Extremely Low-Phase-Noise SAW Resonators and Oscillators: Design and Performance

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Abstract—SAW resonator designs with overmoded cavities, very wide apertures, dual apertures, etc., as well as modified fabrication techniques, have been used to realize an overall reduction in an oscillator's phase-noise spectrum, i.e., white $\phi$M, flicker-FM, and random-walk FM. The incident RF power-handling capability of these SAW resonator designs is typically in excess of $+20$ dBm, a key requirement to achieving an extremely low oscillator-phase-noise floor. A new "burn-in" procedure at relatively high-incident RF power levels ($> +27$ dBm) was also employed to reduce both the flicker-FM and random-walk FM phase-noise levels. Using these various techniques, a $-100$ dBm improvement in the overall phase-noise spectrum for several prototype oscillators was demonstrated. Specifically, a white-$\phi$M-noise floor of $-182$ dBc/Hz, and a flicker-FM noise level of $-110$ dBc/Hz at $f_o = 100$ Hz carrier offset were measured on several 500-MHz SAW resonator oscillators. A 425-MHz SAW resonator oscillator exhibited a fractional frequency stability, $\sigma_x$, of $1 \times 10^{-14}$ for $t = 1 \times 10^8$. This exceptionally good time-domain stability corresponds to an overall phase-noise improvement in the 400- to 600-MHz frequency range. Details of the SAW resonator's design are given, along with extensive measured data that are useful in relating component noise properties to an oscillator's overall phase-noise spectrum.

I. INTRODUCTION

Surface-Acoustic-Wave (SAW) resonator oscillator phase-noise specifications have continually been pushed to lower levels, driven primarily by military radar and navigation system requirements. For example, improved oscillator phase-noise levels will permit next-generation radars to detect reduced radar cross-section targets, as well as to resolve slower moving targets. This requirement for extremely low-noise X-Band sources in next-generation radar systems has been the motivation behind our efforts to improve the overall phase-noise performance of SAW resonator-based oscillators operating in the 400- to 600-MHz frequency range. The prototype oscillators' phase-noise performance is presented in the context of a typical radar system requirement.

The SAW resonator's design, fabrication and electrical characteristics are described in Section II, including a detailed discussion of a new high-incident RF power "burn-in" technique that has been used to consistently reduce a SAW resonator's flicker noise level. Prototype oscillators incorporating these devices are sufficiently quiet (flicker FM) that the feedback loop amplifiers are now likely to be a significant source of flicker-FM noise. This has generally not been the case for oscillators incorporating more conventional SAW resonator designs where the SAW resonator has been shown to be the dominant source of an oscillator's flicker-FM noise [1]–[3]. Section III gives details of the prototype oscillators' design, including a low-noise electronic phaselocking circuit which is appropriate for voltage-controlled oscillator (VCO) applications.

II. SAW Resonator Characteristics

A. Introduction

In order to achieve an overall reduction in a SAW resonator oscillator's phase-noise spectrum, careful attention must be paid to the resonator's design. Fig. 1 illustrates the basic features of a SAW resonator with a single, wide-acoustic aperture. Dual-acoustic aperture devices similar to those reported by Cross et al. [4] have also been evaluated with comparable results. The resonator's central cavity (inner edge of grating to inner edge of grating) is approximately 265 $\lambda$ long, giving an effective cavity length [5] of about 365 $\lambda$. This results in a multimoded response such as that shown in Fig. 2. For filter applications this would obviously be unacceptable. However, for oscillator applications, the phases of the extra modes above and below the desired central peak are both 180 degrees out-of-phase with respect to the phase of the central resonance and thus do not adversely affect oscillator performance. In fact, we have yet to observe any aspect of an oscillator's overall performance that has been degraded due to the presence of these additional resonances. Also, the acoustic aperture is nominally 300 $\lambda$ wide. This combination of a long (multimode) and wide acoustic cavity results in an increased power-handling capability. The resonator's power handling capability is further enhanced by the use of copper-doped aluminum (~4 percent Cu in the evaporation source) for the transducer metalization.

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As a result, the SAW devices can comfortably handle incident RF power levels of +18 to +20 dBm. Devices have been successfully tested in both TO-8 cold-weld [8] and all-quartz package (AQP) [9] enclosures with comparable performance.

B. Burn-In Procedure

Two-port SAW resonators typically exhibit considerable device-to-device variation in their flicker noise levels, even for devices which are otherwise "identical." A resonator's inherent flicker noise may be measured using a technique that is generally referred to as an "open-loop" or "two-port" phase-noise measurement [10]. The standard deviation of open-loop phase noise levels can be reduced and the average phase-noise level improved significantly through the use of a high-incident RF power "burn-in" procedure on each device [11]. The burn-in involves the application of a higher than normal incident RF power level, usually in the range of +24 to +33 dBm, to the device for a short period of time (typically several minutes to as much as one or two hours). During this burn-in process the output port of the resonator is terminated with a 50-Ω load. The frequency of the RF signal is set as close as possible to the resonant frequency of the device under the high-incident RF power condition. Incident RF power levels in the range of +24 to +33 dBm will produce peak compressional stress levels of approximately 1 to 4 × 10^8 N/m^2, with associated nonlinear elastic effects within the device being evidenced [12]. The power dissipated in the device can also raise the SAW resonator's temperature substantially. These two power-related phenomena will both result in temporary shifts of the device's resonant frequency, thus it will be necessary to track the resonant frequency for a short period of time until equilibrium is achieved.

The choice of an appropriate incident RF power level is dependent upon the device's acoustic aperture and effective cavity length. The level of stress developed within the device is inversely proportional to these parameters [7], and irreversible damage may occur (e.g., increased insertion loss, permanent frequency shifts, and higher transverse mode levels) if the stress level is set too high. Our data suggest that a power level that results in a peak compressional stress of about 1 × 10^8 N/m^2 is the minimum required to produce a permanent reduction in a device's flicker noise. Peak compressional stress levels below this value do not lead to a flicker noise reduction for a typical SAW resonator whose initial open-loop phase noise level at 1-Hz carrier offset is in the range of -120 to -130 dBc/Hz. It should be noted, however, that unusually noisy devices have shown improvements at somewhat lower peak compressional stress levels (~5 × 10^7 N/m^2).

Measurements of the SAW resonators' close-to-carrier phase noise were normally performed with an incident RF power level of approximately +8 dBm, which corresponds to a peak compressional stress level of less than 2 × 10^7 N/m^2 for our device designs. Devices were tested at this low RF power level before and after the high incident RF power burn-in was carried out. The overall flicker noise reduction is estimated by fitting a 10 dB/decade straight line to the two sets of data for carrier offset frequencies between 1 Hz and 100 Hz and comparing the results, typically the single-sideband phase noise levels at 1-Hz carrier offset. Generally, system phase noise limitations preclude measurements for carrier offset frequen-
cies greater than 100 Hz. Finally, our experience suggests that an exposure time of 1 h is usually sufficient to achieve most, if not all, of the maximum possible phase-noise reduction. However, some devices have required multiple burn-ins. In a few isolated instances, the phase-noise level has actually increased after the first burn-in and a second burn-in at a slightly higher-incident RF power level was necessary in order to achieve a net reduction in the device's phase-noise level. In any event, incident RF powers that produce peak compressional stress levels approaching $7 \times 10^8$ N/m$^2$ should be avoided.

C. Burn-In Results

Typical "before" and "after" phase-noise measurements are illustrated in Fig. 3 for a device with a 150-\(\lambda\)-wide acoustic aperture. An 8-dB reduction in the SAW resonator's inherent phase noise was achieved for this device. Fig. 4 shows the distribution of close-to-carrier phase noise reductions for 25 SAW resonators of various designs. For each device the pertinent characteristics, e.g., insertion loss, loaded and unloaded Q's, etc., were measured before and after the burn-in procedure. All of these devices were two-port resonators in the 350- to 810-MHz frequency range. They were fabricated on quartz using either an aluminum or copper-doped aluminum transducer metalization, and had acoustic apertures which varied from 130 to 400 \(\lambda\). Common to all of these devices were thick (1.0 to 1.5 \(\mu\)m) busbar metalizations and long effective cavities (~350 \(\lambda\)), as described previously. The data shown in Fig. 4 indicates that the flicker noise reductions ranged from 0 to 11 dB, with an average value of 7 dB. Any permanent change in a device's resonant frequency attributable to the burn-in procedure was less than \(\pm\)1 ppm, which is essentially the limit of our ability to reproducibly make the measurement. Measured changes in insertion loss were on the order of \(\pm0.2\) dB, while changes in the loaded and unloaded Q's were typically found to be less than \(\pm2\) percent. It is worth noting that for the majority of devices the burn-in procedure produced a slight increase in their unloaded Q's.

Fig. 5 illustrates the distribution of single-sideband phase noise levels (at 1-Hz carrier offset) after burn-in for the same 25 devices depicted in Fig. 4. This measured data has an average value of approximately \(-134\) dBC/Hz, which is approximately 8 dB lower than the best results previously published for SAW resonator phase-noise levels [10]. It is important to observe that this average single-sideband phase-noise level (at 1-Hz carrier offset) is only a 4 dB above the measurement system's nominal flicker-noise floor of about \(-138\) dBC/Hz. Many of the devices that exhibited only a small reduction in flicker noise (<4 dB) in Fig. 4 were close to the measurement system's noise floor before burn-in, whereas after burn-in the phase-noise levels were essentially indistinguishable from the system noise floor. In fact, more than 70 percent of the after burn-in phase-noise levels shown in Fig. 5 are sufficiently close to the system noise floor that their accuracy is questionable. Thus the full extent of the phase-noise reductions that were obtained is unknown, and it is likely that somewhat larger reductions actually occurred. To put these results in perspective, a high-performance silicon-bipolar-transistor RF amplifier will typically exhibit an open-loop, single-sideband phase noise level (at 1-Hz carrier offset) in the range of \(-130\) to \(-140\) dBC/Hz, which is comparable to the levels now demonstrated by our burned-in SAW resonators. A num-
ber of SAW resonators were tested in oscillator circuits and they all demonstrated state-of-the-art phase-noise performance, in many instances consistent with an equivalent open-loop phase-noise level of $-140$ dBc/Hz, or better, at 1-Hz carrier offset. The measured oscillator phase-noise levels and their variation with the SAW resonators' loaded $Q$'s, as measured in the feedback loop, indicate in many cases that the loop amplifier, and not the SAW resonator, was the dominant source of the oscillator's flicker noise.

D. Discussion

Several experiments were performed in order that the burn-in procedure might be better understood. These experiments attempted to isolate the physical mechanism(s) responsible for the reduction in a SAW resonator's close-to-carrier phase noise. Several burned-in SAW resonators were examined with a scanning electron microscope; however, no visible changes were evident when they were compared to devices that had not been burned-in. On the other hand, a small reduction in the ohmic resistance of the transducer fingers has been noted for many burned-in devices.

In order to isolate any potential mechanism related to the higher than normal RF currents present in the transducer during the burn-in process, the magnitudes of a two-port SAW resonator's input and output impedances were measured on-resonance, and then off-resonance. Frequencies were then found where the off-resonance, input and output impedance magnitudes were equal to the corresponding on-resonance input and output impedance magnitudes. These frequencies were well outside the 3-dB bandwidth of the main resonance, and were not within the 3-dB bandwidth of any secondary resonances. Each SAW transducer was then driven with a high-incident RF power level at the appropriate off-resonance frequency, thus producing the same RF current magnitude as existed at resonance but without the accompanying peak compressional stress level. No phase-noise reduction was observed as a result of this procedure, indicating that the large peak compressional stress levels associated with applying a high-incident RF power level on-resonance play a key role in initiating the phase-noise reduction process. This same device was then burned-in using the conventional technique previously described and a 5-dB flicker noise reduction was achieved.

In order to simulate comparably high levels of peak compressional stress, another device was exposed to both high and low-temperatures. The high stress level is due to the thermal expansion coefficient mismatch between the transducer metallization and the quartz substrate. First, an ovenite bake at 350°C and then a 2-h emersion in liquid nitrogen ($-196^\circ$C) were performed on the device. Neither procedure resulted in a measurable change in the device's flicker noise level, which was measured before and after the high-temperature bake and once again after the low-temperature emersion. When the device was burned-in using the high-incident RF power technique, a 7-dB reduction in the device's flicker noise was obtained. However, Bray et al. [13] have previously published results indicating that an average 4-dB reduction in flicker noise was achieved for a group of 20 SAW resonator devices that had been emersed in liquid nitrogen. Thus static stress does not appear to be as effective in reducing flicker noise as the large level of dynamic stress produced during the high-incident RF power burn-in process.

An interesting experiment was performed that perhaps sheds some light on a potential source of flicker noise and the role of the burn-in process in reducing it. The experiment involved sequentially ion implanting the transducer metallization of six SAW resonators with 55 and 30 keV Ar$^+$ ions and then measuring the flicker noise before and after a high-incident RF power burn-in. The ion implantation was carried out during fabrication of the SAW resonators at a stage where only the transducer metallization would be affected. A lift-off fabrication process was employed and the ion implant was performed after the aluminum film was deposited but prior to lift-off. This is illustrated in Fig. 6. The implant energies were selected so that the maximum penetration depth was approximately equal to the thickness of the aluminum film. The areas that were protected by metal and photoresist during the implant were therefore free from damage due to the implant after lift-off of the transducer metallization was completed. The implant depth was primarily confined to the transducer metallization, with less than ten percent of the ions penetrating into the quartz substrate.

Prior to burn-in two of the six resonators that were ion implanted exhibited flicker-noise levels that were in excess of $-110$ dBc/Hz at 1-Hz carrier offset. For similar standard devices without the implant, fewer than 5 percent would possess flicker noise levels this high. Also, three "control" devices were fabricated during the same evaporation step as the implanted devices, and their processing was completed in a more conventional manner, without the ion-implant step. The flicker-noise levels of these control devices fell within normal limits. This implies that the damage created in the metal film by the ion implant noticeably increased the average flicker noise in several SAW resonators. Five of the resonators were then burned-in at either +24 dBm or +27 dBm and their phase-noise levels remeasured. Four devices showed a significant decrease in phasenoise level, with the two resonators that were initially the noisiest showing noise reductions of 25 and 30 dB, respectively. Thus the high-incident RF power burn-in appears to remove most, if not all, of the damage caused by the ion implant.

At this time it is difficult to speculate on the exact nature of the burn-in process since we do not as yet have a complete understanding of just what physical mechanisms might be responsible for the flicker-noise levels observed in SAW resonators. A reasonable hypothesis might be that the high-incident RF power burn-in produces an annealing-like behavior in the transducer metallization. The available experimental evidence indicates that a high-acoustic energy density is most effective in promoting the
Fig. 6. Schematic representation of the Ar⁺ ion implantation performed on several SAW resonators during their fabrication.

### TABLE 1
SUMMARY OF TYPICAL 500 MHZ SAW RESONATOR CHARACTERISTICS

<table>
<thead>
<tr>
<th>Design</th>
<th>Insertion Loss (dB)</th>
<th>Loaded Q</th>
<th>Unloaded Q</th>
<th>Group Delay τ</th>
<th>Q'_(f_m = 1 Hz)'</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single aperture</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300 λ, AQP</td>
<td>6.4</td>
<td>5900</td>
<td>10,500</td>
<td>3.5</td>
<td>≤ -140</td>
</tr>
<tr>
<td>Single aperture</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>400 λ, TO-8</td>
<td>7.2</td>
<td>6300</td>
<td>11,200</td>
<td>4.0</td>
<td>≤ -140</td>
</tr>
<tr>
<td>Dual aperture</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>150 λ per section, TO-8</td>
<td>5.2</td>
<td>8300</td>
<td>18,400</td>
<td>5.3</td>
<td>≤ -140</td>
</tr>
<tr>
<td>Single aperture</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>150 λ, TO-8</td>
<td>7.0</td>
<td>10,000</td>
<td>18,100</td>
<td>6.4</td>
<td>-130</td>
</tr>
</tbody>
</table>

*The prime (') denotes open-loop, single-sideband phase noise

Phase-noise reductions that have been observed, rather than either high RF current magnitudes or large static mechanical stresses. Also, our measurements suggest that high and/or low temperature induced processes are not as effective as the high-incident RF power burn-in process. There is considerable evidence that indicates that metal films may play a key role as a potential source of flicker noise in SAW resonators [13]-[15], but instabilities in the quartz substrate itself cannot be ruled out at this time. Since the region of high-acoustic energy storage includes both the transducers and the bare quartz surface as well, it is possible that the high-incident RF power burn-in process interacts simultaneously with one or more physical noise mechanisms in each area, producing a net reduction in the device's flicker-noise level.

E. Summary

Table 1 summarizes typical measured electrical characteristics for TO-8 and all quartz packaged 500-MHz SAW resonators with the design features just described. The open-loop, 1 Hz intercepts for the single-sideband phase-noise spectrum, Q'_(f_m), indicated in Table 1 have been calculated from closed-loop oscillator phase noise measurements, rather than measured directly [10] since the calculated open-loop phase-noise levels for the devices are typically some 3 to 5 dB below the open-loop measurement system's noise floor. This has been the case for a number of prototype wide aperture devices even before a high-incident RF power burn-in was used to further reduce the SAW resonator's flicker-noise level [11]. The open-loop flicker-noise levels that are routinely achieved for these devices after a burn-in are comparable to the open-loop phase-noise levels demonstrated by several state-of-the-art silicon bipolar transistor amplifiers. Additional reductions in an oscillator's flicker-FM phase-noise level will only be possible if the open-loop phase noise levels of the SAW resonator and the loop amplifier can both be further reduced.

### III. OSCILLATOR DESIGN

Fig. 7 contains a simplified block schematic diagram for the prototype high-power SAW resonator oscillators. As indicated, each oscillator contained: a single-loop amplifier; an electronic phaseshifter; a coaxial attenuator and a length of 50-Ω coax for setting the proper loop gain and phase conditions, respectively; a 3-dB power splitter; and a buffer amplifier. System requirements dictated that the oscillator be electronically tunable for phase-locking purposes. Selection of the various electronic components proved to be exacting, since each component could potentially contribute to the oscillator's phase-noise spectrum if not properly chosen. However, the phaseshifter, loop amplifier, buffer amplifier, and of course the SAW resonator itself were found to be the critical components.

The phaseshifter circuit shown in Fig. 7 is basically a high-pass filter whose cutoff frequency is varied by applying a bias voltage to the two varactor diodes. As the
cutoff frequency is tuned electronically, the transmission phasenvelope through the circuit is varied as well. Prior experience with a commercially available electronic phasenonshift indicated that it could indeed be a source of flicker noise in an oscillator’s feedback loop and thus limit the flicker-FM phase-noise level that could be achieved. It was found that single-sideband phase noise levels of −60 to −70 dBc/Hz at f_m = 10 Hz offset from the carrier were typical for oscillators incorporating these commercially available electronic phaseshifters. This is as much as 10 to 20 dB higher than the phase-noise levels measured on the same oscillator with the phaseshifter removed.

Since the prototype oscillators’ flicker-FM phase-noise at f_m = 1 kHz offset from the carrier was specified to be −136 dBc/Hz or better, alternative electronic phasenonshifting techniques were investigated. The result was the circuit shown in Fig. 7, with silicon varactor diodes being used in order to achieve the lowest possible flicker noise levels. The design equations that were used to determine L_1 and establish an appropriate varactor type are

\[ L_1 = Z_n / (2\pi f_o) \]  

and

\[ C_1(V_{MR}) = 1 / (Z_n 2\pi f_o) \]  

where \( f_o \) is the intended operating frequency, \( Z_n = 50 \) Ω is the characteristic system impedance, \( C_1(V_{MR}) \) is the varactor’s capacitance at the center of its voltage tuning range, and \( V_{MR} \) is the value of the tuning voltage at the center of the oscillator’s tuning range. The linearity of the phaseshifter’s characteristic was found to be very good. The 50 to 55 degrees of phaseshift typically achieved is sufficient to tune a SAW resonator oscillator over its entire 1-dB bandwidth. This range of phaseshift was achieved with an associated insertion loss of 0.75 ± 0.2 dB and a 15 to 20 percent fractional bandwidth. Since the insertion phase versus frequency characteristic of a SAW resonator is also reasonably linear over its 1-dB bandwidth, this should result in an oscillator with a very linear frequency versus voltage-tuning curve. This was indeed confirmed on several prototype oscillators, as described in Section IV. Furthermore, this electronic phaseshifter design does not appear to contribute to an oscillator’s phase-noise spectrum, at least for the prototypes evaluated to date.

A very low-flicker-ΔFM noise level for the loop amplifier is critical if good oscillator phase-noise performance is to be achieved. However, this requirement must be met at relatively high-output power levels if a low-noise-floor is also desired. It has been shown that a general expression for a SAW resonator oscillator’s double-sideband, phase-noise-to-carrier ratio, \( S_{\phi}(f_m) \), is [15]:

\[ S_{\phi}(f_m) = \left( \frac{\alpha_R f_o^3}{f_m^3} \right) \left[ \frac{\alpha_s}{f_m} f_o^3 \right] \left[ \frac{\alpha_s Q_L f_o}{f_m} \right] \left[ \frac{\alpha_s}{f_m} + 2GFKT/P_o \right] \]  

where \( G \) is the compressed power gain of the loop amplifier, \( F \) is the noise factor of the loop amplifier, \( K \) is Boltzmann’s constant, \( T \) is the temperature in °K, \( P_o \) is the carrier power level (in watts) at the output of the loop amplifier, \( f_c \) is the carrier frequency in Hz, \( f_m \) is the carrier offset frequency in Hz, \( \tau_s \) is the SAW resonator’s group delay in seconds, \( Q_L = \pi f_m \tau_s \) is the loaded Q of the SAW resonator in the feedback loop, and \( \alpha_R \) and \( \alpha_s \) are the flicker noise constants for the SAW resonator and loop amplifier, respectively. Equation (2) has been shown to accurately model a SAW resonator oscillator’s phase-noise spectrum for carrier offset frequencies in the range of 0.1 Hz to 40 MHz. The SAW resonator’s flicker noise constant, \( \alpha_R \), can be found from an open-loop phase-noise measurement, \( S_{\phi R}(f_m) \), on a resonator using the expression [15]

\[ \alpha_R = \frac{f_m S_{\phi R}(f_m)}{(2Q_L f_o)^3} \]  

where once again the “prime” indicates that it is an open-loop phase-noise measurement. The general relationship \( S_{\phi}(f_m) = 10 \log \{ S_{\phi R}(f_m)/2 \} \) has been used in deriving 3. For the SAW resonators described in this paper, the value of \( \alpha_R \) is approximately \( 3 \times 10^{-40} \text{rad}^2/\text{Hz}^2 \). Prior to this work, a value of \( 2 \times 10^{-39} \text{rad}^2/\text{Hz}^2 \) was typical for more conventional SAW resonator devices. The amplifier’s flicker noise constant may also be found from an open-loop-phase-noise measurement, \( S_{\phi E}(f_m) \), on an amplifier using the expression [15]

\[ \alpha_s = f_m S_{\phi E}(f_m) \]  

where once again the “prime” indicates an open-loop phase-noise measurement. A typical value for \( \alpha_s \) is \( 2 \times 10^{-14} \text{rad}^2 \).

Usually, the third term on the right hand side of (2) is negligible for fundamental frequency SAW resonator oscillators above 100 MHz. The fifth term on the right-hand side of (2) is also negligible in most instances, unless the loop amplifier is excessively noisy. Most SAW resonator oscillators exhibit little, if any, region of \( 1/f_m^2 \) dependence and the phase-noise spectrum is composed primar-
...of flicker-FM noise \( \frac{1}{f_s^3} \) and a white \( \phi M \) phase-noise floor \( f_m^0 \) \cite{16}.

Equation (2) indicates that in order to achieve an extremely low-phase-noise floor the loop carrier power \( P_c \) should be maximized, while the compressed power gain \( G \) and the noise factor of the loop amplifier \( F \) should be minimized. The SAW resonator must obviously be designed to accommodate an incident RF power level that is only some 3 to 4 dB lower than the maximum loop carrier power level. This is evident from the overall circuit topology shown in Fig. 7. It goes without saying that the buffer amplifier should be able to handle the coupled output power level from the loop and not be driven more than 2 or 3 dB into gain compression, if at all possible.

A number of amplifiers were considered for this application. Low flicker noise, good noise factor, high-output power at 3 dB of gain compression, and sufficient small-signal gain to overcome total loop losses while still providing approximately 3 dB of excess loop gain were the principal performance criteria used. Table II summarizes the key performance parameters measured for three potential loop amplifiers and an acceptable buffer amplifier. Detailed open-loop phase-noise measurements on the various amplifier types, as well as phase-noise measurements on a number of oscillators, indicated that the UTO-509 (Avantek) and the A19-1 (Watkins-Johnson) were the best loop amplifier candidates. The UTO-561 (Avantek) has somewhat more gain than might be desired for the buffer amplifier; however, its flicker-noise level is sufficiently low so as to not additively degrade the oscillator's phase-noise spectrum. More specific information concerning the prototype oscillators’ performance is contained in Section IV.

IV. OSCILLATOR PERFORMANCE

Several initial prototype high power, 500-MHz SAW resonator oscillators were assembled and tested using dual acoustic aperture SAW resonators. The circuit topology was essentially as shown in Fig. 7, except that no buffer amplifier was used. In this early development effort the loop amplifier was an A19-1 (W-J), while the power divider was a DS-313 (Anzac). One oscillator included an electronic phaseshifter in order that “two oscillator” phase-noise measurements could be performed for offset frequencies far-from-the-carrier using a standard measurement technique \cite{17}. The A19-1’s combination of high-output power under gain compression and a very good noise factor resulted in an oscillator with an extremely low phase-noise floor. Fig. 8 shows the measured single-sideband phase-noise floor of one oscillator for offset frequencies from 40 kHz to 40 MHz. The noise floor is approximately \(-182 \text{ dBc/Hz}\), which is consistent with separate measurements of \( G, F, \) and \( P_c \), made prior to final assembly of the oscillator. The two spurious signals at approximately 2 and 4 MHz from the carrier in Fig. 8 are due to leakage of a clock frequency from the measurement system’s controller. This early work demonstrated the feasibility of meeting the oscillator’s phase noise requirement of \(-176 \text{ dBc/Hz} \) or better, for offset frequencies greater than 200 kHz. However, the A19-1 amplifier didn’t have sufficient small-signal gain to guarantee the oscillator’s performance in production with the single, wide acoustic aperture SAW resonator design used in later oscillators. The UTO-509 does have sufficient small-signal gain, as well as suitable electrical characteristics to meet the oscillator’s performance objectives, thus further development was based upon the UTO-509.

All subsequent effort built upon the already demonstrated low flicker-noise properties of the single 300-A-wide acoustic aperture, high-power SAW resonator design described in Section II. The UTO-509 was used for the loop amplifier and the UTO-561 was used as the buffer amplifier. An electronic phaseshifter circuit was included based upon the design shown in Fig. 7. All other components, e.g., the power splitter, etc., were the same as before. The phaseshifter’s component values were: \( R_1 = 1 \text{ kΩ}, L_1 = 16 \text{ nH}, \) and \( C_f (4 \text{ V}) = 6.4 \text{ pF}. \) The specific varactors used were frequency linear tuning varactors (FLTVARs), Frequency Sources P/N #15238-15. A typical oscillator’s frequency versus tuning voltage curve is shown in Fig. 9. As anticipated, the curve is monotonic and quite linear.

Fig. 10 shows the measured single-sideband phase-noise spectrum for one high-power, 500-MHz prototype.
oscillator using a UTO-509 loop amplifier, but without a buffer amplifier. The phase-noise floor is approximately \(-179 \text{ dBc/Hz}\), while the flicker FM noise at \(f_m = 10 \text{ Hz}\) carrier offset is \(-80 \text{ dBc/Hz}\). Separate measurements of the oscillator’s fractional frequency stability (square root of the Allan Variance) indicate that \(\sigma_v(\tau) = 1.2 \times 10^{-11}\) for \(\tau = 100 \text{ ms}\). As mentioned in Section III, no region of \(1/f_m^2\) noise is evident. The noise floor is about 3 dB higher than for the result shown in Fig. 8 with the A19-1 (W-J) loop amplifier, rather than the UTO-509 (Avantek). This is to be expected based upon the relative differences in gain, compressed power output and noise figure that were noted in Table II.

Fig. 11 shows the measured single-sideband phase-noise spectrum for the same oscillator with a UTO-561 buffer amplifier. Also indicated in Fig. 11 is the open-loop flicker noise level required of the buffer amplifier in order that it not contribute to the oscillator’s phase noise, primarily in the carrier offset frequency range between 10 kHz and 100 kHz. Measurements on the UTO-561 indicate that it can meet this requirement, even when driven 4 to 7 dB into gain compression. There is no evidence of additive \(1/f_m\) flicker-\(\phi\)M-noise degradation due to the buffer amplifier. However, it is obvious that the noise floor of the oscillator has been degraded by approximately 3 dB, at least partially due to the buffer amplifier’s typical 5- to 6-dB noise figure.

The intended system application for these low noise prototype oscillators involves an X16 frequency multiplication to a nominal 8-GHz center frequency output. Fig. 12 shows a block diagram of the multiplier chain, including specific information on the components which were used. Although not shown in Fig. 12, attenuators were also included, as necessary, in order that the input power rating of each component was not exceeded. Phase-noise measurements were made on three 500-MHz high-power SAW resonators after each successive X2 stage of frequency multiplication. This technique allowed us to extract the individual phasenoise spectrum for the oscillators after each X2 stage in the multiplier chain. The measurements indicated that ideal frequency multiplication (i.e., 10 log \(\{(16)^2\}\) was achieved at the 8 GHz output frequency. For each X2 intermediate stage of frequency multiplication ideal performance (i.e., 10 log \(\{(2)^2\}\) was also confirmed. Fig. 13 shows the X-Band (8 GHz) single-sideband phase-noise spectrum for a single oscillator after X16 frequency multiplication using the circuitry shown in Fig. 12. Fig. 13 also illustrates a “typical” X-Band radar exciter phase-noise requirement for
Fig. 11. Phase-noise spectrum, $\mathcal{L}(f_m)$, for one high-power 500-MHz SAW resonator oscillator with buffer amplifier.

Fig. 12. Block diagram of X16 frequency multiplier chain for X-Band (8 GHz) output frequencies where $F_1$, $F_2$, $F_3$ are Watkins-Johnson FD25HC; $F_2$, is Watkins-Johnson FD15HC; $A_1$, is Watkins-Johnson A19-1; $A_2$, is Avantek APG-2001 M; $A_3$, is Avantek APG-4002 M, and BPFs are 50-percent bandwidth, 12 section, tubular bandpass filter.

Fig. 13. X-Band (8 GHz) phase-noise spectrum, $\mathcal{L}(f_m)$, for one high-power 500-MHz SAW resonator oscillator after X16 frequency multiplication.

next-generation systems. Whereas previous "standard" SAW resonator oscillator performance could not address this specification, especially for carrier offset frequencies greater than 1 kHz, the low-noise SAW resonator oscillators reported herein comfortably meet the overall phase-noise specification.

As mentioned previously in Section II, a high-incident RF power "burn-in" was used on many of the high-power SAW resonator devices to further reduce their flicker-noise levels. An interesting observation was made on several burned-in devices, namely, that not only was a device's flicker ($1/f_m$) noise reduced but its random walk ($1/f_m^2$) noise was reduced as well. Fig. 14 illustrates the difference in an oscillator's fractional frequency stability before and after the SAW resonator device was burned-in. The range of gating times for the measurement corresponds to the flicker FM and random-walk FM portions of the phase-noise spectrum, as noted in Fig. 14. In particular, this 425-MHz SAW resonator (single 150-\lambda wide acoustic aperture) oscillator exhibited a fractional frequency stability, $\sigma_f(\tau)$, of $1 \times 10^{-10}$ for $\tau = 1 \times 10^4$ s. This exceptionally good time domain stability corresponds to a random-walk FM noise process for which $S_{2f}(f_m) = 6 \text{ Hz}^2/\text{Hz}$ at $f_m = 1 \times 10^{-4}$ Hz. Although the improvement in fractional frequency stability for very long gating times corresponds in the frequency domain to carrier offsets considerably less than 1 Hz and is thus not of great importance for most radar applications, the result is nonetheless very relevant for many navigation system requirements. The burn-in process is seen to reduce the "random" component [8] of an oscillator's aging characteristic. A preliminary aging result, based upon 27 weeks of data, is shown in Fig. 15. It indicates that $\pm 1$ ppm/year stabilities are readily achievable for high loop power oscillator designs such as those described herein.

Finally, the UTO-546 (Avantek) was originally considered for potential use as the loop amplifier. Its performance parameters were summarized in Table II. An interesting "anomaly" was observed for its phase-noise floor behavior. Even though the measured values of $G$, $F$, and $P$, for the six oscillators that were tested should have resulted in a noise floor of about $-185 \text{ dBc/Hz}$, this value for the noise floor was actually measured on only one oscillator containing a UTO-546 loop amplifier. Fig. 16 shows a noise-floor measurement for one of the "anomalous" oscillators. The noise floor at $f_m$ = 10-MHz carrier offset is almost 10-dB higher than predicted. Furthermore, there appears to be a second noise-floor plateau for carrier offsets from approximately 100 kHz to 1 MHz. While the source of this "excess" noise floor is unknown, it may perhaps be attributable to an unusually high level of generation-recombination ($G-R$) noise in the particular silicon bipolar transistor chip used in the UTO-546 amplifier [18]. It should be noted that the measured noise figure data was taken under small-signal conditions. In the oscillator's feedback loop the UTO-546 was actually some 2 to 3 dB into gain compression, which may also influence this particular amplifier's phase-noise properties.

V. CONCLUSION

The prototype low-noise SAW resonator oscillators just described have demonstrated state-of-the-art phase noise performance, not only at their fundamental operating frequencies in the 400- to 600-MHz range, but also after X16 frequency multiplication to X-Band as well. The results reported herein are the best published to date for SAW resonator based oscillators in these frequency ranges. In addition, a low noise electronic phaseshifter circuit has been described which does not appear to limit an oscillator's flicker-FM noise level, while also providing a very linear frequency versus tuning voltage characteristic.

Also, a technique has been described that consistently
Fig. 15. Comparison of aging characteristics for low- (+6 dBm) and high-power (+18 dBm) SAW resonator oscillators.

Fig. 16. Anomalous phase-noise floor, $\gamma(f_0)$, for high-power 500-MHz SAW resonator oscillator using UTC-546 (Avantek) loop amplifier.

reduces the close-to-carrier flicker noise inherent in quartz-based SAW resonators. Driving the devices with a high-incident RF power for a short time has resulted in an average 8 dB flicker noise reduction on more than 40 different SAW resonators. The reduction appears to be directly related to the presence of large peak compressional stress levels within the device, typically on the order of $1 \times 10^8$ N/m$^2$.

The primary obstacle to achieving even lower phase noise floors appears to be the buffer amplifier at this time, specifically its non-ideal combination of small-signal gain, noise factor, and power output at 1 dB of gain compression for this application. At this time it is not clear what additional improvements in the prototype oscillator’s flicker-FM noise level can be achieved, since it will first be necessary to clarify whether the SAW resonator or the loop amplifier is the flicker noise source. Future efforts will continue to focus on developing SAW devices, electronic components, and oscillator design techniques which may lead to additional improvements in either the oscillator’s overall phase-noise spectrum or portions thereof.

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**References**


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James A. Greer (M'88) was born in New York, NY, on October 23, 1952. He received the B.S. degree in mathematics in 1975 from Stevens Institute of Technology, Hoboken, NJ. He received his M.S. and Ph.D. degrees, both in physics, in 1976 and 1983, respectively, from Stevens Institute of Technology. His doctoral thesis concerned the measurement of sputtering yields of negative ions from low-work function surfaces.

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