STABLE MICROWAVE SOURCE USING HIGH OVERTONE BULK RESONATORS*

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ABSTRACT

The high overtone bulk acoustic resonator (HBAR) provides the basis for stable microwave sources. The HBAR's high Q, closely spaced, periodic resonances provide stabilization for multiple frequency microwave sources. Recently an L-band source with 5 MHz channels has been developed. This HBAR source has phase noise performance equivalent to that of sources based on low frequency quartz crystal stabilization and multiplication, but it requires only a fraction of the hardware.

The resonators are fabricated by depositing film transducers on the resonator crystal such as YAG, sapphire, lithium niobate, or lithium tantalate. The low-loss material of the crystal gives a Q approximately 10 times that of quartz. Resonators have been fabricated at frequencies as high as 10 GHz and have achieved Q's in excess of 65,000 at 1.5 GHz using the compressional mode. Tuning of the resonators has been achieved by deposition of mass loading materials such as silicon dioxide. Tuning to within 1 kHz of a standard using an active feedback system during deposition has been accomplished. The resonator is assembled into a rigid housing that minimizes the effect of external vibration on the resonator. Vibration sensitivity of 1×10^{-11}/g has been measured.

INTRODUCTION

The HBAR has been described in previous papers by Moore, et al.[1,2] so that a description of its operation will be limited to briefly reviewing its dominant mode structure as shown in figure 1. The HBAR might be considered as an acoustic analog of the optical Fabray-Perot interferometer. Geometrically it is more like present-day microwave delay lines than other acoustic resonators. The transmission resonator illustrated in figure 1 is the form we have found most useful. The main feature of the geometry, the separate transducer coupling to the resonator body, provides the following key operational advantages:

- Coupling to high-order overtones
- Availability of higher-Q nonpiezoelectric substrates
- Confinement of acoustic activity, allowing rigid mounting and lower sensitivity to vibration

The coupling to high-order overtones allows useful resonator coupling directly at microwave frequencies and provides a large number of equally spaced overtones in the operating band. We are using overtone levels of several hundred (as opposed to up to the fifth or seventh with traditional quartz resonators) which, for the resonator described in this paper, provides an overtone spacing of approximately 5 MHz. Even closer overtone spacing could be provided but would limit allowable bandwidth for the oscillator feedback circuit and would limit noise performance. The rigid mounting of the resonator has led to almost two

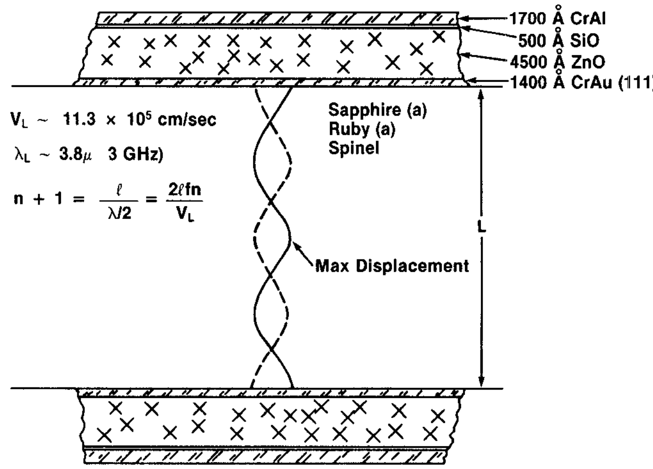

Figure 1. Geometry of HBAR Showing Substrate and Transducer Detail

orders of magnitude suppression in vibration sensitivity, which is described by Rossman and Haynes.[3]

The relationship of HBAR Q to those of other resonators is illustrated in figure 2 in terms of FQ product as a function of frequency. Because Q's of most resonators fall off as reciprocal frequency, the FQ product serves as a good first-order basis of comparison. The sloping lines on figure 2 are of constant FQ product. Quartz is characterized

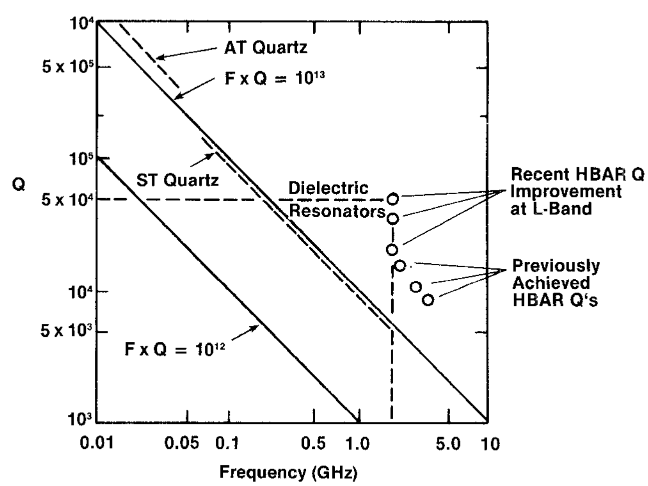

Figure 2. FQ Product Chart Showing Q's of Recently Fabricated HBAR's Relative to Both Crystal Resonators and Dielectric Resonators

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most closely by FQ = 10^{13} with examples indicated slightly above this value for frequencies up to approximately 200 MHz. By contrast, above 1 GHz the HBAR Q's achieved are well above the FQ = 10^{13} at X-band. In this paper we are reporting on the resonator with Q's over 50,000 in the 1.5 to 2 GHz frequency band.

THE RESONATOR

Based on the experiment, we have selected for the resonator design a circular spot transducer with an aperture of 6.3×10^{-8} m^2 which provides the best tradeoff between lowest insertion loss and highest Q. The piezoelectric layer is zinc oxide 4500 Å thick. The bottom contact is chrome-gold 1200 Å thick and the top contact is chrome-aluminum 1800 Å thick.

The substrates are prepared from a boule of laser quality YAG. After X-ray alignment, the boule is sliced into substrates of thickness appropriate for the required peak frequency spacing. The faces are polished using a technique believed to be unique in the industry. The process provides exceptional results for hard, lower-loss media for use at high microwave frequencies.

The transducers are fabricated using standard integrated circuit photolithography. The bottom contact of the active transducer aperture is prepared by the flash evaporation of chromium-gold. The chromium adhesion layer of 50 Å to 100 Å is evaporated first, with a short interval of coevaporation with the gold. This procedure is known to produce ordered gold films.

The zinc oxide is deposited using an RF diode sputtering system. Sputtering is from a zinc oxide target in a 25 percent O_2 to 75 percent Ar atmosphere. The thickness is monitored using an interferometric laser monitor. The top electrode is deposited using a rejection process. After coating the substrate with resist and developing the pattern, a chromium-aluminum layer is evaporated on the surface. A 200 Å layer of chromium is used, and the thickness of the aluminum is determined by the transducer design. Acetone and an ultrasonic cleaner removes the unwanted chromium-aluminum.

The high-overtone bulk acoustic resonator chip is shown at the top of the exploded view of the mounting scheme in figure 3. As indicated in the figure, the HBAR is bonded into a well that has been machined in

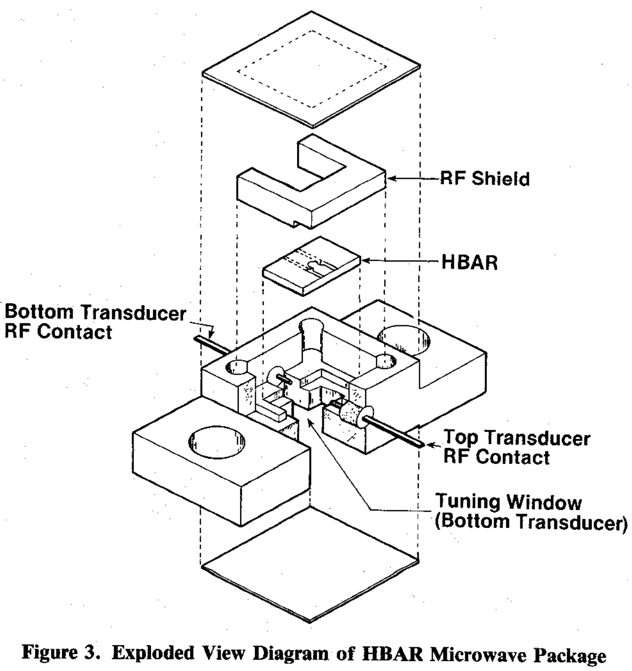

Figure 3. Exploded View Diagram of HBAR Microwave Package

the bottom of the package together with a window to allow vapor deposition on the reverse side of the HBAR. Bonding is accomplished with A-25 conducting polyimide, which is also used to attach the RF shield that isolates the input and output connections. After the tuning procedure is accomplished, lids are welded on the top and bottom as shown.

RESONATOR TUNING

The technique employed is mass loading by dielectric evaporation. A layer of SiO_2 is applied to the resonator while monitoring the resonant frequency of an HBAR overtone. The HBAR crystal is mounted in an open microwave package, which permits evaporation on both sides of the crystal. Monitoring of the resonant frequency during tuning is accomplished by means of special fixturing that top-loads into the vacuum system.

The microwave package is soldered to a microstrip holder that connects to 3.5 mm coaxial connectors. Two packaged HBAR's in microstrip holders are fixed to a temperature-stabilized aluminum block. The block is fixed to a vacuum assembly with coaxial cables that connect through vacuum feedthroughs. The reference HBAR (bottom of aluminum block) and HBAR to be tuned both may be monitored simultaneously external to the vacuum system. The HBAR to be tuned is masked with an aperture plate that covers everything except the transducer area.

The fixture is top-loaded into the vacuum chamber of an electron beam evaporator system shown schematically in figure 4. A standard charge, less than 0.5 gram, of divided quartz is used. The evaporation rate of the SiO_2 can be made quite small, about 1.5 angstroms per second, allowing adequate measurement time for the resonant frequency shift during deposition.

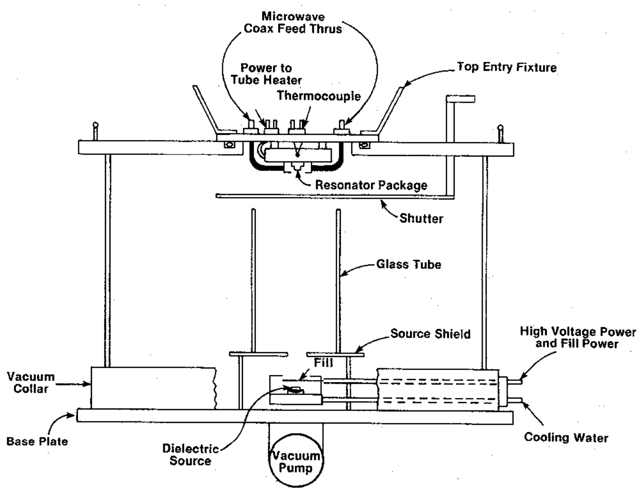

Figure 4. Schematic of Electron Beam Evaporation System Showing Position of Top-Loading Fixture

Figure 5 demonstrates the capability of tuning an HBAR to a given frequency reference. This data is a composite of a number of deposition runs to provide a final frequency match with a tolerance in the difference frequency of less than a kilohertz.

SOURCE STABILIZATION

To fully exploit the HBAR's unique characteristics, an automatic frequency control (AFC) loop technique is used as shown in figure 6. The resonator is used as the frequency-determining element of the frequency discriminator. The output of a low-noise voltage-controlled oscillator (VCO) is applied to the discriminator. At the discriminator output - the mixer output - an error voltage appears that is proportional to the frequency error between the VCO and the particular selected HBAR reso-

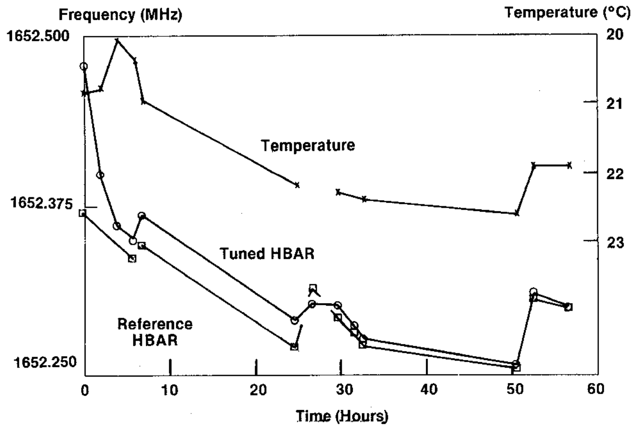

Figure 5. Tuning an HBAR to the Frequency of the Reference

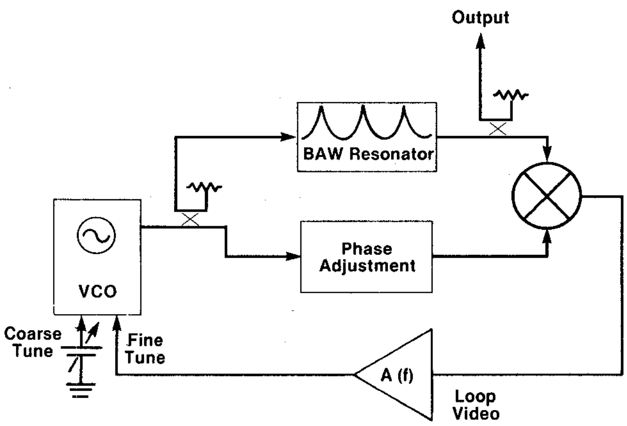

Figure 6. Simplified Diagram of AFC Stabilized Source

nance. This voltage is fed back to the VCO through a loop video amplifier. To take full advantage of the resonator's filtering properties, the output is taken after the resonator.

Multiple frequency operation is achieved relatively simply with the addition of hardware to allow the loop to lock on any of the HBAR's responses within the VCO's tuning band. This implementation is shown in figure 7. The principal addition is a digital controller that accepts a user input and addresses a digital-to-analog converter to preposition the VCO on the proper HBAR response. I and Q mixers provide amplitude and phase data to the controller so that it may adjust the phase shifter for quadrature signals at the mixers at each frequency. Once positioned, the loop locks through the loop video amplifier as previously described.

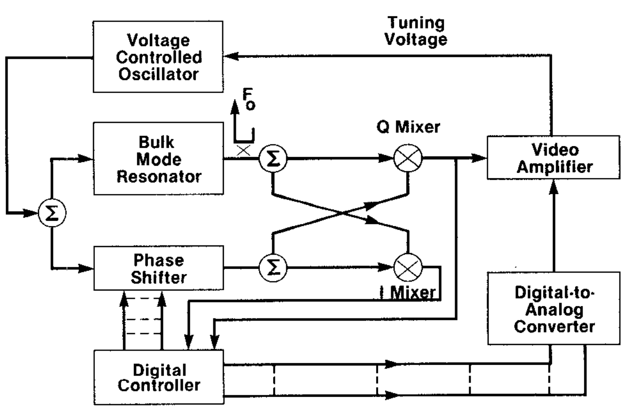

Figure 7. Diagram of Multiple Frequency Source

PHASE NOISE PERFORMANCE

Short-term stability is limited by resonator Q, video amplifier noise, and VCO AM noise at modulation rates below a few kilohertz. Above that point, phase noise is a function of VCO phase noise as modified by loop gains and resonator filtering.

Quantitatively the video amplifier contribution is:

$$L(f) = \frac{F_o^2 \overline{e_o^2}}{8Q^2E^2f_A^2}\left[\left(\frac{f_A}{f}\right)^2 + \left(\frac{f_A}{f}\right)^3\right]$$

where:

$L(f)$ = Single sideband phase noise (1/Hz)
F_o^2 = Output frequency
$\overline{e_o^2}$ = Video amplifier noise voltage floor (V^2 Hz)
Q = Resonator Q
E = Mixer phase sensitivity (V/rad)
f_A = Video amplifier 1/f noise break frequency
f = Modulation frequency

AM noise on the VCO and its power amplifier is converted to phase noise by the mixer LO port acting as an inefficient AM detector. The contribution to phase noise is:

$$L(f) = \frac{F_o^2 I^2 f_o M(f_o)}{2Q^2 f^3}$$

where:

I = Fractional mixer video voltage change per fractional LO power change
$M(f_o)$ = 1/f AM noise spectral density at frequency f_o (1/Hz)

Above a few kilohertz, phase noise performance is determined by first calculating the suppression of VCO open loop phase noise by the AFC loop. Noise is then filtered further by taking the output after the resonator. This effect, along with the above-mentioned contribution, are shown in figure 8. Parameters associated with the L-band source under development were used.

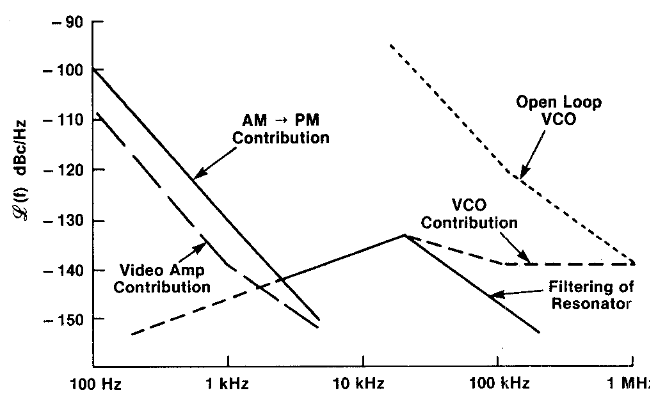

Figure 8. Predicted L-Band Noise Performance

Thus far, a single frequency source at L-band has been fabricated and tested. Measured performance not only agrees reasonably well with predicted performance, but it compares favorably with typical L-band radar requirements. Figure 9 shows measured and predicted phase noise along with a typical requirement. The test set floor is included for analysis.

In the 100 Hz to 1 kHz region, one should note that, although there is an approximately 6-dB discrepancy, the predicted and measured curves are both proportional to $1/f^3$. In this region, VCO AM noise generally

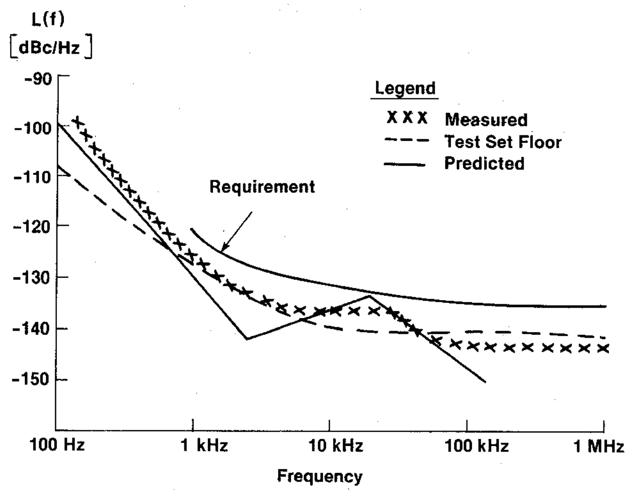

Figure 9. Measured L-Band Phase Noise Performance

is difficult to measure and the prediction is based on a typical value that might reasonably be worse by 6 dB. In the 1 kHz to 4 kHz region, the measurement was test-set-limited as it was above 50 kHz. The measured data does begin to follow the filter response of the resonator above 20 kHz. The test set floor is a measurement of two identical oscillators in the test set. Measurements 3 dB below this floor, in the region above 100 kHz, indicate that the HBAR-stabilized source is at least 10 dB below the noise level of a single test set oscillator. Noted that, to use an existing noise test set, the frequency of the HBAR source was doubled.

CONCLUSIONS

A source making use of the high overtone bulk acoustic resonator has been described. The resonator Q's are over 50,000 at 1.5 to 2 GHz, greater than Q's by any other means at those frequencies. A source with noise performance equivalent to those for which the frequency is multiplied from low-frequency crystal reference oscillators is reported. Much lower hardware levels are required. With improvements in HBAR technology, even superior performance may be possible.

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