. The basic memory loop circuit is shown in Fig. 1. The input signal is allowed to fill the memory loop and then is gated off. Once the loop is filled, the delayed pulse is obtained by turning on the output gate. Essentially, continuously variable delay can be obtained with a single-frequency stored signal by continuously varying the time that the output gate is opened. The output pulse length is controlled by the on time of the gate. The minimum delay time is not limited by the delay in the delay line in this configuration since the output may be opened before the loop is filled.

One disadvantage of the recirculating memory loop is that the loop has preferred frequencies of operation (frequencies at which the electrical length of the loop is an integer number of wavelengths) and hence lacks frequency accuracy since nonpreferred modes have periodic phase shifts spaced at the loop delay time. For this reason single-frequency inputs take on a complicated Fourier spectrum in the memory loop. Therefore, complex signals such as chirp signals are not remembered without distortion. Even if sophisticated phase equalization techniques are developed to eliminate the preferred modes of the loop, the recirculating memory loop can provide only discrete delay increments when varying the time delay of complex signals; i.e., the output can be initiated only at the beginning of the complex pulse cycle, and these cycles are spaced at the delay time of the loop delay which must be at least as great as the pulselength in order to preserve the complex pulse. Delay increments of the order of microseconds therefore result, which are too large for some applications.

C. Mechanically Controllable Variable Delay with Physical Length Change

Microwave variable delay lines that achieve variable delay via physical length changes (i.e., changes in the actual transmission line length) which are controlled mechanically, include sliding acoustic crystals, magnetoelastic variable delay lines, and elastooptical variable delay lines. These three types of delay lines all incorporate acoustic waves and are discussed in Section IV.

D. Mechanically Controllable Variable Delay with Electrical Length Change

In the previous two sections, methods of providing variable delay by changing the physical length of the transmission line were listed. In this section, methods which provide microwave variable delay by changing the electrical length (i.e., changing the velocity of energy propagation) will be considered. Mechanically controllable techniques will be described first.

The energy propagation velocity, or 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. In general, this technique provides for a variation in delay of approximately 1 ns and hence is more suitable as a phase shifter.

A technique that provides for a larger variation in delay is that of operating a waveguide near cutoff and mechanically varying the physical dimension of the guide with a sliding
side wall. Since dispersion is large, however, this technique is not satisfactory for wide-band signals. Therefore, the techniques listed in this section are more suitable for phase shifting or narrow-band microwave variable delay requirements rather than for those applications listed in Section II.

**E. Electrically Controllable Variable Delay with Electrical Length Change**

The following techniques provide variable delay in the microwave region by changing the electrical length of a transmission line by electrical means:

- diode-loaded transmission line,
- electron beam/slow-wave structure interaction,
- electron beam/cross field device (Kluver tube),
- magnetic waves in single-crystal yttrium–iron–garnet,
- helical delay line,
- ferroelectric-loaded line,
- ion beam variable delay line.

Each of these techniques is reviewed in the following paragraphs.

1) **Diode-Loaded Transmission Line**: Diode-loaded transmission lines have been used to provide phase shift or small delay variations at microwave frequencies. Two classes of diode-controlled phase shifters exist: the digital phase shifter controlled by a p-i-n diode, and the analog (continuous) phase shifter controlled by a varactor diode. A digital phase shifter makes 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. Both of these techniques are useful in providing phase shifts on the order of 360°, which correspond to nanosecond delays, but neither technique is suitable for the microwave need of several hundred nanoseconds of variable delay.

2) **Electron Beam/Slow-Wave Structure Interaction**: By controlling the drift velocity of an electron beam, it is possible to obtain microwave variable delay. A technique that allows control of the electron beam drift velocity is the traveling-wave variable delay tube [3]. The basic configuration is shown in Fig. 2. An electron beam emitted by the cathode is accelerated toward the first helix by the accelerating potential \( V_a \). The beam, which is held together by magnetic focusing, passes through the input coupling helix at a constant velocity. Upon leaving helix 1, the beam is further accelerated or decelerated by the potential difference \( V_b - V_a \) between the helix and drift region. The beam moves through the drift region at its new velocity and is then decelerated or accelerated by \( V_a = V_b \) as it passes into the second helix. Energy coupled onto helix 1 is in turn coupled to the beam. The accelerating potential \( V_a \) is adjusted so the beam velocity and helix phase velocity are synchronous, and the length of helix 1 is made to correspond to the Kompfner dip length; i.e., the length at which all the helix energy is transferred to the beam. The variable time delay is obtained by varying the beam velocity in the drift region \( L_d \). If the helix is long enough, amplification is obtained.

The advantages of the electron beam/slow-wave structure variable delay device are 1) wide bandwidth capability (20 to 50 percent), 2) frequency range of operation covering 0.5 to 10 GHz, 3) delays of several hundred nanoseconds, and 4) internal gain capability. Disadvantages are 1) large power requirements for the tube, 2) large control voltage swing (50 to 2000 volts for 50 ns delay variation), 3) limit on maximum delay (on the order of a few tenths of a microsecond), 4) heat generation, and 5) poor phase stability.

3) **Electron Beam/Cross Field Device (Kluver Tube)**: A variable delay mechanism very similar to the technique described in Section III-E2 is the electron beam/crossed field device described by Kluver [5]. An electron gun forms the beam, which then passes through an input modulator, through a drift tube that affects the delay, and finally through an output modulator. To avoid the problems of low beam velocity in the drift region, which restricts the maximum delay time achievable with the traveling-wave electron beam variable delay line, Kluver achieved an effective low electron beam velocity in the drift region by using the property of electron drift in crossed dc electric and magnetic fields. An electron beam moving in a region of a dc electric field perpendicular to a dc magnetic field executes a trochoidal motion. While the exact trajectory depends on the velocity which the electron had before entering the crossed field region, the drift speed in the direction perpendicular to both the electric and magnetic field is equal to the electric field (independent of the entering velocity). Therefore, the drift velocity can be varied by changing either the electric or magnetic field.

Early experiments at 2 GHz by Kluver showed that the electron beam in the drift region could be slowed to speeds on the order of \( 3 \times 10^4 \) cm/s. To demonstrate variable time delay Kluver altered the delay from 0.47 to 1.3 \( \mu \)s by changing the voltage between the center and outer conductors in the drift region from 100 to 18 volts. Although the insertion loss of the device was only about 3 dB, the bandwidth was only 7 MHz. Present investigations of this technique are being directed toward obtaining larger bandwidths. Disadvantages of the Kluver tube are the large power requirements, heat generation, and poor phase stability. The mechanism appears to be extremely promising, however, for
meeting some of the microwave variable delay requirements—at least for small changes in delay—if sufficient bandwidth can be obtained.

4) **Magnetic Waves:** Several techniques employing magnetic waves or coupled magnetic waves can provide microwave variable delay in addition to the mechanically controllable magnetoelastic mechanisms mentioned in Section III-C. These include 1) the use of magnetostatic waves, 2) the use of magnetoelastic waves with internal magnetic field profile shaping, 3) the use of magnetoelastic wave steering, 4) the use of periodic ferrite structures, and 5) the use of adiabatic magnetoelastic conversion in the time domain. The two techniques not using magnetoelastic waves are reviewed in this section, and the magnetoelastic techniques are described in Section IV.

Variable delay can be achieved in yttrium–iron–garnet (YIG) rods using magnetostatic waves. The energy propagation velocity of the magnetostatic modes can be controlled with an applied dc magnetic field. Variations in delay from zero to approximately 10 μs have been obtained [6], but the waves are highly dispersive. Because of the high dispersion exhibited by magnetostatic waves, mechanisms employing magnetostatic waves are generally not suitable for non-dispersive microwave variable delay requirements, but are more suitable for use in pulse compression filters. A periodic linear array of single-crystal YIG spheres operating in the uniform mode of precession and coupled together by their external magnetic fields provides another technique for variable delay [7], [8]. The mechanism is basically as follows: a microwave signal is coupled into one end of the array and drives the uniform mode of magnetic precession in the end sphere. The magnetic field produced by this precession is coupled successively from sphere to sphere in the chain and finally to the output transmission line. Varying the applied dc magnetic control field changes the resonant frequency of the YIG spheres, and hence changes the velocity of propagation of the microwave signal along the array. The bandwidth of a device tested in S-band was 90 MHz and the delay variation was less than 100 ns. Dispersion of the device is unknown, but it appears that the bandwidth might be small and that the delay variation might also be small. Much work remains to be done on this mechanism before it becomes useful for device applications.

5) **Helical Delay Line:** Two types of helical delay lines have been investigated for variable delay properties [9], [10]. One device is a coaxial line with a helical center conductor wound on a ferrimagnetic core embedded in a high permittivity dielectric, as shown in Fig. 3. This configuration increases both the inductance and capacitance per unit length. The delay, which is proportional to the square root of the product of inductance and capacitance, is thereby increased. Variable delay is obtained by biasing the ferrimagnetic core and varying the magnetic bias field. Delays of experimental models have been less than 10 ns/cm. Since variable delay has not yet been observed experimentally, no dispersion data is available. From the experiments to date, it appears that the magnetic material will ultimately set the upper frequency limit of this delay mechanism between 1 and 2 GHz.

The second type of helical delay line properly belongs in the section on mechanically variable electrical length change, but will be discussed here for comparison with the above technique. The mechanism employs a loosely wound helix and control of delay is affected by both the translation and the rotation of a dielectric worm having the same pitch as the helix. The structure is made by winding a coaxial cable into a helical groove cut into a brass cylinder and reaming out the center of the cylinder until the center conductor of the cable is just exposed. A dielectric worm is placed inside the helical coaxial structure, and rotation of the worm moves the dielectric thread with respect to the exposed center conductor. This movement of the dielectric worm varies its effect on the fringing field between the center and outer conductors of the modified coaxial line. When the dielectric thread is aligned with the center conductor, the velocity of propagation is lowest and there is maximum retardation of phase. Minimum phase retardation occurs when the thread is halfway between the turns of the center conductor. Operation of the mechanism has been demonstrated in S- and C-band. However, the mechanism provides an extremely small change in delay and is useful mainly as a phase shifter.

6) **Variable Delay Using Ferroelectric Materials:** Investigations of the electromechanical properties of ferroelectric perovskite-type crystals show that the velocity of elastic waves in these crystals can be varied by changing the strength of an applied electric field and/or by varying the temperature of the crystal. Since this technique uses acoustic waves, it is reviewed in Section IV.

7) **Ion Beam Delay Device:** The variable time delay in the traveling-wave electron beam delay line is limited to only a few tenths of a microsecond (see Section III-E2). The concept of the ion beam delay line was developed to remove this limitation by replacing electrons (in an electron beam device) with slow ions without sacrificing other advantages. The basic theory of operation of the ion beam delay device is illustrated in Fig. 4 [11]. An ion beam is formed by extracting ions from either a discharge or a solid ion emitter. An RF signal is impressed on the beam through a coupler and extracted from the beam after a delay. The delay time is
determined by the transit time of the ions through the delay space, which can be controlled electrically by varying the bias voltage on the drift tube. The ratio of the drift velocities of ions and electrons is given by the square root of the mass ratio. The delay time in an ion beam delay line, compared with the electron beam device, is increased by the same ratio. Thus, a hydrogen ion beam would provide delay approximately 43 times as large as the delay provided by an electron beam for the same drift length and beam voltage. Experiments to date have pointed out one major problem area in using ion beams for a microwave variable delay device. Since the drift velocity of ions is much slower than that of electrons, the ionic wavelengths at microwave frequencies are extremely short, and coupling to the ion beam is a very difficult task. A technique of transferring an RF modulation from an electron beam to an ion beam was demonstrated successfully at lower frequencies, but no effective means of modulation at microwave frequencies has been found. Further work is required before this technique is applicable to variable delay needs at microwave frequencies.

IV. MICROWAVE ACOUSTIC VARIABLE DELAY TECHNIQUES

A. Introduction

In this section, we consider variable delay techniques employing microwave acoustic waves. Microwave variable delay can be obtained 1) by using the interaction of microwave acoustic waves with a laser beam, 2) by using an acoustic delay device in a repetitive pulse memory system, 3) by the use of sliding acoustic crystals relative to one another, 4) by employing acoustic waves in ferroelectric materials, or 5) by utilizing the interaction of a microwave acoustic wave with the magnetic spin of a ferrimagnetic material. Each of these techniques is considered in detail and the last technique, making use of magnetoelastic waves, is shown to have great promise of satisfying some of the microwave variable delay application requirements.

B. Acoustooptical Variable Delay

Using acoustooptical coupling, nondispersive variable delay can be achieved at microwave frequencies [12], [13]. Variable delay is obtained by converting an input RF signal into an acoustic wave at one end of a crystal and then removing this signal via the elastooptical coupling at some variable distance from the input transducer as diagrammed in Fig. 5. The delay experienced is a result of the relatively slow propagation velocity of the acoustic wave. The acoustooptical interaction responsible for the output coupling of the delayed signal is controlled by 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 (serving as a local oscillator) provides a means of recovering the delayed microwave signal.

Experimentally, the technique has been demonstrated at C-band by detecting the envelope of the output light beam, and at S-band by recovering the microwave signal. Experimental models have generally exhibited insertion losses in the high 70 dB although improvements in insertion loss by 10 to 15 dB can be expected. One disadvantage of the mechanism is the narrow band width of the Bragg interaction which is of the order of 150 MHz at 3 GHz and which de-
creases inversely proportional to frequency. Using the anisotropic property of birefringent material, the bandwidth can be increased but only at the expense of insertion loss. For instance, using LiNbO₃ as the diffraction medium provides an acoustooptical interaction bandwidth of about 1 GHz at 3 GHz but the insertion loss increases by approximately 20 dB.

C. Repetitive Pulse Memory Systems

Repetitive pulse memory systems provide many outputs which are replicas of the incident pulse. An example of a microwave repetitive pulse memory system is an acoustic delay line operating in a reverberating mode [14] (see Fig. 6). An input pulse applied to a reverberating acoustic delay line causes a series of identical output pulses spaced at the round-trip acoustic delay in the crystal. By gating the output, one output pulse may be selected and a timing circuit can be used to pass pulses with progressively increasing delay. The result is a digital variable delay device with the delay increment equal to the round-trip acoustic propagation time. One complication of the mechanism is that if the input pulse repetition rate is sufficiently fast so that subsequent pulses arrive while the previous pulse is still recirculating in the acoustic crystal, interference can occur. In this case the input must also be gated, or the acoustic crystal and transducer must be chosen to provide sufficiently short memory times. For repetition rates of the order of 1 kHz, a typical value, the memory time in the crystal must be shorter than 1 ms, which is easily obtainable.

With the recent success in obtaining low-loss microwave acoustic transducers, the repetitive pulse memory is an attractive possibility for satisfying some of the variable delay needs. Loss of the system can be minimized by internally amplifying the acoustic signal. Dispersion is essentially zero. One disadvantage of the technique is that the time increment (between the reverberating pulses and hence between discrete delay steps) must be greater than the input pulse in order to preserve complex signals. Since microsecond pulses must be provided for in many systems requiring variable delay, the delay increment must be several microseconds. Such a large increment is a disadvantage for many microwave variable delay requirements.

D. Sliding Acoustic Crystals

Microwave variable delay can be achieved by mechanically sliding one acoustic crystal relative to the other as shown in
the variable range of velocity for ceramic BaTiO$_3$ can be obtained from Fedotov's experimental work [18]. Fedotov measured the change in the resonant frequencies of his samples as he varied an electric biasing field applied along the longitudinal acoustic wave propagation direction. His measurements indicate that the velocity of the longitudinal wave is increased by 10 percent at a temperature of 270 K by applying a field of $1.5 \times 10^6$ V/m. Near room temperature (292 K) a 10 percent increase in velocity can be obtained by applying an electric field of $2.4 \times 10^6$ V/m. At both of these temperatures, ceramic BaTiO$_3$ is ferroelectric. For a given change in applied field, the variation in velocity is greatest near 273 K where BaTiO$_3$ undergoes a phase transition from a tetragonal to orthorhombic structure. Fedotov's experiments also show that an 8 percent variation in the velocity of the acoustic waves could be obtained by changing the sample temperature from 273 to 320 K. All of his measurements were made between 3 and 6 MHz. One limitation in using ceramic BaTiO$_3$ for a variable delay device is that a considerable time lag exists between the application of an electric field and the corresponding variation in velocity. To obtain 90 percent of the total variation expected for a given applied field, this time lag is of the order of 20 minutes. Since experiments on single-crystal strontium titanate (discussed below) did not exhibit this time lag, it might be reasonable to assume that the time lag could be eliminated by using single-crystal barium titanate. Other effects that are present when using ceramic BaTiO$_3$ for variable delay devices are a nonlinear variation of velocity with applied field and a hysteresis effect in the velocity-applied electric field response.

Single crystals of strontium titanate can also be used for variable delay [19]. Strontium titanate is paraelectric at room temperature and becomes ferroelectric below 112 °K. The acoustic velocity of strontium titanate decreases as an electric field is applied. At room temperature 293 K, there is a 0.01 percent decrease in the [100] longitudinal wave velocity when a field of $1.64 \times 10^6$ V/m is applied and a 0.01 percent decrease in the [100] transverse wave velocity when a field of $2.12 \times 10^6$ V/m is applied. Both of these percentage decreases can be accentuated by lowering the temperature. At 126 °K, a 0.03 percent decrease in the [100] longitudinal velocity can be expected for field of the order of $10^6$ V/m. By lowering the temperature through the transition temperature 112 °K, a decrease in the [111] longitudinal acoustic wave velocity of approximately 5 percent can be obtained. However, all of these conclusions are based on experimental work below 100 MHz. Therefore, small changes in delay of up to 10 percent can be achieved by using acoustic waves in ferroelectric material at frequencies below 100 MHz, but further effort is required before the usefulness of this technique at microwave frequencies is established.

E. Variable Delay Using Ferroelectric Materials

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 and/or by varying the temperature of the crystal.

Fedotov [17] has shown that in a polarized barium titanate ceramic, the velocity of the longitudinal acoustic wave increases with increasing electric field intensity. An estimate of
in low L-band with an insertion delay of slightly over 2 \( \mu s \) and a delay variation of up to 60 ns. Insertion loss was greater than 80 dB. Some disadvantages of the technique include difficulties in shaping the internal magnetic field profile, the small delay variation that is achievable, and the relatively large insertion delay and insertion loss.

A magnetically scanned delay device based on the principle of steering magnetoelastic waves can also be constructed. As shown by Auld [21], the magnetoelastic waves in a YIG sample can be steered because of the anisotropy that exists in the magnetoelastic coupling. When the dc magnetic field is at some angle to the propagation vector, the energy vector of the magnetoelastic wave is caused to bend away from the propagation vector. By changing the field direction, the wave can be guided along different paths to separate output transducers as shown in Fig. 8. Discretely variable delay can thus be accomplished in a single delay crystal. The geometry of Fig. 8 provides for a 0.75 \( \mu s \) change in delay with a minimum insertion delay of 3 \( \mu s \). Experimental investigations of this mechanism [22] show that the operating bandwidth is limited to the order of 30 MHz and that scattering occurs into several modes rather than just one beam. Work remains before this mechanism is suitable for satisfying microwave variable delay requirements.

Adiabatic magnetoelastic conversion in the time domain also allows control of delay. The mechanism utilizes turning-point excitation and detection of spin waves in an axially based rod geometry. When the generated spin-wave energy has been converted to a pure shear elastic wave through magnetoelastic coupling, the bias field decreases sufficiently so that the turning points are removed from the sample. The rod then becomes a shear elastic wave transmission line for the duration of the field pulse. Application of a second field pulse, with the same magnitude but opposite sign, enables an RF echo to be recovered via turning-point detection in either a one-port or a two-port configuration. Dispersion can be made small by controlling the field profile in the vicinity of the turning point. The mechanism has been demonstrated [23] to provide variable delay out to 50 \( \mu s \) at L-band. A disadvantage of the mechanism is that the time interval between which energy can be extracted equals the elastic wave round-trip time.

G. Magnetoelastic Mechanically Variable Delay Mechanism

By properly shaping the internal magnetic profile of an axially magnetized YIG rod, an essentially nondispersive mechanically variable delay may be obtained [24]. A two-port magnetoelastic variable delay configuration that provides variable time delay at microwave frequencies can be realized as follows. Microwave energy is coupled into the 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 at the point of varying dc magnetic field internal to the rod. An output loop then couples the energy in the excited magnetic modes to the output microwave system.

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. Broad-band 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 microwave delay line.

To show what characteristics can be achieved with the magnetoelastic mechanisms over a 10 percent frequency band centered at 1.9 GHz, a device was built to meet the specifications shown in Table I. The packaged device, of dimensions 5 by 4.5 by 2 inches, is shown in Fig. 9, and the measured characteristics of the device are shown in Figs. 10 through 14. Note that all of the specifications of Table I were either met or exceeded. Over the 10 percent bandwidth centered at 1.9 GHz and over the delay range of 1 to 4 \( \mu s \) at
Fig. 9. Mechanically variable magnetoelastic variable delay device. (a) Front view. (b) Back view.

Fig. 10. Mechanically variable magnetoelastic device insertion loss versus frequency.

Fig. 11. Mechanically variable magnetoelastic device insertion loss versus delay.

Fig. 12. Linearity of delay variation for mechanically variable magnetoelastic delay device (frequency = 1.9 GHz).

Fig. 13. Delay dispersion of mechanically variable magnetoelastic delay device.
every frequency in the 10 percent bandwidth, the transmission or insertion loss of the device stayed within the limits of 55 to 65 dB. The delay versus rod position (represented by the dial setting) was linear as shown in Fig. 12. The average dispersion over the 10 percent bandwidth was less than 0.04 \( \mu \)s per 100 MHz as shown by the data of Fig. 13. Fig. 14 shows the linear power out versus power in characteristic of the device for power levels less than the saturation power level. For this device, the saturation power level was about \(+5\) dBm.

The unit described above is a commercially available unit. Recent laboratory prototype units have been operated at higher frequencies, with broader bandwidths, with less insertion loss, and with greater variable delay ranges. The work to date shows that this mechanically variable, magnetoelastic variable delay technique is extremely promising for satisfying many of the microwave variable delay needs.

V. SUMMARY AND CONCLUSIONS

Applications for variable delay devices at microwave frequencies exist and the characteristics of the variable delay devices necessary to meet the application requirements are reviewed. Microwave variable delay techniques utilizing acoustic techniques and nonacoustic techniques have been considered. Of the known techniques, one utilizing the interaction of microwave acoustic waves with the magnetic spin system of a ferrimagnetic material gives most promise of satisfying some of the microwave variable delay requirements. A device utilizing this mechanically variable magnetoelastic mechanism that provides continuously variable delay over a 10 percent bandwidth centered at 1.9 GHz is described. The variable delay range of the device is from 1 to 4 \( \mu \)s, with a maximum insertion loss of 65 dB over the entire 10 percent bandwidth. Based on the results obtained with more recent prototype units, improvements in the insertion loss of 10 to 15 dB can be expected, operation throughout S-band can be achieved, and operating bandwidths of 1 GHz can be approached. Variable delay ranges exceeding the 1 to 4 \( \mu \)s range have also been demonstrated. Hence, it appears that microwave acoustic variable delay devices satisfying some of the application requirements are a reality now and that more demanding requirements will be met in the near future.

REFERENCES

L-Band Variable-Delay-Time YIG-YAG-YIG and YAG-YIG-YAG Delay Lines

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Abstract—Two types of YIG variable-delay-time microwave delay lines are described. These are the YIG-YAG-YIG and YAG-YIG-YAG configurations, both of which provide ~2 \mu s of variable delay in L-band. Two-port operation is achieved in both of these devices with leakage of the undelayed pulse between input and output being attenuated more than 100 dB. These are completely self-contained devices with internal permanent magnets and terminals for connecting a control signal to vary the delay time. Insertion loss, bandwidth, and VSWR data are presented as well as curves showing delay variation with control current. A comparison of these two types of delay lines is also presented, pointing out the advantages and disadvantages of each type.

INTRODUCTION

MICROWAVE delay lines incorporating axially magnetized cylindrical YIG rods [1] are of considerable interest because their delay time can be varied over several microseconds by merely changing the applied magnetic field. The dispersive characteristics of these devices also make them desirable for pulse-compression applications [2], [3]. A disadvantage of these devices is that both input and output signals must generally appear at the same port. Two-port operation can be provided, however, by bonding appropriate pieces of YAG to the YIG rod in a YIG-YAG-YIG [4], [5] or YAG-YIG-YAG [6] configuration. We describe here the construction and performance of L-band devices of these two types.

The principles of operation of these devices have already been described [4], [5], [6] and will not be repeated here. Instead, we will describe the construction and performance of actual prototype models of these devices, an aspect which has not been covered in previous publications. We will describe certain problems encountered which are not readily apparent from the results of the preliminary experiments. Comparisons of the performance capabilities of these two types of delay lines will also be made. Although much of what follows will be applicable to pulse-compression applications, the emphasis will be on variable-delay applications. Theoretical calculations of the relative merits of the YIG-YAG-YIG and YAG-YIG-YAG configurations for pulse-compression applications have already been presented by Collins and Zapp [3].

DEVICE CONSTRUCTION

A sketch showing the construction of the YIG-YAG-YIG device is given in Fig. 1. This device incorporates a permanent magnet (Arnold Engineering Co. Type 5J192) to provide the major portion of the magnetic field (~650 Oe) required by the YIG, and an electromagnet to provide the variable field component (~200 Oe) used to vary the delay time. The YIG and YAG rods used are both about 1 cm long and are oriented with a (100) crystallographic axis along the rod axis. The YIG rods are 3 mm in diameter and the YAG rod is 3.8 mm. The magnet gap is about 3.8 cm and the pole pieces on which the coils are wound are 3.8 cm in diameter. The coils each have approximately 1500 turns of no. 32 wire and

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