S-2300

SURFACE ACOUSTIC WAVE STABILIZED OSCILLATORS

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January 12, 1978

Final Report for NAS5-23701

Prepared for:

Goddard Space Flight Center
Greenbelt, Maryland 20771

1. Report No.

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Surface Acoustic Wave Stabilized Oscillators

5. Report Date
January 1978

6. Performing Organization Code
S-2300

7. Author(s)
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8. Performing Organization Report No.

9. Performing Organization Name and Address
Raytheon Research Division
28 Seyon Street
Waltham, Massachusetts 02154

10. Work Unit No.

11. Contract or Grant No.
NAS5-23701

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt Road
Greenbelt, Maryland 20771

13. Type of Report and Period Covered
Final Report
Sept. '76 - Dec. '77

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

A number of 401.2 MHz surface acoustic wave (SAW) controlled oscillators have been built and tested. The performance of these oscillators has been evaluated for possible use as stable oscillators in communication systems. A short term frequency stability of better than 1×10^{-9} for 1 second has been measured for the SAW oscillators. Long term frequency drift has been measured and was found to be dependent on SAW design and packaging. Drift rates ranging from 15 ppm in twenty weeks to 2.5 ppm in twenty weeks have been observed. Some further improvement is required. The temperature dependence of the SAW oscillators was evaluated and it was concluded that some form of temperature compensation will be necessary to meet the requirements of some communication systems. A high efficiency rf amplifier has been proposed to increase the overall efficiency (DC to rf) of the SAW controlled oscillator.

17. Key Words (Selected by Author(s))
Oscillator
Surface Acoustic Wave
Frequency Stability
Quartz
$LiTaO_3$

18. Distribution Statement

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages

22. Price*

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1.0 INTRODUCTION

Over the past decade surface acoustic wave (SAW) devices have found uses in many radar and communication systems.[1,2] The basic SAW device consists of a polished, oriented crystal, on the surface of which is deposited an interdigital metal electrode structure as illustrated in Fig. 1.1. By properly tailoring the electrode structure, devices for bandpass filtering and matched filtering can be designed. Some specific applications have included devices for generation and correlation of biphase codes for spread spectrum, generation and compression of fm pulses for pulse compression radar, and channel selection for multichannel receivers. The fabrication of SAW devices is readily accomplished by standard photolithographic techniques, and devices in the frequency range from 30 to 1000 MHz can be easily and inexpensively produced.

Another application for SAW devices which has only recently been considered is for stable frequency sources.[3] By using a SAW device as the feedback element on an amplifier, the relatively long delay time available with a SAW device can be used to produce a stable oscillator. When compared to crystal stabilized oscillators, SAW stabilized oscillators offer several potential advantages. First, SAW devices can be designed for higher fundamental operating frequency than crystal resonators. In fact, the convenient operating frequency range for SAW devices begins where crystal resonators become difficult to build. This higher operating frequency eliminates or reduces the complexity of multiplier chains required for many high frequency sources leading to improved spurious rejection, small size, less power, and better reliability. Another advantage of SAW stabilized sources is that they can be designed to operate at higher acoustic power than crystal resonators because of the more massive acoustic medium in the SAW device. This will give better signal-to-noise ratio. Finally, the relatively massive SAW substrate allows the potential for more rugged construction for the SAW device.

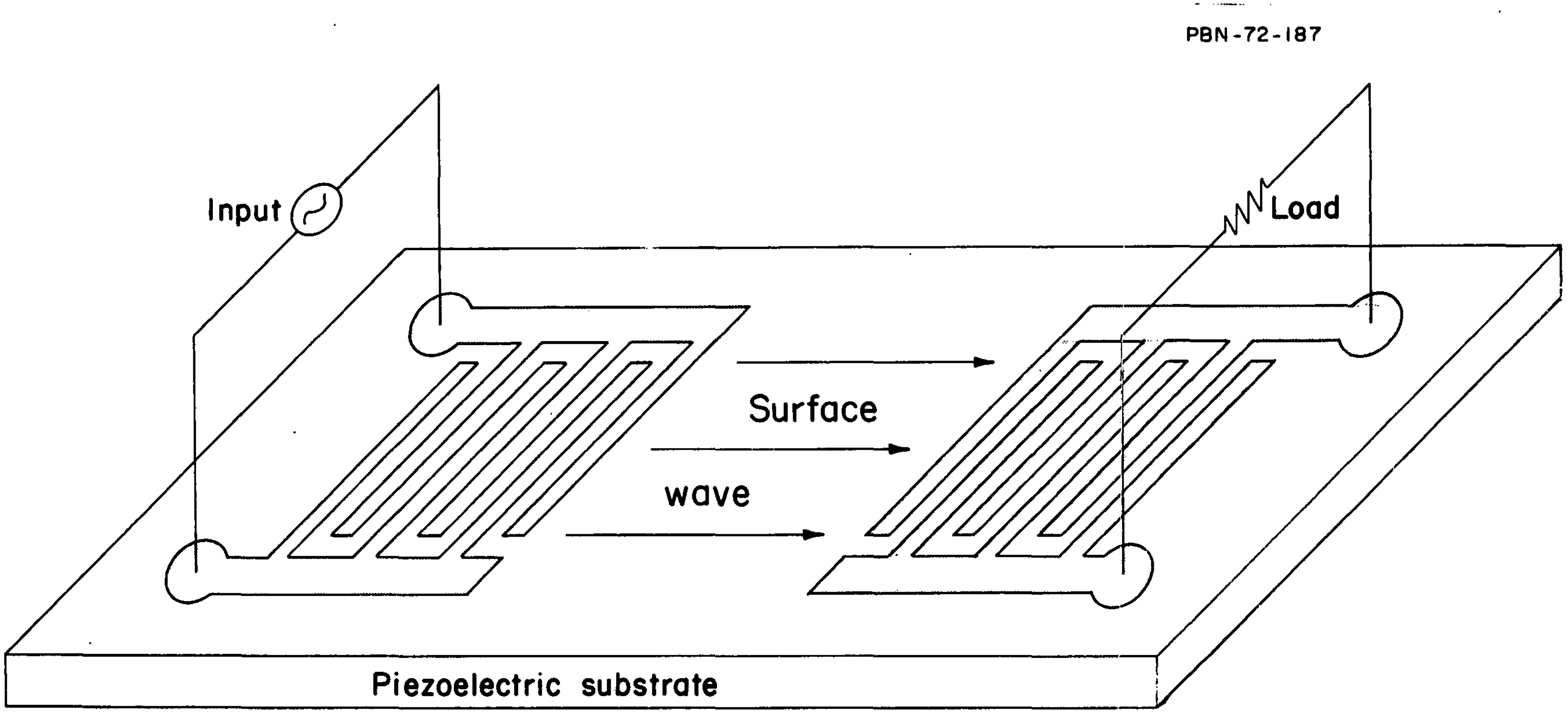

Figure 1.1 Basic Surface Acoustic Wave Delay Line Device.

2. EXECUTIVE SUMMARY

A number of 401.2 MHz surface acoustic wave (SAW) controlled oscillators have been built to demonstrate feasibility and identify problem areas associated with using SAW controlled oscillators as stable frequency sources in advanced communications systems. The performance of these oscillators has been evaluated to determine their advantages and disadvantages over existing techniques. Where problems have been encountered, possible solutions have been investigated.

SAW delay lines were used exclusively in this project, and three different types were evaluated. In the first two, gold or aluminum transducers were used on ST-cut quartz. ST-cut quartz offers a moderate temperature dependence similar to the BT-cut class of bulk wave quartz crystal resonators, and is the easiest material on which to fabricate temperature-stable SAW devices. A more complex composite structure was used for the third type. This approach used aluminum transducers on a $LiTaO_3$ substrate, which was subsequently covered by an SiO_2 film overlay. A temperature stability similar to that of AT-cut quartz can be obtained with this structure.

The circuitry used in a SAW oscillator is extremely simple and consists entirely of an amplifier, or amplifiers, with sufficient gain to overcome the loss of the SAW device, and some means of coupling out part of the signal. In this program wideband commercial UHF amplifiers were used.

The frequency stability of oscillators made with all three types of delay lines has been evaluated. Measurements of FM noise, or short-term stability, have shown that a fractional frequency deviation of less than 1 part in 10^9 is achievable with all three approaches. Measurements in the frequency domain have shown that the "flicker" (1/f) noise level may vary from oscillator to oscillator and that the high flicker noise levels are definitely associated with the SAW devices. Further work will be necessary to isolate the cause for the high flicker noise levels, but even the noisiest devices can meet a stability requirement of 1 × 10^{-9} when the insertion loss of the SAW device is reduced by impedance matching.

The temperature dependence of all three types of oscillators was measured. As expected, the $SiO_2/LiTaO_3$ devices were the best. A total frequency change of 12 ppm was observed on one of these devices for a temperature range of -40°C to +45°C. With more careful fabrication this can be reduced to less than 10 ppm. The devices fabricated on ST-cut quartz show a larger temperature variation of about 65 ppm for a similar temperature range. In order to reduce the frequency variation with temperature, a compensation scheme must be employed with the ST-cut quartz devices. The uncompensated variation of 65 ppm with ST-cut quartz is larger than the typical 20 ppm variation of the AT-cut quartz crystals, and therefore the SAW oscillator will require an improved compensation network.

Long-term frequency stability, or aging, has also been studied under this program. A total of eight oscillators (including at least two of each type) have been undergoing aging tests. The $SiO_2/LiTaO_3$ devices show a large aging estimated to be about -13 ppm in 30 weeks, with little decrease in the aging rate with time. The aluminum on ST-cut quartz devices also show a large initial frequency shift, but the rate of change decreases significantly in 10 to 20 weeks. A pre-aged aluminum device on ST-cut quartz has shown a frequency shift of less than -3 ppm in 14 weeks, and the aging rate has decreased nearly to zero. Two devices with gold transducers on ST-cut quartz have also been tested for aging, and the frequency was observed to decrease between -5 and -8 ppm in 30 weeks.

The pre-aged aluminum device has shown the best aging, but more devices should be tested to confirm this result. The devices with aluminum transducers on ST-cut quartz are the best choice in other respects too. These devices are the easiest to fabricate since no trimming of the SAW devices is required. Also, they tend to be more reproducible and generally have a lower insertion loss than the devices with gold transducers.

Though commercial wideband amplifiers were used throughout this project, it has become obvious that they are not well suited for applications where limited DC power is available. The wideband amplifiers are typically only 1 percent efficient in transforming DC power to rf power, whereas an overall oscillator efficiency of close to 50 percent is desired. We have found that a custom-built amplifier using a dual-gate FET operating in a switching mode and using a relative narrowband matching network can potentially yield an efficiency of better than 80 percent. This performance has not been demonstrated yet, but with further work, we should be able to build and test an oscillator employing such an amplifier.

Our work has demonstrated the operation of a SAW controlled oscillator at 401.2 MHz, and we have found the short-term stability of these oscillators to be suitable for many applications. Long-term frequency drift has been closely examined and some improvement has been made. However, further reduction in drift is necessary. Other areas where improvements in performance would be very useful are temperature stability and amplifier efficiency.

3. PROJECT GOALS AND TECHNICAL APPROACHES

The purpose of this project was to evaluate the use of SAW controlled oscillators as stable frequency sources in advanced communications systems. To determine feasibility a number of SAW oscillators were constructed, and their performance was evaluated. Such operating characteristics as the ability to obtain a specified frequency, reproducibility of the frequency, stability of the frequency, spurious levels, and output power levels have been studied. Areas of performance which need improvement were identified, and either steps were taken to remedy the problem or possible solutions were proposed. The advantages and disadvantages of SAW oscillators over existing frequency sources have been examined, but such a comparison can be difficult because the technology of sources such as quartz crystal oscillators is very mature and many practical problems were solved years ago. Surface wave devices, on the other hand, are still relatively new and have many practical problems left to solve.

To provide a specific performance standard as a goal, the following operating characteristics were chosen.

Frequency: 401.2 MHz ± 6.0 kHz

Temperature range: -40° C to + 45° C

Frequency stability

Short term: $< 1 \times 10^{-9}$ for 1 second
Medium term: $\Delta f < 4.2$ Hz in 15 minutes
Long term: $\Delta f < \pm 1$ kHz per year

Power

Output power: ≥ 25 milliwatts

Though the amplifier and associated circuitry of an oscillator are equally as important to overall performance as the SAW device itself, it was felt that the emphasis during this stage of the project should be mainly on the surface wave device and the problems associated specifically with it. Therefore the areas of investigation were: 1) to determine that the desired frequency can be reliably obtained, 2) to determine what aging rates can be achieved with existing packaging techniques and to determine what improvements are necessary, 3) to verify that the desired short-term stability can be obtained, and 4) to determine what inherent temperature stability is available (i.e., can the $SiO_2/LiTaO_3$ structure be used or must ST-cut quartz be used). Other areas which are just as important but which were not investigated in great detail are those areas associated with the amplifiers and other circuitry. Specific problems here are power efficiency and temperature compensation.

The design of a SAW oscillator is very complex since many facets are interrelated. For example, steps taken to reduce aging may affect short-term stability, or increasing the group delay to improve short-term stability may adversely affect the ability to obtain the desired frequency. Therefore several different approaches were pursued. Three types of surface wave delay lines were designed and tested. Two of these types were fabricated on ST-cut quartz, which has a parabolic temperature dependence similar to the BT-cut class of bulk wave quartz resonators. One of the approaches on ST-cut quartz was designed for aluminum transducers, while the second approach was designed for gold transducers. The third type of delay line was designed for aluminum transducers on the $SiO_2/LiTaO_3$ overlay structure. $SiO_2/LiTaO_3$ was chosen for one approach since it provides the best temperature stability of any known surface wave material.[4] Temperature stability similar to that of AT-cut bulk wave resonators is achievable with this material.

Though the $SiO_2/LiTaO_3$ structure offers the best temperature stability, it is more difficult to use since it requires the careful deposition of an SiO_2 layer on a $LiTaO_3$ substrate. This makes the fabrication of SAW devices more complex, and it may also affect the long-term stability (aging) of this material. Therefore, the other two approaches using ST-cut quartz were also pursued. ST-cut quartz does not require a film overlay for temperature stability, but for the temperature range of -40 to +45° C it shows a total change of about 60 ppm as compared to less than 10 ppm for the $SiO_2/LiTaO_3$ material. However, quartz is well understood and high-quality material is readily available. It was felt that quartz substrates might well offer the best aging results, and this is in fact what we have observed. The transducer metalization can also affect aging, so it was decided to try both aluminum and gold on the quartz devices. (Gold transducers have never been used with the $SiO_2/LiTaO_3$ structure because the poor adhesion of the gold would affect the SiO_2 film overlay.) It was felt that gold transducers might offer lower aging because gold is a very inactive metal, but it was also anticipated that using two different metals would help in isolating some aging mechanisms. The disadvantage in using gold transducers, however, is that gold is a very poor acoustic match to quartz and consequently results in many spurious reflections which can severely distort the passband of the delay line. Aluminum, on the other hand, is a very good acoustic match and very low distortion can be obtained.

The amplifiers used to make the oscillators were commercially available wideband units. Through the course of this program it became obvious that these amplifiers were not the best for minimizing power consumption, but they are extremely stable electrically and therefore made the task of evaluating the stability of the SAW devices much easier.

The remainder of this report will discuss the results of our investigation. Section 4 will cover some general characteristics of the SAW oscillators that were fabricated and tested. Details of the SAW devices and the associated circuitry will be presented and the general operating characteristics will be discussed. In Sec. 5 the frequency stability of the SAW oscillators will be evaluated. Results of aging tests on eight oscillators will be presented, as well as results showing temperature dependence. Noise (short-term stability) measurements made in both the frequency and time domains will be discussed and the results presented. Other parameters which affect frequency stability such as voltage variations and vibration will be discussed. In Sec. 6 a discussion of alternatives to commercial wideband amplifiers is presented, and an estimate is made of the ultimate efficiency which can be achieved. Finally, in Sec. 7 the overall performance of the SAW oscillator will be evaluated. Areas in which further work is needed will be pointed out.

4. SAW OSCILLATORS - FABRICATION AND OPERATION

Conceptually, a SAW-controlled oscillator is a very simple device.[3] It consists of a surface acoustic wave delay line or resonator and an amplifier with sufficient gain to overcome the loss through the SAW device. Also, some mechanism is required to tap out a small part of the signal. Figure 4.1 shows an illustration of such a device. The main purpose of the SAW delay line is to provide a large delay time or, in other words, a large amount of phase shift. Typically, many hundreds of wavelengths of phase shift are used. However, many wavelengths of delay means that there are many frequencies at which the total phase shift around the loop will be a multiple of 2π.

To provide for a means of selecting one of these many frequencies, the SAW device also serves as a bandpass filter. This feature is determined by the design of the transducers. Figure 4.2 shows an illustration of a typical transducer pattern for a delay line intended for use in a SAW oscillator. The numbers shown in Fig. 4.2 apply to the transducer pattern used for devices with aluminum transducers on ST-cut quartz. The transducer on the left is made very long to provide a narrow passband. However, such a long transducer would normally require over a thousand fingers. This can lead to problems due to interelectrode reflections, so the number of fingers is reduced to 120 by using 12 equally spaced groups of 10 fingers. The transducer on the right is a normal broadband design with 120 fingers placed every half wavelength.

Since three different types of SAW delay lines were to be used for this program, three different transducer designs had to be determined by computer analysis and three separate photomasks had to be produced. As mentioned earlier, the pattern in Fig. 4.2 is the one used for devices with aluminum transducers on ST-cut quartz. The pattern used for devices with aluminum transducers on $SiO_2/LiTaO_3$ is very similar to that shown in Fig. 4.2 except that the higher surface wave velocity on this material makes the wavelengths slightly larger ($\lambda = 8.61\ \mu m$) and therefore requires a slightly increased finger spacing. Also, because of the higher coupling coefficient

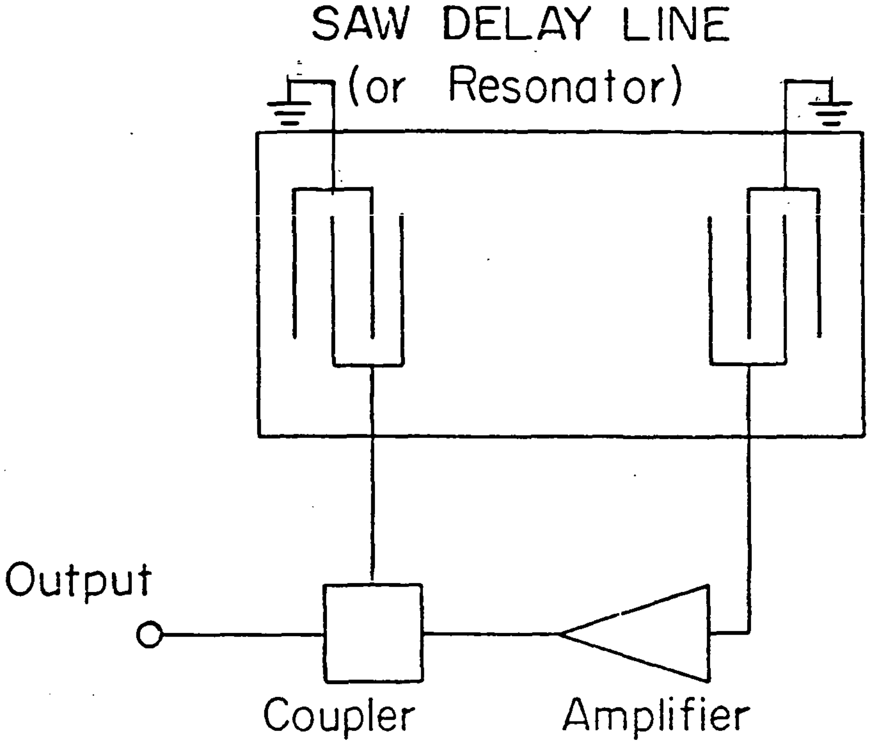

Figure 4.1 Surface Acoustic Wave Controlled Oscillator

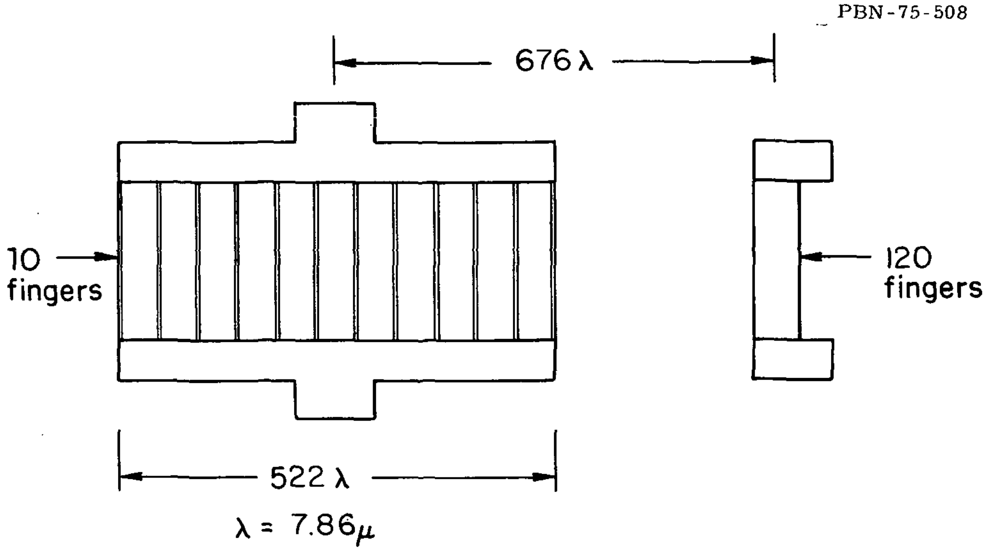

Figure 4.2 Typical Transducer Pattern for a SAW Delay Line Used in a SAW Controlled Oscillator.

with this material, only five fingers were used in each group in the left-hand transducer and only a total of 48 fingers were used in the right-hand transducer.

The pattern used for the devices made with gold transducers on ST-cut quartz was somewhat different from the other two because gold has a significant slowing effect on the surface wave velocity. Therefore, it was necessary that both transducers have approximately the same percentage of the surface area within the transducer covered by gold. This requires that both transducers be similar to the left-hand one in Fig. 4.2. They cannot be identical, however, because this would cause regions of low insertion loss to occur at intervals of about 8 MHz above and below the desired frequency of 401.2 MHz. This could result in oscillation at the wrong frequency. However, by making the spacing between groups of fingers slightly different for the two transducers, these regions of low insertion loss can be eliminated.

In addition to different transducer patterns, the three types of devices required somewhat different fabrication steps. For the devices using aluminum metalization, a thickness of 1000 Å was used. The transducer pattern was produced on the crystal substrate using standard photolithographic procedures.

However, for the devices with aluminum on ST-cut quartz, it was necessary to have the transducers recessed into the surface of the quartz so that the top of the 1000 Å layer of aluminum was flush with the crystal surface. If this is not done the 1000 Å step going from quartz to aluminum (or vice versa) causes a small reflection of the acoustic wave. With over 100 fingers this can cause a large distortion in the passband.[5] The procedure for recessing the transducers involves ion etching the pattern into the quartz to a depth of 1000 Å. The ion-etched region is then filled with aluminum by vacuum deposition. Recessing the transducers was not necessary for the devices made with aluminum on $SiO_2/LiTaO_3$ because the entire surface was eventually covered with approximately 4.8 microns of rf sputtered SiO_2.

The devices with gold transducers required special handling because gold does not adhere strongly to the crystal surface. This fact is potentially useful for reducing aging, but it does complicate the device fabrication. To increase the adhesion of gold to quartz, a thin layer (~ 100 Å) of another metal, such as titanium, was used between the gold and the quartz. This was done in the region of the busbars where wires were to be bonded but the finger areas were left as pure gold. This procedure, however, did require a two-step process involving, first, the deposition of the titanium under the busbars and, second, the deposition of the gold on the busbars as well as on the finger areas. The gold transducers were not recessed because the dominant reflection mechanism from gold is the large difference in acoustic properties between quartz and gold rather than geometric discontinuity at the finger edges. Therefore, recessing would have accomplished very little and possibly even increased the reflections. To keep the reflection problem to a minimum, only 500 Å of gold was used. Nevertheless, a noticeable distortion was present. A further complication with using gold was that the presence of gold on the surface has a significant effect on the frequency of the passband and hence on the operating frequency. The initial deposition of the gold could not be controlled accurately enough, so the procedure was adopted of deliberately making the gold too thick and then ion etching the gold to remove just the right amount to bring the passband into the desired frequency range.

Once fabrication of a device was completed, it was mounted in a Tekform No. 50272 flatpack as shown in Fig. 4.3. The substrate was held in place with two 10 mil gold wire straps. Originally, a number of 3 mil straps were used, but they were found to be inadequate because the wires stretched and the substrate eventually began to move around. The 10 mil wires hold the substrate quite strongly and present no problem with normal handling. Electrical connection was accomplished by bonding 2 mil gold wires between the transducer busbars and the pins of the flatpacks. The ground busbars were connected by a 2 mil wire directly to the bottom of the flatpack. The cleaning and sealing procedures will be discussed in detail in the section covering long-term stability (aging).

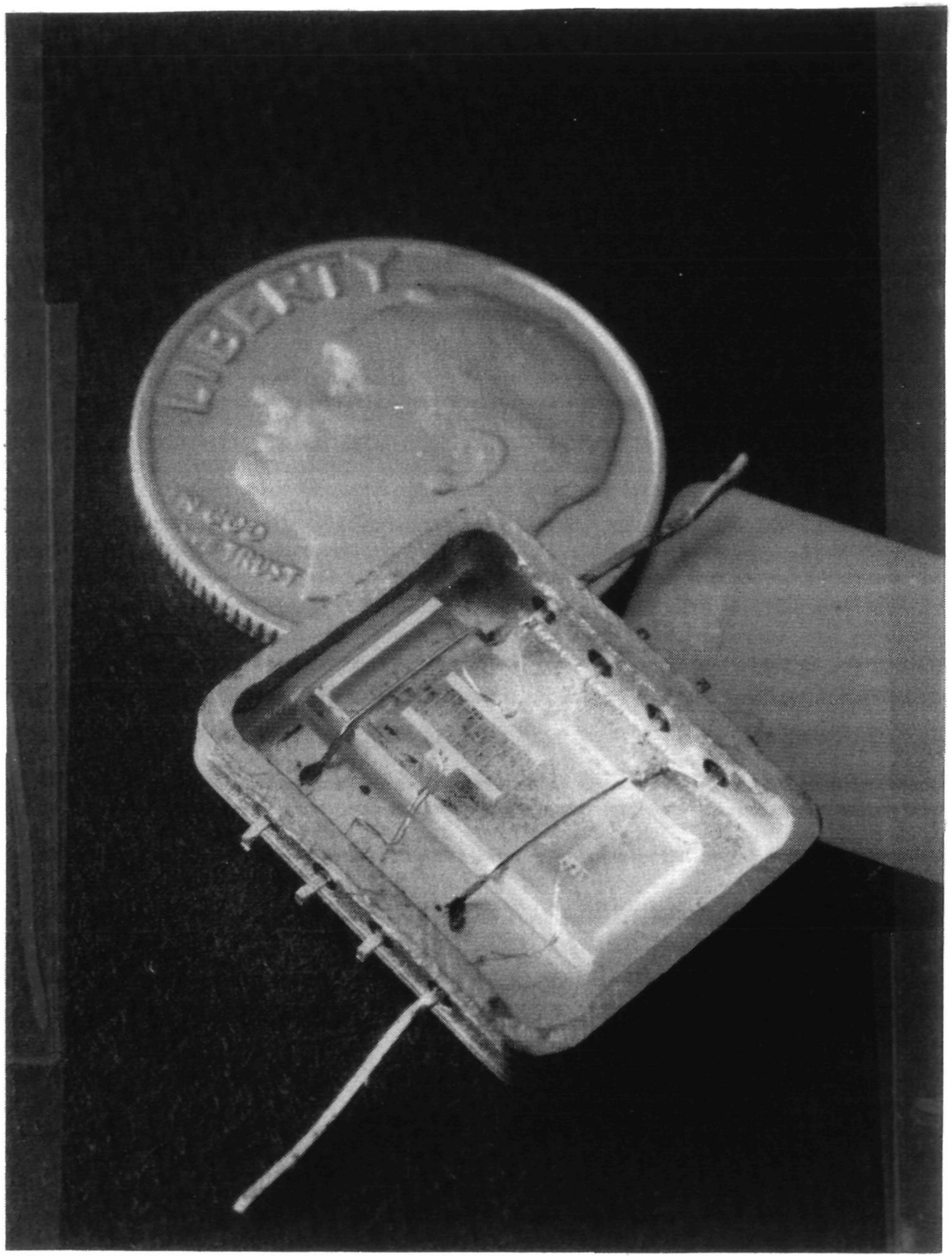

Figure 4.3 Typical SAW Device Mounted in a Flatpack.

After mounting, the packaged devices were placed in a jig for measurement of insertion loss in a 50 Ω system. Plots of insertion loss versus frequency for the three types of devices are shown in Figs. 4.4, 4.5, and 4.6. The Q or T numbers refer to the particular quartz or $LiTaO_3$ substrates that were used, and the M number refers to the mask (transducer pattern) that was used. Figure 4.4 is the insertion loss for a device with aluminum transducers on ST-cut quartz (M295). Figures 4.5 and 4.6 show insertion loss for devices with gold on ST-cut quartz (M 296) and aluminum on $SiO_2/LiTaO_3$ (M297), respectively. Figures 4.4 and 4.5 show the familiar $\frac{\sin x}{x}$ response expected from an unweighted transducer. Some slight distortion is present in the device with aluminum transducers on ST-cut quartz (Fig. 4.4). Figure 4.5 (the gold device) shows a large amount of distortion caused by reflection from the gold fingers. Also, the insertion loss is high because the reduced thickness of the gold causes more resistance in the fingers. Typically, the minimum insertion loss for the devices with aluminum transducers on ST-cut quartz fell between 20 and 22 dB, while the other two types of devices showed larger variations. The gold devices typically varied from 24 to 26 dB while the $SiO_2/LiTaO_3$ devices fell in the range 14 to 19 dB. The cause for this larger variation with the $SiO_2/LiTaO_3$ is related to the more complex fabrication required.

In addition to insertion loss, group delay was also measured on some devices. Group delay is defined as

$$\tau = \frac{\Delta \phi}{\Delta \omega} \quad , \qquad (4\text{-}1)$$

and is easily determined by measuring the change in phase angle, $\Delta \phi$, for a given change in frequency, $\Delta \omega$. If no reflections are caused by the transducer fingers, the group delay should be constant throughout the passband of the SAW device. However, we know that reflections are present in the gold devices, and it was found that the group delay varied from 1.3 to 2.5 μsec on a device designed to have 1.95 μsec of delay. The frequency of maximum group delay has been found to coincide with the frequency of minimum insertion loss. The devices with aluminum on ST-cut quartz also showed some variation in group delay, but to a lesser extent. This is consistent with the low level of distortion seen on these devices. Typically, a variation from 1.4 μsec to 1.75 μsec was observed for these devices which were designed for a delay of 1.60 μsec.

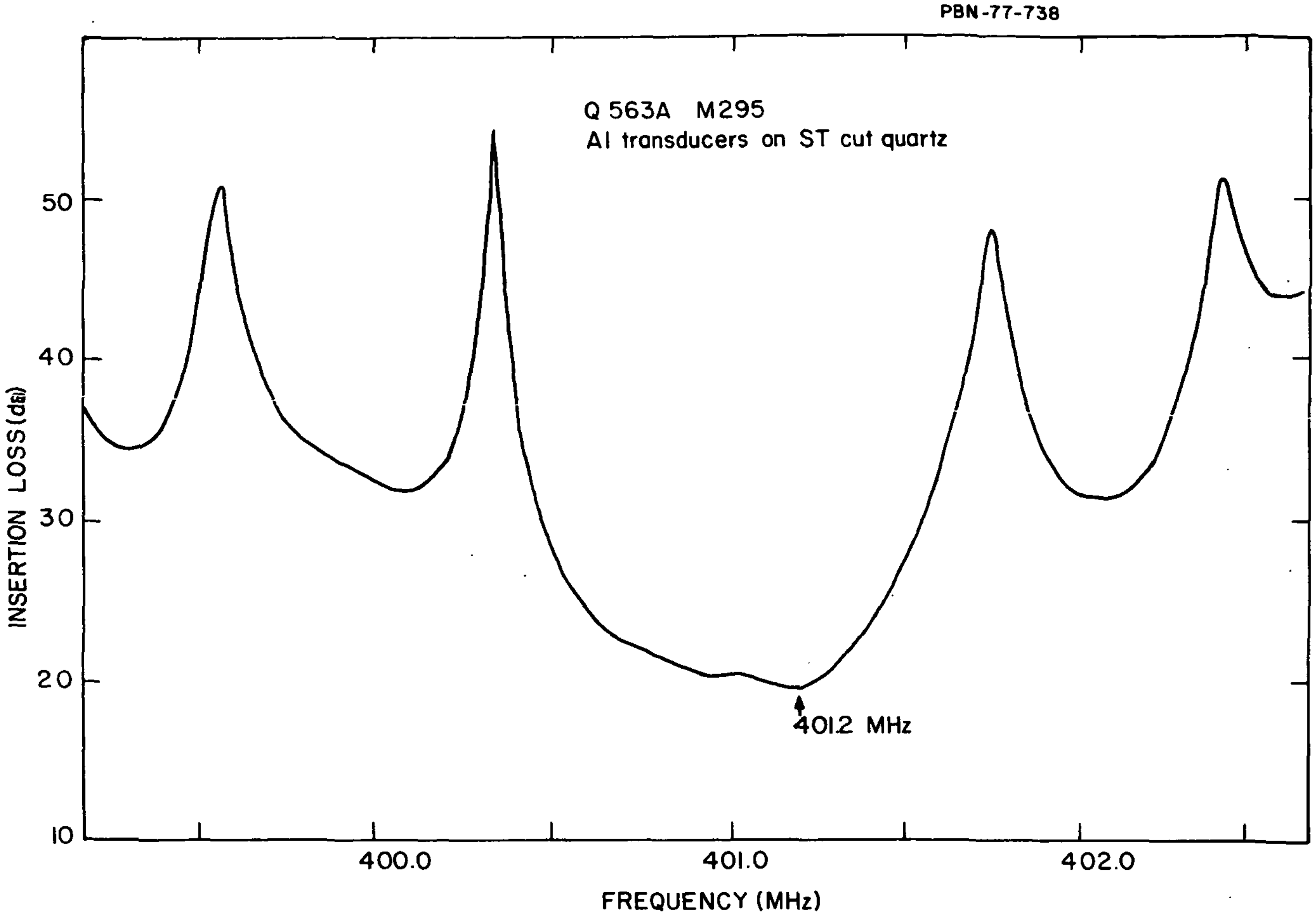

Figure 4.4 Insertion Loss Versus Frequency for Devices with Aluminum Transducers on ST-Cut Quartz.

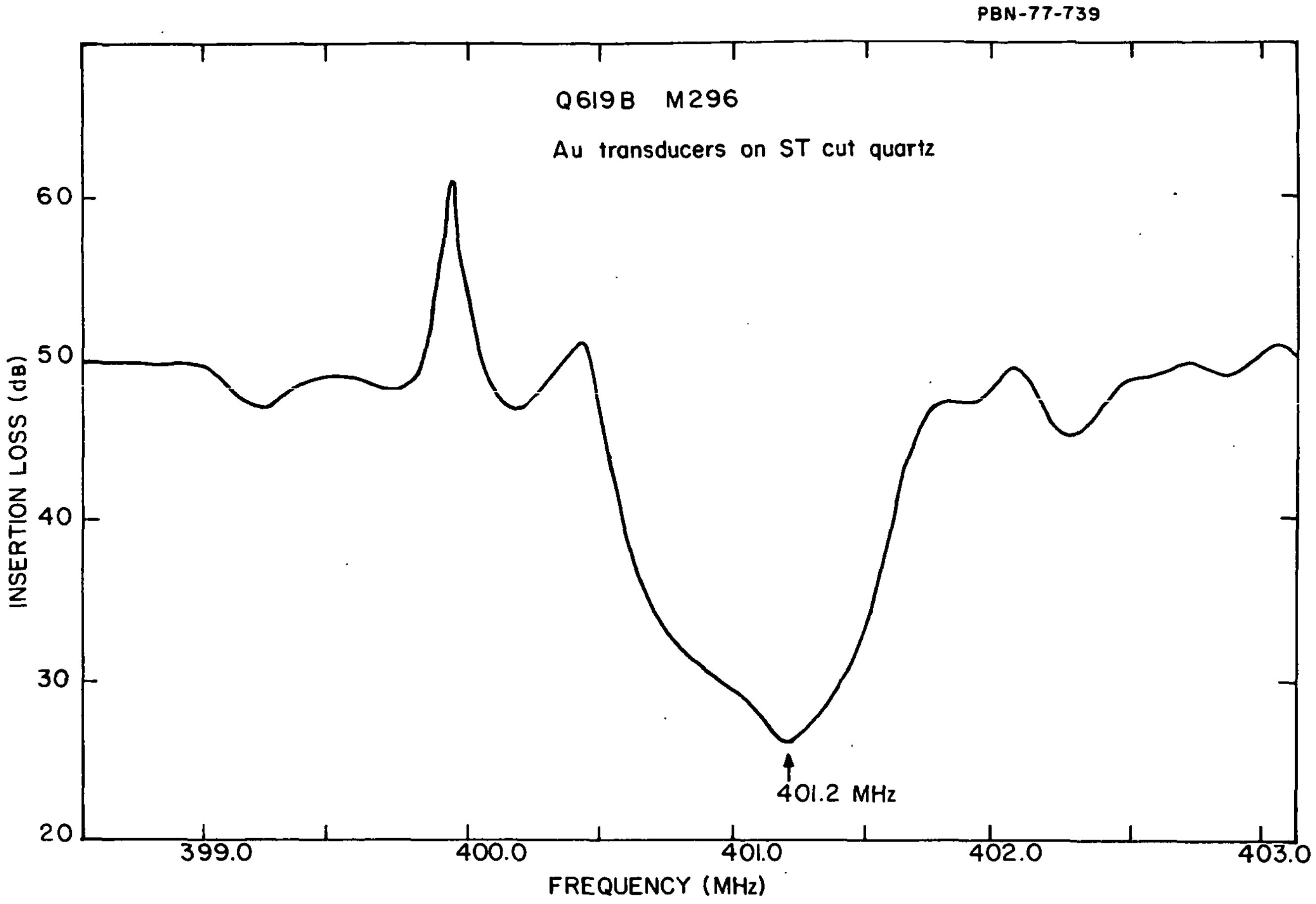

Figure 4.5 Insertion Loss Versus Frequency for Devices with Gold Transducers on ST-Cut Quartz.

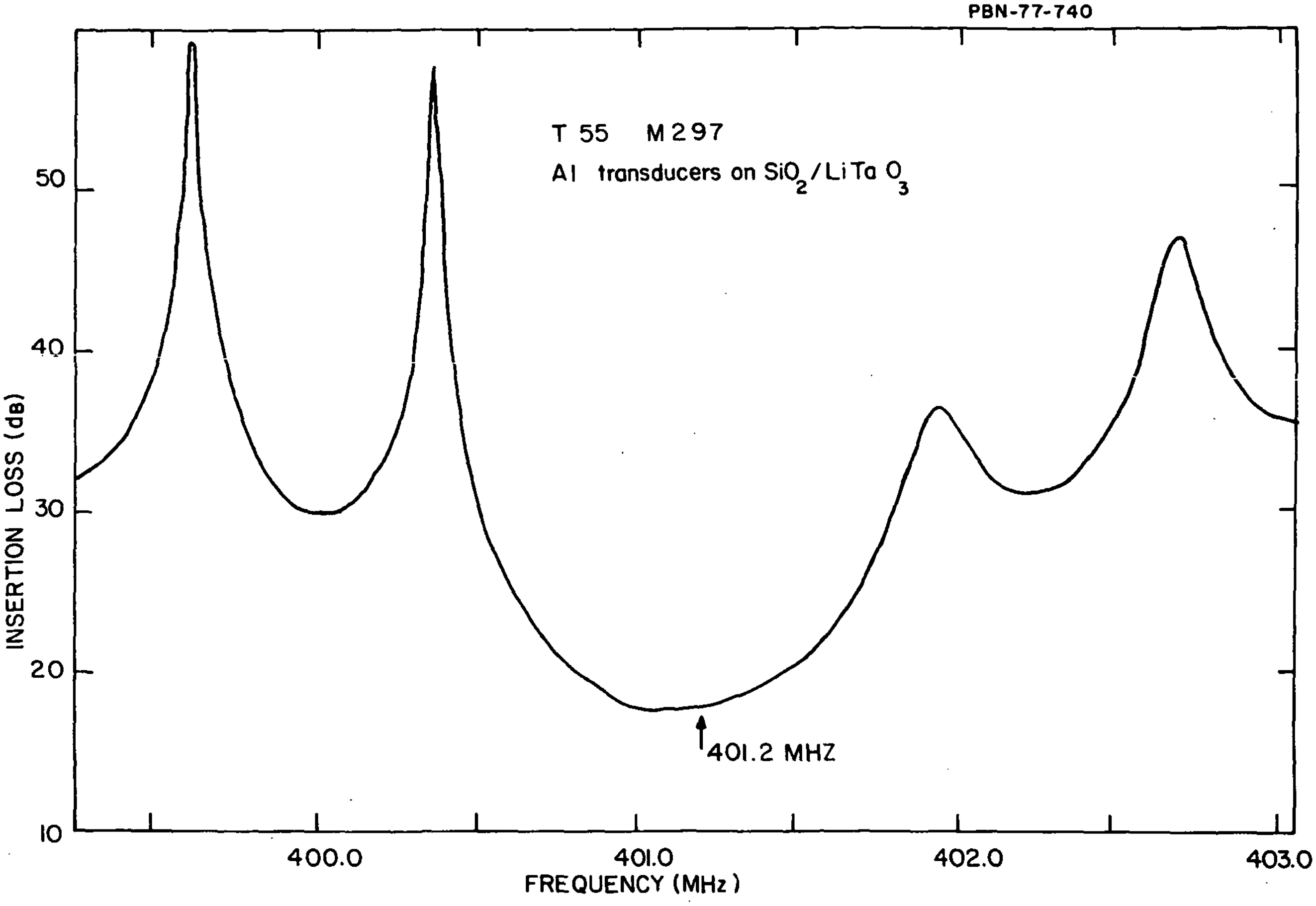

Figure 4.6 Insertion Loss Versus Frequency for Devices with Aluminum Transducers on SiO_2/ $LiTaO_3$.

The circuit used to make the SAW devices operate as an oscillator is shown in Fig. 4.7. Two Avantek amplifiers, the UTO 502 and 503, were used to provide about 24.0 dB gain, and an Anzac CH-134 10 dB directional coupler was used to couple out part of the signal. The combined gain of the amplifier and coupler was typically 23.0 dB. A length of coaxial cable was also used to provide for adjusting the frequency. By properly choosing the cable length the oscillator could generally be made to operate anywhere within the 3 dB bandwidth of the SAW device (provided sufficient gain was available).

The devices with aluminum transducers on ST-cut quartz typically had an insertion loss between 20 and 22 dB, so they could be inserted directly into the circuit with a resulting net gain of 1 to 3dB. This was quite sufficient to provide for oscillation. The gold devices, however, showed an insertion loss larger than the gain of the amplifiers. This problem was easily solved by improving the impedance match between the SAW device and the amplifiers. Typically, both the gold and aluminum devices on quartz had an input and output impedance of 10 to 15 ohms resistance and 40 to 50 ohms capacitive reactance. By tuning out the capacitive reactance of each transducer with a series inductor, the insertion loss could be reduced as much as 4 dB. This was normally done with the gold devices to provide a net gain of 1 to 2 dB.

The $SiO_2/LiTaO_3$ devices had a different problem, however, because their insertion loss was typically too low. If the oscillator loop gain was too large, an excessive amount of distortion was observed. Therefore, the insertion loss was increased somewhat by either series resistors or inductors of large enough value to make the impedance inductive. Obviously, amplifiers with lower gain could also have been used but amplifiers with the right combination of gain and power output were not readily available.

Figure 4.8 is a picture of a finished circuit board. The coaxial cable is on the right and the two amplifiers are located in the lower center. The directional coupler is held under the circuit board by the clamping arrangement

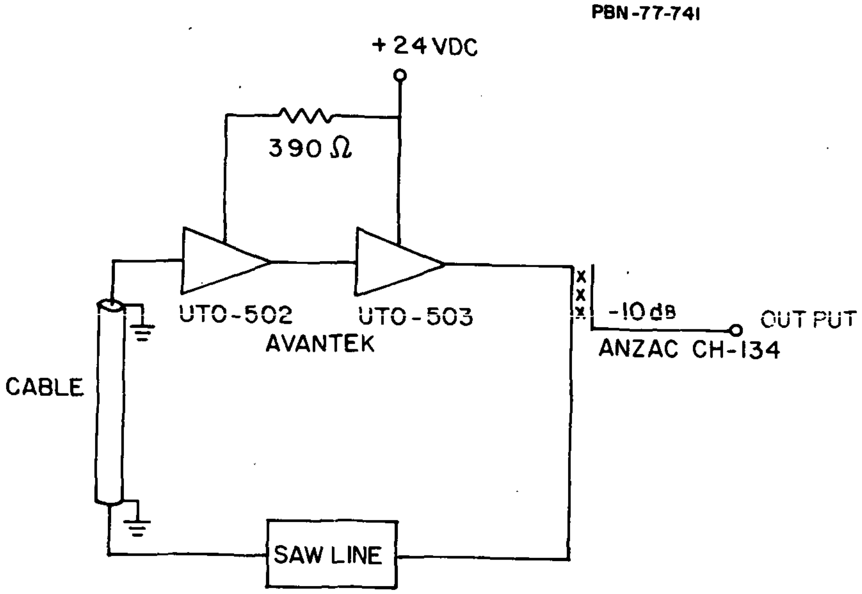

Figure 4.7 Circuit for a SAW Controlled Oscillator.

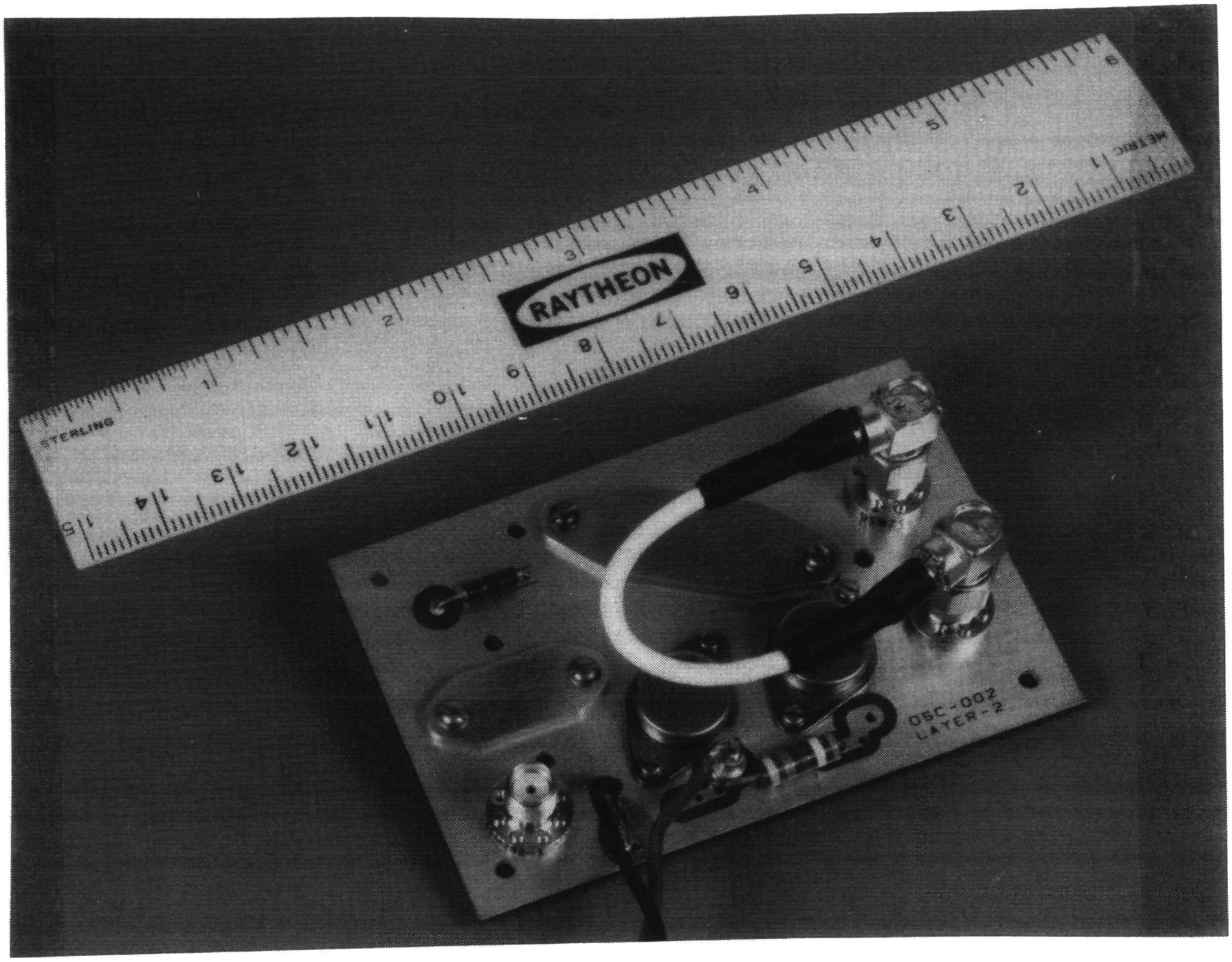

Figure 4.8 Completed SAW Controlled Oscillator.

on the left, and the SAW device is held under the board by the clamp at the top center. The output signal is provided at the connector in the lower left corner. The rf power output was typically 2 to 3 dBm (1.5 to 2 milliwatts) for a dc power input of 24 volts at 71 mA or 1.7 watts.

Two factors determine the frequency at which the oscillator will operate. The most important is the location of the SAW passband. If material or fabrication problems cause the 3dB bandwidth of the SAW device to fall in a range which does not include the desired frequency, the oscillator will then not operate at the desired frequency under any circumstance. This was a significant factor for both the devices with gold on ST-cut quartz and the $SiO_2/LiTaO_3$ devices. A total of six devices were fabricated on the $SiO_2/LiTaO_3$ structure and only three had passbands that included 401.2 MHz. The cause for this problem was found to be variations in the $LiTaO_3$ material, for it was observed that the center frequency of uncoated devices varied by as much as 500 kHz from device to device. When the SiO_2 layer was added, the variation decreased somewhat. There is no practical way of adjusting the passband of a finished $SiO_2/LiTaO_3$ device, so the ones with incorrect passbands simply could not be made to operate at 401.2 MHz.

Devices with gold on ST-cut quartz showed passband variation also, but this was to be expected because the gold has a significant slowing effect on the surface wave velocity. However, with the gold devices the passband could be adjusted by controlling the thickness of the metal. As mentioned earlier, this was done by ion etching to remove gold. Therefore, as long as sufficient gold was originally deposited, the passband could always be adjusted to include 401.2 MHz. This does mean an extra step in fabrication, however.

With the aluminum device on ST-cut quartz the desired frequency of 401.2 MHz always fell within the passband. There is no practical way of trimming these devices, so the mask would had to have been redesigned to correct such a problem. For devices with a correct passband, the second factor in obtaining the desired frequency of operation is to adjust the total phase shift around the loop to be a multiple of 2π at 401.2 MHz. There are two ways of varying the phase shift: (1) a 180° shift can be obtained by reversing the polarity of the busbar connections, and (2) by changing the cable length any phase change can be attained. A cable length of $\approx$ 22 inches provides a 360° phase change, but by also reversing the busbar polarity the cable need never be longer than 11 inches. A phase change of 360° corresponds to a frequency shift of about 600 kHz. Since the surface wave velocity of the $SiO_2/LiTaO_3$ devices and the gold on ST-cut quartz device was so highly variable, cable length anywhere from 1 to 11 inches was used on these devices. However, the devices with aluminum on ST-cut quartz showed less variation. Two devices fabricated at the same time on the same substrate differed by 30 kHz, while two devices fabricated on different substrates from the same crystal lot differed by 60 kHz. The largest variation of 180 kHz was observed between two unsealed devices fabricated nearly a year apart and on different crystal lots. Nevertheless, all of the aluminum devices could be made to oscillate at 401.2 MHz with the proper choice of cable length. The only exceptions to this were a few devices fabricated with 2000 Å of aluminum rather than 1000 Å. Much distortion was observed with these devices even though the transducers were recessed. Also, the very slight slowing effect of the aluminum caused a small shift to a lower frequency.

In operation, a SAW oscillator produces a very clean signal. Except for harmonics of the fundamental, there are no spurious signals. When displayed on a spectrum analyzer, the second and third harmonics of the 401.2 MHz fundamental were observed to be approximately 20 dB below the fundamental. Higher harmonics are reduced even further. Other than harmonics, no other spurious signals were observed down to the 80 dB limit of the spectrum analyzer.

In the following section we will consider how the frequency of operations is affected by noise, temperature, and aging.

5. FREQUENCY STABILITY OF SAW OSCILLATORS

The goals for frequency stability stated in Sec. 3 indicate that three areas of stability must be investigated. The specification of a stability of 1 part in 10^9 for one second represents essentially a noise phenomenon and therefore requires an understanding of noise in SAW oscillators. To meet the specification that the frequency be constant to 4.2 Hz over a 15 minute period, it is necessary that the temperature dependence of SAW oscillators be understood and improved by compensation if necessary. The third requirement is that the frequency not drift more than ± 1 kHz in one year. This last requirement then necessitates knowledge of long-term stability or aging. The first area to be considered will be short-term stability or noise.

5.1 Short-term Stability. Oscillators can have both AM and FM noise. However, AM noise will not be discussed here because with SAW oscillators the amplifier inherently operates in a saturated mode and therefore suppresses AM noise to a level lower than that of FM noise. FM noise can be measured and specified in both the frequency and time domains. The specification of stability to 1 part in 10^9 in one second is a requirement in the time domain. However, noise measurements for this contract were made in both the frequency and time domains because it is easier to determine the various sources of FM noise in the frequency domain. The frequency domain data was converted to the time domain analytically, but to increase our confidence level, stability measurements were also made directly in the time domain.

Let us first consider the various factors that contribute to FM noise as seen in the frequency domain. This noise is conveniently expressed as the single sideband FM noise power spectrum, which is given as the ratio of the power in a single FM sideband for a 1 Hz bandwidth relative to the total carrier power as a function of offset from the carrier. The expression (in dB) for a SAW oscillator is given in Eq. 5-1.

$$\left(\frac{P_{SB}}{P_C}\right)_{dBc} = 10 \log \left\{ \left(\frac{N^2 GFKT}{P_C}\right) \left(\frac{\omega_\alpha}{(\Delta\omega)^3 \tau^2} + \frac{1}{(\Delta\omega)^2 \tau^2} + 1 \right) \right\} \quad (5\text{-}1)$$

where N = multiplication factor
G = closed loop amplifier gain ≈ SAW insertion loss
KT = thermal energy
F = amplifier noise figure
P_C = oscillator power at amplifier output
τ = phase slope (group delay) of SAW device
ω_α = $2\pi f_\alpha$ = flicker frequency
$\Delta\omega$ = $2\pi\Delta f$ = offset or modulation frequency

Equation 5-1 is not an exact expression and some details are left out. However, it does show the basic characteristics of the noise power spectrum and has been found to be accurate to within a few decibels. The last of the three terms enclosed in the right-hand set of parentheses represents the thermal floor, which is independent of modulation frequency, $\Delta\omega$. As one would expect, the noise level in this region depends on the amplifier gain and noise figure as well as KT and the carrier power P_C. If multiplication is used, the noise level is increased by causing N to be larger than 1. In this particular application no multiplication is required, so N will always be 1. The middle term in this expression includes the effect of the group delay or phase slope of the SAW device in the noise power spectrum and results from a frequency modulation of the oscillator caused by phase noise at the amplifier input. The group delay is, of course, a function of the design of the SAW device. In the region where $\omega_\alpha < \Delta\omega < 1/\tau$, the noise power increases at a rate of 20 dB per decade change of $\Delta\omega$. Below the flicker frequency, ω_α, the phase noise begins to increase as $1/\Delta\omega$. This is the so-called flicker noise contribution represented by the left-hand term within the parentheses. This results in a further increase in the spectrum slope to 30 dB per decade.

From Eq. 5-1 it is evident that several steps can be taken to minimize the noise in an oscillator. Specifically, G and F should be minimized and can be controlled to some extent by SAW design and the choice of amplifier. Also, P_C should be made as large as possible. These three steps will reduce the overall noise level as much as possible. The close-in noise level can be further reduced by making τ as large as possible. The upper limit on τ is set by the minimum 3 dB bandwidth which is required to insure operation at the desired frequency. The relation is

$$BW\,(3dB) \approx \frac{1}{\tau} \qquad (5\text{-}2)$$

Flicker noise also affects the close-in noise level, but ω_α is not a design parameter. Flicker noise levels are closely related to fabrication techniques but are poorly understood in SAW oscillator design.

The technique which was used for measuring the FM noise power spectrum is illustrated in Fig. 5-1. With this technique, two similar oscillators are phase locked together, which requires that one of the oscillators be voltage tunable although the other may be fixed.[7] The tunable oscillator was built in a manner similar to that shown in Fig. 4.7 , except that a voltage-controlled phase shifter was inserted between the amplifiers. The same SAW device (aluminum transducers on ST-cut quartz) has been used in this oscillator throughout the program. The oscillator under test is the fixed oscillator. The combined noise level is measured for offset frequencies between 100 Hz and 300 kHz. If the noise levels of both the fixed and tunable oscillators are similar, the measured noise is assumed to be equally divided between the two.

Figure 5.2 shows the results of measurements on three different test oscillators. T49 and Q619B were sealed devices which were eventually put into the aging test. Both Q614B and the SAW device Q563A used in the voltage tunable oscillator were unsealed devices. The solid line is a calculation based on Eq. 5-1 using the values N = 1, G = 159 (or 22 dB), KT = 4×10^{-18} (or -174 dB), F = 4 (or 6 dB), P_C = 20 milliwatts (or +13 dBm), and τ = 2 μsec. Experimental values for ω_α were used. For ΔF larger than 40 KHz, the three

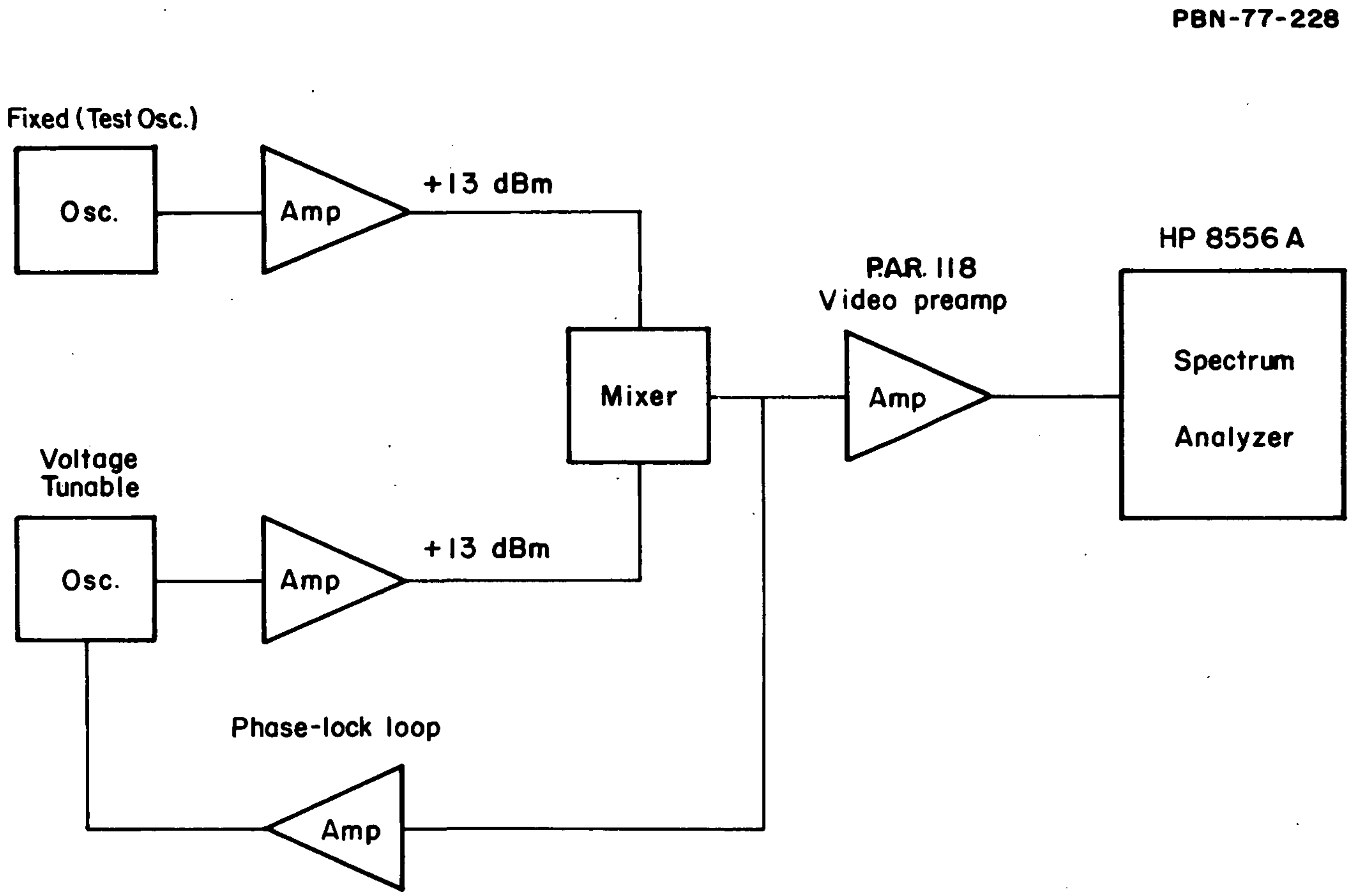

Figure 5.1 Block Diagram of System Used to Measure FM Noise in the Frequency Domain.

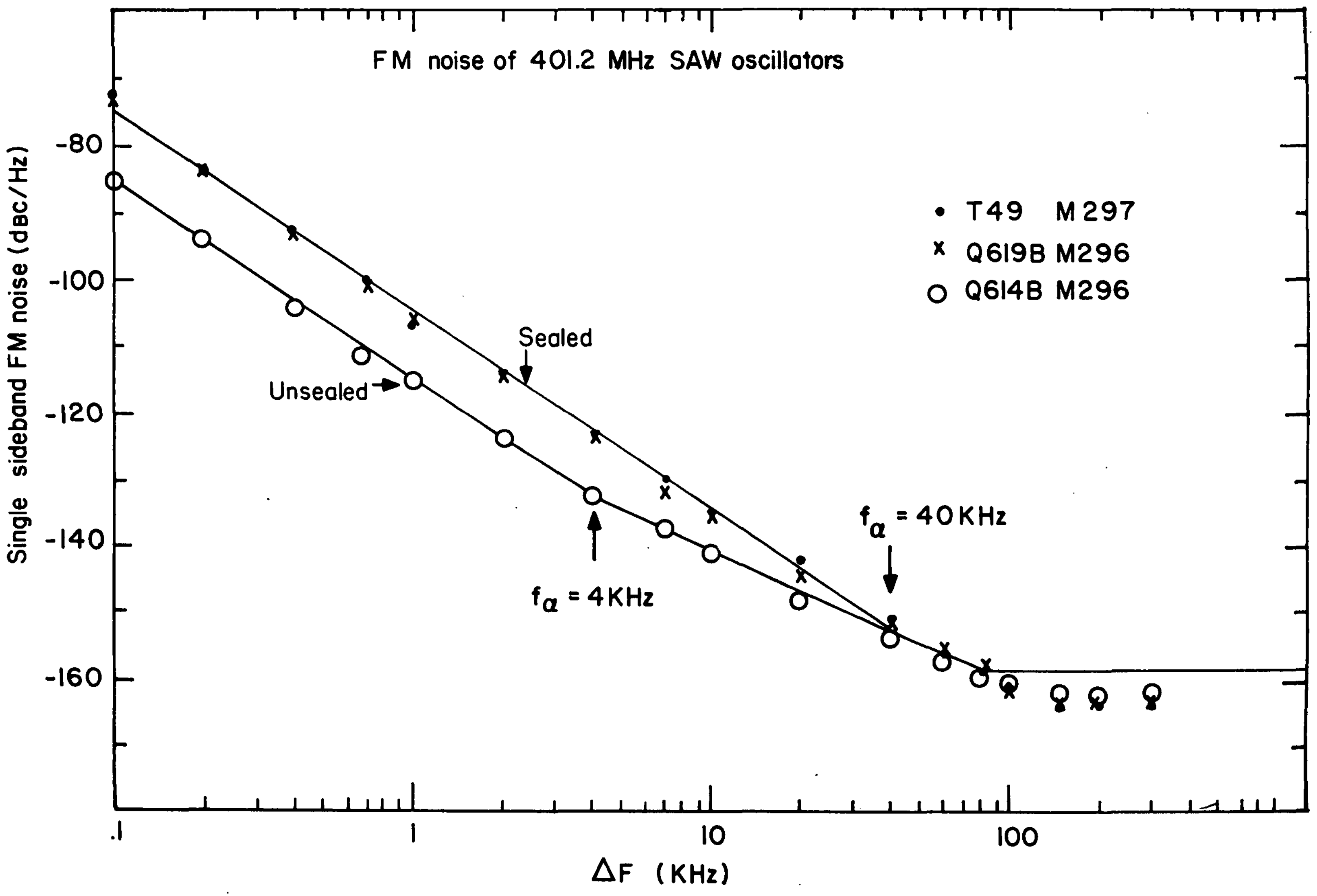

Figure 5.2 Measured FM Noise on Three Test Oscillators. T49 and Q619B are Sealed Devices. Q614B and the VCO are Unsealed Devices.

oscillators are nearly identical and are also in reasonable agreement with the predicted noise levels. Below 40 KHz, flicker noise begins to dominate the two sealed devices, as indicated by the transition to a 30 dB/ decade slope. The unsealed device does not show flicker noise until $\Delta F < 4$ kHz. To verify that the sealed SAW devices and not the amplifier were responsible for the high flicker noise levels, the sealed and unsealed SAW devices were interchanged on the circuit boards. The high noise level was found to accompany the sealed devices. The flicker noise region is very important because it has the dominant effect on the noise as measured by a 1 second count in the time domain.

Figure 5.3 shows the fractional frequency deviation of Q614B as measured with an H.P. 8360A computing counter. The solid line is the predicted stability based on the measured results in the frequency domain shown in Fig. 5.2. The flat region for $T > 10^{-4}$ represents the flicker noise region (30 dB/ decade) of the noise power spectrum, while the two segments shown for $T < 10^{-4}$ represent the 20 dB / decade slope and the thermal floor of the power spectrum. The stability limits of the counter prevent measurements of the SAW stability for measurement intervals less than 50 msec. Therefore, the only way to investigate these regions was through measurements in the frequency domain. As seen in Fig. 5.3, the measured stability of Q614B is in fair agreement with the predicted value and is well below the required stability of 1×10^{-9}. However, the increased flicker noise levels in T49 and Q619B as seen in Fig. 5.2 cause the predicted fraction frequency deviation to increase to about 1×10^{-9}. The actual measured stabilities fall in the range of 1 to 2×10^{-9}. In fact, it was observed that all eight devices sealed for aging tests showed stability levels of 1 to 2×10^{-9}.

Considerable effort has been directed toward finding the cause of the high flicker noise levels, but so far no answer has been found. Throughout most of this program it was observed that all of the sealed devices had high flicker noise levels, while all of the unsealed devices had low flicker noise levels. However, nearly all of the devices fabricated after August 1977 have been noisy, whether sealed or not. Various methods of bonding the electrical

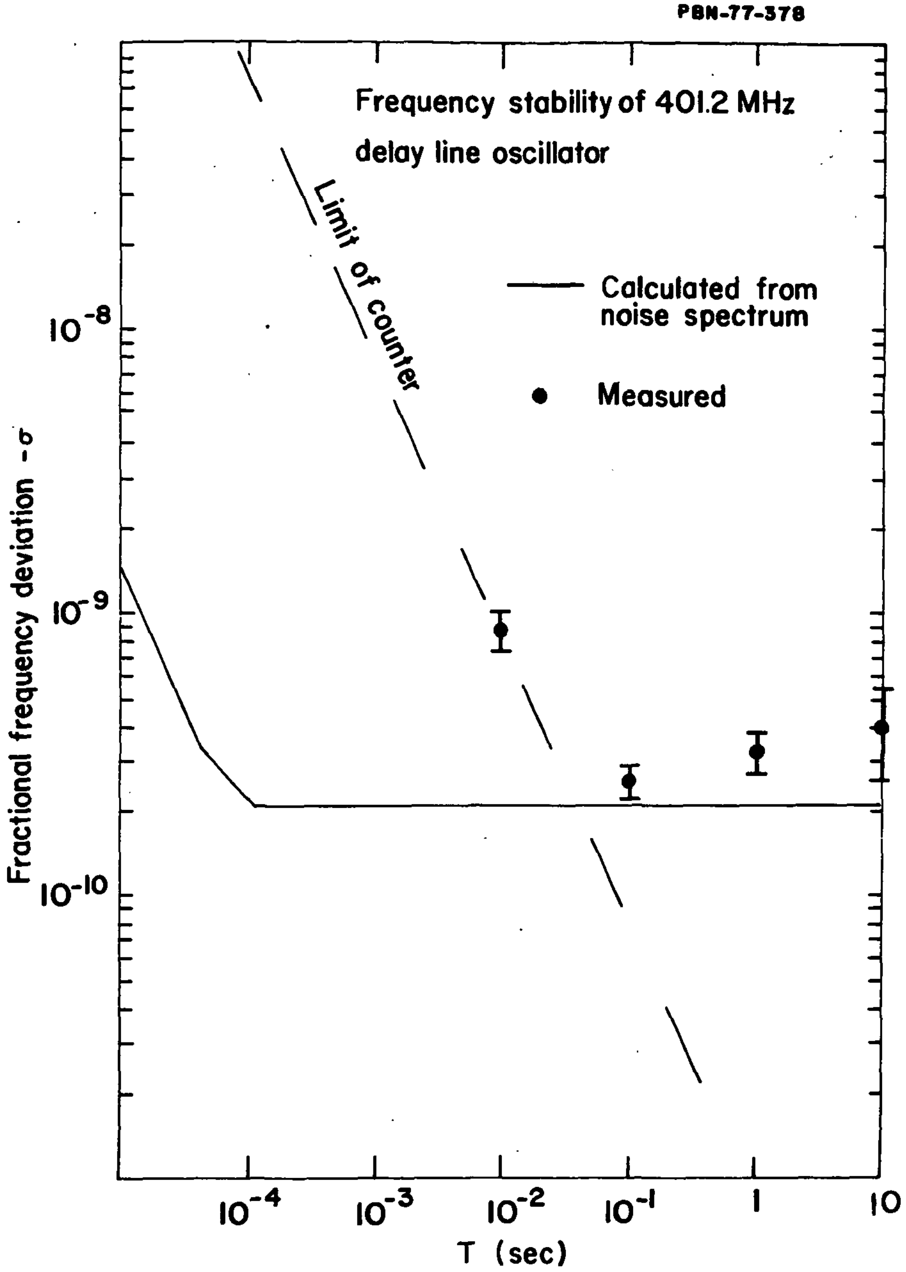

Figure 5.3 Frequency Stability of Device Q614B as Measured in the Time Domain.

connections have been tried, including both gold and aluminum wire, but none was found to have any influence on the noise level. Also, the same lot of quartz substrates yielded both noisy and quiet devices, so it is not likely that the flicker noise problem is related to the substrate preparations. Various packaging arrangements seem to have had no effect on the noise. In only one case was a noisy oscillator made to be quiet, and this device was observed to have some foreign material (possibly silver paint) on the surface. When the surface was cleaned and the material removed, the flicker noise level was reduced.

At this time it is not certain that the high flicker noise level on the sealed devices is related to the high noise level on some unsealed devices, but a relation between the two noise levels is suspected. It appears that the solution to the flicker noise problem will involve examining each step of device fabrication for possible influence on the flicker noise. Process steps will have to be changed or eliminated and their effect observed. Possibly we will also be able to determine if the lower observed flicker frequencies of 2 to 4 kHz are determined by the SAW devices or by the amplifiers.

It is important to note that the flicker noise problem does not have to be solved in order to meet the required stability of 1×10^{-9}. Other steps such as reducing the insertion loss of the SAW devices through improved impedance matching or possibly higher power levels from more efficient amplifiers will lower the overall noise level and give a stability well below 1×10^{-9}.

5.2 Medium-term Stability. The medium-term stability goals are stated in the specifications given in Sec. 3. One is that the frequency be constant to better than 4.2 Hz over a 15 minute period, and another is that the frequency not vary more than ± 6 kHz for a temperature environment of -40° C to +45°C. Since temperature variations can be a primary cause of frequency variations over a time scale of minutes or hours, the stability requirement for a 15 minute period is also, in effect, a requirement on the temperature dependence of the oscillator frequency. However, this requirement is difficult to quantify since it is somewhat uncertain as to what temperature change the oscillator will see if it is well insulated from the outside environment or if an oven is used. If it is assumed that a maximum temperature change on the order of 0.1° C will occur in the oscillator over a 15 minute period, the oscillator temperature coefficient must be not larger than 0.1 ppm/° C if the frequency is to remain constant to better than 4 Hz. If the temperature coefficient is never larger than 0.1 ppm, the total frequency change for the temperature range -40° C to +45° C will be less than 8.5 ppm or 3.5 kHz. Thus, the overall frequency stability requirement for the range -40° C to +45° C will also be met.

In this program our effort was directed mainly toward ascertaining the magnitude of the temperature stability problem and to consider some of the possible solutions. The first step was to compare the requirement with the inherent stability of the available SAW materials. Figure 5.4 shows the temperature dependence of an oscillator made with a device using aluminum transducers on ST-cut quartz. Though the figure does not show data all the way to -40° C, the frequency does continue to drop to a value of approximately -140 ppm in a continuous fashion. The turnover point (the point at which the slope changes sign) is a function of crystal cut angle and can be located virtually anywhere in the -40 to +45°C range. To a lesser extent the transducer metal and amplifier circuitry will also affect the turnover point. Even if the turnover point is located midway between -40° C and +45° C, the frequency change will be nearly 65 ppm and the temperature coefficient (slope) will vary from +2.7 ppm/° C to -2.7 ppm/° C. Obviously, some form of external compensation will be required to improve the temperature stability of an ST-cut quartz oscillator.

Figure 5.5 shows the temperature dependence of an oscillator made with an $SiO_2/LiTaO_3$ device (T55). The temperature dependence of this material is parabolic like ST-cut quartz but is approximately ten times smaller. Like ST-cut quartz, the turnover point can be controlled, but with the $SiO_2/LiTaO_3$

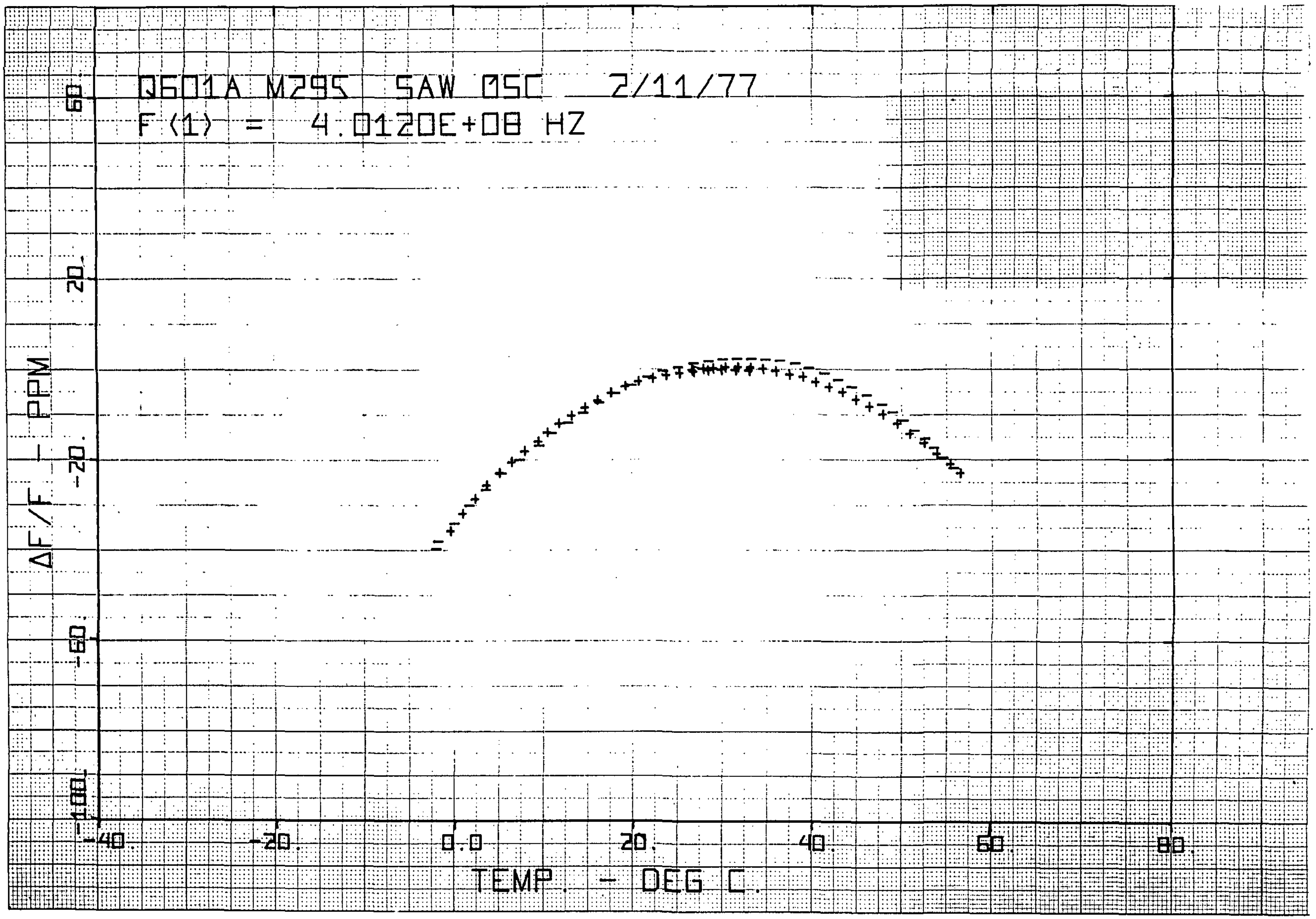

Figure 5.4 Temperature Dependence of a SAW Oscillator Using a Device with Aluminum Transducers on ST-Cut Quartz.

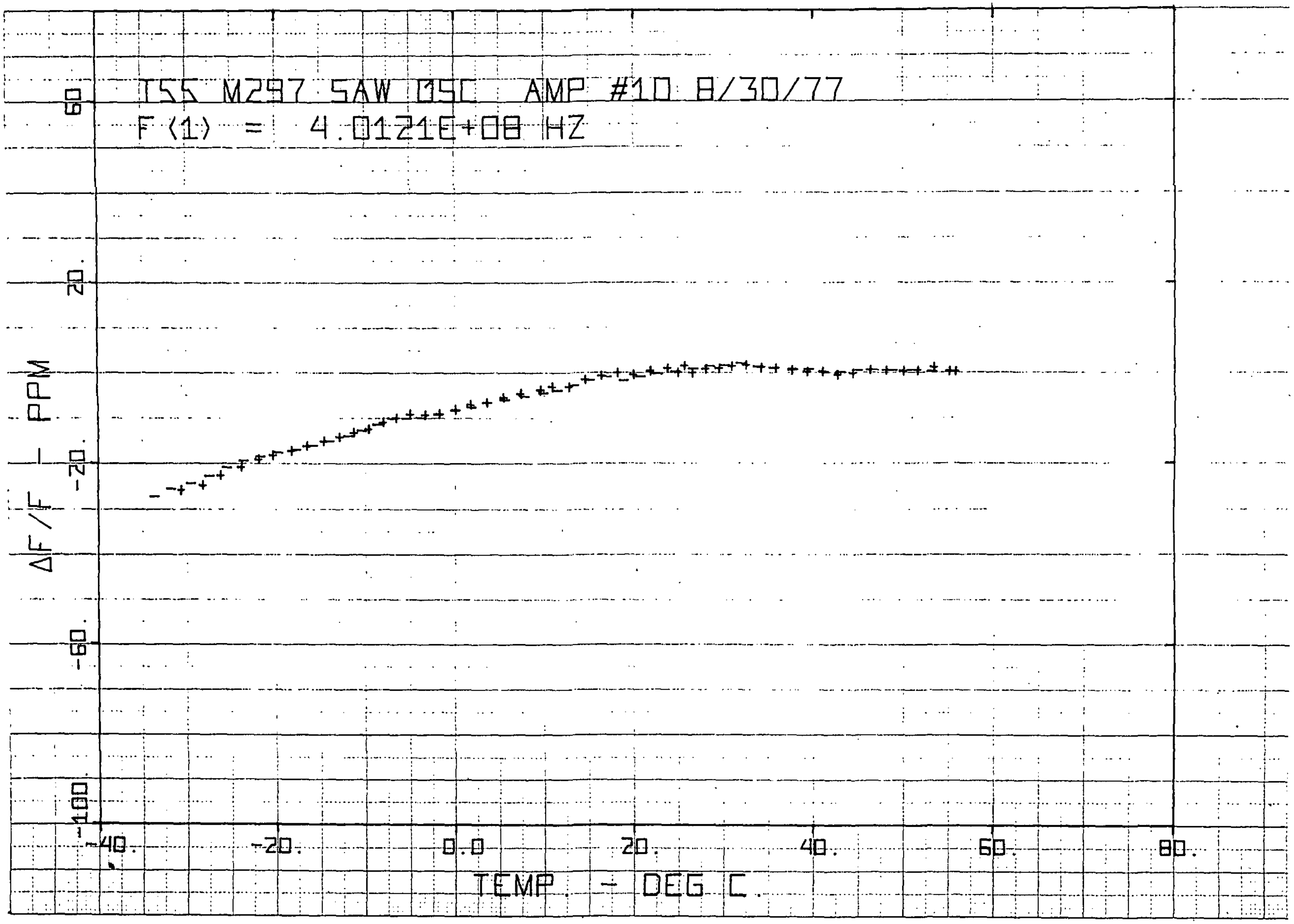

Figure 5.5 Temperature Dependence of a SAW Oscillator Using a Device made with Aluminum Transducers on SiO_2/ $LiTaO_3$.

material this is accomplished by adjusting the thickness of the SiO_2 layer. A half percent change in the SiO_2 thickness (~ 230 Å) will cause the turnover point to move from +45° C to -40° C. Device T49 (not shown) has a turnover point at - 5°C and a total change of 12 ppm in the -40°C to +45°C range.

The procedure used for fabricating the present devices was to deliberately make the SiO_2 layer too thick and then remove SiO_2 until the desired temperature stability was achieved. This involved alternately mounting the device for testing and demounting it for ion etching. The process took considerable time and caused the busbars to wear, so that not all devices were trimmed precisely. However, this procedure can be adapted to testing and etching entirely within the ion etcher's vacuum system, which would greatly reduce the time required and also increase the precision of the trimming.

Even though the $SiO_2/LiTaO_3$ is substantially more temperature stable than ST-cut quartz, some relatively crude compensation scheme would probably be required because the temperature coefficient may become as large as ± 0.50 ppm/°C at the extremes of the temperature range. A much more precise compensation technique is required for the ST-cut quartz devices since the temperature coefficient must be reduced by more than a factor of ten at the extremes of the temperature range.

Where power is available, an active compensation scheme may be used, such as an oven or digital techniques. However, in some applications power consumption is strictly limited and passive compensation must be used. The two types of passive networks which have been identified involve either a circuit which directly produces a temperature-sensitive phase shift or a circuit which produces a temperature-sensitive voltage which can be used to set an electronic phase shifter. The circuit giving a temperature-sensitive phase shift is more direct and probably cheaper, but a scheme for giving a parabolic temperature dependence has not yet been identified. Only a monotonic dependence is produced from a circuit involving a thermistor and reactive components. However, a parabolic voltage versus temperature dependence can be achieved with a circuit involving series and parallel resistors and thermistors. Such a circuit can be used to control an electronic phase (which requires essentially no current) which will adjust the frequency of the oscillators. This scheme requires a stable (~ 1 percent) voltage reference and also the phase shifter is relatively expensive. Obviously, there is considerable work to be done in arriving at some kind of passive temperature compensation scheme which will permit the requirement for frequency stability over 15 minutes to be met.

In addition to temperature variations, there are other factors which may also affect the frequency over a 15 minute period or longer. These factors include voltage dependence and motion or vibration effects. These problems will be addressed after the following discussion on aging.

5.3 Long-term Stability. Any physical change which occurs over a period of days, months, or years and which affects the velocity of the surface wave can be considered an aging mechanism. A given fractional change in surface wave velocity will result in an equal fractional change in frequency. There are many possible mechanisms for affecting the surface wave velocity, but some of the more important are: (1) arrival or departure of foreign material at the substrate surface due to inadequate cleaning or leaks in the package, (2) changes in the physical state of the transducer metal, (3) changes in stress conditions caused by the mounting of the crystal, (4) changes in the stress or damage at the surface caused by polishing, (5) changes in defects present in the bulk crystal material.

When work on SAW oscillator aging began at Raytheon, it became immediately obvious that the SAW device had to be sealed in a dry atmosphere. Quartz is hygroscopic, and if the SAW device was left unsealed the frequency of the oscillator was observed to change by tens of ppm from day to day with the daily changes in humidity. Sealing the SAW device in a hermetic enclosure eliminated this problem, but it was also necessary to insure that moisture trapped on the quartz surface be driven off prior to sealing. This was easily accomplished by baking at elevated temperatures for several hours. If the moisture is not removed, the water content on the surface of the crystal will change with temperature, even though the device is sealed. Under these conditions large frequency hysteresis effects have been observed during temperature cycling.

However, drying and sealing are not all that are required to minimize frequency drift. If the material used for mounting the SAW device in its enclosure outgasses for a long period of time, this material will contaminate the surface and cause frequency drift. RTV is commonly used for mounting SAW devices because it provides a very strong, yet stress-free, hold on the SAW substrate. However, aging studies performed on devices mounted in this material showed very large negative aging rates, as large as 50 to 100 ppm per year in the first year.[8] The evidence from bulk crystal resonator studies is that any mounting scheme involving organic material will cause a large aging rate.

In developing packaging technology for SAW devices we have used, wherever possible, the technology developed over the years for bulk wave quartz crystal resonators. However, the specialized equipment for sealing bulk wave devices is not readily available at Raytheon, and we have had to develop our own packaging techniques. As stated earlier, the devices made for this program were mounted in a Tekform #50272 butterfly case with gold wire straps (see Fig. 4.3). Devices which were to be put under aging test were thoroughly cleaned with detergent, trichloroethylene, and propanol before mounting. After mounting, they were given a final cleaning with ultraviolet light and ozone.[9] The sealing was accomplished in a high-vacuum chamber by heating the entire package to 310° C to melt a solder preform. All devices were sealed with a gold tin solder. Some devices were sealed under high vacuum (2×10^{-7} mm of Hg), while some were sealed in an argon atmosphere at atmospheric pressure. Table 5.1 lists nine devices put under aging tests and shows the various relevant parameters. The device in oscillator No. 5 (Q514A) was not fabricated under this contract, but was packaged at the United States Army Electronics Command at Fort Monmouth, New Jersey, and was tested under a Raytheon research program. This device is included in this report because it illustrates the performance of a device packaged under conditions similar to the best bulk wave devices. A standard HC-36/U enclosure shown in Fig. 5.6 was used for this device. The device was mounted with gold wire straps.

On all of the substrates a chemical-mechanical polish was used by the vendor to produce the surface finish. This has been found to cause much less

Table 5.1 Packaging Parameters of Nine Devices Undergoing Aging Tests.

Oscillator Number	Substrate Number	Frequency at Start (MHz)	Substrate Material	Material Grade	Transducer Metal (thickness)	Package	Atmosphere	Pre-Aged	Mounting Wire Diameter (inches)
1	Q 601A	401.1980	ST Quartz	Pure Z	Al (1000Å)	Flatpack	Vacuum	No	.003
2	Q 617A	401.2088	ST Quartz	U.S. Grade	Al (1000Å)	Flatpack	Vacuum	No	.003
3	Q 638A	400.9611	ST Quartz	Premium Swept Q	Al (2000Å)	Flatpack	Argon	No	.010
4	Q 638B	400.9490	ST Quartz	Premium Swept Q	Al (2000Å)	Flatpack	Vacuum	Yes (11 days @ 90°C)	.010
* 5	Q 514A	310.8199	ST Quartz	U.S. Grade	Al (1500Å)	HC-36	Vacuum	Yes (180 days @ 25°C)	.010
6	Q 619B	401.1920	ST Quartz	U.S. Grade	Au (500Å)	Flatpack	Vacuum	No	.003
7	Q 604	401.2119	ST Quartz	Pure Z	Au (500Å)	Flatpack	Vacuum	No	.003
8	T 49	401.1979	$SiO_2/LiTaO_3$	---	Al (1000Å)	Flatpack	Vacuum	No	.003
9	T 55	401.2083	$SiO_2/LiTaO_3$	---	Al (1000Å)	Flatpack	Argon	No	.010

* Sealed at U.S. Army Electronics Command and tested under an internal Raytheon research program.

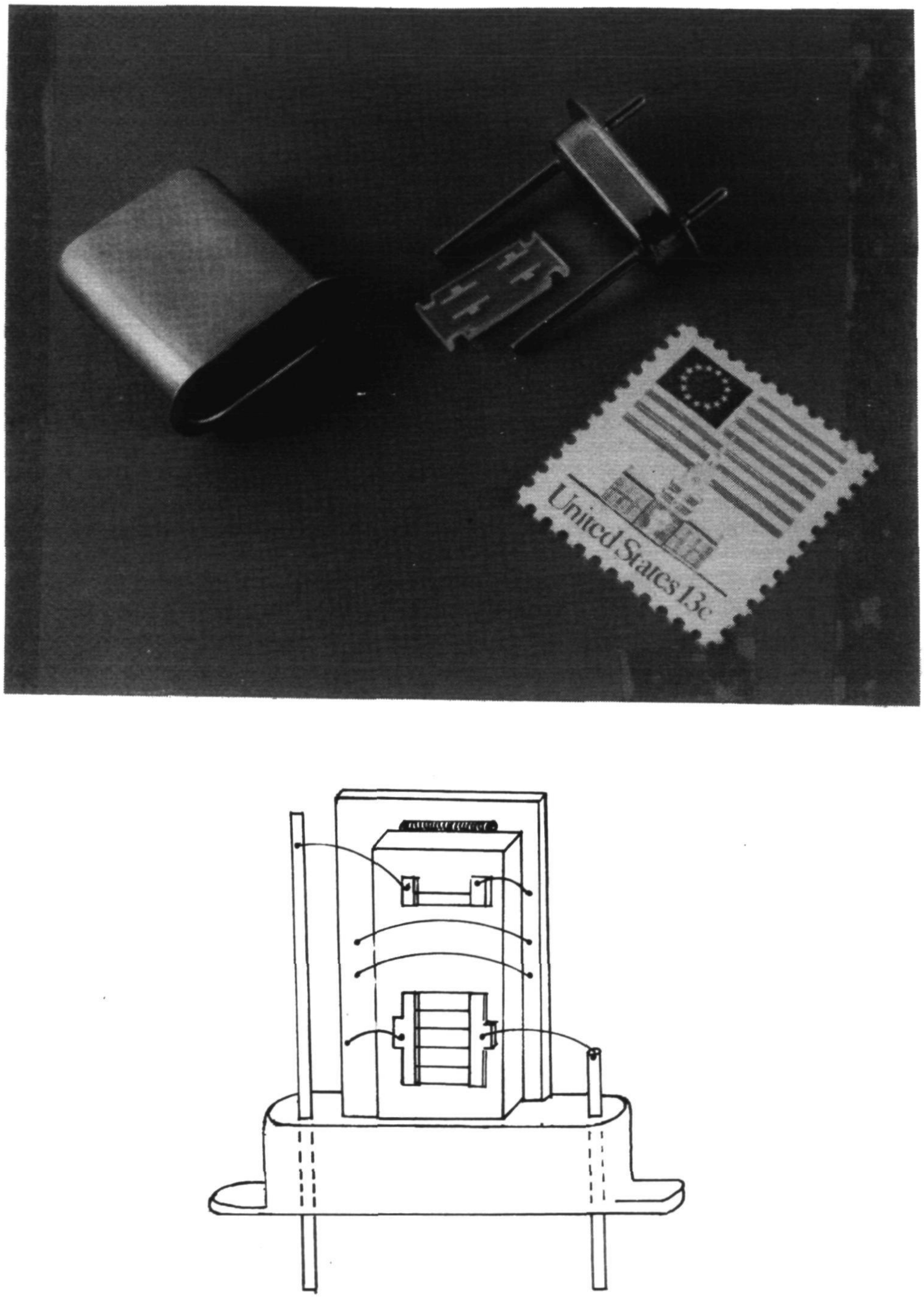

Figure 5.6 SAW Device Mounted in HC-36/U Enclosure.

surface damage than a purely mechanical technique. Several different grades of quartz were used to determine if the quality of the bulk material was related to the observed aging rates. Next to natural quartz (which we did not use) the "premium swept Q" grade has been found to give the lowest aging in bulk wave resontors. Somewhat lower grades are "pure Z" and standard ultrasonic (U.S.) grade.

Also, as discussed in Sec. 4, both aluminum and gold transducers were used to help isolate aging mechanisms caused by the transducer metal. Aluminum is normally the best material to use for SAW transducers on quartz because of its close acoustic match, but it is deposited in a highly stressed state and is active chemically. Aluminum electrodes have been found to cause much higher aging on bulk wave resonators [10] than devices with gold electrodes. Since gold adheres very weakly and is not active chemically, it was felt that devices with gold transducers would offer a good contrast to those with aluminum transducers. This could help in identifying aging mechanisms unique to aluminum and it was felt that the gold devices might offer the lowest aging of all.

There is no evidence that a surface wave device should age significantly faster than a bulk wave resonator <u>of the same frequency.</u>[11] However, surface wave devices are typically operated at frequencies ten to one hundred times higher than bulk wave devices, and this smaller wavelength will make the acoustic wave much more sensitive to surface phenomena. Therefore, with present technology it is not likely that high frequency surface wave devices will reach the low aging rates of 1 part in 10^8 per year seen in the best low-frequency bulk wave devices.

There are some important differences in aging mechanisms between surface and bulk wave devices. In bulk wave devices, when material accumulates on the surface, the frequency drops because the plate becomes thicker. With surface wave devices, however, the frequency (i.e., velocity) goes up or down, depending on the acoustic properties of the foreign material that accumulates on the surface. For instance, if aluminum on the surface oxidizes, the SAW frequency will go up because the velocity increases.[12] On a bulk wave device the same oxidation process will cause the frequency to go down. Therefore, one cannot simply use observed aging effects on bulk wave devices to explain aging effects on surface wave devices.

The aging data on nine SAW devices were obtained by measuring the frequency of nine operating oscillators. The oscillators were kept in an environmental chamber to maintain a constant temperature (20°C ± 0.5°C), but the temperature of each oscillator was also monitored with a thermocouple mounted near the SAW device. To isolate the oscillator from drafts and rapid temperature fluctuations, each circuit board, as shown in Fig. 4.8, was mounted in a cast aluminum box measuring 4 × 2.5 × 1.75 in. Before each oscillator was put into the aging chamber, its temperature dependence and short-term stability were measured. The coefficient determined from the temperature dependence measurements was used to correct the frequency for small temperature variations observed during the aging tests. The frequency of each oscillator was measured once a day, and a weekly average was computed. The counter used for these measurements was checked periodically against a frequency synthesizer with a guaranteed drift of less than 0.6 ppm per year.

Figures 5.7, 5.8, and 5.9 show the observed aging results for the nine oscillators listed in Table 5.1. Figure 5.7 shows the results for five devices with aluminum transducers on ST-cut quartz. Figure 5.8 shows results for two gold on quartz devices, and Fig. 5.9 shows results for two devices on $SiO_2/LiTaO_3$. The numbers on the curves correspond to the oscillator numbers in Table 5.1.

Figure 5.7 shows that the quartz devices with aluminum transducers which were not pre-aged (oscillators 1, 2, 3, and 5) drifted upward, at least initially. This is in comparison to the two devices with gold transducers in Fig. 5.8, which are drifting downward in frequency. If it is reasonably assumed that gold is the more stable material, these results would seem to indicate that the upward drift seen in Fig. 5.7 is caused by some mechanism unique to aluminum.

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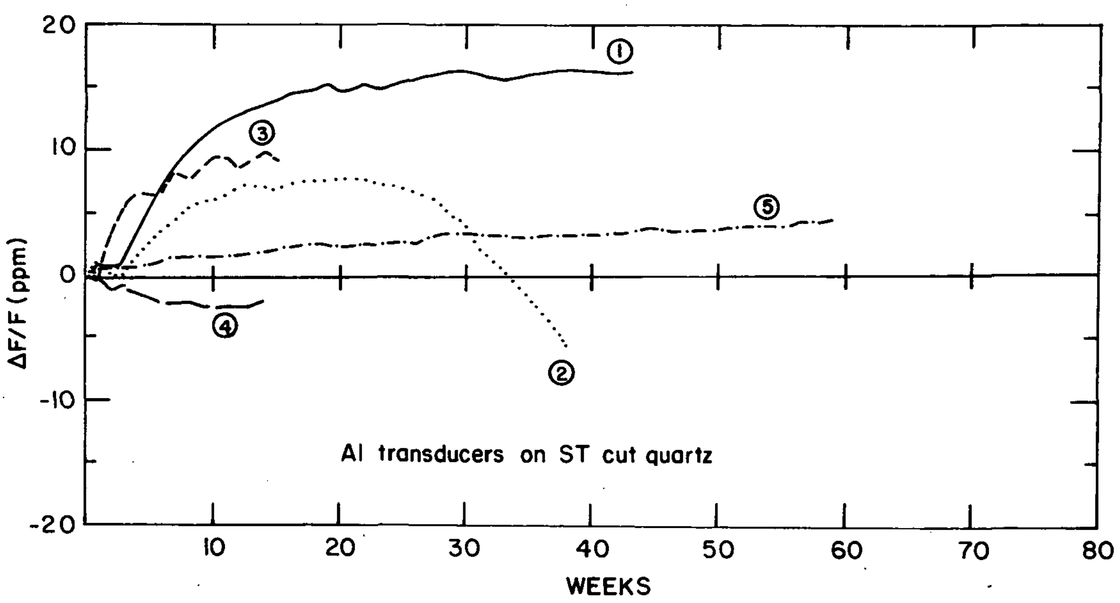


Figure 5.7 Aging of Devices with Aluminum Transducers on ST-Cut Quartz.

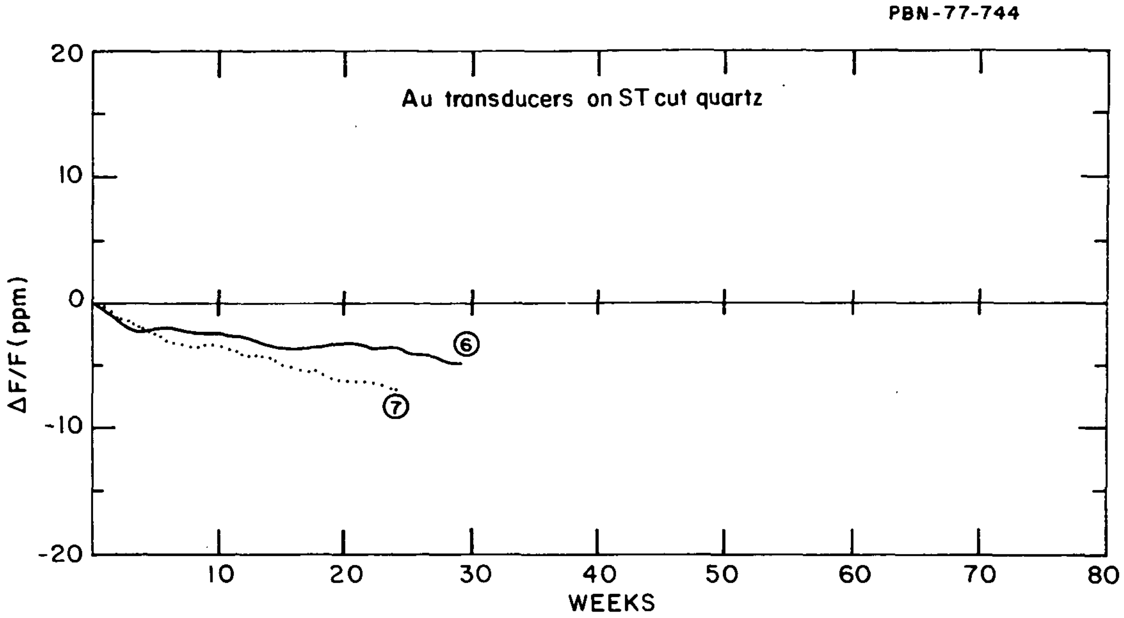


Figure 5.8 Aging of Devices with Gold Transducers on ST-Cut Quartz.

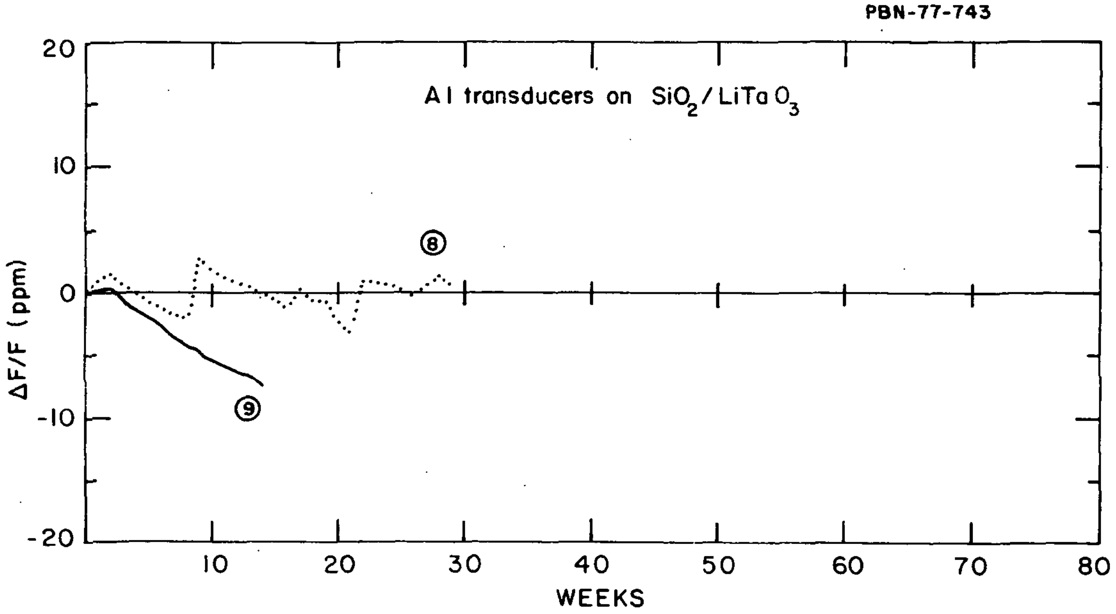


Figure 5.9 Aging of Devices with Aluminum Transducers on SiO_2/ $LiTaO_3$.

Two possible causes for upward drift are the oxidation of the aluminum, or changes in the stress caused by the aluminum film. The rate of oxidation is only slightly sensitive to temperatures below 300° C,[10] but the rate of stress change is strongly dependent.[13] Therefore, storing a device for a period of time at an elevated temperature would accelerate the stress changes but not the oxidation. Since the rate of change for most aging mechanisms decreases with time, a period of accelerated aging will produce a lower rate of drift once the device is returned to normal operating temperature. The device in oscillator No. 4 was pre-aged for eleven days at 90° C after sealing and the results not only show a reduced aging rate but also a change in direction of the frequency drift. This result would appear to rule out oxidation of the aluminum as the aging mechanism.

Another interesting feature of the data in Fig. 5.7 is the change from positive drift to negative drift at 20 weeks, for oscillator No. 2. After 38 weeks of operation the oscillation was stopped and the device was tested for leaks. The package was found to be leaky, which would explain the shift to negative drift. (Moisture entering the package would be adsorbed by the quartz and the SAW velocity would drop.) A similar shift to negative drift at 36 weeks was also observed on a Raytheon device which is not shown.

To slow the entry of contaminants into a leaky package, two devices (oscillators Nos. 3 and 9) were sealed in argon at atmospheric pressure. Argon was used because it is not chemically active and also because it can be obtained highly purified. These devices have not been operating long enough, however, to verify if the argon is serving any useful function.

A better alternative to backfilling is to use a more leak-proof package. This could involve a package with fewer feedthroughs (the current packages have 8) and a coldweld seal. The HC-36/U used for oscillator No. 5 is just such a package, and the results with this oscillator have been very good. Though the low aging exhibited by this oscillator is partially due to the six-month interval between packaging and sealing, the good performance of this device does indicate the advantage of the highest quality packaging. A similar device under aging at ECOM is showing somewhat lower aging.

Oscillator No. 3 in Fig. 5.7 has shown rather erratic behavior because the SAW device was mounted in the flatpack with the gold straps passing diagonally over the ends of the quartz substrate. The temperature dependence of this device showed that the turnover point had shifted from +30° C to +15° C, which indicates that the substrate is under compression. Apparently this stressed condition is responsible for the erratic behavior in the frequency drift. Devices mounted as shown in Fig. 4.3 have not shown any indications of stress or erratic aging.

The two gold devices and the pre-aged aluminum device show the lowest aging rates, but the cause for the downward aging of these devices is not known at this time. One possibility is contamination from slowly leaking packages or inadequate cleaning. Two gold devices have been sent to ECOM for sealing under a joint Raytheon-ECOM experiment, and it is hoped that results from these devices will shed some light on the specific mechanism for the downward drift. Other possible causes for the downward drift are changes in surface stress or damage on the quartz, and changes in the transducer metal. Various grades of quartz have been used, and no correlation has been observed between higher quality and lower aging. A final possible source of aging is the external circuitry. Though wideband devices have been used to minimize the phase shift in the circuit components, it is still possible that these components may contribute to aging. A change in phase shift through the amplifiers and coupler of 0.1 percent will cause a frequency change of approximately 1 ppm.

The aging of two oscillators made with $SiO_2/LiTaO_3$ devices is shown in Fig. 5.9. Oscillator No. 8 has been very erratic, but there is no evidence that the mounting is the problem. It is possible that the SiO_2 layer is unstable, but this is the only device out of five which has shown such behavior. (Three oscillators had been aged on an earlier Raytheon program.) Another factor, which may be only coincidental, is that No. 8 is the only oscillator in which carbon resistors were used in series with the SAW device. Nevertheless, No. 9 and the first 15 weeks of No. 8 indicate a relatively large negative aging rate. From No. 9 it is estimated that the drift will be on the order of 20 ppm in the first year. It is possible that this rate could be improved by pre-aging, but this has not been tried yet.

In addition to frequency, the output power level of all of the oscillators has also been monitored. The power level has been found to be constant to within 0.15 dB for all of the oscillators.

The results of our aging tests indicate that a pre-aged aluminum device is a good choice for low aging. However, it is necessary that the aging tests be made on more pre-aged devices to test their reproducibility. Also, backfilling should be tried in conjunction with pre-aging to evaluate that technique. Another direction which should also be pursued is to evaluate devices sealed in better packages and then pre-aged. It would be very useful to have more devices sealed at the U. S. Army Electronics Command.

5.4 Other Factors Affecting Frequency Stability. In addition to the topics just discussed, other phenomena may affect frequency stability in the short, medium or long term. One possible source of frequency variation is the dependence of oscillator frequency on the power source voltage. Two phenomena cause this dependence: (1) the temperature of the amplifier and SAW device is influenced by power consumption, and (2) the phase shift through the amplifiers is sensitive to the applied DC voltage. The first problem would be solved automatically with temperature compensation, but the second requires voltage regulation. Measurements on an oscillator using a UTO-513 amplifier showed the frequency to change by about 2 ppm per volt. Though this dependence may vary somewhat between amplifiers, the result indicates that voltage regulation will probably be required for the oscillator supply.

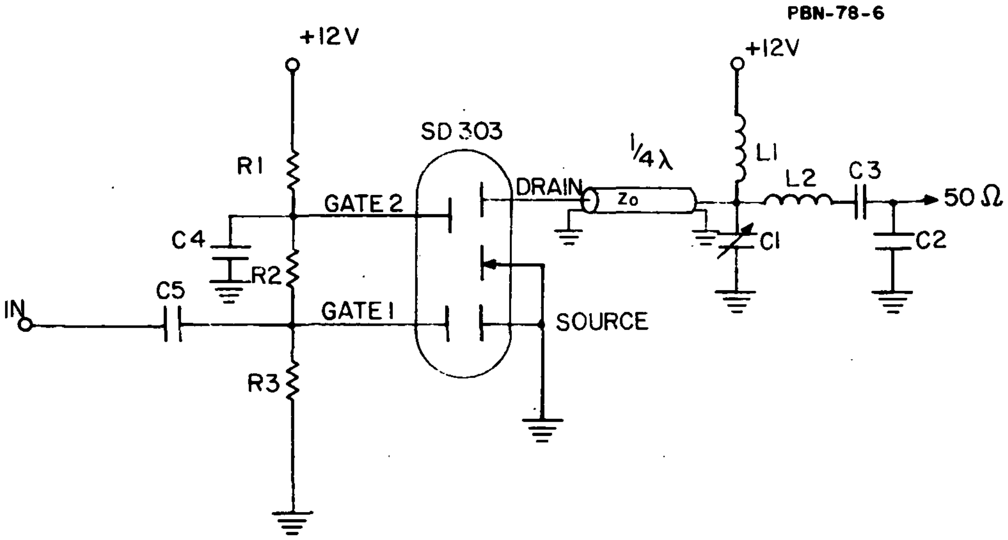
A second source of frequency variation is vibration or motion. Both are related to the way the SAW device is mounted in its enclosure. Any movement of the SAW substrate or connecting wires could cause a problem. Vibration may cause the short-term stability to degrade, or motion and change in position may cause frequency shifts on a longer time-scale. These areas have not been investigated, and it is not known whether or not a problem exists.

6. CIRCUIT CONSIDERATION

Up to this point, most of the discussion has involved the SAW device, but the circuit elements are also important to the overall performance of the oscillator. Circuit elements affect overall performance more with surface waves than bulk waves because the high frequencies at which SAW devices are used limit the available Q (or group delay). The loaded Q of a 400 MHz SAW device on quartz is limited to less than about 10,000 (i.e., 8 μsec), which may be as much as 100 times less than a bulk wave device at a much lower frequency.

Most of the work on this program has been carried out with wideband commercial amplifiers such as the Avantek 502, 503, and 513 or Watkins-Johnson A51. These amplifiers are very stable and have a group delay, τ_g, of about only 1 nsec. However, their power efficiency is typically only a few percent or less. A maximum efficiency of 12 percent is obtainable only on the higher power devices which require over 1 watt of input power. Also, the overall efficiency of the oscillator is reduced even further depending on how much power is coupled out. In most of this work -10 dB couplers were used, but -3 dB couplers could be used. For the circuit in Fig. 4.7, using the Avantek UTO-502 and 503, a typical rf power output of +3dBm (2 mW) was obtained for an input of 24 VDC at 70 ma or 1.68W. If the SAW device was matched to 50 Ω to lower the insertion loss to 12dB, the Avantek 513 could be used. This gives the same rf power output but reduces the DC requirement to 24 VDC at 50 ma or 1.2 W. By using a Watkins Johnson A51, an rf power output of -16dBm (25μW) was obtained for 12 VDC at 4 ma or 48 mW.

Many applications will require more efficient amplifiers, and for this reason a study was conducted by J. Perkins of Raytheon's Missile System Division to determine what magnitude of efficiency could be obtained with a custom-built amplifier. His results show that by using a modified class C amplifier and a relatively narrowband impedance matching network, the amplifier efficiency can be increased to the 75 to 90 percent range. Figure 6.1 illustrates the design of an amplifier using an inexpensive SD 303 dual-gate FET. The FET will operate to well above 1 GHz and is operated



D- MOS FET
N-CHANNEL ENHANCEMENT

Figure 6.1 Proposed High-Efficiency Amplifier Using an SD 303 Dual-Gate FET.

in a switching mode. The FET is biased "ON" so that the oscillator will start, but is driven well into saturation so that it will produce essentially a square wave output. The low "ON" resistance of the FET and the high impedance of the 1/4 λ line at odd harmonics of the fundamental frequency minimizes the power loss in the amplifier. The impedance matching network at the output of the 1/4 λ line serves to match the load impedance to the FET output and also to filter the output signal. The amplifier in Fig. 6.1 is estimated to have a power gain of better than 20 dB, a power output of 25 milliwatts and a power efficiency of 75 to 90 percent. The group delay is estimated to be 10 to 20 nsec.

The coupler used in the oscillator will reduce the overall efficiency somewhat, but it is felt that an oscillator efficiency approaching 50 percent can be achieved. However, it is very important that the overall performance of an oscillator using such an amplifier be thoroughly tested. The larger group delay of this amplifier may adversely affect the frequency stability of the oscillator. Stability in the short, medium and long term would all have to be measured with an oscillator using this amplifier. It may be necessary to compromise between efficiency and group delay, but, nevertheless, it does seem very likely that the oscillator efficiency can be significantly improved over that obtained with commercial wideband amplifiers.

A second area where circuit modification may be necessary was mentioned earlier in the discussion of temperature stability. It is obvious that for many applications some improvement in temperature stability is required, and compensation with a passive or active network may be necessary. It is felt that this work is of primary importance for the application of SAW oscillators to communication systems.

7. CONCLUSIONS AND RECOMMENDATIONS

The work under this contract has demonstrated that a 401.2 MHz oscillator can be built using a SAW delay line with a very simple feedback circuit employing no multipliers. Three types of delay lines have been fabricated and tested in working oscillators. The performance of these oscillators has been evaluated and compared to the typical requirements of a local oscillator in an assumed communication system.

Oscillators employing all three types of SAW devices have demonstrated a short-term stability of better than 1 part in 10^9 for a 1 second count. While some devices showed a fractional frequency deviation as low as 2×10^{-10}, others with high flicker noise levels showed a fractional deviation of 2×10^9. However, the stability of oscillators with high flicker noise levels can be improved to better than 1 part in 10^9 by minor circuit changes to reduce the insertion loss of the SAW device. The conclusion from these tests is that a short-term stability of 1 part in 10^9 for 1 second is readily achievable with SAW oscillators.

Our results from aging tests show that the long-term stability of a SAW oscillator depends strongly on the type of SAW device used and its packaging. Unpre-aged devices with aluminum transducers on ST-cut quartz showed upward frequency drifts of as much as 15 ppm in the first 20 weeks. However, the drift decreased significantly to about +2 ppm for the next 20 weeks. A pre-aged aluminum device has shown a negative drift of 2 ppm in 14 weeks, and a device packaged at ECOM in an HC-36/U enclosure has shown a drift of +4.5 ppm in nearly 60 weeks of operation. Devices with gold transducers on ST-cut quartz have aged downward by 5 to 8 ppm in 30 weeks, while the devices on $SiO_2/LiTaO_3$ will have decreased an estimated 13 ppm in 30 weeks.

Though the long-term stability of ± 2.5 ppm (or ± 1000 kHz) exhibited by present bulk wave oscillators has not yet been achieved, the data on SAW oscillators obtained during this project looks very promising. Pre-aging, backfilling, and/or better enclosures will very likely bring the long-term drift down to 1 to 2 ppm/year.

The temperature dependence of the SAW oscillators was also measured, and as expected the oscillators built with SiO_2/ $LiTaO_3$ devices were significantly better than those on ST-cut quartz. An SiO_2/ $LiTaO_3$ oscillator is capable of showing less than 10 ppm change in frequency for a -40°C to +45°C temperature range as compared to approximately 65 ppm for an oscillator using ST-cut quartz. However, the relatively high aging rate observed on $SiO_2/LiTaO_3$ oscillators probably rules out their use in many applications. Therefore, ST-cut quartz must be used, and it thus becomes necessary to use some form of temperature compensation to achieve the required stability of 4 Hz over 15 minutes. By comparing ST-cut quartz to the AT-cut quartz used for bulk wave oscillators, it is obvious that a sophisticated compensation technique will be required. Several approaches to passive compensation circuits are available and this should receive a major effort in future work.

From an overall evaluation of frequency stability and ease of fabrication, the approach using aluminum transducers on ST-cut quartz appears to be the best. These devices are easily produced and need not be trimmed. The aluminum on ST-cut quartz approach also minimizes the electrical adjustment necessary in achieving a desired frequency. Though ST-cut quartz does not have the best temperature stability, the pre-aged device with aluminum on ST-cut quartz showed a much lower aging rate than the $SiO_2/LiTaO_3$ devices. The gold devices also showed relatively low aging, but these devices are more difficult to fabricate than aluminum devices and also tend to have higher insertion loss.

For all of the present work, commercial wideband amplifiers were used in the oscillator circuits. It was obvious that these amplifiers were not ideal for applications where only limited power is available. Our work has shown, however, that by using a more limited bandwidth circuit and by operating an FET in a highly nonlinear mode, a much more efficient amplifier can be designed. More work is required in this area to produce a working amplifier, but it appears very likely that amplifiers with efficiencies approaching 80 percent can be built and that the overall oscillator efficiency can be increased to nearly 40 percent.

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