Non-linear Effects in MEMS Tunable Bandstop Filters

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***Abstract*—This paper provides the first study of electromechanical non-linearities of MEMS tunable bandstop filters. The studied non-linearity sets a limit on the power handling capability of such filters. A two-pole MEMS tunable evanescent-mode (EVA) bandstop filter is fabricated and measured to validate the non-linear circuit modeling. Good agreement is observed between measurement and modeling. The fabricated tunable bandstop filter exhibits more than 2 W power handling capability around 2 GHz. To the authors' best knowledge this is the highest power handling reported for an L-band bandstop filter based on evanescent-mode cavity resonators.**

***Index Terms*—RF-MEMS, tunable filter, evanescent-mode resonator, non-linearity, power handling**

I. INTRODUCTION

Tunable bandstop filters are important components for reconfigurable RF/microwave systems in today's crowded frequency spectrum. Bandstop filters can be used to suppress interferers which could intentionally or unintentionally saturate nearby receivers. Bandstop filters could also be used to reject narrow band signals for wideband systems such as ultra-wideband systems. Making bandstop filters tunable adds to their flexibility by enabling them to suppress dynamic signals at different frequencies.

Several tunable bandstop filter technologies have recently been demonstrated [1]-[5]. In particular, highly-tunable bandstop filters based on tunable evanescent-mode (EVA) cavity resonators have been demonstrated to achieve high tuning range, high isolation ($>$ 90 dB) and dynamically adjustable bandwidth [6].

To assess the potential applications of such filters, it is critical to investigate their power handling capabilities. Previously the authors examined the power handling capabilities of tunable bandpass EVA filters and identified the electromechanical non-linearities of the tuning elements as one limiting factor [7], [8]. This paper builds upon our previous investigation and focuses on the electromechanical non-linearities in tunable bandstop EVA filters.

II. ELECTROMECHANICAL NON-LINEARITY OF THE MEMS DIAPHRAGM TUNER

In a highly-loaded EVA tunable resonator, there is a high electric field between the top wall and the capacitive post (Fig. 1-a). This electric field, although alternating in direction, introduces a net attractive force between the top wall and the post. When the top wall is flexible, as in the case of MEMS tunable resonators, this force will deflect the top wall towards the post, causing non-linear responses that set a limit to the power handling capability of such tunable resonators.

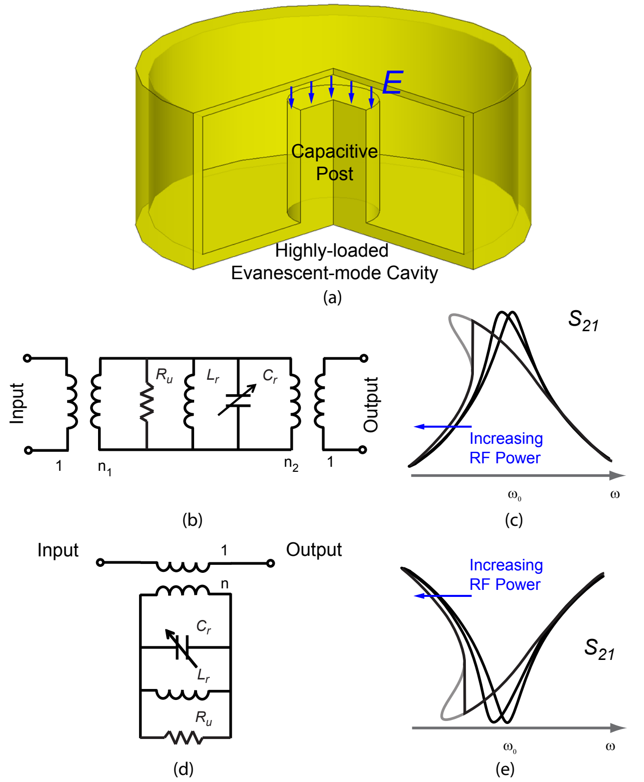

Fig. 1. (a) Capacitively loaded EVA cavity resonator; (b) Equivalent circuit of a bandpass coupled tunable EVA resonator; (c) Non-linear frequency responses of bandpass EVA resonator; (d) Equivalent circuit of a bandstop coupled tunable EVA resonator; (e) Non-linear frequency responses of bandstop EVA resonator.

Previously the authors studied such non-linearities for bandpass resonators/filters [7], [8]. In a bandpass structure, RF signal travels through the resonator (Fig. 1-b) between the input and output coupling structures. The influence of the RF power on the frequency response is conceptually shown in Fig. 1-c. With moderate RF power, the resonant frequency is decreased, and the frequency response becomes asymmetric. With high enough RF power, bifurcation instability occurs and an abrupt discontinuity in the frequency response can be observed. [8] presented a non-linear varactor model of

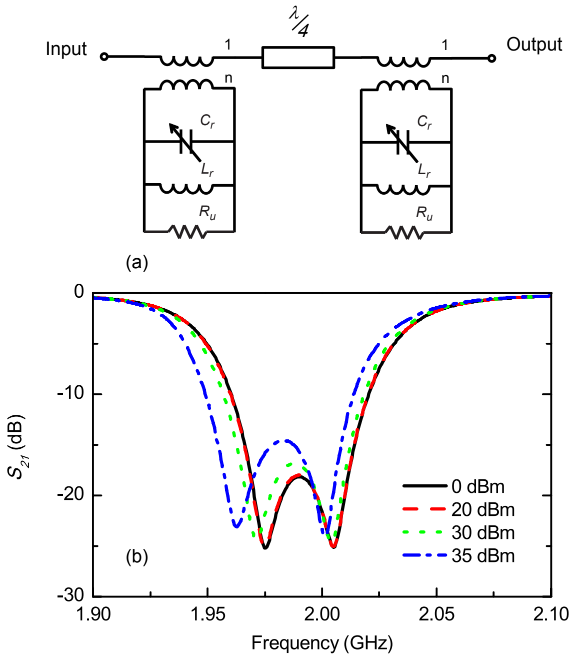

Fig. 2. (a) Circuit model for a two-pole tunable bandstop filter; (b) Simulated large signal response of a two-pole bandstop filter.

such electromechanical non-linearity of tunable bandpass EVA resonators/filters.

Using the above mentioned non-linear model, one can investigate the same electromechanical non-linearity in bandstop structures, such as the bandstop resonator in Fig. 1-d. It is discovered that the frequency response of bandstop structures follows a similar trend as the bandpass structures. At moderate RF power, the frequency response bends towards lower frequencies; at sufficiently high RF power, the same bifurcation instability can be observed.

Fig. 2 shows the simulated non-linear frequency response for a two-pole tunable bandstop filter at 2 GHz (with $C_r = 0.58$ pF, $L_r = 10.95$ nH, $R_u = 47$ kΩ, and $n = 5.7$). These parameters are extracted from simulations and measurements in Section III. Shown in Fig. 2-a, the filter is designed by coupling two tunable EVA resonators, separated by a quarter wavelength, to a transmission line that directly connects the input and output. It is observed that the stopband center frequency decreases from 1.985 GHz to 1.98 GHz as the RF power increases from 0 dBm to 35 dBm. The 10-dB stopband bandwidth increases from 40 MHz to 65 MHz and the mid-band rejection decreases from 18 dB to 15 dB.

III. EXPERIMENTAL VALIDATION

A two-pole MEMS tunable bandstop filter is designed and fabricated to validate the modeling. Fig. 3 shows the bandstop filter structure and pictures of the fabricated filter. The filter consists of two laminated Rogers microwave substrate boards. The top board (RO4350B) contains the feedline and coupling apertures. The bottom board (TMM-3) contains the evanescent-mode resonant cavities. The cavity boundaries are defined by metalized vias as labeled in Fig. 3. Tuning is achieved by integrating electrostatic MEMS diaphragm tuners on top of the evanescent-mode posts. The working principles of the MEMS tuner were discussed in detail in [9].

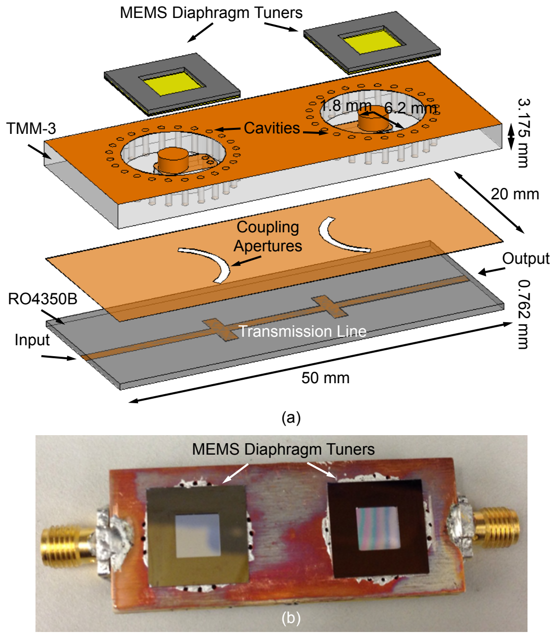

Fig. 3. (a) Structure design of the MEMS tunable bandstop filter; (b) Fabricated tunable bandstop filter.

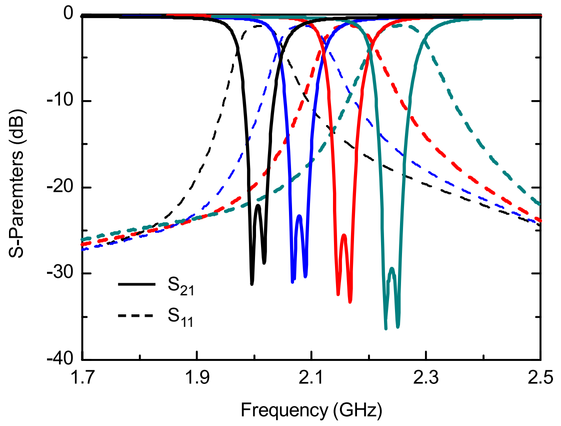

Fig. 4. Measured tuning characteristics of the fabricated filter.

Low power (−10 dBm) linear S-parameter measurement is first done with an Agilent 5227A performance network analyzer (PNA) to extract parameters for the equivalent circuit model. The fabricated tunable bandstop filter covers a frequency range of $2-2.25$ GHz (Fig. 4). The stopband rejection level ranges from 25 dB at 2 GHz to 30 dB at 2.25 GHz with a 10-dB bandwidth of $40 \sim 54$ MHz.

High power (up to 34 dBm) measurement is then taken to experimentally characterize the non-linearities of the fabricated filter. Fig. 5 shows the high power measurement setup. The amplifier provides 43 ± 2 dB gain in the $2 \sim 2.25$ GHz range. The PNA output power is varied between $-45 \sim -9$ dBm to give an input power in the range of $0 \sim 34$ dBm. The PNA is calibrated to the end of the cables. The insertion

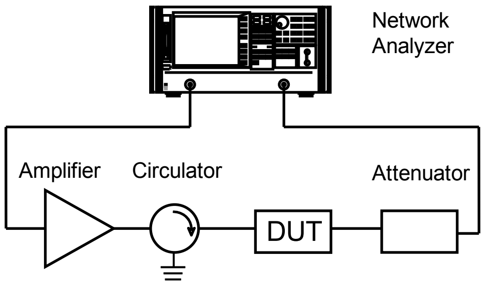

Fig. 5. Measurement setup for large signal measurement of the tunable bandstop evanescent-mode filter.

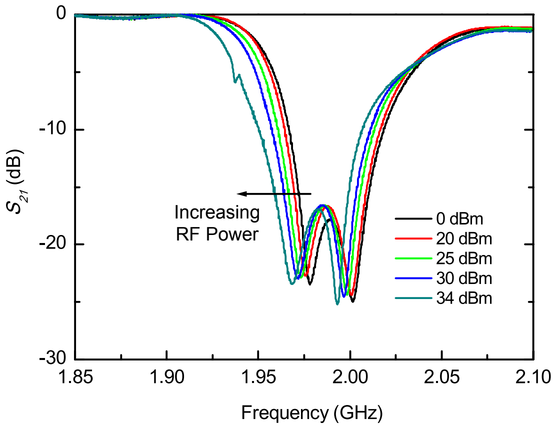

Fig. 6. Measured large-signal response of the fabricated tunable bandstop filter at increasing RF power levels.

losses of the circulator, attenuator and cables are measured separately and subtracted from the measurement to determine the actual power going through the resonator.

Fig. 6 shows the stopband responses of the fabricated tunable bandstop filter with increasing RF power levels. Good agreement is observed with simulation. The frequency response at 34 dBm shows a hint of the instability observed previously in the bandpass filters [8]. It is to be noted that these measurements are taken at the lower end of the tuning range and represent the worst-case power handling capability. When the filter is tuned to higher frequencies, the gap between the diaphragm tuner and the post increases, therefore further increasing the power handling capability.

It is worth noting that under moderate RF power, the resonant frequency shift and frequency response distortion can be compensated by changing the bias voltages on the MEMS tuners. Fig. 7 shows an example. With an input power of 33 dBm, the stopband frequency shifts by 5 MHz and the 10-dB bandwidth changes from 40 MHz to 53 MHz. By applying an additional 1.3 V on the bias electrodes, the frequency response can be pulled back as shown in Fig. 7. The compensated stopband response closely resembles the original response.

IV. CONCLUSION

This paper provides the first investigation of the RF-induced electromechanical non-linearity in MEMS tunable bandstop filters. Such non-linearity is identified as one limiting factor of the power handling capability of MEMS tunable bandstop filters. Circuit modeling accurately captures the non-linear response of such filters under high RF power. The modeling is validated by measurement of a two-pole tunable bandstop filter with 2 W RF power.

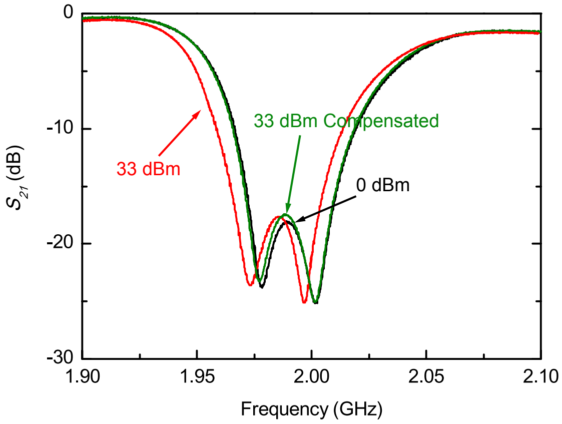

Fig. 7. Measured large-signal response with and without bias compensation.

V. ACKNOWLEDGEMENT

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