System-level characterization of bias noise effects on electrostatic RF MEMS tunable filters

Xiaoguang Liu  
*Birck Nanotechnology Center, Purdue University*

Kenle Chen  
*Birck Nanotechnology Center, Purdue University, chen314@purdue.edu*

Linda P.B. Katehi  
*Birck Nanotechnology Center, Purdue University, katehi@purdue.edu*

William J. Chappell  
*Birck Nanotechnology Center, Purdue University, chappell@purdue.edu*

Dimitrios Peroulis  
*Birck Nanotechnology Center, Purdue University, dperouli@purdue.edu*

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ABSTRACT
This paper presents the first system-level characterization of the effects of bias noise on the performance of high-Q electrostatic RF MEMS tunable filters. By looking at the system-level performance of such a tunable filter, this paper shows that bias noise, if not well controlled, can degrade the RF performance of the tunable filter. Quantified by error vector magnitude measurement, such system level degradation due to bias noise is found to be dependent on the frequency and amplitude of the noise signals.

INTRODUCTION
Remarkable progress has been made over the past few years on designing and implementing high-Q widely tunable RF/microwave filters [1-3]. In [1], a 3.0 – 4.7 GHz 2-pole electrostatic MEMS continuously tunable evanescent-mode cavity filter was demonstrated with very low insertion loss (2.38-3.55 dB with 0.7% fractional bandwidth, equivalent $Q_u=470-650$). Fig. 1 shows the operating principle of this type of filter. A robust electrostatic MEMS diaphragm tuner is placed above the capacitive post of the evanescent-mode cavity filter. When a DC voltage is applied on the bias electrode, the electrostatic force pulls the diaphragm tuner away from the capacitive post to change the center frequency of the filter. In this design, a high quality factor is achieved by preserving the natural current path inside the resonant cavities.

In this type of tunable filters, the actuation voltage is limited below the pull-in voltage of the MEMS tuner so that the center frequency can be continuously tuned. Due to the analog tuning nature of such filters, a stable DC bias voltage is required to maintain stable frequency response. However, in applications such as CMOS-integrated RF electronics and system-on-chip, obtaining a clean and stable high-voltage DC supply can be difficult. For example, a common technique to obtain on-chip high voltage supply is to use a charge-pump. Popular on-chip charge pump designs rely on charge transfer in switched capacitor banks (the Dickson type [4]). One consequence of the switched capacitor design is the output voltage ripple occurring at the clock frequency. Several available charge pump designs show that the output voltage ripple can be as high as 1 V with 20 V output (5% ripple) [5-7]. When such a charge pump is used as the voltage driver for the MEMS tunable filter, the output voltage ripple (regarded as a noise to the DC voltage) may have adverse effects on filter performance.

ANALYSIS
Fig. 2 shows a scenario where bias noise causes filter frequency shifts, leading to a distortion of the filter response.
Figure 2. (a) Low frequency noise on the bias line causes vibration of the diaphragm tuner; (b) The center frequency of the filter oscillates as a result of bias noise, leading to distortion of the RF signal.

Assuming the noise frequency is close to the mechanical resonant frequency of the MEMS tuners, we can calculate the displacement of the MEMS tuners in the presence of a low frequency noise. For simplicity, a single tone noise signal is assumed in the following analysis.

\[
\Delta x \equiv \frac{\varepsilon_{0}A}{2kd^{2}} \left\{ V_{DC}^{2} + \frac{V_{n}^{2}}{2} + 2V_{DC}V_{n}\sin(\omega t) - \frac{V_{n}^{2}}{2}\sin(2\omega t) \right\},
\]

where \( A \) is the area of the bias electrode, \( k \) is the spring constant of the diaphragm, \( d \) is the gap between the bias electrode and the diaphragm, and \( \omega \) is the frequency of the noise signal.

This noise-dependent displacement leads to an instantaneous change in the effective RF capacitance

\[
C_{RF} = \frac{\varepsilon_{0}A_{p}}{(g_{0} + \Delta x)^{2}} ,
\]

where \( A_{p} \) is the top area of the capacitive post and \( g \) is the gap between the diaphragm and the post. Due to \( \Delta x \)'s dependence on \( V_{n} \), \( C_{RF} \) is also dependent on \( V_{n} \).

The frequency response of the filter is dependent on the effective capacitance and is derived for a two-pole filter [8],

\[
S_{21} = \frac{1}{A_{1} + 2A_{2}C_{RF} + A_{3}C_{RF}^{2}} ,
\]

where \( A_{1}, A_{2} \) and \( A_{3} \) are constants related to the effective inductances in the tunable filter [8]. Therefore, the frequency response is also dependent on \( V_{n} \), which represents a slow-varying modulation component and is responsible for the unwanted sideband shown in Fig. 2(b).

MEASUREMENT AND DISCUSSION

Fig. 3 shows the block diagram of the measurement setup for system-level characterization of the effects of bias noise. An Agilent 4433B signal generator is used to generate a QPSK modulated signal within the passband of the tunable filter. The generated RF signal is fed through the MEMS tunable filter into a Tektronix real time spectrum analyzer. The input and output of the tunable filter are also connected to a network analyzer through two 20 dB directional couplers to monitor the center frequency of the filter. The output power of the network analyzer is set to 20 dB below the modulated RF signal power. Together with the 40 dB attenuation from the directional couplers, the frequency sweeping RF signal from the network analyzer has a minimal effect on the distortion measurement. The low frequency bias noise is applied through large de-coupling capacitors. In phase noise signals are used on the two bias electrodes in the measurement. This is justified, as in most cases, the bias lines are placed next to each other and will be affected by correlated noises.

Fig. 4 shows an example of the measured constellation diagrams of the received signals. In the presence of bias noise (5 V peak-peak), the received demodulated signal shows a wider spread around the ideal QPSK constellation. It is observed that phase distortion is more significant than amplitude distortion.
Figure 4. Comparison of the received constellation diagrams for a QPSK signal (a) without and (b) with bias noise on the MEMS tunable filters.

The distortion of the received signal is also evident from the measured spectrum shown in Fig. 5. It is observed that the width of the modulated sideband is roughly in proportion to the frequency of the noise signal.

The error vector magnitude (EVM) is calculated to quantify the amount of signal distortion due to bias noise on the MEMS tunable filters. Fig. 6 shows measured EVM of the received signal as a function of the bias noise frequency and amplitude. The measured EVM is found to be relatively independent on the symbol rate (Fig. 6(a)). In Fig. 6 (b), EVM reaches a peak for bias noise frequency of 1.8 kHz, which is very close to the mechanical resonant frequency (fm) of the MEMS diaphragm tuner. EVM decreases as the noise frequency deviates from the mechanical resonant frequency of the MEMS tuners. Fig. 6 (c) shows that EVM increases linearly with the amplitude of the noise. For noise amplitude less than 1 V, the measured EVM is quite low (< 2%) compared to other non-linear RF modules, such as power amplifiers whose EVM can be as high as 15% [9].

Figure 5. Comparison of the measured signal spectrum with and without bias noise. The plot of the spectrum is normalized to the carrier power (-20 dBm).

Figure 6. Measured EVM vs. (a) Signal symbol rate; (b) Noise frequency; (c) Noise amplitude

CONCLUSION
This paper presents a system-level study on the effects of bias noise and reveals that bias noise can cause adverse effects to RF system performance by introducing unwanted amplitude and phase modulations. Such effects are negligible at small noise level but can become significant if the noise amplitude is not well regulated.
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REFERENCES


