

2009

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# Power Handling Capability of High-Q Evanescent-mode RF MEMS Resonators with Flexible Diaphragm

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**Abstract**—In this paper, we present theoretical and experimental investigations into the power handling capability of high-Q evanescent-mode RF MEMS tunable resonators based on electrostatically-actuated thin diaphragm tuner. The “self-biasing” of the diaphragm tuner from RF signal has been found to cause non-linear effects such as resonant frequency drift, frequency response distortion and instability. A non-linear circuit model has been proposed to predict such non-linearities and provide design guidelines for high power applications. Large signal measurement on a high-Q evanescent-mode resonator with no DC biasing shows good agreement with theoretical predictions.

**Index Terms**—non-linearity, evanescent-mode cavity, MEMS, quality factor, tunable resonator, self-biasing.

## I. INTRODUCTION

There is a growing interest in using evanescent-mode cavity resonators to make highly tunable high-Q RF/microwave filters [1]-[3]. Evanescent-mode tunable filters possess several merits, including high tuning range, high-Q, reduced size/weight and improved spurious free region. Recently an electrostatic MEMS based evanescent-mode tunable resonator has been demonstrated by Liu et al [2]. The operating principle is illustrated in Fig. 1. Resonant frequency of the evanescent-mode cavity resonator is tuned by actuating a single-crystal silicon supported metallic thin diaphragm by electrostatic force. This tunable resonator offers high tuning range ( $\sim 3 : 1$ ), high-Q (650 @ 5 GHz), near zero power consumption and high mechanical stability. Such resonators can be used to make very narrow bandwidth filters that will find applications in automatic instrumentation, wireless communication and sensing systems. These applications have different power handling requirements, ranging from milliwatts to tens of watts. It is therefore critical to investigate the power handling capabilities of the above evanescent-mode tunable resonators and filters.

Several factors limit the power handling ability of RF/microwave filters, including dielectric breakdown, thermal breakdown [4], device non-linearity and of particular importance to RF MEMS, “self-biasing”, which refers to actuation of movable RF MEMS micro-structure by a quasi-electrostatic attractive force from RF signal power [6]. In case of the above mentioned tunable resonator, this RF-induced attractive

force counteracts the DC bias force to pull the diaphragm towards the capacitive post, causing non-linearity effects such as frequency response distortion and intermodulation. Such non-linearities must be modeled accurately for high power applications.

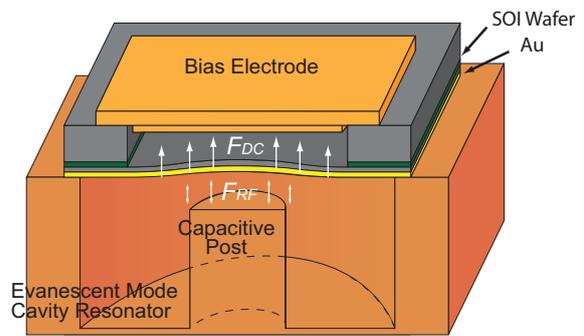


Fig. 1. Electrostatically-actuated evanescent-mode RF MEMS tunable resonator.

This paper studies the “self-biasing” induced non-linearities of evanescent-mode RF MEMS tunable resonator through both theoretical modeling and experimental verification. For simplicity, this study is done with a single resonator. The understanding of the non-linearity of a single resonator will provide insights into future studies of the power handling capability of tunable filters that are built from such resonators.

## II. MODELING

### A. Equivalent Circuit

The evanescent-mode resonator is a distributed implementation of a lumped element resonator [2]. The electric field is predominantly concentrated in the gap region between the capacitive post and the diaphragm, which represents an effective capacitor; the sidewalls of the cavity and the evanescent-mode post constitute a shorted coax line, which is effectively an inductor. Therefore the evanescent-mode resonator can be modeled as an L-C tank shown in Fig. 2 (a), where  $C_r$  and  $L_r$  are the equivalent capacitor and inductor respectively and  $R_u$  accounts for losses in the resonator.

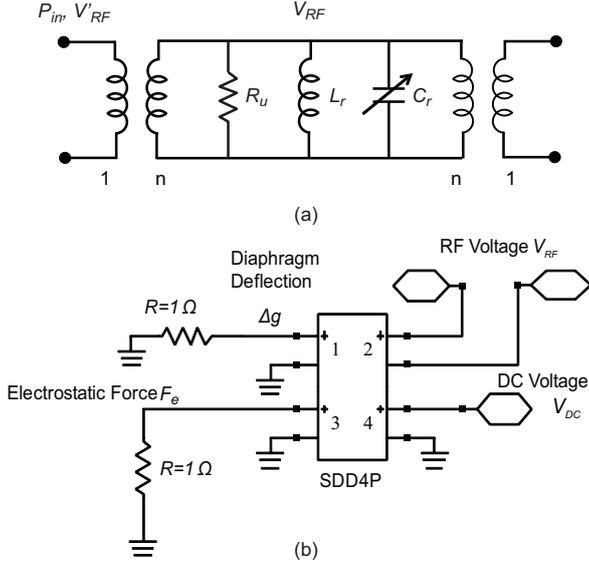


Fig. 2. Non-linear voltage controlled capacitor model using 4-port SDD in ADS [7].

In a narrow band filter, the varactor in Fig. 2 (a) sees higher RF voltage than in a transmission line. In the equivalent circuit of Fig. 2, the input and output coupling to the resonator is modeled by ideal transformers. It can be seen that the RF voltage (peak-peak) inside the resonator ( $V_{RF}$ ) is  $n$  times that of the RF voltage (peak-peak) on the input feed transmission line ( $V'_{RF}$ ),

$$V_{RF} = nV'_{RF} = n\sqrt{2Z_0P_{in}}, \quad (1)$$

where  $n$  is the transformation ratio.  $n$  is directly related to the external quality factor  $Q_{ext}$ , which can be determined from measurement.

$$n = \sqrt{\frac{Q_{ext}}{\omega_0 Z_0 C_r}} \quad (2)$$

### B. Non-linear Varactor Model

The deflection of the diaphragm changes the capacitance of the varactor in Fig. 2 (a), therefore changing the resonant frequency. Using a 1-D spring-mass model (Fig. 3), the deflection of the diaphragm is proportional to the external force  $F_{ext}$ , which consists of an electrostatic actuation force  $F_{DC}$  from the bias electrode and an equivalent force  $F_{RF}$  from RF signal [6].

$$\Delta g = kF_{ext} = k(F_{DC} + F_{RF}), \quad (3)$$

where  $k$  is the spring constant of the diaphragm.

$$F_{DC} = \frac{\epsilon_0 W^2 V_{DC}^2}{2(g_0 - \Delta g)^2}, \quad (4)$$

$$F_{RF} = \frac{\epsilon_0 \pi a^2 V_{RF}^2}{4(d_0 + \Delta g)^2}, \quad (5)$$

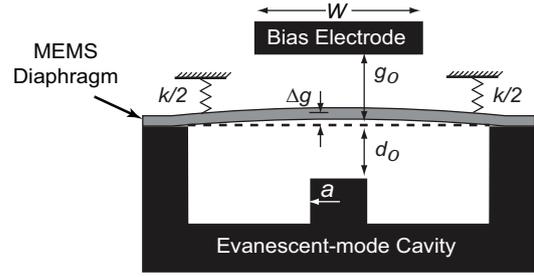


Fig. 3. Spring-mass model for the actuation of the MEMS diaphragm tuner.

where  $W$  is the side length of the bias electrode,  $g_0$  the initial bias gap,  $V_{DC}$  the DC bias voltage,  $a$  the radius of the capacitive post and  $d_0$  the initial capacitive gap.

It is to be noted that (5) can be rearranged as the following

$$F_{RF} = \frac{C_r V_{RF}^2}{d_0 + \Delta g}. \quad (6)$$

It can be seen that, given the same  $C_r$ , evanescent-mode resonators with smaller capacitive gaps are more prone to the attraction from the equivalent force from RF signals.

(3), (4) and (5) are coupled with each other and can be solve numerically by a non-linear solver. Building upon previous work by Lu [5], a non-linear voltage controlled capacitor model (Fig. 2) is constructed in Agilent Advanced Design Systems (ADS) using 4-port Symbolically-Defined Devices (SDD) [7].

The voltage at the four ports of the model are defined as follows:

- 1) Port 1: Diaphragm deflection  $\Delta g$ ;
- 2) Port 2: External force on the diaphragm  $F_{ext}$ ;
- 3) Port 3: RF voltage  $V_{RF}$ ;
- 4) Port 4: DC bias voltage  $V_{DC}$ .

The port current and voltage relationship is defined according to (3), (4) and (5). Therefore both the DC electrostatic bias force as well as the RF induced force can be taken into account.

### C. Resonator Non-linearities

The equivalent circuit with the non-linear varactor model is simulated in ADS to investigate the non-linearities of the tunable evanescent-mode resonator. For simplicity, the resonant frequency is set to 1 GHz ( $C_r = 5.03$  pF,  $L_r = 5.03$  nH and capacitive gap  $d_0 = 10$   $\mu\text{m}$ ). The unloaded quality factor  $Q_u$  is assumed to be 1000 by setting  $R_u = 18849$   $\Omega$ . Transformation ratio  $n = 7$  is assumed, which corresponds to  $Q_{ext} = 130$ . Fig. 4 shows the large signal  $S_{21}$  at different input power levels with no DC biasing.

The simulation shows that for low power ( $< 10$  dBm) input, the resonator remains quite linear. As the input power is increased, non-linearities start to appear. For input power in the range of 15 ~ 20 dBm, self-biasing causes the diaphragm to deflect towards the capacitive post, leading to a drift in the resonant frequency and distortion to the shape of resonance peak. At even higher power ( $\sim 25$  dBm), the RF induced attractive

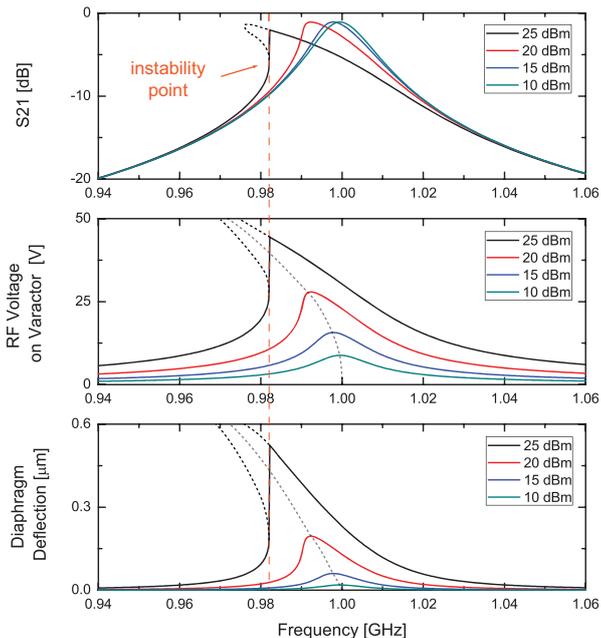


Fig. 4. ADS simulation of large signal responses of an evanescent-mode RF MEMS tunable resonator using non-linear circuit model shown in Fig. 2. (a)  $S_{21}$ ; (b) RF voltage on the varactor; (c) Diaphragm deflection under different input power levels.

force is large enough to pull the diaphragm into the capacitive post. This can be seen in the instability point of the diaphragm deflection plot in Fig. 4, where a sudden jump in the diaphragm deflection is observed. When the diaphragm is pulled into the post, the resonator is shorted and stops functioning. Although the diaphragm will restore to its original position when the RF power is turned off, direct contact between the diaphragm and the capacitive post should be avoided due to reliability considerations. Therefore, the diaphragm deflection instability point sets the higher limit of the power handling capability of the evanescent-mode resonator.

Analysis in Section II-A shows that non-linearities of evanescent-mode resonators are dependent on the strength of external coupling. Fig. 5 shows the simulated large signal response at the onset of instability for resonators with different  $Q_{ext}$  compared with their linear responses. It can be seen that self-biasing is a more severe problem for narrow band systems.

The initial capacitive gap value also plays an important role in the power handling capability of the evanescent-mode resonators. In agreement with the qualitative analysis in Section II-B, Fig. 6 shows the large signal response for resonators with the same input power of 25 dBm but different capacitive gaps. The resonant frequency and  $C_r$  are kept the same for all resonators by setting appropriate post radius values. It is seen that resonators with larger capacitive gaps are less susceptible to self-biasing from RF signal and have larger power handling capabilities.

#### D. DC Bias

Additional notes are in order regarding the DC bias voltage that is used to tune the resonant frequency of the evanescent-

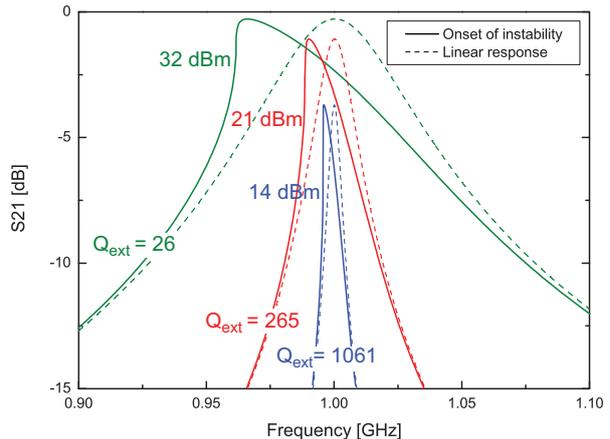


Fig. 5. Large signal simulation of resonators with different external coupling.

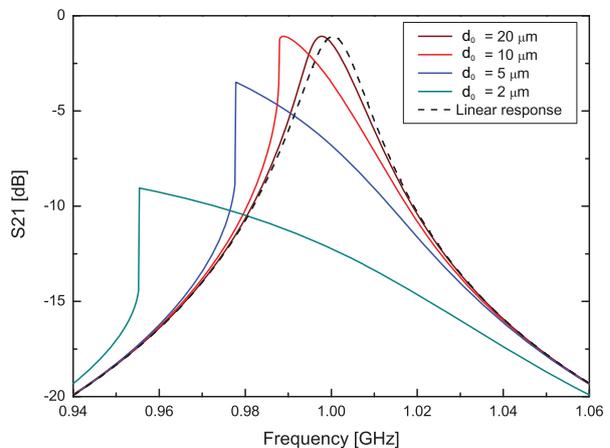


Fig. 6. Large signal simulation of resonators with different capacitive gaps. The resonant frequency and  $C_r$  are kept the same by setting appropriate post radius.

mode resonator. Firstly, the above modeling assumes no DC bias. Since the diaphragm is closest to the post at 0 DC bias, the above modeling and analysis give the worst case power handling capability of evanescent-mode resonators. When DC bias voltage is applied to tune the resonant frequency, the diaphragm is pulled away from the post and the maximum allowable power will be increased. Secondly, the DC bias can be used to compensate for the frequency drift cause by self-biasing. Since the DC electrostatic force is opposite in direction with the RF attractive force, additional DC bias voltage can be applied to pull the diaphragm back when self-biasing happens. This is a benefit of this design with an upper bias electrode.

### III. MEASUREMENT AND DISCUSSION

To validate the non-linear models, an evanescent-mode resonator is fabricated (Fig. 7 (b)) following a similar process outlined in [2]. Low power ( $-10$  dBm) linear S-parameter measurement is first done with an Agilent 8722ET vector network analyzer (VNA) to extract parameters for the equivalent

TABLE I  
EXTRACTED EQUIVALENT CIRCUIT PARAMETERS

Resonant Frequency $f_0$	3.30 GHz
Initial Gap $d_0$	3.02 $\mu\text{m}$
$C_r$	1.86 pF
$L_r$	1.19 nH
$Q_u$	432
$Q_{ext}$	159

circuit model. Table I lists the extracted values.

High power (up to 20 dBm) measurement is then taken to experimentally characterize the non-linearity of the evanescent-mode resonator. The amplifier provides  $43 \pm 2$  dB gain in the 3.2 ~ 3.8 GHz range. The VNA output power is varied between  $-45 \sim -20$  dBm to give an input power in the range of  $0 \sim 25$  dBm.

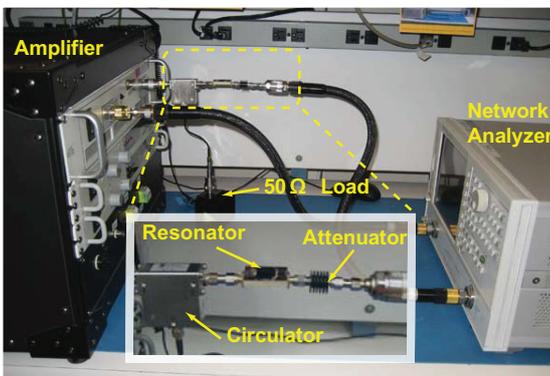


Fig. 7. Measurement setup for large signal measurement on the evanescent-mode resonator. Picture of the actual setup and the tested resonator.

The measured large signal  $S_{21}$  of the tunable resonator is shown in Fig. 8 in comparison with the non-linear equivalent circuit modeling results using extracted parameters from Table I. Good agreement is observed. Diaphragm deflection instability can be observed in the 18.7 dBm near 3.26 GHz where a sudden drop in transmission is observed. This is due to the shorting of the resonator by the self-pullin of the diaphragm. The instability point is well predicted by the non-linear equivalent circuit model. It is to be noted that the major limiting factor in the power handling capability of the tested resonator is the very small capacitive gap ( $\sim 3 \mu\text{m}$ ). ADS simulation shows that the power handling capability can be increased to over 1 W by increasing the capacitive gap.

#### IV. CONCLUSION

Theoretical and experimental investigations of the power handling capability of high-Q evanescent-mode RF MEMS tunable resonator are presented in this paper. It has been shown that “self-biasing” of the MEMS thin diaphragm tuner plays an important role in generating the non-linearities. A non-linear equivalent circuit model is used to predict such non-linearities. Large signal measurement on a high-Q evanescent-mode tunable resonator verifies the accuracy of the circuit model.

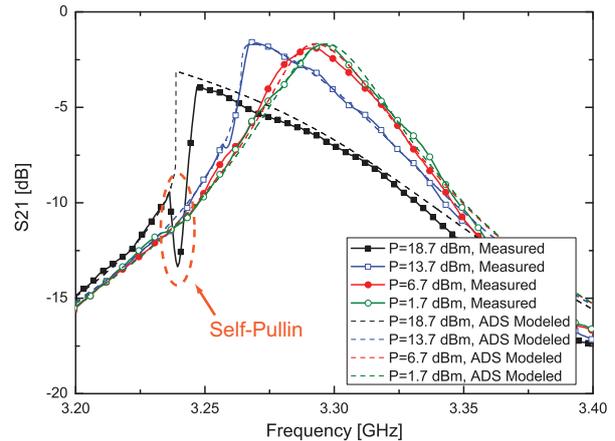


Fig. 8. High power measurement on evanescent-mode resonator in comparison with ADS modeling.

The modeling and analysis presented in this paper provide critical insights in the non-linearities in high-Q evanescent-mode tunable resonators. Further investigation of the power handling capabilities of evanescent-mode RF MEMS tunable bandpass filters are underway and will be presented in future studies.

#### ACKNOWLEDGEMENT

This work has been supported by the Defense Advanced Research Projects Agency under the ASP Program with a subcontract from BAE Systems. The views, opinions, and/or findings contained in this article/presentation are those of the author/presenter and should not be interpreted as representing the official views or policies, either expressed or implied, of the Defense Advanced Research Projects Agency or the Department of Defense.

#### REFERENCES

- [1] H. Joshi, H. H. Sigmarsson, D. Peroulis, and W. J. Chappell, “Highly Loaded Evanescent Cavities for Widely Tunable High-Q Filters”, *2007 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 2133-2136, June 2007.
- [2] 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*, June 2009.
- [3] S. Park, I. Reines, and G. Rebeiz, “High-Q RF MEMS Tunable Evanescent-mode Cavity Filter”, *2009 IEEE MTT-S International Microwave Symposium*, June 2009.
- [4] M. Yu, “Power-handling capability for RF filters”, *Microwave Magazine*, vol. 8, no. 5, pp 88-97, Oct 2007.
- [5] Y. Lu, “RF MEMS Devices and Their Applications in Reconfigurable RF/Microwave Circuits”, *Ph.D Dissertation*, University of Michigan, 2005.
- [6] G.M. Rebeiz, *RF MEMS, Theory, Design and Technology*, New York: J. Wiley & Sons, 2003.
- [7] Agilent Technologies, “Custom Modeling with Symbolically-Defined Devices,” *Advanced Design Systems Documentation*.