

1996 IEEE INTERNATIONAL FREQUENCY CONTROL SYMPOSIUM VIBRATION SENSITIVITY OF AQP SAW OSCILLATORS

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ABSTRACT

All Quartz Package (AQP) SAW oscillators with low vibration sensitivity are achievable by minimizing the external stresses that might otherwise be transferred to the AQP SAW device. If these external stresses are at their lowest possible level, then frit geometry becomes a factor in establishing just how low the vibration sensitivity may be. Optimizing the frit geometry often involves trade-offs with the overall AQP SAW device's size requirements. Through the use of finite element modeling, it was determined that the AQP's cover and substrate thicknesses also could be used to improve vibration sensitivity. The model predicted a decrease in vibration sensitivity, with increasing cover thickness, for the vibration sensitivity component, γ_1 , in a direction normal to the SAW substrate. The model also predicted a degradation in vibration sensitivity with increasing substrate thickness. These results were confirmed experimentally. The other benefit of increased cover thickness was a sizable reduction in the variation of performance among the devices tested. The increased cover thickness decreases the sensitivity of the AQP SAW to variations in the mounting material. The influence of AQP cover thickness on an insufficiently stiffened oscillator was examined. The result was similar, except that the variation in cover thickness had a more dramatic affect than in the sufficiently stiffened case.

I. INTRODUCTION

In the past, we have used primarily thick ceramic stiffeners [1] and mass loading [2] to reduce the vibration sensitivity of AQP SAW resonators. Both methods have been successful, but at the cost of increased size, in the case of ceramic stiffeners, and somewhat impractical to implement, in the case of mass loading. However, cover and substrate thicknesses have emerged as useful variables in reducing vibration sensitivity. The basic construction of the AQP SAW device is shown in Fig. 1, in which the AQP SAW device is shown mounted cover-side down to exploit the cancellation effect ("aspect ratio compensation") of frequency deviation, inherent to AQP SAW resonators [3].

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The AQP SAW device is mounted using a silicone pressure sensitive adhesive (PSA) double-sided tape, which is shown adjacent to a dual-channel 360 MHz AQP SAW resonator in Fig. 2. Three different AQP SAW resonators were considered herein, a 900 MHz single-aperture device, and 325 and 360 MHz dual-aperture (dual-channel) devices.

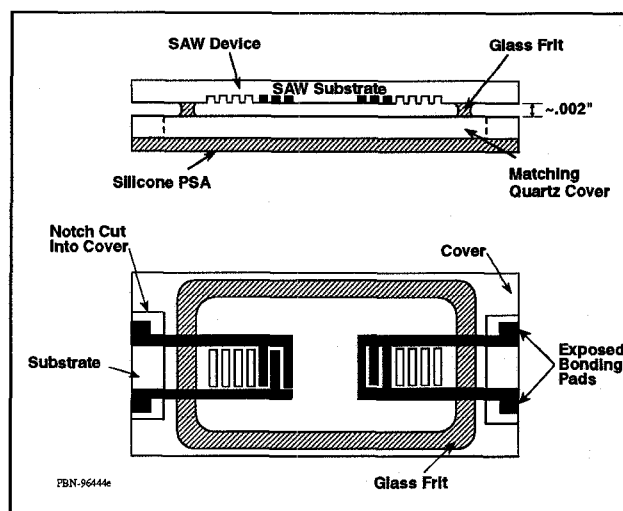


Figure 1. Schematic diagram of an AQP SAW resonator and silicone pressure sensitive adhesive (PSA) mounting material.

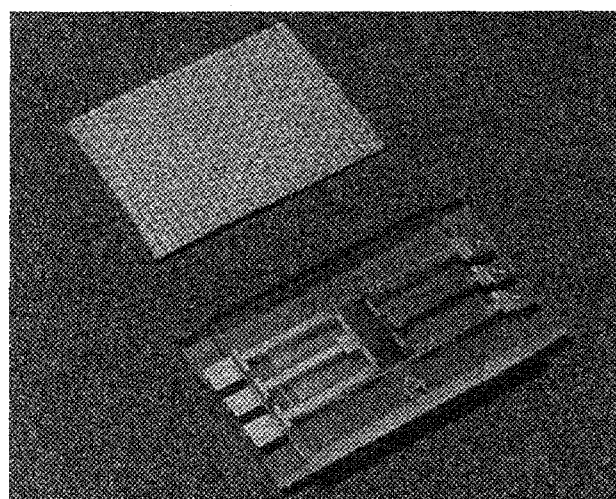


Figure 2. Notchless AQP SAW shown with silicone PSA mounting material.

The sufficiently stiffened case was considered first. The AQP SAW oscillator is bonded to a thick ceramic stiffener, which is mounted on an aluminum vibration fixture. This is illustrated in Fig. 3, which allows rotation for testing the other two orthogonal axes. In this case ("sufficiently stiffened"), the hybrid package stresses have been essentially eliminated, therefore the degradation in vibration sensitivity is due solely to mass loading of the AQP SAW resonator device.

The second configuration considered was the insufficiently stiffened case. This situation is more realistic, since most applications do not allow for thick ceramic stiffeners. The configuration is shown in Fig. 4, where the oscillator is mounted on a somewhat thinner ceramic stiffener, and the whole unit is mounted on isolation bushings (silicone elastomer grommets), which provide vibration isolation beyond 1 kHz. In this case the degradation in vibration sensitivity is due to inertial loading of the AQP SAW and hybrid package stresses which are caused by deflections of the insufficiently stiffened assembly.

II. THE FINITE ELEMENT METHOD AND RESULTS

A detailed understanding of the stresses present in AQP SAW resonators has led to improved vibration sensitivity. This has been accomplished through a combination of finite element modeling and experimentation. The AQP SAW resonators were modeled with the finite element program COSMOS/M [4]. Eight node quadrilateral elements with three degrees of translational freedom were used. The 900 MHz device measured 0.400 inches by 0.500 inches and consisted of 3636 elements and 5568 nodes. A total of 50 elements represented the acoustic aperture region in order to allow for greater resolution of the stresses. The nodes of the silicone PSA mounting material were fixed along the bottom plane where the mounting material inter-

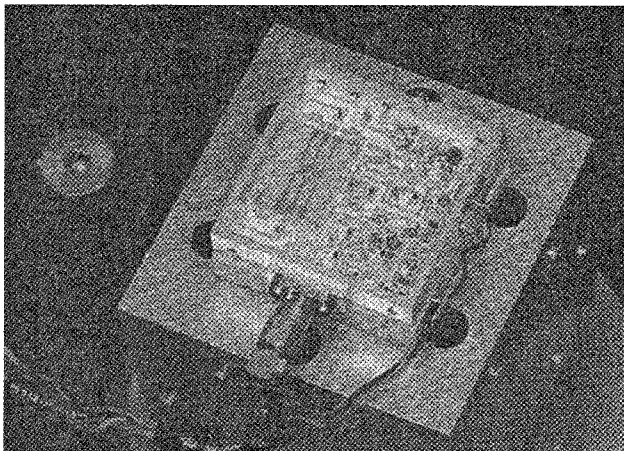


Figure 3. AQP SAW oscillator with sufficient stiffening mounted on vibration test fixture

faces with the hybrid package. A 1g load was applied to simulate the inertial loading, and Fig. 5 shows the deformed model.

The 360 MHz device measured 0.400 inches by 0.675 inches and consisted of 4020 elements and 6729 nodes. A somewhat larger mesh density was chosen for the aperture than in the 900 MHz case to generate a model of reasonable size. The same loads and boundary conditions were used as above for the sufficiently stiffened case. The insufficiently stiffened case was not considered due to the significant additional complexity of the model.

The vibration sensitivity of the AQP SAW resonators was calculated using the stress sensitivity coefficients presented in reference [5]. This is valid since the stresses are fairly uniform in the acoustically active area of the SAW device. The anisotropic elastic coefficients used by the finite element program were calculated for the specific cut angle of the quartz.

The effect of notched versus notchless AQP covers was easily analyzed by finite element analysis. The notched cover version, shown in Fig. 1, allows for access to the bonding pads. The notchless cover version, which is illus-

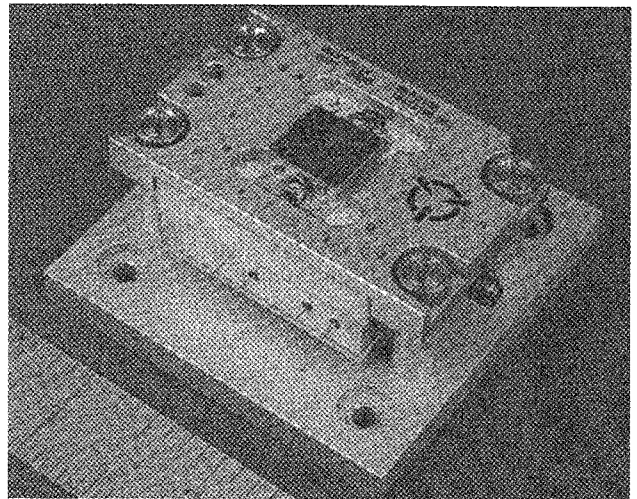


Figure 4. AQP SAW oscillator with insufficient stiffening.

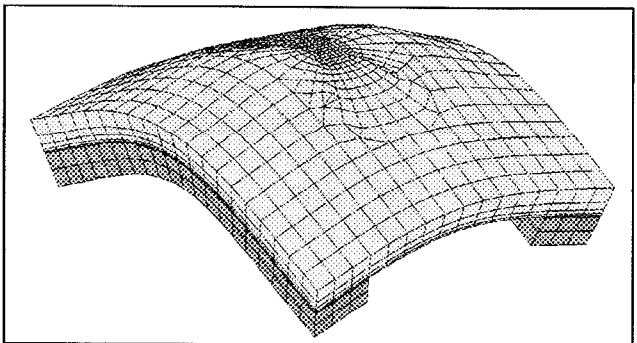


Figure 5. Finite element model of the 900 MHz AQP SAW resonator with γ_1 deformations.

trated in Fig. 2, was developed to improve manufacturability. The program predicted a factor of two increase in vibration sensitivity, in changing from the notched to the notchless cover, but subsequent experimental data proved that the difference was indistinguishable. In reality, variations in the mounting material make it difficult to distinguish differences due to the change in cover design.

The results from finite element analyses for varying cover and substrate thicknesses are shown in Fig. 6. The results are for the 900 MHz AQP SAW, with γ_1 versus cover and substrate thicknesses. The results show that increasing the cover thickness, while holding substrate thickness constant, results in a decrease of γ_1 . Considering the case of increasing substrate thickness, while holding cover thickness fixed, results in an increase in γ_1 . At first this would seem somewhat counterintuitive, since a thicker substrate should decrease the deflections, and hence lower the overall stress in the substrate. But the increased substrate thickness serves primarily to decrease stresses in the direction parallel to SAW propagation (X-axis), as indi-

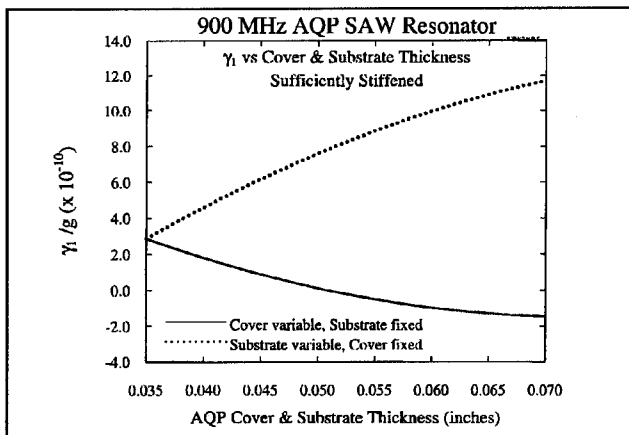


Figure 6. Finite element data for γ_1 versus cover and substrate thicknesses.

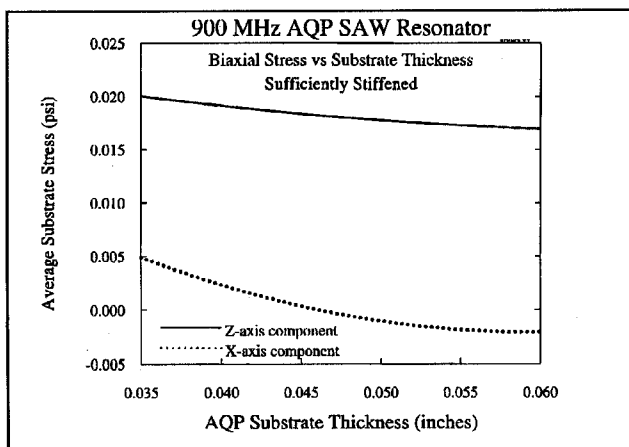


Figure 7. Finite element data of biaxial stress components versus substrate thickness for a 900 MHz AQP SAW oscillator.

cated in Fig. 7, and the cancellative effect for both directions is thereby lost.

The effect of stiffness of the silicone PSA double-sided tape on γ_1 was explored utilizing the finite element model. Results are shown in Fig. 8, which illustrates γ_1 as a function of silicone modulus. Little variation in γ_1 is seen in the finite element data for a very large change in elastic modulus.

III. EXPERIMENTAL RESULTS

The sufficiently thickened case was studied first. A 900 MHz hybrid circuit oscillator was used for the tests and five different AQP SAW devices were tested in the same oscillator housing. To simulate changes in the thickness of the quartz cover, different thicknesses of quartz were bonded to the AQP SAW cover. The AQP SAW was remounted into the oscillator after the quartz plates were added. The results are shown in Fig. 9, with the finite element prediction shown by the solid line.

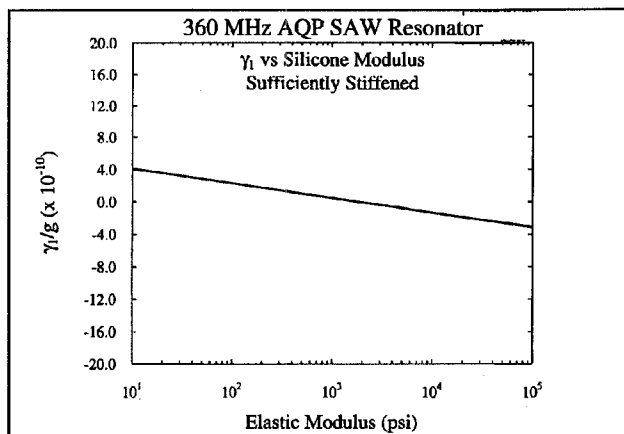


Figure 8. Finite element data for γ_1 versus silicone PSA modulus.

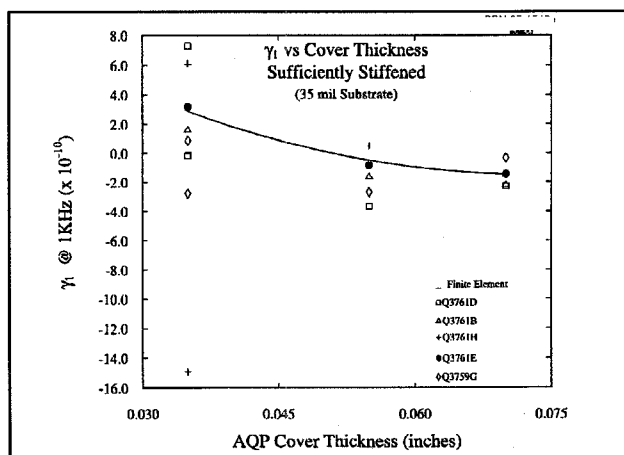


Figure 9. Experimental data of γ_1 at 1 kHz carrier offset frequency versus cover thickness for a typical 900 MHz AQP SAW hybrid circuit oscillator.

The same procedure was repeated for the insufficiently stiffened case, except that the tests were performed on a 360 MHz dual-channel AQP saw resonator. After initial tests using 0.02 and 0.035 inch-thick quartz pieces, it became apparent that thinner pieces were needed to resolve the changes in γ_1 . Due to the weakness of quartz pieces approximately 0.005 inches thick, glass was substituted. The results are shown in Fig. 10, with γ_1 at 100 Hz plotted versus cover thickness. The lower offset frequency was chosen because it is below the resonant frequency of the insufficiently stiffened mounting structure's vibration isolation system. Each AQP SAW resonator was incrementally increased in thickness and remounted in the hybrid oscillator. Although there are differences in phase and magnitude from the 900 MHz data, the trends are similar.

The same experiment on the insufficiently stiffened case was repeated, except that AQP SAW resonators were fabricated with varying cover thicknesses to verify the previous results. Devices were fabricated with covers in 0.005 inch increments. The experimental data is shown in Fig. 11, which indicates a similar trend to that shown in Fig. 10. This time the minimum γ_1 value occurs for a cover thickness between 0.055 and 0.060 inches.

IV. DISCUSSION

The results from finite element analysis show that increasing the cover thickness decreases the γ_1 vibration sensitivity by changing the ratio of the two biaxial stress components. Previously published analyses [6] have suggested that the stress induced frequency shift caused by the two orthogonal biaxial components are opposite in sense, and therefore cancel each other. The effect has been used to lower the γ_1 vibration sensitivity of AQP SAW oscillators, but prior to this work, the only method to change the ratio of the two stresses was through frit geometry.

The effect of cover thickness can be seen directly in Fig. 12 where the two biaxial stress components are plotted versus cover thickness. The Z-axis component (direction normal to SAW propagation) is largely unaffected by changes in cover thickness. However, the X-axis component (direction parallel to SAW propagation) increases by a factor of two over the range of cover thicknesses. The increase in the X-axis component changes the ratio between the two axes, which results in more cancellation between the two axes. This is reflected in Fig. 9, which exhibits a decrease in γ_1 , with a minimum occurring around 0.050 inches. The change in sign of γ_1 in Fig. 9 is also consistent with Fig. 12, because the frequency shift

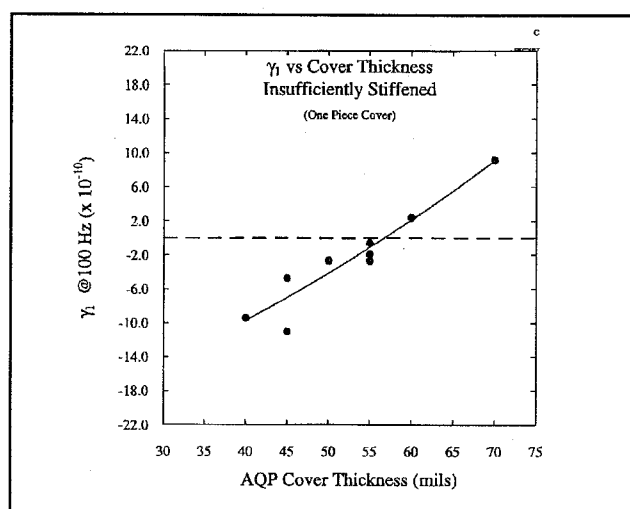


Figure 11. Experimental data of γ_1 at 100 Hz versus cover thickness (one-piece cover) for a typical 360 MHz AQP SAW hybrid circuit oscillator.

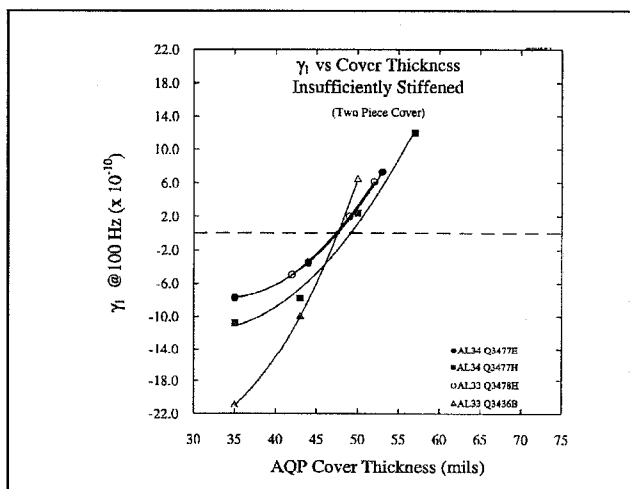


Figure 10. Experimental data of γ_1 at 100 Hz versus cover thickness (two-piece cover) for a typical 360 MHz AQP SAW hybrid circuit oscillator.

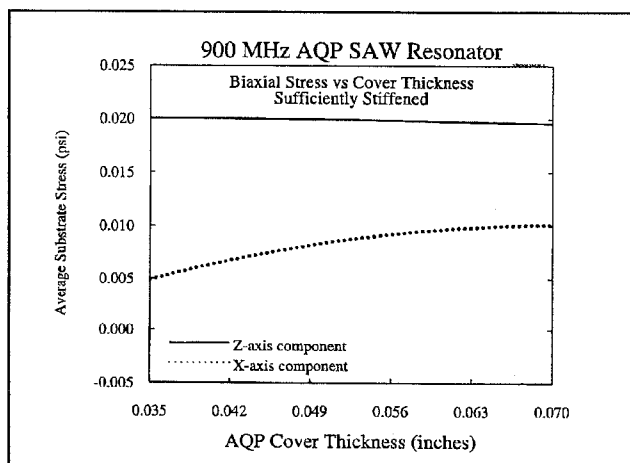


Figure 12. Finite element data of biaxial stress components versus cover thickness for 900 MHz AQP SAW oscillator.

due to the X-axis component dominates as the cover thickness is increased beyond .050 inches.

Another benefit of increasing cover thickness is the accompanying decrease in the variation of γ_1 vibration sensitivity. This is clearly evident in Fig. 9, and it was speculated that the spread in data could be attributed to variations in the silicone PSA mounting material. This was verified by subsequent finite element analysis. The results are plotted Fig. 13, and show γ_1 versus the percentage of area unsupported. To simulate variations in the mounting material, a set of simulations was performed where the mounting material was incrementally removed. This is represented by the percentage increase in unsupported area. The simulation was performed for three different cover thicknesses, and clearly shows that increasing cover

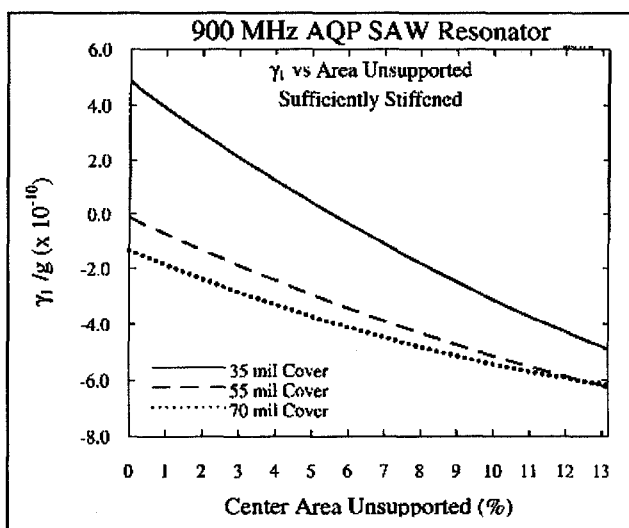


Figure 13. Finite element data of γ_1 versus percentage of area unsupported for a 900 MHz AQP SAW oscillator.

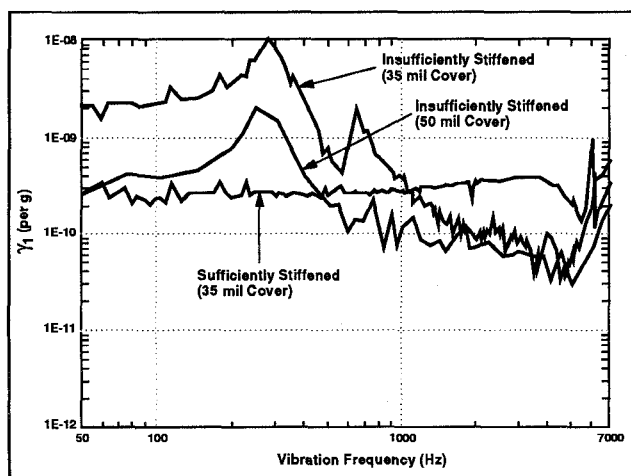


Figure 14. Experimental data of γ_1 vibration sensitivity for a 360 MHz AQP SAW oscillator.

thickness decreases the change in γ_1 as the unsupported area increases.

Cover thickness is also important in the case of insufficiently stiffened AQP SAW oscillators. The results illustrated in Figs. 10 and 11 show similar behavior to the sufficiently stiffened case. Although these two sets of data were derived from similar devices, there are differences in the cross over point and the slope of the curves. This is probably due to the fact that the data in Fig. 10 was generated from devices with two-piece quartz/glass covers, while Fig. 11 is from one-piece quartz covers. However, the spread is consistent between both data sets, which is due to variations in the mounting material.

The usefulness of the cover/substrate thicknesses in improving the γ_1 vibration sensitivity of AQP SAW oscillators has been demonstrated. Substrate thickness is an important parameter, and can be used to change the magnitude and phase of γ_1 vibration sensitivity. The results of this work are illustrated in Fig. 14, which shows the γ_1 vibration sensitivity measurements for the same 360 MHz AQP SAW device under different conditions. The curve for the sufficiently stiffened case is a typical response for this type of resonator. The insufficiently stiffened (0.035 inch-thick cover) data is also typical for an AQP SAW oscillator with vibration isolation mounting. The effect of cover thickness is clearly seen with the reduction in γ_1 vibration sensitivity when the cover is increased to 0.050 inches thickness.

V. DUAL-APERTURE RESONATOR PERFORMANCE

Recently, experiments have been performed to compare the vibration sensitivity performance of dual-aperture 325 MHz AQP SAW resonators mounted up-side-down (USD) ("conventional") versus right-side-up (RSU). For single-aperture devices the performance when mounted up-side-down has always been found to be superior due to the "aspect ratio compensation" effect reported previously [1], [6]. Figures 15(a) and 15(b) show the measured vibration sensitivity magnitudes for two different devices when mounted USD versus RSU. The device in Fig. 15(a) had equal 0.035 inch-thick quartz cover and substrate pieces, while the device in Fig. 15(b) had a 0.055 inch-thick quartz cover and a 0.035 inch-thick quartz substrate. Note that in both cases the vibration sensitivity magnitude was smaller for the RSU mounting arrangement than for the USD mounting configuration, although the results for either mounting configuration (USD versus RSU) of both devices were still quite good. While these results appear to contradict prior "aspect ratio compensation" explanations for the superior vibration sensitivity performance of AQP SAW devices when mounted in the USD configuration, the data is actually easy to interpret.

Figure 16 illustrates the deformed model for the 325 MHz AQP SAW device under a 1g inertial loading. It is now important to realize that the two active acoustic areas for the dual-aperture device are not located at the center of the substrate (near the region of maximum stress). Each device is now actually located in a region of the substrate which is under both tensional and compressional stress, resulting in a partial cancellation of the stress induced frequency shift for the individual devices when the stresses

are integrated over the active acoustic area of each device. This observation has been confirmed experimentally on several test devices, and suggests for dual-aperture AQP SAW resonator devices that the physical location (or separation) of the two resonators is yet another design parameter at our disposal in the quest to achieve further improvements in vibration sensitivity performance.

VI. THREE-PIECE AQP SAW TESTING

Figure 17 illustrates a three-piece AQP SAW resonator device in which an "extra" cover plate (without notches) has been included. The goal of this investigation was to determine whether the three-piece device could be mounted right-side-up (RSU) while maintaining good vibration sensitivity performance. The RSU mounting arrangement was considered to be more suitable for production since wire bonding could be done on the device after insertion into the oscillator hybrid, rather than having to attach "flying leads" to the resonator prior to installation in the oscillator housing. Figure 18 illustrates the typical results found for RSU versus USD mounting, namely that the results are almost identical for either mounting arrange-

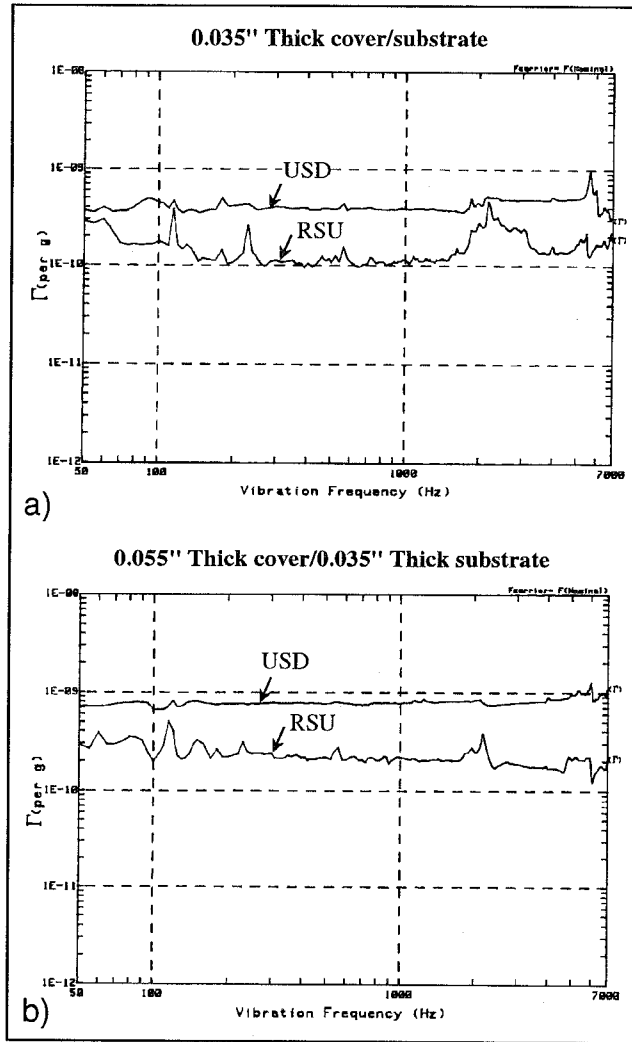


Figure 15. (a) Experimental data for Γ (vibration sensitivity magnitude) for a 325 MHz AQP SAW resonator device mounted right-side-up (RSU) versus up-side-down (USD): cover and substrate thicknesses both 0.035 inches. (b) Experimental data for Γ (vibration sensitivity magnitude) for a 325 MHz AQP SAW resonator device mounted right-side-up (RSU) versus up-side-down (USD): cover thickness of 0.055 inches and substrate thickness of 0.035 inches.

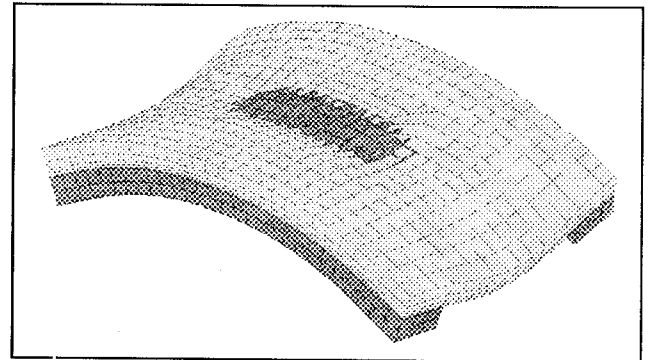


Figure 16. Finite element model of the 325 MHz AQP SAW resonator with γ_1 deformations.

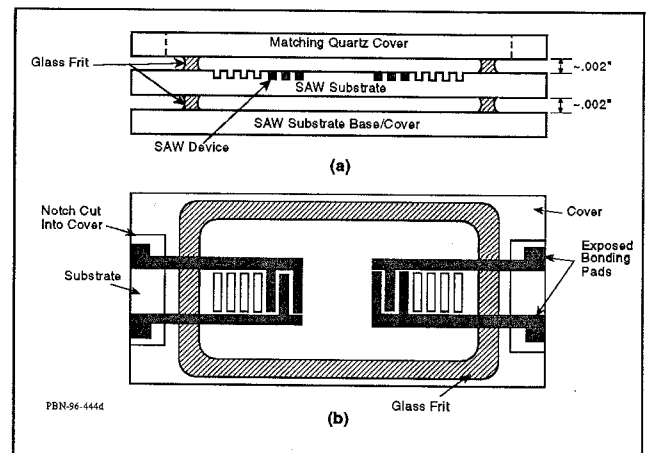


Figure 17. Schematic diagram of a three-piece AQP SAW resonator.

ment (dominated by the γ_1 component in both cases). While it is quite likely that by varying various dimensions a better result could be obtained, the superior results discussed previously for dual-aperture devices when mounted RSU eliminated the three-piece AQP SAW approach from further consideration.

VII. AQP STW RESONATOR VIBRATION SENSITIVITY

A number of 1 GHz AQP surface transverse wave (STW) resonators were fabricated and their vibration sensitivity performance evaluated. Figure 19 illustrates the typical result when the AQP STW devices were mounted in the USD ("conventional") arrangement. The vibration sen-

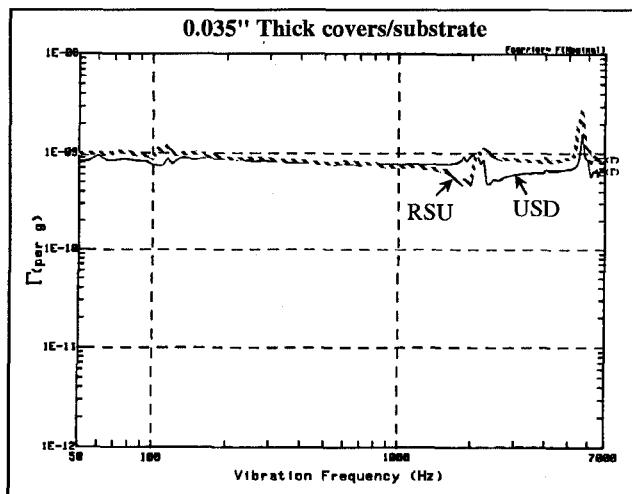


Figure 18. Comparison of vibration sensitivity magnitudes (Γ) for RSU versus USD mounting of the three-piece 325 MHz AQP SAW resonator shown illustrated in Fig. 17.

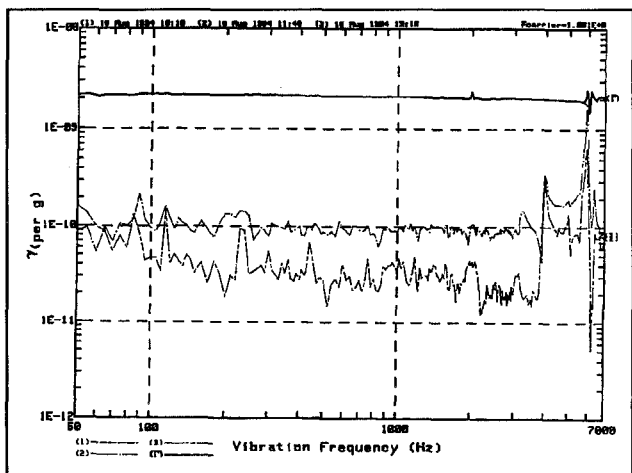


Figure 19. Experimental vibration sensitivity (three-axis) data for a 1 GHz AQP STW resonator device mounted up-side-down (USD).

sitivity magnitudes (Γ) were found to be dominated by the γ_1 component, and were typically in the 2 to $3 \times 10^{-9}/g$ range. Figure 20 shows the results for the same AQP STW device when mounted in the RSU configuration. Although the RSU result is somewhat better than the USD result, the measurements also indicate that in order to achieve "aspect ratio compensation" (these STW devices were single-aperture designs), an impractical width-to-length ratio (almost 6:1) would be needed.

Finally, the same AQP STW device was mounted USD with only "four-corner" support (a non-uniform mounting configuration) and weights were applied to the cover in order to modify the biaxial stress pattern. The result illustrated in Fig. 21 shows that previously documented techniques for reducing the vibration sensitivity magnitude of

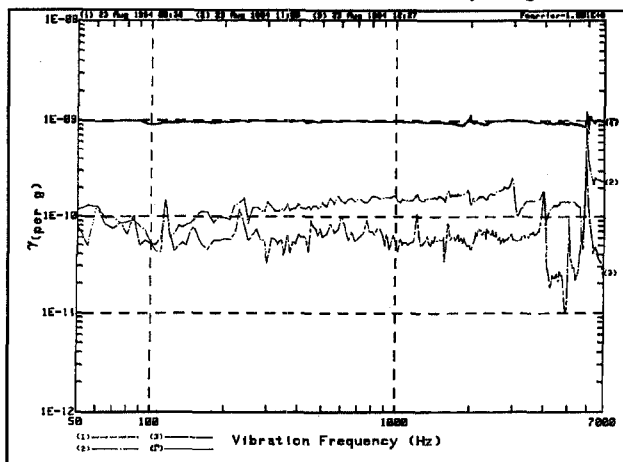


Figure 20. Experimental vibration sensitivity (three-axis) data for a 1 GHz AQP STW resonator device mounted right-side-up (RSU).

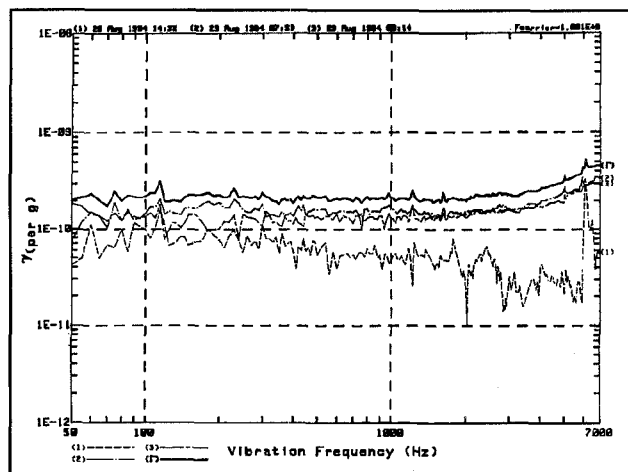


Figure 21. Experimental vibration sensitivity (three-axis) data for a 1 GHz AQP STW resonator device mounted up-side-down (USD) with four-corner (non-uniform) support, and cover weights applied.

AQP SAW resonators may also be applied in the case of AQP STW resonators in order to achieve very good results.

VIII. SUMMARY & CONCLUSIONS

The AQP approach to hermetically encapsulating SAW devices has been shown to offer distinct advantages in achieving state-of-the-art vibration sensitivity performance when incorporated into hybrid circuit oscillator hardware. This is in addition to previously documented state-of-the-art long-term frequency stability and phase noise performance when incorporated into suitably designed hybrid oscillator circuitry [7].

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