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14. ABSTRACT

The goal of this project was to develop the technology necessary to meet the need for a tunable ultra-narrow receiver front-end. We met the challenging major technical milestone of demonstrating that it is possible to tune a high-Q 100 kHz wide filter over a 10% tuning range. Tuning the ultra-narrow filters under this program required a two-generation improvement in tuning technology in both motor and feedback technology. The repeatibility of tuning tip placement was improved by two orders of magnitude during the contract. The tuning range was simultaneously increased by two orders of magnitude. This culminated in a laboratory demonstration of the working technology. Two of the significant technology developments (small/embedded RF feedback and active vibration control) that were demonstrated under this contract were ultimately not integrated into the prototype delivered to NRL for evaluation.

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SUPERCONDUCTOR
TECHNOLOGIES

2059-0005-F

Ultra-Narrow Band Tunable Filter
Final Report

Contract No. N00173-02-C-2059
CLIN 0002, Data Item A0005

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EXECUTIVE SUMMARY

The goal of this project was to develop the technology necessary to meet the need for a tunable ultra-narrow receiver front-end. We met the challenging major technical milestone of demonstrating that it is possible to tune a high-Q 100 kHz wide filter over a 10% tuning range. Our innovative technical work in the area of tunability resulted in an issued patent (US 6,791,430) and an invited scientific talk at a special IEEE symposium (2004 MTT-S in Fort Worth, TX). Tuning the ultra-narrow filters under this program required a two-generation improvement in tuning technology in both motor and feedback technology. The repeatibility of tuning tip placement was improved by two orders of magnitude during the contract, as shown in Figure 1. The tuning range was simultaneously increased by two orders of magnitude (Figure 2). This culminated in a laboratory demonstration of the working technology in March 2004. Efforts for the remainder of 2004 centered on delivering to NRL for evaluation a prototype that included this technology. The prototype was finally delivered to NRL in early 2005, after numerous delays. Two of the significant technology developments (small/embedded RF feedback and active vibration control) that were demonstrated under this contract were ultimately not integrated into the prototype.

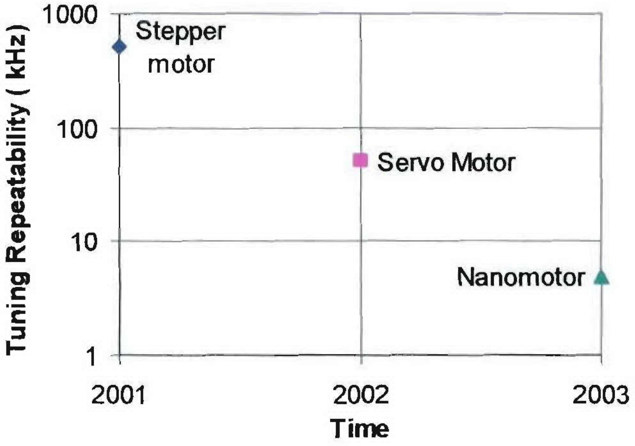


Figure 1. Improvement of tuning repeatability during the contract.

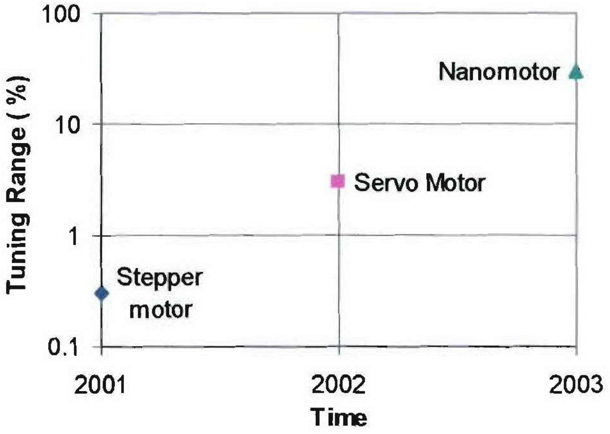


Figure 2. Improvement in tuning range during the contract.

This final report for the narrowband filter task summarizes the following technical accomplishments of the program:

- Achieved couplings accurate enough to make a 100 kHz wide fixed filter
- Achieved 5kHz tip placement accuracy
- Achieved RF feedback using small integrated board rather than network analyzer
- Achieved 10% tuning range for 100 kHz wide filter
- Demonstrated Active Vibration Cancellation with STI cooler
- Delivered single-channel prototype to NRL for lab testing

TECHNICAL PROGRESS

Achieved couplings accurate enough to make a 100 kHz wide fixed filter

We started this program with the goal of making a challenging narrow bandwidth fixed filter. No high-Q technology had ever demonstrated a 0.014% fractional bandwidth in this frequency range (700 MHz). In narrowband microstrip filter designs, the requisite weak coupling is always a challenge. It is hard to realize a very narrow band filter in the convenient microstrip configuration using conventional coupling schemes, due to the slow decay of the coupling as a function of the resonator element separation. To realize the weak coupling required by a narrowband filter, resonator elements in the filter have to be kept apart. This requires either a large circuit size or an elaborate package. Conventional technology is inhibited from realizing ultra narrow band filters because of low Q of the resonators and the large separations required between resonators to achieve very weak couplings. We overcame these limitations using high Q HTS frequency-dependent resonators; we realized the very weak couplings by using a frequency-dependent inductor to increase the value of inter-resonator coupling.

We demonstrated and delivered a 5-pole lumped element band pass filter of center frequency of 691.6 MHz with a bandwidth of 100 kHz. The measured filter exhibited 1.34 dB insertion loss at band center and 15 dB return loss and 0.45 dB noise figure at 70K. The measurements suggest that the unloaded Qs of the resonators are greater than 135,000. Measurement results showed that the very weak couplings were possible to realize if an appropriate inductance slope parameter was chosen for designing the resonator. The filter response is shown in Figure 3.

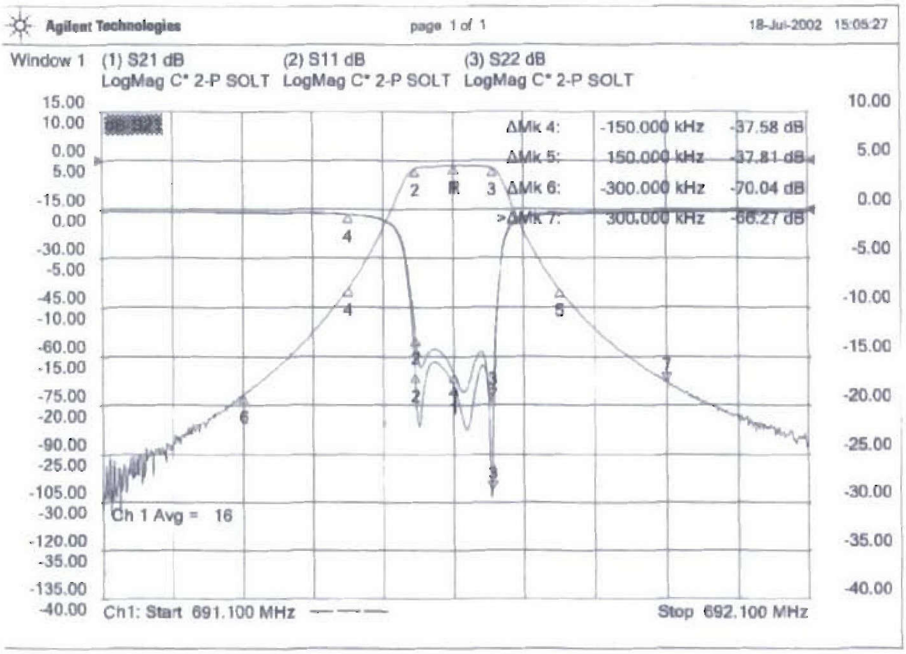


Figure 3. Frequency response of the filter over 1 MHz span.

Having achieved this first program goal and delivered a prototype system, our next task was to determine if an even narrower fractional bandwidth could be achieved. A frequency of 1.375 GHz (a factor of 2 smaller in fractional bandwidth) was chosen. We were able to realize this filter (Figure 4) and delivered this fixed frequency filter in a prototype configuration.

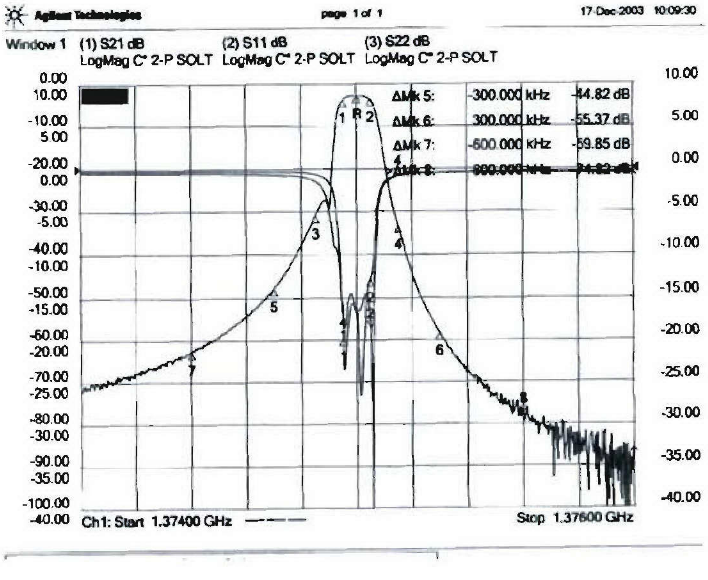


Figure 4. 100 kHz-wide HTS filter at close to 1.4 GHz.

Achieved 5kHz tip placement accuracy

STI has been developing tunable HTS filter technology with funding support from several Government agencies since the year 2000. The goal of this work has been to establish a capability for tuning the frequency of HTS filters while maintaining the unique advantages of the technology, including narrow bandwidth and minimal insertion loss. The bulk of our effort has been based upon electromechanical tuning of the filters whereby an HTS tuning tip is moved in proximity to the filter resonator to affect a frequency shift. In 2001 when this current program started, the tuning method employed a mini-stepper motor with a linear actuator. Feedback was provided by an optical LED-photodiode pair position sensor (shown in Figure 5).

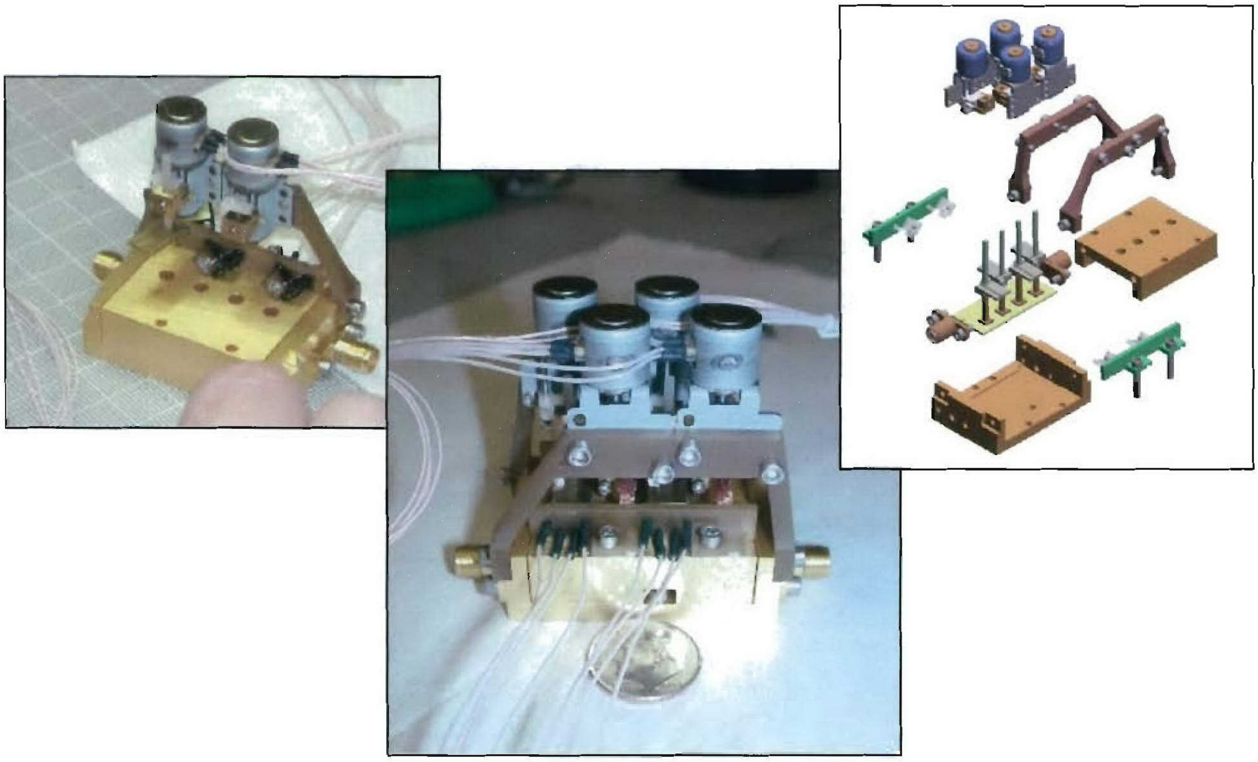


Figure 5. Stepper motor / optical feedback technology at the start of the program.

A two order of magnitude improvement in placement accuracy was needed in order to accomplish the goals of this program. We met these goals through a two-generation evolution. In the second generation design (Figure 6), we replaced the mini-stepper motors (which had an unacceptable heat generation) with a servo-motor. We also replaced the optical-pair feedback with an encoder-based feedback. This solved the drift problems inherent in our first approach, and we achieved an order of magnitude performance improvement. Unfortunately, we could not identify a small encoder wheel with a fine enough grid spacing for achieving the 5 nm placement accuracy required for this program. Therefore, a third generation development of tuning technology was needed.

We determined that we could achieve the required precision if we developed a fine motion system riding on the coarse motion of the servo-motor. We demonstrated this principle using a piezo-chip that could be attached to the end of the motor drive shaft. This chip had only a 0.5 micron travel range which overlapped with the accuracy of the servo-motor. We demonstrated that we could achieve a better than 5 kHz placement accuracy using this system (Figure 7), though the movement was hysteretic (as seen in Figure 8). Rather than solve the hysteresis problem, we were able to identify a motor (known as a "nanomotor") that already had engineered a coarse and fine motion system based on acoustic stick-slip principle.

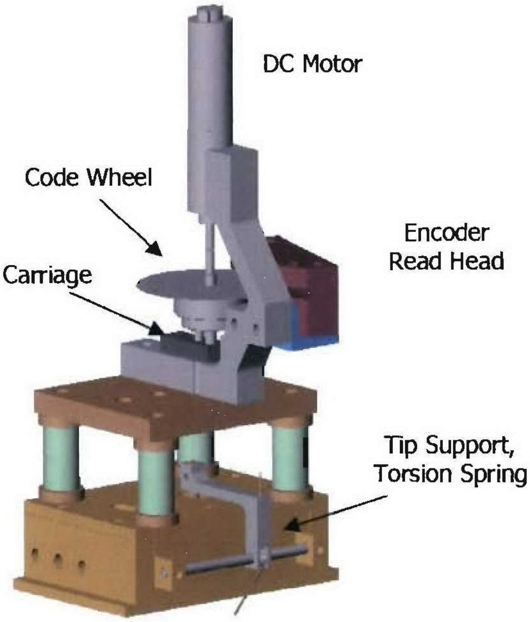


Figure 6. Servo-motor / linear encoder second generation technology.

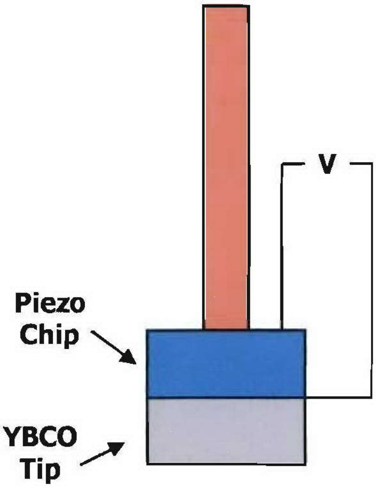


Figure 7. Piezo-chip fine motion system.

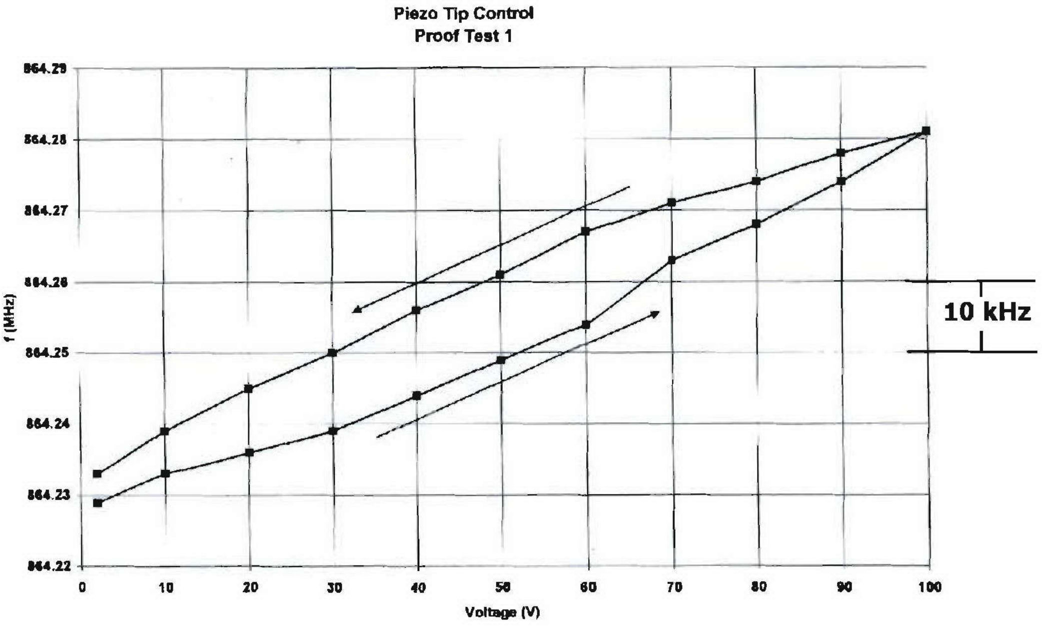


Figure 8. Demonstration of 5 kHz tip placement accuracy.

The nanomotor (Figure 9) proved to have the required accuracy. We also replaced the encoder with a DVRT (differential variable reluctance transducer); this provided the needed position precision and had long-term drift because it is based on an analog measurement. We solved the drift issue by also using RF feedback, as described below. This combination allowed us to achieve a 5 kHz placement accuracy of the tuning tip, which was necessary to reach a 10% tuning range for this ultra-narrow filter.

Achieved RF feedback using small integrated board rather than network analyzer

We developed an algorithm that could be used with a computer and network analyzer to tune a filter under a previous Government program. In order to develop a useful RF feedback system under this program, we needed to show that the feedback could be used to tune to high precision, and that the network analyzer could be replaced with an embedded control board. Both were accomplished on the program. Figure 10 shows a block diagram of the board functionality. All of the functions had to be developed and miniaturized. Some of the most difficult components to miniaturize included the directional couplers; a new generation of surface mount couplers became available from Anaren during the course of this program.

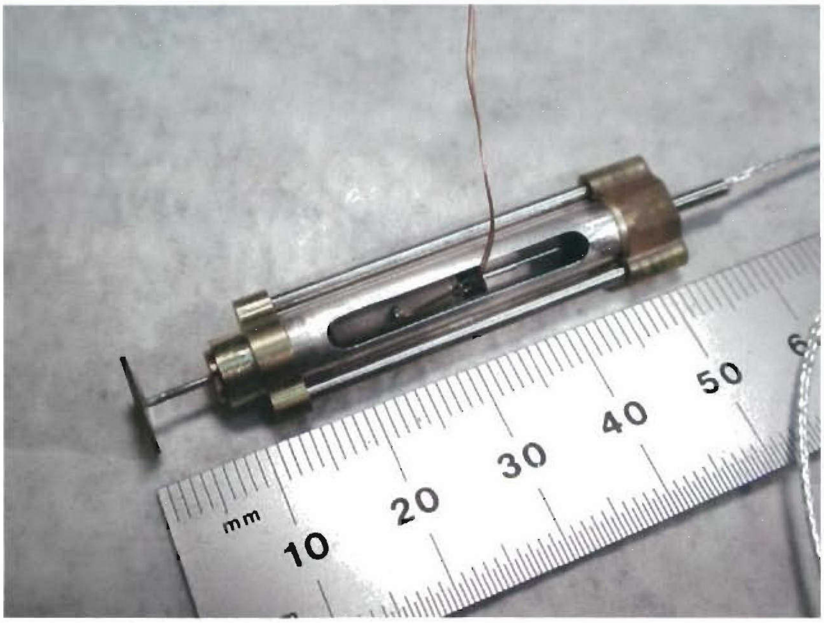


Figure 9. Third-generation tuning system based upon a nanomotor.

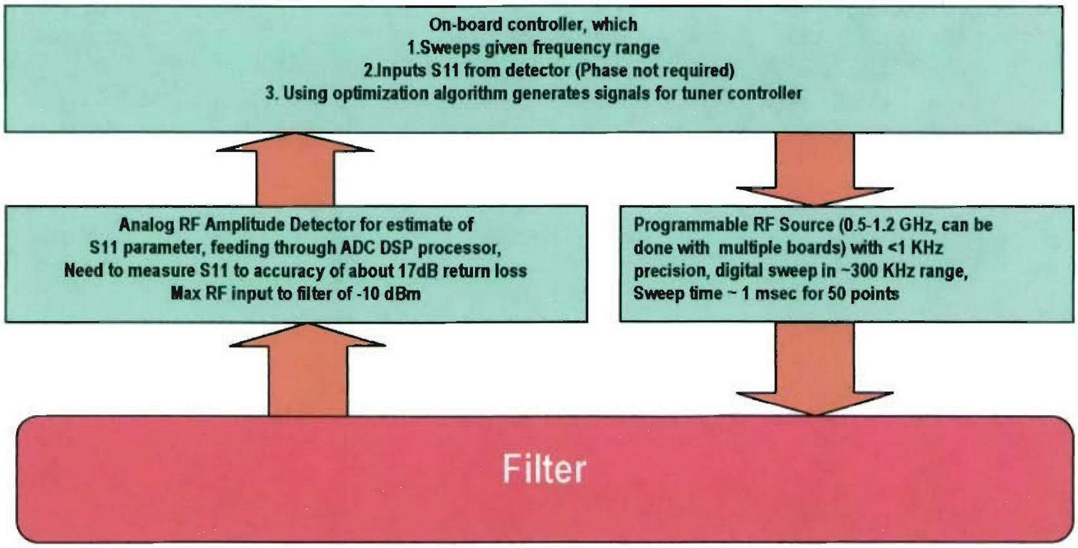
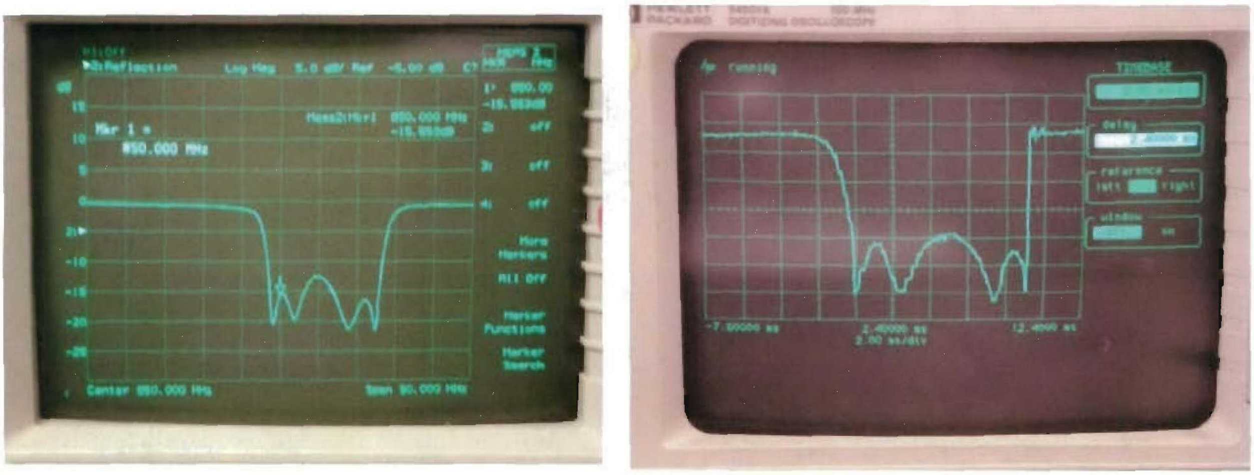


Figure 10. Flow diagram of RF feedback board functionality.

We tested the board readout in two steps. We tested the functionality of the analog RF chain independent of the Analog-to-Digital conversion. The results can be seen in Figure 11. Good agreement is shown between the network analyzer plot and the analog readout. After Analog-to-Digital conversion, the data in Figure 12 shows a full digital readout from the DSP (digital signal processor) of the return loss, enabling the RF feedback board to potentially replace a network analyzer.



S11 on Network Analyzer **S11 at input to ADC**

Figure 11. Demonstration of functional RF chain for readout.

Achieved 10% tuning range for 100 kHz wide filter

This task was a two-year effort to prove the realizability of this technology. At the March 2004 review meeting, we performed a laboratory demonstration showing that we could, indeed, tune this ultra-narrow filter over the target 10% tuning range. The coarse and fine tuning worked together well, and we demonstrated repeated tuning across the entire band. Figure 12 shows the filter performance at both extremes of the band. The insertion loss and rejection of the filter across the band met our expectations. The only limitation of this demo was that we used a network analyzer for the RF feedback, so that we were unable to achieve a tuning speed of less than 20 seconds. We expect a speed of 2 to 3 seconds can be realized with the integration of an embedded RF feedback board. This demonstration proved the feasibility of this technology and represented a major milestone for the program.

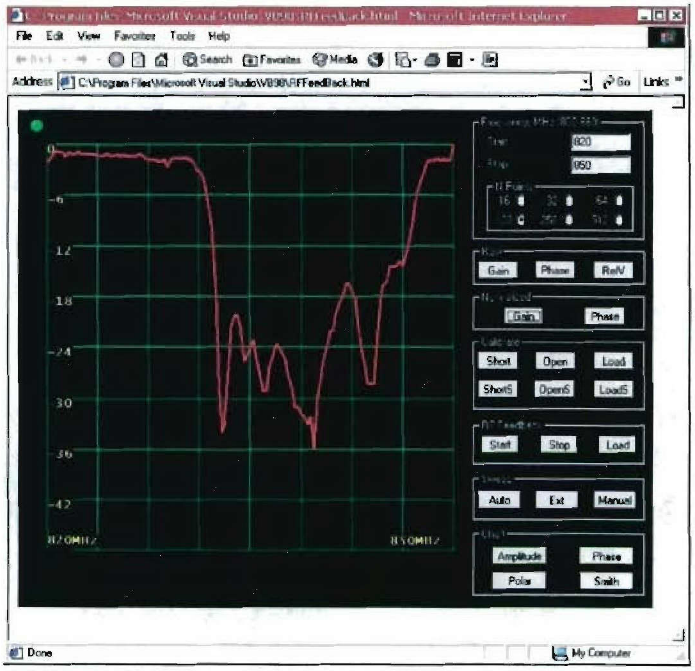
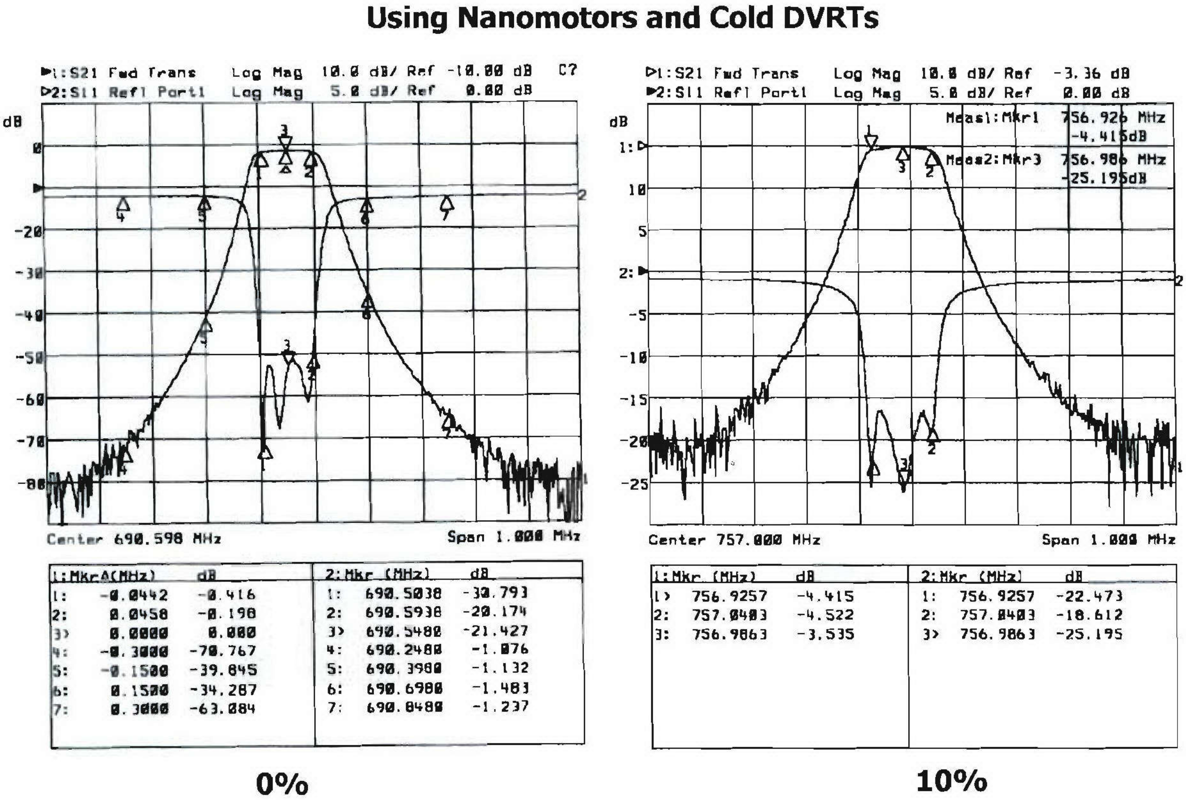


Figure 12. Demonstration of RF readout using embedded feedback board.


Using Nanomotors and Cold DVRTs

```
▶1:S21 Fwd Trans    Log Mag  10.0 dB/ Ref -10.00 dB   C?
▷2:S11 Refl Port1   Log Mag   5.0 dB/ Ref   0.00 dB

Center 690.598 MHz                          Span 1.000 MHz

1:MkrΔ(MHz)     dB          2:Mkr (MHz)     dB
1:   -0.0442   -0.416       1:   690.5038  -30.793
2:    0.0458   -0.198       2:   690.5938  -20.174
3>    0.0000    0.000       3>   690.5480  -21.427
4:   -0.3000  -70.767       4:   690.2480   -1.076
5:   -0.1500  -39.845       5:   690.3980   -1.132
6:    0.1500  -34.287       6:   690.6980   -1.483
7:    0.3000  -63.084       7:   690.8480   -1.237
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▷1:S21 Fwd Trans    Log Mag  10.0 dB/ Ref  -3.36 dB
▶2:S11 Refl Port1   Log Mag   5.0 dB/ Ref   0.00 dB

Meas1:Mkr1  756.926 MHz
            -4.415dB
Meas2:Mkr3  756.986 MHz
            -25.195dB

Center 757.000 MHz                          Span 1.000 MHz

1:Mkr (MHz)     dB          2:Mkr (MHz)     dB
1>  756.9257   -4.415       1:  756.9257   -22.473
2:  757.0403   -4.522       2:  757.0403   -18.612
3:  756.9863   -3.535       3>  756.9863   -25.195
```

0%

10%

Figure 13. Data from lab demonstration of 10% tuning range.

Demonstrated Active Vibration Cancellation with STI cooler

We expected that maximizing the usable tuning range of the prototype system would require a design that would minimize the impact of cooler vibration on the filter. The cooler is nominally driven at 60 Hz, and the drive amplitude is modulated to vary the cooler lift on demand. This leads to a complex vibration spectrum as can be seen in Figure 14. The vibrations from an unbalanced cooler can be reduced in excess of 400× (26 dB) using the active vibration cancellation system (AVCS) that was developed by CSA Engineering for this project. By comparison, passive balancing is only capable of ~20× magnitude vibration reduction.

Given time and funding limitations, we were unable to integrate this technology into the final deliverable unit, as it did not interact well with the standard STI cooler driver electronics when used in "regulate" mode. Substantial effort was invested to get the two systems to work well together; however, we found that the CSA unit would shut itself off shortly after the prototype reached a stable, regulated temperature. It currently remains unclear if the interaction between the AVCS and the STI cooler board was mechanical or electrical, but given the choice between a stable temperature or vibration cancellation we chose temperature. If such a capability should prove to be necessary in the future, a single controller board that includes the temperature control and vibration cancellation functions would need to be designed for manging the interactions between those subsystems.

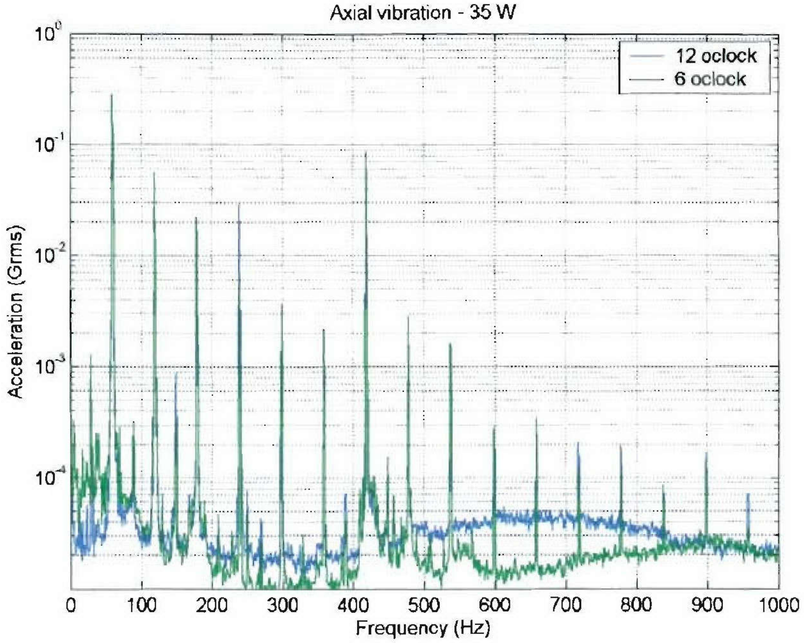

Figure 14. Typical vibration response spectrum for cryocooler.

Delivered single-channel prototype to NRL for lab testing

The single-channel prototype test stand was originally designed to include all of the technologies developed under this program. As already mentioned, the AVCS proved particularly difficult to integrate due to adverse interactions with the standard STI cooler control board. We discovered that the embedded RF feedback was also difficult to integrate, as we continued that effort during the fall of 2004. The finite directivity of the mini-couplers proved to be a significant issue when the filter was detuned, and we found that it was difficult to gather the filter resonators with the positional feedback from the DVRTs alone. In October 2004, we proposed a system redesign using a standard PC with a VNA (vector network analyzer) to provide the RF feedback, and to build the system around a passively-balanced cooler, in order to complete delivery without further delays.

We also had planned to incorporate the high frequency (5 to 10 kHz), high voltage (~100V) nanomotor drive circuits into the test stand., These were removed from the test stand and placed in a separate portable equipment rack (Figure 16) in order to avoid the significant likelihood of noise from those circuits to the STI cooler board. The nanomotor control signals were generated by Ethernet network controllers supplied by the nanomotor vendor, interfaced to the PC via Ethernet. Ethernet was also used to control the HP 8714ES VNA used for development. The DVRT conditioning circuits were also placed in the portable equipment rack along with the nanomotor drivers, housed in their own shielded enclosure. The signals from the DVRTs were fed to a series of ADCs on a National Instruments I/O card in the control PC.

Additionally, we abandoned the tuning approaches previously developed to make up for various undesirable attributes of the system. In particular, we found that it was desirable to *purposely* detune the filter, optimizing the position of each resonator in a given sequence rather than to attempt optimizing a system with 5 coupled variables. This allowed us to work around the positional uncertainty of the tips arising from thermal drift in the DVRT conditioning circuits and mechanical hysteresis in the tip motion. Although we developed this approach using a VNA, this new tuning approach remains compatible with the embedded RF feedback board and DSP controller which might ultimately enable faster closed loop operation.

The cooler and dewar containing the filter were mechanically isolated from the rest of the test station using shock mounts to provide some isolation from external vibration. We found that at 10 % tuning, the effect of vibration from the cooler was less than +/-1 kHz peak-to-peak, and thus had little effect on the filter shape. This effect becomes more pronounced for higher tuning ranges, but is still be acceptable even in the absence of the AVCS at this tuning range. As the filter is tuned even higher in frequency, this effect becomes more pronounced, and the tuning range at which it becomes unacceptable depends on the type of signals being received.

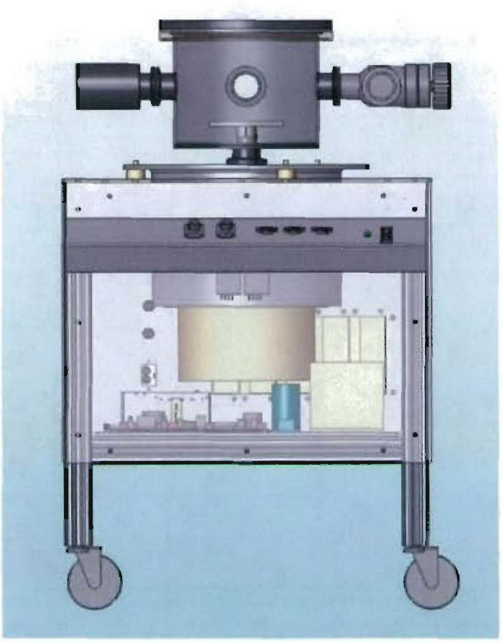

Figure 15. Physical layout of prototype system.

Figure 16. Nanomotor drive circuitry in the portable equipment rack.

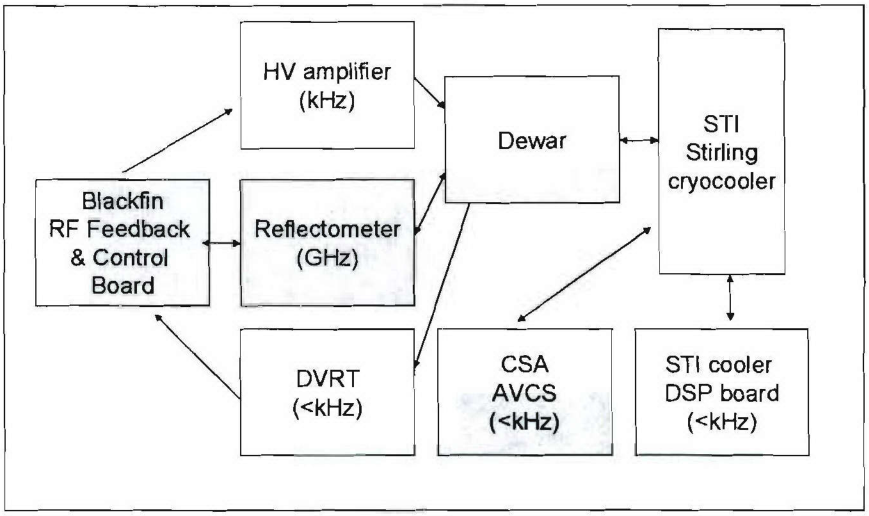

Figure 17. Original block diagram for the single-channel prototype. The shaded boxes represent custom hardware that was developed and demonstrated under this program. All components were to be contained within the test stand.

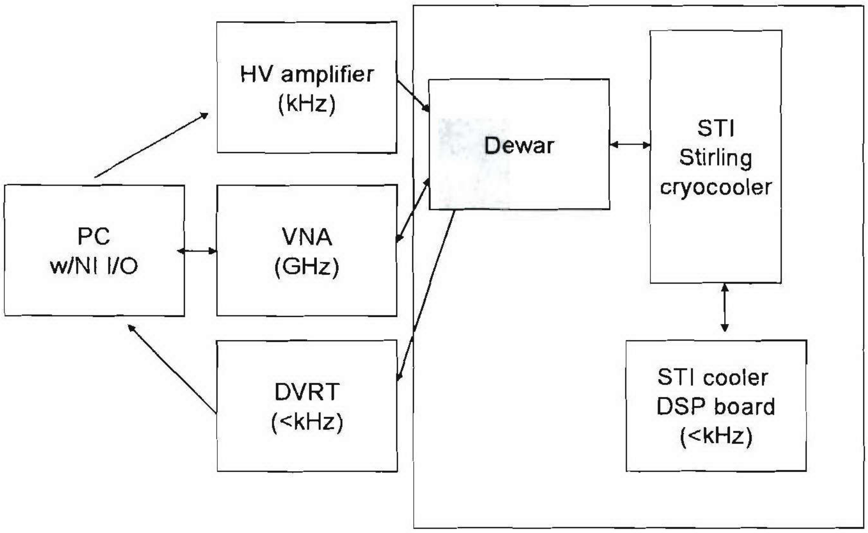

Figure 18. Revised block diagram for the single-channel prototype. Only the custom dewar along with a standard cooler and dewar remained in the test stand, while much of the rest of the equipment was segregated in a portable equipment rack, controlled by a standard personal computer.

SUMMARY

The narrow band filter program resulted in delivery of a single channel tunable filter prototype that demonstrated ultra-narrow (100 kHz) filtering tunable by 10% at a center frequency around 750 MHz. This required a number of key innovations. In addition, several independent technologies were demonstrated that, if successfully incorporated, could improve the baseline tunable filter approach. The usable filter tuning range could be improved by reducing the effect of cooler vibration on tip position, such as with the active vibration control system that was demonstrated. The overall system size, weight and power as well as tuning speed could significantly be improved by use of an embedded RF feedback controller, such as was originally demonstrated under this program. Significant progress has continued under separate funding to enable the use of an embedded tunable filter controller for replacing the PC and VNA that were used in this program's deliverable.