Frequency and Bandwidth Control of Switchable Microstrip Bandpass Filters using RF-MEMS Ohmic Switches

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***Abstract* — In this paper a reconfigurable bandpass filter is designed using ohmic-contact cantilever-type Micro Electro Mechanical Systems (MEMS) switches. The filter can switch between two different states with a center frequency tunable range of 13% in C band. The topology allows achieving two accurate center frequencies, each associated with a precisely defined bandwidth, using six MEMS ohmic-switches. The design carefully takes into account the external quality factor for both filter states to ensure a good impedance match at each frequency. The two sets of coupling coefficients and resonator lengths implemented with the MEMS ohmic switches originate the bandwidths and center frequencies required by design specifications. The filter is designed to have center frequencies of 5.5 and 6.2 GHz, with a fractional bandwidth (FBW) of 5 and 3%, respectively. Filter specifications were successfully met with the proposed topology. The filter was fabricated on a quartz substrate and measured responses are in good agreement with simulations.**

I. Introduction

Reconfigurable filters are a key component in compact communication systems, because they allow selecting different operating bands with a single filter by using integrated tuning elements. Another advantage of the reconfigurable filter is to reduce the total volume of the system. A recent trend in reconfigurable filters is to obtain devices that reconfigure their parameters independently: center frequency [1, 2], bandwidth [3, 4], center frequency and bandwidth [5, 6] or selectivity [7, 8]. Designed filters with MEMS switches include monolithically integrated [9, 10] and planar circuits with integrated commercial MEMS switches [11].

The goal of this work is to design a precise frequency and bandwidth controllable filter topology using MEMS switching elements. This paper presents a bandpass filter designed to produce two fractional bandwidth (FBW), 5% for a low frequency state and 3% for a high frequency state with a center frequency tuning range of 13% in C band. The filter was designed using six ohmic-contact cantilever-type MEMS switches that control transmission line extensions to achieve reconfiguration.

The center frequency is controlled by adjusting the length of the resonators. The bandwidth is controlled by adjusting the coupling between resonators. The external quality factor Q_e is selected using MEMS ohmic-switches to maintain a proper input/output coupling for both states of the filter. The filter is able to reconfigure center frequency and bandwidth accurately.

This paper is divided in five sections. Section II contains a discussion of the proposed filter topology, describing how the filter design parameters, center frequency and bandwidth were controlled. Section III discusses the MEMS technology used to implement the filter on a quartz substrate. Section IV discusses simulated and measured responses of the filter. Finally section V gives an overall conclusion of this work.

II. Filter Design

Table I shows the specifications of the two filter states. Each of the states is defined by three parameters: the external quality factor Q_e which relates the input and output coupling of the filter, the coupling coefficient K between the resonators, and the length of the resonator [12]. To find optimum filter layout using the ADS/Momentum simulator, the coupling between feed lines of the filter and the first or last resonator are calculated in order to match the theoretical values of Q_e. Similarly, by simulating the coupling between resonators, the values of K are found using the well-known methods in [12].

TABLE I
Filter Specifications

	Center Frequency	Fractional Bandwidth
Low frequency state	5.5 GHz	5 %
High frequency state	6.2 GHz	3 %

The topology of the filter, shown in Fig. 1, is based on parallel coupled transmission lines [12]. The topology uses six transmission line extensions switched using ohmic-contact cantilever-type MEMS switches, which set up precisely the three design parameters required to produce the two states of the filter specified in Table I.

In this topology all the MEMS ohmic-switches are off to produce the high frequency state, and are on for the low frequency state. Fig. 2 shows the relationship between the external quality factor Q_e and the overlapping distance Y between the input line and a resonator (see Fig. 1). The values were simulated using ADS/Momentum and considering fixed values for the spacing S_1 and the width w of the input line.

TABLE II

FILTER DIMENSIONS (IN MM)

W_1	S_1	S_2	High resistivity lines		Extension A length	Extension B length	Extension C length	Overlapping distance X	Overlapping distance Y	High frequency resonator	
			Mean length	width						length	width
0.11	0.21	0.5	8.5	0.01	0.37	1.1	0.95	2.15	4.94	26.9	0.5

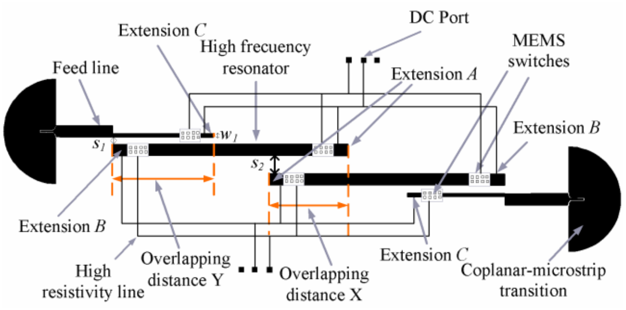

Fig. 1. Switchable bandpass filter topology.

Fig. 2 shows also the relationship between the coupling coefficient K and the overlapping distance X between resonators (see Fig. 1); the values were simulated considering fixed values for the spacing S_2. The length of the resonator extension A (see Fig. 1) is used to accurately determine the K values which define the bandwidth required for each state of the filter.

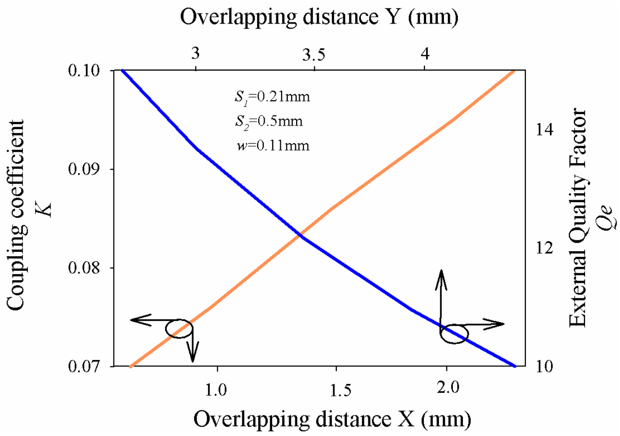

Fig. 2. External quality factor Q_e for different overlapping distances Y, and Coupling coefficient K for different overlapping distances X.

The filter center frequency is determined by the total length of the resonators; however as the bandwidth must take precise values, each resonator is designed to have two extensions. Extension A set the values of K for each state of the filter (see Fig. 1). Extension B defines the total length of the resonator without increasing the coupling between the resonators, which provides independent control of the bandwidth and center frequency of the filter. When both extensions are enabled the response of the filter is set to the low frequency state, while the high frequency state is obtained when the extensions are disabled.

The input and output couplings of the filter are fixed through the extensions B and C, when both extensions are enabled, the input and output coupling of the filter is the optimal for low frequency state, and when the extensions are disabled, the input and output is the optimal for high frequency state.

To define filter layout, each state of the filter was optimized using ADS/ Momentum to produce the required theoretical design parameters Q_e and K for each filter state.

III. MEMS TECHNOLOGY

The fabrication technology for the MEMS reconfigurable bandpass filter is an integrated eight-mask surface micromachining process from FBK [13]. In Fig. 3, a cross section of the ohmic switches used in the design is shown. In this technology, movable bridges/cantilevers are manufactured using a 2-μm-thick electrodeposited gold layer. Another 3-μm-thick gold film is selectively superimposed to increase the rigidity of the central part of the beam and for the patterning of the microstrip lines. A third 150-nm gold layer is evaporated over the underpass metal line to implement a low-resistance metal-to-metal contact. A high performance ohmic-contact series cantilever MEMS switch, with structure and dimensions similar to the one reported in [14] has been used to realize the integrated filter. The cantilever is suspended above an interrupted microstrip signal line and anchored at one end.

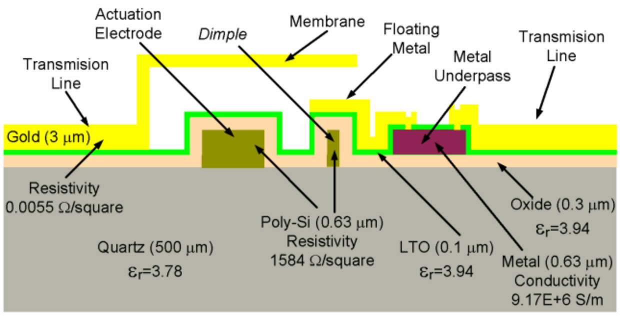

Fig. 3. Diagram of the cantilever MEMS switch on a quartz substrate.

The membrane dimensions are 180 μm (length) and 110 μm (width). In order to generate a good ohmic contact between the cantilever and the line, some dimples have been placed in the contact area of the microstrip line, by using small poly-silicon bumps deposited underneath. The membrane embeds 10 μm x 10 μm holes for the easier removal of the sacrificial layer, increased flexibility and reduced damping. The bias network is made of poly-silicon high resistivity lines to reduce losses.

IV. RESULTS

The fabricated filter is shown in Fig. 4 and Table II contains the filter dimensions. It was realized on a 500 μm thick quartz substrate (ε_r=3.78, tgδ=0.0001). The measurements were taken using a N5242A PNA-X Agilent network analyzer and a probe station. The measured actuation voltage of the MEMS switches is around 50 V. Tables III and IV contain a summary of results. A good agreement in terms of center frequency and bandwidth was obtained for both filter states.

TABLE III
SIMULATED AND MEASURED RESULTS

	Center Frequency		Fractional Bandwidth	
	Low frequency state	High frequency state	Low frequency state	High frequency state
Simulated	5.5 GHz	6.2 GHz	5 %	3 %
Measured	5.48 GHz	6.13 GHz	7.2 %	3.5 %

A comparison between simulated and measured responses of the MEMS switchable bandpass filter is shown in Fig. 5. For the low frequency state the center frequency deviation between simulations and measurements is 20 MHz.

TABLE IV
INSERTION LOSS

	Low Frequency	High frequency
Simulated	2.29 dB	1.47 dB
Measured	8.12 dB	4.5 dB

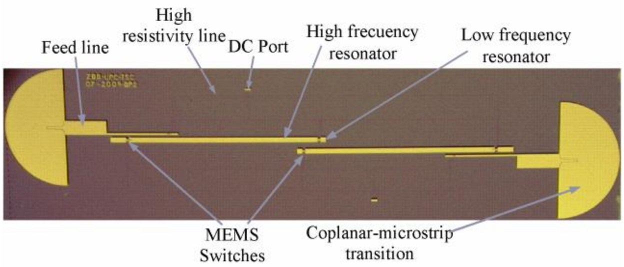

Fig. 4. Photograph of the switchable bandpass filter.

The return loss at the passband of the filter is around 21 dB in simulations, and 15 dB in measurements. The difference between the simulated and measured bandwidth is 2.2 %. Concerning the high frequency state, the center frequency deviation between simulations and measurements is 70 MHz. The difference between the simulated and measured bandwidth is 0.5 %. The return loss at the passband of the filter is found to be at around 24 dB in simulations, and 19 dB for the measurements.

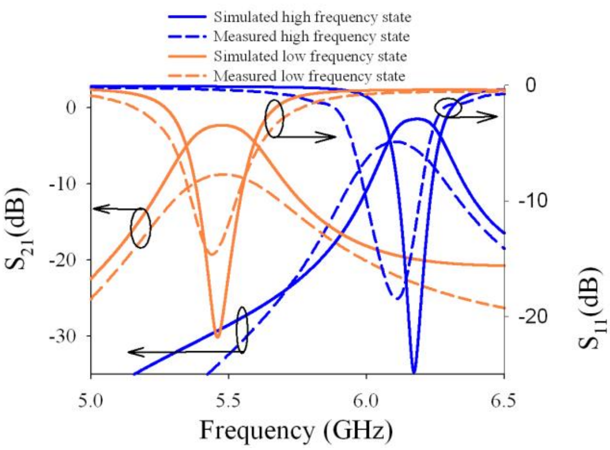

Fig. 5. Simulated and measured results.

The deviations between simulated and measured results are analyzed by simulating the filter with different contact resistances and OFF-state capacitances. Fig. 6 shows the simulated results considering the effect of different MEMS switch contact resistance (r_1=1 Ω, r_2=10 Ω, r_3=20 Ω and r_4=30 Ω) on the filter low frequency response. The simulation includes the high resistivity lines. It is apparent that higher values of contact resistance increase the insertion loss in the ON-state. Simulated contact resistance is *Ron*=32.27Ω.

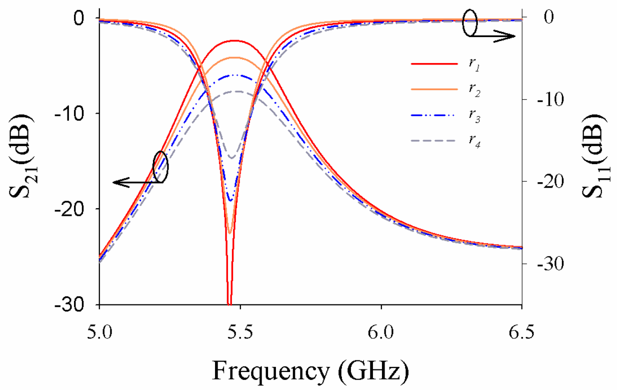

Fig. 6. Simulated results for different series cantilever MEMS switch contact resistance (ON state); r_1=1 Ω, r_2=10 Ω, r_3=20 Ω and r_4=30 Ω.

Fig. 7 shows the simulated results considering the effect of different MEMS switch OFF-state capacitance on the filter high frequency state. The simulation includes the high resistivity lines. The simulations were done using OFF-state capacitances C_1=1fF, C_2=10 fF, C_3=20 fF and C_4=30 fF. It is apparent that the series OFF-state capacitance shifts the center frequency of the filter in the high frequency state. Simulated OFF-state capacitance is *Coff*=23.46fF.

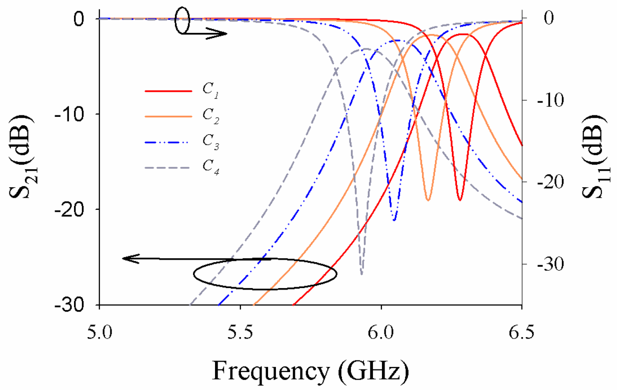

Fig. 7. Simulated results for different series cantilever MEMS switch capacitance (OFF state); C_1=1 fF, C_2=10 fF, C_3=20 fF and C_4=30 fF.

VI. CONCLUSIONS

A bandpass filter switchable between two discrete frequency bands is demonstrated. The filter is designed using ohmic-contact cantilever MEMS switches to switch between two different states with a center frequency tunable range of 13% in C band. Good agreement between simulations and measurements has been obtained for center frequency and bandwidth. Deviations in the measurements with respect to simulations have been analyzed, and were attributed to an increase of the contact resistance and of the OFF-state capacitance of the switch in the fabricated filter.

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