Impact of Mechanical Vibration on the Performance of RF MEMS Evanescent-mode Tunable Resonators

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***Abstract*—This paper presents the first experimental investigation on the impact of mechanical vibration on the performance of MEMS evanescent-mode tunable resonators. It is shown both conceptually and experimentally that mechanical vibration can introduce distortions to the RF signal. Signal distortions are found to be very small (< -40 dBc of sideband or $< 0.5\%$ change in EVM) for a diaphragm based MEMS tunable resonator with a diaphragm size of 7×7 mm^2 and mechanical vibration amplitude of 1g. A novel MEMS tunable evanescent-mode resonator based on two arrays of cantilever beams that replace the diaphragm is also presented to achieve even lower distortion in the presence of mechanical vibration. A $15-25$ dB reduction in the vibration-induced sideband is observed.**

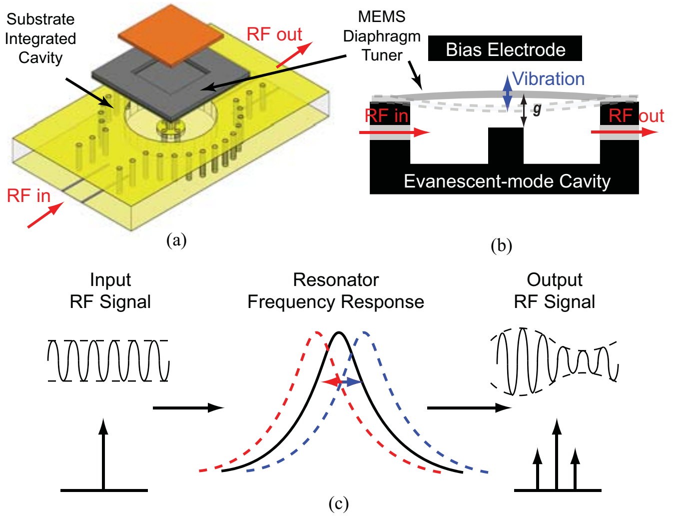
***Index Terms*—RF MEMS, tunable resonator, EVM, vibration**

I. INTRODUCTION

Recently, highly-loaded MEMS tunable evanescent-mode cavity resonators have attracted a lot of research attention as a promising candidate for making widely tunable RF/microwave filters with very high unloaded quality factors (Q_u) [1], [2]. In such resonators, the resonant frequency is very sensitive to this gap between the capacitive post and the top wall of the cavity. Frequency tuning is achieved by changing this gap.

Environmental perturbations, such as electrical noise [3], temperature variation, shock and vibration, may potentially degrade the performance of such highly-tunable resonators when they are deployed in the field. Fig. 1 shows a scenario in which external mechanical perturbation can cause the diaphragm tuner to vibrate, creating an instantaneous change in the RF resonant frequency (Fig. 1(b)). This frequency variation can lead to RF signal distortions by introducing unwanted amplitude and phase modulation of the RF signal that passes through the resonator (Fig. 1(b)) [4].

This paper studies the impact of mechanical vibration on the performance of MEMS tunable evanescent-mode cavity resonators by measuring RF signal distortion. The amplitude of the vibration-induced modulation sideband and the error vector magnitude (EVM) are used to quantify the amount of distortions. In addition, we present a novel vibration-resistant design using fringing-field actuated cantilever beam arrays. Measured results show $15-25$ dB reduction in the modulation sideband with this design.



(a) (b) (c)

Fig. 1. (a) MEMS tunable evanescent-mode resonator [1], [2]; (b) Electromechanical model showing the effect of vibration; (c) signal distortion due to the vibration-induced frequency shift.

II. EXPERIMENTS

A. Experiment Setup

Fig. 2(a) shows the block diagram of the measurement setup. The MEMS tunable resonator is mounted on an electrodynamic shaker platform by a rigid fixture (inset of Fig. 2(b)). The amount of actual vibrations is detected by an Analog Device ADXL001-70 MEMS accelerometer mounted on the same fixture. The direction of sensing is aligned with the direction of the vibration (perpendicular to the shaker platform).

An Agilent 4433B signal generator generates the RF signal, which is fed through the MEMS tunable resonator to a Tektronix real time spectrum analyzer (RTSA). Both continuous wave (CW) and digitally-modulated signals are used in the experiments. In the CW case, the vibration induced sideband modulation products are recorded while in the digital modulation case, EVM is recorded to quantify the amount of distortions due to vibration.

B. Results and Discussion

A strongly-coupled evanescent-mode resonator is used in the tests. The tested resonator has a resonant frequency of 3.44 GHz, insertion loss of 0.75 dB, a loaded quality factor

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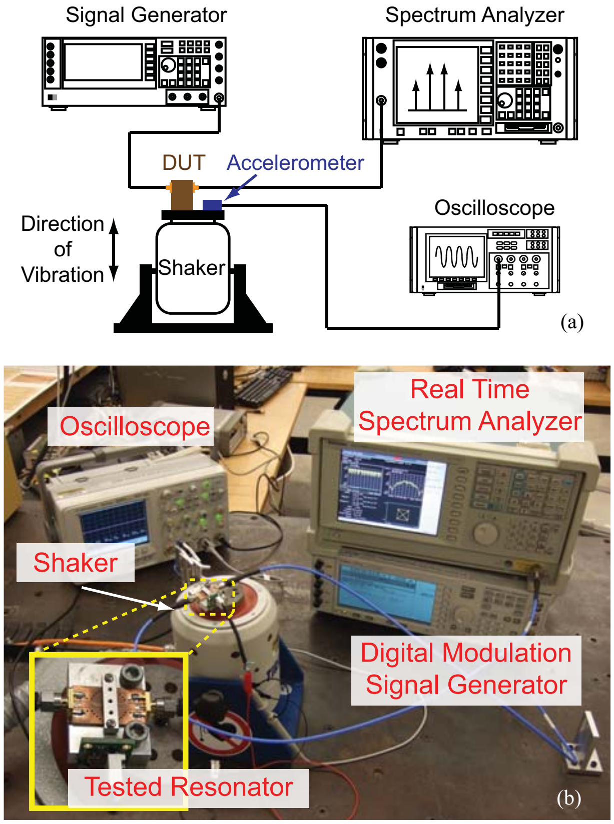

Fig. 2. (a) Block diagram of the measurement setup; (b) Pictures of the measurement setup.

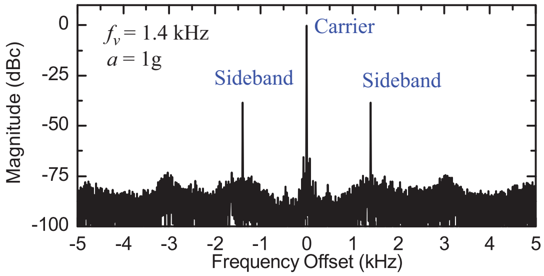

Fig. 3. A typical measured spectrum of the received signal from the MEMS tunable resonator subject to mechanical vibration ($f_v = 1.4$ kHz and $a = 1$g).

of 25 and a mechanical resonant frequency of approximately 1.7 kHz. Since the electromagnetic resonant frequency is most sensitive to g change when the g is the smallest, all tests are performed without applying a DC bias to the tunable resonator.

Fig. 3 shows a typical output spectrum when a CW signal is fed through the resonator in the presence of vibration. The magnitude of the first modulation sideband is recorded for different vibration frequencies (f_v) and amplitudes (Fig. 4). Two peaks in the sideband amplitude are observed in Fig. 4(a). The peak at 1.7 kHz corresponds to the natural mechanical resonant frequency of the MEMS tuner. The peak at 1.4 kHz is attributed to a resonance in the measurement fixture, which is further confirmed in Fig. 8.

Fig. 4(b) shows the relationship between the sideband amplitude and the peak magnitude of acceleration. For common vibration conditions ($f_v < 200$ Hz and $a < 1$g [5]), the sideband amplitude is quite low (< -40 dBc).

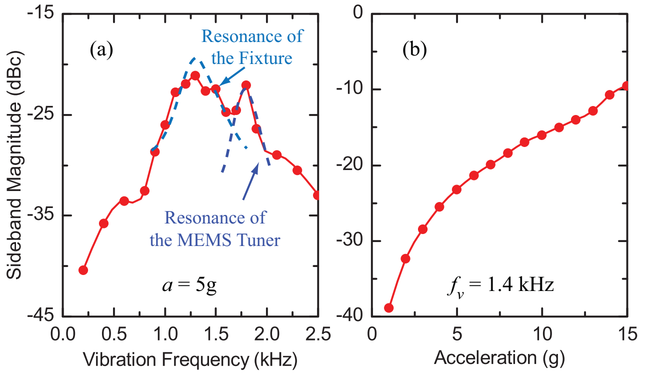

Fig. 4. Measured sideband magnitude for the MEMS resonator subject to different (a) vibration frequencies and (b) amplitudes.

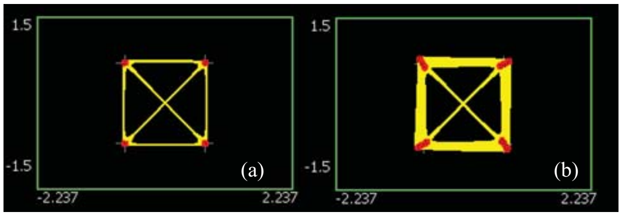

Fig. 5. A comparison of the received constellation diagrams (a) with and (b) without external vibration ($f_v = 1.4$ kHz and $a = 5$g).

Signal distortions can also be characterized by the amount of modulation error introduced by the RF link. For this purpose, a QPSK modulated signal is passed through the tunable resonator and demodulated by the RTSA. Fig. 5 shows a comparison of the received constellation diagram with and without external vibration.

Fig. 6 shows the measured EVM values with different vibration frequencies and amplitudes. The measured EVM values follow a similar trend as that of the sideband magnitude (Fig. 4). Again, very low distortion is observed for common vibration conditions.

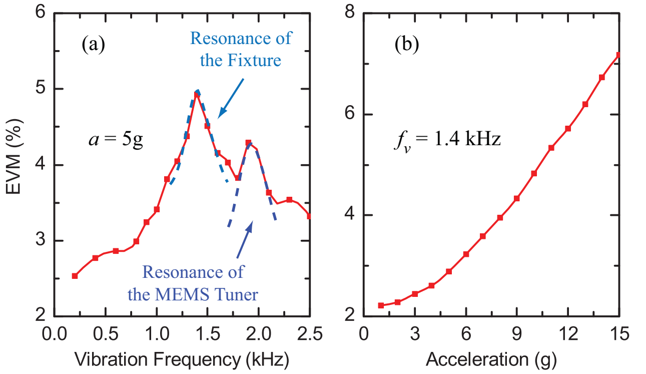

Fig. 6. Measured EVM for different (a) vibration frequencies and (b) amplitudes.

III. MEMS TUNABLE RESONATOR WITH REDUCED VIBRATION SENSITIVITY

To further reduce the susceptibility to external mechanical vibration, we present a novel tunable resonator design using miniature MEMS cantilever beam array. It is well-known that traditional miniature RF MEMS devices are virtually immune

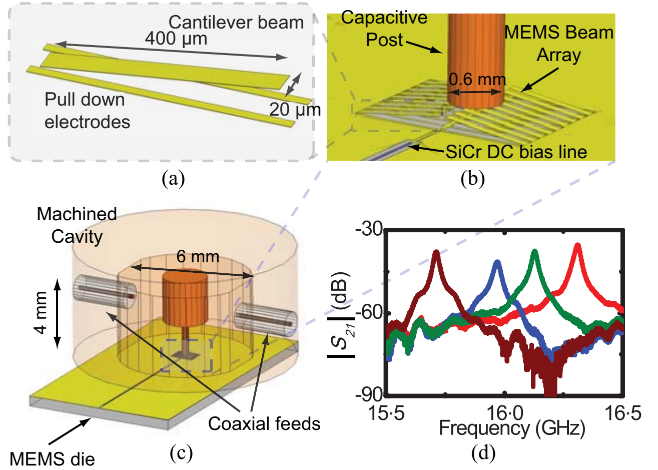

Fig. 7. Novel MEMS tunable evanescent-mode cavity resonator with electrostatic fringing-field beam array. (a) Fringing-field actuated cantilever beam; (b) MEMS beam array; (c) Tunable evanescent-mode cavity design; (d) Measured frequency tuning characteristics for a weakly-coupled tunable resonator.

to vibration due to their extremely small mass and relatively high spring constant (tens of N/m) [6], [7]. However, these MEMS devices usually have very limited deflection, which limits the frequency tuning range in our design.

The authors have previously demonstrated a biasing technique to extend the tuning range of electrostatically actuated MEMS without significantly increasing their size [8]. As illustrated in Fig. 7 (a), the pull-down electrodes are laterally offset from the movable cantilever as opposed to being directly beneath it. This configuration utilizes the electrostatic fringing-field to actuate the cantilever and has been shown to eliminate the "pull-in" effect that limits the deflection range in typical parallel-plate electrostatic designs. The fringing-field actuated cantilever can be designed to linearly deflect the full movable range (up to $60-70$ μm). The mass of these cantilevers is extremely small. For example, a gold cantilever with dimensions of $300 \times 50 \times 2.5$ μm^3 has a mass of 7.3×10^{-10} kg and a spring constant of 1.5 N/m. Under an acceleration of 1g, the tip displacement is no more than 4.7 nm.

Fig. 7(b,c) show the concept design of the fringing-field MEMS tunable evanescent-mode resonator. The array of cantilevers is deflected to change the gap between the post and the cavity; therefore, the resonant frequency is changed. Fig. 7(d) shows a picture of the assembled device. The body of the evanescent-mode cavity is machined from copper, and coaxial connectors are used as feeds. This resonator tunes from $15.7-16.3$ GHz with Q_u of $623-785$. The mechanical resonant frequency of the MEMS beams is estimated to be 7.5 kHz. The initial gap and loaded quality factor are adjusted to be similar to the resonator tested in Section. II.

Due to a limitation in the bandwidth of the RTSA, only CW signal tests were conducted for the fringing-field MEMS tunable resonator. Fig. 8 shows the measured results. The same peak at 1.4 kHz confirms that there is a resonance in the measurement fixture. The small resonance at 500 Hz is believe to be a weaker resonance in the fixture due the difference in the resonator fixture geometry. At vibration frequencies below 200 Hz, the modulation sidebands remain very low (< -50 dB). A $15-25$ dB reduction in the vibration-induced sideband can be observed compared to the diaphragm based tunable resonator (Fig. 4) under the same tested conditions. This reduction is primarily attributed to two factors: a) the smaller mass and, b) the higher mechanical resonant frequency of the cantilever beams.

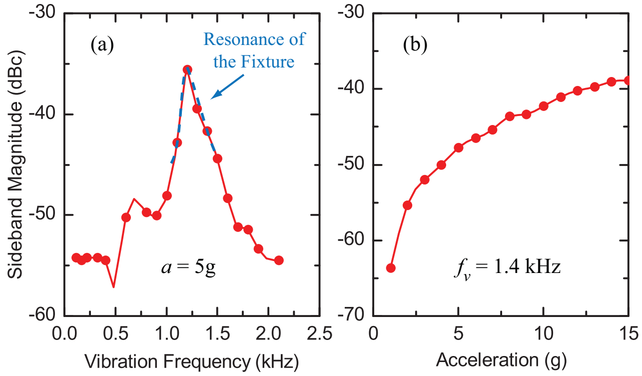

Fig. 8. Measured sideband magnitude for the fringing-field MEMS resonator subject to different (a) vibration frequencies and (b) amplitudes.

IV. CONCLUSION

This paper presents the first experimental investigation of the impact of mechanical vibration on the performance of MEMS evanescent-mode tunable resonators. For the diaphragm based MEMS tunable resonator, signal distortion is found to be very small (< -40 dBc modulation sideband and $< 0.5\%$ EVM increase under common vibration conditions). A novel MEMS tunable evanescent-mode resonator design using electrostatic fringing-field MEMS beams has also been demonstrated to achieve a further reduction of $15-25$ dB in the vibration-induced sideband.

REFERENCES

[1] X. Liu, L. P. B. Katehi, W. J. Chappell, and D. Peroulis, "A 3.4-6.2 GHz Continuously Tunable Electrostatic MEMS Resonator with Quality Factor of 460-530," *2009 IEEE MTT-S International Microwave Symposium*, Boston, MA, USA, Jun. 2009

[2] X. Liu, L. P. B. Katehi, W. J. Chappell and D.'Peroulis, "High-Q continuously tunable electromagnetic cavity resonators and filters using SOI-based RF MEMS actuators", *IEEE/ASMEJournal of Microelectromech. Syst.*, Vol. 19, pp. 774-784, 2010.

[3] K. Chen, X. Liu, A. Kovacs, and D. Peroulis, "Anti-Biased Electrostatic RF MEMS Varactors and Filters," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 58, No. 12, pp. 3971-3981, Dec. 2010

[4] S. Lucyszyn, K. Miyaguchi, H. W. Jiang, I. D. Robertson, G. Fisher, A. Lord and J.-Y. Choi, "Micromachined RF-coupled cantilever inverted-microstrip millimeter-wave filters", *IEEE/ASME Journal of Microelectromechanical Systems*, vol. 17, no. 3, pp. 767-776, Jun. 2008

[5] E. K. Reilly, L. M. Miller, R. Fain, and P. Wright, "A Study Of Ambient Vibrations For Piezoelectric Energy Conversion", *The 10th International Workshop on Micro and Nanotechnology for Power Generation and Energy Conversion Applications, PowerMEMS 2009*, pp. 312-315, Dec. 2009.

[6] G. M. Rebeiz, *RF MEMS, Theory, Design and Technology*, pp. 21-30, New York: J. Wiley & Sons, 2003.

[7] S. Lucyszyn (Editor), *Advanced RF MEMS*, pp. 25, Cambridge University Press, Aug. 2010

[8] J. Small, X. Liu, A. Garg, D. Peroulis,"Electrostatically tunable analog single crystal silicon fringing-field MEMS varactors," *2009 Asia Pacific Microwave Conference*, pp. 575-578, Dec. 2009.