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13. ABSTRACT (Maximum 200 words)

The technical work in this contract was focused on demonstrating the feasibility of creating a tunable high-Q filter in the 600 MHz to 900 MHz range. Applications include ELINT/SIGINT and wireless communications systems, and mitigation of co-site problems in frequency agile military communications systems. The building blocks for the high-Q filter are a thin film high temperature superconducting (HTS) microstrip circuit with a variable capacitor inserted as a tunable element. The requirements on the variable capacitor are a high level of controllable behavior, the proper range of capacitance to tune the circuit, and low loss in the capacitor so as not to compromise the Q of the HTS filter. We evaluated several variable capacitor designs and fabricated device prototypes for evaluation, characterization, and integration with HTS resonator circuits. We made progress in several fundamental areas including the design of a fixed resonator to accommodate a variable element to provide a single-pole tunable filter, the analysis of filter response including loss mechanisms, and strategies to integrate these two technologies. Our results show that filters with unloaded Q's in the range of 10,000 to 20,000 can be fabricated and tuned over 20% of their center frequency using our approach.

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4. Scientific Progress and Accomplishments

Overview

The technical work in this contract was focused on developing and demonstrating the feasibility of creating a tunable high-Q filter in the 600 MHz to 900 MHz range. The applications for such a filter include many with military relevance, including filters for ELINT and SIGINT, cellular, PCS, and other wireless communications systems, and reception and mitigation of co-site problems in frequency agile filter communications systems such as SINCGARS, DAMA, and HaveQuick. The building blocks for the high-Q filter are a thin film high temperature superconducting (HTS) microstrip circuit into which a variable capacitor was inserted as a tunable element. The requirements on the variable capacitor are a high level of controllable behavior, a proper range of capacitance change to tune the circuit, and a low loss in the capacitor itself so as not to compromise the Q of the entire tunable filter circuit. In a different contract, we have shown that tunable elements can be used to in HTS circuits with a moderate impact on the Q of the resonator. The measured unloaded Q of these circuits was still quite high and is sufficient for many applications. We are investigating several pathways to improve the Q of the circuit.

There are at least two distinct methods for placing a tunable element in an HTS circuit: inserting a tunable element that is either a variable capacitor or a variable inductor. This is really an oversimplification in either case as the elements in a microstrip filter are actually distributed and there is a complex interplay between the properties of the tunable element and the rest of the circuit. So as the capacitance of a variable capacitor changes, its impedance as seen by the rest of the resonant circuit also changes. This effects the response of the resonant circuit in ways that are difficult to model. The primary scientific result of this contract is that we have shown that the circuit response of a frequency agile filter does behave in a predictable and useful fashion to be used in a wide range of applications. In addition, we have created the variable capacitor and HTS design building blocks to exploit this design synergy.

The primary focus of the effort in this contract is to provide an evaluation of several variable capacitor designs and to fabricate several prototypes for evaluation and integration with the HTS resonator circuits. The primary objective is to identify designs that can provide a high degree of tunability, be operable at the 77K temperature required for the HTS materials, be fabricated from low-loss materials to preserve the circuit Q, and be resistant to vibration as instability induced by mechanical vibrations is expected to be the primary cause of performance limitations. Three approaches for insertion of a tunable element into an HTS circuit were identified: 1) hybrid in which a variable capacitor is packaged with an HTS resonator, 2) integrated in which the variable capacitor and resonator are fabricated on the same substrate, and 3) assembled in which the plates of HTS material are assembled into a variable capacitor on the resonator circuit. We chose to initially pursue the hybrid approach as this would lead to earliest demonstration of the concept and functionality with the fewest changes in standard processing for either MCNC or STI. We also focused on developing, in parallel, the techniques necessary to pursue the integrated approach.

Variable Capacitor Device Fabrication and Evaluation

Three specific variable capacitor designs were evaluated for the hybrid approach. The first is a linear comb drive based on an interdigitated capacitor. The interdigitated fingers are driven by an electrostatic force on one side of the capacitor to produce a roughly linear capacitance change on the other side of the capacitor. The design, a portion of which is shown in the SEM in Figure 1, is similar to those used in the MEMS community for capacitive accelerometers. We introduced several design changes in order to fabricate the capacitor from low loss materials and compensate for the large thermal changes that the structure must tolerate. Upon release of the devices, however, residual stress in the plated gold caused some of the long, suspended comb anchors to bow out of plane. Additionally, there is no realistic pathway to fabricating this structure out of HTS materials to increase the overall device Q. Therefore the development of this approach was suspended after the first couple of design iterations.

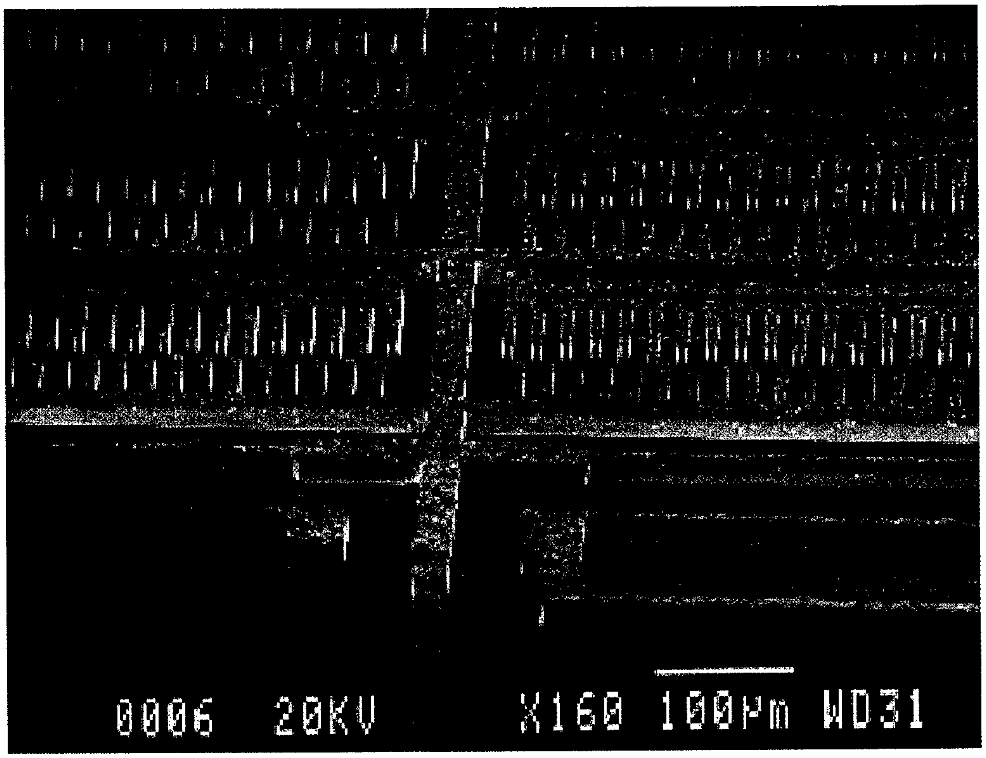

Figure 1. SEM micrograph of the interdigitated comb capacitor.

The second design is a polymer/metal bimorph flap capacitor. The perspective view of this electrostatic flap device is shown in Figure 2. The operating principle of this type of capacitor is that an electrostatic force applied through a voltage to the upper and lower plates of the capacitor overcomes the bimorph stress and unrolls the upper flexible electrode, the flap, down upon the

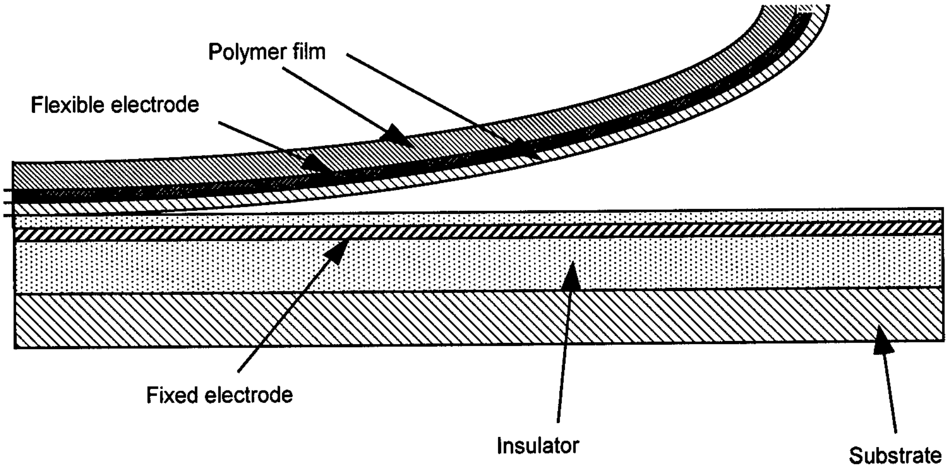

Figure 2. Schematic perspective of polymer/metal flap variable capacitor showing the composition of the horozontal layers to create this structure.

lower, or fixed, electrode to produce the capacitance change. The bimorph was fabricated with gold as the metal and polyimide as the polymer, although other material combinations can be used as well. For instance, a low loss polymer would reduce the RF losses in this device and increase the circuit Q. The polymer/metal bimorph has the added flexibility in its design that the electrodes in the upper flap can be electrically separated by the polymer in order to separate the DC forcing electrodes from the RF signal electrodes to reduce the effect of the bias circuitry on the RF signal path. The initial prototypes, shown in Figure 3, were fabricated on a silicon substrate. During testing, they produced roughly a 1 pF to 3.5 pF capacitance change with bias up to 100 Volts. Since this variable capacitor design was fabricated on a silicon substrate, the device was not inserted into the HTS circuitry for RF measurement and characterization (silicon is too lossy at frequencies in the 800 MHz range to provide a meaningful measurement). The devices were operated at liquid nitrogen temperatures. The team did work through the fabrication sequence for fabrication on low loss quartz substrates, but these devices did not produce results through the performance period of the contract due to some problems with the adhesion of deposited metals on the quartz.

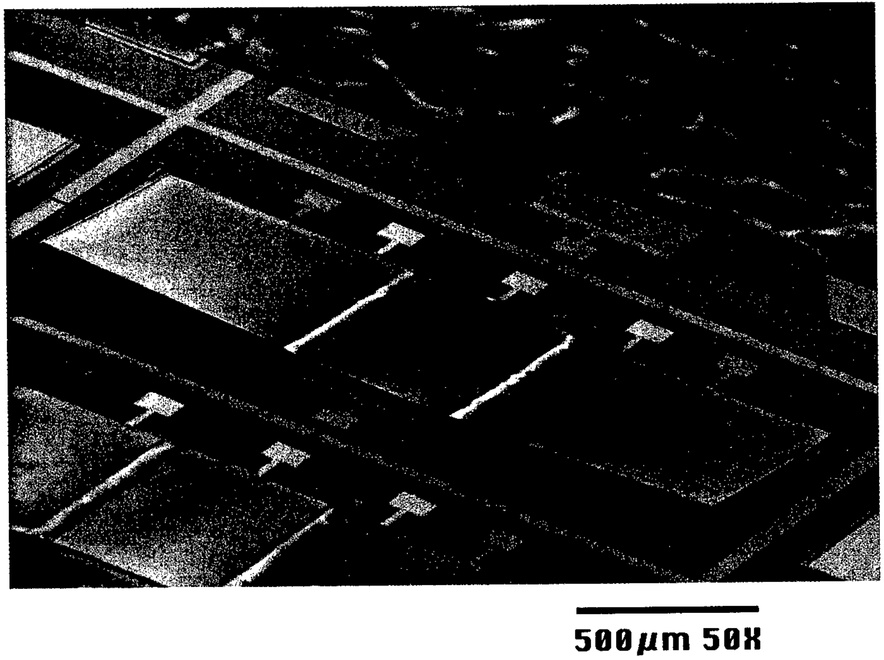

Figure 3. SEM micrograph of a metal/polymer variable capacitor showing the inner RF electrode and two outer control or drive electrodes.

Typical capacitance versus voltage curves for the polymer/metal bimorph at room temperature are shown in Figure 4. This capacitance versus voltage curve is typical of both types of electrostatic flap devices and the features of the curve would be the same at 77K temperatures as well. You can see some hysteresis in the capacitance curve, as is typical of these devices. In a practical application, the control circuit would be designed to eliminate any deleterious effects from the hysteresis.

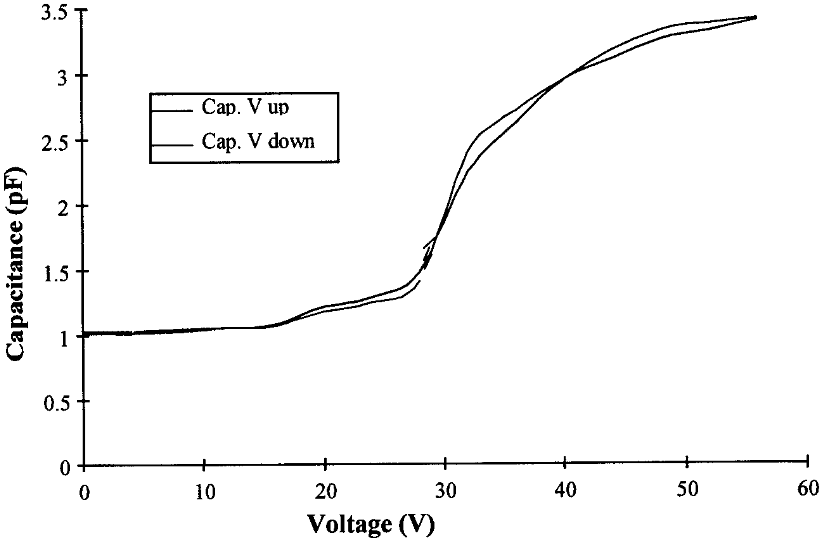

Figure 4. Typical capacitance versus voltage curve for an electrostatic flap MEMS variable capacitor.

The third design is a variation of the design described above in that it is a bimorph flap variable capacitor. In this design, however, the bimorph is between two different metals on the upper electrode and is called an all-metal or metal/metal bimorph. As with the polymer/metal bimorph, the all-metal bimorph upper flap pulls away from the lower electrode as the device is cooled with the ultimate separation at liquid nitrogen temperatures designed to produce the minimum capacitance (largest gap). A good representation of this curvature is shown in the SEM in Figure 5. A thick gold layer was chosen for the bottom electrode, and a low-loss dielectric was used as an overcoat on the lower electrode. The first devices were fabricated on silicon and no RF testing was done due to the nature of silicon losses at these frequencies. Device fabrication runs were also done with quartz substrates.

In parallel to these efforts, STI performed experiments to evaluate the applicability of pre-existing thermally actuated devices in the HTS environment. The thermally-actuated devices have several limitations in terms of operating speed and the impact on the thermal environment of the HTS materials in the dewar, but the technology was the most mature actuator technology at the beginning of this contract, so the evaluation is justified. The experiments in a liquid nitrogen bath indicated that the effect of the thermal actuator on a silicon substrate in close proximity to an HTS resonator coil significantly lowered the resonator Q and the thermal load raised the temperature of the HTS device by about 1 Kelvin. Thus, these devices were not developed further for this project.

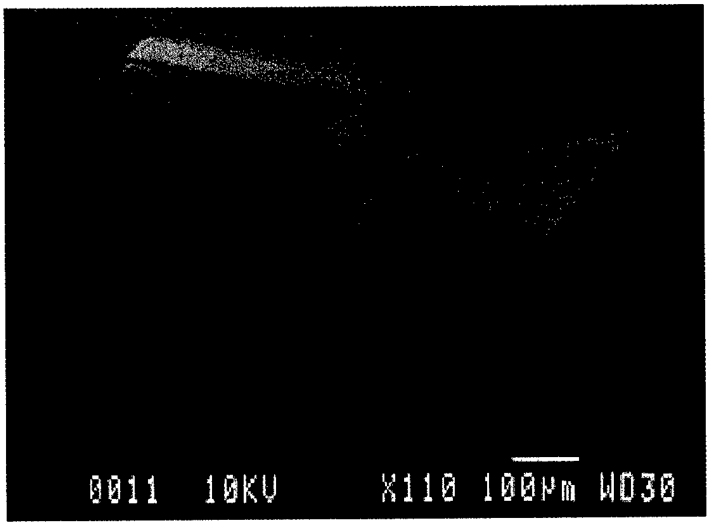

Figure 5. SEM micrograph of the metal/metal bimorph flap.

RF Design

The focus of a great deal of the work on this contract has been on the development of an appropriate variable capacitor design and many types of variable capacitors have been investigated, designed and fabricated. The design of the unit test cell, the HTS resonator circuit topology that can accommodate a tunable element was also accomplished in this contract. Several alternatives were considered for a unit cell or prototype circuit design to demonstrate the operability of the HTS resonator with a MEMS tunable capacitor. The design chosen has a serpentine HTS inductor with an opening at the opposite end for a variable capacitor wire bonded in the circuit. Input and output coupling capacitances are located adjacent to the lines interconnecting the HTS inductor to the variable capacitor. Without a tuning capacitor, the resonator coil is designed to resonate near the middle of the frequency bands allocated for American cellular telephone services (~850 MHz). The resonator is capable of greater than 10% tuning range with a factor of 2 change in capacitance in the 0-2 pF range as indicated in the calculated results in Figure 6. The minimum capacitance of the variable capacitor will determine the highest frequency achievable in the tunable resonator, generally around 800 MHz. As presented, the tunable resonator Q is dominated by the Q of the variable capacitor, since the vast majority of the electric energy must be stored in it. Thus the Q may be relatively low if lossy materials such as metals or certain lossy dielectrics are present within the active area of the capacitor. However, one can always trade-off tunability for selectivity, by using a lossy variable capacitor in conjunction with a high Q all HTS one. However, the details of how the variable capacitor Q affects the resonator as a whole will ultimately depend quite heavily on the resonator topology and the precise nature of the capacitor itself. Modeling at STI has shown that the integrated approach of using a MEMS variable capacitor in this circuit can result in Q's of 10,000 to 20,000 over a tuning range of 10% of the center frequency.

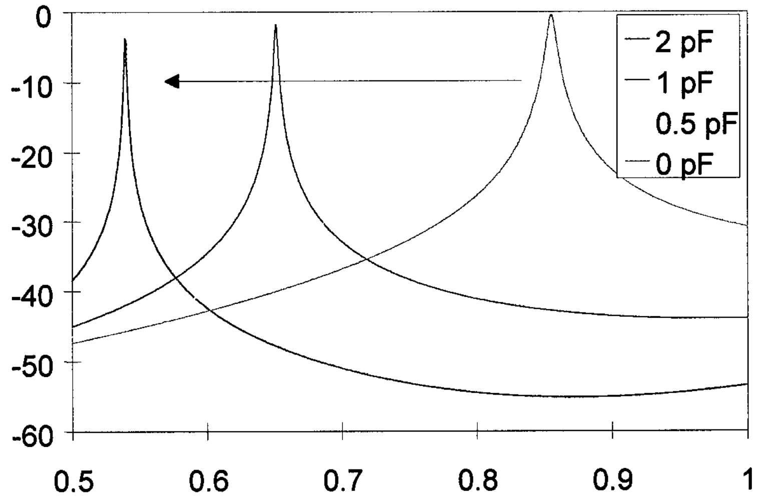

Figure 6. Calculated frequency response of the resonator unit cell versus capacitance of the variable capacitor.

These details have been studied and initial measurement results indicate that the circuit behaves as expected. Using only a single resonator unit cell does not bring into perspective several other issues such as the coupling between multiple resonator sections as would occur in a multi-element filter. In this case, each inter-resonator coupling may itself need to be tuned to achieve the proper filter shape across a large frequency band. Also, we have chosen to use a unit cell design that places the tunable element in the low energy part of the circuit, to minimize the effect that the tunable element will have on the input and output coupling. Other approaches, such as using a tunable inductor or resonator, may require further work in the designing proper coupling and fixed filter sections to properly tune over large frequency ranges without a significant degradation of the insertion loss.

Integration of HTS Circuitry with Tuning Elements

The technical challenges in developing a tunable filter technology based on the integration of these two very different fields of study span many scientific disciplines. Two crucially important aspects are the proper design of the HTS resonator to allow for a large tuning range with a small change in capacitance and the design of the variable capacitor to produce a capacitance change that varies smoothly with applied voltage and has a minimal amount of hysteresis or stiction. In addition to these technology approaches, there are other practical considerations with integrating these two different technologies, including RF, thermal, and processing compatibility of materials; the implications of tuned elements on the microwave impedance of a high-Q resonator; and the thermal and electrical impact of the tuning device on the packaged HTS circuit in the dewar. Each of these considerations requires careful analysis to avoid design and application pitfalls. In this section, we will briefly discuss some of our findings.

There are three basic approaches to developing a method for inserting a tunable element into a HTS microstrip circuit. Those three we have termed the integrated approach, the hybrid approach, and the assembled approach. The distinction between these approaches is important since each involves a different level of integration between HTS and semiconductor fabrication processes, differing levels of assembly are required, and, depending on the exact structure which is built, offer various potential performance in terms of electrical loss. There exists a complex interplay between complexity in process and assembly. In the hybrid approach, the tunable element is fabricated separately from the remainder of the HTS microstrip circuit. Each device is then mounted in a package and connected by a wire bond or strap. This approach has the advantage that processing compatibility of the variable element and HTS circuit is not required making fabrication easier and potentially less costly. Losses due to separating the RF ground plane and to the wire bond are expected to dominate the loss of the circuit. In the integrated approach, the tunable element and the remainder of the microstrip circuit are fabricated on the same substrate. This has the potential to provide excellent RF performance, but there are fabrication complications intrinsic to this approach. The YBCO or TBCCO films needed for the microstrip circuit are generally not stable above 200°C, they suffer from degradation upon a certain level of exposure to aqueous solutions, and many processing steps are incompatible with these materials. The choice of materials and processes will be made based upon their compatibility with HTS materials and substrates, and not necessarily on the materials available for making the highest performing actuator. This is an unfortunate but necessary constraint since almost any conceivable approach requires that the HTS materials be deposited before the fabrication of the variable capacitor actuator is complete. In the assembled approach, the MEMS actuator is fabricated and assembled onto the substrate that holds the HTS microstrip circuit. The actuator can either be fabricated out of materials that form the floating HTS plate, or HTS materials can be attached to the actuator. This approach has some of the advantages of each of the methods above. By using HTS for the active area of the tunable element, the losses can be kept much lower than with metals. This is a major factor in preserving the system Q. Also, the HTS inductor and the remainder of the circuit can be assembled on the same substrate which eliminates the need for split substrates and off-chip connections.

The simplest method of combining the technologies is the integrated approach in which the HTS resonator and the tunable element are fabricated separately, then placed on the same substrate and wire bonded together. This was the focus of the initial work on the contract. The ultimate performance of an integrated HTS resonator is limited by the materials of the tunable element, since it is not fabricated from HTS, and the wire bond connecting the tunable element into the HTS resonator circuit. The integrated approach is necessary if the procedures necessary to fabricate the tunable element are not compatible with the HTS materials, which is the case for MEMS variable capacitors. Analysis at STI indicates that the integrated approach should be able to provide unloaded circuit Q's in the range of 10,000. This compares favorably with the unloaded Q of the HTS resonator itself which is in the range of 30,000 – 50,000. An example of the integrated approach is described in this report where the MEMS variable capacitor fabricated separately is diced and connected with a wire bond into the HTS resonator circuit.

The hybrid approach with a variable capacitor fabricated on the HTS substrate was not a viable option during the performance of this contract since several fabrication issues remained to be worked out. For instance, the HTS material, such as TBCCO, is formed by a laser ablation process. Laser ablation results in thin films with a significant amount of surface roughness. For fixed filter applications, the roughness of the top side of the HTS material does not play a great role in the unloaded Q of the circuit. If, however, one needs to fabricate the top capacitor electrode directly over an HTS lower electrode, the surface roughness of the bottom film is very important since the highest capacitance is related to the spacing of the bottom and top electrodes. Other issues such as the deposition of several metal and polymer layers each with precise thickness on the MgO substrate also have not been solved within this contract but remain areas of future research.

An example of the assembled approach is shown schematically in Figure 7 In the assembled approach, two substrates containing HTS circuitry are held in precise position with one another and their separation is controlled via a microfabricated or bulk actuator. This approach has the best potential for achieving high resonator Q's since the resonator can be formed with all circuitry that carries RF power made from HTS materials. In this approach, the upper electrode of an HTS capacitor or resonator would be fabricated using a standard thin film HTS substrate and assembled precisely over the bottom section on the HTS circuit. An all-HTS approach may be required for multiple section filters as each resonator section in a multiple section filter needs to have a higher unloaded Q than the overall filter will have. For instance, to produce a three-section filter with an unloaded Q of 10,000, each resonator section may need to have an unloaded Q of

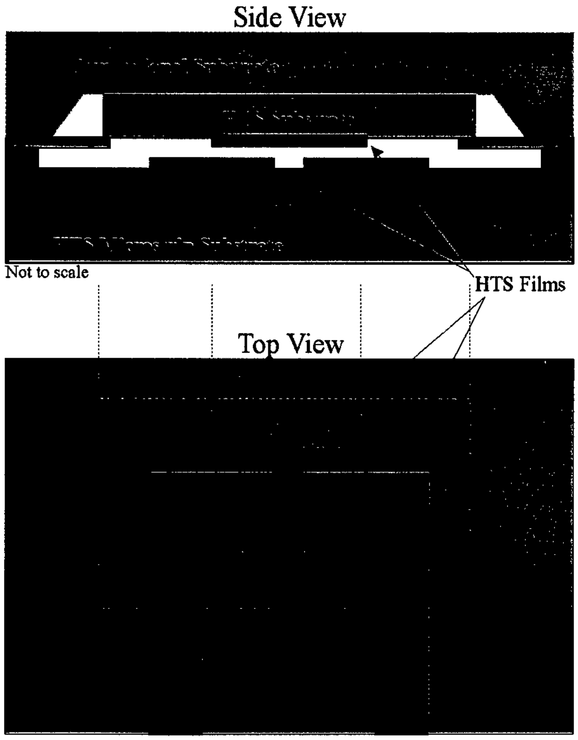

Figure 7. Stylized representation of an all-HTS assembled tunable element.

50,000. The alignment, control, and movement of the HTS plates in the assembled approach are the critical elements of the system design.

Conclusion

We have developed several technologies for creating high-temperature superconducting (HTS) tunable filters having low loss and large tuning range. The research in this program has resulted in the development of MEMS variable capacitors to provide the tuning element in a fixed HTS resonator circuit. Several fundamental issues with regard to creating these filters are now understood, including the behavior of the resonant response over the large frequency ranges with the relatively lossy variable capacitor when the capacitor is made from non-HTS materials. The RF design of several resonator circuits were evaluated and a prototype chosen based on the availability of tuning element approaches. The research in the contract has shown the feasibility of tuning a high-Q resonator circuit with a MEMS variable capacitor element. Several MEMS variable capacitor designs were developed and fabricated using processes similar to standard MEMS surface micromachining. Much future work is necessary to demonstrate the performance parameters of these tunable filter unit cells and a larger electrical and mechanical performance analysis would also be necessary to prove utility in particular system applications. The work described herein, however, is an important proof of concept in the evolution of this unique coupling of emerging technologies.

5. Important Results

The work in this contract has produced several important results, including the design of several MEMS variable capacitors to act as tunable elements in a specific high-Q HTS circuit design. We have designed, fabricated, and characterized several different variable capacitors with appropriate capacitance ranges for tuning an single resonator circuit over 10% of its center frequency and developed an HTS test resonator for such a purpose. Although there are many technical details remaining in the process of developing this technology, we have shown the feasibility of inserting variable capacitors into HTS circuitry while preserving Q's in the range of ten to twenty thousand. This performance surpasses that of other tunable filter technologies such as ferroelectric and ferrite materials, and varactor diodes. Mechanical tuning has the additional advantage of lower or non-existent intermodulation products since the mechanical cutoff frequency is far below signal frequencies of interest. In contrast, electrical tuning methods are susceptible to intermodulation due to the varying amplitude of the desired signal changing the response of the tuning device. We expect the ultimate results of the research in these technologies to be tunable high-Q filters with many military and commercial applications.

7. Personnel Supported Under Contract

In addition to the principal investigator, Dr. Joseph Mancusi, several other researchers had portions of their time covered under this contract. MCNC personnel covered include Mr. Vijay Dhuler, Dr. Ed Hill, Dr. Scott Goodwin-Johansson, Mr. David Koester, Dr. Ramaswarmy Mahadevan, Dr. Dev Palmer, Dr. Mark Roberson, Dr. David Vellenga, and Mr. Lindsey Yadon. From STI, Dr. Bob Hammond, Dr. Bruce King, and Dr. Balam Willemsen were supported under this contract.

8. Report of Inventions:

MCNC: Tuner for High Q RF Applications, V. Dhuler
Variable Capacitor for RF Tuning Applications, V. Dhuler, D. Koester