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Final Report

January 31, 2002

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Summary

The goal of this project is to prove the feasibility of high Q tunable actuators to be used at cryogenic temperatures. The end result is to include a tunable resonator structure fabricated with superconducting materials utilizing piezoelectric materials to provide tunability.

This project has shown that tunable resonators can be fabricated using polycrystalline piezoelectric elements with tunability of up to 25%. Although these studies were carried out at room temperature, it has also been shown that single crystal piezoelectric elements will have similar actuation at cryogenic temperature. In phase II of this program, superconducting resonators will be used in conjunction with single crystal piezoelectric actuators to fabricate high Q, tunable resonators at cryogenic temperatures.

In phase I of this project, tunable resonators were fabricated and tested at room temperature using metallic conductors. A polycrystalline piezoelectric element was used to provide actuation required to fabricate the tuning element of the resonator. It has been shown in previous work that single crystal piezoelectrics fabricated at TRS Ceramics have approximately the same strain at cryogenic temperatures as polycrystalline piezoelectrics at room temperature. Therefore, feasibility at cryogenic temperatures was modeled using polycrystalline materials at room temperature.

Tunable structures based on ring resonators were fabricated with two methods of tuning. The first was a variable air gap between the resonator and a ground plane above the resonator. The second was a movable dielectric slap with could be moved relative to the ring resonator. Results were very encouraging with tunability of up to 25% being achieved.

The movement required for the tunable resonators was created with a polycrystalline piezoelectric unimorph style actuator. Data on similar actuators fabricated with single crystal piezoelectric element shows very high strain. Therefore, single crystal

piezoelectric unimorphs should have no problem providing the actuation required for tunable resonators at cryogenic temperatures.

Results

Tunable Resonator Structures

Work on this project was roughly broken up into three different areas:

1. Fabrication and testing of tunable resonator structures
2. Modeling of tunable structures
3. Proof of concept for cryogenic actuators

Initial work focused on a tunable ring resonator which was designed with a movable ground plane for tuning purposes. This ground plane was attached to a polycrystalline pzt unimorph to control its position. A tunability of 18 percent was achieved for a resonator centered at approximately 3 GHz.

The standard ring resonators and ground planes were drawn in silver paste (Dupont 6160) using a Micropen (OhmCraft, Inc.) on a 2 x 2 in. square 96% alumina substrate. The substrate was then fired at 850 °C for 15 minutes.

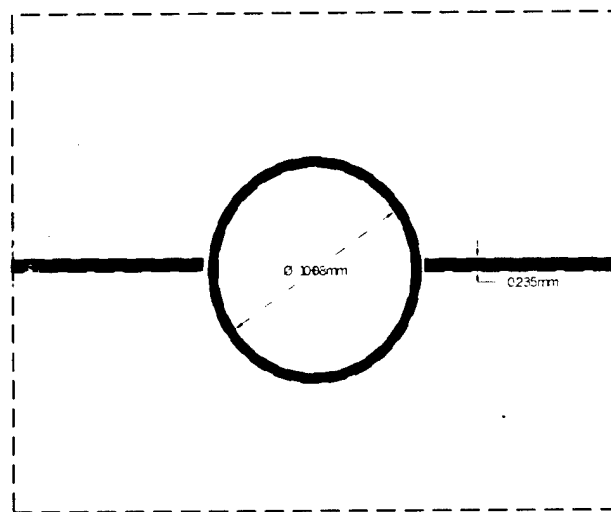


Figure 1. Top view of the ring resonator. The thickness of substrate is 0.517 mm, the width of the ring is 0.21 mm.

A piezoelectric unimorph was used to position the ground plane at a variable distance from the ring resonator. The unimorph consists of PZT disc bonded to the circular brass plate, which is much larger in diameter (approximately 25 mm) than the ring part of the ring resonator (10 mm). When the voltage is applied to the PZT, it changes its lateral dimensions due to a large piezoelectric d_{31} coefficient. As a consequence of an intimate

bond between PZT and brass, a bending moment is developed at the interface between them and the structure bends. The displacement of the unclamped actuator was about 250 microns based on the preliminary measurements with the LVDT.

The ring resonator with the actuator assembly is shown in Figure 2. A tape with thickness of 0.05 mm was used to cover the ring resonator and feed lines. It was placed there to protect against the short circuit when the unimorph has the maximum downward displacement. A unimorph bender was placed on top of a thicker tape (0.35 mm) permitting a maximum actuator displacement range of approximately 0.3 mm.

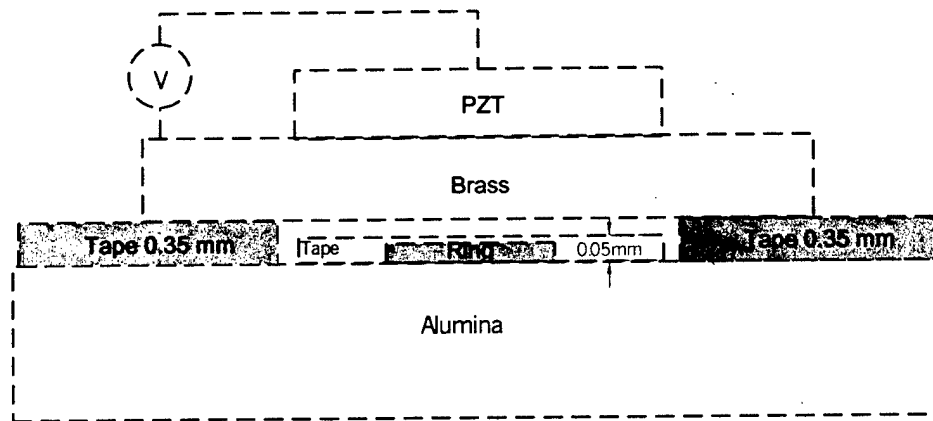


Figure 2. Schematic drawing of the tunable resonator assembly with the feed line perpendicular to the plane of the drawing.

S_{21} parameters were measured in the frequency range of 2 to 4 GHz using an HP 8510C network analyzer and custom-built test fixtures. Our preliminary measurements using a piezoelectric unimorph actuator to drive the ground plane towards and away from the plane of the ring resonator are shown in Table 1. The actuator was partly clamped to keep it radially fixed during operation that probably reduced displacement level.

Actuator Bias (Volts)	Fundamental Mode Resonant Frequency (GHz)	$(\Delta f)/f$ (%)
0	3.12	0
-200	2.66	14.7
50	3.24	17.9

Table 1. Tunability as a function of bias applied to piezoelectric unimorph tuning actuator.

For the forward bias with respect to the poling direction (-200V), the actuator moved closer to the ring resonator, increasing the effective dielectric constant of the device and

lowering the resonant frequency. It was possible to use a modest reverse bias (50V) to further increase tunability; however, at higher voltage, depoling of the actuator took place.

Following completion of initial experiments, the experimental setup was modified by making the gap variable, controlled by a micrometer as shown in figure 3. The micrometer is used as a micropositioner. A metal ball soldered to the brass layer of the unimorph device and a magnet attached to the micrometer form the movable contact. This approach permits an easy and accurate control of the air gap. Acrylic coating (approximately 0.025 mm thick) was used to protect the ring resonator from being shorted when the movable brass plate touched it. We determined that the acrylic coating does not affect the Q of the ring resonator. The other side of the unimorph bender was fixed on top of a tape (0.35 mm) well above the acrylic layer.

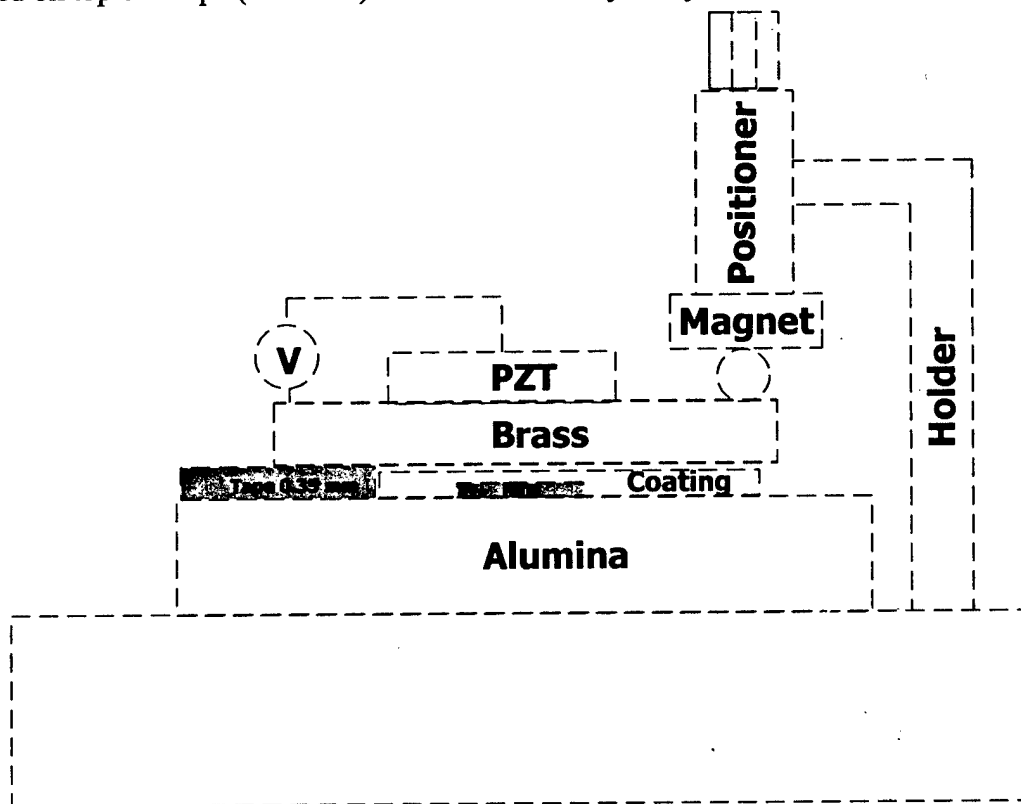


Figure 3. Experimental Set-up for piezoelectrically-tuned ring resonator.

To study tunability, a forward bias was applied to the PZT layer for a given gap. With a forward bias of 200 V the PZT layer shrinks laterally and the unimorph bends concavely downwards, decreasing the gap. The largest tunability of the resonant frequency occurs at the fundamental mode compared to the other modes. A comparison of the fundamental resonant mode for no applied bias (0 V) and a forward bias of 200 Volts is shown in Figure 4. The resonant frequency shifts to a lower frequency when the gap is reduced (200 Volts).

The tunability increase with reduced gap size is shown in Figure 5. The gap is measured by the micrometer in the micropositioner. Tunability increases to 20% when the gap size approaches the movement span of the actuator. The apparent reduction in tunability for smaller gaps is likely due to the actuator pressing against the acrylic covering the ring resonator. The fundamental resonant frequency for 200 Volt forward bias is almost unchanged for the three smallest gaps measured, which is consistent with the actuator being flush against the acrylic coating.

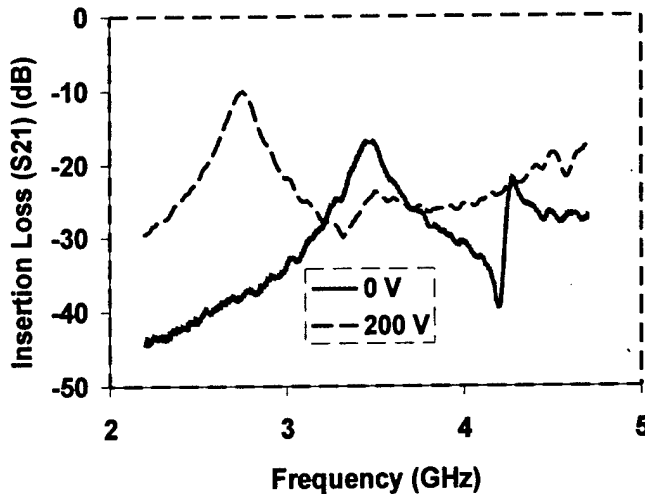


Figure 4. Frequency shift of the Fundamental Mode for an applied voltage

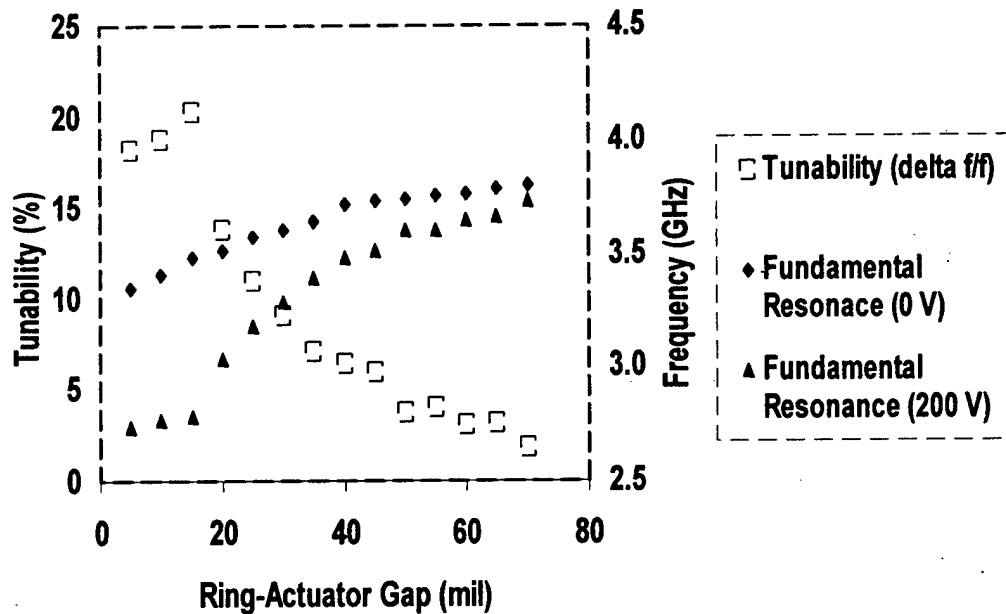


Figure 5. Tunability and resonant frequency of the fundamental mode vs. gap.

In the next set of experiments, tunability was studied for dielectric and metal tuning plates. Tunability of 25% was achieved with a brass plate as well as with a dielectric plate. Among the dielectric materials tested, the best tunability was obtained for a plate having a dielectric constant of 22. High tunability for a moderate K material is promising for future development of high Q highly tunable resonators and filters.

Originally a piezoelectric unimorph actuator was used to control the air gap. However, to more precisely control the air gap, to keep the gap uniform, and to permit easy substitution of different tuning plate materials. The experimental apparatus shown in Figure 6 was used to obtain the data reported below. All of the dielectric tuning plates had fired-on silver electrodes on one side, which was grounded during measurement. A circular brass plate was also grounded during measurement. The silver sample was a thick film fired-on electrode in an open circuit.

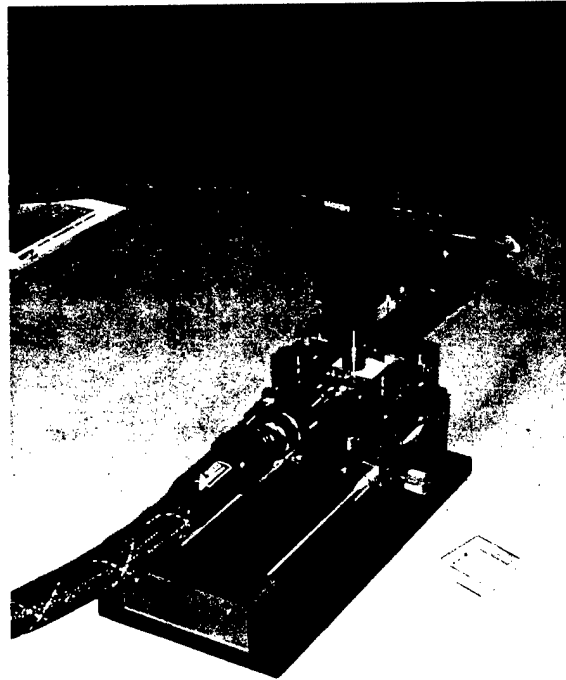


Figure 6. Experimental apparatus for tunable ring resonator. A micrometer holds an interchangeable dielectric plate directly over the ring resonator.

Using the apparatus shown in Figure 6, tunability was studied for tuning plates made out of various dielectric materials with dielectric constants in the range of 7 to 2500. We also studied silver and brass for comparison. For $K = 2500$ material no tuning was observed but new modes were generated when the dielectric gap was changed. For all of the other materials, significant tunability was observed as shown in Table 2. In all cases, tunability increased the most for the smallest gap, with the most tunability occurring for the gap changing from zero to 100 microns.

Tuning Plate Material	Description	K	Tunability (%) 1 st Res. Mode	Tunability (%) 2 nd Res. Mode
P/N 951-875C	0.5" square, t = 0.94mm	7.4	11.1	8.6
Alumina	0.5" square, t = 0.5 mm	9	10.6	8.6
P/N K20-875	0.5" square, t = 0.66mm	22.1	24.8	25.2
P/N CTS (Zr,Sn)TiO4	0.5" square, t = 1.17mm	38	14.5	17.1
P/N CTS LB2	0.5" square, t = 1.02mm	88.3	16.4	17.9
Brass	0.5" dia. circle, short circuit		-26.9	
Silver	0.5" square, t = 0.01mm, open circuit		-12.0	

Table 2. Maximum tunability for tuning plate materials

For all of the dielectrics, as the gap was reduced the resonance frequency also decreased, due to increase of the effective dielectric constant. In contrast, for the metals the resonance frequency moved in the opposite direction. In general, Q was higher for the second resonance than for the first, as in Figure 7. For dielectric losses, Q is proportional to $1/f$, while for metal losses, Q is proportional to \sqrt{f} , suggesting that for the high Q dielectrics used in this study, it was the loss from the metal electrodes on the ring resonator that limited Q.

P/N K20-875, with $K=22.1$, was the most tunable dielectric, having the same magnitude of tunability as brass. The tunability of 25% was approximately the same for both the first and second resonance modes, as shown in Figure 7.

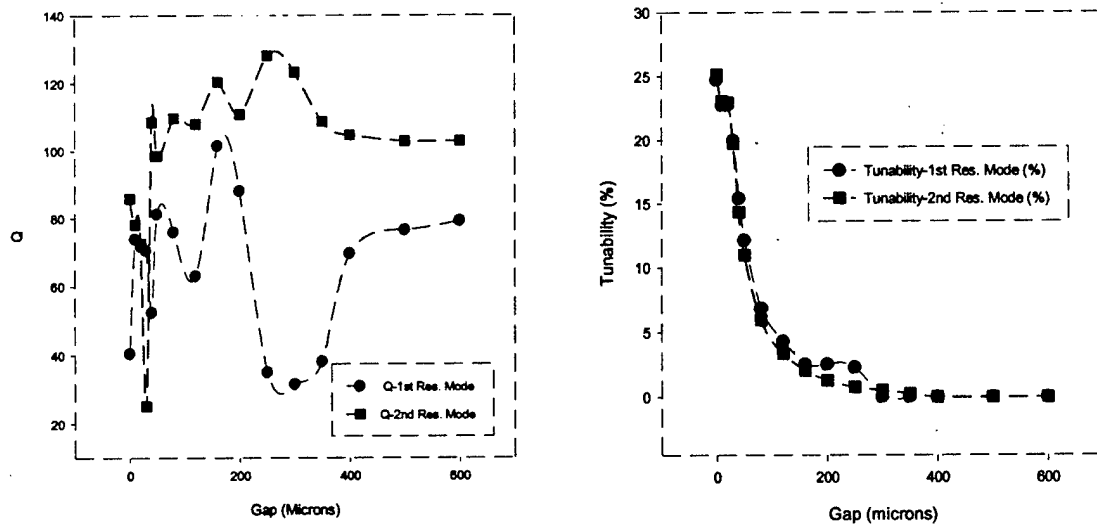


Figure 7. Q and Tunability of P/N K20-875

There is a smooth shift of the resonant peak towards lower frequency as the gap is reduced, as shown in Figure 8.

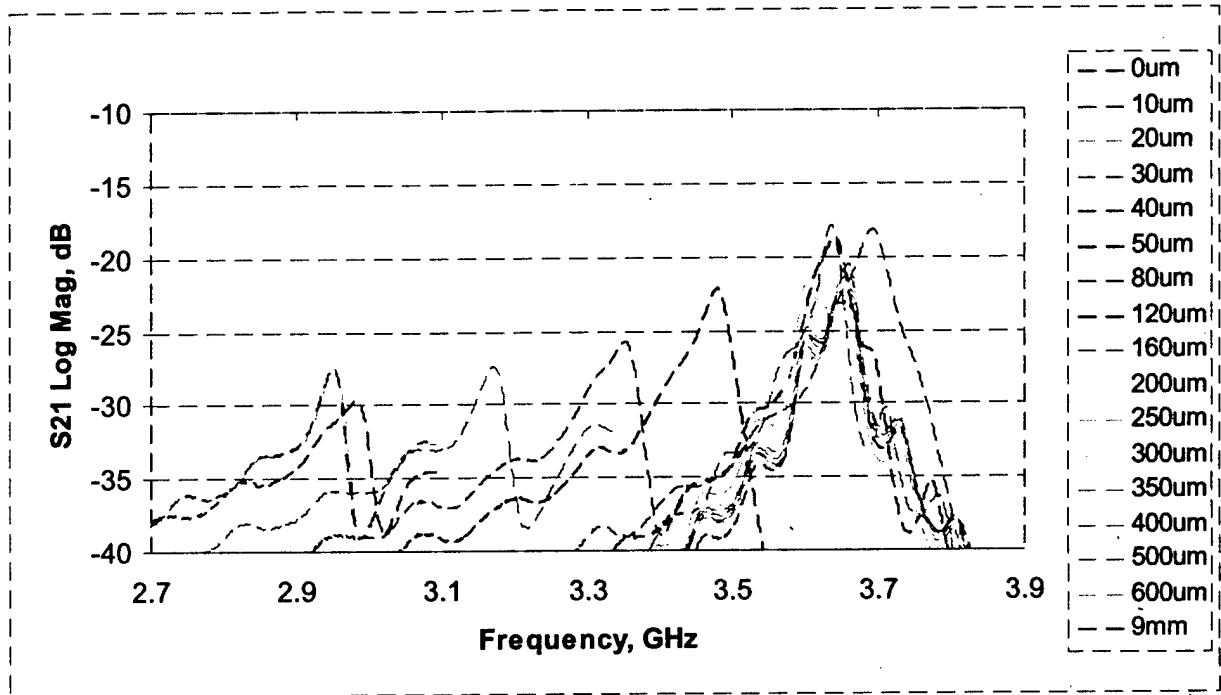


Figure 8. S_{21} vs. frequency for P/N K20-875, first resonance.

An excellent tunability of 25% was obtained for the ring actuator using metal and dielectric tuning plates. P/N K20-875, with $K=22.1$, was the most tunable dielectric, having the same magnitude of tunability as brass. The tunability for all dielectric tuning plates was approximately the same for both the first and second resonance modes, but Q was usually higher for the second mode. Having high tunability for K of 22 is promising for future development of high Q , highly tunable resonators, since there are a number of materials with K around 20 that have very large Q s. In future work, superconducting electrodes can be used to take advantage of high Q materials.

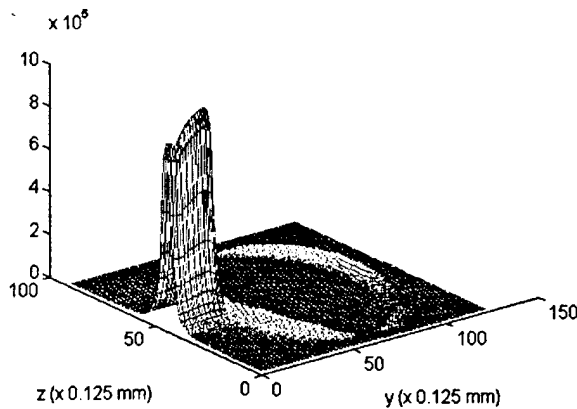
Modeling

Finite Difference Time Domain Modeling was utilized to study the effects of the dielectric constant of the substrate and of the gap width on the performance of a piezo tuned ring resonator. In the case of tuning with the metal plate, transverse electromagnetic modes (TEM) are not possible and a cutoff frequency exists. This situation is analogous to conventional waveguides with a cutoff frequency.

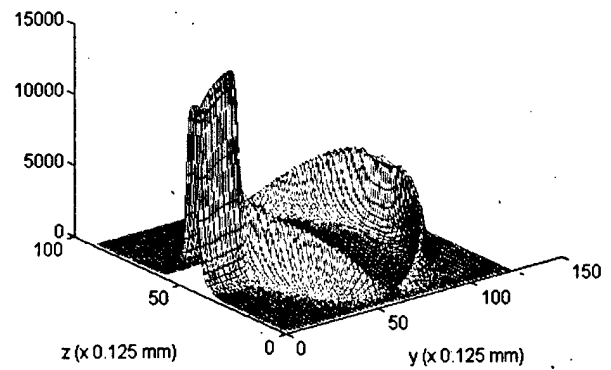
According to the model, there is a very weak resonance for a gap of 0.2 mm and a much stronger resonance for a gap of 0.6 mm. The field contour maps for the fundamental resonances are shown in Figure 9. The model also predicts that the resonance should

move to higher frequency as the gap between the metal plate and the ring resonator is reduced. The resonance modes correspond to the minimum insertion losses (S_{21}). The fundamental (lowest) resonance modes are at 4.25 GHz for a 0.2 mm gap and at 3.75 GHz for a 0.6 mm gap.

As in the fundamental mode, all other modes are shifted with changing gap size as shown in Figure 10. The nature of this shift is influenced by the dielectric constant of the substrate. For higher K substrates, the shift of the resonant frequencies is less regular than for low K substrates. However, in all cases, the frequency shifts upwards with smaller gap size.

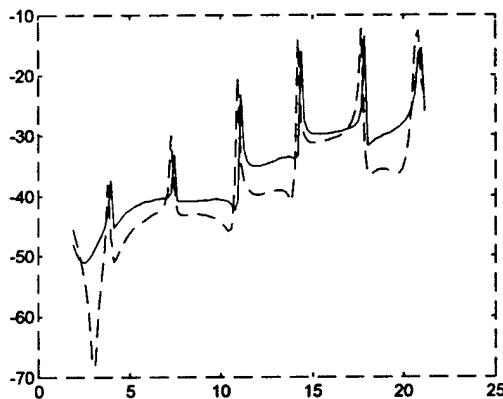


(A) K=10, gap=0.2 mm

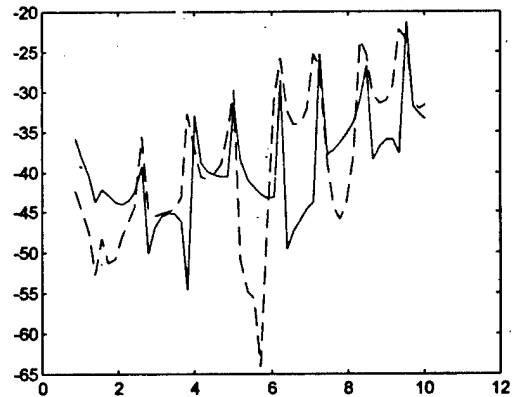


(B) K=10, gap=0.6 mm

Figure 9. FDTD model of field contour maps for the fundamental resonance modes.



(A) substrate K=10



(B) substrate K=90

Figure 10. FDTD model of insertion loss $|S_{21}|$ vs. frequency for (A) substrate K = 10, (B) substrate K = 90. Legend: dashed line = 0.6 mm gap, solid line = 0.4 mm gap.

Cryogenic Actuation

As shown in the tunability experiments using polycrystalline piezoelectric unimorphs, up to 25% tunability can be achieved. However, as temperature is decreased to cryogenic temperatures, the piezoelectric properties are drastically reduced. Recently, Park and Shroud discovered that anomalously high displacements can be provided by actuators fabricated with $\langle 001 \rangle$ oriented $\text{Pb}(\text{Zn}_{1/3}\text{Nb}_{2/3})\text{O}_3\text{-PbTiO}_3$ (PZN-PT) single crystals.^(1,2) As shown in Table 3, these materials offer significantly larger displacements than conventional piezoelectric and electrostrictive polycrystalline ceramics with room temperature d_{33} value > 2000 pC/N.

Property	Type II PZT (TRS200)	Type III PZT (TRS300)	Type VI PZT (TRS610)	PZT-4.5%PT Crystal	PMN-33%PT Crystal
Dielectric Constant	2050	1000	3900	5200	8000
Dielectric Loss	0.018	0.003	0.025	0.008	0.008
Curie Temperature	340°C	300°C	210°C	155°C	166°C
Piezo. Coeff. d_{33} (pC/N)	400	225	690	2000	2250
Coupling Constant k_{33}	0.73	0.64	0.79	0.91	0.91
Young's Mod. (GPa)	59	74	47	8.3	12
Mech. Quality Factor, Q_m	77	800	46	40	~50
Uses	Accelerometers, Actuators, Flow Meters, Hydrophones	Sonar Projectors, Cleaners, Therapeutic Ultrasound	Ultrasound Imaging Transducers, Actuators, Hydrophones	Ultrasound Imaging, Actuators, Sonar, Accelerometers	Ultrasound Imaging, Actuators, Sonar, Accelerometers

Table 3. Comparison of the piezoelectric properties of polycrystalline and single crystal piezoelectric materials.

Work at TRS has investigated the piezo properties of single crystal piezoelectric at cryogenic temperatures. Single crystals were shown to have a $d_{33} > 400$ pC/N at 30K, more than an order of magnitude higher than polycrystalline materials. Piezoelectric coefficients of single crystal PZN-PT single crystals as a function of temperature are shown in Figure 11.

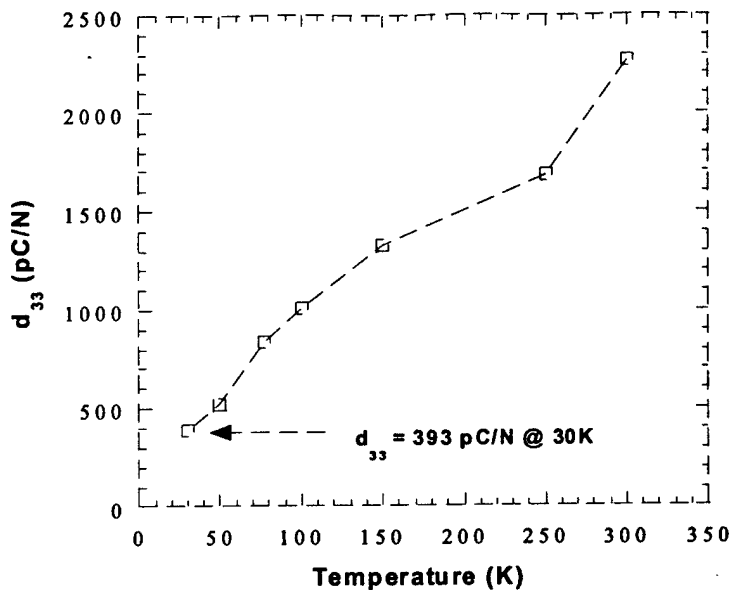


Figure 11. D_{33} as a function of temperature for PZN

Cryogenic measurement of piezoelectric single crystals show that high actuator is available even at very low temperatures. Therefore, single crystal unimorphs should have similar performance at cryogenic temperatures to polycrystalline unimorphs at room temperature. Examples of single crystal benders are shown in Figures 12 and 13. Figure 12 shows a high performance hydrophone fabricated with a 22mm diameter single crystal unimorph by Acoustech. Results show a 3 dB improvement in performance at room temperature showing increased sensitivity using single crystal piezoelectric elements. Figure 13 shows a unimorph type bender fabricated by Boeing. Extremely large bending deflections were obtained as shown in Table 4.

Although single crystal unimorphs have not been tested at cryogenic temperatures, the combination of piezo data a cryogenic temperatures and high actuation at room temperatures give a high probability of high actuation levels at cryogenic temperatures. It is expected that actuation levels will be similar to those obtained for polycrystalline unimorphs at room temperature. This will provide the required actuation for tunable cryogenic filters to be fabricated in phase II of this program.

Summary and Conclusions

Phase I of this program has proven the basic building blocks for cryogenic tunable filters are feasible. Testing of prototypes at room temperature showed that a ring resonator with metallic conductors could be tuned by up to 25% by moving either a metallic ground plane or a dielectric slab closer or farther away from the plane of the resonator.

More than enough actuation was delivered by polycrystalline piezoelectric unimorphs. To obtain similar actuation levels at cryogenic temperatures, single crystal piezoelectrics can

be used. Single crystal piezoelectrics have been shown to have similar actuation levels at cryogenic temperatures to polycrystalline piezoelectric actuators at room temperatures. In addition, several examples of unimorphs fabricated with single crystals have been built and successfully tested at room temperature.

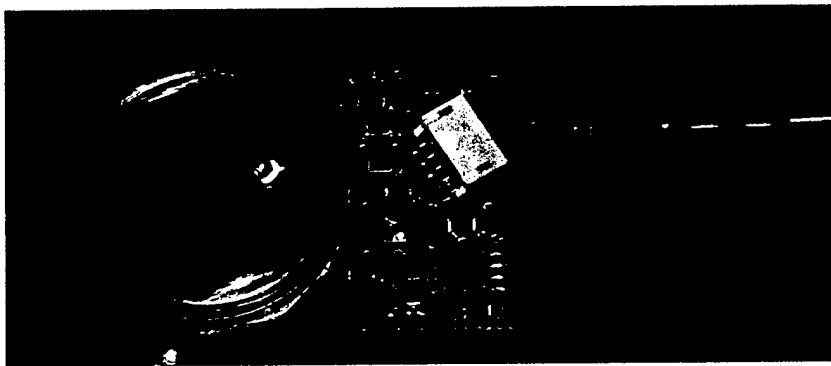
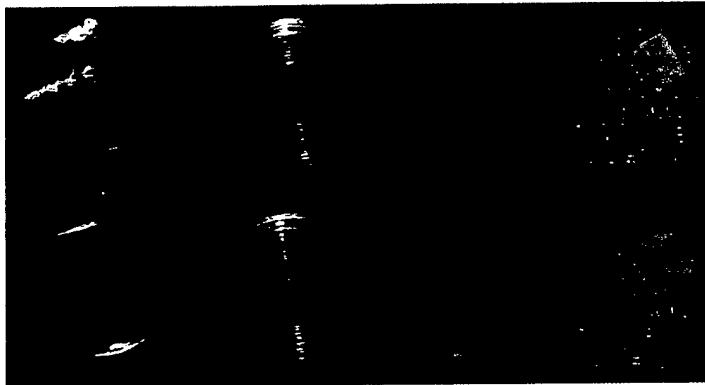


Figure 12. Q-77B Hydrophone with PMN-32%PT bimorph element.

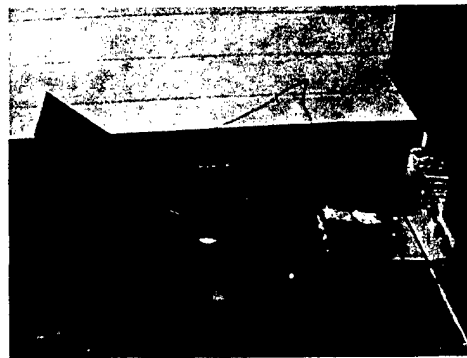


Figure 13. Unimorph fabricated with single crystal piezoelectric element.

Unimorph	Configuration	Drive Field (MV/m)	Tip Displacement (mm)	Frequency (Hz)
2	Single Wafer	1.2	6	251
3	Single Wafer	1.2	6	248
4	Single Wafer	1.2	7	240
5	Single Wafer	1.2	7	240

Table 4. Displacements obtained with single crystal piezoelectric unimorphs as shown in Figure 13.

In phase II of this program, filters fabricated with superconducting conductors will be combined movable superconducting ground planes and movable dielectric slabs to realize tunable, superconducting filters at cryogenic temperatures. Single crystal piezoelectric unimorphs will be used to provide the actuation required for the movable elements. This combination of proven technologies will allow high Q tunable filters to be realized.

TRS will work with end users to determine target applications for this novel technology. The phase II proposal will focus on providing solutions for specific projects requiring high Q tunable filters and other related structures.

References

1. S. E. Park and T. R. Shrout, *Mat. Res. Innovat.* (1997) 1:20-25.
2. D. S. Paik, S. E. Park, and T. R. Shrout, *J. Mat. Sci.* **34**, 469-473 (1999).