LOW NOISE MICROWAVE SIGNAL GENERATION: RESONATOR/OSCILLATOR COMPARISONS*

M.M. DRISCOLL
(301) 765-2451

Westinghouse Electric Corporation
Electronic Systems Group, MS 75
Baltimore, Maryland 21203

ABSTRACT

This paper will compare existing and projected microwave signal spectral performance obtainable using various types of acoustic and non-acoustic high Q resonators. Included will be a discussion of recent progress in resonator technology such as recent improvements in conventional dielectric resonator and quartz crystal resonator performance, development of composite, UHF resonators such as the high overtone bulk acoustic resonator (HBAR) exhibiting tenfold increase in Q and decrease in vibration and sensitivity (compared to quartz), and superconducting cavity type resonators exhibiting ultrahigh Q directly at microwave frequency.

INTRODUCTION

Requirements for improved radar and communication system performance, in terms of increased dynamic range, necessitate the achievement of high degree of spectral purity in the microwave transmitter and receiver local oscillator signals.

The use of highly stable, high Q resonator for oscillator stabilization and narrowband spectral cleanup filters provides a means for generation of extremely low noise, microwave carrier signals. The choice of resonator type, operating frequency, drive level, and circuit utilization scheme significantly impact the degree of output-signal frequency stability obtained.[1]

The resulting signal phase noise spectrum consists of two distinct regions: a near-carrier region and a noise floor region. In the near-carrier region, the signal spectrum is characterized by flicker of frequency noise due to resonator short-term-instability and/or oscillator sustaining stage flicker-of-phase noise. The spectral density of the fractional frequency fluctuations, Sy(f), provides a convenient measure for comparing the short stability of sources utilizing various types of resonators operating at different frequencies. In general, lowest near-carrier [Sy(f)] noise is obtained via oscillator implementation using extremely high Q acoustic resonators and low l/f noise silicon transistors in the VHF range, followed by low noise frequency multiplication to microwave. Lowest noise floor levels, on the other hand, are obtained via oscillator/resonator implementation at highest possible operating frequency at high drive using a low noise figure sustaining stage amplifier in order to avoid spectral degradation necessarily resulting from the frequency multiplication process.

In addition, it is very important to note that the (resonant frequency) sensitivity of the oscillator resonator to environmental stresses such as short-term temperature fluctuation and vibration is such that these effects can degrade the signal spectra to a far greater degree than that due to electrical noise. This is especially true in the case of vibration encountered in airborne platforms.

In most cases, therefore, obtainable microwave signal spectral performance is directly related to resonator characteristics that include unloaded Q, maximum drive level, operating frequency range, short-term frequency stability and environmental effects (vibration, temperature) immunity. In this regard, selection of optimum resonator technology or technologies must be tailored to meeting specific signal generator short-term spectral requirements.

OSCILLATOR-RESONATOR SPECTRAL RELATIONSHIPS

Figure 1 shows two alternative methods for designing (and analyzing) acoustic resonator-stabilized harmonic oscillator circuits. As shown in the figure, the sustaining stage portion of the circuit can be considered as 1) a feedforward amplifier with the resonator included in the positive feedback circuit, or 2) a two-terminal negative-resistance generator to which the resonator is attached.

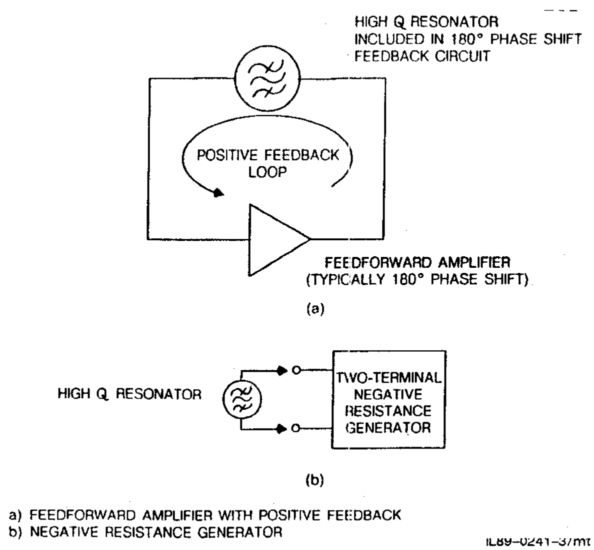

Figure 1. Typical Oscillator Configurations

* A portion of this work sponsored by the Electronics Technology and Devices Laboratory, U.S. Army LABCOM Contract DAAL01-87-C-0718.

Figure 2 shows how the sustaining circuit open-loop phase noise sideband spectrum is related to that of the (closed-loop) oscillator output signal. In the oscillator there is a conversion of open-loop circuit signal phase perturbations to closed-loop signal frequency perturbations. This conversion is a consequence of required maintenance of the steady-state quiescent signal phase relationships, and it is proportional to the reciprocal of the closed-loop signal group delay.[2] The delay is primarily determined by the resonator loaded Q.

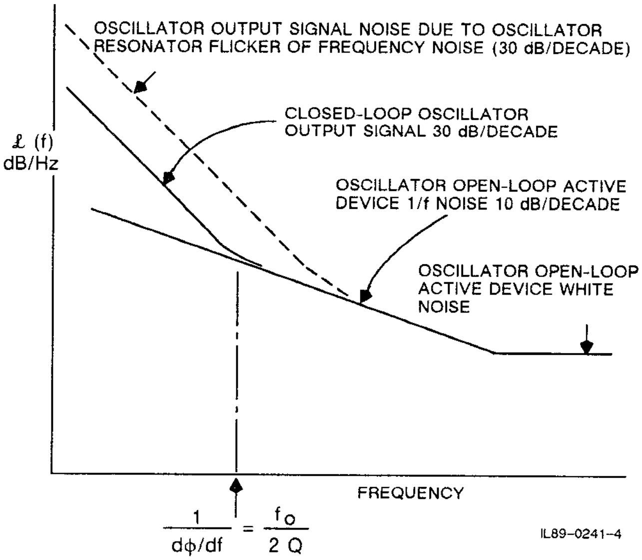

Figure 2. Oscillator Signal Spectral Relationships

As shown by the solid curves of figure 2, the effect of the conversion is a 20 dB/decade increase in the output-signal phase noise sideband level at carrier offset frequencies less than the resonator half-bandwidth.[2] In this regard, the resonator Q may be thought of as a measure of its ability to suppress the effects of phase noise in the oscillator sustaining stage circuitry.

In many cases, the near-carrier noise level exhibited by high stability oscillators is significantly higher than that predicted by sustaining stage phase noise and resonator loaded Q alone. In the case of piezoelectric (i.e., quartz crystal) resonator-stabilized oscillators, "excess" flicker noise (dashed curve in figure 2) can result from short term frequency instability in the resonator itself. Figure 3 shows an example of the large variations in resonator flicker noise level exhibited by identically fabricated VHF quartz crystals.[3] Determination of the physical mechanisms responsible for resonator flicker noise, together with methods for increasing the yield of low noise devices, constitutes an area of active investigation in the frequency-control community. In general, resonator-induced flicker noise is usually dominant at carrier offset frequencies extending to (and sometimes several octaves beyond) the resonator half-bandwidth.[4]

Script L(f) in figures 2 and 3 is a commonly used measure for describing carrier signal phase noise and is defined as the phase noise sideband level, in a per hertz bandwidth, at an offset (modulation) frequency f from the average carrier frequency. In addition to script L(f), the

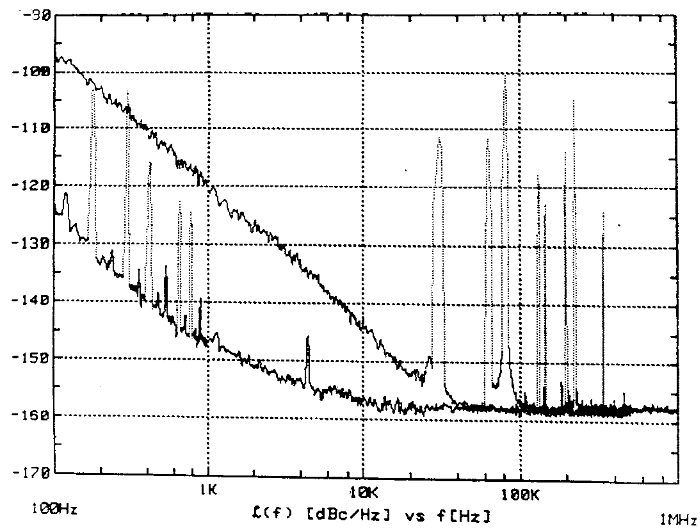

Figure 3. Phase Noise Spectra for 160 MHz Oscillator-Doublers Using "Quiet" and "Noisy" 80 MHz Quartz Crystal Resonators

spectral density of the signal fractional frequency fluctuations, Sy(f), provides a convenient measure for comparing signal near carrier noise levels for oscillators and resonators operating at different frequencies since the magnitude of Sy(f) is unaffected by frequency multiplication/division.

Figure 4 shows the measured fractional frequency spectra for a pair of low noise Westinghouse crystal oscillators. The minimum value for Sy(f) corresponds to a fractional frequency fluctuation (i.e., $\Delta f_{RMS}/fo$) $Sy(f)^{0.5} = 6x10^{-14}$ per oscillator. Figure 4 shows, for example, that for typical values ($1x10^{-9}$ per g) of quartz crystal resonator vibration sensitivity, vibration levels on the order of 10^{-4} g rms would degrade the oscillator signal spectrum. In a similar fashion, resonator (frequency) sensitivity to other forms of environmental stress such as temperature and pressure can seriously degrade signal near-carrier spectral performance.

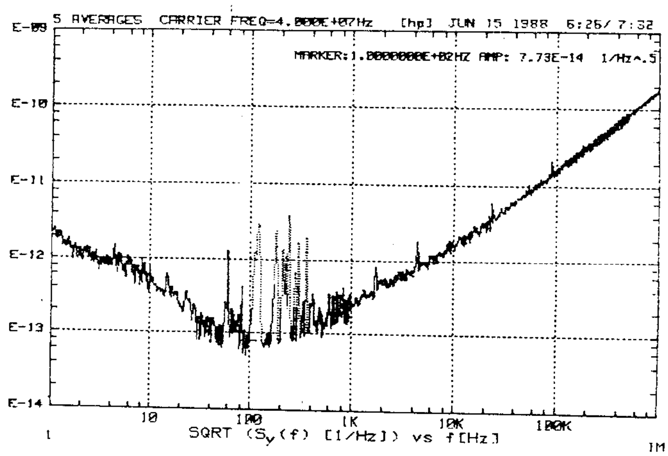

Figure 4. Spectral Density of the Fractional Frequency Fluctuations (Plotted as $\sqrt{Sy(f)}$ for Two Low Noise Crystal Controlled Oscillators

OSCILLATOR-RESONATOR PERFORMANCE COMPARISONS

Table 1 lists a comparison of attainable performance characteristics for oscillators employing several types of high Q resonators. The table includes mature technologies in widespread use as well as emerging technology devices such as superconducting resonators for which little actual measured performance data exists.

It should be noted that the data depicted in table 1 is intended to represent neither state-of-the-art nor commonly available performance, but rather performance readily attainable using low noise components and circuit configurations.[1]

Table 1 shows that for mature technologies, bulk wave quartz technology provides best near-carrier spectral performance, quartz SAW technology best performance at moderate offset frequencies, and (due to higher operating frequencies), dielectric resonator technology best noise floor performance. One method for obtaining overall superior spectral performance is to use a combination of technologies such as a dielectric resonator or SAW oscillator phase locked to a frequency multiplied bulk wave crystal oscillator signal.

Table 1. Oscillator/Resonator Performance Comparison

Resonator Type	Bulk Quartz	SAW Quartz	Dielectric (DRO)	HBAR	Sapphire-Nb Cavity (4°K) Ref. [7]	Sapphire-Nb Stripline (4°K)
Frequency Range (MHz)	1–250	250–1500	1–20 GHz	300–3000	10 Ghz	1–20 GHz
Max Drive Level (MW)	1–10	10–100	10–100	10–20	10	0.5 [8]
Temp Coeff (ppm/°C)	0	0	± 2 – ± 10	–40 (YAG) 0 ($L_1Ta_aO_3$)	0	?
Vibration Sensitivity (Δf/f per g)	$5x10^{-10}$ to $2x10^{-9}$	$2x10^{-9}$	$2x10^{-9}$ to 10^{-7}	$1x10^{-11}$ to $5x10^{-11}$	$3x10^{-11}$	?
Q-f Product	10^{13}	$5x10^{12}$	10^{13} – 10^{14}	10^{14}	10^{19}	$>10^{14}$
Self Noise Sy (100 Hz)	$5x10^{-26}$	$5x10^{-24}$	10^{-22}	$3x10^{-25}$	$6x10^{-28}$*	10^{-19} [8]
Sy (10 kHz)	$5x10^{-24}$	10^{-25}	10^{-24}	$5x10^{-26}$	?	?
Sy (1 MHz)	$5x10^{-20}$	10^{-22}	10^{-23}	$5x10^{-23}$	?	?
Resonator Frequency for Noise Data	40 MHz 5th O.T.	500 MHz	1.3 GHz	640 MHz	*Predicted 10 Ghz	3 GHz

It is interesting to note that in spite of the fact that dielectric resonator materials have been developed whose Q-f product exceeds that of piezoelectric quartz resonators, reported DRO near-carrier noise levels are normally inferior to those for UHF SAW oscillators. Possible explanations for this are: usual use of high (compared to silicon) 1/f noise GaAs transistor-based sustaining stage circuitry at DRO frequencies above S-band, excessive resonator loading, environmentally induced noise, and/or yet undefined resonator flicker noise similar to that encountered for acoustic resonators.

With regard to emerging technologies, included in table 1 is a high overtone, bulk acoustic resonator (HBAR) which has been under development at Westinghouse for several years.[5],[6] The HBAR is similar to the traditional quartz bulk-wave resonator, except for the method of transducing the electrical energy into and out of the resonating crystal. As shown in figure 5, the piezoelectric transducers (sputtered ZnO films) are separate from the crystal. The operation of the is as follows. High Q, resonant responses occur at frequencies for which the parallel surface separation is an integral multiple of acoustic half-wavelengths. Utilization of separate transducers allows injection and extraction of signals at microwave frequencies so the very-high-order harmonics of the crystal fundamental resonance can be used. The unique HBAR transducer has the added advantage that it is no longer necessary that the crystal display piezoelectric properties when excited. Thus the HBAR is not limited to piezoelectric crystals or orientations for which the piezoelectricity is significant. This has opened the way for consideration of many crystals with Qs at microwave frequencies an order of magnitude greater than quartz. These crystals include yitrium aluminum garnet (YAG), sapphire, lithium niobate, lithium tantalate, and others. This technology results in a resonator with an fQ product at microwave frequencies of $8x10^{13}$, representing the highest

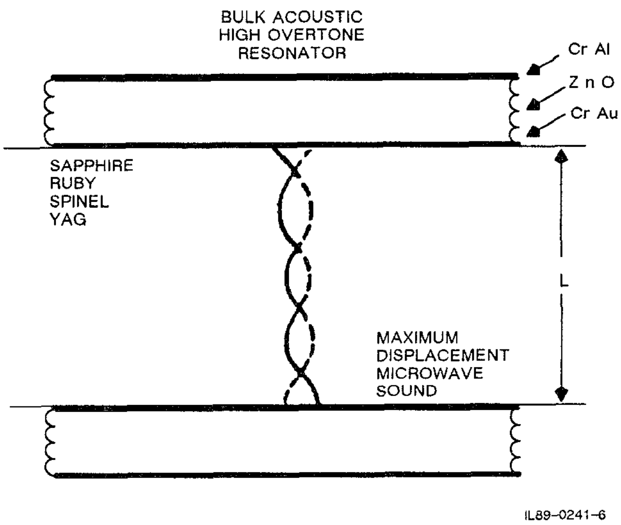

Figure 5. Construction of the High Overtone, Bulk Acoustic Resonator (HBAR)

non-superconducting resonator Q in the VHF through microwave frequency range. Another unique and very important device characteristic is its low vibration sensitivity. Prototype resonators have been fabricated exhibiting frequent changes on the order of several parts in 10^{11} /g. This is 100 times lower than the typical values for conventional quartz resonators.

Initial prototype devices utilized longitudinal wave propagation and exhibited large frequency-temperature coefficient. Efforts are currently underway at Westinghouse to further improve HBAR performance. These include development of tunable shear-mode devices exhibiting zero temperature coefficient at compatible oven-control temperatures. Also included are studies (similar to those being conducted for conventional quartz resonators) aimed at reducing transducer self-noise levels.

Superconducting resonator technology provides a means of achieving ultra high Q devices directly at microwave frequencies, and impressive results have been obtained, especially for low-temperature superconductor (LTS), sapphire-filled cavities operating at liquid helium temperatures. Unloaded Qs on the order of 10^9 at X-band have been reported for sapphire-filled niobium cavities exhibiting excellent (projected) short-term frequency stability and vibration sensitivity performance [7].

In contrast, measurements of unloaded Q and flicker noise for niobium-on-sapphire resonators configured in stripline form have not been as impressive [8]. LTS resonators are not in widespread use primarily due to the impracticality associated with required 4°K operation. The rapid advances being made with regard to discovery and growth of high temperature superconductors (HTS) has spawned renewed interest for material use in the fabrication of high Q resonators. Much work needs to be accomplished in this area, however, before accurate predictions of obtainable signal spectral performance can be made.

CONCLUSIONS

Generation of low noise microwave signals depends, to a large extent, on resonator performance parameters including Q, short-term frequency stability, drive level, operating frequency, and environmental effects immunity. Some of these parameters are quite process-variable and consideration of device yield is important.

Selection of optimum resonator technology (or multiple technologies) must be tailored to specific signal spectral performance requirements.

REFERENCES

[1] M. M. Driscoll, "Low noise signal generation using bulk- and surface-acoustic-wave resonators," IEEE Trans. and Ultrason, Ferroelec. Freq. Contr., UFFC-35, No. 3, May 1988, pp. 426-434.

[2] D. B. Leeson, "A simple model of feedback oscillator noise spectrum," in Proc. IEEE, Vol. 54, No. 2, February 1966, pp. 329-330.

[3] M. M. Driscoll and B. W. Kramer, "Spectral degradation in VHF crystal controlled oscillators due to short term instability in the quartz resonator," in Proc. 1985 IEEE Ultrason. Symp., October 1984, pp. 340-344.

[4] T. E. Parker, "1/f frequency fluctuations in acoustic and other stable oscillators," in Proc. 39th Freq. Contr. Symp., May 1985, pp. 97-106.

[5] J. T. Haynes, et al., "Stable microwave source using high overtone bulk resonators," 1985 IEEE Microwave Theory and Techniques Symp. Digest, pp. 243-246.

[6] H. L. Salvo, et al., "Shear mode transducers for high Q bulk microwave resonators," in Proc. 41st Freq. Contr. Symp., May 1987, pp. 388-390.

[7] A. G. Mann and D. G. Blair, "Ultra-low phase noise superconducting cavity stabilized microwave oscillator with application to gravitational radiation detection," J. Phys. D.: Appl. Phys., 16 (1983), pp. 105-113. Also, personal commun. with authors.

[8] B. R. McAvoy, et al., "Superconducting microstrip resonator performance," Proc. Applied Superconductivity Conference, San Francisco, CA, August 1988.