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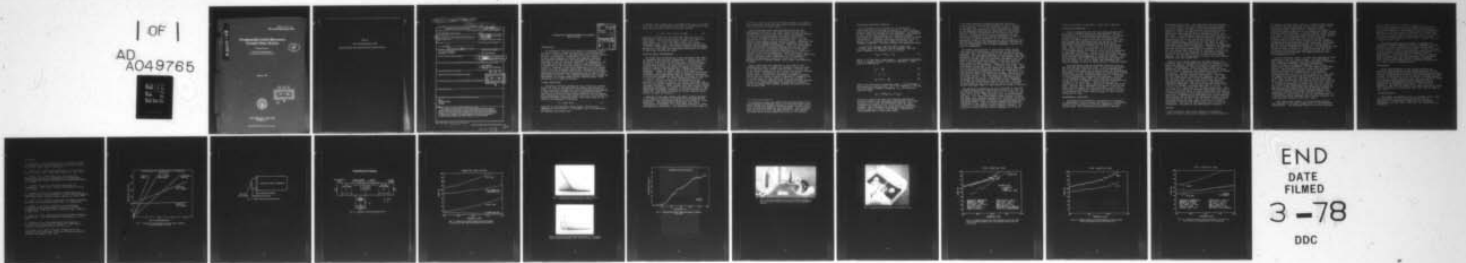
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# Cryogenically-Cooled Microwave Acoustic Delay Devices

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NRL Memorandum Report 3620 ✓	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) CRYOGENICALLY-COOLED MICROWAVE ACOUSTIC DELAY DEVICES.	5. TYPE OF REPORT & PERIOD COVERED Interim report on a continuing NRL problem.	
AUTHOR(s) R. D. Gurney	6. PERFORMING ORG. REPORT NUMBER	
7. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Research Laboratory Washington, D. C. 20375	8. CONTRACT OR GRANT NUMBER(s)	
11. CONTROLLING OFFICE NAME AND ADDRESS	12. REPORT DATE Jan 1978	10. NUMBER OF PAGES 23
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report) UNCLASSIFIED	
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) B		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Delay Microwave acoustic Cryogenic		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) RF components which provide delay of microwave signals are important elements of deception electronic warfare systems. Acoustic devices are attractive for this application because of their small size and lack of dispersion, but at high frequencies and longer delays the insertion loss is substantial. This report describes work toward the development of cryogenically-cooled sapphire delay devices operating in I/J band (8-20 GHz).		

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INTRODUCTION

RF components which provide delay of microwave signals are widely used in deception electronic countermeasures systems. Techniques for implementing delay include lengths of coax and waveguide transmission line, and acoustic devices using mercury or quartz and sapphire crystals. The acoustic devices have the advantage of small size (because of the low acoustic velocity), no dispersion, and loss less than that for long lines at high frequencies.. A comparison of the relative losses at 10 GHz is shown in Figure 1. Because of the basic superiority of the crystal delay lines for microwave system use, designers have been trying to further reduce their loss to allow less stringent requirements on associated components such as solid state amplifiers and TWT's. This report describes work toward the development of cryogenically-cooled sapphire delay lines operating in I/J band (8-20 GHz).

SYSTEM CONSTRAINTS

Electronic warfare systems can only tolerate a certain amount of loss in the delay device before the signal-to-noise ratio (s/n) becomes too low for acceptable performance. In many systems the delay device is sandwiched between amplifiers to best maintain signal strength, and by making some assumptions about these amplifiers, we can estimate the maximum allowable insertion loss. The noise level at the input to an amplifier is given by

$$N = (NF) kT B \quad (1)$$

where NF is the amplifier noise figure, kT the room temperature noise power (-114 dB/MHz), and B the bandwidth.

Note: Manuscript submitted January 3, 1978.

A typical noise figure for a broadband high gain 1 watt TWT is 25 dB. Let the bandwidth be 8 GHz or 39 dB above 1 MHz. Then the equivalent input noise power becomes

$$N = 25 - 114 + 39 = -50 \text{ dBm} \quad (2)$$

Assuming a minimum s/n of 10 dB then requires that the input signal must not fall below -40 dBm to be useful in the system. If the maximum signal level into the delay device is 1 watt (+30 dBm), which is a typical transducer power limit, the maximum allowable delay loss is 70 dB. These results will vary slightly with the exact system, but the above are reasonable assumptions by which to set delay line design goals.

#### ACOUSTIC DELAY FUNDAMENTALS

The chief task in achieving a low loss delay line lies in designing an efficient transducer to convert the input RF signal to and from an acoustic one. A significant portion of the total loss is associated with this double transduction process. We know that if an oscillating electric field is placed across a properly cut piezo-electric crystal, the crystal will vibrate at the same frequency. Quartz is widely used in this manner as a resonator. Since for best coupling efficiency the crystal thickness should approximate half an acoustic wavelength, at microwave frequencies the desired thickness is less than 0.5 micron (5000 Å). At lower frequencies (below 0.5-1.0 GHz) a crystal platelet can be mechanically and chemically polished to achieve the proper thickness, but for the thin layers needed at high frequencies this becomes extremely difficult. Most workers have used various vacuum deposition techniques to create a crystalline layer of the piezoelectric material directly on the end surface of the delay rod. The basic structure of a bulk acoustic delay device is shown in Figure 2.

Sapphire is the most widely used delay crystal because it is readily available in good quality and because its attenuation for longitudinal waves is the lowest of known materials. Researchers have determined that lower attenuation is possible for a few other crystals if shear propagation is permitted. The generation of this mode is

difficult, however, using thin films because it is hard to grow transducer films with the proper crystal orientation thin enough for microwave use.<sup>+</sup>

Early transducer work used cadmium sulfide as the piezoelectric material, but most recent projects have concentrated on zinc oxide (ZnO), which is somewhat easier to grow and which has higher conversion efficiency<sup>3</sup>. Zinc oxide is deposited onto the delay crystal rod by sputtering it from a disc of compressed ZnO. With thin layers a true single crystal does not result; generally the c-axis grows perpendicularly to the substrate, with the other axes at random orientations. Since for longitudinal waves the degree of coupling depends only on the c-axis positioning, this crystalline structure is sufficient. The longitudinal wave coupling coefficient,  $k$ , which is a measure of the electromechanical energy conversion, is 0.28 for bulk ZnO, but deposited thin films rarely reach this value<sup>4</sup>. Improper growth conditions or the presence of impurities apparently cause the c-axis to tilt from perpendicular or become random; this lowers the effective  $k$  value.

Metal electrodes are required on each side of the piezoelectric layer to apply the external electric field. It is important that these films be thin ( $\sim 1000 \text{ \AA}$ ) and of the proper materials so as to incur the minimum acoustic signal loss. Furthermore, any acoustic mismatch significantly affects the transducer frequency response. Silver has the closest acoustic impedance to sapphire and is a good match to zinc oxide as well, but because of silver's oxidation tendency gold is generally used instead. A very thin (100-200  $\text{\AA}$ ) layer of chromium or titanium serves to improve the adhesion between the gold film and the crystal face.

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<sup>+</sup>It should be noted that RCA<sup>1,2</sup> has done promising work using magnesium aluminate spinel in the shear mode as the delay crystal and properly oriented single crystal platelets of lithium niobate as the transducer. The platelets were thinned down with ion beam milling to the desired thickness after being bonded with gold to the crystal.

## TRANSDUCER ELECTRICAL BEHAVIOR

The transducer may be modeled by an equivalent electrical circuit as shown in Figure 3. This circuit differs from the usual one<sup>5</sup> by the presence of a variable acoustic load,  $R_T$ , across the top electrode. The behavior of this circuit was analyzed in a computer program (described in a separate report<sup>6</sup>) similar to that of other researchers<sup>5</sup>. Materials and layer thicknesses could be varied, and the program would compute and plot the frequency response. The main results are summarized here.

If one first assumes that the metal layers are extremely thin, so that they may be ignored, then the input impedance at terminal 1-1 is given by

$$Z_{in} = 1/j\omega C_o + Z_a \quad (3)$$

where  $C_o$  is the layer capacitance,  $\omega$  the angular frequency, and  $Z_a$  a complex acoustic radiation impedance. These terms are defined by

$$C_o = \frac{\epsilon A}{t} \quad (4)$$

$$\omega = 2\pi f \quad (5)$$

$$Z_a = R_a + jX_a \quad (6)$$

where  $A$  is the active transducer area,  $t$  its thickness,  $\epsilon$  the dielectric permittivity, and  $f$  the frequency. At the half-wavelength resonant frequency,  $\omega_o$ , of the piezoelectric layer

$$R_a = (4k^2 R_D / \pi Z_o) (1/\omega_o C_o).$$

From this form we see that the coupling coefficient directly affects the transducer performance; for every halving of its value the conversion loss for each transduction rises by 6 dB, or 12 dB for the entire process. The transducer is capacitive and presents a severe mismatch to the 50 ohm system, reflecting a considerable part of the input power.

The exact computer analysis shows that having a finitely-thick bottom electrode adds 2-4 dB of ripple in the passband. If no top electrode acoustic loading is assumed, the thickness of that electrode is crucial to the passband shape because destructive interference from the surface reflections can introduce large loss poles. In cases in which the top electrode can be intimately attached to an acoustic absorber, as when a gold wire is tightly bonded to it for electrical connection, most of the stray energy will be absorbed and not seriously affect the frequency response (the overall loss is increased 2-3 dB for each transducer, though, as might be expected<sup>8</sup>.)

The other contributions to the overall delay device loss come from diffraction, attenuation in the bottom electrode mode, and attenuation in the crystalline delay material. For the small diameter top electrodes that are desirable for best electrical match, the acoustic beam will spread out enough that the receiving transducer will not pick up all the available energy. Given the electrode size, crystal length, and frequency, the loss due to diffraction can be estimated. Typically this might vary from about 6-8 dB near 6 GHz to 2-3 dB at 12-15 GHz. Loss in the thin bottom electrode material is fairly negligible for longitudinal propagation because the attenuation in gold is only about 2 dB/micron at 10 GHz. The major loss contribution comes from scattering-induced attenuation in the delay crystal. The loss even for sapphire is about 22-26 dB/ $\mu$ sec at 10 GHz. Furthermore, the attenuation increases in proportion to the square of the frequency: at 15 GHz the loss would be about 54 dB/ $\mu$ sec. The main contributions to the total loss of the 0.75  $\mu$ sec delay device discussed later in this report are shown in Figure 4.

The material attenuation can be controlled in two ways. For many applications a short delay (0.125-0.25  $\mu$ sec) is sufficient, which keeps the loss, even in J band, on the order of 10-14 dB. When possible this is the preferred approach. For those cases where longer amounts of delay are imperative, however, operation of the delay device at cryogenic temperatures (60-80°K) will significantly reduce the attenuation. This is because temperature-dependent vibration in the crystal is much reduced resulting in a lessening of the acoustic signal phonons' scatter. By cooling to below 50°K the loss in sapphire at 8 GHz is

lowered from about 13 dB/ $\mu$ sec to less than 1 dB/ $\mu$ sec.

#### TRANSDUCER FABRICATION

The ZnO transducers for the test delay devices were deposited on freshly evaporated chromium/gold bottom electrodes in a DC sputtering vacuum system. By placing a large voltage (2-3 KV) across the electrode plates holding the sample crystal and the zinc oxide disc, the argon-oxygen gas introduced into the system is ionized. The charged particles accelerate toward the disc, physically knocking ZnO atoms from it onto the crystal face. With a bias of 3 KV across a 2.5 cm gap and an argon-oxygen (80-20) pressure of 6.67 Pa (50 microns), a film approximately 0.4 microns thick could be deposited in less than 15 minutes. During a run the target was cooled with running water and an auxiliary liquid nitrogen cold trap kept the atmosphere as clean as possible. The initial power level under these conditions was slightly over 100 watts, but as the target was bombarded this rapidly dropped to about 30 watts where it remained stable.

Film thickness could be estimated from the color of the film and the sputtering time. A more precise method was to etch away a portion of the film with phosphoric acid, and then examine the interface under an interference microscope. At the thickness step the interference fringes shift in proportion to the thickness and it is possible to fairly accurately determine the thickness. With the 7.5 cm diameter target used, the thickness uniformity across the 0.6 cm diameter crystal face was acceptable but not good (~30% variation). This variation made it impractical to use a quartz monitor to control the thickness. Growing good, repeatable transducer films was the most difficult aspect of this experiment, since slight variations in deposition conditions or impurities in the vacuum system can cause inactive layers or poor crystal structure to form.

#### EXPERIMENTAL CONDITIONS

To measure the attenuation reduction as a function of temperature a delay crystal was mounted in a waveguide holder at the bottom of a variable temperature liquid helium dewar (the temperature controlled by heating

evaporated helium gas.) The insertion loss was measured by RF substitution in a very sensitive superheterodyne receiving system. Because of the extreme temperature variation (leading to metal holder contraction) and the length of a test, the material loss was determined by subtracting the measured loss of successive echos from each other. This procedure removed all common errors in the data. Figures 5 and 6 show oscilloscope targets of the echo patterns of a 0.55  $\mu$ sec delay crystal at 70 $^{\circ}$ K and 225 $^{\circ}$ K respectively. Because of the low material loss at 70 $^{\circ}$ K many more echoes are visible. (In fact, in some cases where good triple-travel echo suppression is required, such low loss would be a hindrance.) Figure 7 displays the measured loss versus temperature of sapphire at 8 GHz. For this figure the loss at 4 $^{\circ}$ K is set equal to zero; the actual residual loss, depending on crystalline defects, typically is less than 2 dB but is hard to accurately measure. The curve graphically portrays the improvements possible with the cooled line.

Clearly such a dewar cannot be included as part of a practical piece of equipment for field use because it is bulky and fragile, as well as requiring a source of liquid helium. Fortunately, relatively small closed-cycle mechanical refrigerators are available which can reach 60 $^{\circ}$ K or lower, requiring only electricity (about 600 watts) to operate. We chose the laboratory version of a militarized infrared detector refrigerator, the model CS-1003, made by Air Products and Chemicals, Inc. The two versions differ only in the compressor; for economy the lab type uses a large modified air conditioning compressor while the other has a small high speed dry lubricant compressor. The military version weighs about 7.26 kg (16 pounds), occupies less than 71 cu. cm (0.25 cu. ft.), and costs \$13K in small quantities. The cold head fits inside an evacuated stainless steel can for thermal insulation while an inner shield made from layers of aluminized plastic film superinsulation further reduces heat loss. Temperature is monitored with a Fe/Au-Chromel thermocouple and an electrical resistance heater provides fine temperature control. The RF signal is carried by a miniature stainless coax cable, which has low thermal conduction. The various refrigerator parts, minus the compressor, are shown in the photograph in Figure 8.

## RESULTS

The transducers were first tested in a waveguide holder in which a particular frequency could be tuned by

adjusting a sliding short circuit. A short probe coupled the energy from the waveguide to the delay crystal, with electrical contact made with a miniature bellows (Servometer Corp. type SK-4125). However, in order to compare transducer behavior to the theoretical model untuned response must be measured. A 50 ohm coaxial holder mounted on a small three-axis positioner was made for this purpose. Because it was untuned the overall loss increased somewhat over that measured with the waveguide holder. A simple holder using a short length of 50 ohm microstrip transmission line wirebonded to the transducer electrodes was the final configuration tested, this one primarily for use in the cryogenic refrigerator. A photograph of this holder is shown in Figure 9. Some difficulty was found in bonding to the small top electrode because the dot was hard to see and because the bonding pressure sometimes damaged the ZnO.

One of the delay lines (.75  $\mu$ sec) was measured at room temperature with all three holders. All measurements were taken by RF substitution using calibrated attenuators and a sensitive heterodyne receiver arrangement. Figure 10 shows the measured response along with a theoretical curve adjusted to fit the coaxial probe data points. The thickness and area values were estimated from the evaporation parameters while the coupling coefficient and, to a lesser extent, the material attenuation were varied to yield a decent fit. The value for sapphire attenuation was increased from the normal 22 dB/ $\mu$ sec (10 GHz) to 27 dB/ $\mu$ sec to better follow the data. More importantly, the coupling coefficient had to be lowered to 0.11 from the bulk value of 0.28. While it is virtually impossible to obtain the bulk value with a thin film, other researchers have been able to reach as much as 0.25 with good films<sup>9</sup> and Larson and Finnley of the Electronics Division of NRL have obtained 0.16<sup>10</sup>. If a higher degree of coupling had been possible the insertion loss would have been reduced by about 14 dB. Improvements, particularly at the high frequency end, of a few dB would have resulted from a smaller diameter top electrode and slightly thinner ZnO layer.

This same delay crystal, in the microstrip mount, was measured at cryogenic temperature in the mechanical refrigerator. The averaged results from three separate

runs at about 65°K are shown in Figure 11. A substantial reduction in loss is observed although the slope would indicate that there remains some residual material attenuation. The reduction would have been more impressive with an excellent transducer; the final loss then would have been about 50 dB at 10 GHz. This amount of loss could easily be recovered with a solid state amplifier or TWT, leaving a good signal-to-noise ratio at a useable power level.

The theoretical curves of Figure 12 suggest the magnitude of improvement that could be expected by using cryogenic cooling to achieve low crystal attenuation. Two ZnO/sapphire delay lines are shown, 1.0 and 0.25  $\mu$ sec in length, with a fairly good coupling coefficient of 0.22, both at normal and cryogenically-reduced values of attenuation. A residual loss of 3 dB/ $\mu$ sec at 10 GHz is used as suitable for 60-70°K operation. The cryogenic case has both lower and flatter frequency response. The 1.0  $\mu$ sec device remains near or below 60 dB even up to 16 GHz, which is extremely good.

#### CONCLUSIONS

Noise considerations in ECM system restrict the insertion loss of delay devices to approximately 70 dB. The room temperature loss of microwave bulk acoustic delay devices, which because of their size are desirable for such systems, is above this limit for delays in excess of about 0.5  $\mu$ sec in J band, even with high quality transducer films. This program has demonstrated that improved loss is achievable at temperatures which a relatively small mechanical refrigerator can provide. With the loss reduced to the 50-60 dB range it is likely that solid state (FET) amplifiers or medium gain TWT's can then be used in the circuit.

#### ACKNOWLEDGEMENTS

The author is grateful to Dr. G. Friedman and A. Elia for assistance with the circuit analysis, Dr. E. Alexander for suggestions concerning the transducer deposition, and Dick Prom, Code 2358, for performing the wirebonding.

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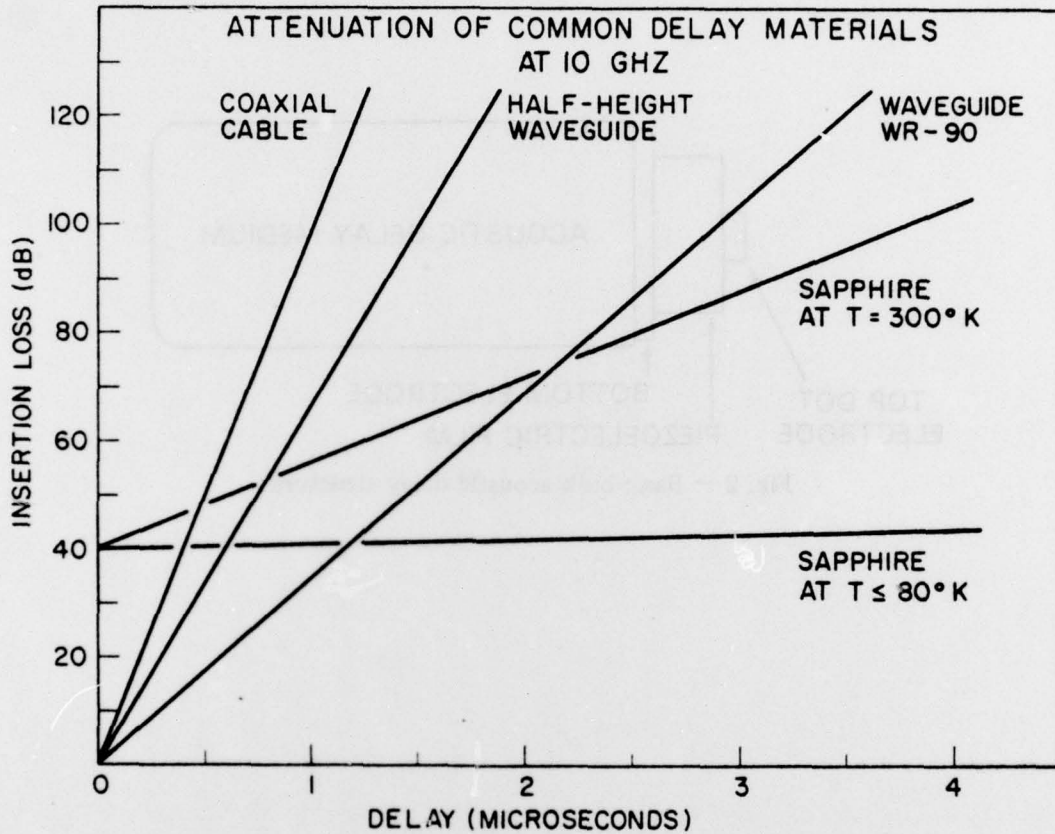


Fig. 1 — Comparison of approximate loss versus delay of different delay approaches at 10 GHz

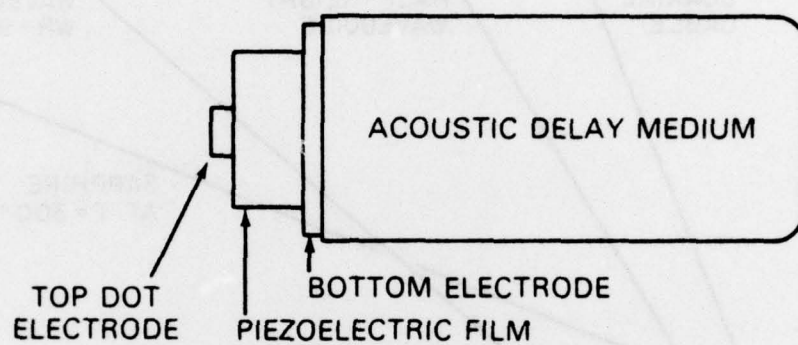


Fig. 2 - Basic bulk acoustic delay structure

## TRANSDUCER MODEL

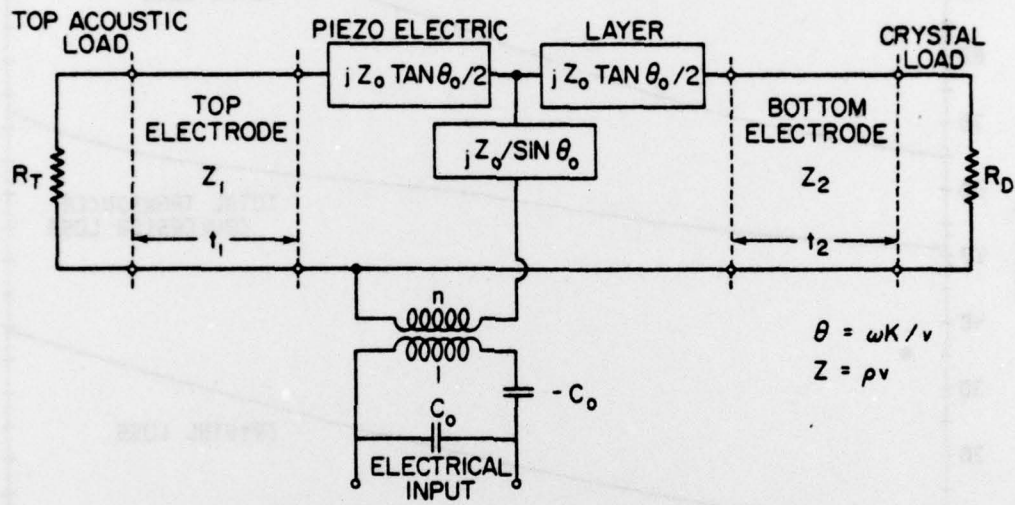


Fig. 3 - Transducer electrical equivalent circuit

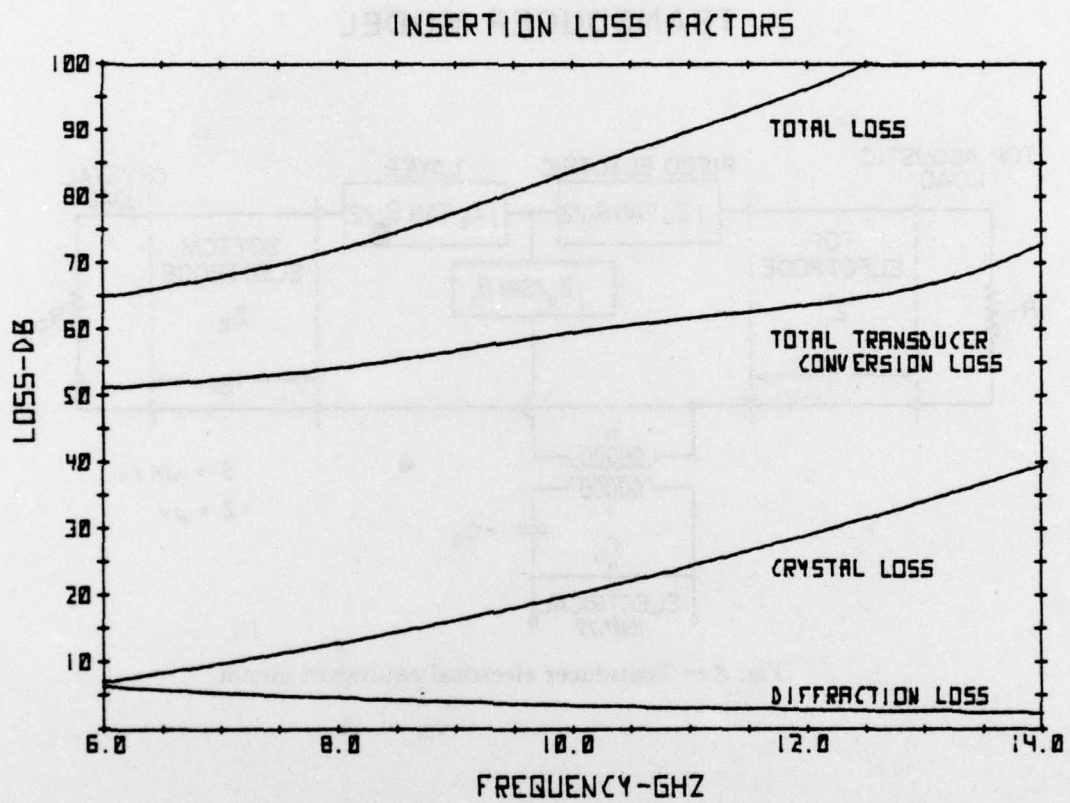


Fig. 4 - Insertion loss versus frequency along with sources of loss for 0.75  $\mu$ sec delay line described in text and Fig. 9

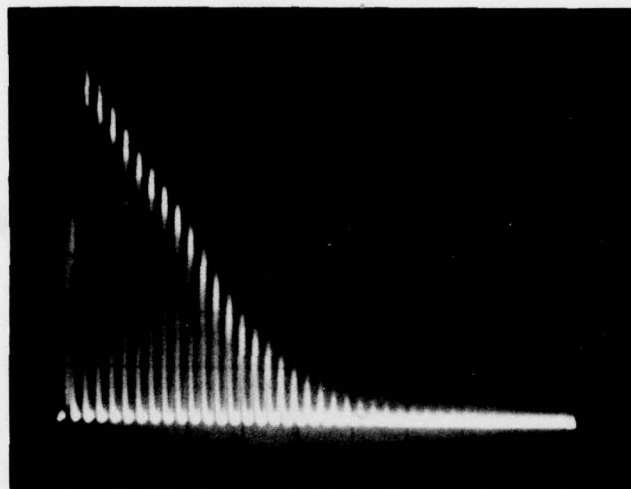


Fig. 5 — Multiple acoustic echos of 0.55  $\mu$ sec delay crystal at 70 °K. Vert.: 0.05 V/div. Horz.: 5  $\mu$ sec/div.

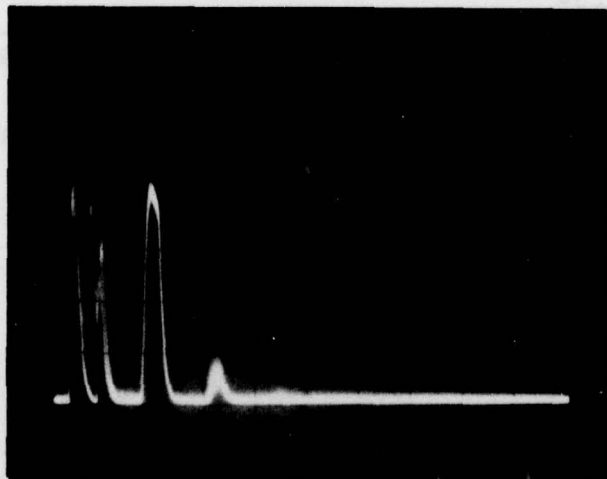


Fig. 6 — Acoustic echos of same delay crystal at 225 °K. First ragged peak due to transmitter leakage. Vert.: 0.05 V/div. Horz.: 1  $\mu$ sec/div.

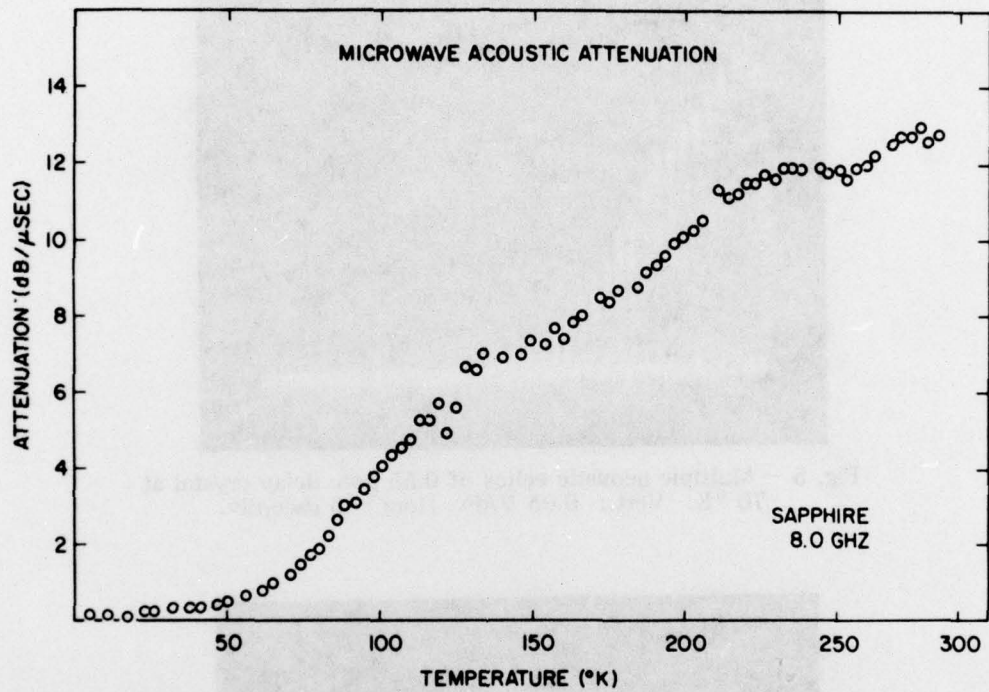


Fig. 7 — Measured attenuation versus temperature of sapphire at 8.0 GHz

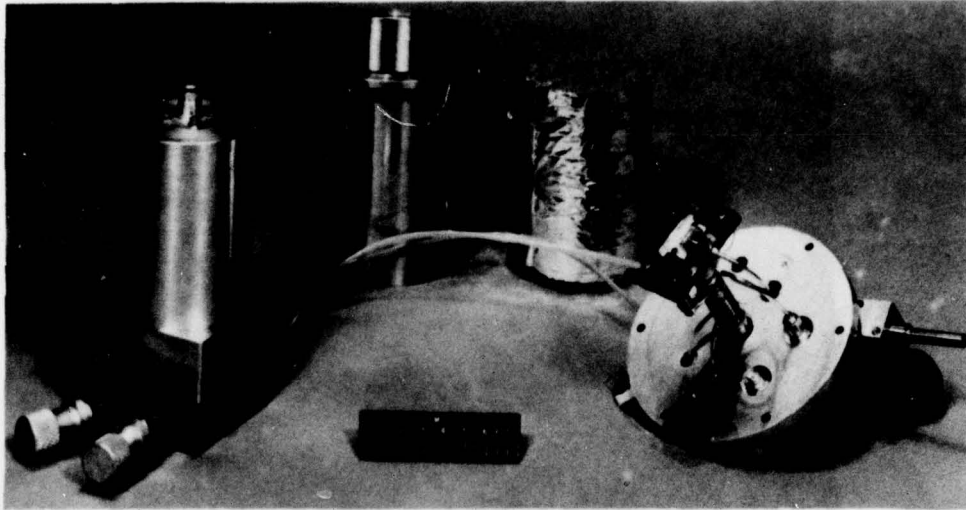


Fig. 8 — Mechanical refrigerator parts, minus compressor, showing cold head with mounted delay device, evacuation can, and superinsulation shielding

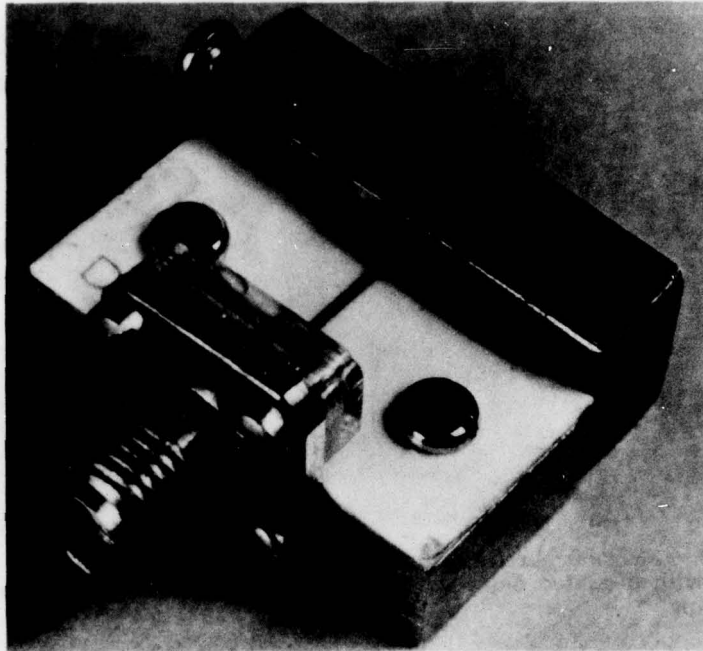


Fig. 9 — Microstrip holder with sapphire crystal bonded in place

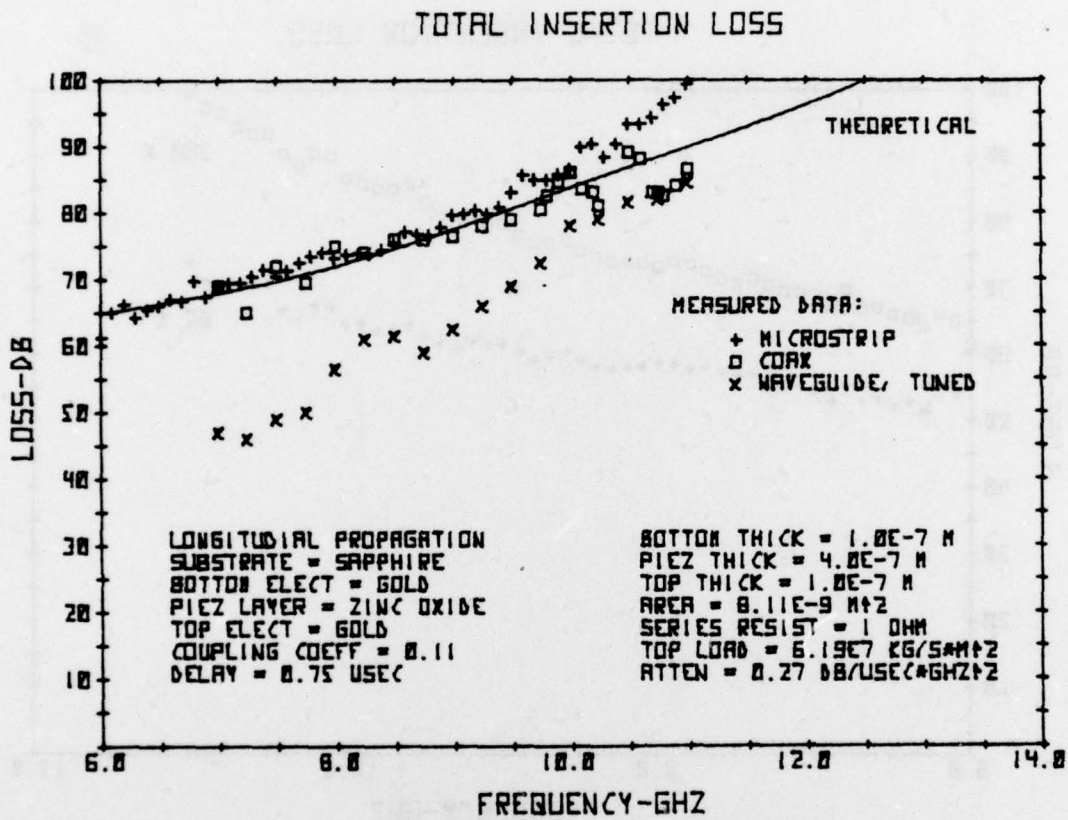


Fig. 10 — Measured insertion loss versus frequency of 0.75  $\mu$ sec delay device along with theoretical curve. The computer program input values are listed.

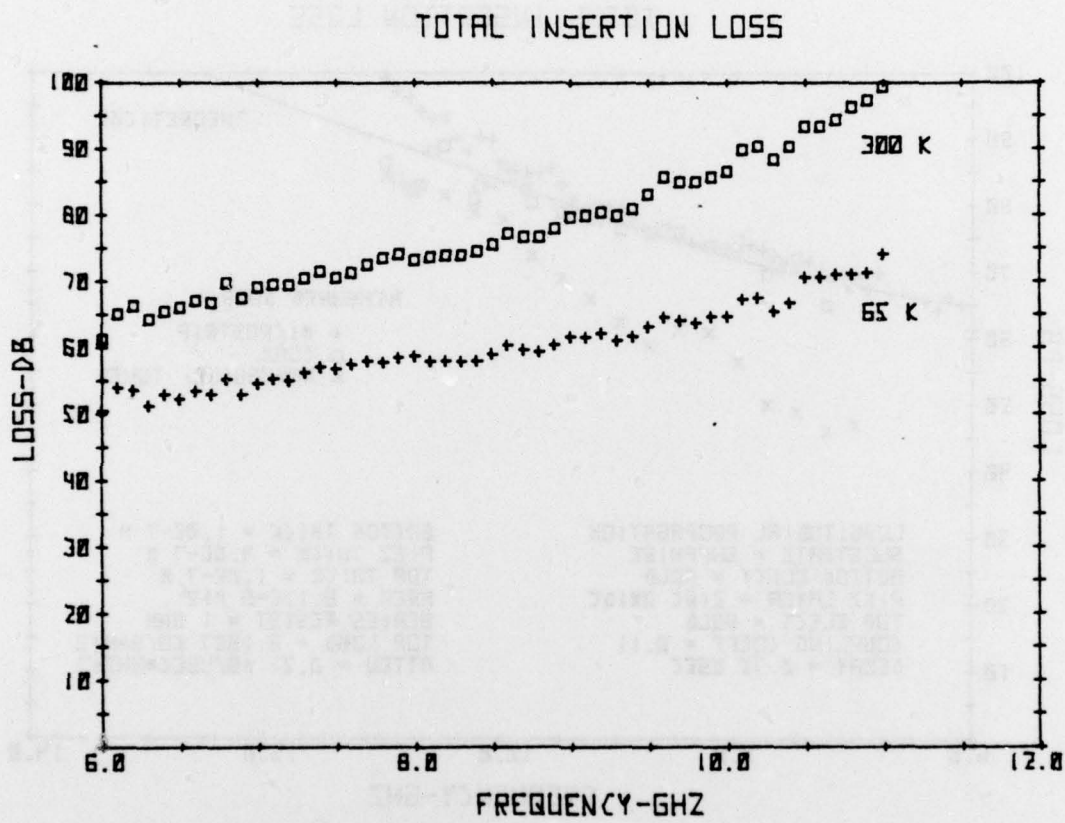


Fig. 11 — Measured insertion loss versus frequency of the same delay device in microstrip mount at 65 and 300 °K

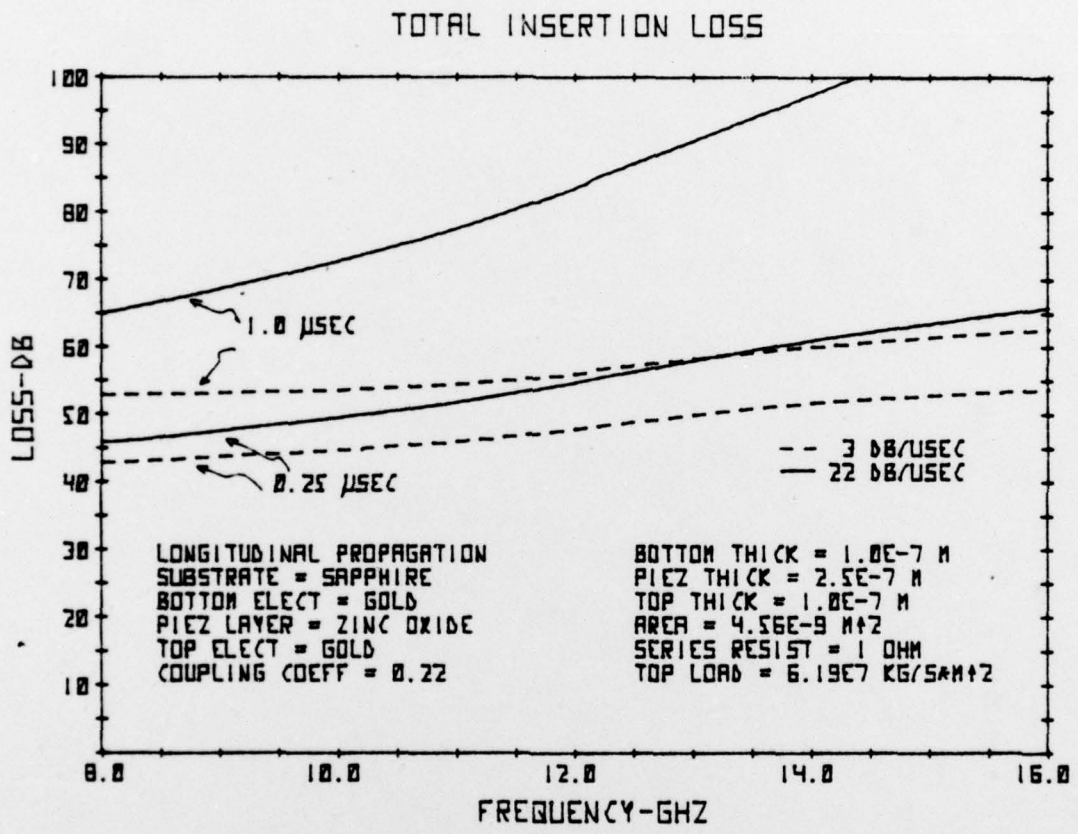


Fig. 12 — Theoretical insertion loss versus frequency of 1.0 and 0.25 μsec devices at low temperature and room temperature