

X-band RF MEMS tuned combline filter

C.D. Nordquist, C.L. Goldsmith, C.W. Dyck, G.M. Kraus, P.S. Finnegan, F. Austin IV and C.T. Sullivan

A three-pole combline filter tuning from 8.2 to 11.3 GHz using RF MEMS switched capacitors is reported. This structure, measuring $2.85 \times 2.15 \text{ mm}^2$, allows 31% tuning with 11% 3 dB bandwidth for the four tuning states and insertion losses ranging from 4.4 to 6 dB.

Introduction: Microwave filters are critical components for electronic warfare, radar, and communications systems, but typical tunable filters are bulky, expensive, and consume large amounts of power. Radio frequency microelectromechanical systems (RF MEMS) technology provides the possibility of low-loss, high linearity filtering in volumes comparable to those of integrated circuits [1]. The maturation of this technology will allow further miniaturisation of radar and communication sub-systems.

To date, there have been several examples of monolithic RF MEMS tuned filters [2–7]. The tuning range of these filters is limited either by the tuning range of the MEMS components [4, 5], or by the frequency range over which the filter elements maintain their reactances and coupling relationships. While traditional combline filters with tapped or coupled line transformer inputs fed from the grounded end of the resonators offer a broad tuning range [8], the tuning range can be increased by feeding the input and output coupled line transformers from opposite the grounded ends of the resonators, as described by Hunter [9]. In this design, the coupling in the transformer and coupling between the resonators change in offsetting directions, allowing extremely broad tuning ranges. In addition, this filter has fewer RF MEMS components than other designs [3–5]. Thus, this combline filter design is ideally suited for implementation using RF MEMS.

To vary the loading capacitance, we use RF MEMS capacitive switches on the end of each resonator to select fixed metal-insulator-metal (MIM) capacitors, rather than using individual continuously tunable capacitors. In addition to allowing a broader tuning range, the digitally switched bank offers better reproducibility and stability across a broad range of environmental conditions than analogue tuned devices. This type of implementation will be essential for the acceptance of RF MEMS based components into fielded systems.

Filter design and technology: The design goal was to deliver 1 GHz bandwidth with 2 bits of tuning covering 8 to 12 GHz. This >30% tuning range presents a challenge for RF MEMS based filters. Filter parameters for traditional microstrip combline filters were determined at 10 GHz using the method described by Vincze [10]. However, filters designed using these parameters showed a significant bandwidth variation across the tuning range, so the direction of the input coupling was reversed to improve the filter's range [9].

The microstrip resonator impedances are 50Ω , which is a compromise between the larger tuning range provided by a high impedance line and the higher Q of a low impedance line. The resonators are 45° at 10 GHz, slightly shorter than the typical 50° to 55° length for combline filters to accommodate the additional length of the RF MEMS loading networks. The physical length of the resonators including the loading networks was 2 mm, with loading capacitances ranging from 150 to 300 fF.

The filter was fabricated on $254 \mu\text{m}$ -thick alumina with CuW-filled via holes and $0.025 \mu\text{m}$ final polish. The switch bottom electrode is $0.3 \mu\text{m}$ -thick gold, and the dielectric used to realise both the switch and capacitors is $0.3 \mu\text{m}$ of silicon oxynitride ($\epsilon_r \sim 5.5$), which offers a compromise between the high dielectric constant of silicon nitride and the reduced charging of silicon dioxide. The transmission lines are $2.5 \mu\text{m}$ -thick gold and the sacrificial layer is $4 \mu\text{m}$ of photoresist, while the RF MEMS bridges and capacitor top plates are $1 \mu\text{m}$ -thick aluminium patterned by reactive ion etching. A $1 \text{ k}\Omega/\square$ resistor layer is used to bias the RF MEMS switches without impacting the RF performance of the circuit significantly.

Using this technology, we have developed both cantilever and bridge capacitive switches, with the cantilever structures used here because of their smaller size and ease of use in a series configuration. The switches are $80 \mu\text{m}$ wide and $200 \mu\text{m}$ long, with an up-state capacitance of approximately 100 fF and a down-state capacitance of 500 fF. While the roughness of the alumina substrate reduces the down-state

capacitance of the switch, these values and contrast ratio are adequate for this application. The switch has a loss of 0.1 dB at 10 GHz and a pull-in voltage of approximately 30 V at room temperature. The switches are used to select two MIM capacitors per resonator, resulting in two bits of tuning, with the down-state capacitance determined by a fixed loading capacitor connected to each resonator via an airbridge. Fig. 1 shows an optical image of the filter with a scanning electron micrograph of one of the RF MEMS switches and MIM capacitor loading networks. The die size 2.85 by 2.15 mm , the transmission lines are $250 \mu\text{m}$ wide, and the outer and inner gaps between the coupled lines are 80 and $320 \mu\text{m}$, respectively. The RF signal is introduced through coplanar-to-microstrip converters, while the DC bias for controlling the switches is applied to the pads at the lower edge of the filter die.

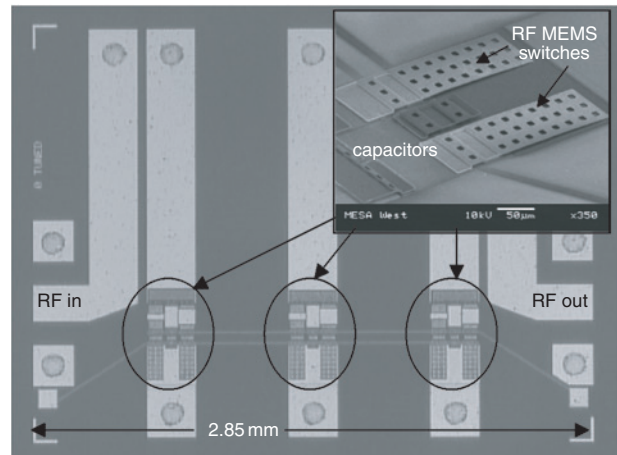


Fig. 1 Optical micrograph of completed RF MEMS filter

Inset: Scanning electron micrograph of RF MEMS switches and loading network

Results: The filters were tested in laboratory ambient from 50 MHz to 25 GHz utilising a network analyser and on-wafer probe station. The switches were actuated with a bipolar square waveform with a maximum voltage of $\pm 50 \text{ V}$ to mitigate charging effects without impacting the down-state capacitance of the switch.

The measured insertion loss and return loss in the four tuning states are shown in Figs. 2a and b, respectively. The centre frequencies of the states are 8.2, 9.2, 10.2 and 11.3 GHz, demonstrating the desired 30% tuning range with nearly complete coverage. The filter's 3 dB bandwidth ranges from 10.5 to 11.5% for all of the states, demonstrating the excellent bandwidth stability provided by this design. The rejection slopes are typical for a three-pole filter, with the excellent rejection and steep slope on the high side of the passband due to via hole ground inductance. Additionally, there are no spurious passbands up to the highest measured frequency of 25 GHz, indicating good rejection through at least three times the filter's centre frequency.

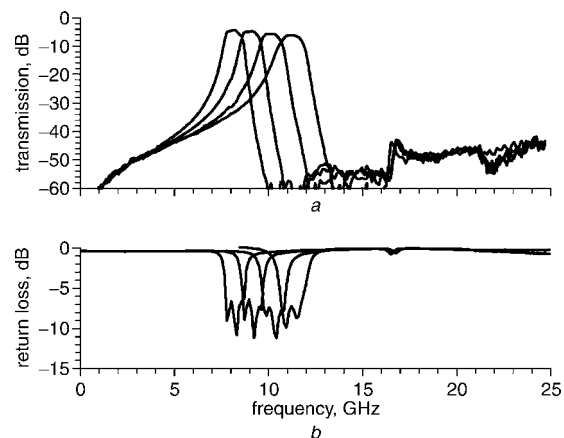


Fig. 2 Insertion loss and return loss of RF MEMS tuned combline filter

a Insertion loss
b Return loss

The passband return loss of 7 dB is worse than desired, and is the likely result of the large length of tuning network that is not coupled with the input line. Electromagnetic simulations indicate that extending the input and output coupled line transformers to include the entire length of the resonator lines and loading networks will improve the return loss to better than 10 dB. The filter demonstrates insertion losses ranging from 4.5 to 6 dB, corresponding with an unloaded resonator Q of approximately 17, lower than the expected Q of 100. The primary source of loss is high metal resistance in the bottom contact layers and aluminium bridge layers. We expect to improve the insertion loss to about 2 dB by optimising the design and deposition of these layers, raising the Q of both the switches and MIM capacitors.

Conclusion: This monolithic X-band combline filter is the first demonstration of using RF MEMS to realise this filter topology. With its broad tuning range, compact size, and small number of RF MEMS devices, this filter is promising for applications requiring a large tuning range and a fixed bandwidth. While the measured filter loss ranges from 4.5 to 6.0 dB, it has the potential to demonstrate less than 2 dB of loss. In the future, we expect to improve the insertion loss and return loss characteristics and expand the filter design to add more bits of tuning and address other frequency ranges.

Acknowledgments: These parts were fabricated in the MESA West (CSRL) facility. Sandia National Laboratories is a multiprogramme laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

© IEE 2005

11 October 2004

Electronics Letters online no: 20057375

doi: 10.1049/el:20057375

C.D. Nordquist, C.W. Dyck, G.M. Kraus and C.T. Sullivan (*Sandia National Laboratories, PO Box 5800, MS 0603, Albuquerque, NM 87185, USA*)

E-mail: cdnordq@sandia.gov

C.L. Goldsmith (*MEMtronics Corp., Plano, TX, USA*)

P.S. Finnegan (*L & M Technologies, Albuquerque, NM, USA*)

F. Austin IV (*The Plus Group, Albuquerque, NM, USA*)

References

- 1 Brown, E.R.: 'RF-MEMS switches for reconfigurable integrated circuits', *IEEE Trans. Microw. Theory Tech.*, 1998, **46**, pp. 1868–1880
- 2 Peroulis, D., Pacheco, S., Sarabandi, K., and Katehi, L.P.B.: 'Tunable lumped components with applications to reconfigurable MEMS filters', *IEEE MTT-S Int. Microw. Symp. Dig.*, 2001, **1**, pp. 341–344
- 3 Brank, J., Yao, Z.J., Eberly, M., Malczewski, A., Varian, K., and Goldsmith, C.L.: 'RF MEMS-based tunable filters', *Int. J. RF Microw. Comput.-Aided Eng.*, 2001, **11**, pp. 276–284
- 4 Abbaspour-Tamijani, A., Dusspot, L., and Rebeiz, G.M.: 'Miniature and tunable filters using MEMS capacitors', *IEEE Trans. Microw. Theory Tech.*, 2003, **51**, pp. 1878–1885
- 5 Liu, Y., Borgioli, A., Nagra, A.S., and York, R.A.: 'Distributed MEMS transmission lines for tunable filter applications', *Int. J. RF Microw. Comput.-Aided Eng.*, 2001, **11**, pp. 254–260
- 6 Kim, H.-K., Park, J.-H., Kim, Y.-K., and Kim, Y.: 'Low-loss and compact V-band MEMS-based analog tunable bandpass filters', *IEEE Microw. Wirel. Comp. Lett.*, 2002, **12**, pp. 432–434
- 7 Fourn, E., Pothier, A., Champeaux, C., Tristant, P., Catherinot, A., Blondy, P., Tanne, G., Rius, E., Person, C., and Fabrice, H.: 'MEMS switchable interdigital coplanar filter', *IEEE Trans. Microw. Theory Tech.*, 2003, **51**, pp. 320–324
- 8 Matthaei, G.L.: 'Comb-line bandpass filters of narrow or moderate bandwidth', *Microw. J.*, 1963, **6**, pp. 82–91
- 9 Hunter, I.C.: 'Electronically tunable microwave bandpass filters', *IEEE Trans. Microw. Theory Tech.*, 1982, **30**, pp. 1354–1360
- 10 Vincze, A.D.: 'Practical design approach to microstrip combline filters', *IEEE Trans. Microw. Theory Tech.*, 1974, **22**, pp. 1171–1181