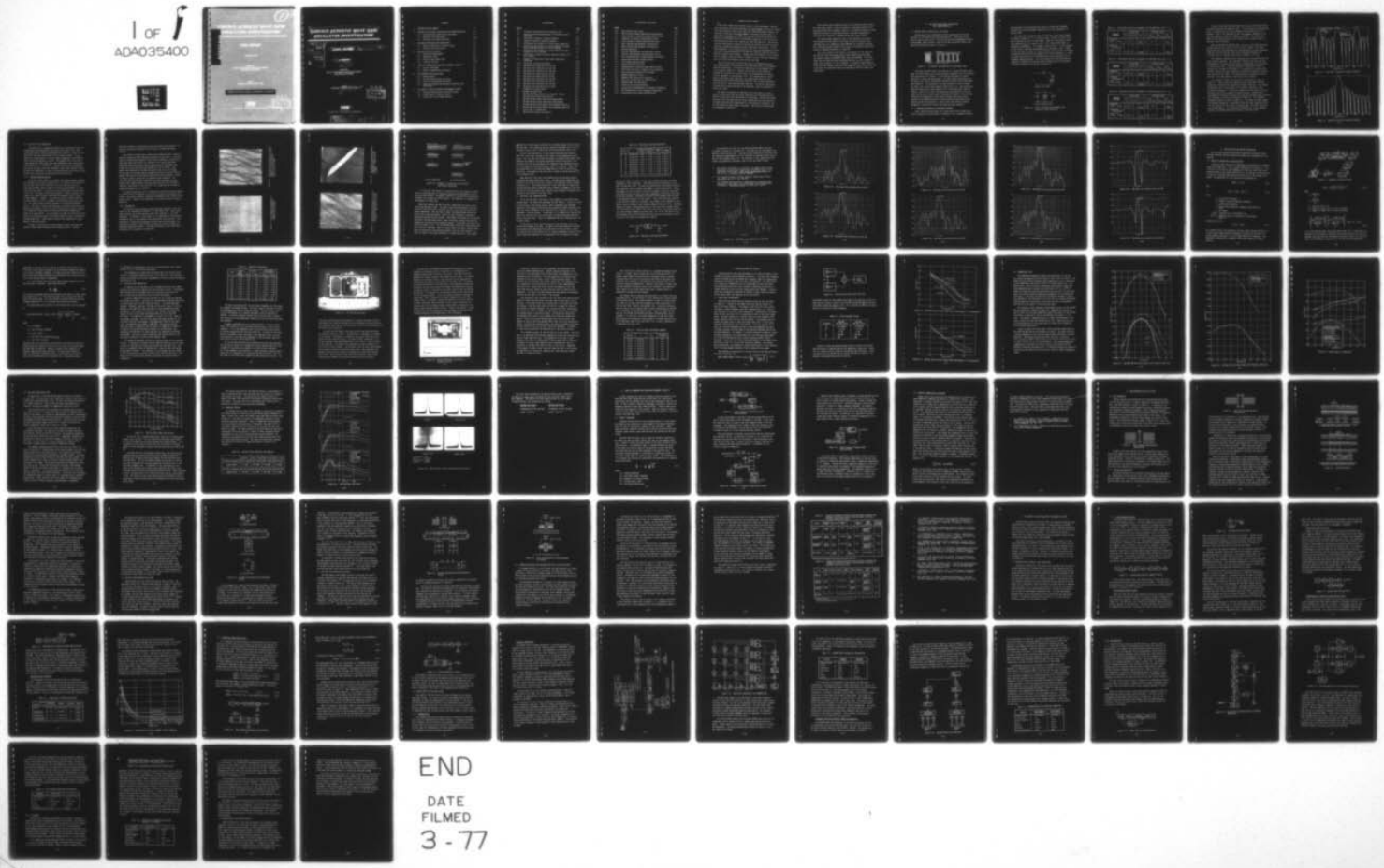
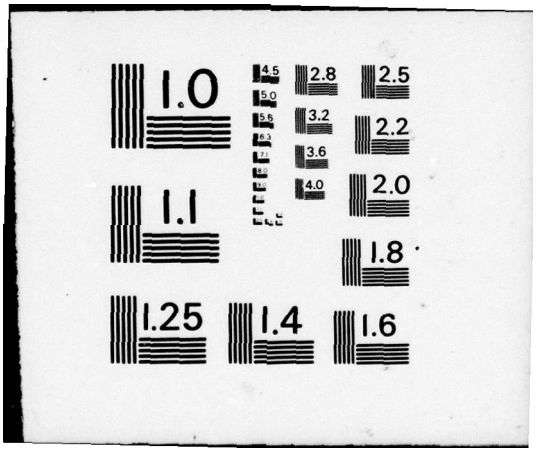
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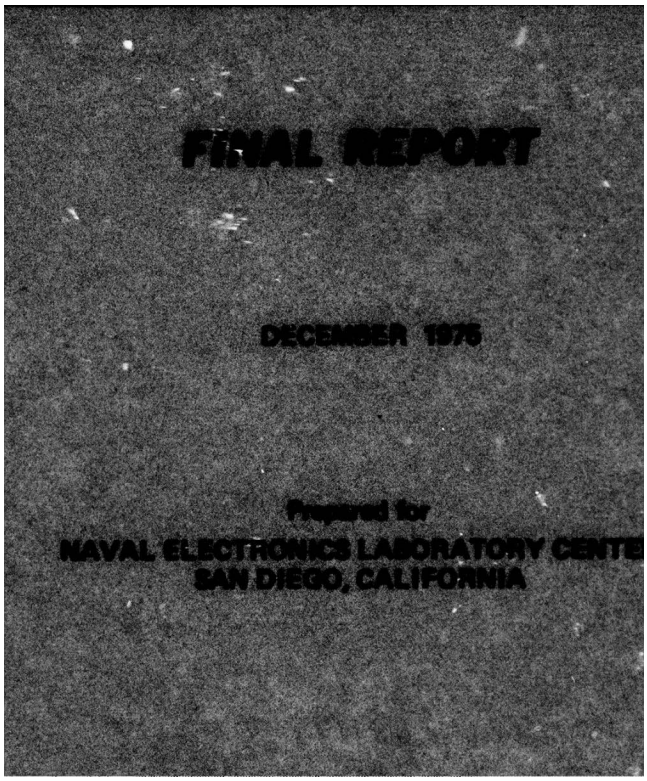
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FINAL REPORT
DECEMBER 1976
Prepared for
NAVAL ELECTRONICS LABORATORY CENTE
SAN DIEGO, CALIFORNIA

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# 1. INTRODUCTION AND SUMMARY

This final report describes the results of the development, fabrication, evaluation and test performed by TRW Systems, under Contract No. N00123-75-C-1182, Surface Acoustic Wave (SAW) Oscillator Development Program, for the Naval Electronics Laboratory Center. The period of performance was March 1975 to December 1975. The main purpose of the SAW oscillator program was to investigate the key performance parameters of SAW oscillators and particularly their short, medium and long term stability. SAW oscillators were fabricated to operate at 250 MHz and 500 MHz, and their performance was evaluated and compared against theoretical predictions. As the data presented in the following sections will show, the performance of these oscillators closely approaches or exceeds the currently reported state-of-the-art in nearly every respect. Perhaps even more important, this performance is related to the fabrication processes in such a way that directions for still better performance can be clearly seen.

The oscillators which received the bulk of the attention during this program were of the type which use a SAW delay line in the feedback loop of an amplifier. The insertion phase delay of the feedback loop in an integral number of $2\pi$ radians, and the gain of the amplifier exceeds the insertion loss of the loop, thus guaranteeing oscillation. The key component is the SAW delay line. Its Q determines oscillator phase noise (short term stability); its temperature coefficient determines the oscillator medium term stability; and its aging determines the oscillator's long term frequency stability. The design, fabrication and electrical characterization of the SAW delay lines are presented in Section 2, below.

The theory of operation of SAW delay line oscillators is given in Section 3 after which the oscillator electronics are discussed and the details of the oscillator fabrication are presented. The SAW oscillators have been fully characterized for short, medium and long term stability, for power variation with temperature, for the effects of vibration, and for the effects of power supply variations. The results of these tests are presented in Section 4.

Three studies were conducted as part of the SAW oscillator program. The first study, which is given in Section 5, addressed methods of improving SAW oscillator frequency stability. The methods studied included injection locking to a more stable source, electronic compensation techniques and a method of compensating the SAW crystal itself.

The second study subject was that of SAW resonator oscillators. The discussion of this type of oscillator is given in Section 6 and concludes that, for frequencies below 800 MHz, the resonator approach will eventually become superior to the delay line approach except when tuning or frequency modulation is required.

The final section of this report is an analysis of the impact of the SAW oscillator technology upon military communications systems. The subject systems are SEEKBUS/ITACS, GPS and FLTSATCOM. This study shows that the SAW oscillator technology has much to offer systems of these types although it is not a panacea. In properly chosen applications, the size, weight, power and cost reductions which accrue when bulk oscillators and multiplier chains are replaced by SAW oscillators are significant.

# 2. SAW DELAY LINE DESIGN, FABRICATION AND CHARACTERIZATION

## 2.1 SURFACE ACOUSTIC WAVE DELAY LINE DESIGN

The SAW delay lines fabricated for this program were of the open structure or the thinned electrode configuration. These delay lines were the same as those used in the TRW 1974 sponsored Independent Research & Development (IR&D) program. Both the 250 MHz and 500 MHz delay lines used the configuration shown in Figure 2-1.

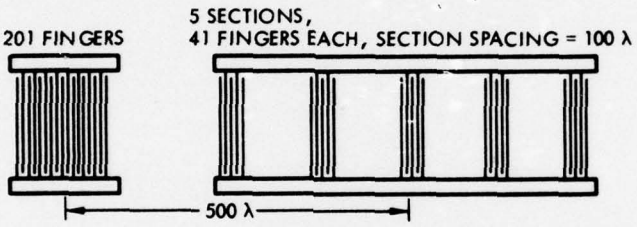



Figure 2-1. Transducer Configuration for SAW Delay Lines

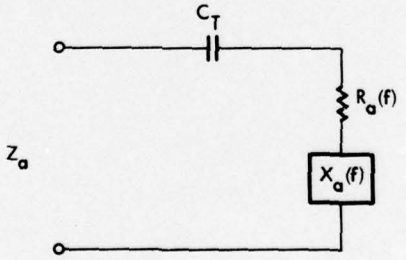
This open structure delay line consists of a closed structure transducer with 201 fingers and an open structure transducer with five sections, each consisting of 41 fingers. In this design the center to center separation is about 500 wavelengths. This path length separation gives the delay line a high Q and enables the SAW oscillator to have good short term stability. The advantage of an open structure is that it allows the delay line to have good frequency selectivity (i.e., very narrow pass band and large acoustic path length) with a relatively small number of fingers. One of the criteria for good short term stability is for the delay line to have a large acoustic propagation distance. With the open structure the propagation of the surface acoustic wave takes place largely on the unmetalized quartz surface minimizing the second order effects within the transducers. These second order effects manifest themselves in distortion of both amplitude and phase response.

### 2.1.1 Computer Simulation of Transducer Patterns

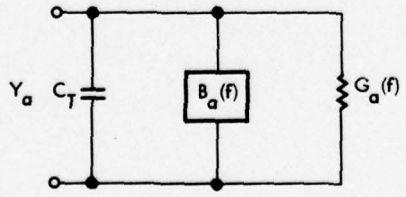
Both a delta-function model and an equivalent circuit model were used to simulate the characteristic responses of the transducer patterns.

The equivalent circuit approach was used to calculate the impedance characteristic and the minimum insertion loss of the transducers in the pass band.

The equivalent circuit for the "in line" and "cross field" models are shown in Figure 2-2.[1] A series circuit is shown in Figure 2-2(a) and is obtained for the "in line" model. When $f=f_o$ the acoustic radiation reactance $X_a(f_o)$ is equal to zero. The "cross field" model is expressed in admittance. It is shown in Figure 2-2(b). At the frequency $f_o$ the acoustic radiation susceptance $B_a(f_o)$ is equal to zero. Tables 2-1 and 2-2 show the summary of the calculated immittance for the 250 MHz and 500 MHz delay lines as calculated at the center frequency $f_o$. Table 2-3 shows the results for the 250 MHz delay line as measured on an HP Automatic Network Analyzer. The film resistance of the electrodes was measured at 250 MHz far below the center frequency and was subtracted off before presenting the results in Table 2-3.




(a) SERIES "IN LINE" MODEL




(b) SHUNT "CROSS FIELD" MODEL

Figure 2-2. Series and Shunt Representation for Electrical Input Immittance

Table 2-1. Calculated Electrical Parameters for 250 MHz Delay Line $f = f_o$

| ELECTRICAL PARAMETERS | "IN LINE" MODEL | | | | "CROSS FIELD" MODEL | | | |
|---|---|---|---|---|---|---|---|---|
| | $C_T$ pf | $R_a(f_o)$ Ω | $X_a(f_o)$ Ω | $Z_a(f_o)$ Ω | $C_T$ pf | $G_a(f_o)$ $10^{-3}$ MHOS | $B_a(f_o)$ $10^{-3}$ MHOS | $Y_a(f_o)$ $10^{-3}$ MHOS |
| TRANSDUCER A<br>N = 201 A = 180 λ | 11.7 | 11.32 | 0 | 11.32 - j 51.97 | 11.7 | 4.0 | 0 | 4.0 + j 18.37 |
| TRANSDUCER B<br>(OPEN STRUCTURE)<br>NSEC = 5, N = 41<br>IR = 100 λ A = 180 λ | 11.93 | 11.30 | 0 | 11.3 - j 50.88 | 11.93 | 4.16 | 0 | 4.16 + j 18.73 |

Table 2-2. Calculated Electrical Parameters for 500 MHz Delay Line $f = f_o$

| ELECTRICAL PARAMETERS | "IN LINE" MODEL | | | | "CROSS FIELD" MODEL | | | |
|---|---|---|---|---|---|---|---|---|
| | $C_T$ pf | $R_a(f_o)$ Ω | $X_a(f_o)$ Ω | $Z_a(f_o)$ Ω | $C_T$ pf | $G_a(f_o)$ $10^{-3}$ MHOS | $B_a(f_o)$ $10^{-3}$ MHOS | $Y_a(f_o)$ $10^{-3}$ MHOS |
| TRANSDUCER A<br>N = 201 A = 180 λ | 5.85 | 11.32 | 0 | 11.32 - j 51.97 | 5.85 | 4.0 | 0 | 4.0 + j 18.37 |
| TRANSDUCER B<br>(OPEN STRUCTURE)<br>NSEC = 5, N = 41<br>IT = 100 λ A = 180 λ | 5.96 | 11.3 | 0 | 11.3 - j 50.88 | 5.96 | 4.16 | 0 | 4.16 + j 18.73 |

Table 2-3. Measured Electrical Parameters for 250 MHz Delay Line $f = f_o$

| ELECTRICAL PARAMETERS | "IN LINE" MODEL | | | | "CROSS FIELD" MODEL | | | |
|---|---|---|---|---|---|---|---|---|
| | $C_T$ pf | $R_a$ Ω | $X_a$ Ω | $Z_a$ Ω | $C_T$ pf | $G_a$ $10^{-3}$ MHOS | $B_a$ $10^{-3}$ MHOS | $Y_a$ $10^{-3}$ MHOS |
| TRANSDUCER A<br>N = 201 A = 180 λ | 12.95 | 11.0 | - | 11 - j 49.46 | 12.95 | 4.28 | - | 4.28 + j 19.26 |
| TRANSDUCER B<br>(OPEN STRUCTURE)<br>NSEC = 5, N = 41<br>IR = 100 λ A = 180 λ | 11.52 | 11.0 | - | 11 - j 55.3 | 11.52 | 3.59 | - | 3.59 + j 18.08 |

In order to minimize both the insertion loss and diffraction effects an acoustic aperture was chosen at 180 $\lambda$. For this type of configuration, there is minimum loss, but slight skewing of the desired $(\sin x/x)^2$ response. That is the rejection of the low frequency sidelobes is less than the rejection of the high frequency sidelobes. The node points remain at the desired points so this skewing has no adverse effect for SAW delay line oscillators.

Both the 250 MHz and 500 MHz delay line had a calculated unmatched minimum insertion loss value of 16 dB in a 50 $\Omega$ system. This value agrees well with the measurement of a 250 MHz delay line whose unmatched insertion loss was 18.4 dB. With series inductance matching, the insertion loss of a 250 MHz delay line was reduced to 12.6 dB.

The frequency response of the transducers were calculated using the delta function approach. This approach is based on the fact that the displacement of a surface acoustic wave is proportional to the gradient of the electric field. Since the gradient of the electric field is primarily at the edge of the fingers, it is possible to calculate the transfer function for each transducer by summing the radiation contribution from the finger edges. This approximation is especially true for material in the weak coupling limit such as ST-cut quartz.

The frequency response for each of the transducers is shown in Figure 2-3. These curves were obtained by using the delta function approach to calculate their respective transfer functions. The response of the delay line is the product of the transfer functions of the individual transducers. In order to suppress the side lobes, the first minimum of the first transducer (closed structure) is made to be at the maximum of the main side lobe of the second transducer (open structure). This technique is clearly illustrated in Figure 2-3. The resultant frequency response is shown in Figure 2-4. The center to center separation between transducers is adjusted so that the phase condition allows only one solution at the center of the pass band. All other solutions are on nodal points. This minimizes the possibility of any frequency hopping or multimode generation occurring in the oscillator.

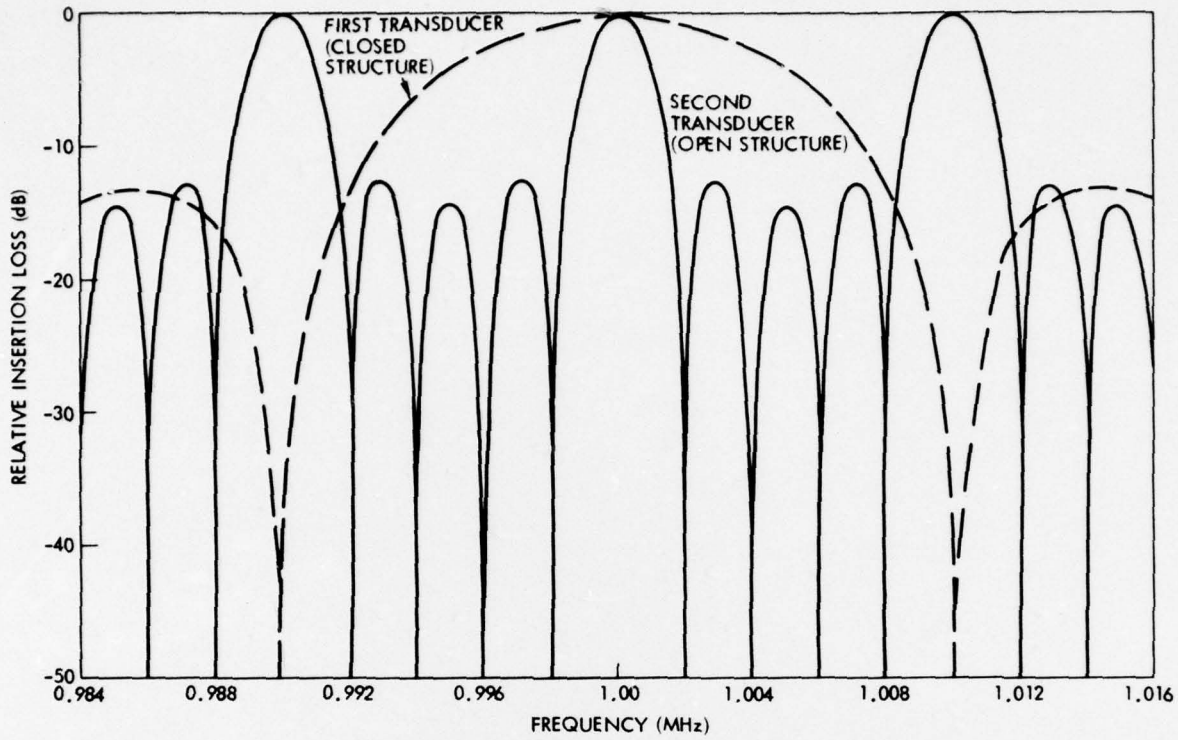



Figure 2-3. Individual Transducer Frequency Response

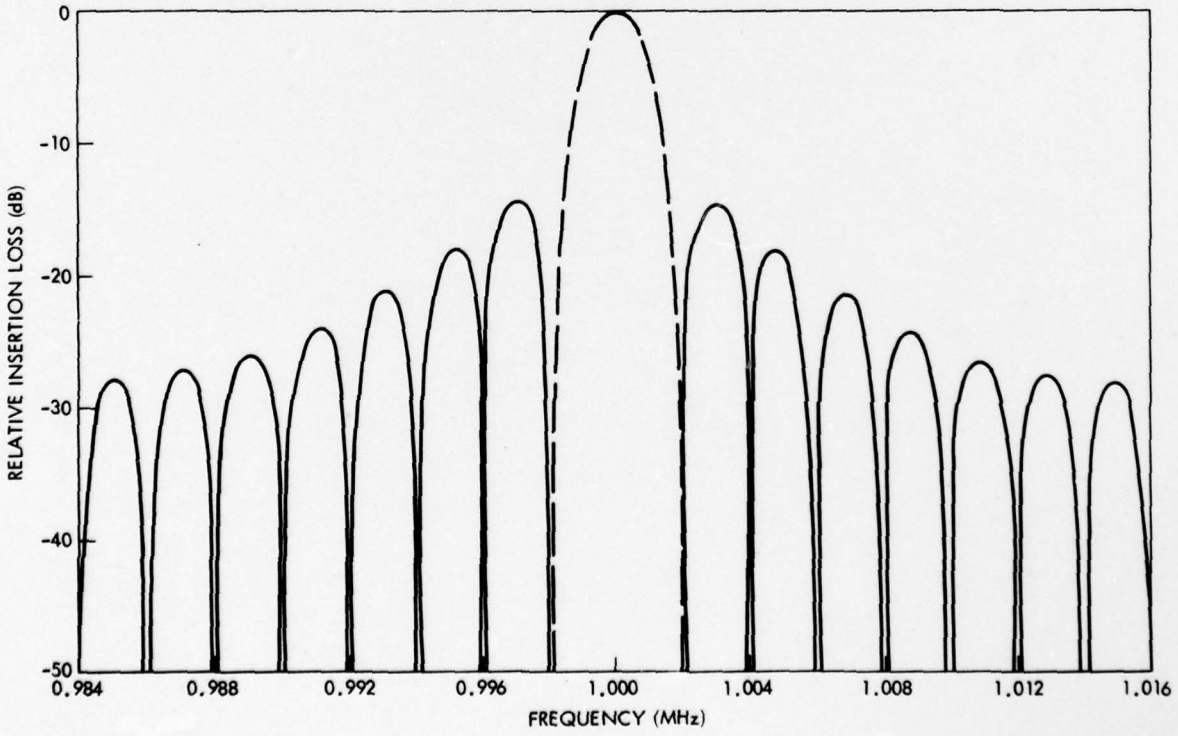



Figure 2-4. Composite Structure Frequency Response

## 2.2 SAW DELAY LINE FABRICATION

The medium term or temperature stability of the SAW oscillator is determined by the temperature coefficient of the delay line. Most system applications require good medium term stability. Thus, all the SAW delay lines were fabricated on ST-cut quartz crystals. ST-cut quartz was chosen because it has the lowest temperature coefficient of delay for any piezoelectric crystal. This material has a zero first-order-temperature coefficient near room temperature and a second-order-coefficient of $+ 31 \times 10^{-9}(^{\circ}C)^{-2}$. Further, since the aging mechanism was one of the major questions addressed in this study, several investigations were undertaken in order to characterize both the surface of the crystal and the fabrication techniques of the delay line.

### 2.2.1 Surface Characterization

The ST-cut quartz plates as purchased from Sawyer Research Products were polished to an acoustic grade finish. The grooves and scratches in the polished surface were specified to be less than one microinch. They were polished using a mixture of cesium oxide and water in a free flow polishing system. The particle size of the cesium oxide was from 1μm to 3μm. This type of polishing procedure is widely accepted in the industry for surface acoustic wave devices operating at up to several hundred megahertz. However, since SAW oscillators are more sensitive to aging effects, we felt a systematic investigation should be carried out. The ceisum oxide polishing procedure is an abrasive mechanical polish. This type of polish has been known to introduce both stress and deep micro-scratches in the first several microns of the quartz surface. The relaxation of these types of stress would manifest themselves in terms of an aging effect. The scratches may either be filled with cesium oxide or be collecting centers for organic materials used in processing the SAW delay lines. These organic materials may subsequently outgas, adding to the aging effect.

In order to minimize this surface damage, we have repolished some quartz crystals using a Monsanto sytron chemical polish. Chemical

polishes are known to give better stress and scratch free surfaces. At least 25 microns were removed from the surface of these repolished crystals.

The surface of these quartz crystals were examined using a scanning electron microscope (SEM) and energy dispersive X-rays (EDX). Four basic types of surfaces were examined, virgin quartz substrates, virgin quartz substrates which were etched for 5 minutes in HF, quartz substrates which were repolished using a sytron chemical polish, and quartz substrates which were repolished and etched in HF for 5 minutes. The samples were examined by the SEM with magnification of up to 25,000. The two types of unetched samples showed qualitatively little difference. However, the results of the etched samples were quite different. Figure 2-5 shows a typical surface for an unetched quartz substrate. The sytron polished samples were completely free from scratches, but the etched virgin sample showed a few scratches which were ten millimeters long and a few tenths of a micron wide. This comparison can be made by examining Figures 2-6, 2-7, and 2-8.

An energy dispersive X-ray in conjunction with SEM was used to examine the atomic percent of elements on the first 1/2 micron of the quartz substrate. The results showed no noticeable contaminate on the surface of the quartz crystal. However, this technique is not very sensitive to organic materials.

### 2.2.2 Fabrication

The standard photolithographic techniques were employed in the fabrication of the interdigital transducers for the delay lines. These transducer patterns can be fabricated by either the "etching" or "lift-off" technique. In "etching," a thin metal film is deposited on the substrate, followed by spin or dip coating of the photoresist on the surface. The photoresist is exposed and developed to form a mask over the metal film. The metallic pattern is then defined by chemically etching through the developed photoresist pattern. The basic principles of this fabrication technique are illustrated in Figure 2-9a.

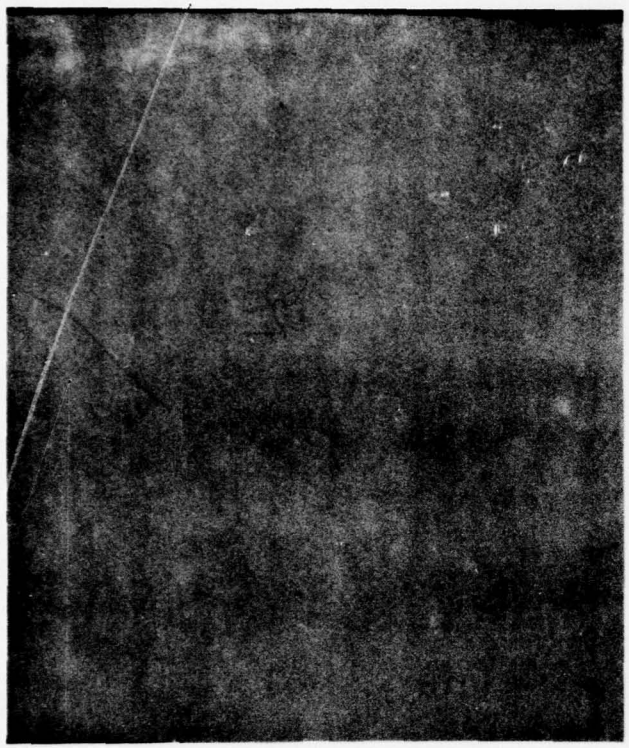


Figure 2-5. SEM Showing the Surface of a Virgin Quartz Substrate. Magnification 20,000x

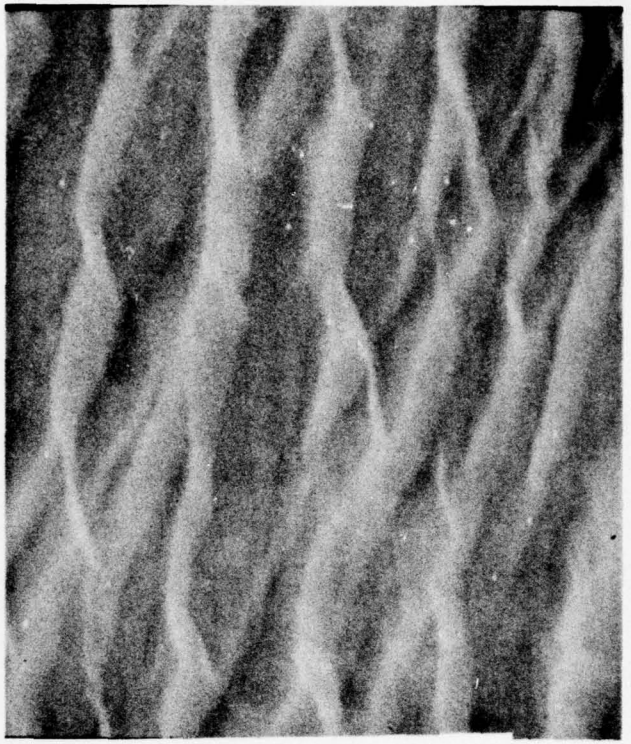


Figure 2-6. SEM Showing the Surface of a Sytron Chemical Polished Quartz Substrate Etched in HF for 5 Minutes. Magnification 10,000x



Figure 2-7. SEM Showing the Surface of a Virgin Quartz Substrate Etched in HF for 5 Minutes. Magnification 10,000x



Figure 2-8. SEM Showing a Scratch on Quartz Substrate Etched in HF for 5 Minutes. Magnification 10,000x

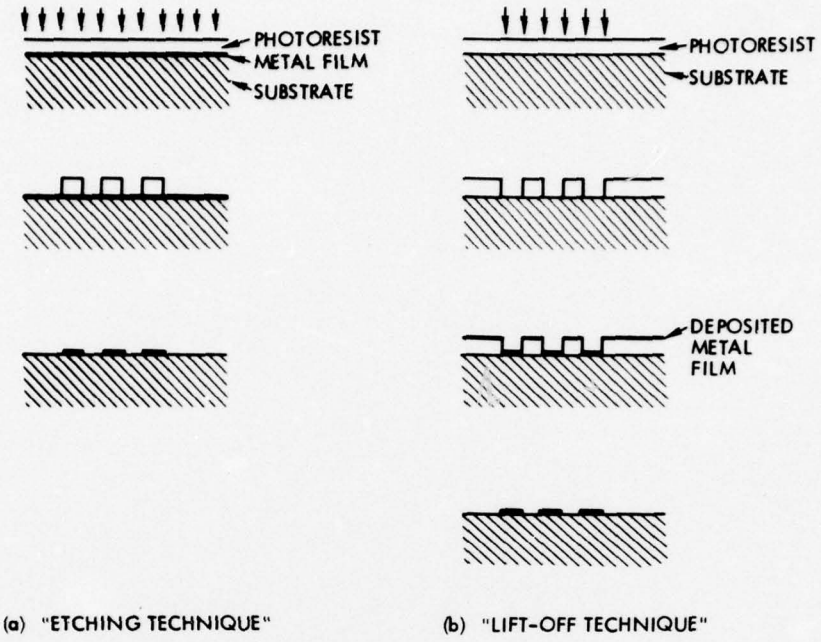



Figure 2-9. Schematic Illustration of the Planar Fabrication Techniques

In "lift-off," the process is reversed; spin or dip coating of photoresist on the substrate is followed by exposure and development to form a mask over the surface. The metallic pattern is then defined by deposition of metal film through the relief pattern. The technique is schematically represented in Figure 2-9b.

Both the "etching" and the "lift-off" techniques were used in fabricating the SAW delay lines. The delay lines were fabricated on both commercially polished quartz substrates and the sytron chemically polished quartz substrates. This was done in order to determine what effects the polish had on long term aging. Results to date indicate no noticeable difference between the two polishes. The finger line widths for the 250 MHz SAW delay lines were made using a light field mask, Shipley 1350 positive photoresist and etching the transducer pattern. At 500 MHz, the finger line widths are about 1.5 μm. All the 500 MHz delay lines were constructed using the "lift-off" technique – that is, using a dark field mask, Shipley 1350J positive photoresist and evaporating metals into the relief pattern. In order to improve line width resolution, a vacuum frame with a thin rubber

membrane to lift the quartz substrate into intimate contact with the photomask was used. This technique was only recently developed at MIT Lincoln Laboratory and was used in making both the 250 and 500 MHz delay lines.

Prior to the evaporation, all the quartz substrates were baked at 200°C for a half hour, and then slowly cooled to room temperature under vacuum. This was done to minimize the amount of absorbed gases which might otherwise be trapped on the quartz substrate surface by the metal film. The metal films for the transducers are formed by flash evaporating about 75 Å of chromium and evaporating about 1,250 Å of aluminum. These films were evaporated at a low substrate temperature in order to minimize the grain size. The chromium films were used in order to ensure good adhesion of the aluminum films.

Some SAW delay lines were also examined with the scanning electron microscope and energy dispersive X-rays. The SEM results showed that the surface of the quartz was similar to that of the unetched samples examined in Section 2.2.1. The energy dispersive X-rays (EDX) used in conjunction with the SEM were used to determine atomic percent of elements on the first 1/2 micron of the SAW delay lines. Results again showed no noticeable contaminate on the surface of the delay line.

## 2.3 SAW DELAY LINE CHARACTERIZATION

All of the SAW delay lines used in the assembly of oscillators were characterized. The tests were performed for two reasons. First, as a check of the accuracy of the design process used to determine the transducer dimensions, and second to provide the data required to match the delay line input and output impedances to the characteristic impedance of the other components in the oscillator. In addition, it is necessary to know the SAW delay line insertion loss so as to be able to select the proper amplifier gain for the oscillator. Table 2-4 summarizes the basic characteristics of the delay lines.

Following the initial characterization of the SAW delay lines, the devices were matched to 50 ohms. The delay lines were matched to optimize the coupling of the SAW delay line to the rest of the oscillator circuit. The insertion loss of the delay lines is strongly dependent on how well the highly capacitive impedance of the transducers can be matched to 50 ohms.

Table 2-4. SAW Delay Line Characteristics

| SERIAL NO. | $f_o$ | RETURN LOSS (MATCHED) | | INSERTION LOSS | 3 dB BANDWIDTH |
|---|---|---|---|---|---|
| | | INPUT | OUTPUT | | |
| 104 | 249.820 MHz | 6.0 dB | 12.5 dB | 21.0 dB | 550 KHz |
| 105 | 249.790 MHz | 8.5 dB | 5.0 dB | 21.5 dB | 500 KHz |
| 106 | 249.740 MHz | 9.0 dB | 13.0 dB | 15.0 dB | 550 KHz |
| 107 | 249.750 MHz | 6.5 dB | 6.5 dB | 18.5 dB | 550 KHz |
| 108 | 249.750 MHz | 12.5 dB | 7.0 dB | 17.5 dB | 525 KHz |
| 109 | 249.725 MHz | 5.0 dB | 9.0 dB | 17.0 dB | 550 KHz |
| 111 | 249.750 MHz | 4.5 dB | 12.5 dB | 16.0 dB | 525 KHz |
| 205 | 493.545 MHz | 6.5 dB | 10.0 dB | 17.0 dB | 400 KHz |
| 206 | 493.615 MHz | 8.5 dB | 7.5 dB | 22.0 dB | 400 KHz |

The network shown in Figure 2-10 was used to match the input and output impedances of the transducers. Chip capacitors and hand wound coils on nylon toriods were used. The match was optimized by substituting different chip capacitors and by changing the number of turns on the coils. Tuning adjustments can only be made in discrete increments using this technique, which explains why the input and output impedances of the delay lines were not exactly matched. Continuously variable tuning elements were not used in the matching networks for two reasons. First, the long-term stability of the variable elements is uncertain. Any change in the impedance of the SAW will cause a change in the insertion phase of the delay line. Any phase change will cause a corresponding shift in the oscillator frequency which will contribute to the overall oscillator aging rate. The second reason for not using variable elements was their size. All of the high quality variable elements which were available were too large for the package in which the delay lines were to be hermetically sealed.

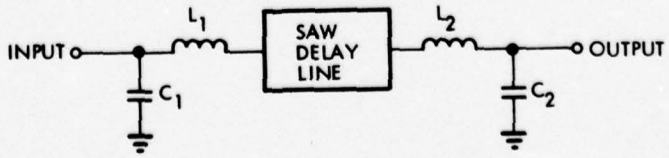



Figure 2-10. SAW Delay Line Matching Network

The insertion loss plots for the 250 and 500 MHz delay lines are included in Figures 2-11 through 2-19. The plots are for the matched, hermetically sealed delay lines. The out-of-band rejection of the delay lines was reduced by approximately 3 dB to 10 dB due to radiation across the surface of the packaged delay line. The reduction in the rejection did not affect the operation of the delay lines in the oscillator circuit.


1. W.R. Smith, H.M. Gerard, J.H. Collins, T.M. Reeder and H.J. Shaw, "Analysis of Interdigital Surface Wave Transducers by Use of an Equivalent Circuit Model," IEEE Trans. on Microwave Theory, Vol. MTT-17, No. 11, November 1969, pp. 856-864.

2. R.H. Tancrell and M.G. Holland, "Acoustic Surface Wave Filters," Proc. IEEE, 59, (1971), pp. 393-409.

3. R.F. Mitchell and N.H. Reilly, "Equivalence of δ-Functions and Equivalent-Circuit Models for Interdigital Acoustic-Surface-Wave Transducers," Electronics Letter, 8, (1972), pp. 329-331.

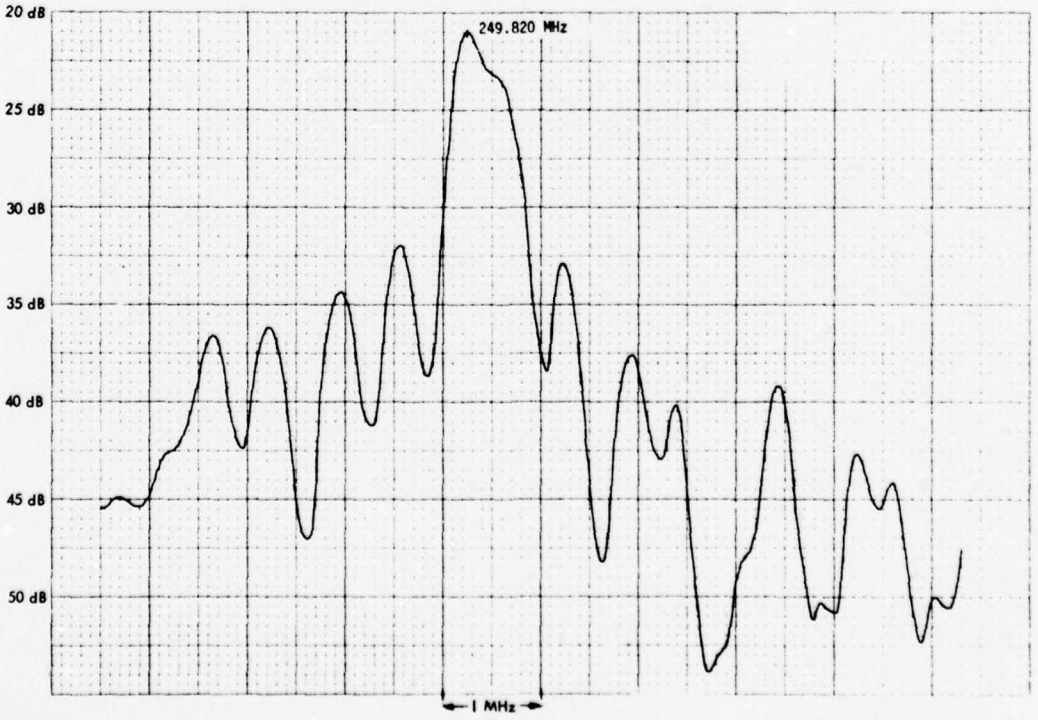




Figure 2-11. SAW Delay Line Insertion Loss S/N 104

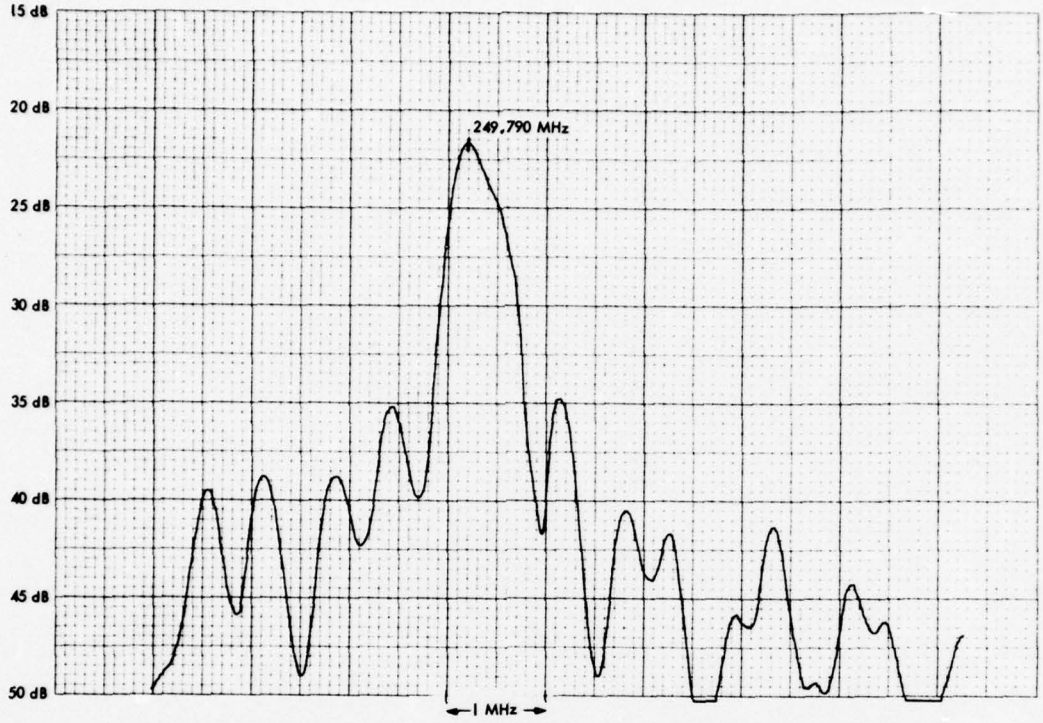



Figure 2-12. SAW Delay Line Insertion Loss S/N 105

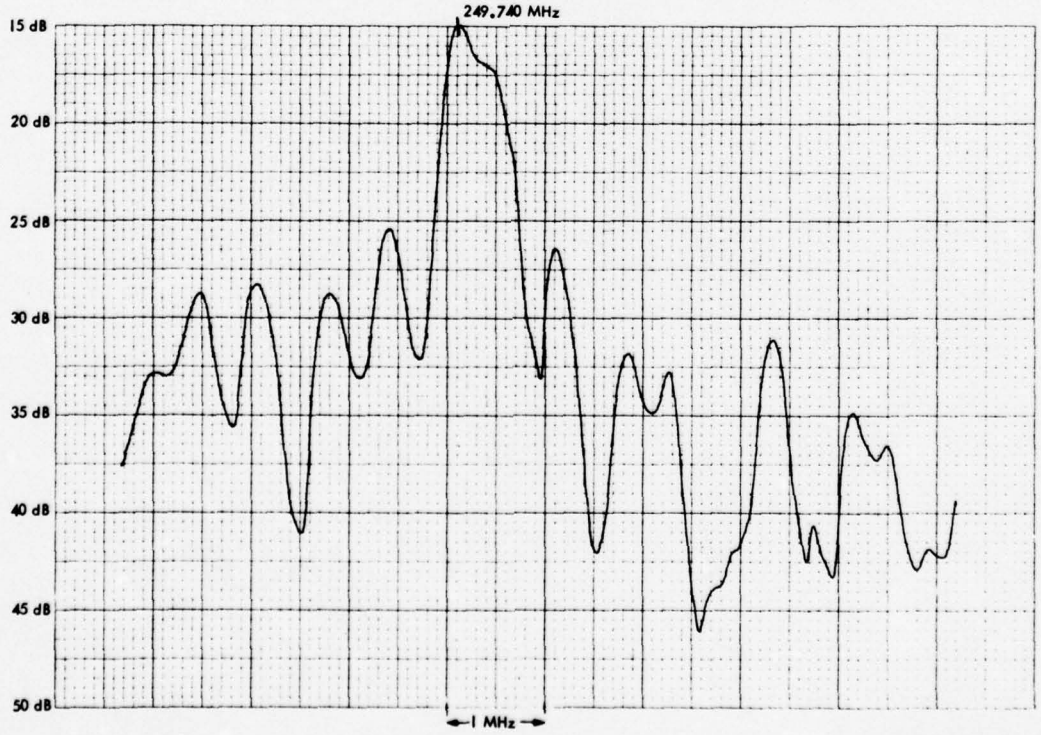



Figure 2-13. SAW Delay Line Insertion Loss S/N 106

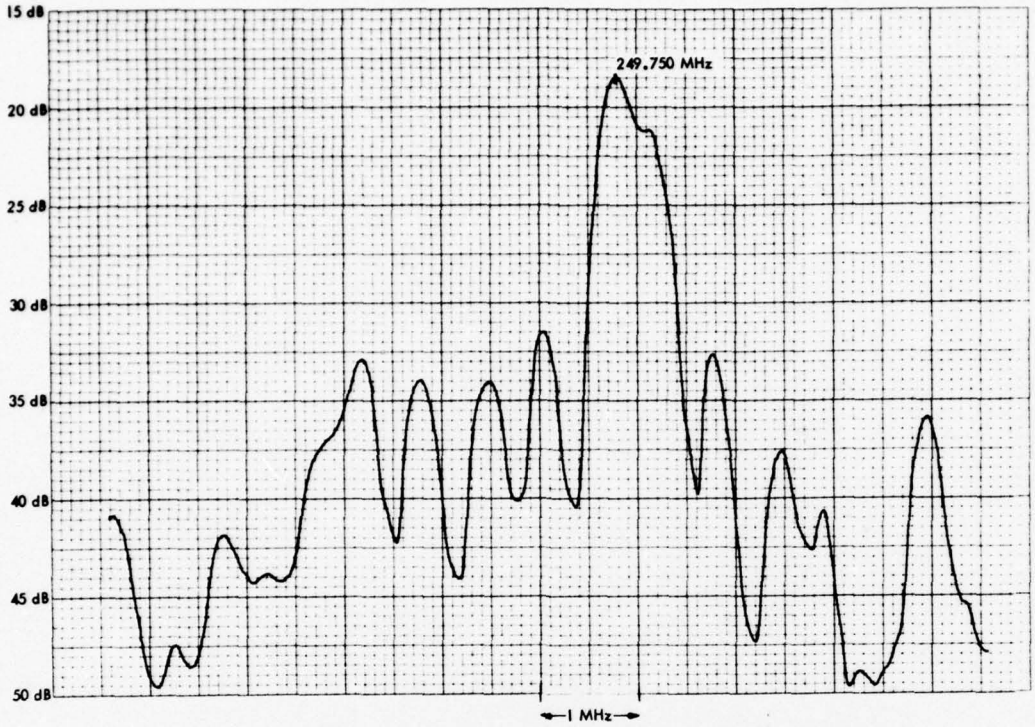



Figure 2-14. SAW Delay Line Insertion Loss S/N 107

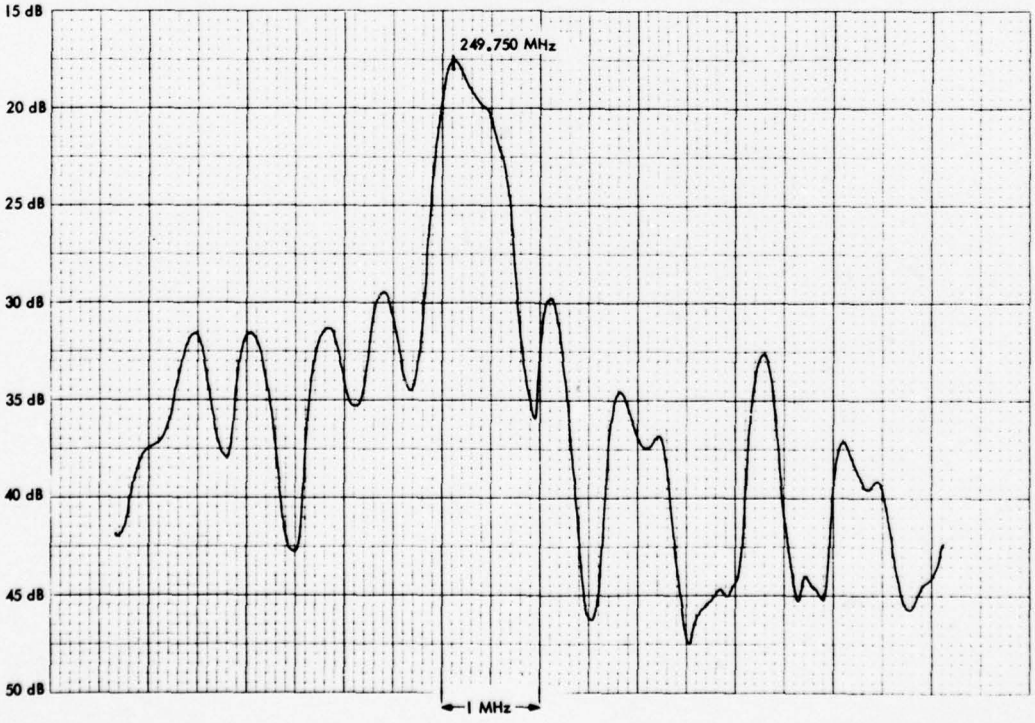



Figure 2-15. SAW Delay Line After Scaling S/N 108

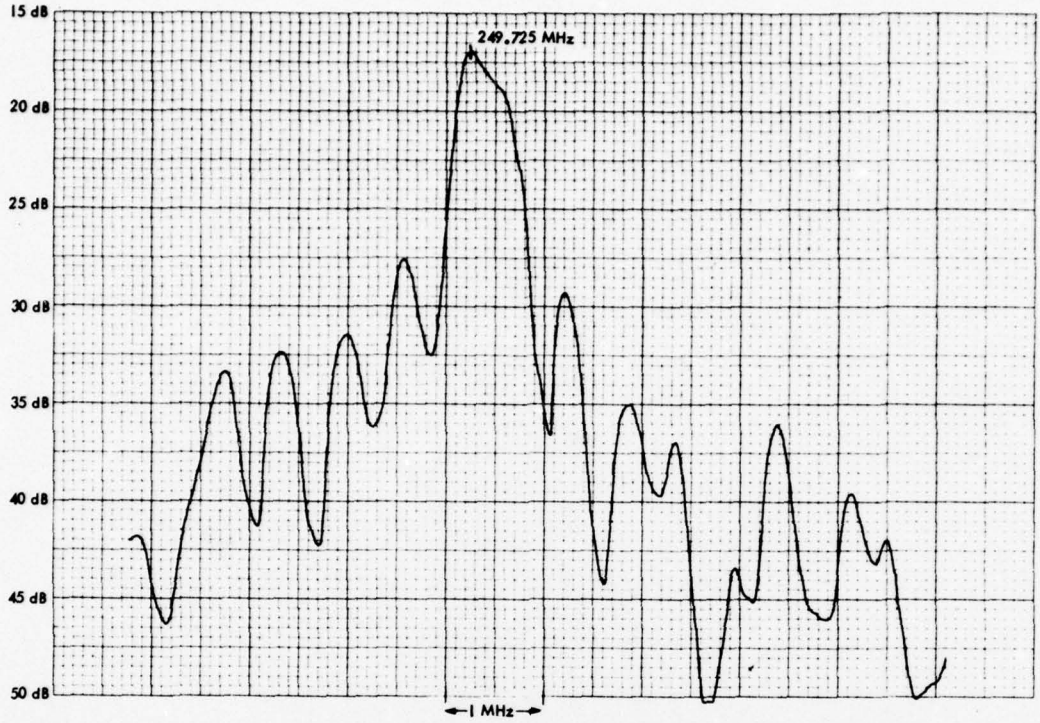



Figure 2-16. SAW Delay Line Insertion Loss S/N 109

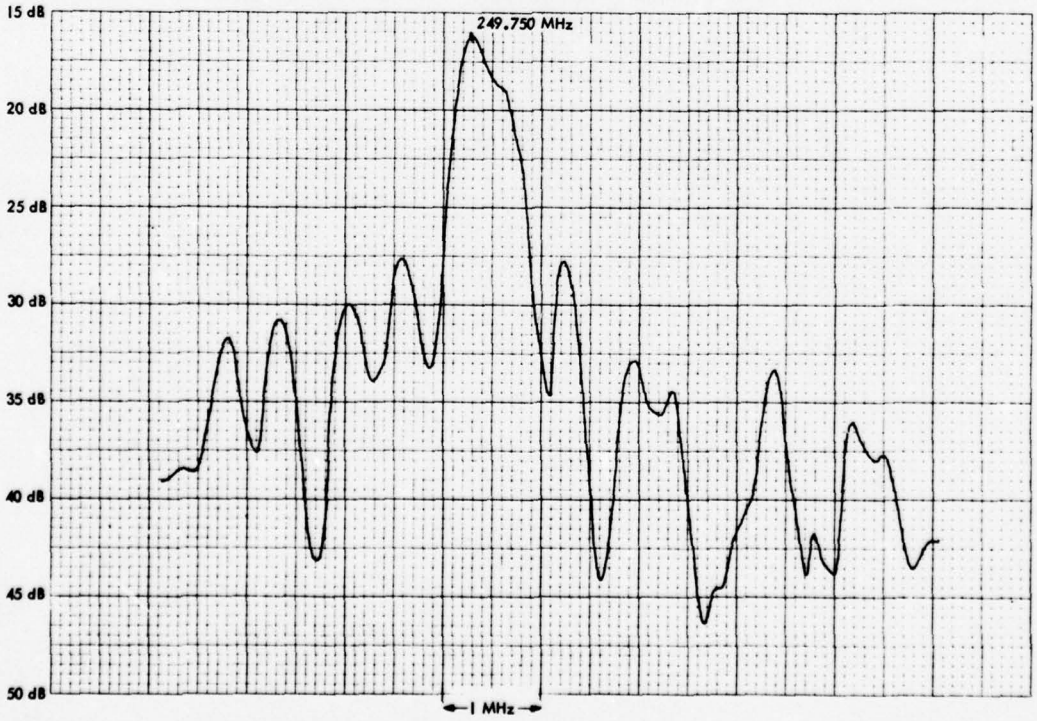



Figure 2-17. SAW Delay Line Insertion Loss S/N 111

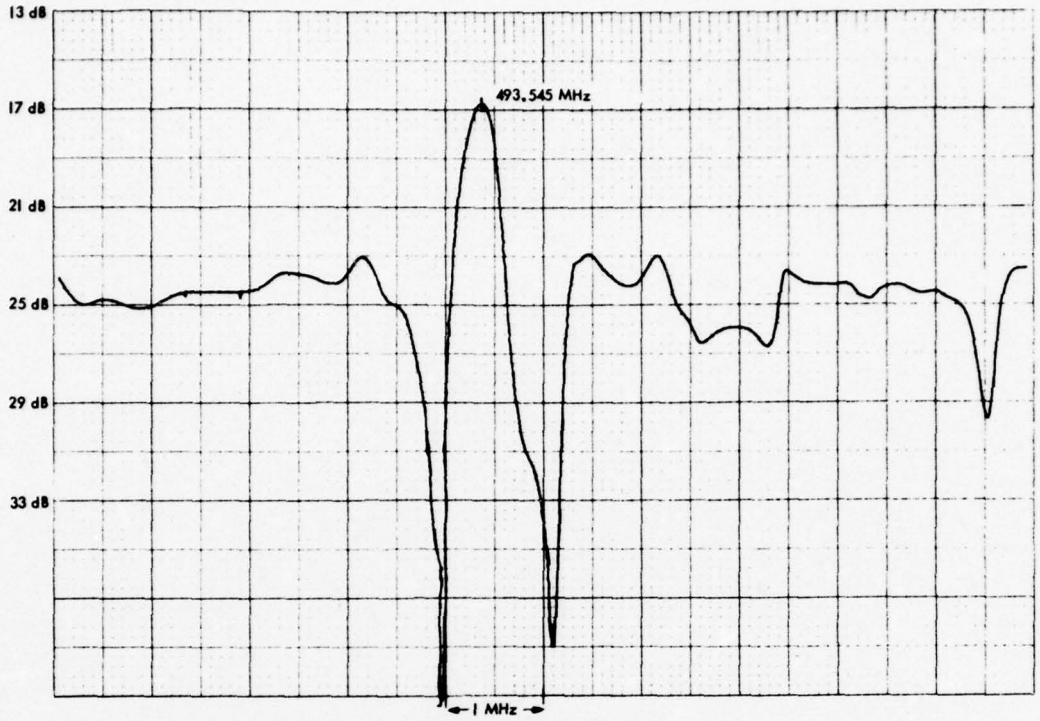



Figure 2-18. SAW Delay Line Insertion Loss S/N 205

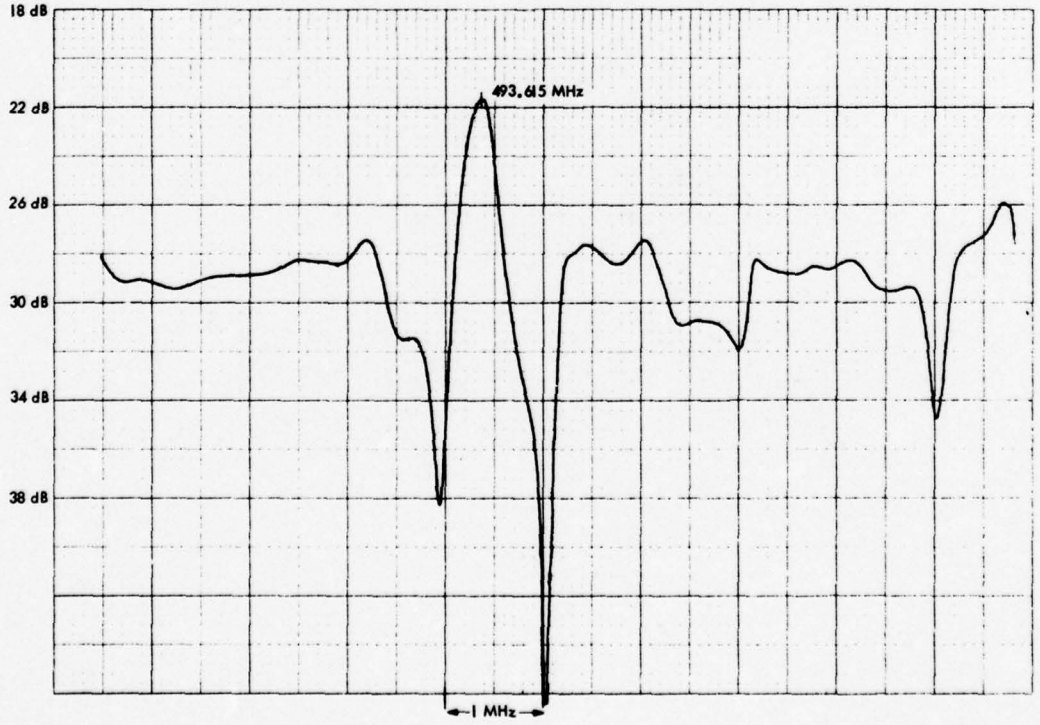



Figure 2-19. SAW Delay Line Insertion Loss S/N 206

# 3. SAW OSCILLATOR DESIGN AND FABRICATION

This section discusses the theory of operation of SAW oscillators and then describes the way in which this theory was implemented for this program.

## 3.1 THEORY OF OPERATION OF SAW OSCILLATOR

A SAW oscillator consists of a SAW delay line connected in a feedback loop with an amplifier. This is shown schematically in Figure 3-1. This circuit will oscillate at any frequency for which the total phase shift around the loop is an integer multiple of $2\pi$, and the gain of the amplifier is equal to or greater than the net insertion loss of the feedback elements. The conditions for oscillation can be expressed as:

$$\frac{2\pi f \ell}{V} + \phi = 2n\pi \tag{3.1}$$

and

$$L_S(f) + L_1(f) = G(f, A) \tag{3.2}$$

where

$f$ = oscillation frequency

$\ell$ = center to center transducer separation

$V$ = surface wave velocity

$\phi$ = phase shift through all elements except SAW delay line

$n$ = an integer

$L_S(f)$ = insertion loss of SAW delay line

$G(f, A)$ = amplifier gain as a function of f and output level, A

Solving (3.1) for f

$$f = \frac{V}{\ell}\left(n - \frac{\phi}{2\pi}\right) \tag{3.3}$$

As a general rule, $L_1(f)$ and $G(f,A)$ are very slowly varying functions of f over a broad range around the frequency for which the oscillator is being designed, but $L_S(f)$ is a very strong function of frequency. The SAW delay is designed as a bandpass filter whose response is ideally given by

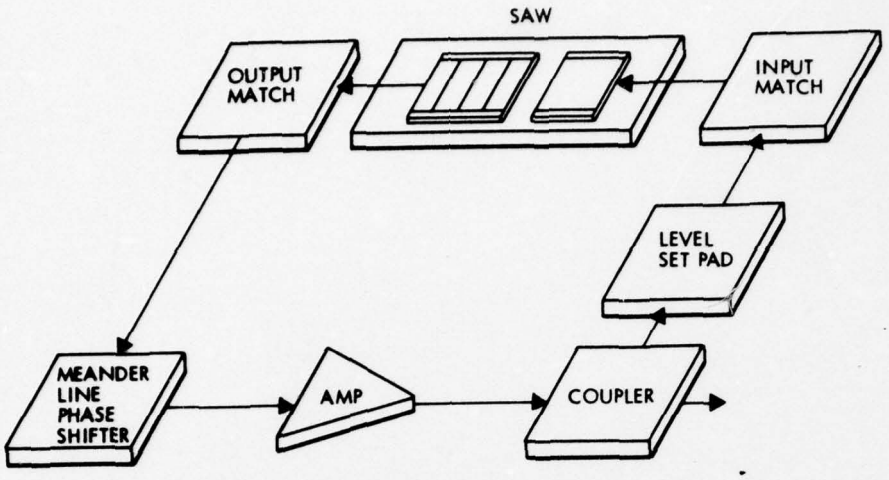



Figure 3-1. Schematic of SAW Oscillator

$$L_S(f) = K\left(\frac{\sin X}{X}\right)^2\left(\frac{\sin Y}{Y}\right)^2 \tag{3.4}$$

where

$$X = \frac{2\pi N(f-f_o)}{f_o}$$

$$Y = \frac{2\pi M(f-f_o)}{f_o}$$

K = insertion loss at $f_o$

N = number of finger pairs in first transducer

M = number of finger pairs in second transducer

$$K\left[\frac{\sin\left(\frac{2\pi N(f-f_o)}{f_o}\right)}{\frac{2\pi N(f-f_o)}{f_o}}\right]^2\left[\frac{\sin\left(\frac{2\pi M(f-f_o)}{f_o}\right)}{\frac{2\pi M(f-f_o)}{f_o}}\right]^2 = G(f_o, A) - L_1(f_o) \tag{3.5}$$

It is clear that the ideal case would obtain when (3.3) is satisfied at $f_o$. Equation (3.3) has nearly n solutions, but the gain term of (3.5) can be adjusted such that the only simultaneous solutions to both (3.3) and (3.5) occur in the immediate vicinity of $f_o$. The fact that the appropriate

adjustment of the gain term is possible is evident from Figures 2-11 to 2-19 which clearly show a minimum of 10 dB difference between the response at $f_o$ and any secondary responses. So long as only one solution to (3.3) falls within the primary response of the SAW delay line, single mode operation of the SAW oscillator is guaranteed.

It is also evident from (3.3) that some frequency modulation of the SAW oscillator is possible. Taking the derivative

$$\frac{df}{f} = \frac{-Vd\phi}{2\pi\ell\phi} \tag{3.6}$$

This gives the expected result that the smaller the center to center transducer separation, i.e., the lower the delay line Q, the greater the SAW oscillator tuning range. The usual method of accomplishing the tuning or frequency modulation is via a varactor diode phase shift network.

The output phase noise density of the SAW oscillator can be expressed by

$$\text{noise power density} = KT+N.F.+L+20\ \text{Log}\left[\sqrt{1+\left(\frac{\omega_o}{2Q\Delta\omega}\right)^2}\right]\ \text{dbm/Hz} \tag{3.7}$$

where

$KT = -174$ dBm/Hz

$\omega_o$ = the oscillator frequency

$L = L_1(\omega) + L_S(\omega)$

$Q$ = the delay line loaded $Q(f_o/\Delta f_{3dB})$

$\Delta\omega$ = the offset frequency

Even when the bias conditions of the amplifier are carefully controlled, thermal noise and transistor noise will still result in oscillator phase and amplitude fluctuations. However, the phase noise component will generally dominate the amplitude noise. The noise power exhibits a floor at large offset frequencies which is determined by the amplifier noise figure and the delay line insertion loss. Minimum phase noise

is achieved for minimum delay line loss, minimum amplifier noise figure, maximum filter Q, and maximum output power.

The preceeding has established the design goals for the oscillator circuit, in particular equations (3.3), (3.5), and (3.7). The following discussion relates to the actual implementation of the circuitry surrounding the SAW delay line.

## 3.2 SAW OSCILLATOR FABRICATION

In addition to the SAW delay line, a feedback amplifier and a power splitter are required to complete the SAW oscillator circuit. A selectable phase shifter and an attenuator were also included in the circuit to aid in evaluating and optimizing the oscillator performance.

A single, common amplifier was selected for use in both the 250 MHz and 500 MHz oscillators. The amplifier, manufactured by Aertech Industries, is a multistage thin film MIC transistor design. The broad bandwidth (200 MHz - 600 MHz), high gain (>30 dB) and low noise figure (<1.9 dB at 250 MHz) of the amplifier were specified to insure optimum oscillator performance. Each stage of the amplifier was carefully optimized with respect to gain, noise figure and output power for use in the SAW oscillator. The amplifier is packaged in a single 1.0" X 0.5" dual-in-line hermetic package. The thin film design was chosen because of its excellent electrical performance, high temperature stability and small size. The amplifier part number is AMT 5010. The data for the ten amplifiers used in assembling the oscillators is summarized in Table 3-1. In addition to the data provided by Aertech on the amplifiers, the saturation characteristic for each amplifier was determined at 250 MHz and 500 MHz. This data is used to determine the required value of the selectable attenuator in the oscillator feedback loop.

The remaining components required for the oscillator are all straightforward. A commercial 3 dB power divider (ANZAC DS-109) was used to couple a portion of the amplifier output back through the SAW delay line. The device is broadband (10 MHz to 500 MHz) and is used for both the 250 MHz and 500 MHz oscillators. The attenuator in the feedback loop was simply a "TEE" configuration attenuator utilizing thin film chip resistors. The values of the resistors were selected to provide the required level of attenuation.

Table 3-1. Amplifier Performance

| SERIAL NO. | MINIMUM GAIN (200 MHz-600 MHz) | NOISE FIGURE | | OUTPUT POWER AT 1 dB COMPRESSION | |
|---|---|---|---|---|---|
| | | 250 MHz | 500 MHz | 250 MHz | 500 MHz |
| 23311 | 35.4 dB | 1.9 dB | 2.0 dB | +11.2 dBm | +9.6 dBm |
| 23312 | 32.8 dB | 2.0 dB | 2.4 dB | +10.4 dBm | +9.0 dBm |
| 23313 | 33.6 dB | 1.9 dB | 2.0 dB | +11.0 dBm | +10.4 dBm |
| 23314 | 36.1 dB | 1.8 dB | 2.0 dB | +11.2 dBm | +9.4 dBm |
| 23315 | 35.3 dB | 1.8 dB | 2.1 dB | +11.0 dBm | +9.0 dBm |
| 23316 | 34.3 dB | 1.9 dB | 2.2 dB | +11.2 dBm | +9.8 dBm |
| 23317 | 33.6 dB | 2.0 dB | 2.4 dB | +10.4 dBm | +9.0 dBm |
| 23318 | 33.6 dB | 2.0 dB | 2.1 dB | +10.8 dBm | +8.8 dBm |
| 23319 | 32.5 dB | 2.5 dB | 2.4 dB | > +10 dBm | > +10 dBm |
| 23320 | 33.2 dB | 2.0 dB | 2.0 dB | > +10 dBm | > +10 dBm |

The total loop phase shift (or oscillator frequency) was fine tuned by a meander line phase shifter. The total length of the line is varied by interconnecting lines of different lengths. Relative phase shifts of up to 360 degrees in 2.5 degree increments could be selected at 250 MHz. A variable capacitor network could have been used to perform this function, but the temperature stability of the oscillator would have been degraded.

A common requirement for all of the electronics in the oscillator loop is the stability of the insertion phase and gain or loss of each component. All of the components used in the oscillator were selected for maximum temperature and long term stability. In order for the aging tests to accurately reflect the aging in the SAW delay lines, the long term stability of the remaining components in the oscillator should be significantly better than the SAW crystal.

All of the SAW oscillators were assembled using the same technique. The oscillators consist of a hermetically sealed matched SAW delay line, an amplifier substrate and a meander line phase shifter substrate. All of the components were mounted in a single machined aluminum chassis. Figure 3-2 is a photograph of a completed 250 MHz oscillator. The lid and clamp for the delay line package have been removed for clarity. The

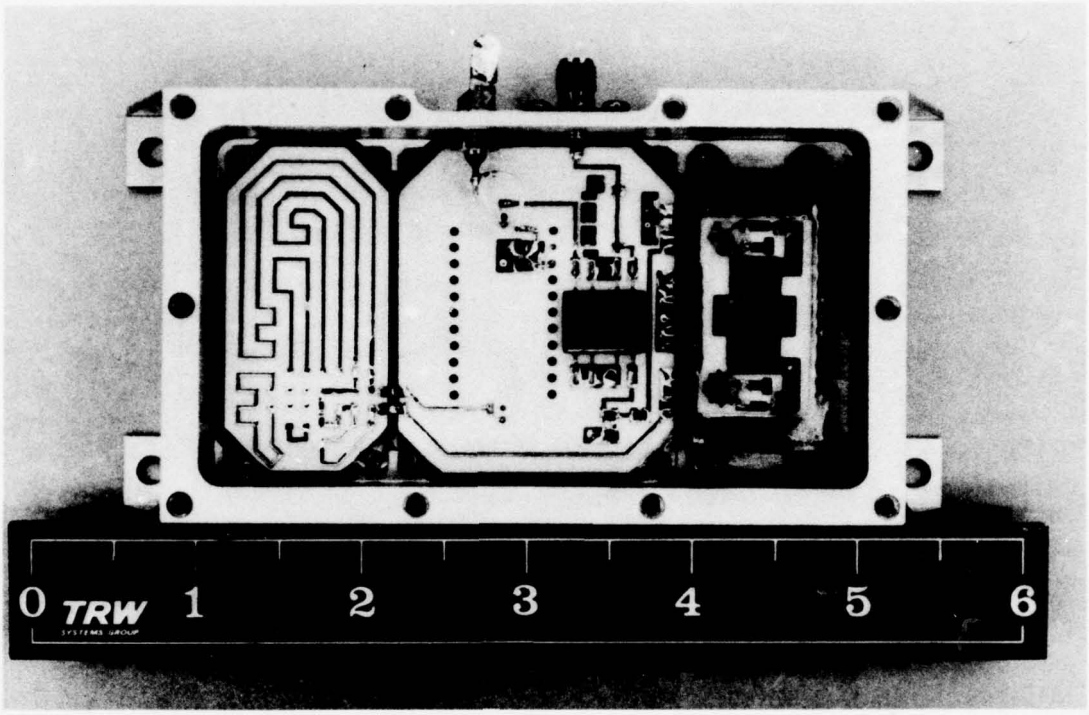



Figure 3-2. 250 MHz SAW Oscillator

oscillators were designed and assembled in a manner consistent with the requirement that vibration testing was to be performed on the oscillators. The techniques used have all been previously proven to be both mechanically and electrically acceptable.

The amplifier and meander line phase shifter were both fabricated on alumina microstrip circuits. The amplifier is contained in a hermetic 22 pin package. The package is mounted on the ground plane side of the substrate using conductive epoxy. The power divider, attenuator, bias by-pass capacitors and interconnecting circuitry are all on the top side of the substrate. The meander line substrate is simply a number of 50 ohm lines of various lengths. The different lines are then interconnected using ribbons to select the required phase shift. Both substrates are mounted on Kovar carriers which are attached to the oscillator chassis with screws. Spring finger frames under each substrate insure a good ground contact between the substrate ground plane and the chassis.

The SAW delay line and matching network were mounted in a hermetic flatpack on an alumina carrier. Figure 3-3 is a photograph of an assembled 250 MHz delay line prior to sealing. The delay lines were hermetically sealed to protect the surface of the crystals. The center frequency of the delay lines is very sensitive to any contamination (particularly moisture) on the surface of the delay line. In addition to protecting the face of the SAW crystal, the packaging technique for the delay line must also protect the crystal from mechanical stresses. The quartz crystal is attached to the alumina carrier with Dow Corning RTV #6-1104. This material is particularly suited to this application for the following reasons. First, the material exhibits a minimum of outgassing. This is important to prevent contamination of the SAW crystal after it is sealed. Second, the material is flexible and acts as both a mechanical shock absorber for the crystal and absorbs the stresses due to the different thermal coefficients of expansion of the quartz crystal and the alumina carrier. Finally, the material is used to absorb the acoustic waves which reach the edges of the SAW crystal and would otherwise be reflected back to the transducers.

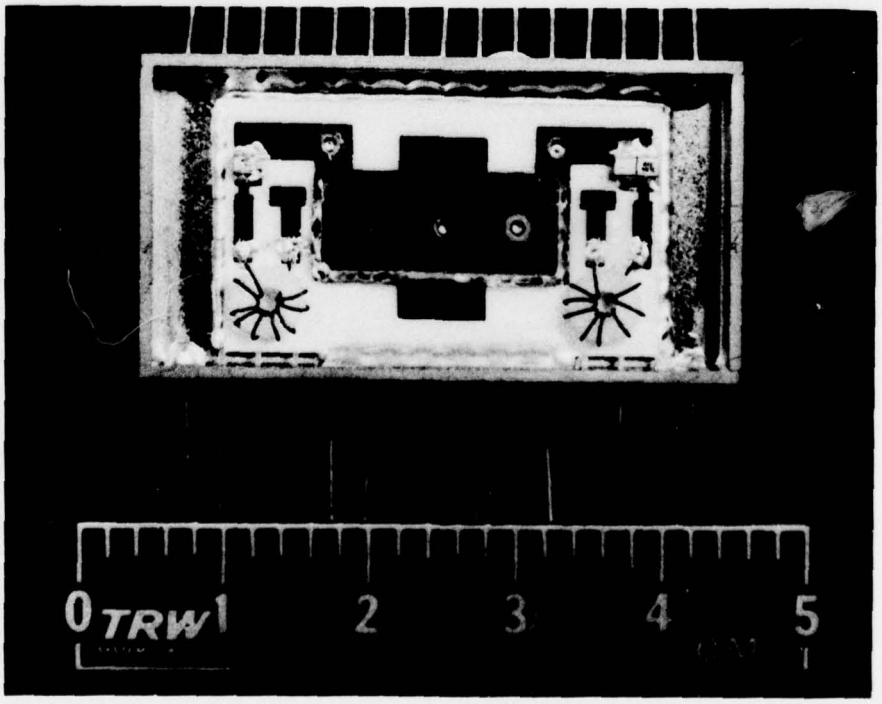



Figure 3-3. 250 MHz SAW Delay Line Prior to Hermetic Staling

Electrical connections to the transducers are made using ultrasonically bonded aluminum wires. Thermal compression bonding is not used due to the requirement that the SAW crystal be preheated to a high temperature prior to bonding. The chip capacitors and inductors were attached to the carrier using a silver filled conductive epoxy. This material was also selected for minimum outgassing. The components were not soldered due to the possibility of flux or solder contaminating the delay line. Finally the entire carrier was mounted in the flat pack using the same conductive epoxy that was used to attach the chip components. The input and output connections were made by wire bonding from the carrier pads to the leads of the package.

The processing steps followed to seal the delay lines were carefully chosen to insure that the delay lines were kept as clean and as dry as possible. The crystals were first cleaned with a fine camel hair brush and acetone. They were next blown dry with dry nitrogen to clean any dust particles from the packages. The crystals were then vacuum baked for 24 hours at 150 $^{\circ}$F to further dry the quartz crystal and to minimize the trapped gasses in the RTV and epoxy. Following the vacuum bake, the packages were stored in dry nitrogen until they were hermetically sealed. Finally, the sealed packages were both fine and gross leak checked to confirm that the packaged delay lines were truly hermetically sealed. Following the sealing process, the input and output return loss and the insertion loss of the delay lines were rechecked. In general, no significant degradation was measured due to the sealing process.

The alignment process for the oscillators is very simple. The first step is to determine the difference between the delay line insertion loss and the linear amplifier gain. The attenuator in the loop is then changed so that there is approximately 3 dB of excess gain in the loop. The amount of excess linear amplifier gain determines the level of saturation in the amplifier when the loop is oscillating. Regardless of the amount of excess linear loop gain, when the loop is oscillating, the amplifier will saturate or compress until the total gain around the loop is reduced to unity.

The 3 dB value of excess loop gain is a compromise between several factors. A higher level of excess gain in the loop would result in greater output power from the oscillator and would provide a greater assurance that the loop will continue to oscillate as the delay line insertion loss increases or the amplifier gain decreases due to the effects of aging and temperature. However, high levels of excess loop gain and therefore saturation result in an increase in the amplifier noise figure (or oscillator phase noise) and in higher levels of harmonically related spurious outputs.

The second step in aligning the oscillators is to adjust the total loop phase shift. The oscillator is first tested with a nominal amount of extra phase shift. The output frequency is then fine tuned either up or down to the exact desired frequency by either decreasing or increasing the total length of the meander line. Using this technique, the oscillators can be adjusted over a range of approximately $\pm$100 KHz with a resolution of approximately $\pm$5 KHz. Table 3-2 summarizes the data for the 250 MHz and 500 MHz oscillators following their initial alignment. In each case, the output frequencies of the oscillators were adjusted to correspond to the frequency of minimum insertion loss of the SAW delay used in the oscillator, i.e., to the $f_o$ referred to in equations (3.4) and (3.5).

Table 3-2. SAW Oscillator Performance Summary

| SERIAL NO. | $f_o$ | $P_{OUT}$ | BIAS CURRENT AT +15 V |
|---|---|---|---|
| SN 23311 | 249.699 MHz | 9.9 dBm | 67 mA |
| SN 23313 | 249.757 MHz | 10.2 dBm | 68 mA |
| SN 23315 | 249.704 MHz | 9.2 dBm | 66 mA |
| SN 23316 | 249.784 MHz | 10.0 dBm | 68 mA |
| SN 23312 | 249.809 MHz | 10.0 dBm | 52 mA |
| SN 23317 | 249.703 MHz | 8.7 dBm | 51 mA |
| SN 23318 | 249.710 MHz | 9.8 dBm | 50 mA |
| SN 23319 | 493.955 MHz | 8.7 dBm | 65 mA |
| SN 23320 | 493.640 MHz | 10.6 dBm | 70 mA |

# 4. SAW OSCILLATOR TEST RESULTS

Characterization tests were performed on five SAW oscillators: three 250 MHz oscillators and two 500 MHz oscillators. The short term frequency stability (phase noise) and medium term frequency stability (temperature dependence) and aging of each oscillator was measured. The output power as a function of temperature was also determined for each oscillator. Two 250 MHz SAW oscillators were vibrated to determine the effects of random vibration on the oscillator output power and frequency. Finally, tests were performed to determine the effect of power supply variations on the output power and frequency of the oscillators.

## 4.1 PHASE NOISE MEASUREMENTS

SAW oscillator phase noise was measured using the test set shown in Figure 4-1. Assume for the moment that both SAW oscillators are exactly the same frequency. The output of the mixer will then contain two terms, a double frequency term and a baseband term (i.e., the sum and difference of the mixer input frequencies). Additionally, the phase noise of each oscillator will be translated to both of the mixer output terms. The wave analyzer is a receiver which will not respond to the double frequency term, and this can be ignored. The baseband term will contain the phase noise of both oscillators which will, in this case, represent approximately equal contributions. The wave analyzer can be tuned to a desired frequency and set to a desired bandwidth such that its meters present the noise power at the selected frequency within the selected bandwidth. For example, if the wave analyzer is tuned to 10 kHz and 200 Hz bandwidth, the output meter will give the phase noise power at 10 kHz from the SAW oscillator center frequency within a 200 Hz bandwidth. Since both oscillators contribute equally to the phase noise, the noise of each is 3 dB less than the actual reading. For uniform data presentation, the bandwidth is always normalized to 1 Hz by subtracting 10 log (measurement bandwidth) from the measured noise power.

The theoretical expression for the phase noise of the SAW oscillators was given in Section 3 as

$$\text{NOISE POWER DENSITY} = kT + N.F. + L + 20 \log \left[ \sqrt{1 + \left( \frac{\omega_o}{2Q\Delta\omega} \right)^2} \right] \quad (3.7)$$

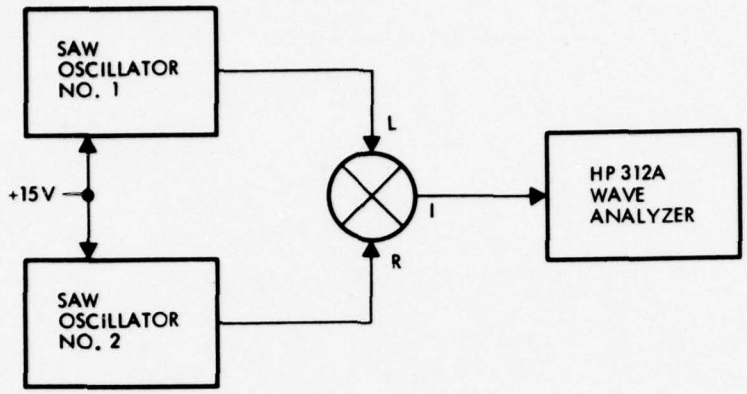



Figure 4-1. SAW Oscillator Phase Noise Test Set

The nominal values for the elements described in the previous section are known and are listed in Table 4-1 for the 250 and 500 MHz SAW oscillators. Given these values and equation (3.7), it is possible to predict the phase noise as a function of offset frequency.

Table 4-1. Noise Parameter Values

| Parameter | 250 MHz SAW Oscillator | 500 MHz SAW Oscillator |
|---|---|---|
| kT | -174 dBm/Hz | -174 dBm/Hz |
| NF | 2.0 dB | 2.0 dB |
| L | 17 dB | 17 dB |
| $f_o$ | 250 MHz | 493 MHz |
| Q | 500 | 1250 |

Figure 4-2 shows the measured phase noise of three of the 250 MHz SAW oscillators as compared against the theoretical prediction. Figure 4-3 is a similar plot for either of the 500 MHz SAW oscillators. Since there were only two 500 MHz SAW oscillators the data on Figure 4-3 is actually the average phase noise of the two.

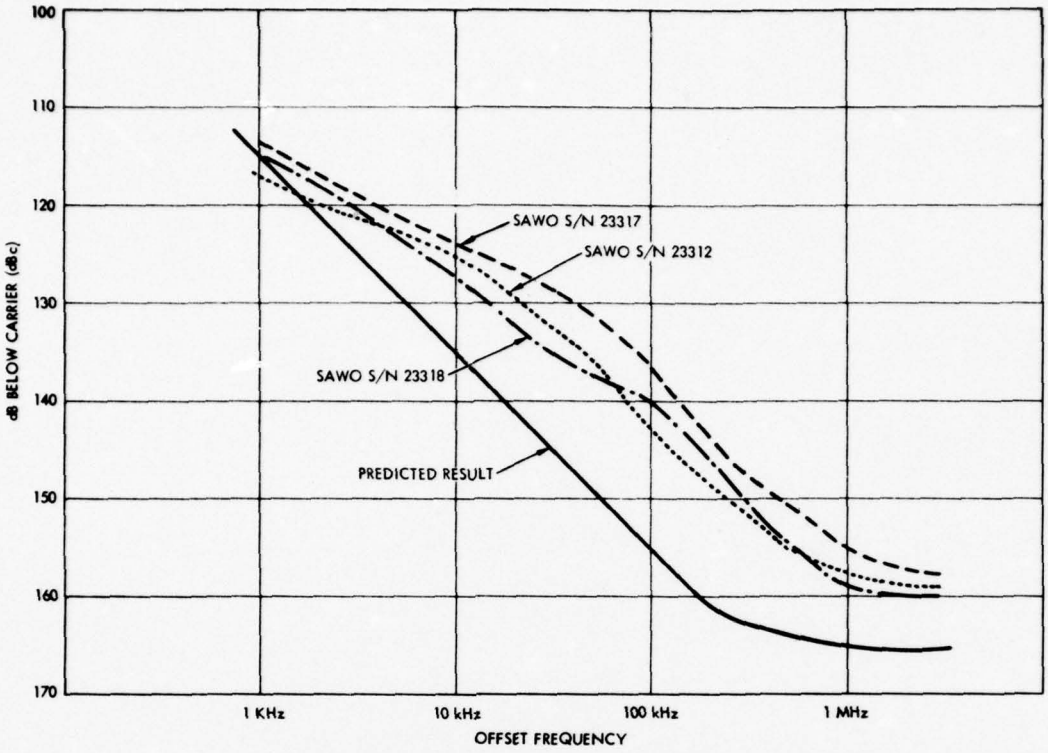



Figure 4-2. 250 MHz SAW Oscillator Phase Noise Measurements (1 Hz Bandwidth)

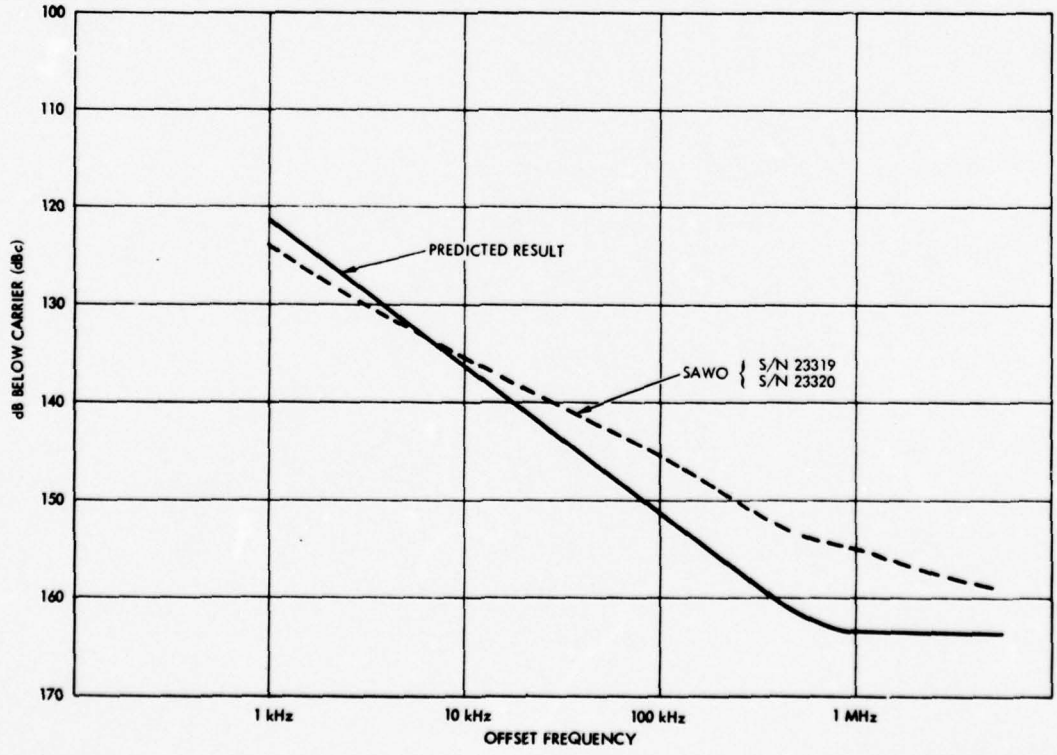



Figure 4-3. 500 MHz SAW Oscillator Phase Noise Measurements (1 Hz Bandwidth)

## 4.2 TEMPERATURE TESTS

The temperature dependence (medium term stability) of the five oscillators was measured over the range of -65°F (-54°C to +100°C). The shape of the oscillator frequency versus temperature curve is dominated by the temperature coefficient of the ST-cut quartz delay line. This material has a zero first-order temperature coefficient of delay near room temperature and a second order coefficient of $+17.2 \times 10^{-9}/°F^2$. Figure 4-4 shows the predicted temperature characteristic for the quartz delay line and the measured temperature dependence for the 250 MHz SAW oscillators. The curves indicate that the measured response is better than predicted. The difference is partially due to a linear contribution from the amplifier and partially due to the fact that the temperature coefficient of the quartz is not accurately known.

The frequency versus temperature measurement results for the 500 MHz SAW oscillators are plotted on Figure 4-5. Comparison of Figures 4-4 and 4-5 shows that the zero temperature coefficient point for the 250 MHz oscillators is about 60°F, but for the 500 MHz oscillators it is at -30°F. The change is apparently due to a slight misorientation of the quartz crystals on which the 500 MHz delay lines. These results point up the desirability of an accurate check of crystal axis orientation prior to device fabrication.

Figure 4-6 shows the output power versus baseplate temperature for the three 250 MHz and the two 500 MHz oscillators. The power variation is mainly dependent on the saturated output power variation of the loop amplifier. The output power variation was less than 1.5 dB over -65°F (-54°C) to +220°F (+105°C) and was less than 0.5 dB over 0°F(-18°C) to +125°F (+50°C) for all of the oscillators. With simple temperature compensation in the amplifier bias circuitry and by optimizing the amplifier saturation characteristics, it should be possible to reduce the variation to less than 0.5 dB over the full -65°F to +220°F temperature range.

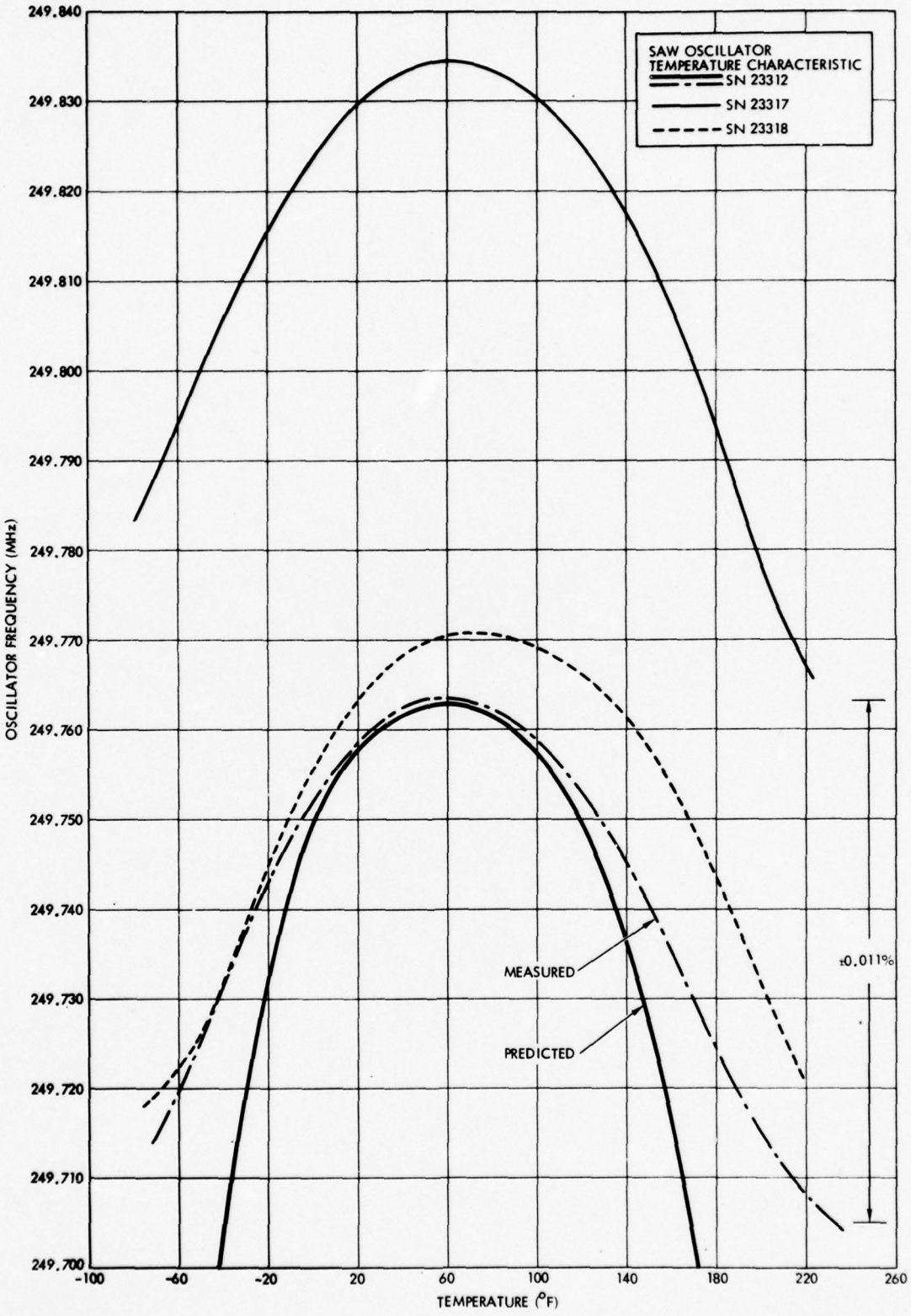



Figure 4-4. 250 MHz SAW Oscillator Medium Term Frequency Stability

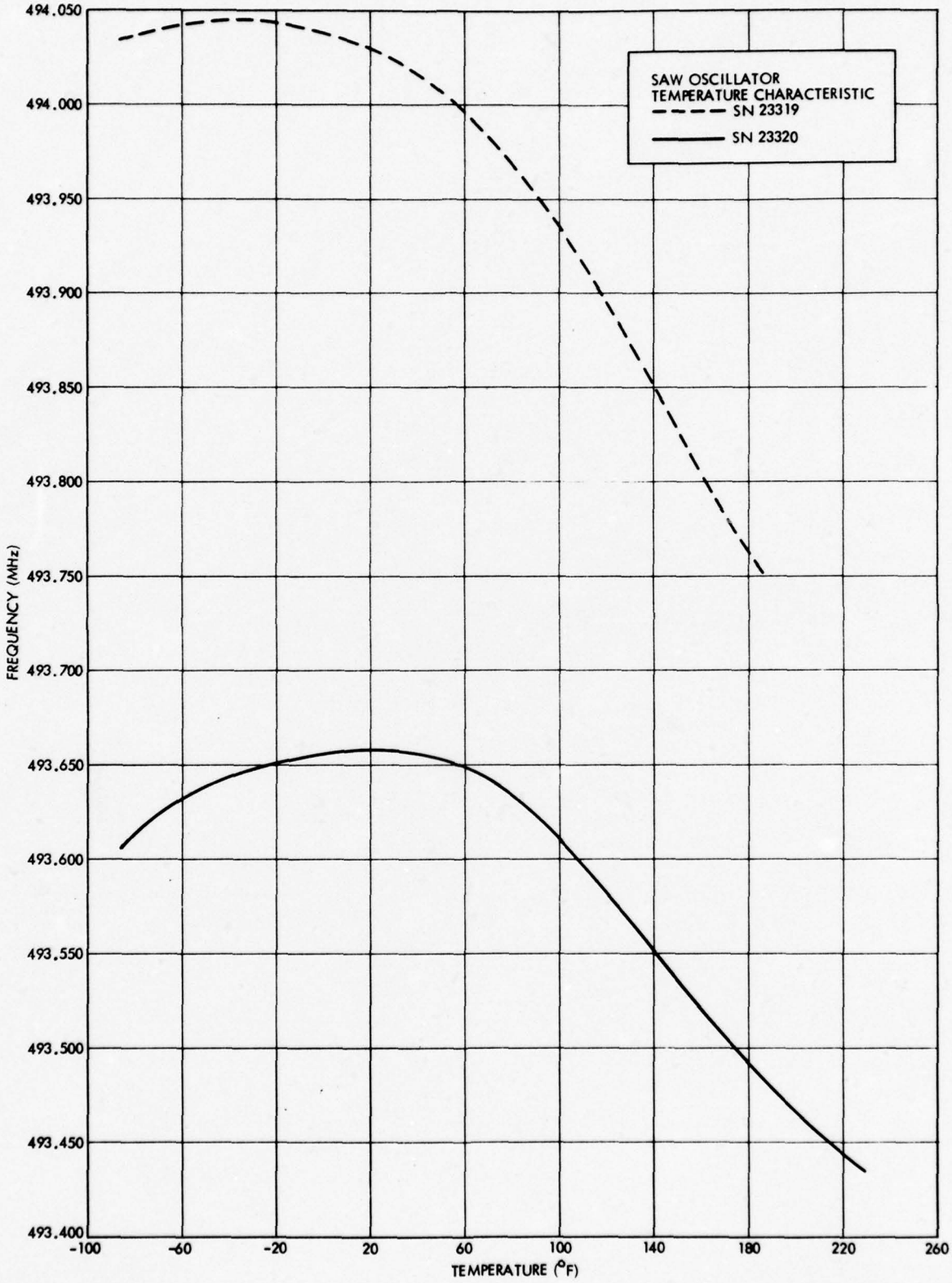



Figure 4-5. 500 MHz SAW Oscillator Medium Term Frequency Stability

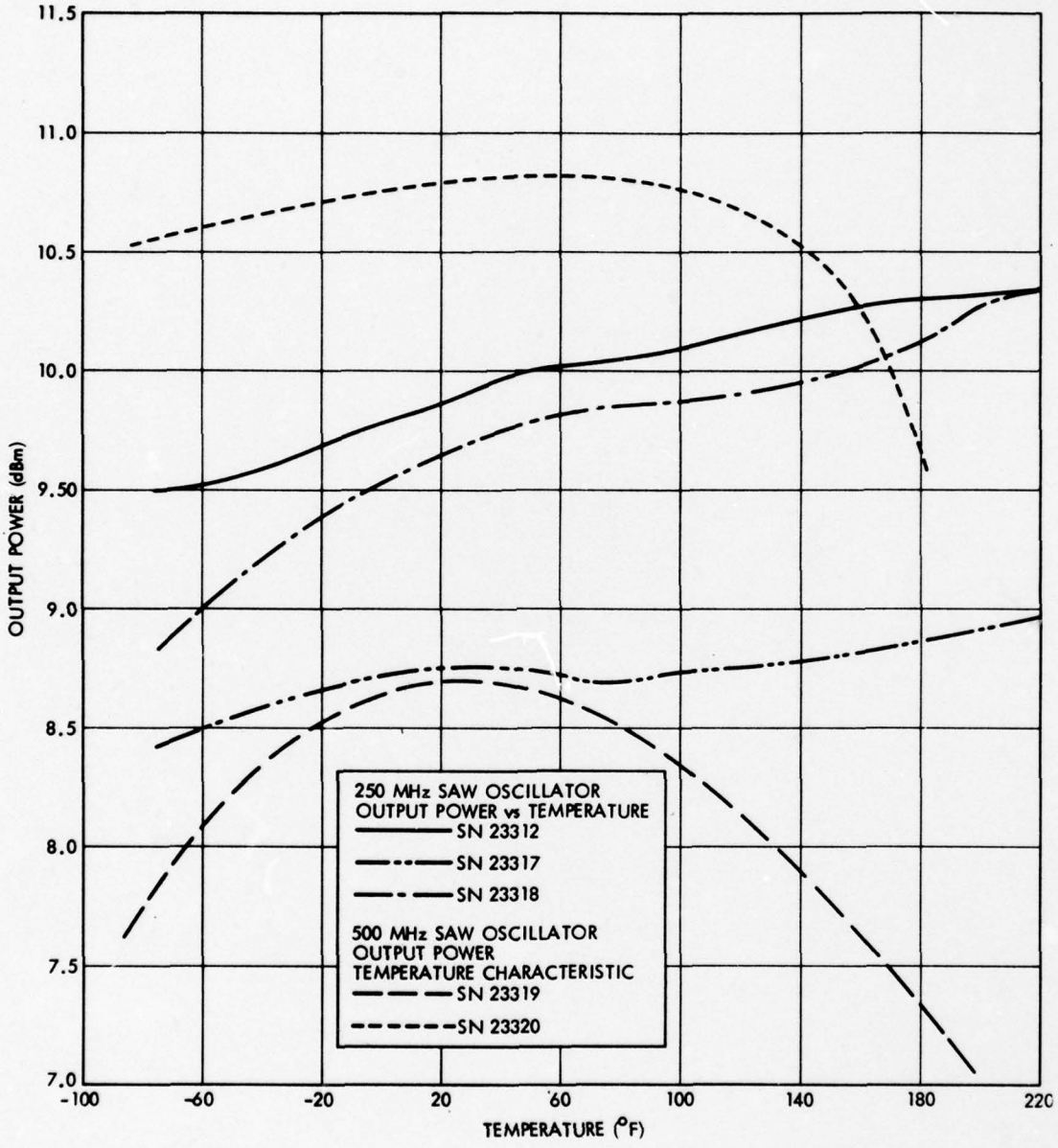



Figure 4-6. Output Power vs Temperature

## 4.3 SAW OSCILLATOR AGING TESTS

The aging test of the four 250 MHz SAW oscillators was started on 17 July 1975. The oscillators were assembled in identical housings using hermetically sealed SAW delay lines. All four oscillators were mounted on a common baseplate. Finally, the oscillators were mounted in a thermally isolated environment and temperature stabilized at 92°F.

The oscillators were first subjected to a 168 hour burn-in period. This type of burn-in is standard for high reliability components and is done for two reasons: to screen the semiconductors for early catastrophic failures, and to separate the short-term burn-in effects of the oscillator performance from the long-term aging effects. During the burn-in period the oscillator output powers varied from -1.0 dB to +0.4 dB and the output frequencies varied from +1.8 ppm to -2.8 ppm.

During the aging test the oscillator baseplate temperature was continuously monitored. The data was recorded at the same time early each morning. During the period of the test, the baseplate temperature of the oscillators varied less than $\pm$0.5°F. Temperature changes of this magnitude will result in oscillator frequency variations of less than $\pm$0.2 ppm. For this reason, it was not necessary to compensate the oscillator frequency data due to ambient temperature changes.

The frequency aging characteristics of the four oscillators are shown in Figure 4-7. Following the initial burn-in period, the oscillator output powers varied less than $\pm$0.05 dB. The frequency aging characteristics of the oscillators exhibited two different trends. The output frequencies of two of the oscillators have aged less than 2 ppm/mo. The output frequencies for these oscillators increased approximately 2 ppm during the first month. During the second month the frequencies varied less than $\pm$1 ppm. During the third and fourth months, the frequency aging for the two oscillators stabilized at a constant rate of approximately -2 ppm/month. The frequency aging characteristic for the other two oscillators was significantly different. During the first two months, the frequencies aged at constant rates of -4 ppm/month and -6 ppm/month respectively. During the third and fourth months the frequency aging rates for both oscillators dropped to approximately -3 ppm/month.

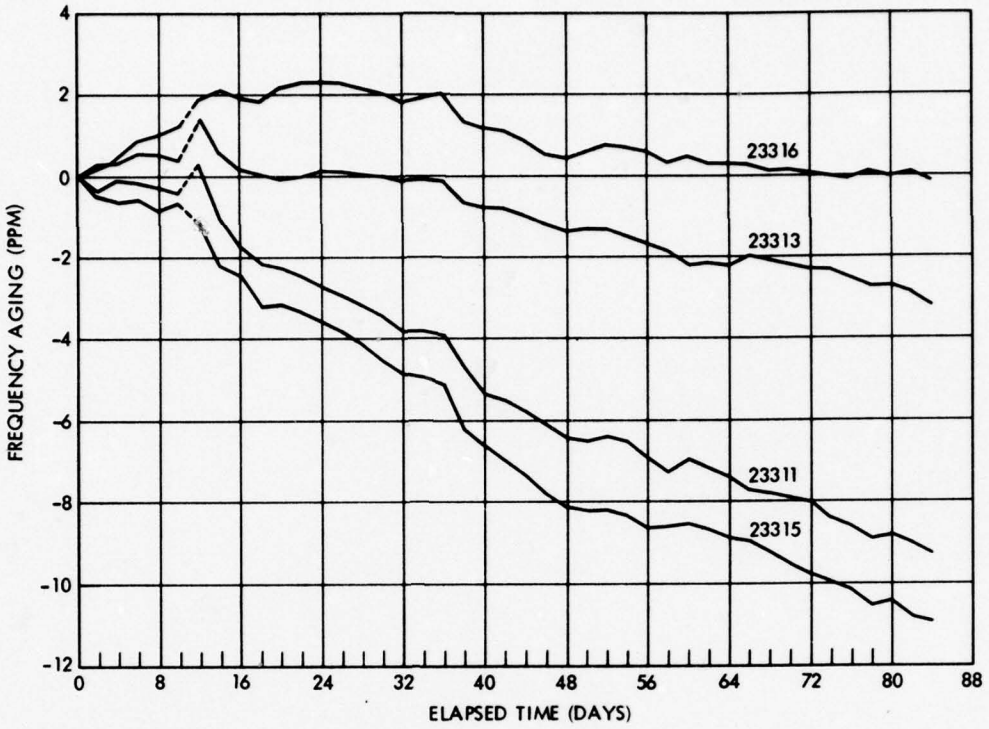



Figure 4-7. SAW Oscillator Aging Test Results

On day ten (10), (Saturday-August 2nd), there was a scheduled power outage at our facility. For this reason the oscillators were turned off over the weekend, with testing resumed the following Monday. It is interesting to note that for two of the four oscillators, the aging appears to have continued in spite of the fact that the oscillators were off.

Following the first two months of aging tests, the processing and alignment data for the four oscillators was reviewed to determine if there was any difference which would explain the two different aging characteristics. The only difference between the two pairs of oscillators that correlated with the aging trends was the excess gain in the oscillator feedback loop. To determine if this difference was the cause of the different aging rates, three additional oscillators with different levels of excess loop gain were placed on test. After one month of test, the aging rates of all three oscillators were all approximately -5 ppm. The results of this test indicate that the different levels of excess gain in the oscillators were not responsible for the two different aging trends.

The current aging rate for the SAW oscillators is approximately an order of magnitude higher than the aging rate for typical low frequency bulk crystal oscillators. The aging rates for SAW oscillators are equal to the best rates reported in the current literature covering SAW oscillators. The aging test of the oscillators will continue until a minimum of 12 months of aging have been accumulated.

## 4.4 VIBRATION TESTING

Two 250 MHz SAW oscillators were vibrated in three axes to determine the random effects of vibration on the oscillator output frequency and power. Figure 4-8a-c shows the dynamic levels that the oscillators were exposed to. The levels are typical for acceptance testing for space qualified microwave components. Table 4-2 summarizes the performance of the oscillators after each axis of vibration. The total shift in oscillator frequency after all three axes of vibration was less than $\pm$250 Hz ($\pm$1 ppm). The output spectrum of the oscillators was monitored continuously during the testing. Figure 4-9 shows spectrum analyzer photographs for one of the oscillators taken during vibration. No difference was detectable in the oscillator output spectrum while the oscillators were being vibrated. The results of these tests indicate that the SAW oscillators are rugged and basically insensitive to vibration.

Table 4-2. SAW Oscillator Vibration Test Results

| | Baseline | Post Z Axis | Post Z Axis | Post Y Axis |
|---|---|---|---|---|
| S/N 23318 Frequency | 249.714 MHz | 249.715 MHz | 249.715 MHz | 249.715 MHz |
| Output Power | +7.7 dBm | +7.6 dBm | +7.8 dBm | +7.8 dBm |
| S/N 23317 Frequency | 249.702 MHz | 249.703 MHz | 249.703 MHz | 249.703 MHz |
| Output Power | +8.6 dBm | +8.5 dBm | +8.3 dBm | +8.3 dBm |

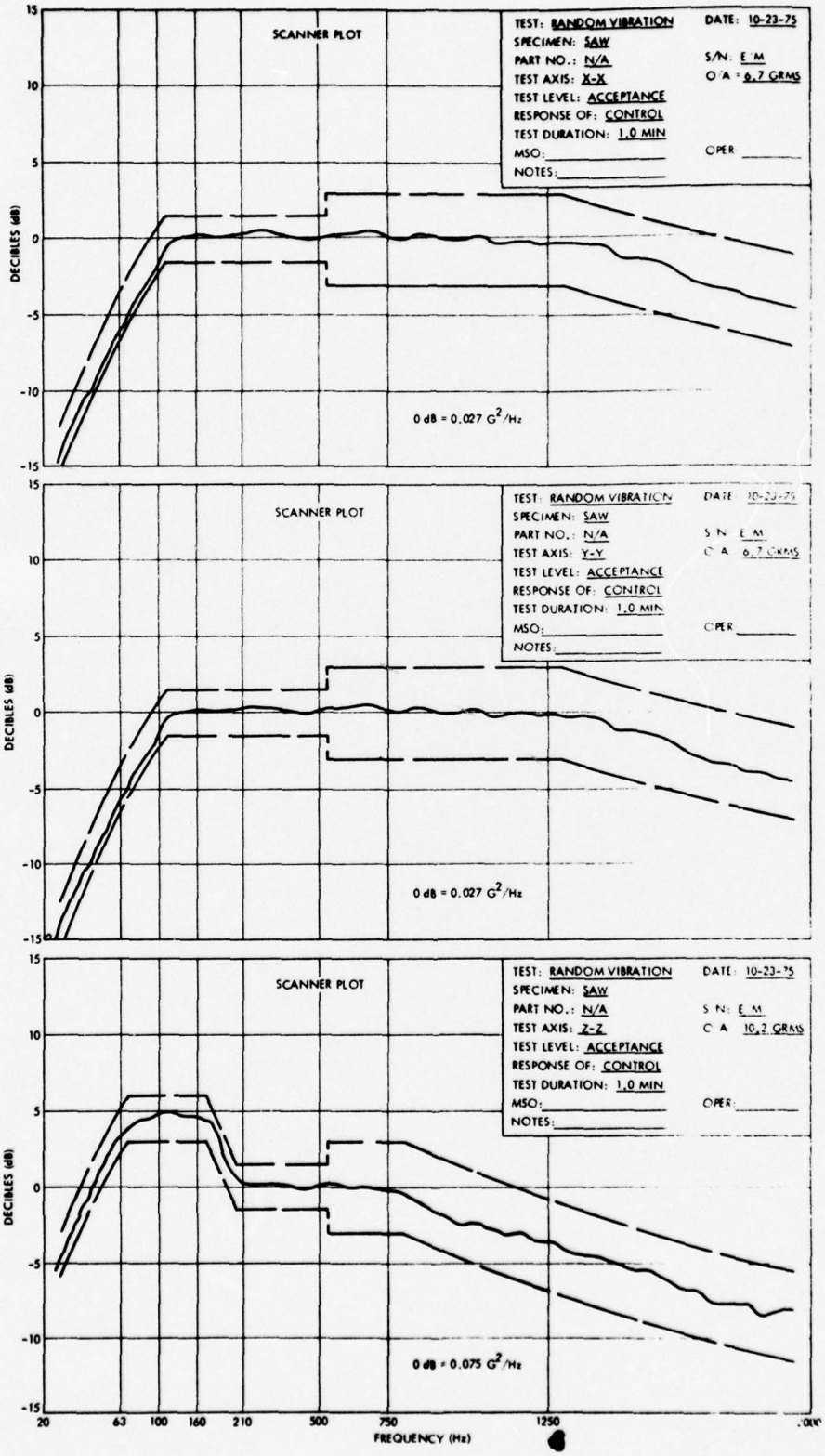
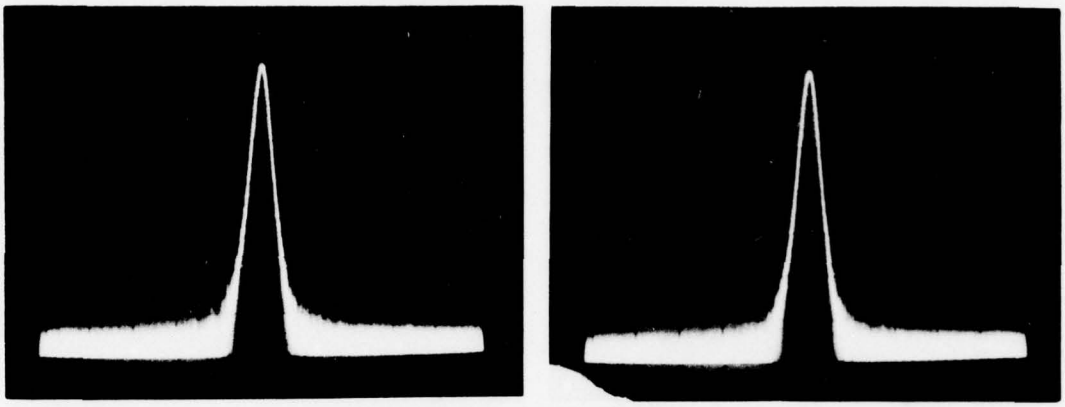
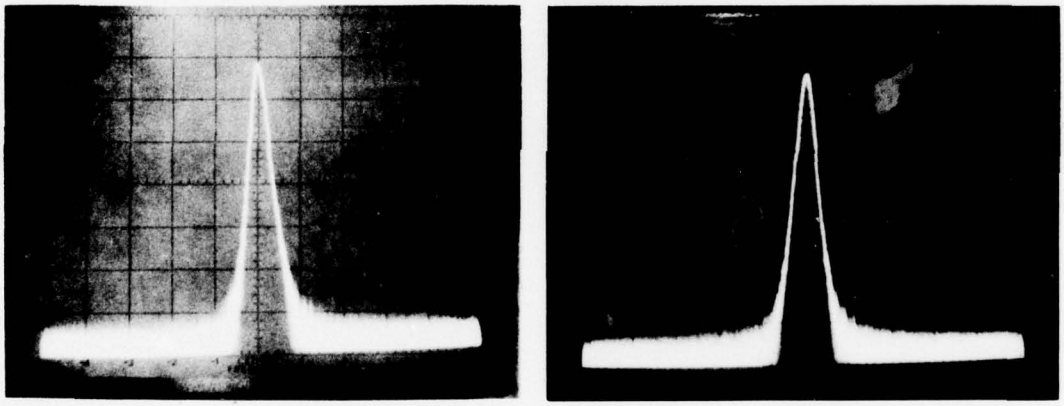



**Figure 4-8. SAW Vibration Test Levels**



BASELINE

DURING Z AXIS



DURING X AXIS

DURING Z AXIS

IF BANDWIDTH = 3 $kH_3$
SCAN = 20 $kH_3$/DIV
LOG REFERENCE = 20 dBm
VERTICAL = 10 dB/DIV

Figure 4-9. SAW Oscillator Output Spectrum During Vibration

The final tests performed on the SAW oscillators were to determine the effects of power supply variations on the oscillator output power and frequency. The typical oscillator sensitivities to a ±5% change in the oscillator line voltage are as follows:

| 250 MHz Oscillator | 500 MHz Oscillator |
|---|---|
| Δfrequency=±2.5 KHz (±5 ppm) | Δfrequency= ±3 KHz (±3 ppm) |
| Δpower = ±0.5 dB | Δpower = ±0.5 dB |

# 5. STUDY OF IMPROVED SAW OSCILLATOR FREQUENCY STABILITY

In some instances the level of frequency stability offered by the basic SAW oscillator design may not be sufficient for a particular application, but the designer may wish to take advantage of SAW oscillators. In this situation, there are techniques available to improve the frequency stability of the basic SAW oscillator. Three of these techniques will be discussed in this section. They are injection locking, varactor tuning (VCO), and the use of more than one material in the fabrication of the SAW delay line.

## 5.1 CIRCUIT TECHNIQUES

Injection locking refers to the synchronization of a free-running oscillator by the injection of a weak signal of the desired frequency which is close to the natural frequency of the oscillator. Among other functions, injection locking can be used to accomplish oscillator frequency stabilization, power amplification, AM limiting and FM modulation.

The basic SAW oscillator can be injection locked by injecting an RF signal into the oscillator loop at the input of the feedback amplifier. Figure 5-1 shows the block diagram of the basic injection locked SAW oscillator. The reference signal is injected between the output of the delay line and the input of the amplifier to avoid the delay line insertion loss and to take advantage of the amplifier gain. The oscillator locking bandwidth is a function of locking gain (ratio of oscillator output power to injection signal level). The characteristic is a straight line function as predicted by the expression for injection locked oscillators

$$\frac{\Delta f}{f_o} \propto \frac{1}{Qx} \sqrt{\frac{Pi}{Po}} \qquad (5.1)$$

where

$\Delta f$ = locking bandwidth

$f_o$ = oscillator center frequency

Qx = external Q of the oscillator

Pi = locking signal level

Po = oscillator output power

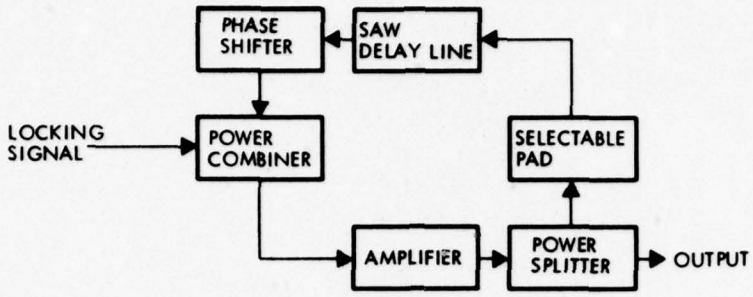



Figure 5-1. Block Diagram of Injection-Locked SAW Oscillator

A simple improvement to the basic injection-locked SAW oscillator can be realized by adding a third transducer to the SAW. In this case the injection signal is added to the main feedback signal in the SAW transducer. The advantage of this scheme is that the reference signal is filtered by the SAW delay line and does not have to be carefully filtered to reject all of the unwanted spurious signals.

The second method of frequency stabilization that was investigated was electronic tuning. As indicated in Section 3, it is possible to frequency tune the oscillator by introducing a controlled phase shift into the oscillator loop. A network utilizing varactor diodes can be used to perform the phase shifting function. A schematic for the circuit is shown in Figure 5-2.

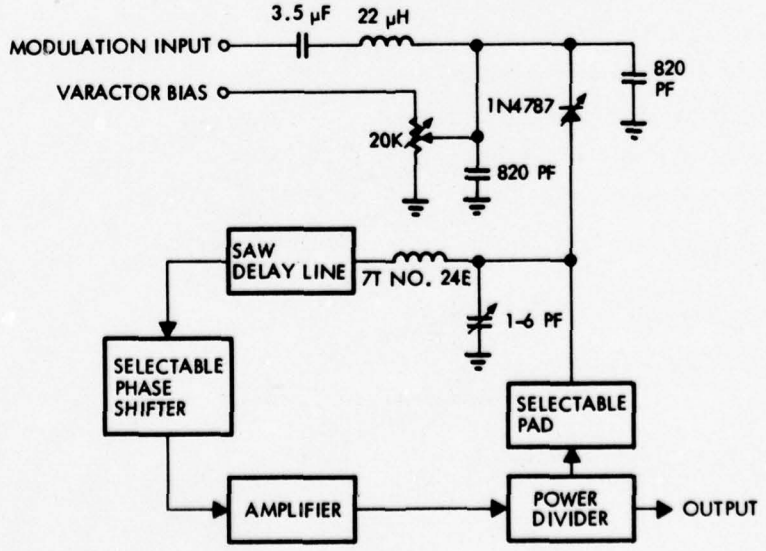



Figure 5-2. Schematic of Varactor Tuned SAW Oscillator

There are two different ways to implement a stabilized SAW oscillator utilizing the voltage tuning capability of the oscillators, the first of which is a phase-locked loop approach. Figure 5-3 shows the block diagram for this circuit. Using this approach, the oscillator frequency is locked to a lower frequency reference. By carefully designing the loop, it is possible to take full advantage of both the excellent SAW oscillator phase noise and the long term stability of the reference oscillator. In addition, it is possible to realize a system with several SAW oscillators of different frequencies, all of them coherent with a common reference oscillator.

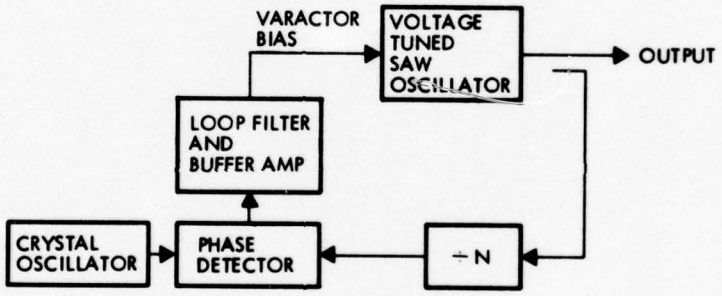



Figure 5-3. Block Diagram of Phase-Locked SAW Oscillator

The second method of temperature compensating a SAW oscillator is a free-running approach. The baseplate temperature of the oscillator is sensed by a thermistor whose output drives a temperature compensation (T. C.) network. The SAW oscillator temperature behavior is such that it should be tuned higher in frequency if the baseplate temperature moves either way from room temperature. The thermistor output will be a linear function of temperature. Therefore, the T.C. network will be designed to have a parabolic output in response to a linear input. This is a routine circuit design problem and will not be detailed.

## 5.2 MATERIAL COMPENSATION TECHNIQUES

Recent results have shown that RF-sputtered $SiO_2$ film overlays are a good temperature compensating method for piezoelectric crystals. This technique is a worthy alternative to using ST-cut quartz.[1,2] $SiO_2$ films deposited on YZ $LiNbO_3$ have a temperature coefficient similar to that of ST-cut quartz, but this composite material has a coupling coefficient of 6.2 percent. Results using $SiO_2$ films on YZ $LiTaO_3$ are significantly better. The temperature coefficient is considerably better than that of ST-cut quartz. Here the $SiO_2$ film overlays were 0.59 $\lambda$ in thickness, where $\lambda$ is an acoustic wavelength. This overlay film produced a zero first-order coefficient and a second order coefficient of $+3 \times 10^{-9}$ $(°C)^{-2}$, an order of magnitude smaller than that of ST-cut quartz. The coupling coefficient of the $LiTaO_3$ overlay structure is 1.4%, about an order of magnitude higher than that of ST-cut quartz. The propagation loss was measured to be $\approx$0.6 dB/$\mu$sec at 330 MHz, compared to about $\approx$0.3 dB/$\mu$sec at 330 MHz for ST-cut quartz. Even though the propagation loss is larger, the conversion efficiency of the $SiO_2/LiTaO_3$ composite system would be theoretically as much as about 9 dB better than ST-cut quartz. Since the conversion efficiency is the dominant effect in regards to insertion loss of SAW delay line, $SiO_2/LiTaO_3$ would have a much lower insertion loss. This lower insertion loss will manifest itself in better short term stability of the SAW oscillator. It would also enable the amplifier to have a much lower gain and thus the oscillator would also have a much better DC efficiency. The $SiO_2/LiTaO_3$ composite system is, however, a dispersive medium. That is, there is a frequency dependence to the propagation velocity. This dispersion is

$$\frac{1}{V}\left[dV/df\right] = -60 \text{ ppm/MHz} \qquad (5.2)$$

where V is the surface wave velocity and f is the acoustic frequency. Because of the dispersive nature of composite systems, they will be primarily limited to narrowband device applications. This composite system can be easily applied to fixed frequency SAW oscillators. For these $LiTaO_3$ overlay structures, the slope of the temperature coefficient of delay depends on the thickness of the $SiO_2$ films and can be adjusted to

be either slightly negative or positive. This slope can be therefore adjusted to compensate for the linear temperature coefficient of an amplifier when using a $LiTaO_3$ overlay structure in a SAW oscillator configuration. Such SAW oscillators have a temperature coefficient which is better than an AT-bulk quartz. SAW oscillators constructed from delay lines using composite structure of $SiO_2$ overlayed on $LiTaO_3$ have excellent medium term stability.


1. T.E. Parker, M.B. Schulz, and H. Wichansky, "Temperature Stable Materials for SAW Devices," Proc. of the 28th Annual Frequency Control Symposium, 96, May 1974.

2. T.E. Parker and M.B. Schulz, "Stability of SAW Controlled Oscillator," Proc. 1975 Ultrasonic Symposium.

# 6. SAW RESONATOR OSCILLATOR STUDY

## 6.1 SAW RESONATORS

Surface acoustic wave technology has now progressed sufficiently to allow the construction of simple, compact UHF narrowband SAW resonators. The SAW resonator is shown in Figure 6-1. It consists of an interdigital transducer placed between two periodic reflecting gratings. The interdigital transducer generates a freely propagating Rayleigh wave which is reflected between the two periodic gratings. The coherent reflections set up large standing waves inside of the cavity. The interdigital transducer is used to couple energy into and out of the cavity. The one port SAW resonator shown in Figure 6-1 is a very high Q device and is electrically equivalent to the bulk crystal devices used in conventional crystal oscillators and crystal filters.

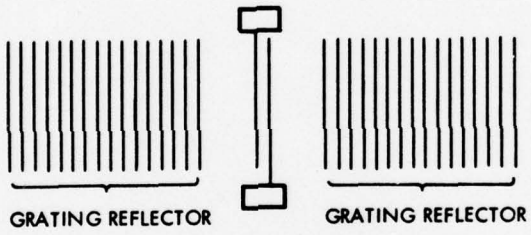



Figure 6-1. Basic One-Port SAW Resonator Configuration

In some circuit applications it is more convenient to have a two-port device rather than a one-port device. Two-port SAW resonators are easily implemented by the addition of a second interdigital transducer inside the cavity. The basic configuration is shown in Figure 6-2. The added flexibility of the two-port resonator is not without some sacrifice. The addition of the second interdigital transducer pulls energy out of the cavity thus lowering the Q of the system.

### 6.1.1 SAW Grating Reflectors

The grating reflector is an essential constituent of the SAW resonator. Reflections from the grating arise from an impedance discontinuity of the surface wave. The grating reflectors, which provide more than 98% reflection, may consist of reflecting sections of etched grooves, and

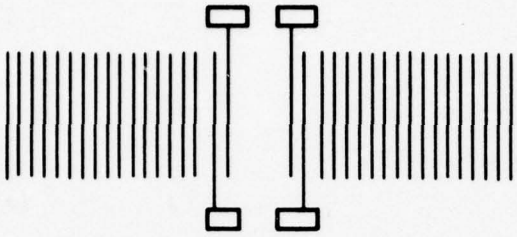
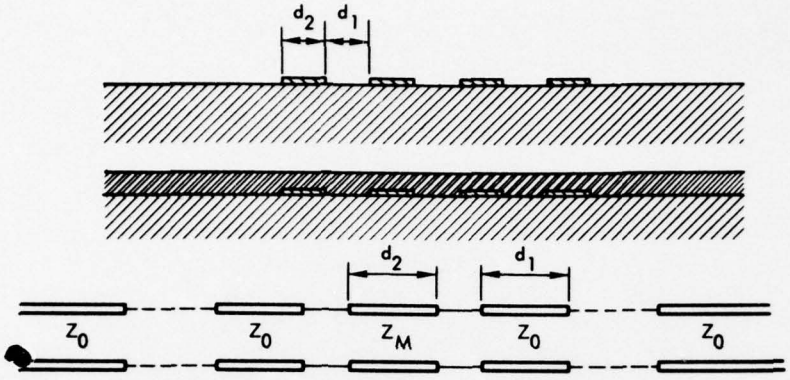


Figure 6-2. Basic Two-Port SAW Resonator Configuration

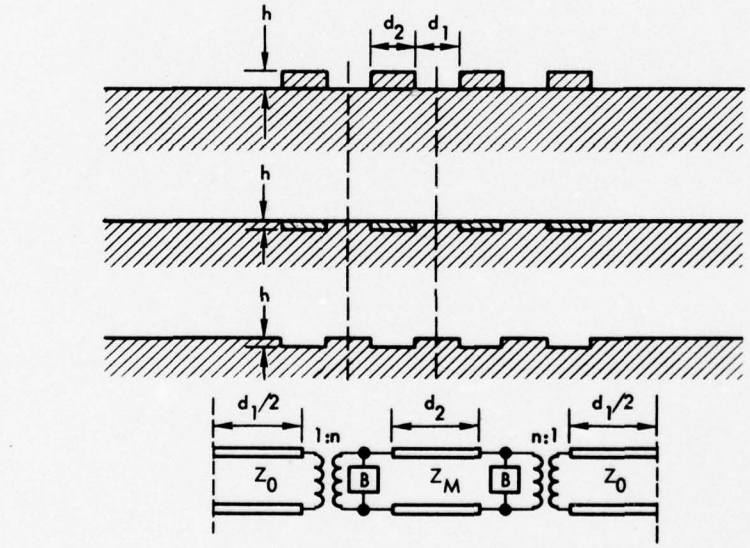
overlaid metallic or dielectric or ion implanted strips. These grooves or strips produce reflections by either piezoelectric loading, deformation loading or mass loading, or a combination of these effects. By virture of the periodicity of the reflectors, the grating reflects strongly over a narrow frequency band in the passband response. The location of this narrow band must be known accurately to permit an optimum design of the resonator.

Theoretically a repetitively mismatched transmission line equivalent network can be used to obtain the stopband characteristics of the grating. The analysis is based upon transmission-line representation for Rayleigh waves and an equivalent network representation for a single step discontinuity in the substrate surface. These constituent networks, as shown in Figure 6-3, can then be cascaded to yield an overall equivalent network for the grating reflectors, from which the reflection properties can be easily derived.

There are basically three types of loading mechanisms for surface acoustic wave gratings: piezoelectric, mass, and deformation loading. One of the easiest ways to fabricate a SAW grating is to use piezoelectric loading on a strong electromechanical coupling material such as $LiNbO_3$. Since the grating is formed by metallic strips, both the intedigital transducer and the grating can be fabricated together. The amount of loading is related to the piezoelectric coupling constant of the substrate material and can be quite large, as in the case of $LiNbO_3$. A grating can be formed on $LiNbO_3$ with about 200 lines or less. However, $LiNbO_3$ has very poor temperature stability, 94 ppm/$^{\circ}$C. A SAW grating constructed by using piezoelectric loading on low temperature coefficient, low coupling materials like ST-cut quartz requires an extremely long




(A) PIEZOELECTRIC LOADING, COMPOSITE PIEZOELECTRIC LOADING GRATING REFLECTORS AND EQUIVALENT NETWORK




(B) MASS LOADING, ION IMPLANTED GRATING ETCHED GROOVES REFLECTORS AND EQUIVALENT NETWORK FOR A UNIT CELL

Figure 6-3. Grating Reflectors

grating, making piezoelectric loading impractical for low coupling materials. One can, however, employ mass loading techniques on ST-cut quartz. Mass loading refers to the application of a material of mass different from that of the piezoelectric substrate to form the reflecting grating. The lines of this type of grating may be formed by sputtered ZnO, evaporated aluminum or gold films. The amount of loading can be much larger than piezoelectric loading, but this type of loading introduces a considerable amount of dispersion. This dispersion must be corrected for in the design of the SAW resonator.

Deformation loading refers to physical deformation of the substrate surface, i.e., cutting slots or forming ridges for the reflecting grating. This type of loading introduces a considerable amount of dispersion. This dispersion must be corrected for in the design of the SAW resonator. Deformation loading refers to physical deformation of the substrate surface, i.e., cutting slots or forming ridges for the reflecting grating. This type of loading also introduces dispersion into the surface acoustic wave and requires a rather elaborate fabrication procedure not readily adaptable to production.

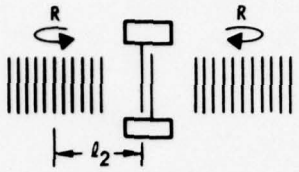
The selection of a type of grating for SAW resonators is more often determined by the temperature stability requirements. Piezoelectric loading on $LiNbO_3$ gives poor temperature stability, but piezoelectric loading using composite structures has excellent temperature stability. These composite structures are formed from RF sputtered $SiO_2$ on $LiNbO_3$ or $LiTaO_3$. The temperature stability of $SiO_2/LiTaO_3$ composite structure is similar to ST-cut quartz. However, the $SiO_2/LiTaO_3$ composite structure is considerably better than ST-cut quartz. Its temperature coefficient is similar to that of AT-cut bulk crystal quartz. This composite also has dispersive effects which must be considered in design of SAW resonators.

Ion implanted gratings on ST-cut quartz also offer a viable way of obtaining temperature stability. The implantation of ions in quartz causes a ridge to be formed. Thus, there is a deformation loading effect. In addition to the deformation loading there is a velocity discontinuity in the implanted region showing that this loading is similar to piezoelectric loading.

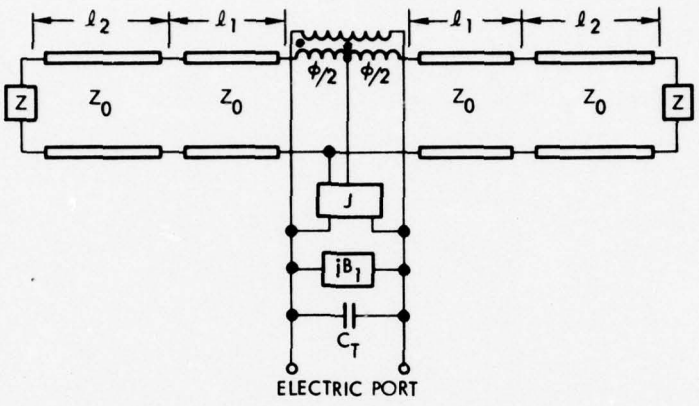
The medium term stability of a SAW resonator oscillator is determined by the temperature stability of the SAW resonator. In a similar manner the long term aging of a SAW resonator oscillator is determined by the temperature stability of the SAW resonator. The aging characteristic of the SAW resonator is primarily determined by the grating. In order to obtain high Q's at least four hundred metallic lines are required for a SAW. Any aging mechanism of the lines would markedly change the grating response. It has also been postulated that there are stresses which are produced on the piezoelectric surface during the evaporation of the metal films which would cause a severe aging effect. This aging mechanism would be produced in metallic lines whether they are used for piezoelectric loading or mass loading. A composite structure would also have the aging problem associated with the overlaid films of $SiO_2$. Mass loaded gratings formed by RF sputtered ZnO film on ST-cut quartz are said to have a severe aging effect due to the ZnO in addition to their reproducibility problems. Perhaps the best solution to the aging problem is grooved gratings. It has been conjectured that grooved gratings would not have the aging effect previously described. This reasoning is based on the results which indicate that sputter etched surfaces are free of surface damage. This result may not carry directly over to grooved gratings, however, since there is a step discontinuity of materials with gratings. At the steps, large stresses could be set up which would then relax out slowly with time.

## 6.2 ONE-PORT SAW RESONATOR-OSCILLATOR

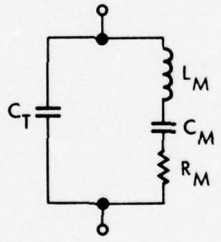
SAW resonators are very high Q UHF devices with low loss. The equivalent circuit for a one-port SAW resonator is shown in Figure 6-4. It is exactly the same as that of a bulk crystal resonator. Thus, all the applications of bulk crystals, for example, multipole filters, oscillators and so forth, carry directly over to one-port SAW resonators. For example, one-port SAW resonators can replace quartz crystals in a simple one-transistor grounded base oscillator circuit.[1,2] However, initial attempts by the Royal Radar Establishment to implement this circuit met with limited success.[1] Spurious oscillations occurred due to the fact that the transducer capacitance away from resonance had a low impedance. It appears that this type of problem might be cured by more elaborate design considerations.




(A) ONE PORT SAW RESONATOR




(B) EQUIVALENT NETWORK




(C) EQUIVALENT CIRCUIT

Figure 6-4. One-Port SAW Resonator and Equivalent Circuit

The performance of a one-port SAW resonator oscillator is limited by the type of SAW resonator chosen. One of the easiest types of SAW resonators to fabricate uses piezoelectric loaded grating reflectors on $LiNbO_3$. This requires only aluminum lines for the grating and so the device can be produced in a single photolithographic process. Using this technique Q's of a few thousand can readily be obtained up to a frequency of about 650 MHz.[3] With these devices one could produce SAW resonator oscillators which would have very good short term

stability. A SAW resonator using piezoelectric loading has been built at 860 MHz, but with a Q of 800. A 1-GHz SAW resonator has also been attempted, but with rather poor results.[4] Thus, the experimental results indicate that the Q of SAW resonators will decrease substantially as the frequency is increased above 800 MHz. This is not totally unexpected since SAW resonators operate on the principle of extremely low loss. At higher frequencies the loss mechanism of surface acoustic waves increases substantially. For example, the propagation loss increases as the square of the frequency. Theoretical calculations for unloaded cavities of grooved SAW resonators show this marked decrease in Q [5]

The short term stability of a $LiNbO_3$ SAW resonator oscillator is very good because of its high Q and low loss. From our earlier discussion on gratings one expects long term stability should be quite poor. The medium term stability of a SAW resonator oscillator can be improved by either using mass loading, ion implantation or a composite structure; however, one expects the poor aging characteristics.

If sputtered or plasma etched grooves truly leave the surface of the SAW resonator stress free, then the real solution lies in producing SAW resonators using grooving on ST-cut quartz. Q's as high as 22,000 at 140 MHz have been recently reported.[6] With such high Q's one can have both short term, medium term and long term stability.

## 6.3 TWO-PORT SAW RESONATOR-OSCILLATOR

The Royal Radar Establishment solution to spurious oscillation problems encountered in a one-port SAW resonator oscillator was to use a two-port SAW resonator.[3] The equivalent circuit for the two-port resonator is shown in Figure 6-5. The two-port SAW resonator has an equivalent circuit which is not a direct analogy to a bulk crystal. The addition of the second interdigital transducer allows the energy to be coupled in one transducer and out the other thus eliminating some of the impedance problems associated with the one-port SAW resonator. The two-port resonator also allows the additional flexibility that the Q of the SAW resonator can be varied by changing the load conditions. The Q values have been shown to be externally variable by a factor of 7:1.[3] Therefore, when a two-port SAW resonator is used

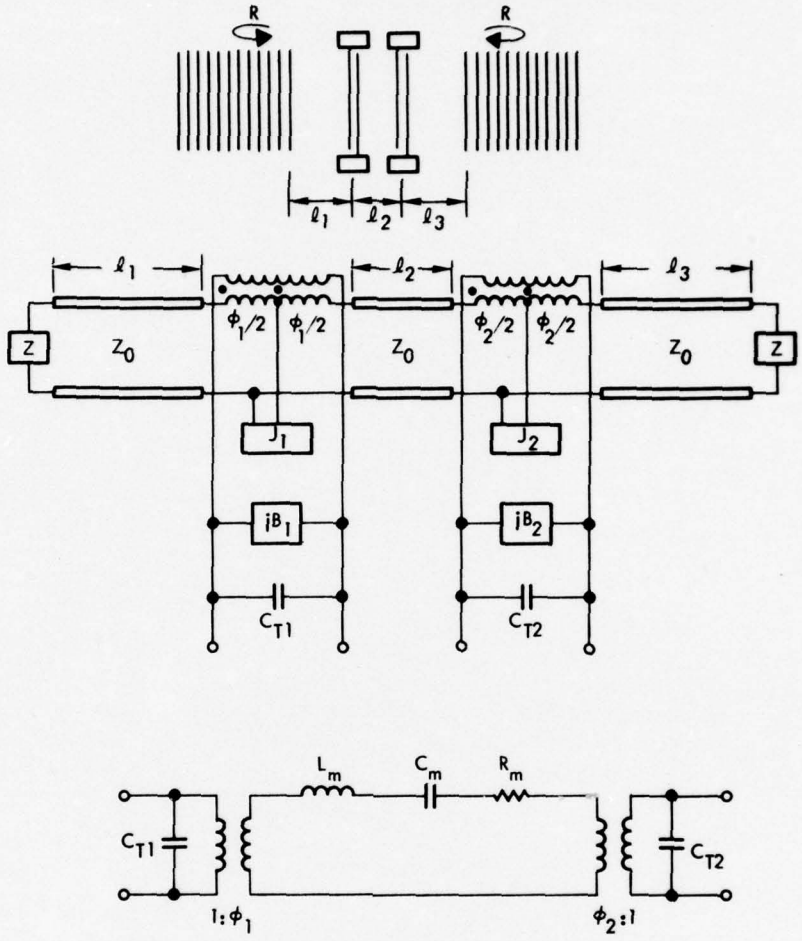
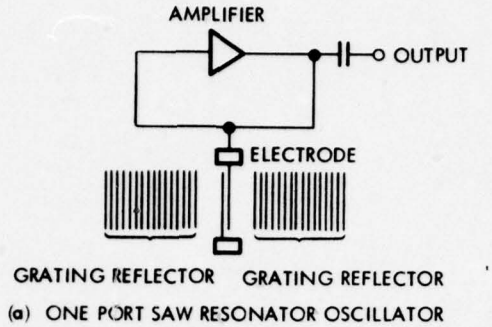


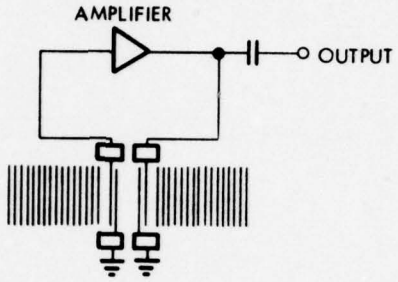

Figure 6-5. Two-Port SAW Resonator and Equivalent Circuit

to control a feedback oscillator, the Q may be adjusted to the optimum value if frequency modulation is required.

The basic SAW resonator-oscillator configurations are shown in Figure 6-6. The material and grating considerations for a one-port SAW resonator and a two-port SAW resonator are identical. All the material and grating tradeoffs can be extended to two-port SAW resonators. If short, medium and long term stability are required, then a two-port resonator should be constructed on ST-cut quartz with grooved gratings for the reflections. If extremely good short term stability is required then a one-port configuration is probably better, since the addition of the second interdigital transducer lowers the Q for the SAW resonator.




(a) ONE PORT SAW RESONATOR OSCILLATOR




(b) TWO PORT SAW RESONATOR OSCILLATOR

Figure 6-6. Basic Configurations of SAW Resonator Oscillators

## 6.4 COMPARISON BETWEEN SAW RESONATOR AND DELAY LINE OSCILLATORS

To compare SAW delay line oscillators and SAW resonator oscillators, a number of factors should be considered, including the oscillator application, feasibility, frequency range, DC to RF efficiency and cost. The two types of oscillators considered here are fixed frequency sources and frequency modulated oscillators.

The performance parameters of interest for fixed frequency sources are their stability, the DC to RF efficiency and the accuracy with which the required frequency can be set. The short term stability, or phase noise performance is determined by the Q of the feedback element. As the preceeding discussion has indicated, below ≈800 MHz, the one port resonator has the highest Q, and the two port resonator is intermediate between the one port resonator and the SAW delay line. At higher frequencies, from 800-2000 MHz, the delay line has the highest Q, chiefly because of fabrication difficulties associated with the resonator gratings.

The medium term stability of a SAW oscillator is independent of the type (resonator or delay line), but is determined entirely by the choice of delay line material. However, the long term stability (aging) does depend upon the type of oscillator because of the fabrication processes involved. Insufficient data exists on SAW resonator oscillators to quantify their long term stability, but they are expected to age more rapidly than delay line oscillators. The resonator fabrication process produces greater surface stresses than the delay line fabrication process. The relaxation of these surface stresses exhibits itself as oscillator aging.

The DC to RF efficiency of a SAW oscillator is dependent on only two factors, the efficiency of the amplifier and the insertion loss of the SAW device. It is reasonable to assume that similarly efficient amplifiers would be chosen for either a delay line or resonator oscillator. The insertion loss of a resonator (below 800 MHz) is considerably less than that of a delay line, and thus the resonator oscillator will be more efficient.

The amplifier and raw material costs for a SAW oscillator are identical whether a delay line or resonator is used. The difference in price derives from two factors: the cost of fabricating the SAW device, and the cost of setting the oscillator to the exact frequency required. SAW delay lines are fabricated using a photolithographic process. Resonators use the same photolithographic process for the transducers, and require a multi-step plasma grooving process for the gratings. Thus, SAW resonators are more expensive than delay lines to fabricate. Secondly, the relative ease with which an oscillator can be tuned to a specified frequency via the circuitry external to the SAW device is inversely proportional to the device Q. Devices with very high Q's have very narrow bandwidths and are difficult to tune. SAW resonators have higher Q's than SAW delay lines, and will result in more expensive oscillators.

The degree to which a SAW oscillator can be frequency modulated is also inversely proportional to device Q. If a SAW delay line is constructed with a large bandwidth and a short propagation length, it

can be made into an oscillator with up to about 1% frequency modulation.[7] Utilizing more complicated delay line configurations, SAW delay line oscillators can be continuously electronically tuned over a range of 30% or more.[8] In contrast a SAW resonator oscillator would only have a few tenths of a percent frequency modulation capability. For example, the one-port resonator whose equivalent circuit is analogous to a bulk crystal would have roughly the same range of frequency modulation, about 0.1%. Using a two-port SAW resonator this modulation is greatly increased, but at the expense of the Q.[3] In the case of a two-port SAW resonator oscillator the frequency can be tuned by changing the load impedance of the output transducer. The change of impedance changes the phase of the surface wave in the cavity. It can easily be shown that the fractional change in frequency is directly proportional to the fractional change in phase, and the number of wavelengths across the cavity and inversely proportional to the number of finger pairs of the interdigital transducer.[9] Applying these conditions, one can estimate that a two-port SAW resonator oscillator should have about 0.4% modulation capability.

The comparison between SAW resonators and delay lines is summarized on Table 6-1. Table 6-2 is a similar comparison between oscillators implemented with these devices. As a matter of interest, bulk crystal devices and oscillators are also included.

Table 6-1. Comparison Between SAW Delay Line Oscillator, One-Port SAW Resonator Oscillator, Two-Port SAW Resonator Oscillator and Bulk Crystal Oscillator

| DEVICES | FREQUENCY RANGE | BANDWIDTH | INSERTION LOSS | Q | SPURIOUS MODES | MATERIAL AND FABRICATION | UNIT COST FOR LARGE QUANTITIES |
|---|---|---|---|---|---|---|---|
| SAW DELAY LINE | 20 MHz-2 GHz | 0.02 ~ 12% | ≈12 dB* | 200-5000 | GOOD | ST-CUT QUARTZ PHOTOLITHO-GRAPHIC TECHNIQUE | $ 45 |
| ONE-PORT SAW RESONATOR | 30 MHz-800 MHz | 0.005 ~ 0.16% | ~1 dB-8 dB | 600-20,000 | EXCELLENT | ST-CUT QUARTZ MULTI STEP PROCESS PLASMA GROOVING | $245 |
| TWO-PORT SAW RESONATOR | 30 MHz-800 MHz | 0.01 ~ 0.33% | ~2 dB-12 dB | 300-10,000 | GOOD | ST-CUT QUARTZ MULTI STEP PROCESS PLASMA GROOVING | $245 |
| BULK CRYSTAL | <40 MHz | 0.00005 ~ 0.02% | <2 dB | 5000-2,000,000 | POOR | AT-CUT QUARTZ | $ 40 |

*UNIDIRECTIONAL TRANSDUCERS WOULD REDUCE THIS VALUE BY ABOUT 6 dB

Table 6-2. Comparison Between SAW Delay Line Oscillator, One-Port SAW Resonator Oscillator, Two-Port SAW Resonator Oscillator and Bulk Crystal Oscillator

| DEVICES | FREQUENCY RANGE | DC TO RF EFFICIENCY | SHORT TERM STABILITY | MEDIUM TERM STABILITY | LONG TERM STABILITY | FREQUENCY SET ABILITY | MATERIAL AND FABRICATION | UNIT COST FOR LARGE QUANTITIES |
|---|---|---|---|---|---|---|---|---|
| SAW DELAY-LINE OSCILLATOR | 20 MHz-2 GHz | 7.5% ** | GOOD ** | GOOD | GOOD | GOOD | ST-CUT QUARTZ PHOTOLITHO-GRAPHIC TECHNIQUE | $150 |
| ONE-PORT SAW RESONATOR OSCILLATOR | 30 MHz-800 MHz | 20% | EXCELLENT | GOOD | UNKNOWN (PROBABLY GOOD) | POOR | ST-CUT QUARTZ MULTI STEP PROCESS PLASMA GROOVING | $350 |
| TWO-PORT SAW RESONATOR OSCILLATOR | 30 MHz-800 MHz | 15% | EXCELLENT | GOOD | UNKNOWN (PROBABLY GOOD) | FAIR | ST-CUT QUARTZ MULTI STEP PROCESS PLASMA GROOVING | $350 |
| BULK CRYSTAL OSCILLATOR | 40 MHz | 2.5% * | EXCELLENT | EXCELLENT | EXCELLENT | POOR | AT-CUT QUARTZ | $600 * |

* INCLUDES MULTIPLICATION

** THE USE OF UNIDIRECTIONAL TRANSDUCERS WOULD IMPROVE BOTH THE DC TO RF EFFICIENCY AND THE SHORT TERM STABILITY

1. F.G. Marshall, "Surface Acoustic Wave Resonators Constructed of Aluminum on ST Quartz for Use in High Stability Feed Back Oscillators," 1975 IEEE Ultrasonic Symposium, Los Angeles, California, September 22-24, 1975.

2. P. Hartemann, "Acoustic Surface Wave Resonator Using Ion-Implanted Gratings," 1975 IEEE Ultrasonic Symposium, Los Angeles, California, September 22-24, 1975.

3. J.S. Schoenwald, R.C. Rosenfeld, and E.J. Staples, "Surface Wave Cavity and Resonator Characteristic-VHF to L-Band," 1974 IEEE Ultrasonic Symposium, Milwaukee, Wisconsin, November 1974.

4. J.S. Schoenwald, W.R. Shreve, and R.C. Rosenfeld, "Surface Acoustic Wave Resonator Development," Proc. of 29th Annual Frequency Control Symposium, May 28-30, 1975.

5. R.C.M. Li, J.A. Alusow, and R.C. Williamson, "Experimental Exploration of the Limits of Achievable Q of Grooved Surface-Wave Resonators," 1975 IEEE Ultrasonic Symposium, Los Angeles, California, September 22-24, 1975.

6. S.P. Miller, R.E. Stigall, and W.R. Shreve, "Plasma Etched Quartz Resonator," 1975 IEEE Ultrasonic Symposium, Los Angeles, California, September 22-24, 1975.

7. M.F. Lewis, "The Surface Acoustic Wave — A Natural and Timely Development of the Quartz Crystal Oscillator," Proc. of the 28th Annual Frequency Control Symposium, May 1974.

8. I. Browning, J. Crabb, and M.F. Lewis, "A SAW Frequency Synthesizer," 1975 IEEE Ultrasonic Symposium, Los Angeles, California, September 22-24, 1975.

9. K.M. Lakin and T.R. Joseph, "Surface Wave Resonators," 1975 IEEE Ultrasonic Symposium, Los Angeles, California, September 22-24, 1975.

# 7. THE IMPACT OF SAW OSCILLATORS ON MICROWAVE SYSTEMS

Surface acoustic wave oscillators offer some apparent advantages when substituted for conventional oscillators in many electronics systems. TRW has, as part of the current contract work, made a detailed examination of several microwave systems to quantify the impact of the SAW oscillators, both in terms of cost and performance. The systems which served as subjects for this study were selected by mutual agreement of NELC and TRW and include SEEKBUS/ITACS, GPS, and FLTSATCOM.

The impact of the SAW oscillator technology is assessed in a 1978 time frame under the assumption that the technology will by that time be reasonably mature. The impact is first addressed at the subsystem level, and this information is used to determine the system level impact. This section is organized as follows: Section 7.1 discusses the various subsystems which can be configured using SAW oscillators, Section 7.2 gives the impact for the above mentioned systems, and the conclusions are given in Section 7.3.

## 7.1 SUBSYSTEM APPLICATIONS OF SAW OSCILLATORS

The general approach for the study at the subsystem level has been to consider operating at ≈ 500 MHz and to a set of specifications which are of the commercial application type. Comparisons are made between the SAW subsystem and the best alternative implementation, both projected to 1978. The prices quoted are in today's dollars. In each case it will be seen that the small quantity price for the SAW approach is considerably higher. This primarily reflects the cost of producing the mask from which the SAW delay line is fabricated. When this cost can be amortized over a moderate number of delay lines, it will be seen that the cost of the SAW approach drops below that of the conventional approach. The phase noise performance is based on measurements conducted at TRW. The same measurement equipment was used for measurements of both the SAW and the conventional circuits. The absolute accuracy of the results is ≈ 2-3 dB, and the relative accuracy is a few tenths of a dB.

### 7.1.1 Fixed Frequency Sources

The primary application of a SAW oscillator is as a low noise, highly stable fixed frequency source. The chief advantage of the SAW oscillator is its high fundamental frequency of operation as compared against a bulk crystal oscillator. As a method of quantifying the impact of SAW oscillators at the subsystem level, an arbitrarily chosen requirement for a 500 MHz frequency source was taken to provide a basis for comparing several alternative oscillator implementations. The best conventional implementation is a bulk crystal oscillator followed by a frequency multiplier chain as shown in Figure 7-1. The crystal oscillator operates at 20 MHz and is followed by an amplifier and a X5 frequency multiplier. The bandpass filter at 100 MHz is one of the key elements in this circuit. If it does not provide sufficient rejection of the fourth and sixth harmonics in particular, intermodulation products formed in the second X5 multiplier will lead to outputs at 480 MHz and/or 520 MHz which can cause serious problems in the system's operation. If the system is a receiver, for example, it is entirely possible for the receiver to lock on one of the spurious outputs and in effect to be totally disabled.

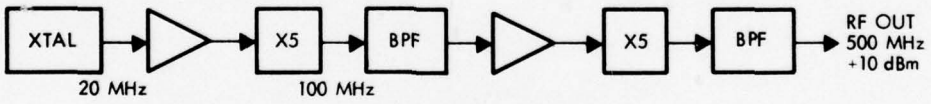



Figure 7-1. Conventional 500 MHz Frequency Source

As the block diagram shows, the 100 MHz output is again amplified, multiplied and filtered to provide the desired output. The amplifiers are included primarily to compensate for the conversion loss of the frequency multipliers, typically 6 to 7 dB each.

#### Free Running SAW Oscillators

There are three SAW oscillator approaches which can provide a frequency source at 500 MHz whose performance is in several respects improved over the conventional approach. The most straightforward design is shown in Figure 7-2. The SAW delay line is used as the feedback element providing positive feedback to the amplifier. The amplifier gain must be sufficient to compensate for the SAW's insertion loss, about 16 dB at 500 MHz using

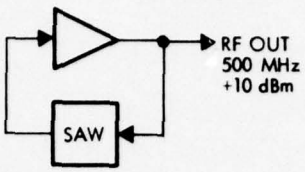



Figure 7-2. Free Running SAW Oscillator

TRW's current design, and to provide the 10 mW output. Because the SAW oscillator operates directly at 500 MHz the problem of spurious outputs close to the desired frequency is entirely avoided. There will be low level harmonically related outputs which can be easily filtered out because of their wide separation from the desired output.

The pertinent performance parameters for any frequency source are output frequency and power, phase noise, long term frequency stability, frequency dependence on temperature, size, weight, and DC power or DC to RF efficiency. All frequency sources considered in Section 7.1 are designed to the same frequency and power output, and will exhibit the same temperature performance. The temperature dependence is the same whether the oscillator is a bulk-effect or SAW oscillator, because in either case it is determined by the temperature coefficient of quartz.

The free running SAWO exhibits phase noise performance which is superior to that of the conventional source by a factor of approximately 4 dB at any offset frequency. The phase noise of the SAWO is inversely proportional to the square of the Q of the SAW delay line, which can be made higher by increasing the center to center separation of the input and output transducers. The 4 dB advantage for the SAWO's phase noise performance is based upon a center to center transducer separation of 500 wavelengths, as per TRW's current design. The SAWO's DC to RF efficiency is better than that of the conventional source by a factor of seven, and its size and weight are less by a factor of about 16. Estimated values for these parameters are tabularized after the discussion of the other two types of SAW sources.

The chief disadvantage of the free running SAWO as compared with the conventional source relates to its long term frequency stability. The SAWO's output frequency changes at a rate of about three parts per million per month (PPM/M). This is apparently due to aging effects in the SAW

delay line. The causes of the aging were discussed in previous sections. There are two oscillator configurations which can be used to improve SAW oscillator long term stability, if improvement is required.

Phase-Locked SAW Oscillators

Figure 7-3 shows a block diagram for a SAW oscillator whose long term frequency stability is improved by phase-locking it to a low frequency bulk crystal oscillator. The SAW frequency is divided to the frequency of the bulk crystal where the phase comparison takes place. The phase-locked loop in effect replaces the multiplier chain in the conventional source. The SAWO is made tunable by introducing an electrical phase shifting element such as a varactor diode into the feedback loop. This scheme has the advantage of giving the SAWO the long term stability of the bulk crystal oscillator while retaining the phase noise performance of the SAWO. The phase noise performance is retained because the introduction of the phase locked loop does not effect the Q of the SAW delay line, and because of the relatively slow rate at which the SAWO can be tuned. The phase locked SAWO has the disadvantage of requiring extra hardware and DC power when compared to the free running SAWO, but it is still smaller and more efficient than the conventional source. The third SAWO design will be seen to require less hardware, although it is a slightly higher risk approach.

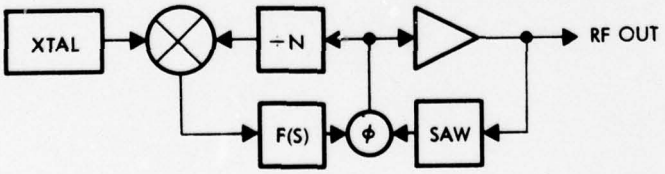



Figure 7-3. Phase-Locked SAW Oscillator

Subharmonically Injection-Locked SAW Oscillator

In the design shown in Figure 7-4, the 20 MHz crystal oscillator drives a step recovery diode (SRD) impulse generator, the output of which is a comb of frequencies at intervals of 20 MHz. The SAW delay line has three transducers, the first two of which serve as a narrowband, high Q band-pass filter at 500 MHz. The second and third transducers serve as the

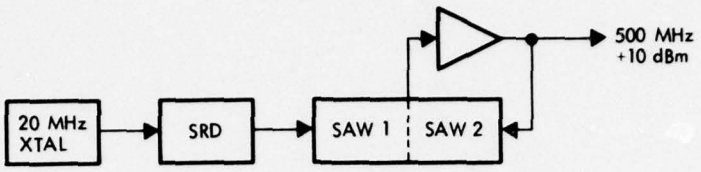



Figure 7-4. Subharmonically Injection-Locked SAW Oscillator

normal delay line in the amplifier's feedback loop. The 500 MHz line is selected from the comb by the first two transducers and injection locks the SAWO. This design approach has advantages similar to those of the phase locked SAWO. Namely, the phase noise performance would be as good as that of the free running SAWO, and the long term stability would be the same as that of the bulk crystal. Although the hardware is simpler, the risk is somewhat higher because of uncertainty about the rejection of the unwanted comb frequencies. It should be possible to provide at least 80 dB of rejection with careful design of the three transducers, but the design is as yet untried.

Subsystem Level Tradeoffs

The performance of the four oscillator types is summarized in Table 7-1. Based on the table, the free running SAW oscillator would be the best choice if the somewhat poorer long term stability can be tolerated. The stability of 3 PPM/month is perfectly adequate in, for example, doppler radar applications where short term stability and phase noise are the key concerns. For use in a communication system where improved long

Table 7-1. Comparison of 500 MHz Oscillators

| PARAMETER / APPROACH | PHASE NOISE dBc/Hz AT $f_m$ = 100 KHz | LONG TERM STABILITY | DC TO RF EFFICIENCY | SIZE AND WEIGHT |
|---|---|---|---|---|
| XTAL XN | 150 dB | 0.1 PPM/MONTH | 2.5% | 8 CU IN. 0.4 LBS |
| FREE RUNNING SAW OSCILLATOR | 154 dB | 3 PPM/MONTH | 7.5% | 0.5 CU IN. 0.05 LB |
| PHASE LOCKED SAW OSCILLATOR | 154 dB | 0.1 PPM/MONTH | 5% | 1 CU IN. 0.05 LB |
| INJECTION LOCKED SAW OSCILLATOR | 154 dB | 0.1 PPM/MONTH | 5% | 1 CU IN. 0.05 LB |

term stability is required, the best choice would be the injection-locked SAWO. The difference between the last two oscillators is not clear from the table, but Figures 7-3 and 7-4 show that the injection-locked SAWO is simpler than the phase locked SAWO.

The remaining factor important in establishing the necessary trade-offs at the subsystem level is cost. The cost per oscillator as a function of the number of oscillators fabricated is shown graphically for the four types in Figure 7-5. The cost estimates are based on a constant manufacturing cost once the initial engineering model is complete. This situation is likely to be closely approximated within a couple of years by any company which engages in the manufacture of SAW devices on a regular basis. As the graph shows, in spite of the high cost of making the mask for the SAW device, the SAW oscillators are less expensive after a surprisingly small number of units have been produced.

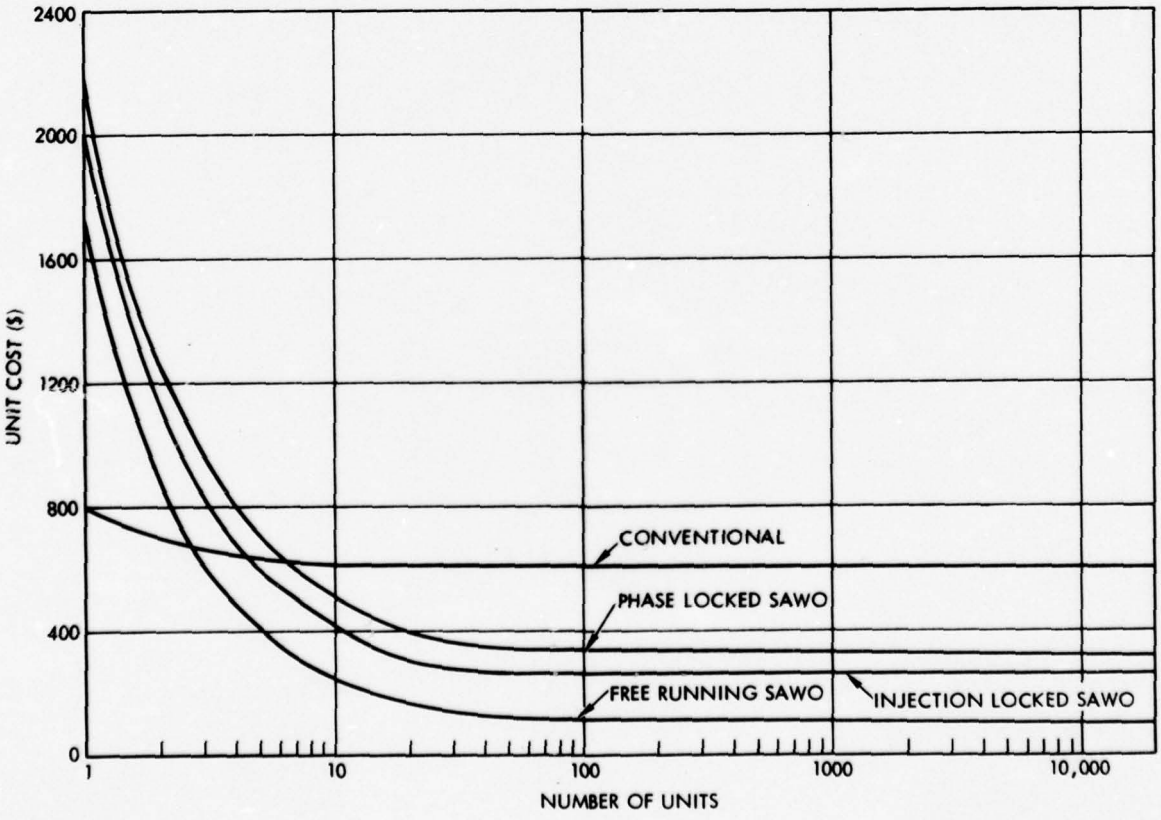



Figure 7-5. Oscillator Unit Cost vs Number of Units Required

### 7.1.2 Additional SAWO Applications

It is possible to use SAW devices to perform more than one circuit function by adding additional transducers to the basic two required for the delay line. Two applications of SAW devices are presented here to illustrate the circuit simplifications which can be realized when SAW devices are employed. The first such application combines elements of a SAW oscillator and a phase or frequency detector on the same quartz substrate. This is shown schematically in Figure 7-6 along with the conventional approach to such a circuit. When the SAW frequency and the RF input frequency are the same, the inputs are summed by superposition in the output transducer producing an output whose amplitude is inversely proportional to the phase difference between the inputs. If the inputs are sin ($\omega t$) and sin ($\omega t+\phi$) then the output is given by

$$\text{output} = \sin(\omega t) + \sin(\omega t+\phi) \tag{7.1}$$

$$\text{output} = 2 \sin[1/2\ (2\ \omega t+\phi)] \cos(1/2\ \phi) \tag{7.2}$$

$$\text{output} = 2 \sin(\omega t+\phi) \cos(\phi/2) \tag{7.3}$$

thus the output amplitude is 2 cos ($\phi/2$) which can be amplitude detected and utilized in, for example, a phase-locked loop circuit. If the two inputs are different in frequency then

$$\text{output} = \sin \omega_1 t + \sin \omega_2 t \qquad \omega_1 \neq \omega_2 \tag{7.4}$$

$$\text{output} = 2 \sin[1/2\ (\omega_1 t + \omega_2 t)] \cos[1/2\ (\omega_1 t - \omega_2 t)] \tag{7.5}$$

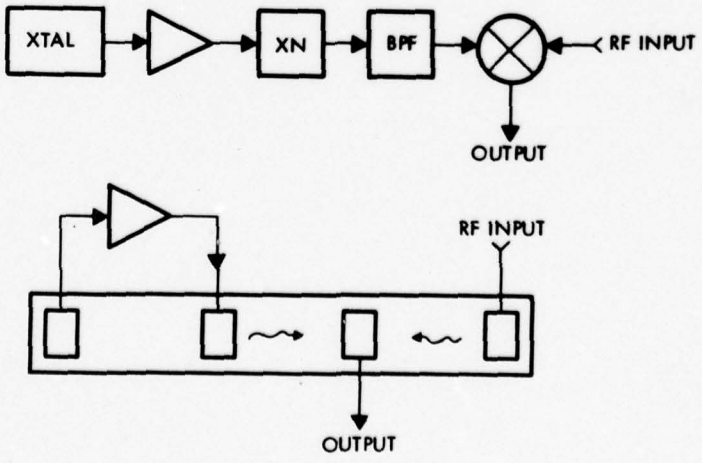



Figure 7-6. Phase Detector/Frequency Discriminators

Now assume that $\omega_1$ and $\omega_2$ are both relatively close to the transducer's center frequency ($\omega_0$) so that

$$\frac{\omega_1 + \omega_2}{2} \simeq \omega_o \tag{7.6}$$

$$\frac{\omega_1 - \omega_2}{2} = \frac{\Delta\omega}{2} \tag{7.7}$$

The output can then be written as

$$\text{output} \simeq 2 \sin(\omega_0 t) \cos\left(\frac{\Delta\omega t}{2}\right). \tag{7.8}$$

The output amplitude will vary sinusoidally at a frequency equal to half the difference of the two input frequencies. Thus the circuit can also be used as a frequency discriminator. The addition of the two additional transducers to the SAW delay line adds very little to the size required for the SAW oscillator. The addition of a conventional double-balanced mixer would, on the other hand, represent a significant increase in the size and weight.

Another circuit simplification which can result from including additional elements on the SAW delay line occurs in the fabrication of an oscillator/BPSK modulator circuit. Two possible approaches to this circuit are shown in Figure 7-7. The conventional circuit uses a double balanced mixer as the phase modulator. It is possible, instead, to put two output transducers on the delay line which differ in phase by 180°. An external switch can select between the two phases in response to the incoming data stream. Again, the additional transducers require much less additional size and weight than the double balanced mixer.

While not enough is known about either of these two SAW circuits to adequately predict their performance, it is reasonable to assume that they can be made to work as well as the conventional circuits. Their size and weight should be less than 10% that of the alternative circuits and the quantity cost reduction similar to that for the free running SAW oscillator.

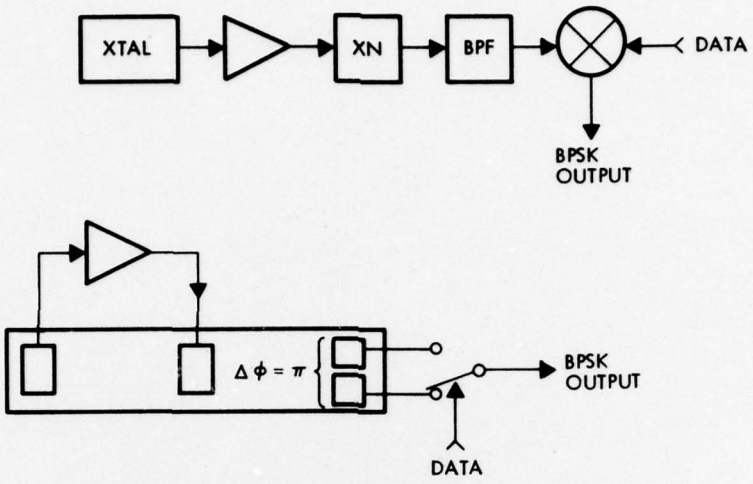



Figure 7-7. Biphase Modulator Circuits

The purpose of describing these two circuits is to illustrate the way in which circuit functions can be combined on the SAW delay line to give an overall savings even greater than the savings associated with the oscillator alone. The cost of adding these circuit functions adds to the cost of the fabricating the basic delay line only to the extent that the yield is affected. This factor is not expected to be significant.

## 7.2 SYSTEM IMPACT OF SAW OSCILLATORS

The impact of SAW oscillators has been evaluated for the systems previously listed. This section discusses the SEEKBUS/ITACS system in some detail so that the methodology will be made explicit. The results for the FLTSATCOM and GPS systems will be summarized much more briefly, but the study was carried out in the same way for all of the systems. The cost comparisons are made on a per unit basis, and it is left to NELC to determine the total savings based on the total number of units required.

### 7.2.1 SEEKBUS/ITACS

The SEEKBUS/ITACS terminal baseline design contains two subsystems which could be implemented with SAW oscillators: a frequency synthesizer and a frequency division multiplex tone generator. The following discussion gives sufficient detail about the current design so that it will be clear that the implementation of these subsystems with SAW oscillators will completely satisfy the system requirements.

## Frequency Synthesizer

The SEEKBUS/ITACS frequency syntehsizer is required to provide coverage of the 1.152 to 1.407 GHz frequency range in commandable steps of 1 MHz at a power level of +10 dBm. The synthesizer is required to settle to the commanded frequency from any other frequency in less than 20 μsec. The currently proposed design (Figure 7-8) is an indirect second order phase locked loop. The loop bandwidth is set at 120 KHz to meet the settling time requirement, and the loop gain is normalized over its tuning range to provide uniform loop characteristics. There is also a slew aiding circuit which slews the loop at a much higher rate during the nonlinear acquisition mode.

The loop feedback is accomplished by first mixing down to the 42 to 297 MHz range, and then dividing to 3 MHz via programmable dividers. The frequency commands are given by controlling the division ratio in response to a pseudo random number (PRN) sequence from the PRN generator. The basic output step size is equal to the reference frequency (3 MHz), and fine tuning is accomplished by choosing between 1.109, 1.110, and 1.111 GHz at the mixer L.O. input.

The estimated size of the currently proposed design is 200 cubic inches, based on the known size of its various components. The DC power requirement is approximately 2 watts, and the large quantity cost is expected to be $3500.

An alternative to the indirect synthesizer discussed above is a direct synthesizer technique. Figure 7-9 shows a proposed design for a direct synthesizer implemented with SAW oscillators. There are four SAWO's operating at 867.39 MHz, 931.39 MHz, 995.39 MHz, and 1059.39 MHz respectively. A total of 12 other frequencies are generated by dividing the outputs of the SAWO's by 4, 16 and 64. The output frequencies are derived by combinations of sums of these 16 basic frequencies, the summing being accomplished in three double balanced mixers (DBM's). The selection of the output frequency is made by means of the single pole four throw switches.

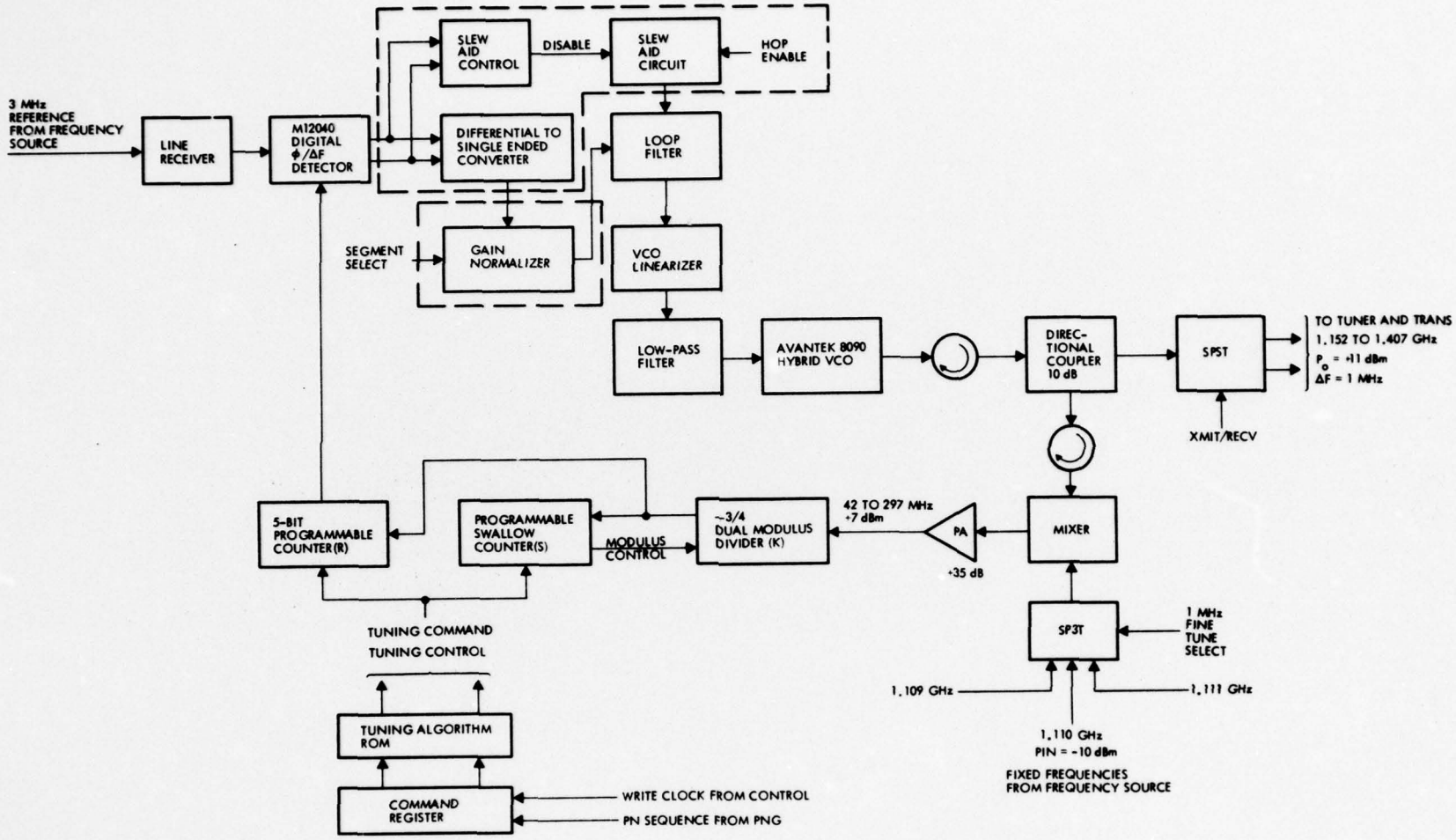



Figure 7-8. SEEKBUS/ITACS Synthesizer (Indirect)

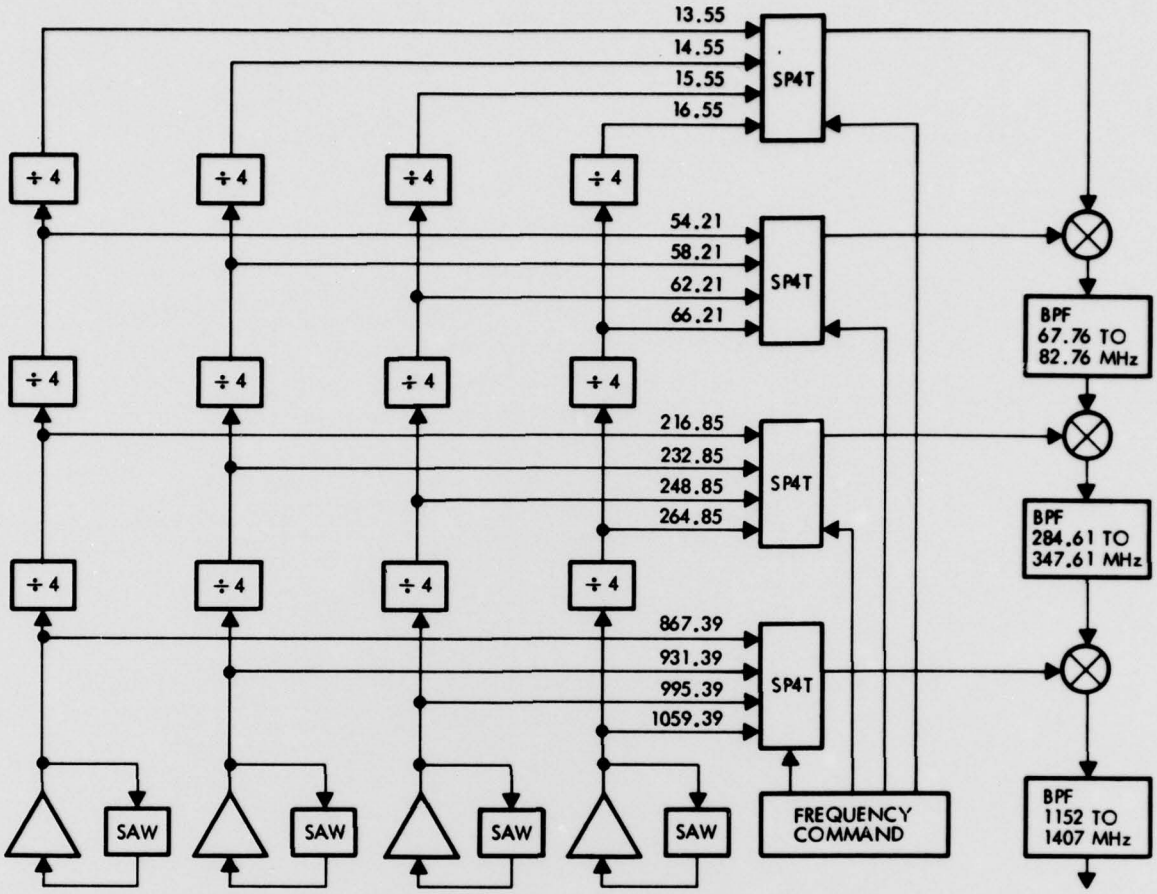



Figure 7-9. SAW Direct Synthesizer for SEEKBUS/ITACS

Although there appear to be more blocks on the block diagram of Figure 7-9 than that of Figure 7-8, in fact a substantial simplification has been achieved. All four of the SAW delay lines would share a common substrate and would use identical amplifiers. The four SAWO's would be housed in a common package whose size would be about 2 cubic inches, and whose DC power requirement would be about 300 mW. The frequency dividers would be Plessey SP8600A's which are packaged in 8-lead TO-5 cans and require 160 mW of DC power each.

The switch modules would be of the Alpha MT3854 type, which are TTL compatible, have a volume of 0.5 cu. inches, and require 15 mW of DC power. Diode switches of this type have a switching speed of less than 50 nanoseconds. The double balanced mixers would be similar in size, but require no DC power.

The total size of the SAW direct synthesizer, again based on the known size of its components, is estimated to be 20 cubic inches. The total DC power requirement is 2.8 watts, and the settling time would be less than 100 nanoseconds. Table 7-2 summarizes the parameters of the two frequency synthesizer approaches.

Table 7-2. SEEKBUS/ITACS Synthesizer Alternatives

| PARAMETER | INDIRECT SYNTHESIZER | SAW DIRECT SYNTHESIZER |
|---|---|---|
| FREQUENCY RANGE | 1152 TO 1407 MHz | 1152 TO 1407 MHz |
| STEPSIZE | 1 MHz | 1 MHz |
| POWER OUTPUT | +10 dBm | +10 dBm |
| SETTLING TIME | 18 μSEC | 0.1 μSEC |
| SIZE | 200 CU IN. | 20 CU IN. |
| WEIGHT | 10 LBS | 1 LB |
| DC POWER | 2 WATTS | 2.8 WATTS |

It is seen that, for equivalent RF performance, the SAW direct synthesizer is considerably smaller, lighter and faster, but requires 40% more DC power. The additional power is not significant to the total system, but the size savings is. The large quantity cost of the indirect synthesizer is currently estimated at about $3500. The SAW direct synthesizer cost in large quantities should be about $2300. Two things are responsible for the cost savings: the parts cost is lower ($1600 versus $1925) and the assembly and test time is much lower. Tracing any signal path from source to output it is seen that the circuitry is much simpler in the SAW direct synthesizer than in the indirect synthesizer. The phase-locked loop in the indirect synthesizer is much more difficult to tune, particularly considering the wide output bandwidth, than any of the circuitry in the direct synthesizer. This accounts for the primary difference in cost between the two approaches.

Frequency Division Multiplex (FDM) Tone Generator

The SEEKBUS/ITACS tone generator is required to generate two sets of frequencies in the 210 to 580 MHz range. The first set consists of 10 tones at 20 MHz intervals from 210 MHz to 390 MHz. The second set of 10 tones are placed at 20 MHz intervals from 400 MHz to 580 MHz.

The currently proposed block diagram for the tone generator is shown in Figure 7-10. The step recovery diode comb generator produces a spectral line at each multiple of its driving frequency. The comb generator output is amplified and prefiltered in a broadband bandpass filter. Next there is a bank of narrowband bandpass filters centered at each desired frequency, followed by a separate amplifier for each tone. In the presently proposed scheme, there are 20 narrowband filters, 20 narrowband amplifiers, two broadband filters and amplifiers, two comb generators and one divide-by-two frequency divider. Since all tones must be continuously present, all amplifiers must be continuously powered, but

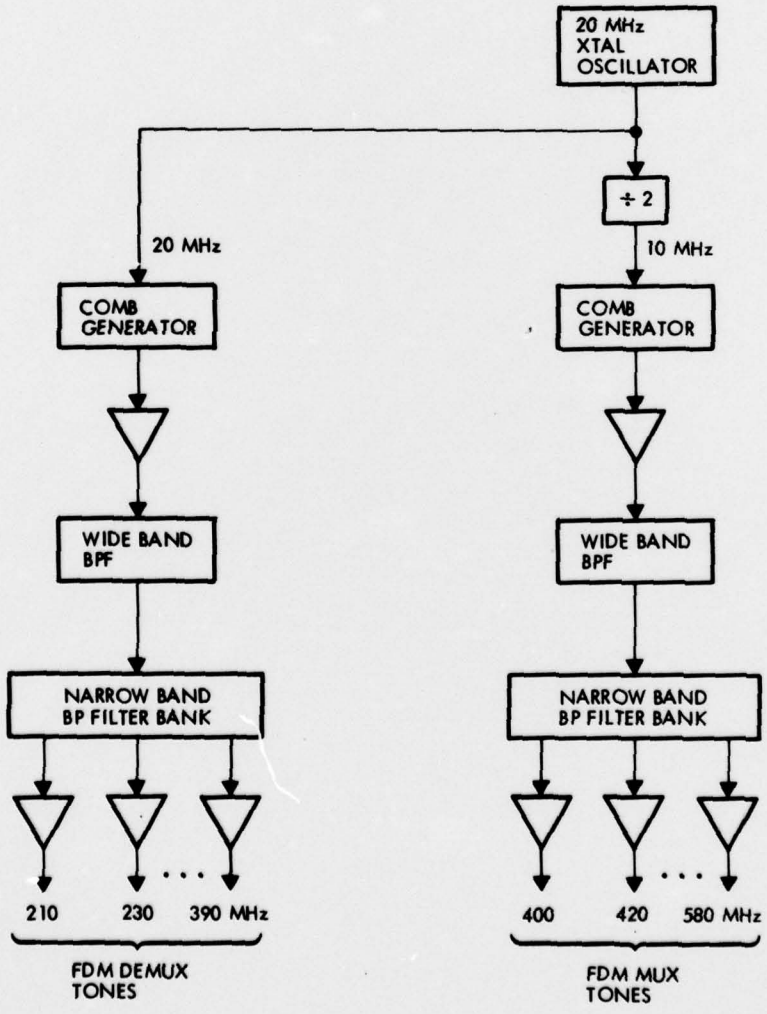



Figure 7-10. SEEKBUS/ITACS Tone Generators

no switching matrix is required. The output amplifiers would deliver to 10 mW of RF power each and would operate at an efficiency of about 10%, requiring 2.0 watts. The amplifiers immediately following the comb generators are wideband and must be operated in a linear mode to avoid intermodulation problems. These two amplifiers would require a minimum of .3 watts each of DC power. The frequency divider would require 160 mW DC power, and the crystal oscillator about 200 mW. Thus the total DC power requirement for the block diagram of Figure 7-10 is 2.96 watts. The size of this tone generator would be about 40 cubic inches, the weight about 2 pounds, and the large quantity cost about $6000.

Considerable savings can be realized if the SEEKBUS/ITACS tone generator is implemented with SAW oscillators instead. The block diagram would consist of 20 separate SAWO's, each like the one shown in Figure 7-2. The DC to RF efficiency of these oscillators is somewhat dependent on the operating frequency, but would average about 10%. A total of 2.0 watts would be required for the tone generator. The size would be a maximum of 10 cubic inches and the weight a maximum of 0.5 pounds. Further reductions in size and weight could be achieved by fabricating several SAW delay lines on each quartz substrate, but at the risk of insufficient isolation between the outputs. Table 7-3 summarizes the performance of the SEEKBUS/ITACS tone generators. As in the frequency synthesizer, the chief savings is in size, weight and cost. The cost of the SAW approach is based on a cost of $100 per oscillator plus $500 for packaging the required twenty into a common housing. If more than one delay line can be fabricated on each quartz substrate, the cost would be even less.

Table 7-3. SEEKBUS/ITACS Tone Generator Comparison

| PARAMETER | COMB GENERATOR TONE GENERATOR | SAW OSCILLATOR TONE GENERATOR |
|---|---|---|
| FREQUENCY RANGE | 210 TO 580 MHz | 210 TO 580 MHz |
| NO. OF TONES | 20 | 20 |
| OUTPUT POWER/TONE | +10 dBm | +10 dBm |
| SIZE | 40 CU IN. | 10 CU IN. |
| WEIGHT | 2 LBS | 0.5 LB |
| DC POWER | 2.96 WATTS | 2.0 WATTS |
| COST (LARGE QUANTITY) | $6000 | $2500 |

### 7.2.2 GPS Receivers

A simplified block diagram of the GPS receiver is shown in Figure 7-11. There are a number of alternative ways in which this receiver can be configured. For example, the code correlation could be done prior to the A/D converter, but regardless of the configuration, the RF front end must contain a frequency generator which provides two L-band outputs and a clock signal for the code generator, all of which are coherent with a reference oscillator at approximately 5 MHz. The conventional implementation of the frequency generator is shown in Figure 7-12. The complexity of this frequency generator arises from the fact that the two RF output frequencies must be coherent, but they have no common factors (other than the reference frequency) larger than four. Where, on Figure 7-12, two frequencies or division or multiplication ratios are shown at a particular point, the numbers on the left are used for $L_1$, the higher output frequency, and those on the right are used for the lower output frequency.

The size of the circuitry shown in Figure 7-12 is estimated to be about 30 cubic inches, the weight 1.5 pounds, and the DC power requirement about 2.5 watts. The large quantity cost of this frequency generator is about $4500.

Figure 7-13 shows the way in which the required frequencies could be generated using surface acoustic wave oscillators. The basic circuit is a frequency divider phase locked loop as in Figure 7-3. With all the switches in the position shown, the voltage controlled SAWO operates at 378.5 MHz. Part of its output drives a times four frequency multiplier to provide $L_1$ (1514 MHz).

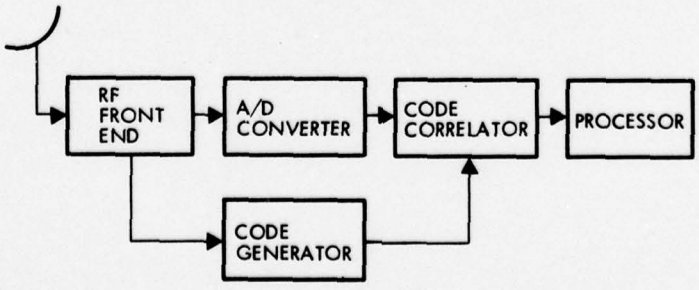



Figure 7-11. Global Position System Receiver

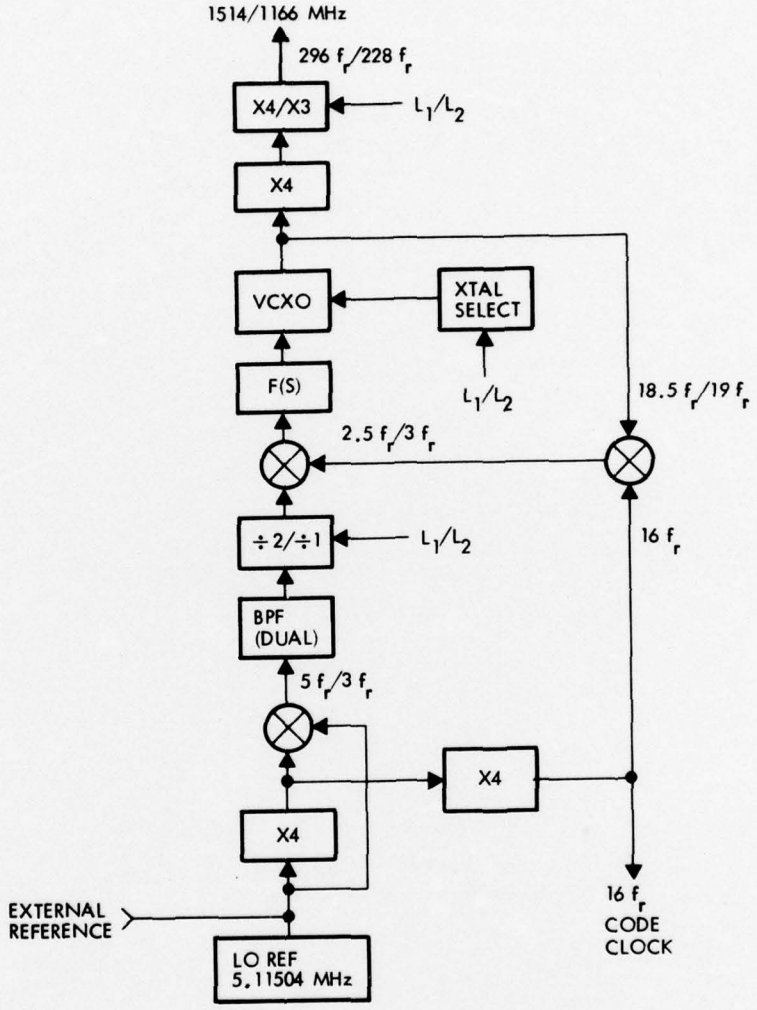



Figure 7-12. Conventional Implementation of Frequency Synthesizer

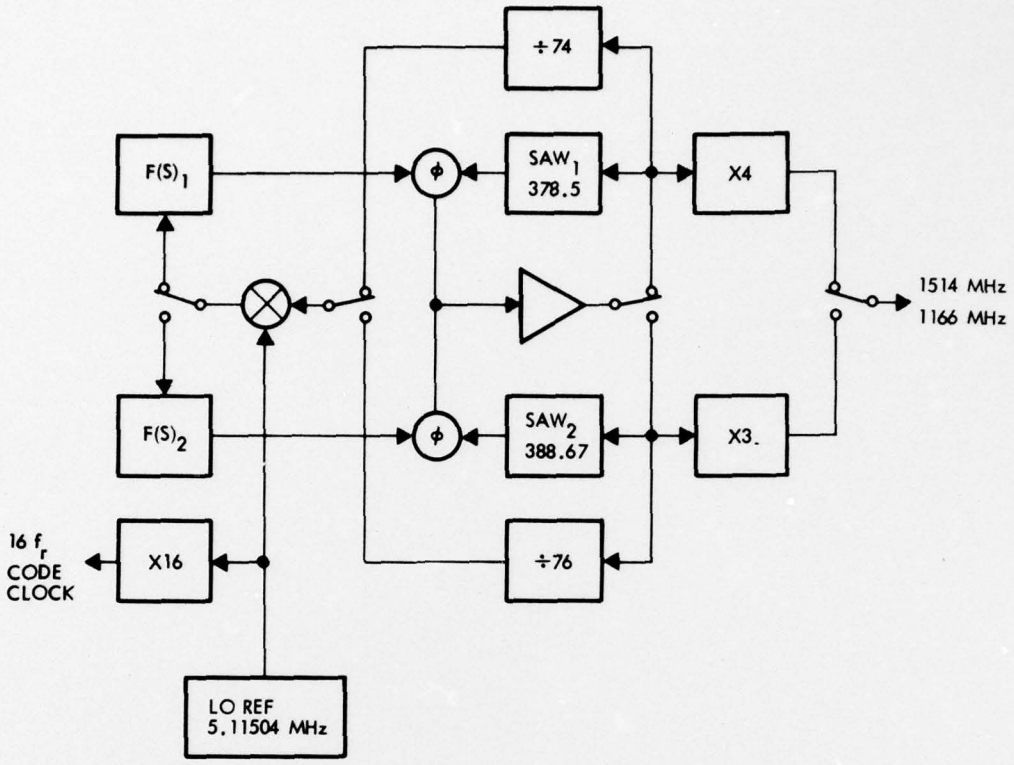



Figure 7-13. SAW Implementation of GPS Frequency Synthesizer

The other portion of the output of SAW is divided to the reference frequency in two steps (÷2, ÷37). Phase detection is accomplished at the reference frequency by a double balanced mixer. The mixer's output is scaled by F(S) (a loop filter) to keep the VCO phase coherent with the 5 MHz reference. If all the switches are moved to the lower positions, the second output frequency (1166 MHz) is produced in a very similar fashion. The lower SAW delay line is at nearly the same frequency as $SAW_1$, and so it is perfectly reasonable to use the same amplifier for both voltage controlled SAWO's. The division of the output of $SAW_2$ is again accomplished in two steps, ÷4 and ÷19. Both of the frequency dividers require division by relatively large prime numbers. While neither a ÷19 nor a ÷37 is commercially available, and a special design would be required, they can be fabricated in exactly the same way as commercially available dividers, and pose no particular difficulties.

The size of the SAW implementation of the GPS frequency generator is estimated to be about 9 cubic inches, and the weight less than one half pound. The DC power requirement would be about 0.9 watts, and the cost in large quantities would be less than $2000 each. Table 7-4 summarizes the pertinent parameters for the conventional and SAW frequency generators. It is seen that the SAW approach leads to a substantial reduction in size, weight, power and cost. Further, the phase noise performance of the SAW frequency generator should be about 4 dB better, and since no more than four frequencies are ever present at one time, there will be fewer problems with spurious outputs. In the conventional approach as many as eight different frequencies may be present within the circuitry and this could pose filtering problems.

Table 7-4. GPS Frequency Generator Alternatives

| PARAMETER | CONVENTIONAL | SAW |
|---|---|---|
| OUTPUT FREQUENCIES | 81.8, 1166, 1514 MHz | 81.8, 1166, 1514 MHz |
| OUTPUT POWER | +10 dBm | +10 dBm |
| SIZE | 30 CUBIC INCHES | 9 CUBIC INCHES |
| WEIGHT | 1.5 POUNDS | 0.5 POUNDS |
| DC POWER | 2.5 WATTS | 0.9 WATTS |
| LARGE QUANTITY COST | $4500 | $2000 |

### 7.2.3 FLTSATCOM

The Satellite Broadcast System (SBS) has two types of frequency sources which could be implemented with SAW oscillators. SBS communications links include satellite to ground and ground to satellite channels at SHF, and a satellite to user channel at UHF. The SHF channels have frequency sources which are currently derived from temperature compensated crystal oscillators (TCXO's) operating at about 5 MHz, followed by long multiplier chains. The SHF uplink and downlink frequency need not be phase coherent with the SHF frequencies, and is at about 300 MHz.

First addressing the SHF sources, Figure 7-14 shows a block diagram of a typical frequency multiplier chain to accomplish the frequency translation from 5 MHz to 500 MHz. Both of the SHF frequencies must be

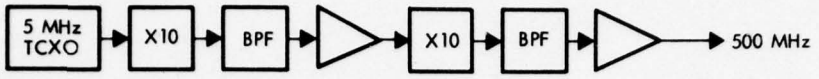



Figure 7-14. Conventional Ultra-Stable 500 MHz Source

generated in both the satellite and the ground station, as one is required to receive and the other to transmit. The highest common denominator of these two frequencies is around 500 MHz. The long term frequency stability requirement for the 500 MHz source is beyond that currently projected for free running SAW oscillators, and so the phase-locked SAW oscillator is selected as the best alternative to the conventional source. The block diagram is exactly like that shown in Figure 7-3, with N, the division ratio, being equal to 100. The SAWO is essentially used as a VCO operated in a frequency divider phase-locked loop. It would not, however, be feasible to substitute a conventional transistor VCO, as it would not approach the phase noise performance of the SAW VCO. The performance of the conventional and SAW approaches to the 500 MHz frequency source are summarized in Table 7-5. Not tabularized, but also of importance, is the freedom from spurious outputs of the SAW approach. Since the spurs from the transmit frequency, using the conventional approach, would fall into the receive band, the filter requirements for the conventional approach are stringent. The frequency divider phase-locked source will generate no spurs.

Table 7-5. Comparison of Conventional and SAW Sources for FLTSATCOM

| PARAMETER | CONVENTIONAL | SAW |
|---|---|---|
| OUTPUT FREQUENCY | 500 MHz | 500 MHz |
| POWER OUT | +10 dBm | +10 dBm |
| PHASE NOISE dBc/Hz AT $f_m$ = 100 KHz | 150 dB | 154 dB |
| DC POWER | 300 MW | 200 MW |
| SIZE/WEIGHT | 3 CU IN./0.15 LB | 1 CU IN./0.05 LB |
| COST (LARGE QUANTITY) | $550 | $300 |

The UHF sources (300 MHz) appear in the satellite and in the receivers of all the users. The conventional implementation of the 300 MHz source is similar to that shown in Figure 7-14, with the following exceptions. The source need not be as stable as that used for the SHF, therefore, the reference oscillator would be at 20 MHz rather than 5 MHz. The appropriate multiplication ratio is 15 and would again be accomplished in two steps, this time a X5 followed by a X3.

The requirements for the UHF source are such that the performance of a free running SAW oscillator would be adequate. That being the case, the chief advantage would be in cost. The size and weight savings aren't particularly important where the user is a ship, and not very significant even for an aircraft, but considering the large number of UHF receivers, the cost savings are significant. The cost of the free running SAW oscillators would be about $100 each, compared to about $500 each for the conventional sources.

The impact of the SAW technology upon the SBS is seen to be two-fold. The satellite in particular is benefitted by the reduction in size and weight, as well as improved performance. The users of the UHF transmission benefit chiefly from cost reductions, performance being about the same and size and weight savings being relatively unimportant. The following section presents the conclusions of this brief study of the impact of the SAW technology.

## 7.3 CONCLUSIONS OF SAW IMPACT ANALYSIS

SAW oscillators are in no sense a panacea to all frequency source problems. However, it is clear that in properly chosen applications, SAWO's will have a beneficial impact on future microwave systems. In small quantity, high performance systems, the SAWO's will offer lower phase noise, far fewer spurious outputs, and significant size and weight savings. The DC power tradeoff must be examined on a case-by-case basis. If, for example, a large number of different frequencies must be generated, and these frequencies have a high common denominator, say >100 MHz, the SAW approach will probably use less power. If, however, the common denominator is low as in the SEEKBUS system, the SAW approach may require slightly more power. It is likely that when only a few SAWO's are

required at the same frequency, the cost of the SAW approach will be higher. This disadvantage may, however, disappear if, in the future, a decision is made by the military to adopt a frequency standardization policy. This has apparently been the case for bulk crystal oscillators, as 1 MHz and 5 MHz sources appear in a great many different systems.

The impact of SAW oscillators will also be beneficial in applications where the performance requirements are slightly less stringent, but the quantities involved are larger. As Figure 7-5 shows, the large quantity cost of SAWO's is significantly lower than that of the bulk oscillator/multiplier chain approach. For applications like the FLTSATCOM user equipment, a free running SAWO will easily meet all performance requirements and will result in substantial cost savings. If 500 UHF receivers are anticipated, approximately one quarter million dollars would be saved in initial acquisition costs alone.