# A 25 Watt RF MEM-tuned VHF Bandpass Filter

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*Abstract* — **A VHF RF bandpass filter capable of a 25 watt input power, tuned through the use of Microelectromechanical (MEM) microrelays, is presented. The calculated filter through-put loss is less than 1 dB at any frequency of operation. The filter tunes a 3:1 frequency range using 14 frequency steps. The performance of a newly developed MEM microrelay for high power RF use is discussed. The development of the microrelay model and the use of a CAE tool in the filter development are presented.**

## I. Introduction

Communication equipment has required frequency selective circuits (RF filters) to provide interference free signaling for many decades. The filters provide rejection of unwanted signals from the antenna when used in receivers, or rejection of unwanted signals to the antenna when used in transmitters. In the case of transmitters, this requires filters capable of operating at the full rated RF power output of the transmitter.

Modern military communication equipment is being driven toward designs that cover a very wide frequency range, and capable of operating in dense RF environments. The United States military is endorsing the Software Defined Radio concept [1] as implemented in the new Joint Tactical Radio System [2]. This technology emphasizes cost effective design while providing superior operation in conditions of high interference. The need to provide minimal interference while operating in high signal density environments affects receivers in terms of required input dynamic range. RF selectivity at the antenna can help reduce the dynamic range burden on the active circuitry of the receiver. RF selectivity at the output of transmitters reduces spurious signals, noise, and assists in the reduction of intermodulation products due to the presence of other high power signals mixing in the non-linearities found in the transmitter output system (reverse intermodulation distortion). In all cases, the RF selectivity needs to be capable of being tuned electronically over wide spans of frequency.

Electronic tuning of RF filters designed for minimum size as well as excellent performance is currently performed by the use of electronically variable capacitors (varactor diodes) or by the use of PIN diodes as switching devices for fixed tuning capacitors. The use of varactor diodes can provide continuous tuning, but large RF signals present on the diodes as a result of interference can modulate the instantaneous diode capacitance and generate a nonlinear characteristic in the filter. PIN diode based tuning results in discrete frequency steps in the filter tuning process. RF filters tuned with PIN diodes are also subject to nonlinear effects created in the tuning diodes. In either case, RF circuit isolation from the control (tuning) line is needed as well as biasing power supplies. There is also a heat dissipation and power consumption issue with PIN diodes and the required support circuitry.

The commercial availability of Microelectromechanical Systems (MEMS) RF microrelays created an opportunity to explore the application of RF MEMS to the tuning of high power RF filters. We have previously published our work on high power (greater than 10 watts) MEMS RF device applications [3]. The use of MEM devices is particularly interesting in eliminating the non-linearity problems associated with current technology diode tuning methods. The MEMS of interest are metal contact systems operated by mechanical actuation techniques. This paper discusses a new version of the RF MEM microrelay previously reported, and its application to a high power RF filter capable of tuning the entire military SINCGARS [4] VHF band. The new microrelay was successfully retested at the 25 watt power level in the VHF bandpass RF filter previously reported [3], and the current results are discussed here. A new wide frequency coverage RF high power filter design based on the current MEM device parameters is also presented. The filter performance was simulated using the Agilent Advanced Design System (ADS) CAE tool. This is an extension of the previously published information into new regions of performance and usability. The information presented here is intended to demonstrate the feasibility of using MEMS for tuning high power RF filters. It is not intended to represent a producible item since many other factors contribute to a successful hardware product.

## II. Overview of MEM Tuning for RF Filters

There are several types of MEM devices that may be used to tune RF filters. There is work reported on a continuously variable MEM capacitor [5] that can replace the varactor diode and theoretically provide continuous tuning of the RF filter. An alternative technique is the use



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of an array of discrete capacitive MEM microswitches [6] to form the required capacitance at each tuned frequency. This will provide discrete tuning steps in place of the PIN diode tuning process. Both of these devices have a common signal path for RF and tuning functions, requiring RF isolation techniques. Both of these devices are also subject to self-actuation by the high power RF signal, wherein the impressed RF signal voltage becomes a significant portion of the control voltage for the device and changes the operating state of the MEMS. This is always an "RF power on" event and is destructive. The voltage issue is particularly important in RF filters since the use of MEM capacitors in the reactive tuning process exposes them to the effects of voltage and current multiplication due to the RF power storage ("Q") of the resonant network of the RF filter.

The previously mentioned MEM tuning techniques use MEM RF switches, where the control is common with the RF signal. The use of RF microrelays, with a separate and isolated actuation system, will help relieve the self-actuation problem. Even in microrelays, self-actuation can occur due to RF coupling onto the control path or by electrostatic forces on the signal contact structure itself generated by the high RF voltage. It is important to realize that MEMS electrostatic forces will respond to high frequency AC and RF as well as DC.

A MEM microrelay having metal signal contacts is the device we have selected to use in tuning our RF filter. The MEM microrelay is fabricated by MEMSCAP North America (previously Cronos Integrated Microsystems, and MCNC before that) [7]. The metal signal contacts are used to connect or disconnect fixed tuning capacitors as part of the tuned resonant reactive network of the RF filter. This is the same tuning process used for PIN diode tuned filters. A selection of capacitors is made for each tuned frequency needed in the filter to cover the operating range of the filter.

There are no MEM variable RF inductors, nor any MEM inductors appropriate for low loss, high power RF filters known to the authors. All tuning is based on varying the resonating capacitance associated with the use of conventional fixed high "Q" inductors to form the required resonant reactive network of the low loss high power RF filter.

Operation at high power levels requires "cold" switching of the microrelays if any reasonable amount of contact life is to be achieved. Fortunately, operation of transmitters is always a controlled process, and adequate switching time for microrelays will be a part of the tuning process.

## III. THE MEMS RF HIGH POWER MICRORELAY

The MEM microrelay discussed here is a metal contact device using a thermal actuation design. A SEM photograph of the MEM microrelay is shown in Fig. 1. The microrelay is fabricated by MEMSCAP North America.

The MEM signal contacts are gold plated, and are visible in the top right area of the photograph (the contact structure). The contact is a single ball and socket structure, with a shield system surrounding the RF signal path and isolating the input bond wire pad from the output bond wire pad as well as the rest of the actuation structure.

The main actuation structure is mechanically connected through an insulation structure to the signal contact structure. The actuation structure moves up to open the contacts (shown open in Fig. 1), and moves down to close the contacts. The actuation process is thermally compensated, and a resistive element under the structure heats the actuator when energized, causing thermal forces to move the actuator down and close the contacts.

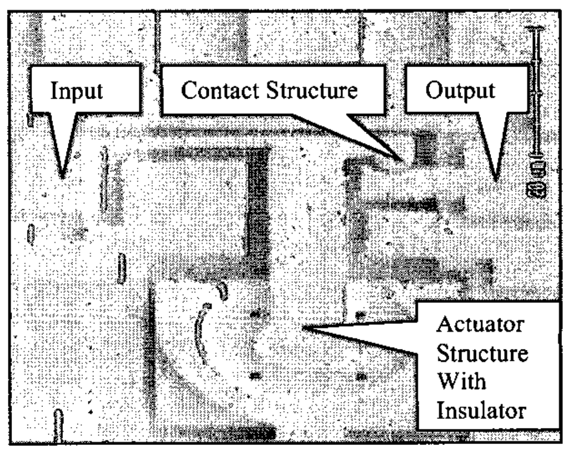


Fig. 1. MEMSCAP Microrelay

### *A. MEM Contact Life Test Results tested in the RF Filter*

We have previously reported [3] the exceptional life verified for the contact structure of this type. The microrelays previously reported were installed in the RF filter and were life tested for four months continuously without failure. The microrelays were cycled about 5 times a second, and completed over 53 million open-close contact cycles. The contacts were operated at approximately 125 volts rms in the open circuit condition and about 350 milliamperes rms in the closed circuit condition. No degradation of the contact surfaces could be seen in SEM images of the surfaces [3].

*B. RF Performance of the Present Microrelay*

Previous versions of this microrelay experienced a significant substrate power loss when used in the RF filter. This was due to capacitive coupling onto and through the silicon substrate, as previously reported [3]. The present MEM design has overcome this restriction in its application to the MEM tuned filter.

The measured insertion loss (contacts closed) of the packaged microrelay is shown in Fig. 2. The measured isolation (contacts open) of the packaged microrelay is found to be better than 53 dB for frequencies below 500 MHz, and better than 45 dB for all frequencies below 2 GHz. These packaged measurements are comparable to the MEMSCAP North America data for two different bare (unpackaged) die of the microrelay. The data on the packaged microrelay shows virtually no degradation in RF performance due to the package. The data was taken in a test fixture, with the test fixture calibrated out of the data measurements to yield the device performance.

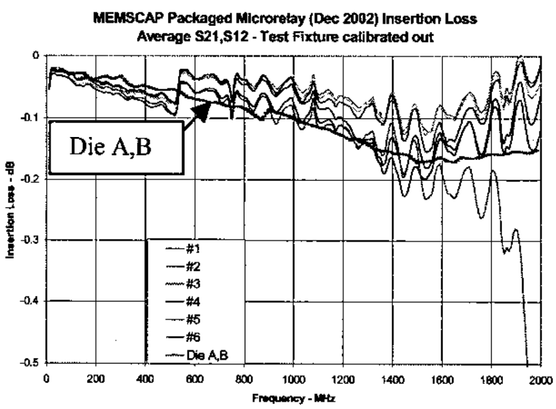


Fig. 2. Microrelay Insertion Loss

We evaluated six sample new MEM microrelays in the 25 watt RF bandpass filter previously reported [3]. The center frequency insertion loss was .92 dB at the lowest tuned frequency (all MEMs closed) and was .93 dB at the center frequency of the highest tuned frequency (all MEMs open). The response characteristic of the filter with the new MEMs is shown in Fig. 3.

## IV. THE MEM TUNED RF FILTER

The MEM tuned RF bandpass filter previously discussed [3] was a two pole capacitively coupled design. The RF input and output were matched with a tapped inductor. Tuning was accomplished by switching in or out three capacitors across each resonant pole as needed to tune to one of four different frequencies. Fig. 3 presents the measured performance of the filter with new MEMS switches used for frequency control. This data demonstrates lower loss compared to previously published results [3].

The filter was modeled using the Agilent ADS CAE package, and the model was used to provide specific information that would be very difficult to measure, including the MEM contact voltages and currents. The ADS model has been expanded to cover the full 30 MHz to 88 MHz VHF military frequency band to explore and illustrate some of the issues in the design of MEM tuned high power RF filters.

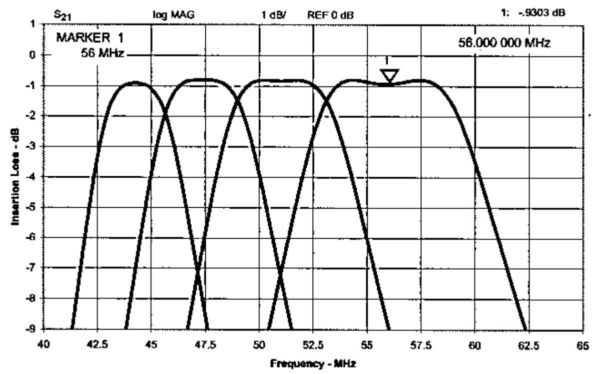


Fig. 3. Filter Frequency Response

*A. Equivalent Circuit of the Packaged Microrelay*

Fig. 4 shows the model for the microrelay based on the best approximation to the measured S parameters of the new packaged device shown in Fig. 2.

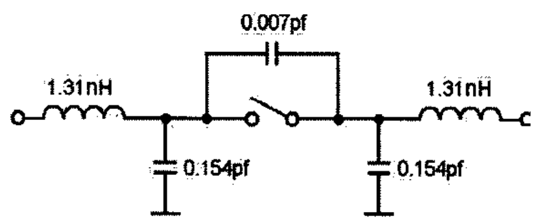


Fig. 4. Model of the MEM Microrelay

*B. The Model of the Full Band RF Filter*

The full band RF filter continues to be a two resonator capacitively coupled design with tapped inductors for the RF input and output impedance matching [3]. Fig. 5 illustrates the full band RF filter design. We have used 14 tuned frequencies to cover the full band instead of the original 4 frequencies [3]. This requires 13 switched capacitors on each resonator instead of 3. The coupling capacitor is now tuned with nine microrelays to help control the filter passband characteristics in place of the original fixed coupling capacitor. A MEM selected shunt inductor has been paralleled with each tapped inductor to provide coverage of the high frequency region of the 30 to 88 MHz band. The filter now requires a total of 43 microrelays in place of the original 6 microrelays for the filter previously published [3]. The loaded 3 dB bandwidth of the filter design varies from about 10% to about 17% over the full band. The tuning steps and the modeled insertion loss based on realizable element Qs "Q"s yield a total modeled insertion loss varying from 0.4 dB to slightly less than 1.0 dB for any frequency in the full band. This includes the roll-off loss for operation between each tuned frequency. Fig. 6 indicates the computed total loss of the full band RF filter. This figure includes the overlay of each tuned frequency response over the full band of operation, allowing visibility into the throughput loss at any operating frequency. In use, only one frequency response of the 14 shown would be used at any one time.

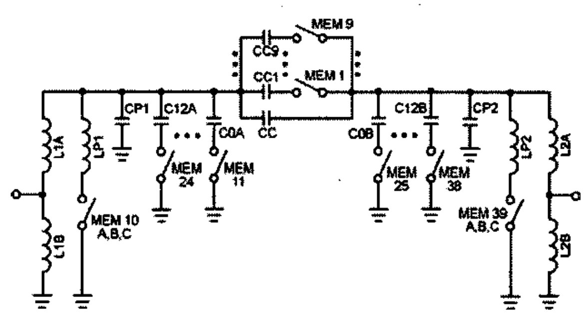


Fig. 5. Model of the MEM tuned Filter

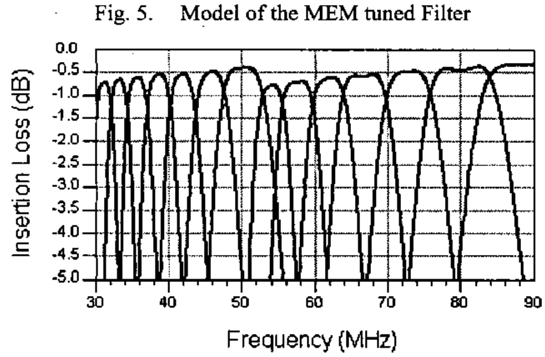


Fig. 6. Insertion Loss and Loss at any Frequency

The peak RF voltage across the resonator tuning capacitor open contact microrelays cannot be allowed to exceed the 300 volt rating of the microrelay. The ADS model indicates that the maximum voltage at any frequency with 25 watts RF input power is under 160 volts peak. The peak RF current in each microrelay cannot exceed a peak value of 1 ampere. The ADS model indicates most microrelays have less than 0.5 peak amperes, with the worst case microrelay/frequency having a peak current of less than 0.9 amperes. The microrelays used to switch coupling capacitors as a function of frequency will have less than 250 volts peak at any frequency, and less than 0.15 ampere peak current. The microrelays used to switch the shunt inductors for the upper operating frequencies will be subject to less than 160 volts RF peak. A total of three microrelays are needed for each switched inductor. The current in each switched inductor microrelay will be less than 0.95 amperes for any frequency within the 30 to 88 MHz operating band, including the off-resonant peak current.

## V. Conclusion

We have presented a high power VHF filter that is tunable through the use of MEM microrelays and covers a 3:1 frequency tuning range. The microrelay performance is measured and presented. The calculated stress levels of the MEM devices used in the filter, both open circuit voltage and closed circuit current, are presented and within the microrelay rated contact operating values.

## Acknowledgements

The assistance of Vivek Agrawal and Robert Wood of MEMSCAP North America is greatly appreciated.

## References

[1] Current SDR information is available at http://sdrforum.org/ and by internet search.

[2] Current Joint Tactical Radio System information is available at www.jtrs.saalt.army.mil and by internet search.

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