Capacitive Monitoring of Electrostatic MEMS Tunable Evanescent-Mode Cavity Resonators

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***Abstract*— This paper presents for the first time a novel concept for monitoring the resonant frequency of electrostatic MEMS tunable high-Q evanescent-mode cavity resonators through capacitance measurement. The proposed scheme relies on the fact that there is a one-to-one correspondence between the actuation capacitance C_s and the resonant frequency f_0. This relationship is derived theoretically using a spring-mass model. The proposed monitoring concept is then validated by static measurement using a capacitance meter. Discussions are given on implementing a dynamic monitoring scheme by using custom-designed integrated high-speed CMOS capacitance sensors.**

***Index Terms*— tunable resonator, feedback control, evanescent-mode resonator.**

I. INTRODUCTION

Recently, high-Q widely tunable RF/microwave filters have been successfully demonstrated with MEMS tunable evanescent-mode resonators [1]–[3]. In [2], a $3.0-4.7$ GHz two-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 $Q_u = 470-650$). Frequency tuning is achieved by electrostatically deflecting the diaphragm tuner (Fig. 1(b)) to change the gap between the diaphragm and the capacitive post, therefore changing the resonant frequency. Due to the high sensitivity of the resonant frequency to the gap, the stability of such filters is of critical concern. Although the electrostatic MEMS evanescent-mode resonators have demonstrated very high stability under constant bias, other factors such as mechanical vibration and temperature variation can also cause shifts in the resonant frequency. It is expected that a dynamic monitoring and control system is needed to improve the stability of such narrow bandwidth tunable filters.

Previous effort in monitoring the frequency response of such resonators/filters relies on s-parameter measurement, which requires very complicated circuits and is not likely to be integrated on the board level [4]. This paper presents a novel monitoring scheme through simple real-time capacitance measurement. Fig. 1 shows a conceptual illustration of the design. The basic working principle is based on the fact that there is a one-to-one correspondence between the resonant frequency and the actuation capacitance C_s. Therefore by measuring the change in capacitance between the bias electrode and the diaphragm, the resonant frequency of the resonator can be inferred. An advantage of the proposed method is that the monitoring circuit does not interfere with the RF signal path and therefore does not require any design changes in the RF circuit. In this paper, we demonstrate the proposed monitoring concept by static measurement using a capacitance meter.

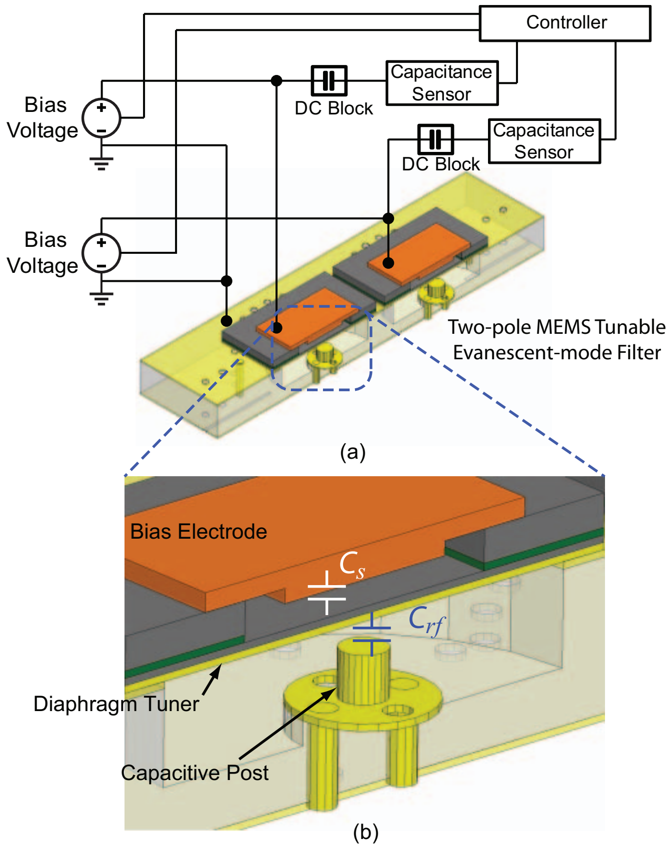

Fig. 1. (a) Concept illustration of tunable filter monitoring through capacitance measurement. (b) The method relies on the one-to-one relationship between C_s and f_0 (which is determined by C_{rf}).

II. WORKING PRINCIPLE

The resonant frequency changes monotonically in response to variation of C_{rf}, which is directly determined by the deflection of the MEMS diaphragm. With bias voltage V, the deflection Δx of the diaphragm is given by [5]

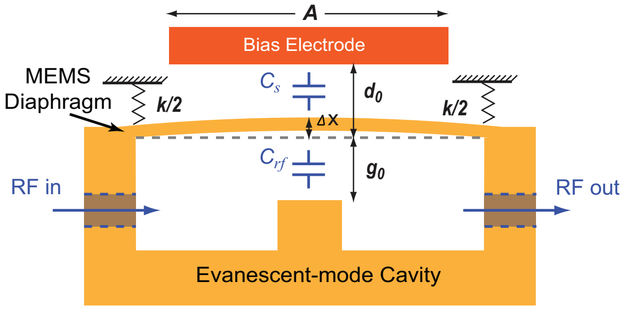

Fig. 2. Spring-mass model of the MEMS tunable evanescent-mode resonator [6].

$$\Delta x = \frac{2}{3}g_0 + \frac{\sqrt[3]{4}g_0^3 k}{3K} + \frac{K}{3\sqrt[3]{4}k}, \tag{1}$$

$$K = \sqrt[3]{-4g_0^3k^3 + 27\epsilon_0 A k^2 V^2 + 3k^2 J},$$

$$J = \sqrt{81\epsilon_0^2 A^2 V^4 - 24\epsilon_0 A V^2},$$

where d_0 is the initial gap between the bias electrode and the diaphragm tuner, g_0 is the initial gap between the diaphragm and the post, k is the spring constant of the diaphragm and A is the area of the bias electrode.

The sensing capacitance C_s and the equivalent RF capacitance C_{rf} can therefore be calculated by

$$C_s = \frac{\epsilon_0 A}{d_0 - \Delta x}, \tag{2}$$

and

$$C_{rf} = \frac{\epsilon_0 \pi r^2}{g_0 + \Delta x}, \tag{3}$$

where r is the radius of the capacitive post.

Equations (2) and (3) reveal the mathematical relationship between C_s and C_{rf}. Fig. 3 shows the calculated C_s and C_{rf} for a typical tunable evanescent-mode cavity resonator. There is clearly a one-to-one relationship between C_s and C_{rf}.

Previous modeling work also shows that the resonant frequency of a highly-loaded evanescent-mode resonator is monotonically dependent on the deflection of the diaphragm and can be approximated as

$$f_0 = \frac{1}{2\pi\sqrt{L_0 C_{rf}}}, \tag{4}$$

where L_0 is the equivalent inductance of the resonator [2].

Plugging (2) and (3) into (4), we can derive the relationship between C_s and f_0

$$f_0 = \frac{1}{2\pi\sqrt{\dfrac{L_0\epsilon_0\pi r^2}{g_0 + d_0 - \dfrac{\epsilon_0 A}{C_s}}}}, \tag{5}$$

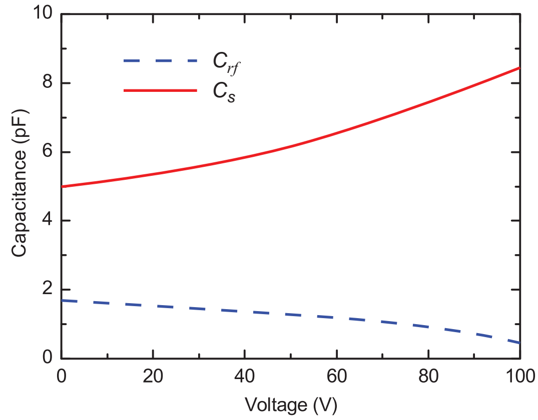

Fig. 3. Calculated C_s and C_{rf} with respect to bias voltage.The calculation assumes the following parameters: initial gap $g_0 = 5$ μm, electrode size 6×6 mm^2, and actuation gap $d_0 = 60$ μm.

Equation (5) lays mathematical foundation for monitoring of the tunable evanescent-mode resonator through capacitance measurement. Fig. 4 shows the calculated relationship between C_s and f_0 for a typical MEMS tunable evanescent-mode resonator.

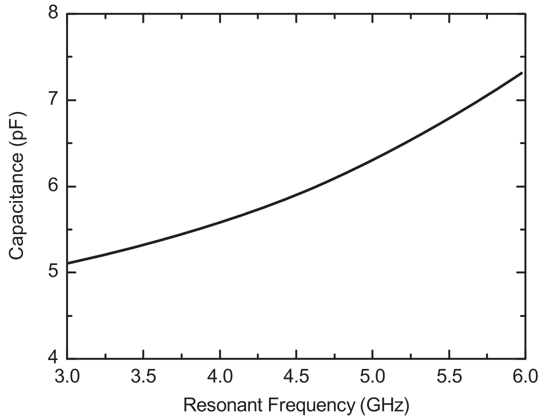

Fig. 4. Calculated C_s with respect to the resonant frequency using the same parameters are assumed in Fig. 3.

III. Experimental Validation

A. Setup

Capacitance versus resonant frequency measurement is performed to validate the above theory. Fig. 5 shows a block diagram of the measurement setup. An Agilent 4278A capacitance meter is used to measure the actuation capacitance C_s. The capacitance meter measures the capacitance with an internal oscillator output of 1 MHz. A large DC blocking capacitor is used to prevent the high bias voltage from damaging the capacitance sensor circuit. The supply voltage and clock signal to the sensor are provided by an external power supply and a function generator.

The resonant frequency is read from the vector network analyzer (VNA). It is to be noted that the VNA is used only

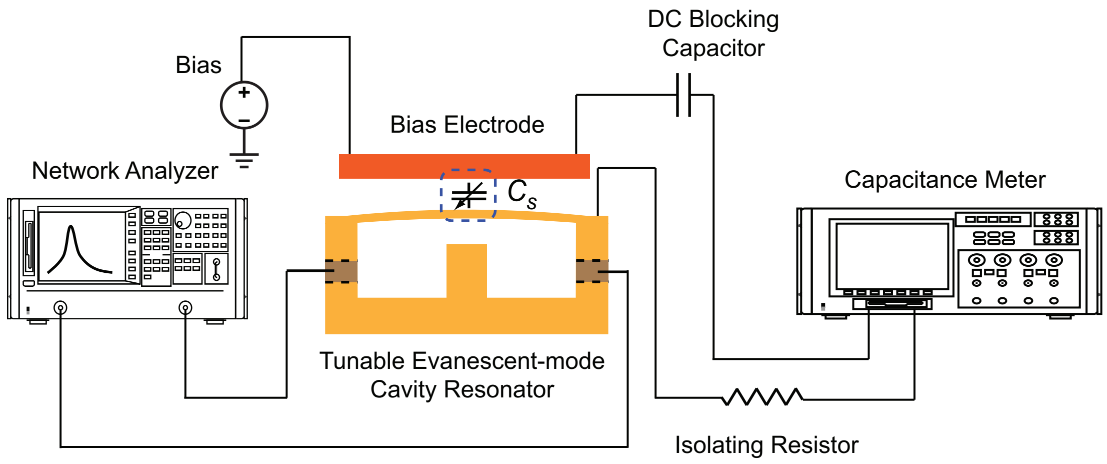

Fig. 5. Block diagram of the measurement setup.

for validation of the theory in this measurement. In actual monitoring, the resonant frequency is calculated from the measured actuation capacitance. Fig. 6 shows pictures of the measurement setup.

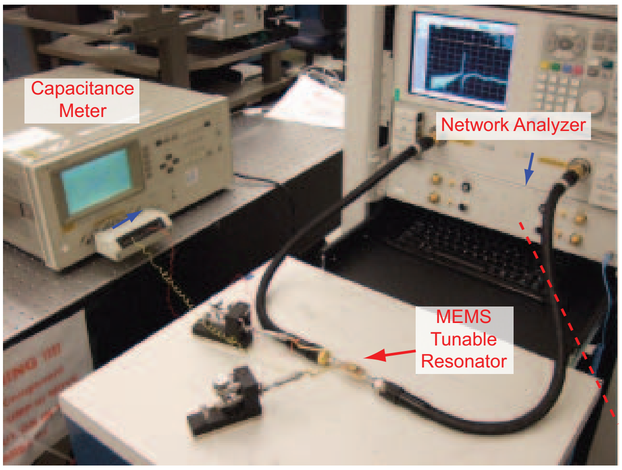

Fig. 6. Picture of the measurement setup.

B. Results and Discussions

A high-Q MEMS tunable evanescent-mode cavity resonator is used in the measurement. The resonator has a tuning range of $4.33 - 5.58$ GHz with an actuation voltage less than 80 V. The critical dimensions of the tested resonator are as follows: $g_0 = 7$ μm, $d_0 = 50$ μm, $k = 485$ N/m, and $A = 5 \times 5$ mm^2.

The capacitance between the bias electrode and the diaphragm tuner is read directly from the capacitance meter. At each frequency point, ten capacitance readings are averaged to generate one data point. Due to the limitation in operating speed and data acquisition speed, the measurement is taken in a "static" manner and no attempt is made to read capacitance dynamically.

Fig. 7 shows the measured actuation capacitance and resonant frequency with respect to the bias voltage. It is shown that the measured C_s tracks the resonant frequency very well.

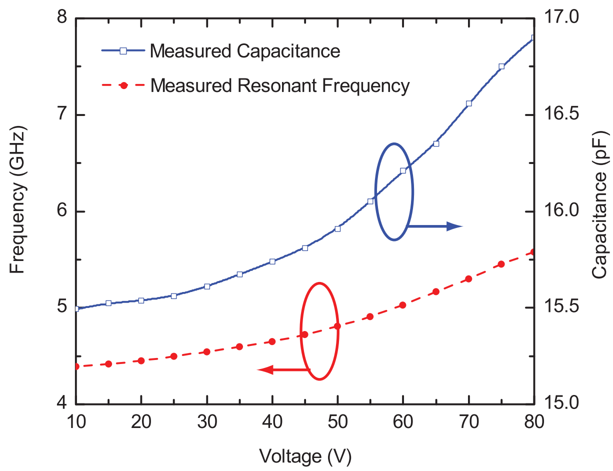

Fig. 7. Measured C_s and resonant frequency with respect to bias voltage.

To implement a dynamic monitoring scheme which can track the resonant frequency of the tunable resonator in real time, a high-speed capacitance sensor is needed. The authors of this paper have previously demonstrated dynamic monitoring of the deflection change of a RF-MEMS switch using a custom-designed high-speed CMOS capacitance sensor [7]. The sensor has a large operating bandwidth (up to 5 MHz), consumes very low power (< 250 μW) and has a small footprint (3×3 mm^2 for the packaged chip). These characteristics make it a great candidate for on-board integration with the MEMS tunable evanescent-mode resonators/filters to achieve real-time high precision monitoring and control.

In order to minimize the influence of the parasitic capacitance and jitter, the sensor needs to be placed as close to the sensing node as possible. Integration of a crystal oscillator and low-noise battery can also dramatically improve the measurement precision and accuracy. The substrate-integrated cavity resonator design is particularly suitable for integration with other circuit components. Fig. 8 shows a proposed design in which the back side (relative to the feedline side) copper laminate is utilized for circuit routing and integration with the capacitance sensor. The wire connection between the sensor and the actuation capacitance is minimized to reduce parasitic and jitter. Dynamic frequency monitoring with improved precision and accuracy is the focus of ongoing development.

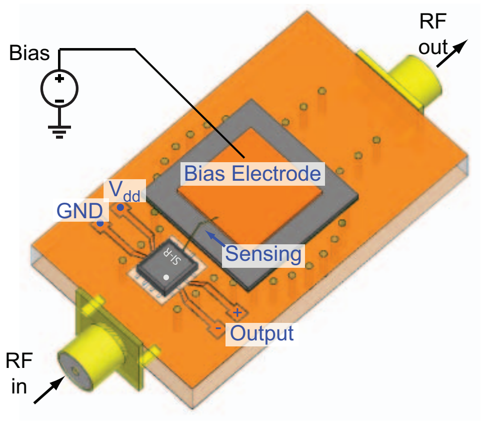

Fig. 8. Concept illustration of a MEMS tunable evanescent-mode cavity resonator with integrated monitoring circuitry.

IV. Conclusion

This paper presents a novel concept for monitoring the frequency response of high-Q MEMS tunable evanescent-mode cavity resonator. The method takes advantage of the one-to-one relationship between the actuation capacitance and the resonant frequency. Static measurement with a capacitance meter validates the concept of the proposed method with good agreement between the modeling and measurement. The monitoring precision, accuracy and speed can be further improved by integrating a custom-designed high-speed capacitance sensor directly on the substrate-integrated evanescent-mode cavity resonator.

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