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A SURVEY OF DELAY LINE TECHNIQUES

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INTRODUCTION

A group of delay lines is required for the interferometer system. These delays range from 1.5 - 3040 nanoseconds. The frequency range is from 2 - 12 MHz. At present these delays are achieved with coaxial cables, which take four equipment racks to house.

A literature search was undertaken to determine whether a more suitable arrangement could be found.

The delay system investigation was divided into ultrasonic delays, lumped parameter networks, cables, magnetostrictive devices and yttrium-iron-garnet solid state delays.

No attempt has been made to limit the discussion to delay devices which meet the above specifications. Rather, a general search was made since there is a possibility that the system requirements might change in the future.

ULTRASONICS

Ultrasonic delay lines consist basically of transmitting and receiving transducers separated by a delay medium which is typically Mercury (Hg), water, quartz, etc.

The input transducer has a signal impressed upon it which is converted into an ultrasonic wave. This wave traverses a prescribed path and finally impinges on a receiving transducer for conversion back into a usable signal. Thus the delay is dependent upon the path length and the velocity of propagation in the medium.

Solid quartz lines are rapidly replacing both the Hg and water lines due to their smaller size and lighter weight.

A typical quartz delay line consists of a quartz blank to which two Y-cut quartz crystals are fixed by Indium bonds. The main beam is collimated by coating the edges of the reflecting facets with an absorbing material. This reduces spurious responses in the medium. These delay lines are usually packed into a hermetically sealed can which has been filled with an insulating material.

Figure 1 shows some typical quartz delay line shapes.

Some fairly typical characteristics of quartz delay lines using quartz transducers are:

Delay times	250-2000 μsec
Carrier frequency	15-40 MHz
Bandwidths (= 1/2 carrier freq.)...	7-20 MHz
Attenuation (α)..................	40-70 dB
Characteristic impedance.........	75 Ω

The insertion loss due to quartz transducers can be reduced by using ceramic (barium titanate) transducers. The most serious difficulty is that a ceramic transducer operating above 10 MHz must be extremely thin and therefore is very brittle.

Some quartz delays using ceramic transducers have been built with a 1 millisecond delay and an insertion loss of 20 dB into 50 Ω. This was with a 6.7 MHz bandwidth and a center frequency of 18 MHz [1]. While these lines have desirable characteristics, they are not practically feasible due to many technical difficulties.

The trend in quartz delay lines is towards higher frequencies and larger bandwidths. Ceramic and quartz transducers are limited in frequency range due to the difficulties in handling the thin transducer plates which would be required for higher frequencies.

Current research into the use of extrinsic piezoelectric semiconducting materials as transducers promises to solve many of the difficulties now encountered [2]. The transducing region of the semiconductor is a thin, flat, high-resistance depletion layer which can be generated on the surface of the semiconductor plate. An additional advantage is that this depletion layer thickeness (and thus the transducer resonant frequency) can be varied over a very large range by a DC biasing field. The frequency range of these transducers is from near 300 MHz to perhaps greater than 10 GHz.

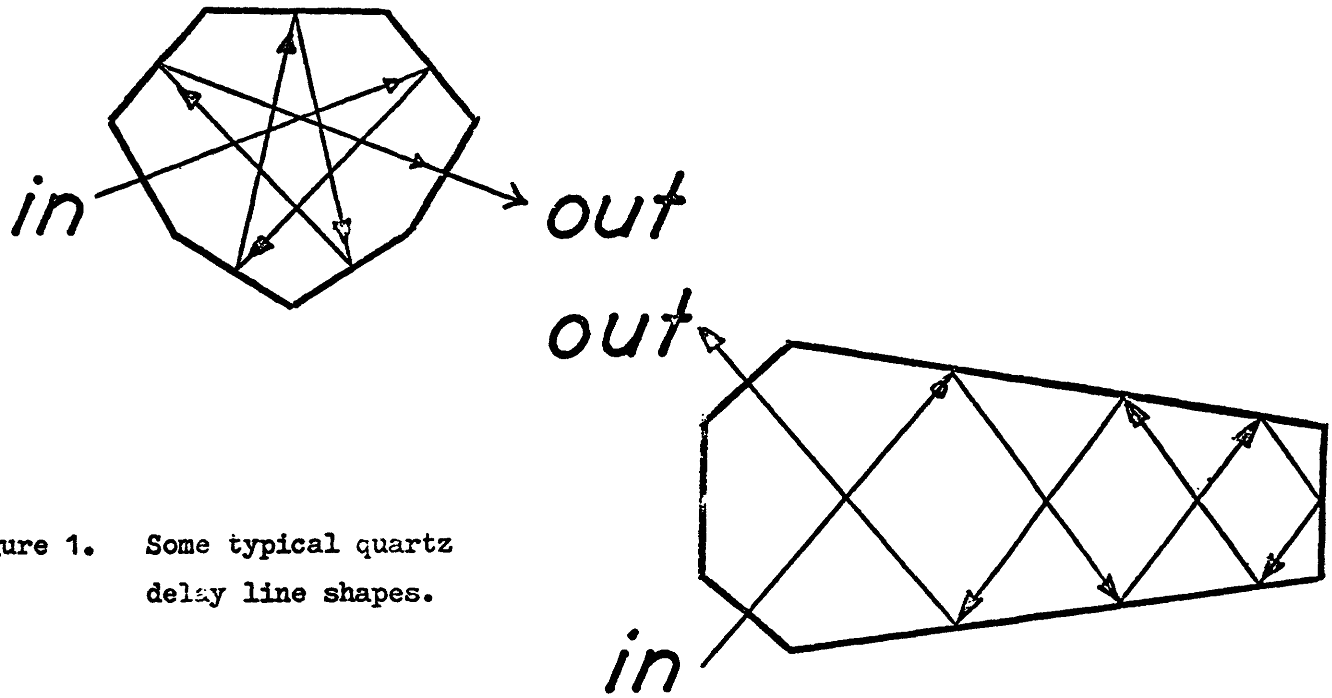


Figure 1. Some typical quartz delay line shapes.

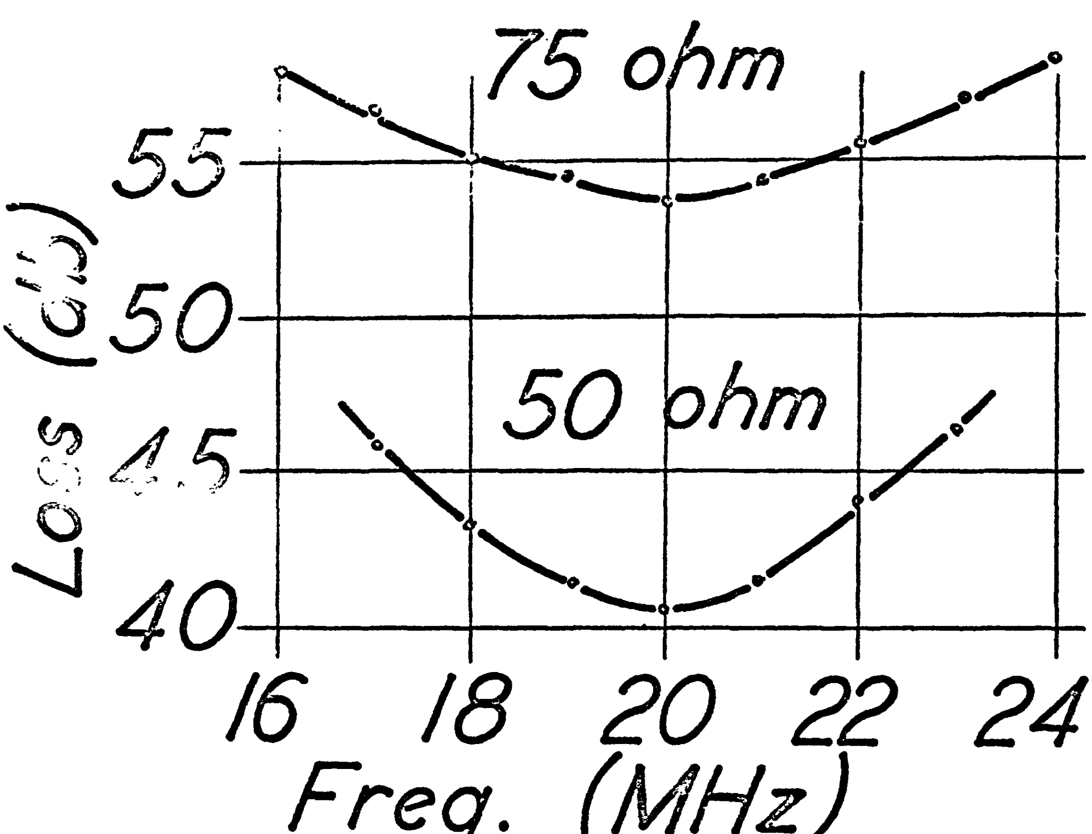


Figure 2. Performance of a 1 ms delay line shown above to illustrate the effect of impedance on bandwidth and insertion loss.

Further study of piezoelectric semiconductor materials has led to the discovery of direct amplification of ultrasonic energy in CdS crystals subjected to certain conditions [3]. Gains of 18 dB's at 15 MHz and 38 dB's at 45 MHz have been reported.

As was mentioned earlier in the report, water is sometimes used as the delay medium. A typical delay line with water as a delay medium will exhibit the following characteristics [4]:

Delay time .... 25-55 μsec

Insertion loss .... 50-75 dB

Bandwidths will run as high as 10 MHz centered as high as 30 MHz.

An interesting variation on quartz delay lines is the so-called "Photo-Elastic" delay line. Fused quartz becomes birefringent (i.e., it will rotate the plane of polarization of light passing through it) when subjected to strain [5]. Figure 3 shows the application of this phenomena to delay lines.

As can be seen in Figure 3, a piezoelectric transducer is bonded to a quartz bar, which is placed between crossed polaroids (or Nicols prisms).

A signal injected into the bar by the transducer will, upon passing the slits, rotate the plane of polarization of the light passing through and thus illuminate the detector. The bandwidth is determined by the width of the slits relative to the signal wavelength and also the orientation of the plane of polarization.

It is obvious that this method is well suited to either variable or multiple tap delay lines since the detector is not in physical contact with the line itself.

Photoelastic delay lines have been built by Cornings with up to 150 microseconds delay at frequencies up to 30 MHz.

An interesting property of this type of delay is that if two quartz bars with their polarizers are sandwiched between one light source and one detector, then the instantaneous light output will be proportional to the products of the instantaneous signals in both lines. With certain modifications such an arrangement can be used for producing autocorrelation [6], [7].

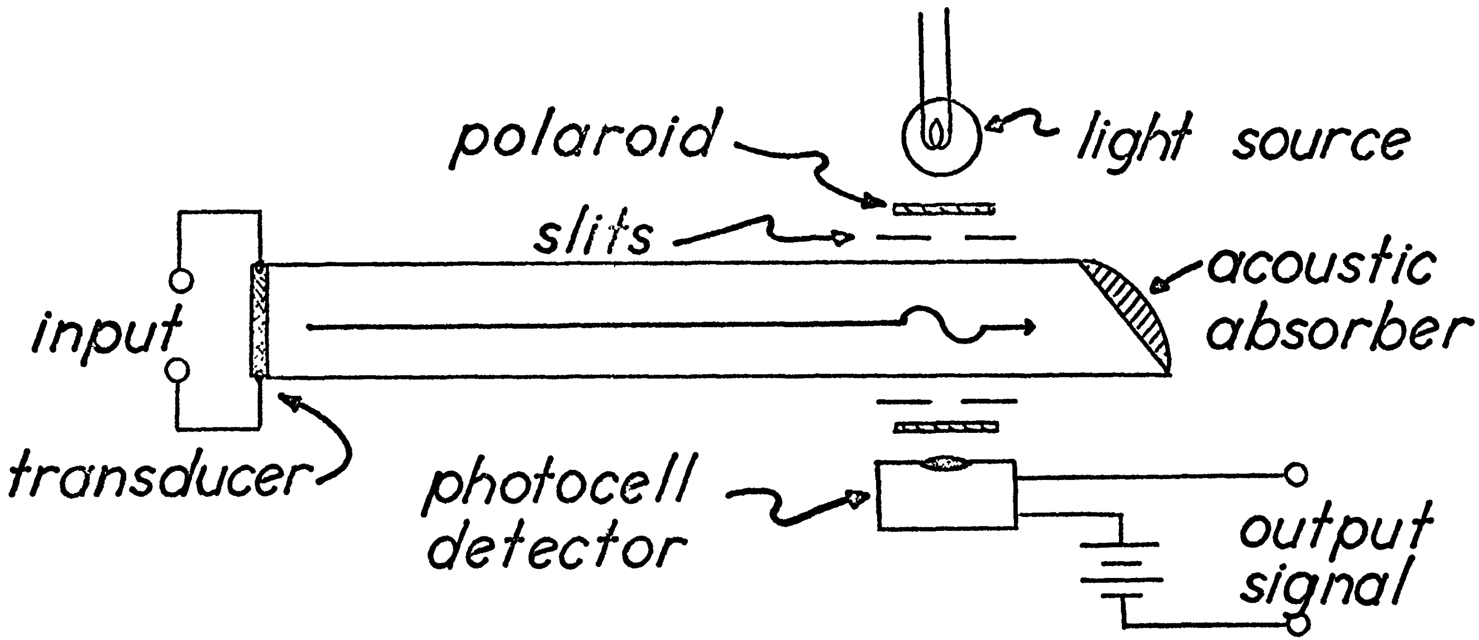


Figure 3. Drawing of Photo-elastic delay line.

CABLES

One of the simplest devices for delaying a signal is a length of coaxial cable. Knowing the velocity of propagation of a particular type of cable enables one to calculate quite readily the length of cable necessary to obtain a given delay.

Coaxial cables are normally selected on the basis of their frequency characteristics (frequency domain) or their pulse or transient characteristics (time domain).

FREQUENCY DOMAIN OPERATION

The following characteristics determine the most economical cable construction:

A. Impedance
B. Attenuation
C. Input power
D. Input voltage
E. Ambient temperature
F. Environment

TIME DOMAIN OPERATION

The following characteristics determine the most economical cable construction:

A. Impedance
B. Rise time
C. Amplitude
D. Overshoot
E. Input voltage
F. Ambient temperature
G. Environment

The normal impedances used in coaxial delays are 50, 75, and 100 Ω.

The usable frequency range is normally 60 Hz to around 30 GHz although some cables have a higher cutoff frequency.

Almost all cables are capable of handling a kilowatt and most will handle several kilovolts.

Considering the frequency range from 2-12 MHz, the velocity of propagation will vary by approximately 4 percent for small cables and 0.5 percent for large cable.

The impedance of the cable will increase by about 4 percent over the 2-12 MHz range depending on the size of the cable.

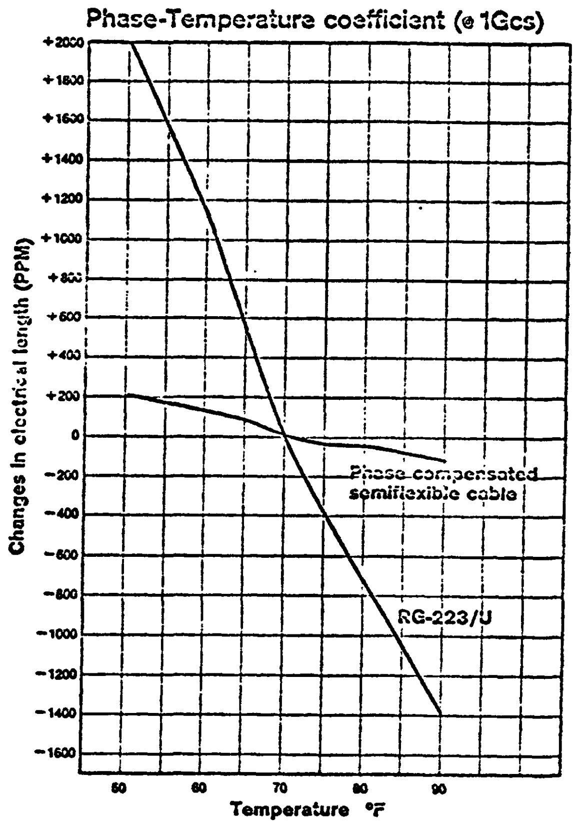
Some delay errors to be encountered are [8] :

1. Delay temperature coefficient - 90 ppm/°F for standard flexible coaxial cable.
2. Delay error due to storage temperature extremes — 110 ppm — average worst condition.
3. Delay flexure error — 100 ppm dependent on conditions.
4. Delay frequency error — with a VSWR of 1.2, the maximum error to be expected due to reflection is of the magnitude of 0.1 ns.
5. Delay measurement error — with a VSWR of 1.2, an error of 0.1 ns could be expected due to the difference in reflection summation dependent on whether the delay measurement technique is on a reflection (resonant) basis or transmission basis.

Most cable companies manufacture a phase compensated cable which reduces the above errors by about one order of magnitude.

An analysis of the phase (electrical length) characteristics of a delay line or interconnecting cable system should include the following parameters:

1. Temperature coefficient — change with operating temperature.
2. Temperature stability — change with time.
3. Flexure — change with bending, shock, or vibration.
4. Frequency — non-linear change over bandwidth.
5. Pressure — change in air-articulated dielectric.
6. Humidity — change in flexible foam or air-articulated dielectric.
7. Tension — change with installation or handling.
8. Cutting — error due to variation in velocity of propagation.
9. Measurement — error due to difference in phase as measured by reflection technique vs. phase by transmission technique.



Characteristic	Time Domain Data	Frequency Domain Data
Impedance, ohms	50 or 75	50 or 75
Reflection Coefficient	1% max.	As required (5% typical to 2Gc)
Delay	5, 10, 20, 50, 100, 200 & 500	As required (5% typical to 2Gc)
Delay accuracy-absolute	0.1%	±0.2° (2-30mcs)
Delay accuracy-relative	±1 picosecond	±0.1° (to 3Gcs)
Delay-temperature coefficient	±10ppm/°F max	±10ppm/°F Max.
Delay-long term stability	20ppm	20ppm
[illegible]	1.9db/500ns*	6.0db/100′ @ 1Gc
Rise time—output	7.5ns (10-90%)*	——
Operating temperatures	[illegible]	−20° to 120 F
Storage temperatures	−65° to 160°F	−65° to 120 F

*Input pulse: 0.34ns rise time (10-90%): 20ns pulse width (50%).

Figure 4. Some typical specifications of phase compensated delay cable manufactured by Times Wire and Cable Company.

In theory the cable-type (distributed) delay line yields superior performance but in practice trouble is frequently encountered due to mismatching in short sections. To prevent such troubles, it is usually convenient to use lumped elements in m-derived sections.

In the usual filter arrangements, the coils must be adequately separated so as to prevent intercoupling. Also, trimmer capacitors are frequently used so that the normal "line" is relatively bulky.

Solov' ev [9] shows that short circuited coils will allow the sections to be placed closer together. He also shows that trimmers may be eliminated by utilizing the distributed capacitance of the coil arrangements.

The parameters of the m-derived sections of the line are calculated in accordance with conventional delay line theory. The actual construction of such lines is outlined in an article by C. Heaton-Armstrong [10].

Figure 5 shows the construction of such a delay line.

The characteristics of the above described delay line are approximately as follows:

Time delay/rise time	10/1
Useful range of time delay	100-600 ns
Bandwidths	5-20 MHz
Characteristic impedances	0.3-1.5 kΩ

Using the method of construction outlined by Heaton-Armstrong, the size of a delay cable can be greatly reduced. While the performance is not completely predictable, a design, once finalized, can be reproduced easily and consistently on the production line. A comparison with delay cable showed that for the same time delay and a similar bandwidth, a line may be constructed which is considerably easier to match and occupies only 1/12 of the volume.

No figures were given concerning attenuation.

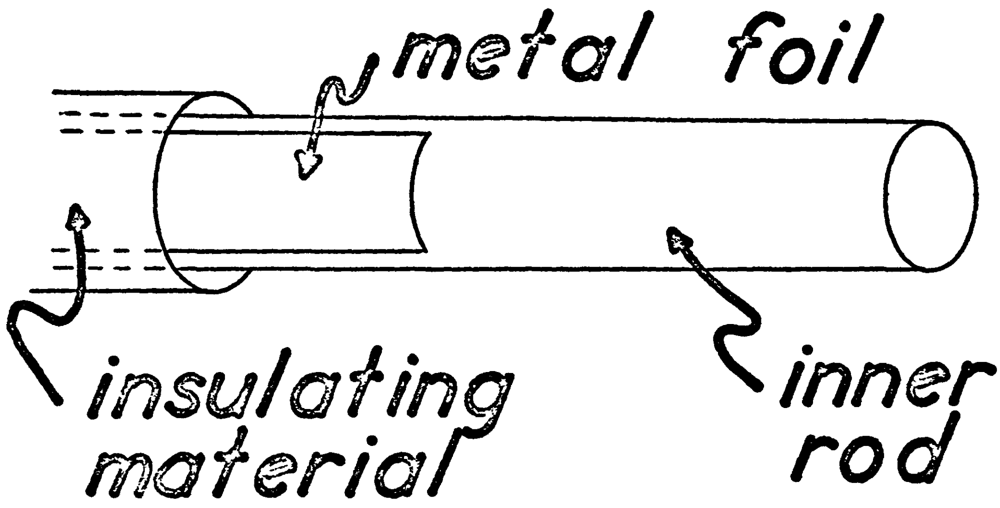


Figure 5 (a). Construction of the Former.

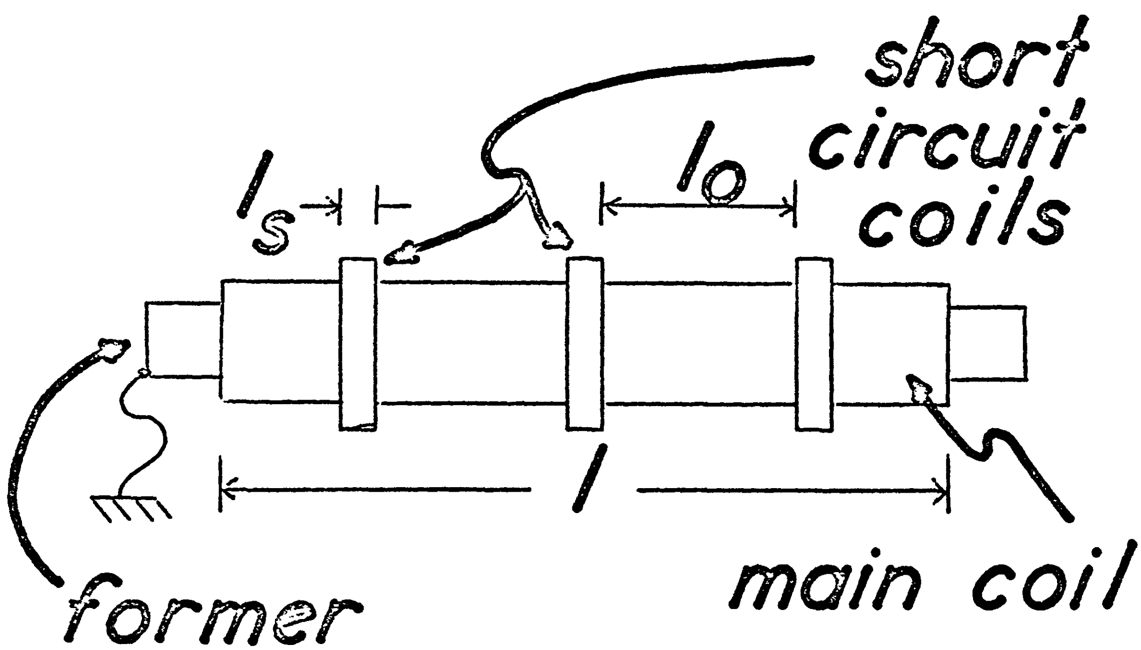


Figure 5 (b). Construction of the Delay Line.

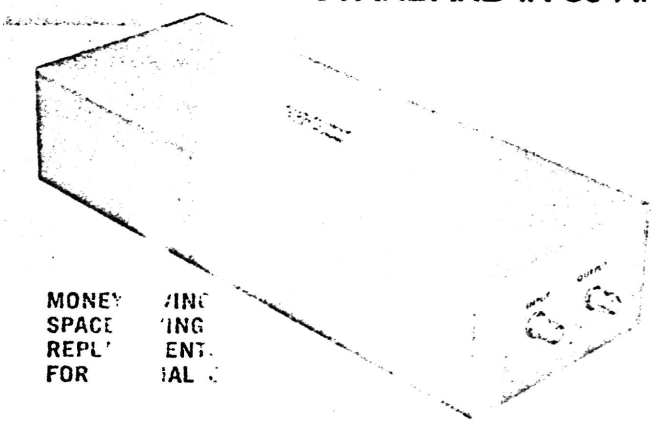
$$\frac{\text{TIME DELAY}}{\text{RISE TIME}} = \frac{100}{1}$$

Series "HF"

HIGH F[illegible]Y

LUM[illegible] C[illegible]STANT

STANDARD IN 50 AND 75 [illegible]HM I[illegible]EDANCE



MONE[illegible] [illegible]IN[illegible]
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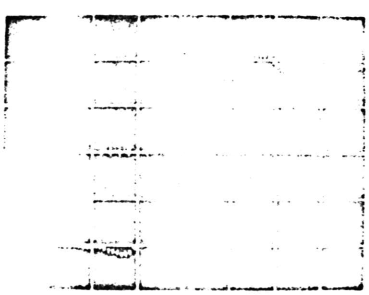


[illegible]YPICAL RESPONSE OF "HF" SERIES

For the lack of a suitable replacement, coaxial cable has been used to delay signals where high frequency transmission was required. Lumped Constant Delay Lines could not be manufactured in required time delays with fast enough rise times or suitable bandwidths.

Now, in the "HF" series, Allen Avionics brings to the industry, for the first time, a group of delay lines which in most cases will serve as more than adequate electrical replacements for coaxial cable. The inconvenience of handling and storing cable would be eliminated by these high frequency Lumped Constant Delay Lines. Also, in most applications, appreciable savings in cost will result.

The "HF" series is an extremely high quality group of delay lines. Superior temperature stability, excellent phase linearity and low pulse distortion characterize this group.

These delay lines extend the frequency range of Allen Avionics "HR" series by a factor of 5. Standard impedances of 50 and 75 ohms are available. Units are normally supplied with BNC connectors for input and output connections. These lines can be manufactured with taps to your specifications. Time delays other than those shown below can also be supplied.

50/1 RATIO
[illegible]NUATION 9db MAXI[illegible]
SIZE: 2½"x4¼"x12"

[illegible] Delay [illegible]seconds	Rise Time Nanoseconds Maximum	Bandwidth (3db) Megacycles
.5	.10	36.0
.6	12	30.0
.7	14	25.7
.8	16	22.5
.9	18	20.0
1.0	20	18.0
1.25	25	14.4
1.5	30	12.0
1.75	35	10.3
2.0	40	9.0
2.5	50	7.2
3.0	60	6
3.5	70	5.15
4.0	80	4.5
4.5	90	4.0

75/1 RATIO
ATTENUATION 12 db [illegible]AXIMUM
SIZE: 3½"x4½"x[illegible]2"

Time Delay Microseconds	Rise Time Nanoseconds Maximum	Bandwidth (3db) Megacycles
2.0	26.7	13.5
2.25	30	12.0
2.50	33.4	10.8
2.75	36.7	9.8
3.0	40	9.0
3.25	43.3	8.3
3.50	46.7	7.7
3.75	50	7.2
4.0	53.4	6.75
4.25	56.7	6.35
4.50	60	6.0
4.75	63.4	5.7

[illegible]/1 RA[illegible]O
ATTENUAT[illegible]N 15 [illegible] MAXIMUM
SIZE: 4½"x5[illegible] [illegible]15"

Time Delay Microseconds	Rise Time Nanoseconds Maximum	Bandwidth (3db) Megacycles
3.0	30	12
3.25	32.5	11.1
3.5	35	10.3
3.75	37.5	9.6
4.0	40	9
4.25	42.5	8.48
4.5	45	8
4.75	47.5	7.58

TO ORDER, SPECIFY "HF" [illegible] HIGH FREQUENCY), THE RATIO, [illegible]E TIME DELAY AND THE IMPEDAN[illegible]

Figure 6

A continuously variable delay line for use at frequencies below 100 MHz has been developed by Brueckmann and Campbell [11]. This line can be used for phasing the elements of antenna arrays, measuring delays and phase, measuring VSWR, and delaying signals in fast computers.

At frequencies below 100 MHz, this line stretcher is better than other variable delay lines because it has truly continuous control of delay or electrical stub length without change in characteristic impedance; reduced size, making it practical for use at HF and VHF frequencies; reliability through the absence of sliding contacts; and little variation of delay with frequency.

The design was based on the fact that in a line whose propagation medium is air, the characteristic impedance does not change if the air is replaced by a medium with a relative permeability equal to its relative dielectric constant. However, the propagation velocity of the line varies inversely with the square root of the product, $v = 1/(ue)^{1/2}$; and the time required for a signal to travel through a unit length of the line is, $t = (ue)^{1/2}$.

The delay time is varied by moving the ferrite slug axially; it is a maximum when the slug is fully inserted into the line, and a minimum when the slug is removed. The delay varies linearly with the position of the slug.

In the prototype model of this type of delay line the propagation velocity was reduced to about 1/9 the velocity of propagation in free space. The propagation velocity could be reduced further by alternately stacking disks of ferrite and high permittivity ceramic. The disks could be made very thin to simulate a uniform line. The ceramic material used in the prototype was titanium dioxide.

The maximum delay of the experimental 30-inch line was measured at about 13 nanoseconds. The minimum delay was one nanosecond (propagation in free space). At constant frequency, the measured deviation from linearity between the time delay and slug position was less than 0.3 nanoseconds. The measured delay increased about 14 percent with frequency over the range of 30 to 76 MHz. Standing wave ratio measurements indicated that the characteristic impedance was higher than 50 Ω and was slightly frequency dependent. The unit itself has a VSWR less than 1.05.

Attenuation measurements at each of three frequencies were 0.005 dB/ns at 30 MHz, 0.018 dB/ns at 50 MHz, and 0.18 dB/ns at 76 MHz.

LUMPED PARAMETER NETWORKS

An ideal delay line is a network whose output voltage $e_2(t)$ is related to the input voltage $e_1(t)$ by:

$$e_2(t) = He_1(t - \tau)$$

In other words, ignoring the multiplicative constant, H, the output voltage is equal to the input voltage delayed by a specific time τ. This therefore implies that the network has a frequency transfer characteristic given by:

$$\frac{e_2(jw)}{e_1(jw)} = He^{-jw\tau}$$

It can be demonstrated that no finite collection of circuit elements can yield a network with the above transfer function. The problem is thus one of synthesizing the above function.

One of the easiest filter designs to achieve is the m-derived filter. The m-derived synthesis procedure is simple and direct as well as possessing low tolerance requirements on elements [12].

M-derived sections are advantageous over constant-k low pass in that they allow a higher proportion of the pass-band to be used.

Usually m-derived sections are employed to achieve linear phase characteristics in limited bandwidth applications. However, for precision time domain applications, this design is undesirable because of the unavoidable amount of distortion (overshoots and undershoots) in the time response.

With modern synthesis techniques available, a direct approach can be made. First, one approximates an ideal delay function by a physically realizable transfer function and then realizes a delay network from the approximated function.

Storch [13] uses such a technique to realize low-pass networks with a maximally flat delay function and good time response. However, his method is useful only when the ratio of delay to rise time is very small and becomes extremely inefficient and impractical when the ratio is a little larger than unity.

A method has been proposed by Kuh [14] for delay line synthesis which yields large delay-rise time ratios. A cascade connection of a low pass and an all pass network is used. Kuh's synthesis is based on the potential analog method.

Of current importance are the lumped parameter delay lines commercially available.

A specification sheet of a commercially produced unit is reproduced in Figure 6.

MAGNETOSTRICTIVE DEVICES

A magnetostrictive material is one whose length changes when placed in a magnetic field. One such material is nickel, which shrinks in the direction of the field.

If a coil is placed around a nickel strip and a current is suddenly passed through the coil, the resulting contraction of the nickel causes a shock wave to travel in both directions at the speed of sound.

Another coil can be placed around the nickel with a magnetic field passed through the coil and nickel by means of a small permanent magnet. The shock wave will then cause some flux to cut the second coil as the nickle's magnetic reluctance changes due to material straining. This generates an EMF which can be used as the output of a longitudinal mode magnetostrictive delay line. This arrangement is shown in Figure 7.

A change in the input current produces an output voltage very much like the <u>second derivative</u> of the input, the duration of which depends on the transducer coil length. This means that the pulse repetition rate, or frequency, is a basic property of a line. Also, the output contains no DC component.

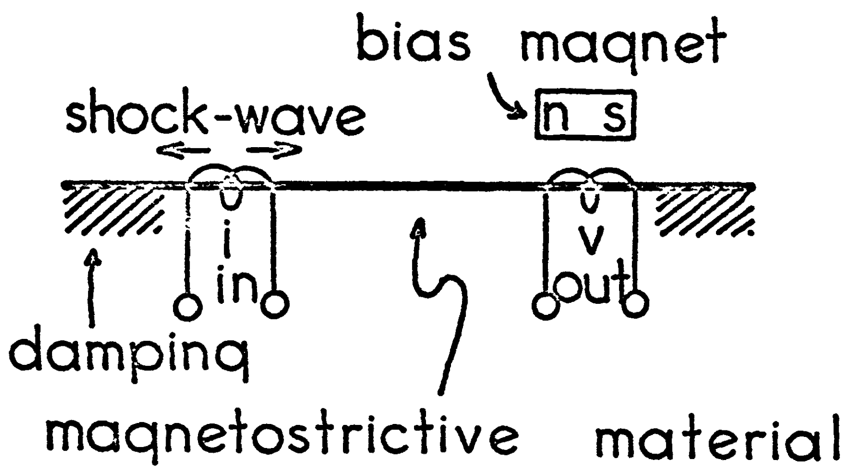


Figure 7. Diagram of magnetostrictive delay line.

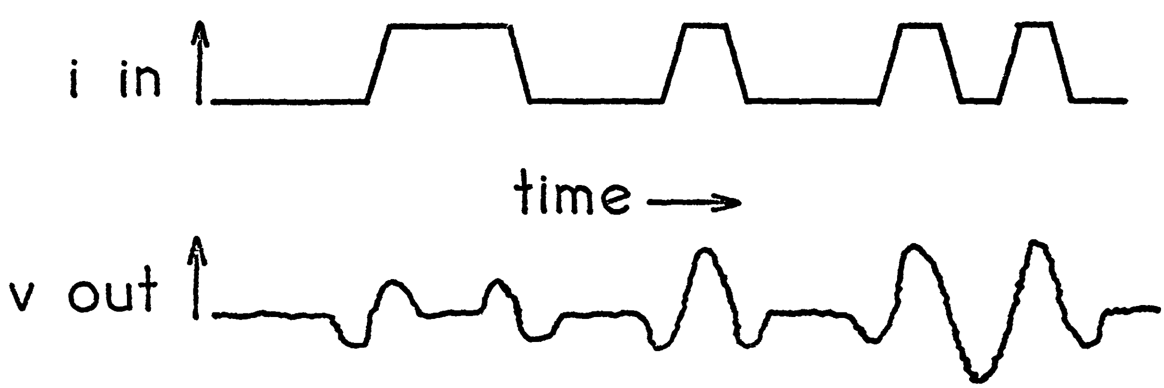


Figure 8. Waveforms associated with longitudinal mode magnetostrictive delay line.

The longitudinal line has a delay of approximately 5 μsec/inch and can be easily adjusted by moving the transducer along the tape or wire used as the delay or magnetostrictive medium.

By modifying the above arrangement, a torsional mode pulse can be made to propagate along the wire. The velocity of this pulse is about one-half that of the longitudinal mode so twice as much delay per unit length is achieved.

Temperature coefficient, frequency response, and amplitude are all improved by using a large diameter coil so that except for short delays, diameters should equal 3 or 4 inches. A simple 8 1/2 x 7 1/2 x 1/2 inch torsional line can have a delay of 5 μsec [15].

The factors which determine delay line design are: Frequency, delay time, temperature coefficients of delay and amplitude, physical size limitations, delay adjustments, taps, environmental specifications, impedances and amplitudes.

The frequency excursions of a typical delay line range from 150 kHz to 2 MHz. Frequencies of 5 and 10 MHz can be achieved with a degradation of some of the other parameters.

The shortest standard delay time is 2 μsec. Delays as short as 0.5 μsec are possible but require special shielding techniques to prevent the pickup of undelayed signals.

The longest time delay depends on the frequency but delay-frequency products of 5 kHz are usual. This is equivalent to 5 μsec at 1 MHz.

YTTRIUM-IRON-GARNET DEVICES

The ability to delay microwave signals and, in particular, to control the delay electronically, is important to certain electronic systems. There has been considerable activity in this field recently, with the most significant non-cryogenic results being achieved through the use of various delay processes in single-crystal yttrium iron garnet (YIG) [16].

A number of favorable conditions and phenomena suitable for microwave delay applications exist in a ferrimagnetic material such as YIG.

The propagation of magnetostatic waves in a longitudinally magnetized rod of YIG has been used to accomplish microwave variable delay. The magnetic waves result from the transverse microwave magnetic field applied at the end region of the YIG rod. The magnetic disturbance propagates through the crystal in the form of long-wave length spin waves, and, because the medium is dispersive, the velocity of the waves can be controlled by varying the applied DC magnetic field in the dispersive region. Thus, variable delay is achieved by changing the group velocity of the waves rather than by varying the physical length of the propagation path [17], [18], [19].

YIG delay lines are currently in production and are available on the market.

The Amecom Division of Litton Systems, Inc., advertises a delay which operates in the L and S bands. The L-band device exhibits a 20% bandwidth, while the S-band device has a 10% bandwidth. These devices have 40 dB insertion loss at L-band and 50 dB at S-band. Both models offer 1 → 5 μsec delay in fixed delay operation and 0-3 μsec in variable-delay mode.

The prototype models available are capable of 3 to 6 dB less loss with a narrower (approximately 5%) bandwidth. Rise time is also a function of bandwidth while maximum pulse length is dependent on the acoustic filling time of the YIG crystal. The lines handle inputs under 1 mW and saturate at about 0 dBM.

Prices of these devices range from $1,200 to $2,000.

Sperry Rand Research Center is currently developing an X-band delay line that exhibits a gain. This device exhibits about 35 dB gain but requires 100 watts of Ku band energy as a pump source.

ACKNOWLEDGMENTS

The author wishes to thank Dr. W. C. Tyler for his timely comments and also to A. W. Robichaud and J. R. Coe for their guidance and discussion.

Type 314-S86 VARIABLE DELAY LINE

This variable delay line finds general application as a wide-band phase-shifting device, particularly when it is desired to delay a wide-band signal without the introduction of phase distortion.

Good transient response is obtained by a skewed-turn method of delay equalization.* The "baseline ripple," caused by variation in characteristic impedance along the line, has been reduced to 5% or less of the signal amplitude. End reflections have been minimized by the use of tapered capacitance elements at the ends of the winding. Materials are chosen for reliable operation under varying conditions of temperature and humidity.

There is no "ringing" or overshoot, and the delay is constant over a wide frequency range.

*See F. D. Lewis and R. M. Frazier, "A New and Better Variable Delay Line," *General Radio Experimenter*, 31, 7, October, 1956.

SPECIFICATIONS

Delay Range: 0 to 0.5 μsec.

Characteristic Impedance: 200 ohms $\pm$ 15% up to 4.5 Mc.

DC Resistance: Not over 20 ohms.

Delay vs Frequency (with respect to delay at 1 Mc): $\pm$1% at 10 Mc; $\pm$2% at 15 Mc; $\pm$4% at 20 Mc measured at maximum delay.

Amplitude Response vs Frequency: Loss at max delay, 9% (0.8 db) at dc; 30% (3 db) at 6 Mc; 60% (8 db) at 10 Mc; 90% (20 db) at 25 Mc.

Pulse and Step Response: See accompanying oscillograms.

Resolution: 1 nsec.

Voltage Rating: 1500 volts peak, winding to ground.

Dimensions: Diameter, including terminals, 3¼ inches (83 mm); depth 1½ inches (39 mm), exclusive of shaft; shaft diameter ⅜ inch (10 mm); shaft extends beyond body ¾ inch (20 mm). Knob is furnished.

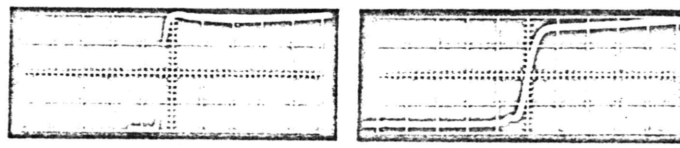
Net Weight: 6 ounces (0.2 kg).

Shipping Weight: 1 pound (0.5 kg).

Type		*Code Number*	*Price*
314-S86	Variable Delay Line	0314-9917	$60.00

PATENT NOTICE. See Note 20, page viii.

Oscillogram showing pulse shape and amplitude as delay setting is varied. Tektronix 541 Oscilloscope, 53K/54K Pre-Amplifiers; sweep, 0.1 μsec/cm.



Step response of 0.5-μsec, 200-ohm variable delay line with skewed winding; (*left*) step input, (*right*) step output at 0.5-μsec delay. Scope photos taken on Tektronix 541 Oscilloscope, 0.1-μsec/cm sweep.

Type 301-S104 VARIABLE DELAY LINE

The Type 301-S104 Variable Delay Line is a small distributed-winding unit with a sliding tap for adjustment of delay. Precious-metal wire is used in the winding to ensure reliable contact. Capacitive coupling between the terminals is minimized by shielding.

Applications for this line will be found in such fields as computers, nuclear physics, radar, and any place where an adjustable, linear phase shifter or wide-band, pulse-delay network is useful.

SPECIFICATIONS

Delay Range: 0 (approximately) to 25 nanoseconds ($\pm$10%).

Resolution: 0.06 nsec.

Characteristic Impedance: 190 ohms $\pm$ 15%.

Pulse Rise Time: 2.4 nanoseconds (approx) at maximum delay.

DC Resistance: 5.5 ohms ($\pm$20%).

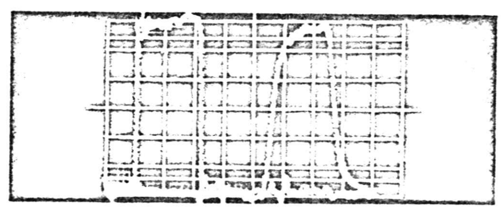
Voltage Rating: 1500 volts, peak, winding to ground.

Dimensions: Diameter, including terminals, 2 inches (51 mm); thickness, exclusive of shaft, 15/16 inch (24 mm); shaft diameter, ¼ inch (7 mm); shaft extension beyond body ¾ inch (20 mm).

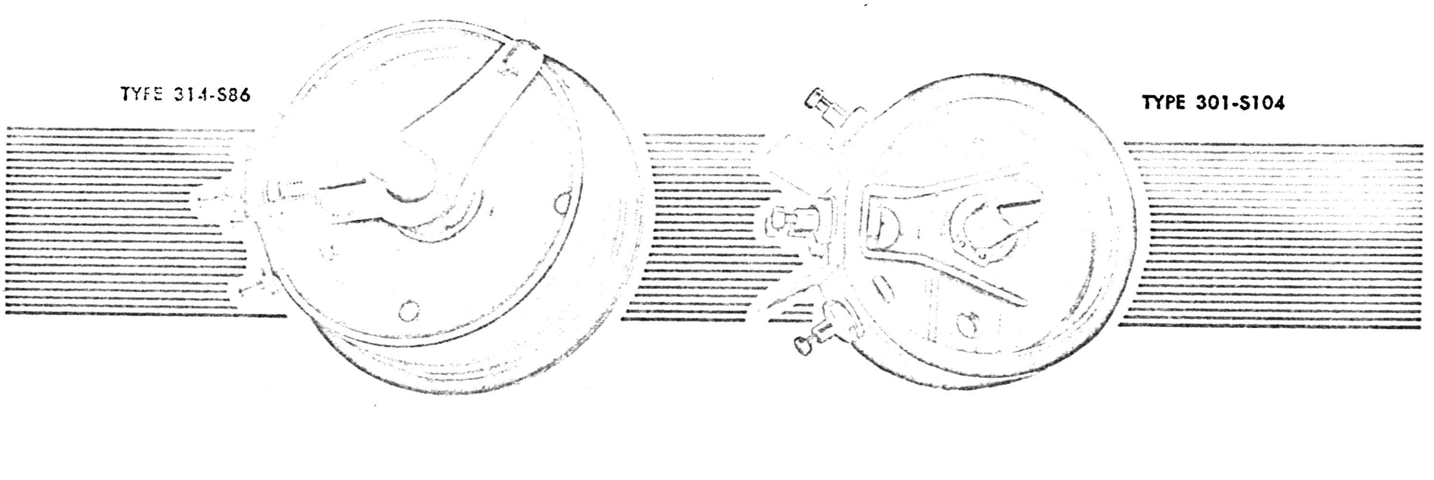
Net Weight: 1½ ounces (43 grams).

Shipping Weight: 1 pound (0.5 kg).

Type		*Code Number*	*Price*
301-S104	Variable Delay Line	0301-9489	$48.00



Photograph taken from the screen of a Lumatron 112 oscilloscope. The sweep speed is 5 nsec/cm. The photograph shows two sweeps superposed, the first with the delay line set for minimum delay, and the second trace with the line set for maximum delay. Delay, rise time, baseline ripple, and pulse distortion can be measured from the photograph. Attenuation may differ slightly among units.



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