*This is a preprint of an article to appear in the 1998 IEEE Ultrasonic Symposium Proceedings*

# Effect Of Wraparound Electrodes on Ultrasonic Array Performance

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***Abstract*** **-** In many ultrasonic transducer array structures, it is convenient to make electrical connection to the top and bottom electrodes of thickness driven array elements by wrapping one or both electrodes around the elevational edges of the element. This is called a "wraparound electrode". The high, non-uniform electric fields at the corner(s) of the element where the opposite polarity electrodes are in close proximity result in a significant degradation of the electromechanical coupling constant and a large down-shift in acoustic velocity. Incorporating isolation cuts along the azimuthal edges of the array elements provides an air or polymer filled gap that greatly reduces the electric fields in the corner. As a result, the coupling constant and acoustic velocity are restored to the values expected from the structure without wraparound electrodes.

## INTRODUCTION

It is common practice to make electrical connection to transducer array elements using wraparound, or edge, electrodes. For example, to minimize the footprint of a transducer array, sputtered or CVD metal electrodes can be provided that completely cover the edges as well as top and bottom surfaces of a piezoelectric ceramic slab before dicing into elements. Two opposing corners of the slab can be masked or beveled after electrode deposition, to separate the two electrodes (Figure 1) This provides one edge connected to the top electrode on one side of the array, with the other edge connected to back side. Flex circuits are often connected to the edges of the element before, or after, dicing to provide interconnection to coaxial cables or integrated electronics.

Measurements of coupling, resonant frequency and dielectric constants of ceramic slabs or array elements with wraparound electrodes show anomalous characteristics. Frequency downshifts expected from dicing, which result in the reduction of stress on the diced edges of the element, are significantly larger than the expected 12% for PZT5H-class materials. The coupling constant is significantly reduced, measuring 

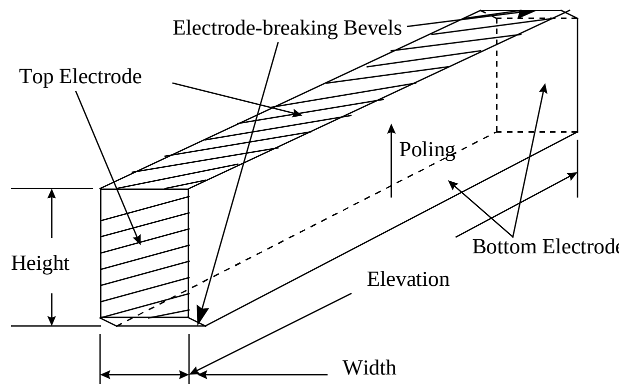


**Figure 1:** Schematic of array element with wraparound electrodes.

0.5 or less, and the clamped capacitance increases about a factor of 2.

These effects were simulated using finite element analysis and excellent correlation to measurements was demonstrated. A means for correcting these anomalies is presented that works in arrays with large elevational dimension. Excellent correlation between experiments and simulations verify the efficacy of the solution.

## DEVICE DESCRIPTION AND ISSUES

A 1.5 D curved linear array operating at approximately 3.5MHz center frequency was designed as part of a DARPA program to demonstrate the integration of beamformer and front end electronics into the probe handle. The demonstration array consisted of 192 elements in azimuth and 8 elements in elevation. Maximum element beamwidth was to be achieved, necessitating the complete separation of the acoustic matching layers. Completely dicing the matching layers as well as the piezoelectric ceramic into individual elements isolates the top electrodes of the array elements from each other, complicating electrical connection to these electrodes. Several schemes have been employed in the past to solve this issue, including the formulation of electrically conductive matching

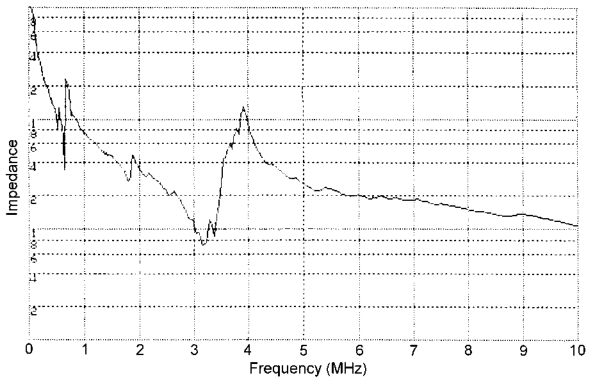


**Figure 2:** Measured electrical impedance of single array element.

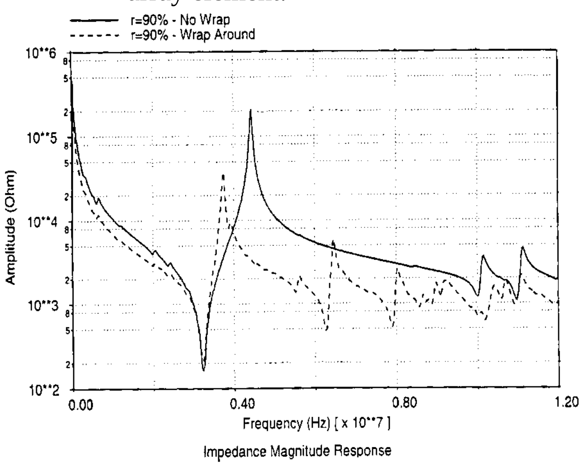


**Figure 3:** 2D finite element simulation of 90% subdiced array element with and without wraparound electrodes.

layers[1], introduction of an acoustically thin, conductive membrane[2], through-hole vias[3], and conventional wraparound electrodes. Issues related to the wraparound electrode scheme are discussed here.

Initial concerns about the wraparound scheme were related to the high, non-uniform electric fields in the region of the element around the electrode breaking bevels. These fields were expected to excite shear and possibly symmetric longitudinal modes not seen in elements with electrodes only on the top and bottom surfaces. These modes along with harmonics of the elevational lateral resonance could couple to and deleteriously effect the desired transducer fundamental response. Consequently, in order to study these effects, experimental elements were constructed and compared to 2D and 3D finite element simulations (PZFlex, Weidlinger Associates).

| Element Geometry | Effective Velocity | Downshift | Effective Coupling Constant |
|---|---|---|---|
| Plate | 4710 m/s | - | 0.25 |
| Long Plank | 4145 m/s | 12% | 0.54 |
| Post | 4074 m/s | 13.5% | 0.62 |
| Short Plank (DARPA element) | 3485 m/s | 26% | 0.32 (sim.) 0.35 (exp.) |
| Note: Only the DARPA element had wraparound electrodes | | | |

**Table 1:** Effective constants for various transducer geometries and electrode configurations.

Figure 2 shows the electrical impedance (magnitude only) of one such piezoelectric element 0.465mm thick by 0.150mm wide by 2.15mm long. Conventional design rules predicted that a parallel resonant frequency of 4.46MHz, a series resonant frequency of 3.23MHz, and a coupling constant ($k^2$) of 0.54 would be obtained. The measured series resonant frequency is close to the design value, although the resonance is somewhat obscured by coupling to a lateral length mode harmonic. However, the parallel resonance is significantly lower in frequency than expected (3.92MHz). The coupling constant, calculated from the standard IEEE formula, is only 0.35. The low coupling constant could potentially be the result of depoling during the sawing process; this possibility was checked and discounted during subsequent PZFlex analysis. The effective velocity, calculated from the parallel resonant frequency, is significantly reduced as well.

A 3D finite element simulation of this element (not shown) showed exactly the same behavior as the measurement, except that the lateral length harmonics and other extraneous modes were far more prevalent in the simulation. Other PZFlex simulations were also made which demonstrated that the overly large parallel resonant downshift was not the result of coupling to these modes or depoling. This is best demonstrated in Figure 3. In this 2D finite element calculation, the same element was subdiced 90% through the thickness along the elevation dimension. Subdicing results in moving the lateral length harmonics well above the desired fundamental thickness mode and clearly isolates the

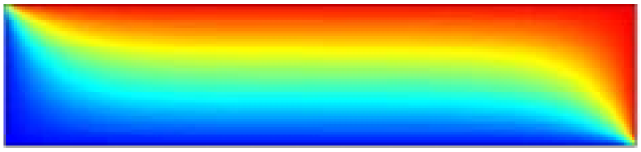

**Figure 4:** Equipotential contours in an element with wraparound electrodes

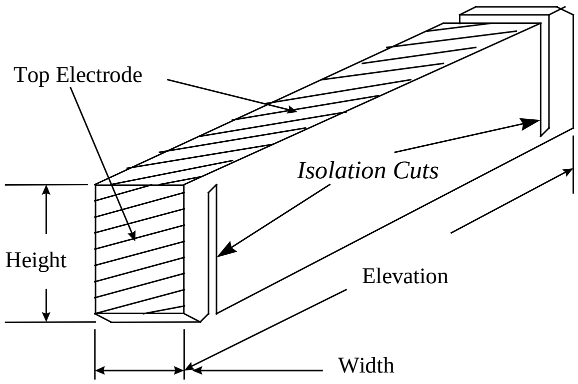


**Figure 5:** Schematic of array element with wraparound electrodes and isolation cuts.

effect of the wraparound electrode. Figure 3 shows the same subdiced element with unwrapped and wraparound electrodes. The wraparound electrode curve clearly shows the parallel resonance downshift, additional high frequency modes not excited in the unwrapped case, and an effective doubling of the element capacitance seen from the level shift in the impedance magnitude at high frequency. Table 1 tabulates the effective velocity, velocity downshift, and effective coupling constant for several standard transducer configurations calculated from PZFlex analyses. The anomalous behavior of the wraparound element is evident.

## SIMPLE PHYSICAL CONSIDERATIONS

In Figure 4 the equipotential contours between the electrodes of the wraparound element are plotted, based on a 2D finite element calculation. As clearly seen, there are high fields in the corners where the electrodes are in close proximity. This field pattern is much different than the simple parallel field lines seen in an element with only top and bottom electrodes. It is reasonable to assume that the overall capacitance of the of the element would be increased over a similar element with the typical electrode arrangement because the contribution of the “corner capacitances” is larger than that of

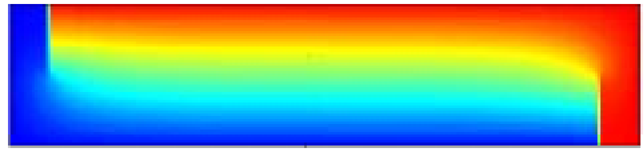

**Figure 6:** Equipotential contours in an element with wraparound electrodes and isolation cuts

parallel plate capacitors occupying the same real estate. The effective distance between electrodes in a capacitor resides in the denominator. A decrease in that distance will obviously increase the capacitance, resulting in the factor of 2 level shift in the electrical impedance seen in the simulation.

The anomalous downshift in frequency in the parallel resonance can be largely explained by the effective increase in the dielectric constant as well, from the following expression:

$$k_{33}'^{\,2} = \frac{e_{z3}^{\;2}}{(c_{33}^{E}\,\varepsilon_{33}^{S} + e_{z3}^{\;2})} \qquad \textbf{Eqn. 1}$$

where

- $k_{33}'^{\,2}$ is the effective coupling constant
- $e_{Z3}$ is the piezoelectric constant
- $c_{33}^{E}$ is the unstiffened stiffness constant
- $\varepsilon_{33}^{S}$ is the dielectric constant

If we assume that the piezoelectric and stiffness constants are unchanged by the wraparound electrodes, doubling the dielectric constant will reduce the coupling constant by a factor of 1.8 for PZT5H-class materials. In addition, the piezoelectrically stiffened velocity would be reduced. In 1D simulations, these changes would account for a 10% downshift in the parallel resonant frequency versus the 16% shift observed. Clearly, other things are going on than simply a doubling of the dielectric constant, but it would appear to be the major component. Obviously, any change in the configuration of the wraparound electrode will have a dramatic effect on the observed coupling and acoustic velocity of the array element.

## SOLUTION AND RESULTS

If wraparound electrodes are to be employed in an array element, and if the full coupling and a predictable resonance are to be recovered, some means must be devised to reduce the electric field strengths in the

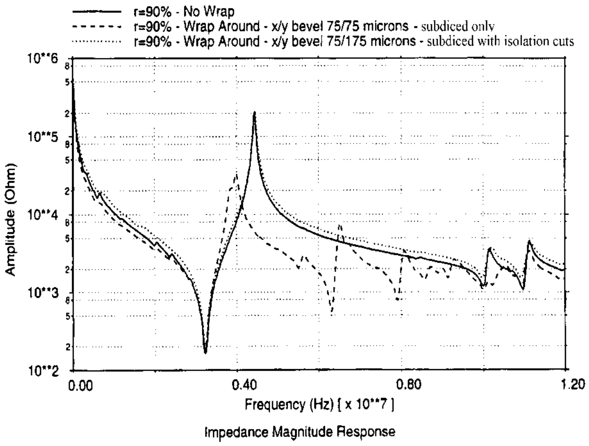


**Figure 7:** 2D finite element simulation of 90% subdiced array element with (1) standard electrodes, (2) wrap-around electrodes, and (3) wrap-around electrodes and isolation cuts.

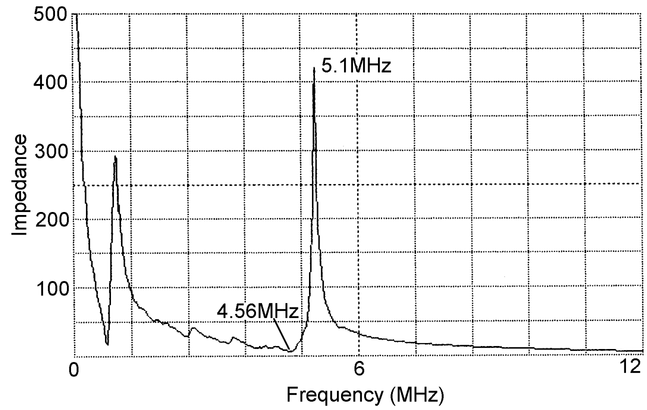


**Figure 8:** Electrical impedance of a piezoceramic plate with both wraparound electrodes and isolation cuts. Element dimensions are 0.465mm thick by 2.15mm in elevation.

corners. A simple means for accomplishing this is shown in Figure 5. In this case, opposing isolation cuts are made along the azimuthal edges of the element. These cuts serve to introduce a very low dielectric region (air or epoxy, for instance) between the electrodes in close proximity. These cuts extend a large distance through the element to reduce the “corner fields” to a relatively small level, as can be seen in the finite element generated equipotential contour plot shown in Figure 6.

Here the cuts are spaced from the edge of the element to a distance equal to 25% of the element height and extend 50% through the element. The equipotential contours are quite uniform in this case, and the regions in the corners are now at the same potential. Finite element analysis reveals that the cleanest electrical impedance response is obtained when the isolation cuts into the material are made as deep as possible. It is apparent that these isolation cuts recover the nearly parallel equipotential surfaces expected in an element with top and bottom electrodes only. The low dielectric constant material in the isolation cuts serves to cut off the field lines in the corners.

In Figure 7, PZFlex simulations of the electrical impedance of three element configurations are compared. All three cases have elements that are subdiced 90% deep through the ceramic as before to eliminate elevation lateral mode harmonics in the passband. The first case has standard top and bottom electrodes (no wraparound), and the expected high coupling constant and parallel resonant frequency are achieved. The second case shows the same element with wraparound electrodes, and the downshifted parallel resonant frequency and low coupling are observed. In the third case, opposing isolation cuts are employed with the wraparound electrodes as shown in Figure 5 to a depth of 90% of the element height. Clearly, the third case with the isolation cuts is virtually identical to the case with the unwrapped electrodes, demonstrating the efficacy of this solution.

In Figure 8**,** the measured electrical impedance of a plate of piezoelectric ceramic with wraparound electrodes and isolation cuts is shown (i.e. the parent ceramic prior to the sub-dicing process to form the 1D linear array). This configuration is comparable to the 2D finite element model of an element without subdicing, and would resonate in the thickness mode, not the effective extensional mode of a diced element. A clean, thickness mode resonance is observed, and a coupling constant of 0.234 and a stiffened velocity of 4704 m/s are calculated. These values are exactly those expected from the material parameters. The lateral mode harmonics are much less prevalent in the measurement than that predicted by the finite element model. This is probably due to a slight lack of planarity and parallelism in the actual element. The efficacy of the isolation cuts is clearly demonstrated in this measurement.

## CONCLUSIONS

Electrical connections in 1.5D and 2D transducer arrays where the matching layers are completely separated for minimum acoustic crosstalk present some difficult engineering problems. Wraparound electrodes are certainly one solution to making contact to the top electrode that can be employed along with unconventional array construction techniques. However, as has been demonstrated, high fields in the element corners where the electrodes are in close proximity cause a large reduction in the coupling constant as well as a downshift in the parallel resonant frequency. These effects can be completely ameliorated by applying opposing isolation cuts as shown in Figure 5. As a result, maximum bandwidth can be achieved in the overall transducer design. Of course, the radiating area of the element has been reduced appreciably, an effect that needs to be traded off against the additional bandwidth obtainable with the increased coupling coefficient. It would be very difficult to implement this solution in an array with multilayer piezoelectric ceramic. Note that these effects will be observed in any array element where conductive paths connect the top electrode to the bottom side of the element down the edge, corner, or interior of the element where the conductive path is in intimate contact with the piezoelectric material.

## ACKNOWLEDGMENTS

This work has been supported by DARPA under contracts N00014-96-C-0191 and N00014-96-C-0192 issued by the Office of Naval Research.

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