A Radar System Application of an 840-MHz SAW Resonator Stabilized Oscillator

WILLIAM J. TANSKI, MEMBER, IEEE, RAYMOND A. ST. CYR, MEMBER, IEEE, PHILIP G. DRAGONETTI, MEMBER, IEEE, AND EDWARD G. KOSCO

Abstract—**An 840-MHz SAW resonator stabilized oscillator has been developed and is being manufactured for incorporation into a radar system. This stable fundamental-mode frequency source is simple and compact (1 in^3 in volume) and delivers a relatively high output power of +25 dBm. These advantageous characteristics are made possible by the high-frequency low-loss distortion-free/linear-phase response of the two-port SAW resonator filter incorporated in the design. Details of the device and circuit design and oscillator performance are presented.**

I. Introduction

We have developed an 840-MHz fundamental-mode oscillator which utilizes a two-port surface acoustic wave (SAW) resonator filter [1]–[3] as the frequency stabilizing element. The purpose of this development was to reduce the complexity, size, weight, and power consumption of UHF and L-band oscillators through the use of high-Q SAW resonators. These resonators, which we can fabricate to operate at frequencies over 1400 MHz, were chosen for use because of their low insertion loss ($\leqslant 3$ dB electrically matched), high-loaded Q values (in excess of 1000), their distortion-free/linear-phase response characteristics, and their relatively high power capacity. SAW delay lines have not yet been built with this highly desirable combination of characteristics due to the formidable problems involved, and fundamental mode bulk acoustic crystals [4]–[5] are difficult to fabricate at frequencies above 30 MHz.

This 840 MHz oscillator delivers a +25-dBm, low FM noise, output signal, and the oscillator exhibits good uncompensated flatness of frequency and power over a 0° to 60°C temperature range. FM noise is less than 0.005 Hz per $\sqrt{\mathrm{Hz}}$, 10 kHz removed from the carrier.

Here we discuss the resonator design as well as the design and performance details of the oscillator. The performance specifications for this oscillator have been met without difficulty, and the advantages of this SAW resonator stabilized oscillator over conventional approaches using a low frequency bulk mode crystal can readily be seen. This work was performed in 1979 and to our knowledge is the first systems application of a UHF SAW resonator. In 1980, we developed a 500-MHz SAW resonator for use as a noise suppression filter in an earth–satellite frequency source. Details of this 500-MHz filter are presented in [6]–[8].

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W. J. Tanski and R. A. St. Cyr are with Sperry Research Center, Sudbury, MA.

P. G. Dragonetti and E. G. Kosco are with Sperry Microwave Electronics, Clearwater, FL.

II. Two-Port SAW Resonator

In order to meet the temperature stability requirements the resonators are fabricated on the ST (42.75° rotated y) cut of quartz, and to minimize losses and the aging rate, etched-groove reflectors are being used. Also, to minimize losses and distortions we utilize recessed-aluminum transducers, which are overlap weighted, and the cavity length and width have been limited. This type of resonator, which is shown schematically in Fig. 1, has been discussed at length previously [9]–[12] and we shall only summarize the design and fabrication procedures here. Fig. 1(a) shows all the elements of the two-port resonator filter, and Fig. 1(b) illustrates the physical configuration of the reflectors and the transducers. We are able to approach or attain the maximum possible device Q value (due to irreducible material viscosity losses) of 12 500, unloaded at 840 MHz, consistently using this configuration, and we have been successful in eliminating all forms of distortion.

The design parameters for the resonator are listed in Table I. The wavelength λ_0 was selected on the basis of known velocity data [9] and previous experience in the design of devices near 840 MHz. One iteration in the mask design, in which the cavity length [9] was adjusted, was required to attain the desired resonance frequency. Experimentally we have found it necessary to limit the acoustic aperture to a maximum value of $50\lambda_0$, in addition to overlap weighting the transducers, in order to completely suppress higher order transverse mode resonances. The etch depth was chosen to be shallow enough to reduce bulk acoustic mode losses [9] but deep enough to minimize transducer ohmic losses and the length of the reflectors. The transducer length was maximized to reduce the input impedance of the device and to facilitate electrical matching. The upper limit of $50\lambda_0$ on the acoustic aperture produces a transducer with a relatively high input impedance. An equivalent circuit for a resonator, valid near resonance, is given in Fig. 2, along with the electrical matching network used.

The transmission response of a typical 840-MHz device is given in Fig. 3 where both narrow and broad-band views

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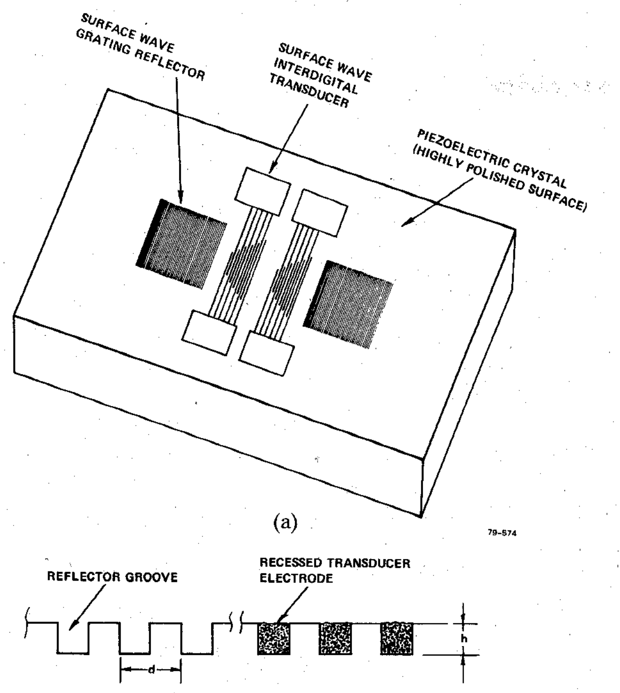

Fig. 1. (a) Diagram of a two-port SAW resonator, showing all the elements of the two-port resonator filter. (b) Section view of the two-port SAW resonator filters used to stabilize the oscillator. Overlap-weighted-recessed-aluminum transducers are used to suppress unwanted transverse mode resonances and acoustic reflections.

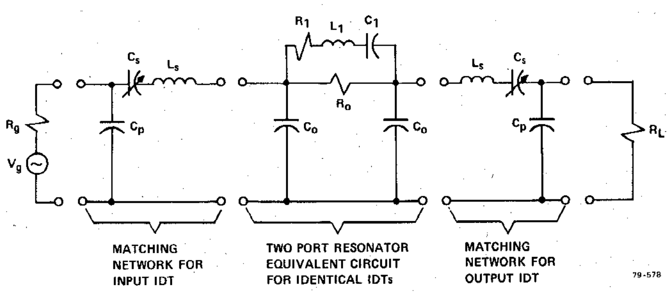

Fig. 2. Two-port resonator equivalent circuit valid in the vicinity of the resonance frequency, and the matching networks.

are shown. Both input and output ports have been conjugately matched to the 50-Ω measurement system to make this measurement. Average values of the device response are loss=2.4 dB; $Q=1500$, and out of band rejection=14 dB. The input impedance (with the opposite port conjugately matched) is approximately $R=2500\ \Omega$ in parallel with $C=0.7$ pF. We have calculated resonator equivalent circuit parameter values [1] and have found them to be as follows:

$$R_1 \simeq 240\ \Omega,\ L_1 \simeq 1280\ \mu\text{H},\ C_1 \simeq = 7.9\times 10^{-5}\ \text{pF}$$

$$R_0 \simeq = 15.4\ \text{k}\Omega \text{ and } C_0 \simeq = 0.6\ \text{pF}$$

$$\times (\text{which includes 0.5 pF of parasitic capacitance}).$$

The approximate values of the matching circuit components are $L_s \simeq = 2\ \mu$H, $C_s \simeq 2$ pF, and $C_p \simeq 3$ pF. Using these component and equivalent circuit values, we calculate

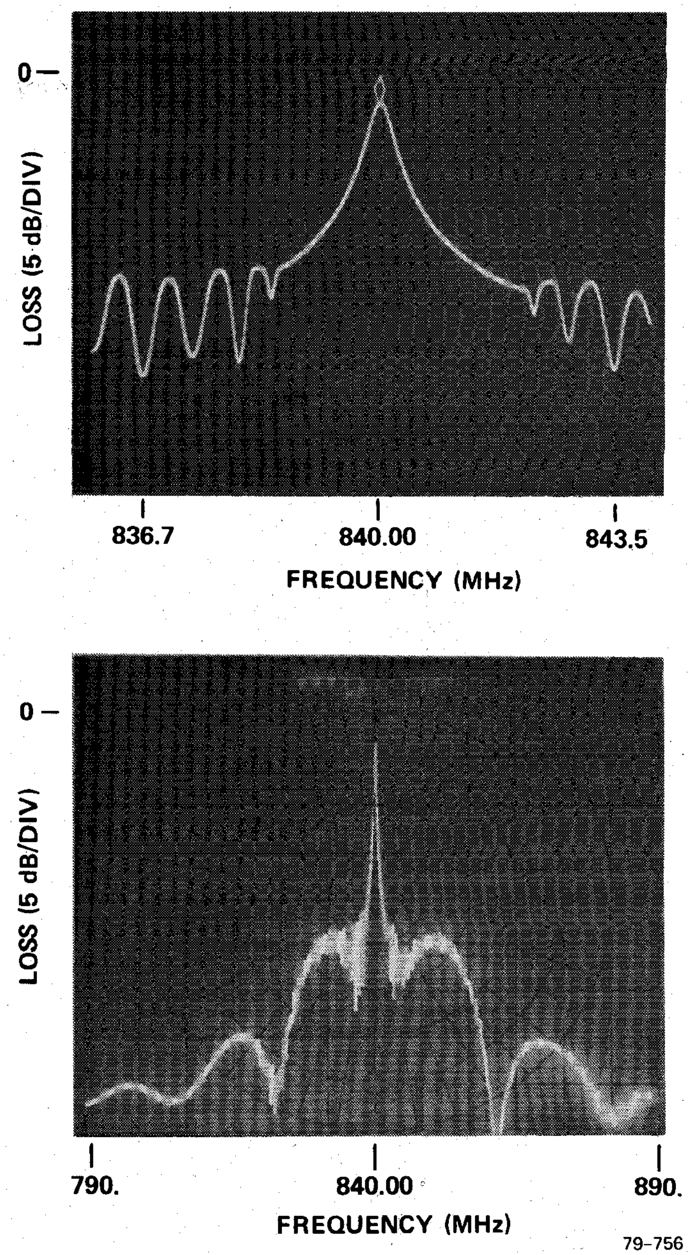

Fig. 3. The electrically matched frequency response of a typical two-port resonator used to stabilize the oscillator. The loaded Q value exceeds 1500 with an insertion loss of 2.4 dB. Both narrow and wide-band views of the response are shown.

TABLE I
840-MHz RESONATOR DESIGN PARAMETERS

Wavelength	$\lambda_0 = 3.752\ \mu$m
Line period	$\lambda_0/2$
Line width	$\approx\lambda_0/4$
Acoustic aperture	50 λ_0
Cavity length	80.0286 λ_0
Design etch depth	440 Å (h/λ_0 = .012%)
Reflectors	900 grooves
Transducers	61 electrodes (30 λ_0)

an input impedance of $R=2560\ \Omega$ in parallel with 0.61 pF, which agrees well with the measured input impedance.

The devices are fabricated [11] by replicating twelve patterns on a substrate, ion etching the grooves, followed by metalization, liftoff, and dicing the substrate into chips. The chips are then cleaned, bonded into 3/8-in square flatpack at one end only, using a low outgassing polyimide adhesive [13], electrical leads are bonded on, and a lid is brazed on the flatpack in the presence of dry nitrogen. The yield of useable devices is about 80 percent with a resonance-frequency variation of about ± 50 kHz for the chips on a given substrate.

III. SAW Oscillator

The two-port SAW resonator was selected as the frequency determining element because of its advantages of low-loss, high-power capacity, high Q-low-distortion, and linear-phase characteristics. The resonator provides shunt feedback from the output to the input of a common emitter transistor stage. Fig. 4 is a circuit schematic broken down into functional blocks. To facilitate design and testing, particularly of the SAW device, each block was designed to a 50-Ω impedance level as indicated by the asterisks in Fig. 4.

The SAW block contains the two-port resonator and impedance matching networks. These networks are needed to transform the relatively high SAW resonator input/output impedance to 50 Ω. Note that this matching network, using series inductors, incorporates the input capacitance of the SAW device. The matching networks are low in loss, however, because of the relatively high impedance of the SAW device, these networks account for a large part of the total phase shift across the total matched resonator circuit. SAW resonator design techniques used to eliminate transverse acoustic modes resulted in an unmatched device input impedance of about 2500 Ω. The elimination of all forms of distortion yields a resonator with a very smooth phase versus frequency curve in the vicinity of the center frequency. This is essential to smooth frequency tuning and frequency stability particularly during temperature slewing. Fig. 5 is a polar plot of transducer gain of the conjugate-matched resonator. For this particular device and network, the insertion phase is shown to be -295 deg and the insertion loss is 3.5 dB.

Following the matched resonator is the oscillator amplifier which uses an HP5102 transistor. At 840 MHz it provides 16.5 dB of gain with as much as 27-dBm output power. Bias stability is provided through a separate transistorized feedback circuit which allows the emitter of the HP5102 to be well grounded.

The output of the transistor stage is split into two paths by the power splitter. One path leads, through a low-pass filter, to the output. The other path lightly couples the signal (9-dB loss) to the SAW resonator input. To protect the SAW device against excessive RF input power and transients, back-to-back limiter diodes were placed across its input. When oscillations build up to their final amplitude, the limiter has an effective loop loss of 4 dB.

Having made a full circle around the feedback loop it is apparent that the above loop losses and gains sum to 0 dB thus satisfying one requirement of oscillation. The total phase shift from the amplifier input to the limiter output is -425 deg, which includes the nominal -180 deg common emitter phase reversal. When the matched resonator phase shift of -295 deg is added the resultant output is in phase (-720 deg) with the amplifier input and the zero phase shift requirement of oscillation is satisfied.

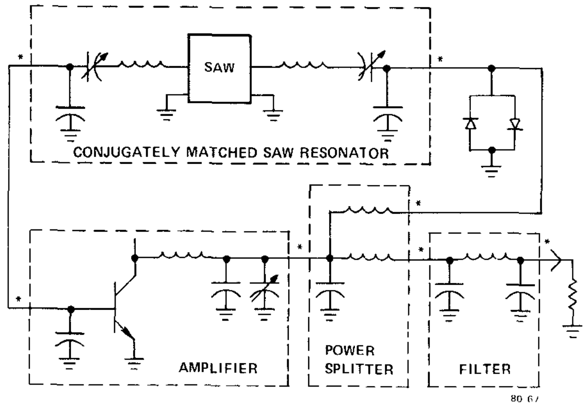

Fig. 4. Oscillator block diagram and matching networks.

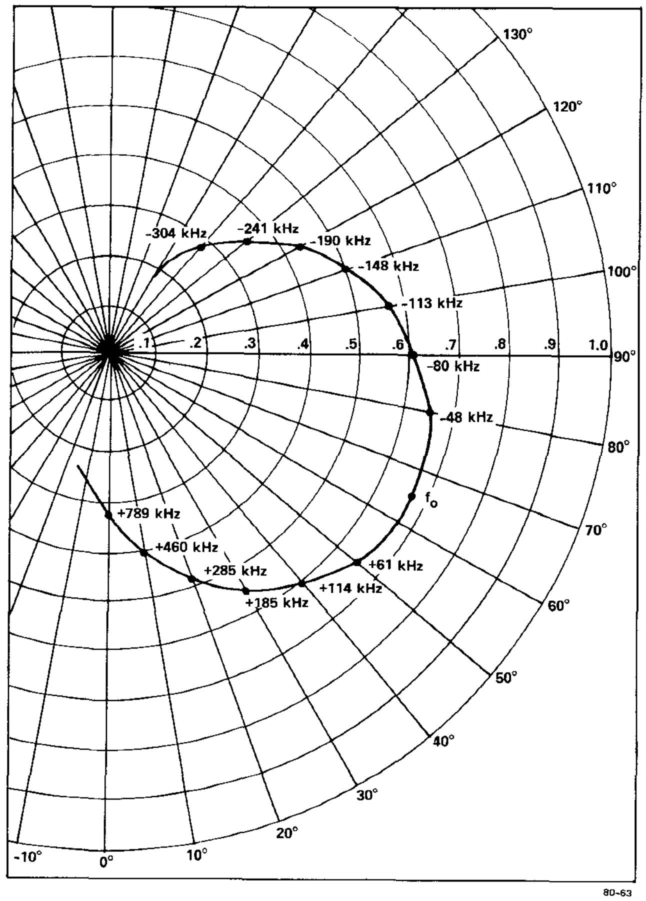

Fig. 5. Transmission response S_{21} of conjugately matched SAW resonator.

IV. Performance

In Table II we list the physical and electrical performance characteristics of the SAW oscillator and the bulk-mode crystal based oscillator which was previously used. We note that the previous oscillator design had such a

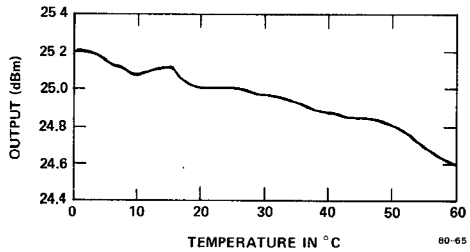

Fig. 6. Power variation versus temperature.

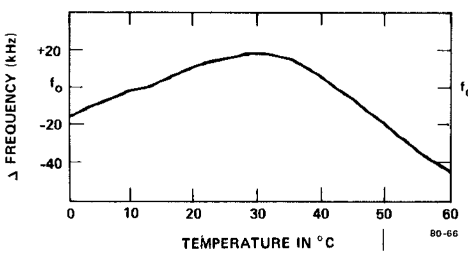

Fig. 7. Frequency variation versus temperature.

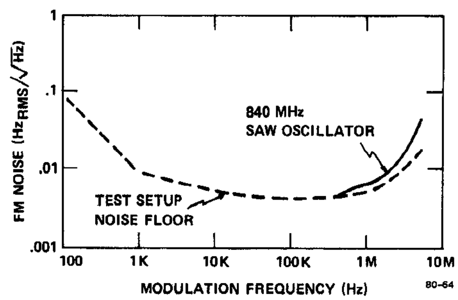

Fig. 8. Noise test results.

TABLE II
COMPARISON OF SAW OSCILLATOR WITH CRYSTAL OSCILLATOR

	SAW OSCILLATOR	CRYSTAL OSCILLATOR WITH MULTIPLIERS
Volume	1 Inch^3	16.5 Inch^3
Number of Stages	1	5
Power Supply	1.5 Watts	5.28 Watts
Power Output	320 MW at 840 MHz	320 MW at 840 MHz
Frequency Variation with Temperature	60 kHz Peak to Peak	15 kHz Peak to Peak
Frequency Variation with Tuning	±100 kHz	±12 kHz
Power Output Variation with Temperature	.6 dB Peak to Peak	2.5 dB Peak to Peak* .4 dB Peak to Peak**

*Without DC Feedback Loop
**With DC Feedback Loop

large variation in output power with temperature that a dc feedback loop circuit was required to reduce this variation to acceptable levels. The power output variation of the SAW oscillator is acceptable without the use of a feedback loop. The data in Table II illustrate clearly the advantages of the SAW oscillator design. In the following paragraphs we discuss the performance of the SAW oscillator in greater detail.

A. *Power Variation*

Fig. 6 shows the power output of the oscillator versus temperature. The nominal output power is 25 dBm with a total variation of 0.6 dB peak-to-peak (p–p) from 0° to 60°C. This small degree of power variation results partly from the fact that the matched two-port resonator, unlike the SAW delay line, is low in loss. Since the amplifier has about 4 dB of gain more than needed for starting, the output power is determined by the sharp clipping characteristic of the diodes rather than the gain/temperature variation of the amplifier.

B. *Frequency Variation*

In Fig. 7 we show the oscillator frequency variation with temperature. The total peak-to-peak frequency variation from 0° to 60°C is 65 kHz. We have tested the SAW resonator, electrically unmatched and matched, and have found that for both cases the turnaround temperature (the temperature at which the frequency variation with temperature is zero) is approximately 0°C. The frequency variation of the oscillator with temperature is thus not due to the SAW device or matching components, since the oscillator has a turnaround temperature of about 30°C. We, therefore, conclude that the observed frequency variation is due to the semiconductor components in the circuit.

C. *FM Noise*

The FM noise performance is shown in Fig. 8. The noise measurement is made at baseband with a noise setup having a low noise floor [14]. The latter is set by the noise figure of the baseband amplifier which precedes the wave analyzer, which is a frequency selective power meter. With this measurement system the SAW oscillator noise was undetectable up to 500-kHz offset from carrier but begins to contribute to the measured noise near 1-MHz offset from the carrier.

D. *Impedance Measurement*

It is difficult to measure the SAW device impedance accurately because it greatly exceeds the 50 Ω of the measurement system. This difficulty is caused by the insufficient directivities of the directional couplers in the network analyzer used. To overcome this problem, a special setup was constructed which cancels out any reflected signal due to nondirectivity of the directional coupler. At the single frequency of 840 MHz, this cancellation is not difficult to perform and it has been necessary to avoid the possibility of very large errors.

E. *Power Limitation*

SAW resonators of the type used in this oscillator have been found to be capable [8] of continuous operation at power levels in excess of 15 dBm. The input power to the SAW resonator in this oscillator is approximately +12 dBm; however these devices have been tested with input power levels of +18 dBm for several days with no change in performance detected. Device performance will deteriorate, due to electromigration and stress-induced migration of the electrode metal, in a matter of minutes at an input power level of +24 dBm and higher. The performance change consists of a decrease in resonance frequency, a slight decrease in Q, and the development of higher order transverse resonant modes [8]. The threshold for device change is fairly sharp (in the neighborhood of +22 dBm) and an input of +12 dBm is thus quite conservative.

F. Tunability

The tuning adjustments incorporated into the circuit (Fig. 4) provide for a tuning or pulling range of ±100 kHz about F_0. While high Q requirement precludes a much larger tuning range, this amount is sufficient to correct for device tolerance and aging.

G. Size

A significant advantage of this SAW oscillator is the small volume required, only 1 in^3. The unit being replaced required 16.5 in^3 and we see that the SAW scheme affected an order of magnitude decrease in volume.

H. Power Supplies

The SAW oscillator requires a single 15-V dc power source and draws 100 μA. The previous system required two power supplies and consumed four times as much power as the SAW unit.

V. Conclusions

A SAW resonator operating at 840 MHz has been developed for use as the stabilizing element in a radar system test set oscillator. The SAW resonator characteristics of high frequency, low insertion loss, high power capacity, a distortion-free/linear-phase response, and small size are seen to allow significant reductions in subsystem size, weight, complexity, and power consumption. The oscillator meets all system requirements such as high power output, frequency settability, and low noise in a relatively simple manner made possible by this, the first systems application of a UHF SAW resonator.

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