TEMPERATURE CHARACTERISTICS OF MICROWAVE ACOUSTIC RESONATORS*

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ABSTRACT

Bulk acoustic resonators offer Q's greater than are available by any other means for microwave frequencies. The use of separate resonant substrates and transducers allow higher Q media not available when excitation is by means of the piezoelectricity of the substrate. Resonators with Q's to 20,000 have been tested. Analysis of temperature propagation characteristics for high Q materials is reported with examples illustrated. Diamond appears to be a candidate for low temperature sensitivity.

Introduction

The main contribution to improving the stability of fundamental frequency microwave oscillators comes from the design of a high-Q cavity with a suitable, low temperature coefficient.[1] Bulk acoustic resonators are under development for control of low noise microwave oscillators operating directly at microwave frequencies. Q's greater than 5000 are typical and have been fabricated to 20,000 for the frequency range of 1 to 4 GHz. Resonators operating through 10 GHz have been tested. Figure 1, illustrates the Q's as a function of volume for the bulk resonator in comparison with present resonators available for direct operation at microwave frequencies.

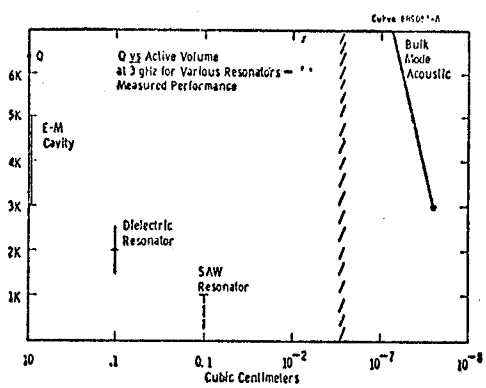

Figure 1. Q vs active volume at 3 GHz for various resonators - measured performance.

The combination of high Q and useful electroacoustical coupling are achieved through the geometries shown in Figure 2, which is a typical cross section. The geometry consists of a substrate of high acoustical Q medium, large compared with the wavelength at the operating frequency and a piezoelectric film transducer. Figure 2 suggests sapphire, ruby and spinel. YAG and diamond are also under investigation. External coupling is provided through a piezoelectric film transducer for which typical dimensions are given.

The use of a separate body and electroacoustical coupling mechanism has two key advantages:

a. A much higher overtone resonance can be used usefully.

b. The resonator itself is no longer restricted to being piezoelectric.

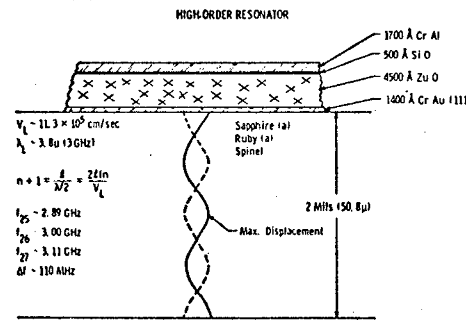

Figure 2. Geometry of microwave acoustic resonator showing substrate transducers.

By using a separate transducer, coupling is not limited by high overtone levels of operation. Performance through X-Band has been demonstrated. Operation at these frequencies is allowed even with resonator thicknesses up to a large fraction of a millimeter. This provides for greater physical rigidity and lower vibration sensitivity than even high Q VHF quartz resonators demonstrate.

Because the substrate need not be piezoelectric for coupling, a large variety of media (as suggested by Figure 3) have Q's which are an order of magnitude greater than quartz. (Q is related to propagation attenuation by the relation $Q = \frac{\pi}{\alpha\lambda_a}$ when λ_a is the acoustic wavelength).

A number of these are under investigation. Specifically, our effort has been directed towards sapphire, spinel, and YAG. Diamond is now receiving some attention.

Surface process techniques are sufficient to avoid any significant negative influence on the intrinsic Q of these indice. The influence of the substrate surface condition on Q may be estimated by relating the Q to the surface reflection coefficient, r. If we take, to first order, $r \approx 1-2K^2\bar{\mu}^2$ where $k = 2\pi/\lambda$ and $\bar{\mu}^2$ is the R.M.S. roughness of the surface, then

$$Q = \frac{1}{1 - |r|^2} \sim \frac{1}{k^2 \bar{\mu}^2} = \frac{\lambda^2}{4\pi^2 \bar{\mu}^2}$$

and

$$\bar{\mu}^2 \sim \frac{\lambda^2}{4\pi^2 Q} .$$

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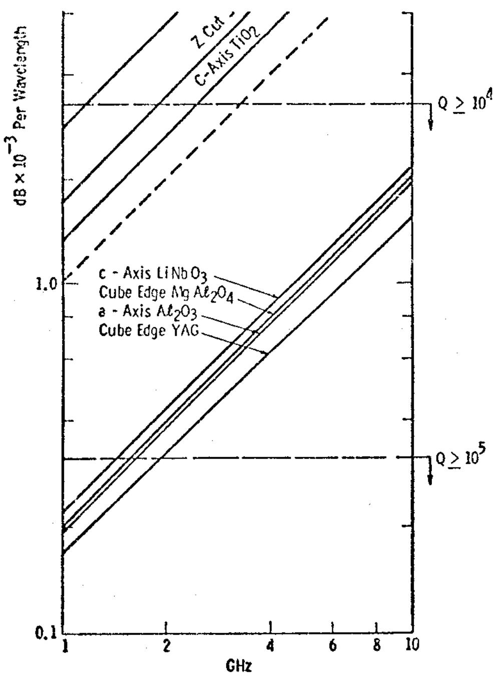

Figure 3. Graph of propagation loss in Q's of substrate media suitable for microwave acoustic resonator. Note that except for lithium niobate, non-piezoelectric media are superior to piezoelectric media.

If we take, for convenience, $\lambda = 2\pi$ micrometers and $Q = 10^4$ then $\bar{\mu}$ is of the order of 100Å. This estimate states that for acoustic wavelengths of about 6 micrometers (~2 GHz in sapphire) the surface damage depth and profile must be near 100Å. By proprietary techniques, we have been able to prepare substrates with $\bar{\mu}$ approaching 10Å.

The resonator can be operated either in the reaction mode or in transmission. Transmission resonators are fabricated with a transducer on both surfaces in the geometry rather than one side as in Figure 2. Figure 4 gives the transmission response of a resonator operating in 4 GHz with overtone resonance separations of approximately 6 MHz. The measured Q is over 13,000.

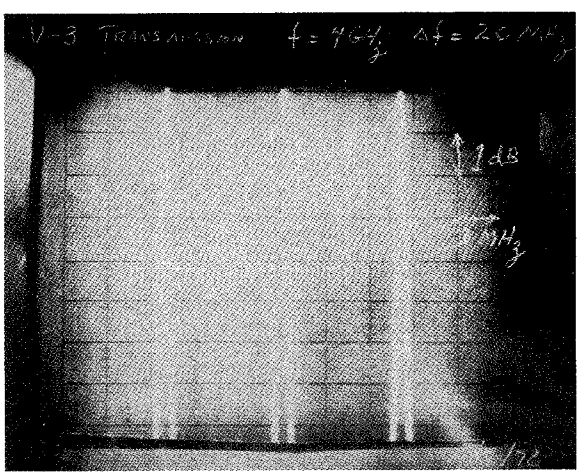

Figure 4. Example of resonant response of an overtone microwave acoustic resonator.

FACTORS AFFECTING TEMPERATURE SENSITIVITY

The controlling influence on temperature sensitivity of bulk microwave acoustic resonators is the temperature sensitivity of the substrate. Experimental data cited later show that to the accuracy of present measurement, the effect of the transducer is minimal. nonetheless, analysis is currently being carried out on both substrate characteristics and geometric relationships. The analysis on substrate characteristics is reported in this paper. Except for the above-mentioned temperature snesitivity data, analysis of the geometry will be reported subsequently.

The principle criteria for resonator substrate selection is the availability of propagation directions with zero power flow angles and zero or near zero temperature coefficients of delay (frequency). The latter goal requires a compensating mechanism in the substrate medium whereby a temperature induced dimensional change is mitigated by velocity change so the propagation delay (resonant frequency) remains unchanged. As a general rule this means a sign reversal among the elastic moduli and the temperature coefficients of these moduli. Over the past decade or so, the moduli and coefficients have been measured for many materials including YAG, spinel, sapphire and diamond. In general, the temperature coefficient of delay profile and inverse velocity (slowness) surfaces are quite complex and vary significantly as a function of direction. If zeros of the temperature coefficient are not available for a given material then propagation directions may be chosen for which it is a minimum. The best cuts are those for which this minima and a zero power flow angle direction coincide.

ANALYSIS OF SUBSTRATE MEDIA

The temperature analysis of substrate media is aided by two computer generated plotting formats - one polar and the other rectilinear. Hidden line drawings of 3-dimensional temperature coefficient data are planned but not yet implemented.[2] This latter format will be a substantial aid in determining the most suitable directions for low temperature coefficient resonators because they are easily visualized.

Our previous experiences with optimization routines in searching for zero temperature SAW directions showed that in general many cases require a larger amount of computer time. Also, our experience has been that larger numbers of manual runs are necessary, especially for high resolution data.

The Cristoffel equation[3] and the equation for the power flow angle[2] form the basis of the calculation carried out by the computer program. The Christoffel equation is a third order matrix equation whose roots are equal to the mass density of the crystal multiplied by the square of the phase velocity of one of the planar wave solutions. The normalized eigenvectors are the corresponding particle velocity components. The computed phase and particle velocities are used to compute the power flow vector. With knowledge of the temperature coefficients of the elastic moduli a simple iterative procedure over desired temperature increments yields the velocity change with frequency. This result, corrected for acoustic path length change, gives the temperature coefficient of delay.

Provision has been made to present data in terms of a set of Miller indices and Euler angle corrdinates. Visualizing the data, as well as the coordinate transformations, is made somewhat easier with this presentation. As mentioned, 3-D hidden line drawings are expected to be the most useful. Data input can be read from punched cards or from a previously prepated data element stored in a user defined file. A conversational routine with prompts is used to call out crystal planes of interest and what data is required.

Any crystal cut (scan plane) is available as is shown in Figure 5, which is the temperature coefficient delay for an arbitrary cut in spinel ($MgAC_2O_4$). The longitudinal mode (solid line) is seen to slightly vary about the 24 ppm/^oC coordinate as a function of direction in the plane. The dashed lines in the plot are the two shear modes. Figure 6, shows the temperature coefficient plot for Lithium niobate in the X-2 plane. Along the X direction the temperature coefficient exceeds 70 ppm/^oC for the longitudinal mode decreasing to about half that value in the Z direction.

Diamond, at present, seems to be a very good candidate for bulk mode resonators as is shown in Figure 7. Here, again, the X-Z plane is presented but the maximum temperature coefficient for any propagation direction in the plane is less than 8.0 ppm/^oC.

RESULTS OF MEASUREMENT

A temperature measurement has been carried out on a resonator of sapphire("a"oriented propagation) for which the substrate temperature sensitivity is 32 ppm/^oC. This substrate was used to provide a first order evaluation of the effort of the transducer on temperature sensitivity while the investigation of suitable substrate is still in progress. In all regards except temperature sensitivity, the sapphire, "a" orientation substrate would be suitable. Thus, it makes a good test vehicle for temperature sensitivity tests at this time.

Measurements were carried out between 6^oC and 51^oC and were made at five different temperatures, 23^oC was considered the frequency reference. For this range of temperatures the resonator displayed 31 ppm^oC. This is a difference of 1 ppm/^oC from the intrinsic substrate-within the uncertainty of the experiment.

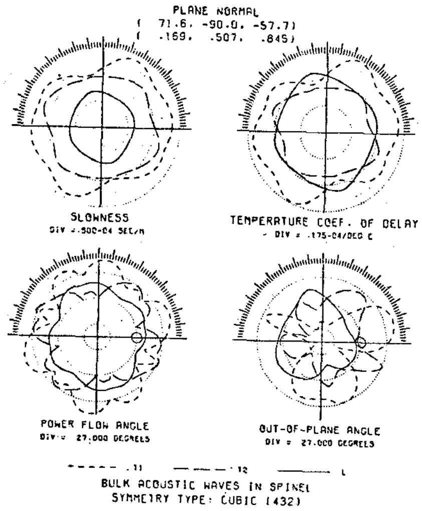

Figure 5

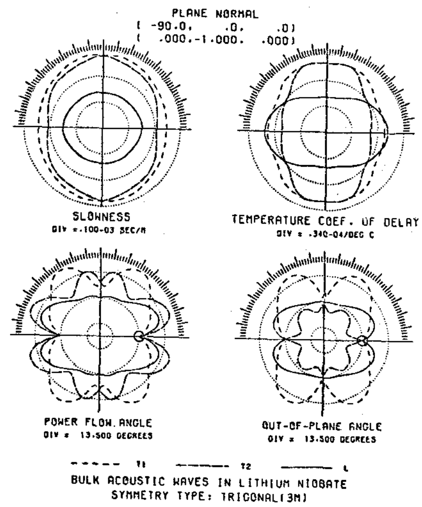

Figure 6

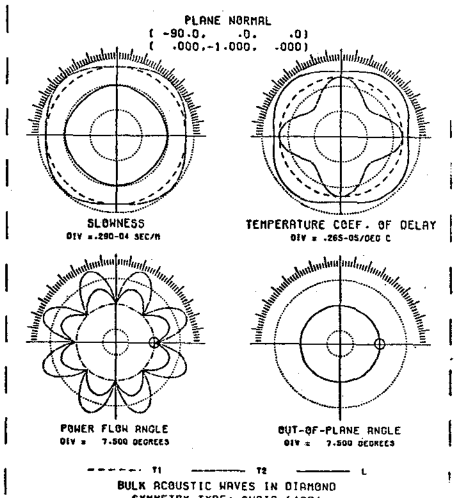

Figure 7

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