Variable MEMS Capacitors Implemented Into RF Filter Systems

Robert L. Borwick, III, Philip A. Stupar, Jeffrey F. DeNatale, *Member, IEEE*, Robert Anderson, and Robert Erlandson, *Member, IEEE*

***Abstract*—A microelectromechanical systems analog tunable capacitor has been designed and fabricated for implementation into a two-pole UHF filter. Recent developments on the capacitor have improved the RF device performance significantly, and have resulted in improved UHF filter performance. In the 225–400-MHz range that this device is intended for, Q values are in excess of 100. In addition, an 8.4 : 1 tuning ratio has been achieved with continuous tuning over a 1.4 : 11.9-pF range. When implemented into a two-pole UHF filter, tuning over the entire 225–400-MHz range was achieved with a loss under 6.2 dB.**

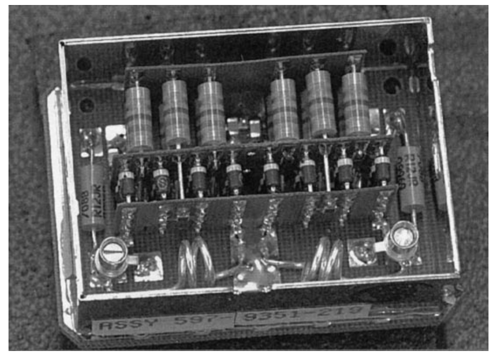
***Index Terms*—Reliability, RF microelectromechanical systems (MEMS), tunable capacitors, tunable filters.**

I. Introduction

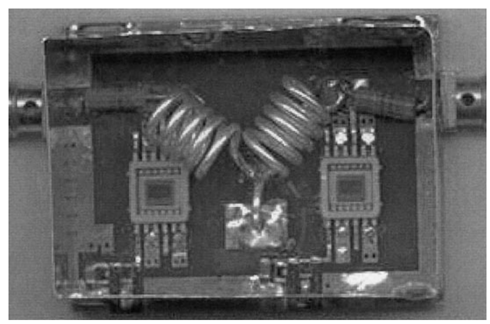
MICROELECTROMECHANICAL systems (MEMS) technology offers an attractive capability for RF systems, particularly in support of switching and tuning functions. One such component is a micromechanical analog tunable capacitor, which can enable wide tuning ranges and high-quality (Q) factors. Existing solid-state varactors typically have limited linearity, high resistive losses, and low self-resonance. Recent advances in micromechanical tunable capacitors have shown promise in improving these characteristics [1]–[5]. Previous MEMS tunable capacitors have shown Q values up to 290 at 1 GHz [2], tuning ratios in excess of 270% [3], and a self-resonance as high as 83 GHz [4].

The MEMS tunable capacitor is ideal for RF filter applications and offers many advantages over conventional varactor-based filters, including an increased dynamic range and a dramatic parts reduction. When implemented into a two-pole UHF filter, the MEMS-based filter enables an 82% reduction in parts over a varactor-based filter (Fig. 1) and, therefore, facilitates a much smaller system.

In this paper, we will present a brief description of the capacitor, and the UHF filter in which the device was demonstrated. The capacitor maintains a Q greater than 100 over the 225–400-MHz range, with a capacitance range of 1.4 to 11.9 pF. The MEMS-based filter presented achieved continuous tuning over a 225–400-MHz range with a loss below 6.2 dB and a 1-dB bandwidth below 3%.



(a)



(b)

Fig. 1. (a) Varactor and (b) MEMS capacitor-based tunable two-pole UHF filter.

II. Tunable Capacitor

The tunable capacitor must meet several specifications before it can be successfully implemented into the two-pole filter. There are three primary specs to consider. First, a tuning range greater than four times must be achieved to compensate for all packaging and filter parasitic capacitance. Second, the device Q must be above 100 over the desired range to maintain a filter Q greater than 50. Finally, the device is required to have an operation lifetime on the order of 10-billion cycles.

To meet these filter specifications, a previously presented MEMS-based tunable capacitor was implemented [5]. This capacitor consists of a 40-μm–thick single-crystal silicon actuator suspended over a glass substrate (Fig. 2). Through the use of a large throw electrostatic comb drive and a separate area tuning capacitor, a wide tuning range and high Q can be achieved. Long operational lifetimes have been achieved

Manuscript received April 13, 2002. This work was supported by the Defense Advanced Research Projects Agency/Microsystems Technology Office Microelectromechanical Program under Contract F30602-97-C-0091.

R. L. Borwick, III, P. A. Stupar, J. F. DeNatale, and R. Anderson are with Rockwell Scientific, Thousand Oaks, CA 91360 USA (e-mail: rborwick@rwsc.com; pstupar@rwsc.com; jdenatale@rwsc.com; randerson@rwsc.com).

R. Erlandson is with Rockwell Collins, Cedar Rapids, IA 52498 USA (e-mail: rjerland@rockwellcollins.com).

Digital Object Identifier 10.1109/TMTT.2002.806519

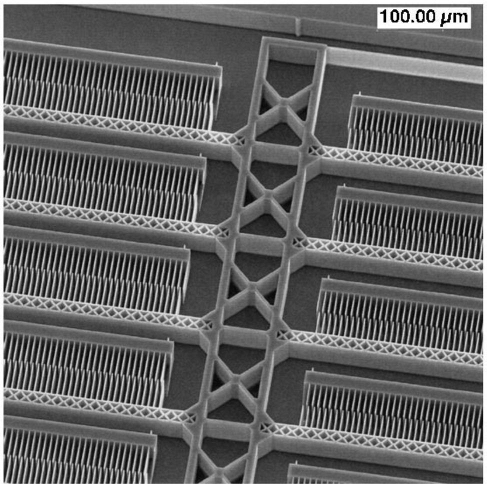


Fig. 2. SEM of a 40-μm-thick tunable capacitor with separate electrostatic comb drive actuation (left-hand side), and area tuning capacitor (right-hand side).

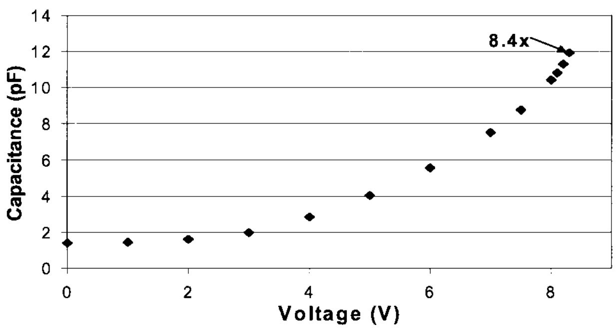


Fig. 3. Tuning range of the device measured at 500 MHz.

because the device consists of a single crystal silicon layer with only a thin aluminum conductive layer. An addition aluminum layer is also often added to further reduce series resistance and eliminate the effects of coefficient of thermal expansion (CTE) mismatch stresses. However, this added aluminum layer should not have an effect on device lifetime because failure of the bottom metal layer will not lead to failure of the device.

The MEMS tunable capacitor has an exceptionally large tuning range, larger than 8.4 : 1 (Fig. 3). Although the filter only needs a tuning range of 4 : 1 to tune over the 225–400-MHz range, parasitics in both the package and filter circuit force the tunable capacitor to have a larger capacitance range, up to 5.5 : 1. The large tuning range of the MEMS capacitor easily meets this requirement. Actuation voltages for full throw of the device are dependant on suspension and capacitor design and range from 3 to 30 V.

The series resistance of the MEMS tunable capacitor is less than 1 Ω in the frequency range of this device. This low series resistance leads to a high Q. Figs. 4 and 5 show the $S11$-parameters and the device Q. The device has a low parasitic inductance and is not near self-resonance out to a frequency of 3 GHz. The device also has a Q above 100 out to 700 MHz, making it ideal for the tunable filter application over 225–400 MHz, the desired communication system frequency. In addition, the device has a Q above 30 up to 2.25 GHz, making it suitable for higher frequency applications.

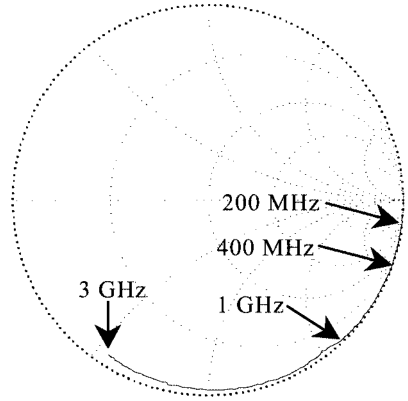


Fig. 4. $S11$ plot of the device from 100 MHz to 3 GHz with no actuation and a capacitance of 1.5 pF.

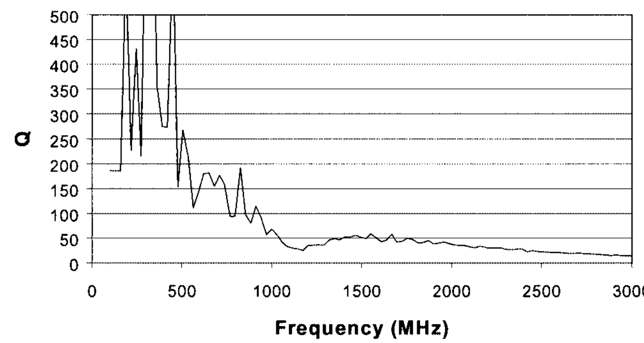


Fig. 5. Q factor of the device from 100 MHz to 3 GHz with no actuation and a capacitance of 1.5 pF.

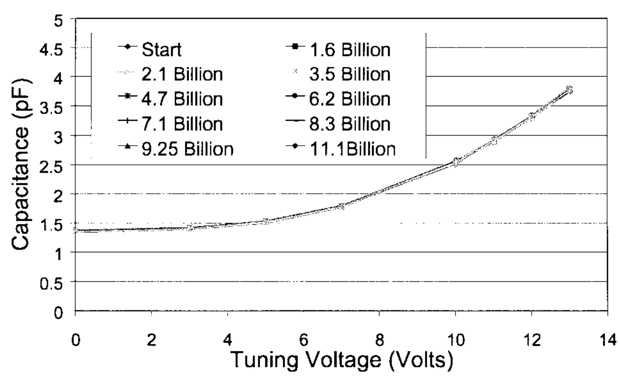


Fig. 6. Change in capacitance versus tuning voltage after 11.1-billion cycles. All ten curves overlap each other within 1%.

Some filter applications require lifetimes of over 10-billion cycles. To meet this specification, the MEMS tunable capacitor is fabricated from single-crystal silicon, a material that has a large elastic deformation region and shows very little fatigue. The predicted failure mechanism is the fatiguing of the thin aluminum layer evaporated onto the silicon surface. This failure would cause a dramatic increase in the series resistance. The device lifetime is currently under test, and has shown no degradation after 11.1-billion cycles. The capacitance versus tuning voltage has not changed significantly, less than 2%, which is within measurement error (Fig. 6). In addition, the series resistance showed very little change (Fig. 7).

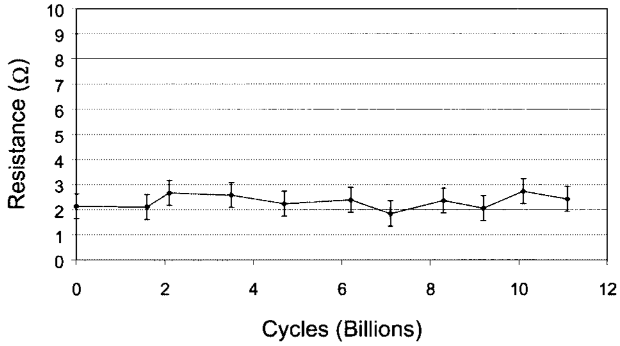


Fig. 7. Change in series resistance after 11.1-billion cycles.

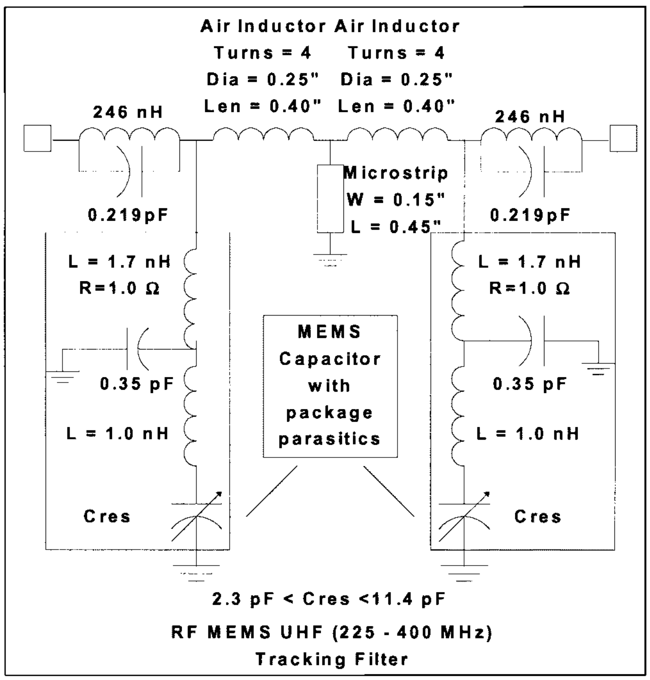


Fig. 8. Circuit diagram for the MEMS variable capacitor-based two-pole UHF filter.

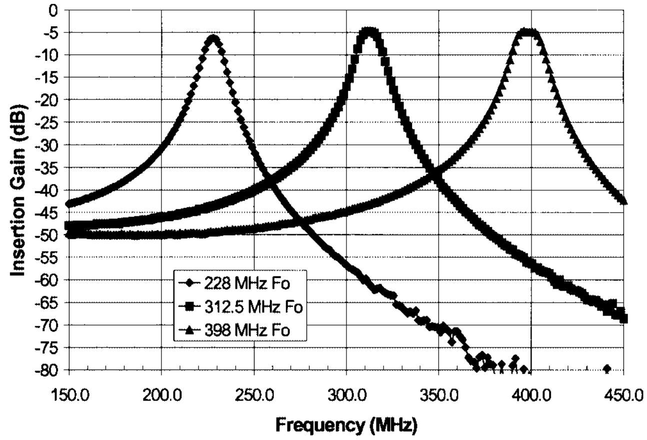


Fig. 9. Frequency response of the two-pole MEMS-based tunable filter.

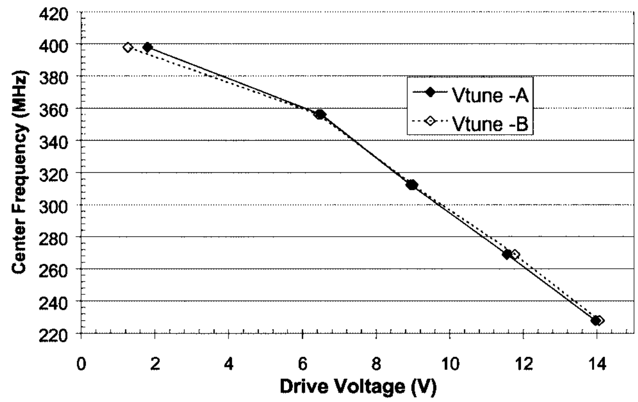


Fig. 10. Voltage needed to tune the UHF filter over the 225–400-MHz range.

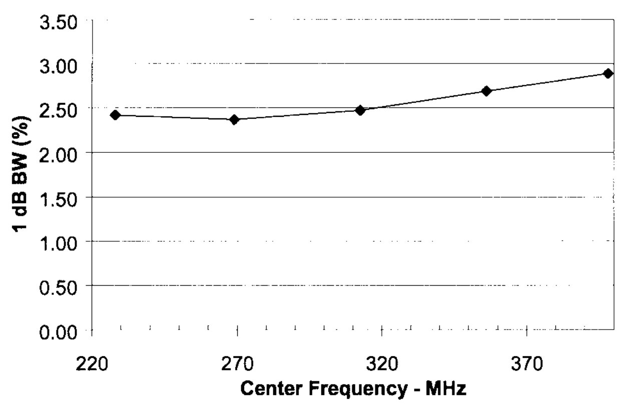


Fig. 11. 1-dB bandwidth of the UHF filter over the 225–400-MHz range.

III. MEMS-Based UHF Filter

The design of the MEMS-based two-pole UHF filter is shown in Fig. 8 including the parasitics of the tunable capacitor devices. The entire circuit consists of only 11 parts, as compared to the varactor-based design, which contains 62 parts. This dramatic reduction in parts allows the MEMS-based filter to be significantly smaller than existing technologies. Current device size is 5 mm^2 placed in a package that is 7×7 mm.

The improved RF characteristics of the MEMS tunable capacitor make it suitable for implementation into a two-pole UHF filter. Fig. 9 shows the frequency response of the filter at different center frequencies. The filter has a wide tuning range, high rejection, and a low loss. The tuning is plotted over the entire frequency range in Fig. 10. The tunable filter was able to achieve the full tuning range with an actuation voltage under 14 V. The 1-dB bandwidth is below 3% over the entire frequency range (Fig. 11). The filter does show some widening at the high end of the frequency range, which is reflected in a slight increase in the bandwidth at the higher frequencies. Previous devices were unable to keep the filter loss under 8 dB, thereby making them unable to meet the specification for the UHF filter. The center frequency loss of the new filter is shown in Fig. 12. The loss is below 6.2 dB over the entire frequency range. This low loss is a direct result of the recent increase in Q of the MEMS tunable capacitor [5].

The measured filter rejection at ±13, ±26, and ±53 MHz (Fig. 13) remains high over the entire frequency range. The high linearity of the filter has been validated using a two-tone response. The third-order intercept point (IP3) of the filter was

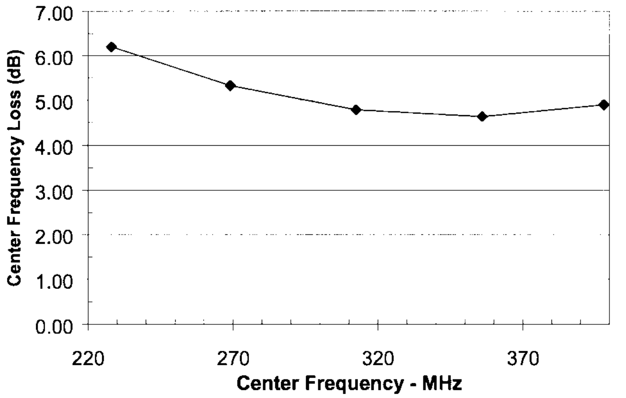


Fig. 12. Center frequency loss of the UHF filter over the 225–400-MHz range.

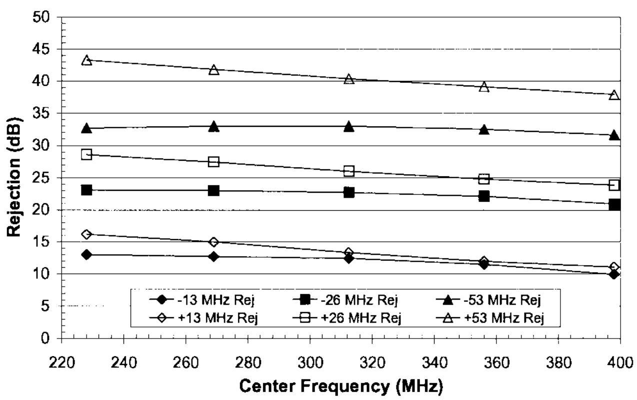


Fig. 13. Tunable filter rejection over the 225–400-MHz frequency range.

measured at five points, in-band, with a frequency separation of 200 kHz. The IP3 of the device ranged from 30 to 38 dBm. The intermodulation is caused by the effective voltage from the RF signal. For large RF powers, this voltage can detune the capacitor. Stiffer structures are being looked at to compensate for this problem.

The mechanical resonant frequency of the tunable capacitor device ranges from 500 to 2000 Hz, depending on the suspension design. The device used in the two-pole filter has a resonant frequency of 1.5 kHz and a theoretical response time of 330 μs. However, due to the extreme underdamping of the tunable capacitor, ringing often occurs during a step response. This causes much slower response times because the ringing must completely die down before the filter will be accurately positioned at the required center frequency. Typical response times for the filter have been as high as 6 ms. However, by packaging the device in a high viscosity gas environment, near critical damping can be achieved [5]. This makes the device easier to control and dramatically decreases the response time. The filtered step response for a tunable capacitor device in both damped and underdamped states has been measured with a 10$\times$ improvement in filter response time (from 6 ms to below 600 μs for the damped case). The underdamped nature of the device also causes a sensitivity to vibration for the lower frequency devices. Although device damping will also improve the sensitivity to vibration, further compensation may be required. Closed-loop operation will compensate for vibration and other causes of error such as temperature instabilities.

IV. Conclusion

A micromechanical tunable capacitor was designed and fabricated for implementation into a 225–400-MHz tunable filter circuit. Using new design and process concepts, a 740% continuous tuning range has been achieved with Q factors above 100 for the operating conditions of the tunable filter. In addition, the tunable filter achieved continuous tuning with a center frequency loss below 6.2 dB. Cycling the device over 11.1-billion cycles without any performance degradation has validated the lifetime of the filter. In addition, adaptation into higher frequency ranges has been proven feasible with Q factors over 35 for frequencies up to 2 GHz. Trading off the tuning range for higher Q by stiffening up the device suspension could also make additional gains.

Acknowledgment

The authors thank the cleanroom staff, Rockwell Scientific, Thousand Oaks, CA, for their help in fabricating these devices. Specifically, the authors thank K. Garrett for her support in all areas of development for this project.

References

[1] D. J. Young and B. E. Boser, "A micro-machined variable capacitor for monolithic low-noise VCO's," in *Solid-State Sensors and Actuators Workshop Tech. Dig.*, 1996, pp. 86–89.

[2] J. Yoon and C. Nguyen, "A high-Q tunable micro-mechanical capacitor with movable dielectric for RF applications," in *Int. Electron Devices Meeting Tech. Dig.*, 2000, pp. 489–492.

[3] Z. Feng, H. Zhang, W. Zhang, B. Su, K. Gupta, V. Bright, and Y. Lee, "MEMS-based variable capacitor for millimeter-wave applications," in *Solid-State Sensors and Actuators Workshop Tech. Dig.*, 2000, pp. 255–258.

[4] L. Dussopt and G. M. Rebeiz, "High-Q millimeter-wave MEMS varactors: Extended tuning range and discrete-position designs," in *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 2, 2002, pp. 1205–1208.

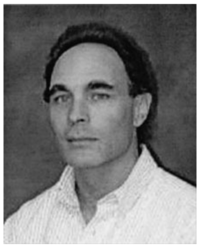
[5] R. Borwick, P. Stupar, J. Denatale, R. Anderson, C. Tsai, and K. Garret, "A high Q, large tuning range tunable capacitor for RF applications," in *IEEE MEMS Conf. Tech. Dig.*, 2002, pp. 669–672.

Robert L. Borwick, III received the B.S. degree in physics and mathematics from the California Lutheran University, Thousand Oaks, CA, in 1997.

In 1995, he joined Rockwell Scientific, Thousand Oaks, CA. He was involved with laser optics and material science until 1998 when he became a Member of the Technical Staff with the MEMS Group. Within this group, he designs, fabricates, packages, and tests switches, sensors, and RF devices.

Philip A. Stupar received the Ph.D. degree in mechanical engineering from the University of California at Berkeley, in 2001.

While with the Berkeley Sensors and Actuators Center, he performed research in the area of MEMS for data storage and microfluidics. Since 2001, he has been a Research Scientist with Rockwell Scientific, Thousand Oaks, CA, where he is currently involved with MEMS for sensors and RF systems.



Jeffrey F. DeNatale (M'01) received the B.S. M.S., and Ph.D. degrees in material science and engineering from the University of California at Davis, in 1980, 1983, and 1985, respectively.

He is currently the Manager of the MEMS Department, Rockwell Scientific, Thousand Oaks, CA. Since joining Rockwell Scientific, he has been involved with a broad spectrum of advanced research and development programs, including advanced optical thin-film materials, polycrystalline diamond thin films, high-temperature superconductors, and the first-ever demonstration of nonlinear thin films of the rare-earth nickelate family. Since 1997, he has led the MEMS efforts at Rockwell Scientific, directing a broad range of device activities. These include innovative projects in RF MEMS, industrial microsensors, optical MEMS, microassembly technologies and microthermal management devices. He has coauthored over 65 publications. He holds three U.S. patents with four pending.

Robert Anderson received the B.S. degree in chemistry from Arizona State University, Tempe, in 1966.

In 1976, he joined Rockwell Scientific, Thousand Oaks, CA, where he is currently involved with the development of MEMS device fabrication.

Robert Erlandson (S'66–M'68) received the B.E.E. and M.S. degrees in electrical engineering from the University of Minnesota, Minneapolis–St. Paul, in 1967 and 1968, respectively.

He is currently a Principal Engineer with Rockwell Collins Inc., Cedar Rapids, IA. Since 1975, he has gained extensive experience in global positioning system (GPS) and other microwave avionics hardware design and system analysis. Since 1997, he has been actively involved with Rockwell Collins Inc. RF MEMS technical investigations.

Mr. Erlandson is a member of Tau Beta Pi and Eta Kappa Nu. He is a member of the IEEE Microwave Theory and Techniques Society (IEEE MTT-S) and is involved with numerous chapter activities.