In situ compensation of surface acoustic wave filter response

R. W. Cohn and R. S. Wagers
Central Research Laboratories, Texas Instruments Incorporated, Dallas, Texas 75265

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An experimental methodology is demonstrated for compensating the response of surface acoustic wave (SAW) bandpass filters. For a filter on (*YZ*) $LiNbO_3$, we present measurements of changes in the SAW impulse and frequency response produced by *in situ* perturbations to the transducer's apodization. Many transducer electrodes are perturbed in their length to determine filter sensitivity to electrode length variation. A methodology that is adaptive in these length variables is applied to determine the optimal apodization for the compensation of frequency domain sidelobes initially at the − 26 dB level. They are deterministically reduced to the − 39 dB level.

It is apparent that any perturbation to the structure of a surface acoustic wave (SAW) device will modify its electrical response. In the past, *in situ* perturbation procedures have been applied to the frequency tuning of resonators,[1] and combined amplitude and phase correction of dispersive reflective array filters[2] by using properties of mass loading, electrical loading, and reflectivity perturbation of Rayleigh waves. It is also possible to perturb the geometric structure of the interdigital transducer (IDT) and accurately measure changes in the electrical response of SAW bandpass filters without unpackaging, damaging, or modifying the device in any way.[3] These results have been extended and applied in the adaptive compensation of an apodization weighted bandpass filter on (*YZ*) $LiNbO_3$. Described below is the methodology for measurement of filter sensitivity to *in situ* modification of the length of individual electrodes. The characteristics of this type of perturbation are described. Finally, an optimal set of perturbations is determined, in an iterative fashion, that reduces the overall sidelobe level from − 26 to − 39 dB.

The procedure for determining filter sensitivity consisted of (i) accurately measuring the insertion loss and phase angle of the device from 44 to 144 MHz, (ii) mechanically scribing a precisely measured length off the end of an electrode, (iii) remeasuring the frequency response of the perturbed device, and (iv) calculating the algebraic difference between the two complex measurements.

The frequency response of the device was measured on an HP8507 automatic network analyzer (ANA) operated in its phase locked configuration. With a source frequency stability of 10 Hz, the ultimate resolution of a complex-valued measurement by the ANA of a high level signal was 0.01 dB and 0.1° (without averaging). This was the resolution achieved with measurements in the passband of the filter. Initially, in the sidelobe region of the filter response measurement repeatability (and thus effective resolution) was degraded due to the low signal levels. This problem was corrected by cascading a broadband amplifier with the filter and averaging several complex-valued measurements. Under these conditions the effective resolution was 0.1 dB and 0.5° over the entire frequency range.

A commerically available probe station[4] was used to scribe open portions of the metal electrodes. The scribe used was capable of cleanly severing 2-μm-wide electrodes placed on 5-μm centers. Placement accuracy of better than 1 μm was possible using a reticle eyepiece in the microscope of the micropositioning probe station. Scribing could be performed in a few minutes on a packaged device with complete flexibility.

The specific filter designed and compensated was fabricated on (*YZ*) $LiNbO_3$. The center frequency wavelength was 36.6 μm which resulted in a 94 MHz center frequency. The filter, shown in Fig. 1, consisted of an unapodized 2 7/8λ_0 long, double-electrode input transducer; a 110 stripe multistrip coupler (MSC); and an apodized 15 7/8λ_0 long, double-electrode output transducer. The aperture of each transducer measured 167λ_0. The aperture of the MSC was 352λ_0 and the stripes and spaces were both $\lambda_0/6$. The device was mounted on a metal header and the input and output transducers were ball bonded with 1 mil gold wire directly into a 50-Ω transmission measurement system. No intermediate circuit elements were included to impedance match the electric ports.

The first perturbation experiment was performed by shortening a single electrode located near the center of the apodized transducer. This electrode was shortened in 5λ_0 increments from its initial length of 164λ_0. Measurements of the frequency response were made after each perturbation. Six perturbation measurements were calculated as the difference between the unperturbed frequency response and the frequency response after each trim. Since many first-order properties of SAW bandpass filter performance are commonly described in terms of device impulse response, the unperturbed filter frequency response and the perturbation

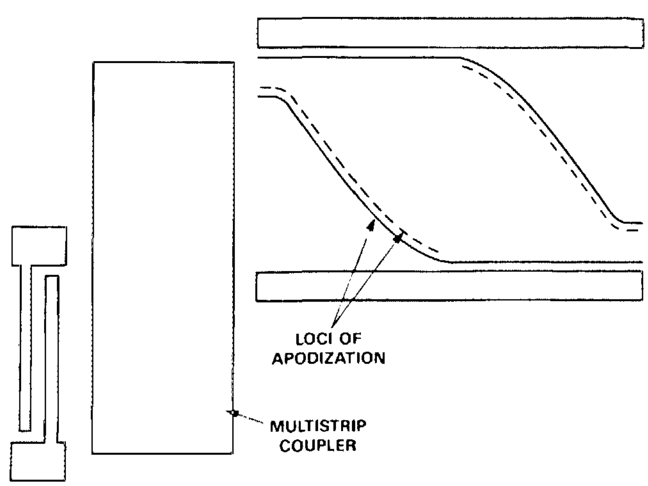

FIG. 1. Layout of the SAW filter structure. The dashed lines indicate regions of the apodized transducer where the electrode lengths were trimmed.

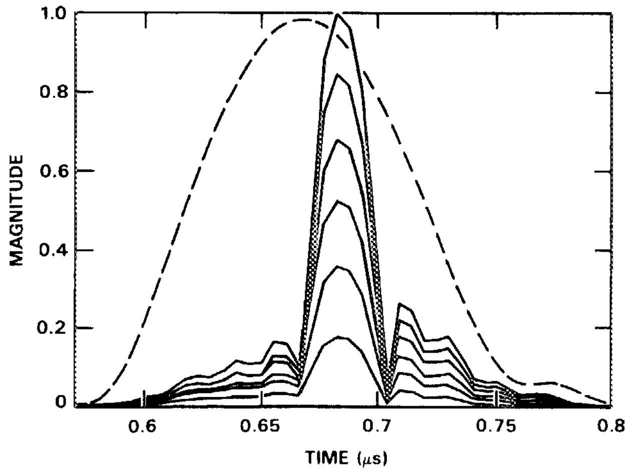

FIG. 2. Impulse response data of the SAW filter. Dashed curve shows overall filter response before perturbations. Solid curves show impulse responses associated with trims to an electrode in $5\lambda_0$ steps up to a total shortening of $30\lambda_0$. The perturbation responses were scaled by a factor of 15.

response measurements were Fourier transformed. These results are shown in Fig. 2.

Several general observations are apparent when examining these results. Except for a magnitude scale factor each perturbation measurement plot appears identical in shape and amount of delay. The time responses of the perturbation measurements are narrow as compared to the filter impulse response. However, a single electrode trim should be even narrower having a time extent equal to approximately the wavelength divided by the Rayleigh wave velocity (10.4 ns). The broadening of the perturbation measurement impulse response is due to convolution of the perturbation to the apodized transducer response with the unapodized transducer response.

Regeneration is seen to affect both the trailing and leading portions of the perturbation impulse response. In the perturbation response regeneration is larger in relation to the peak response than in the case of the full filter impulse response. Based on perturbation measurements of various electrodes in the apodized transducer it was found that the regeneration response of each perturbation response peaks at $\sim 0.67\ \mu s$ (which is the static delay of the filter).

The perturbation technique was evaluated by two methods to determine the degree to which the perturbations could be linearly superposed. The first examination was to determine if the magnitude of the perturbation response increased linearly with increasing trim to the length of a single electrode. The second experiment was to determine if trims to various electrodes interacted with each other or affected the linearity of subsequent perturbations to the original electrode.

The successive perturbation measurements illustrated in Fig. 2 increased almost linearly with the amount of electrode perturbation. A least-squares fit to a straight line at the peak of each response gave a maximum deviation of $\sim 1\%$ relative to the full $30\lambda_0$ trim. The phase response deviated from constant by 7°. In the frequency domain even better linearity and phase constancy was found over the range which covered the first two upper and lower sidelobes, 74–114 MHz.

After the sixth perturbation of the central electrode, in order to evaluate the possible interaction of perturbations to distinct electrodes, trims totaling $35\lambda_0$ were made on electrodes near each end of the transducer. The electrical response of the filter was measured and perturbations on the central electrode were resumed. The subsequent perturbations to the central electrode had essentially the same relative effect as the first six perturbations. Changes of $35\lambda_0$ on remote electrodes appear to have a negligible amount of interaction with perturbations to the central electrode.

Starting with an unperturbed device the sensitivity of the filter was measured in preparation for compensation of the frequency response. A perturbation measurement was made on every other double electrode of the apodized transducer (i.e., every wavelength a trim was made). Trims of $5\lambda_0$ were made on 16 electrodes. Each trim produced an impulse response change with an envelope similar to that shown in Fig. 2. The two end trims produced responses that were most clearly different in magnitude from the other 14. Excluding the end electrodes, identical electrode length changes produced perturbation signals with variances in peak amplitude of $+/-$ 10% throughout the transducer. The information provided by this *learning set* was sufficient for compensating the filter frequency response.

A compensation algorithm was sought which used the linear superposition of perturbations validated in the experiments discussed above. The compensation algorithm specified modifications to the uncorrected apodization by choosing some set of electrode perturbations which, over the given frequency range, mimimized the integral of the squared magnitude of the difference between the desired and uncorrected frequency responses. In the case where the perturbation responses obey linear superposition, a set of real coefficients can be determined exactly which specify the optimal electrode perturbations through inversion of matrix. In the application of this technique a constraint was applied to the least squares cost function that limited the total change allowed to the electrode lengths. Since the mechanical scribing procedure only permitted length reductions, the optimizer was also constrainted from predicting length increases.

After carrying out the optimization, the electrodes are then perturbed according to the solution and the filter is remeasured. This partially compensated response is then used in place of the precompensated response in calculating a revised cost function. As long as the cost function can be reasonably reduced in each iteration a new *learning set* of perturbation measurements is not required.

In executing the compensation algorithm the desired filter was specified to be one with perfect rejection out of band and no change in band. In this way all compensation effort was focused on obtaining the best sidelobe reduction. The filter was compensated in two iterations. For both passes the perturbation data obtained from the initial set of $5\lambda_0$ trims to the 16 electrodes were used in the error function expansion. Figure 3 shows the filter transmission characteristics prior to compensation and the results achieved after the second iteration. After compensation a sidelobe level of -39 dB was achieved over the frequency band of 44–144 MHz. That level represents a 13 dB overall improvement.

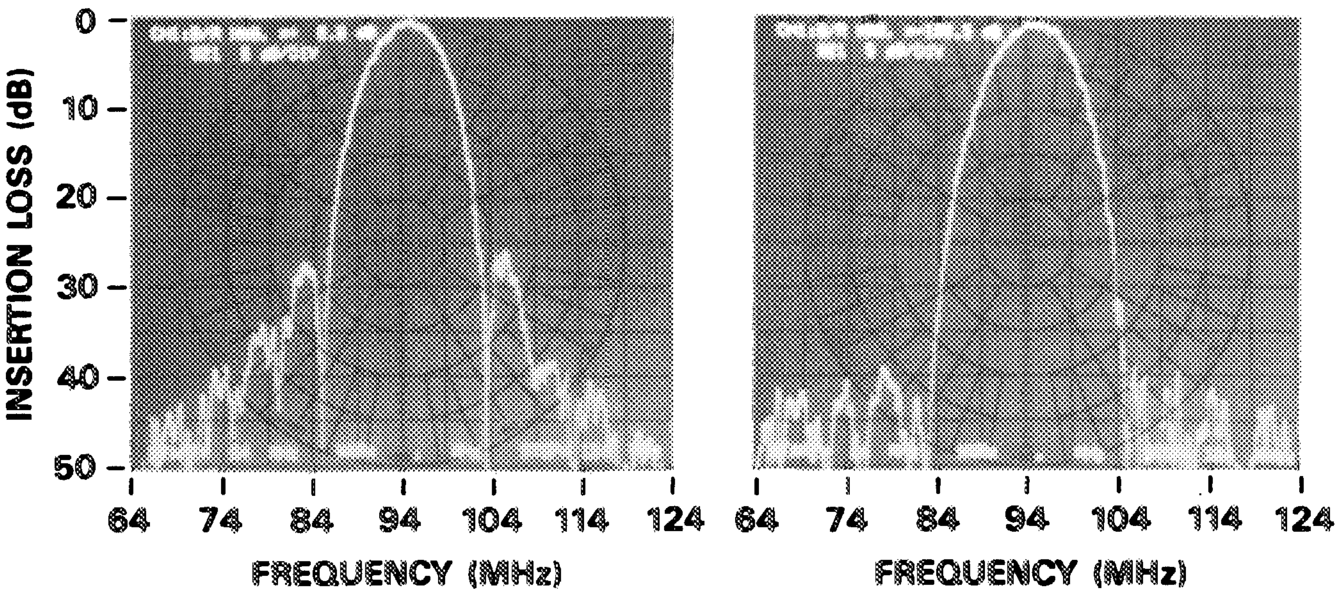

FIG. 3. Responses of compensated SAW filter. (a) Frequency response of the as-fabricated filter. (b) Frequency response after perturbing the apodized transducer electrodes in accordance with the algorithm predictions.

The transition band widened somewhat; this was to be expected since no constraints were directly imposed on the transition band and since the apodization weighting function is more sharply tapered after trimming. At each iteration the predicted and achieved complex-valued responses were in extremely close agreement over the entire frequency band.

We have illustrated that the frequency response of SAW filters can be improved through *in situ* apodization perturbation in a controlled, understandable manner within the limitations of current instrumentation and measurement techniques. We have also demonstrated the ability to compensate SAW filters using a simple and fast algorithm. These points are significant in demonstrating the feasibility of adaptive systems which synthesize and/or compensate SAW bandpass filters. Such systems would accelerate the development of new filter prototypes, extend the performance levels and confidence levels in SAW designs, improve lot yields, and lead to new experimental methods of characterizing SAW filters and describing SAW physics.

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[3]R. S. Wagers and R. W. Cohn, *Proceedings of IEEE Ultrasonics Symposium*, Atlanta, Georgia, 1983 (IEEE, New York, 1983), pp. 5–10.
[4]Micromanipulator Co., 1100 Corbett Street, Carson City, NV 89701.

Acceleration sensitivities of surface acoustic waves propagating on a cantilever quartz beam

D. Hauden and B. Loewenguth
Laboratoire de Physique et Métrologie des Oscillateurs du CNRS associé à l'Université de Franche-Comté–Besançon, 32 avenue de l'Observatoire, 25000 Besançon, France

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High accuracy quartz accelerometers are built on the principle of an electronic servoloop circuit. We study the performance of open loop quartz accelerometers which have surface acoustic wave (SAW) delay lines (or resonator) as sensitive component mounted in an oscillator. Sensitivities versus bending forces and compression force are calculated as a function of quartz crystal anisotropy. Comparison with experimental values obtained with SAW oscillator shows that transverse acceleration has a very low sensitivity for single rotated cut ($Y \pm \theta$).

Surface acoustic waves (SAW's) are attractive for sensor applications when they can be made selectively sensitive to a particular physical quantity.[1–3] Their sensitivities are mainly due to the nonlinear properties of the medium which couple the high-frequency wave with the external perturbations. In fact, the perturbation induces a predeformation of the medium superimposed on the SAW vibrations. By considering that the vibration does not influence the perturbation and