A Miniature 800–1100-MHz Tunable Filter with High-Q Ceramic Coaxial Resonators and Commercial RF-MEMS Tunable Digital Capacitors

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***Abstract*—This paper presents the design and characterization of a miniaturized tunable bandpass filter utilizing high-Q ceramic coaxial resonators and commercially available RF-MEMS tunable digital capacitors. A proof-of-concept 2-pole tunable filter occupying only $10 \times 10\,\mathrm{mm}^2$ is demonstrated with a frequency tuning range of 800–1100 MHz and bandwidth tuning range of 6-13%.**

***Index Terms*—coaxial resonator, RF-MEMS, tunable filters**

I. Introduction

Since their inception, radio-frequency microelectromechanical (RF-MEMS) devices have shown great promise in either enhancing the performance of current RF/microwave systems or enabling new capabilities for future systems [1]. Arguably the best tuning elements, RF-MEMS devices, such as switches and varactors, are known to exhibit very low-loss, wide bandwidth, high linearity, and near zero power consumption [2]. In particular, these characteristics make RF-MEMS devices an ideal candidate for use as tuning elements in high-Q tunable RF filters for reconfigurable wireless systems. In fact, many RF-MEMS enabled tunable filters have been demonstrated with excellent performance in terms of tuning range and quality factor [3]–[5]. However, the use of custom designed and fabricated MEMS tuners and the lack of a standardized process has limited their adoption into a wider range of applications.

In addition, high quality factor often comes at a cost of larger volume, especially at low-GHz frequencies. In [4], for example, unloaded quality factor (Q_u) of more than 300 has been demonstrated for 2–5 GHz range with tunable highly-loaded evanescent-mode cavity filters. However, the sizes of these filters are typically large ($40 \times 28\,\mathrm{mm}^2$ for a two-pole filter).

In this work, we propose to use a combination of high-Q ceramic coaxial resonators and commercially available RF-MEMS tuners to realize miniature high-Q tunable filters (Fig. 1). Coaxial resonator takes advantage of the high dielectric constant and low loss tangent of certain dielectric materials to achieve high-Q resonance in a small volume. Unlike solid dielectric resonators, coaxial resonators are coated with a highly conductive metal, such as silver, to form a transmission line resonator in length of $\lambda/4$ or $\lambda/2$ with one end either short- or open- circuited. The quasi-TEM nature of coaxial resonators make it very easy to integrate with lumped tuning elements.

On the other hand, commercialization efforts in the RF-MEMS community has made RF-MEMS switches and varactors increasingly available as standardized and commodity tuning elements [6]–[8]. Using commercially available RF-MEMS devices offers several advantages, such as lower prototyping cost, faster turn-around time, better uniformity and repeatability, and easier control (in many cases, the control circuitry is integrated into the packaged RF-MEMS device) [9].

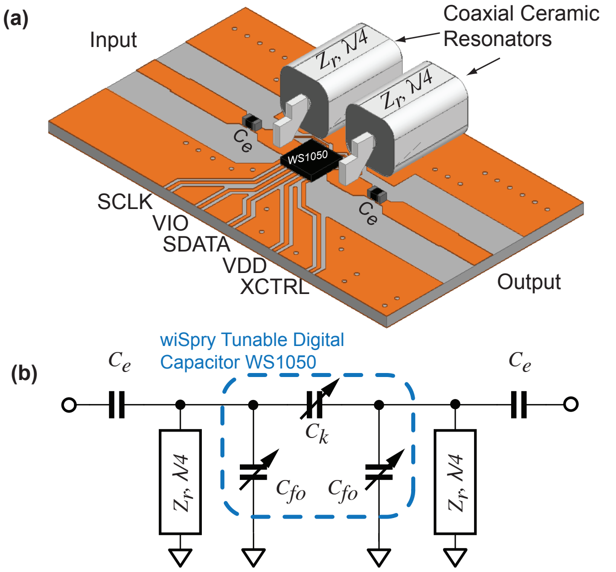

Fig. 1. (a) Proposed two-pole tunable bandpass filter and (b) equivalent circuit model.

In this paper, we propose a miniature tunable bandpass filter using Trans-Tech ceramic coaxial resonators and WiSpry tunable digital capacitor arrays. A prototype two-pole filter achieves a frequency tuning range of 800–1100 MHz while only occupying $10 \times 10\,\mathrm{mm}^2$ area.

II. Design

A. WiSpry Tunable Digital Capacitor (TDC)

In this work, we utilize a WiSpry WS1050 TDC, which is a high-Q RF variable capacitor array. Each WS1050 packaged IC consists of three high-resolution, tunable capacitor banks. Each capacitor bank has a combined series capacitance with a tuning range of ≈ 0.5–$5.75\,\mathrm{pF}$. The series equivalent capacitance is modeled as

$$C_{eq} = (index - 1) \times 0.0938 + 0.50\ pF, \qquad (1)$$

where $index$ ranges from 1 to 57. The $index$ or the capacitance is controlled by a MIPI Alliance RFFE v1.1 serial interface. The WS1050 chip comes in a compact $2.68 \times 2.60\ \mathrm{mm}^2$

LGA package compatible with standard surface mount assembly processes.

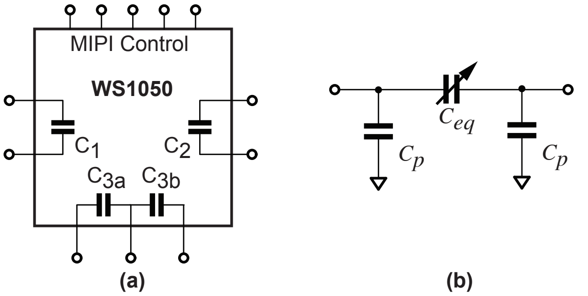

Fig. 2. (a) Schematic of the WiSpry WS1050 TDC IC; (b) Equivalent circuit of the WS1050 showing the tunable series capacitance and shunt parasitic capacitance.

B. Filter Design

In this work, we present a two-pole tunable bandpass filter as a proof-of-concept demonstration of the proposed technology. For tunable filter designs, the parasitics of the TDC must be carefully taken into account. In WS1050, each series capacitor terminal has a shunt parasitic capacitance C_p as shown in Fig. 2-b. The existence of the parasitic capacitances alters the frequency tuning and coupling characteristics of the coaxial resonators.

For example, Fig. 3-a shows the simulated frequency tuning range of a Trans-Tech D8800 LP-size $\lambda/4$ (at 2 GHz) resonator loaded with an WS1050 capacitor bank (C1 or C2). Because of the parasitic C_p, the frequency tuning range is reduced to ~ 1.45 from a theoretical 3.39 ($\sqrt{5.75/0.5}$, if we consider a constant inductive part).

Due to the existence of C_p, the coupling coefficient k can not be directly calculated based on well-known filter design theories [10]. Fig. 3-b shows the simulated coupling coefficient between two resonators with one WS1050 capacitor bank as an inter-resonator coupling element. It can be observed that the coupling coefficient k does not change monotonically with frequency. In addition, C_p will further load the adjacent resonators and reduce their tuning range.

Fig. 4-a presents a schematic of the prototype two-pole tunable filter including all the parasitics from the WS1050 IC. C1 and C2 of the WS1050 are used for frequency tuning while C3 is used for bandwidth adjustment. In order to account for any additional parasitics, the PCB layout is imported into Ansys HFSS and simulated with 3-D models of the coaxial resonators. The exported multi-port s-parameters from HFSS simulation is then used in Keysight Adavanced Design System (ADS) with WS1050 capacitor models to simulated the filter. Simulation result shows that a realistic tuning range of 0.8–1.1 GHz can be achieved with all the parasitics considered.

III. EXPERIMENTAL VALIDATION

The two-pole filter is fabricated on a 30-mil Rogers 4350B substrate with $\epsilon_r = 3.66$. The printed circuit board (PCB) is fabricated by a professional PCB manufacturer and assembly is done manually in-house. Fig. 5 shows a picture of the fabricated filter. Owing to small size of both the resonators and the TDC, the entire filter occupies only $10 \times 10\,\mathrm{mm}^2$ (this excludes the input and output transmissions and the SMA connectors). In the following measurements, the filter is tuned by a micro-controller board through the MIPI interface.

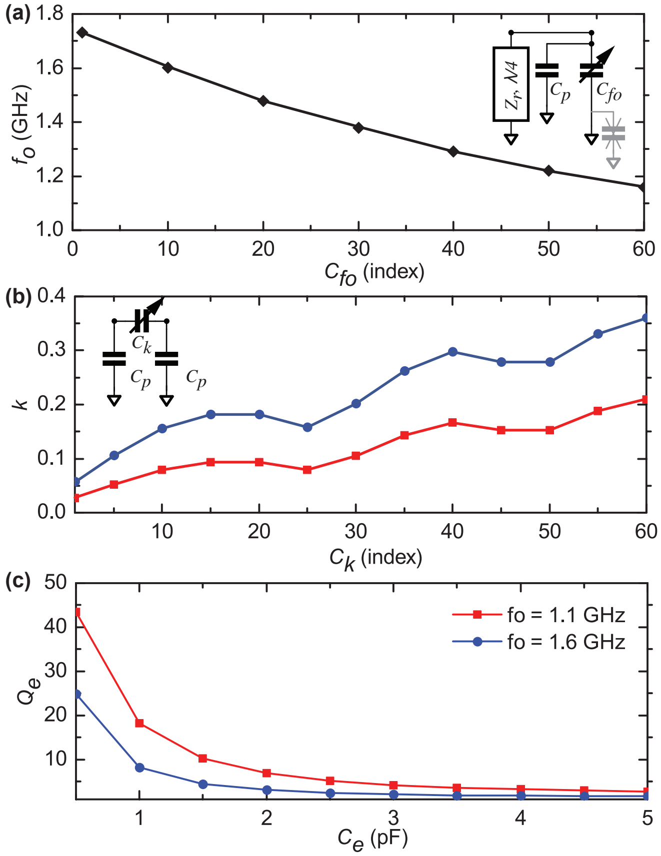

Fig. 3. Simulated (a) resonant frequency of an ideal quarter-wave shorted transmission line ($Q = 450$) in parallel with C_{fo} (b) inter-resonator coupling k between two resonators and (c) external quality factor Q_e.

As predicted by the simulation, the fabricated filter has a frequency tuning ranges from 0.8 GHz to 1.2 GHz (Fig. **??**). The measured insertion loss varies from 1.2 dB at higher frequencies to 2.9 dB at lower frequencies. The measured insertion loss is higher than what the simulation predicts. This largely attributed to the imperfect assembly of the wiSpry TDC as the small LGA package proves to be very difficult to hand solder. Slight misalignment has resulted in higher a contact resistance, leading to high insertion loss. The measured filter response show significant widening as the filter is tuned to higher frequencies. This is predicted by simulation and is attributed to the capacitive coupling structures used to the internal and external couplings. The inset of Fig. 6 shows a wider frequency sweep showing the out-of-band spurious response. The first spurious pass come around 2.5 GHz, which roughly corresponds to the $\lambda/2$ of the coaxial resonators (when loaded by the tuning capacitors).

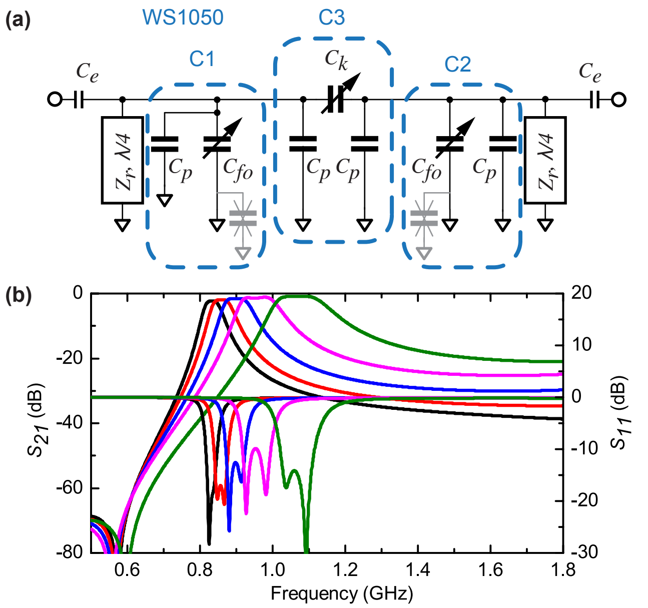

Fig. 4. (a) Equivalent circuit of the two-pole filter design. (b) HFSS-ADS co-simulated filter tuning performance.

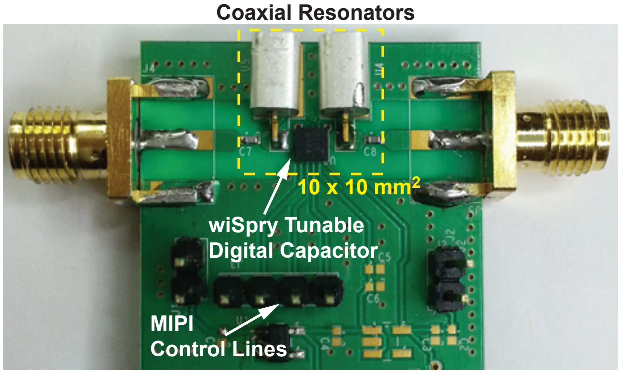

Fig. 5. A picture of the fabricated miniature tunable filter.

Measured results in Fig. 7 shows both tunable bandwidth and center frequency. Bandwidth can be adjusted within a range of 6–13%. Results are presented for cases where the return loss is better than 10 dB.

IV. CONCLUSION

This work presents a 800–1100-MHz miniature tunable bandpass filter designed and fabricated with high-Q ceramic coaxial resonators and commercially available RF-MEMS tunable digital capacitors. The effective area of the filter occupies only $10 \times 10\,\mathrm{mm}^2$. The fabricated prototype demonstrated flexible tuning capabilities in terms of both center frequency and bandwidth. Future work will focus on exploring design methods for reducing the impact of TDC parasitics and improving the fabrication/assembly process to reduce filter loss.

REFERENCES

[1] G. M. Rebeiz, *RF-MEMS: Theory, Design, and Technology*. Wiley, 2003.

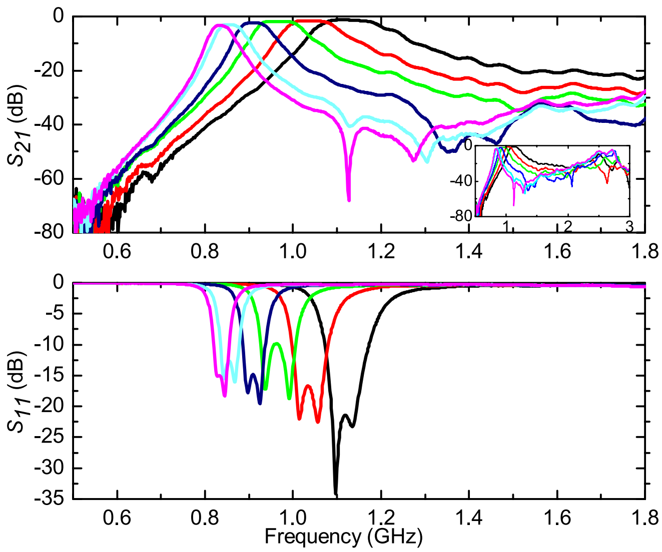

Fig. 6. (a) Measured two-pole filter s-parameters with frequency tuning from 0.8–1.2 GHz.

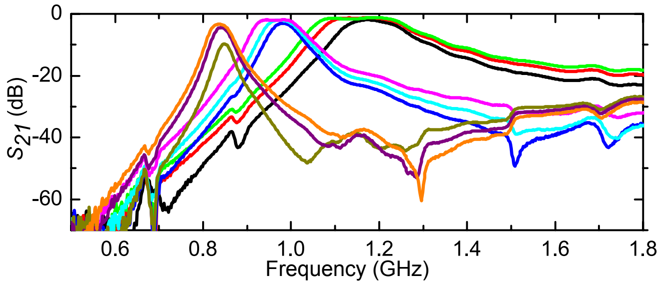

Fig. 7. Measured bandwidth tuning characteristics of the fabricated tunable filter.

[2] G. M. Rebeiz, K. Entesari, I. C. Reines, S.-J. Park, M. A. El-Tanani, A. Grichener, and A. R. Brown, “Tuning into RF-MEMS,” *IEEE Microwave Magazine*, vol. 10, no. 6, pp. 55–72, 2009.

[3] K. Entesari, K. Obeidat, A. R. Brown, and G. M. Rebeiz, “A 25C75-MHz RF MEMS Tunable Filter,” *IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES*, vol. 55, no. 11, pp. 2399–2405, 2007.

[4] X. Liu, L. Katehi, W. Chappell, and D. Peroulis, “High-q tunable microwave cavity resonators and filters using soi-based rf mems tuners,” *Journal of Microelectromechanical Systems*, vol. 19, no. 4, pp. 774–784, Aug 2010.

[5] A. Abbaspour-Tamijani, L. Dussopt, and G. M. Rebeiz, “Miniature and Tunable Filters Using MEMS Capacitors,” *IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES*, vol. 51, no. 7, pp. 1878–1885, 2003.

[6] Radant MEMS. [Online]. Available: http://www.radantmems.com

[7] Wispry. [Online]. Available: http://www.wispry.com

[8] Cavendish Kinetics. [Online]. Available: http://www.cavendish-kinetics.com

[9] C. Ko, K. M. Ho, R. Gaddi, and G. M. Rebeiz, “A 1.5-2.4 GHz Tunable 4-Pole Filter Using Commercial High-Reliability 5-Bit RF MEMS Capacitors,” in *IEEE International Microwave Symposium Digest*, 2013.

[10] J.-S. Hong, *Microstrip Filters for RF/Microwave Applications*. New York: Wiley, 2011.