MEMS Switchable Interdigital Coplanar Filter

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***Abstract*—This paper presents a tunable interdigital coplanar filter with tapped-line feedings. Microelectromechanical systems capacitors are used as a high contrast capacitive switch between a quarter-wavelength resonator and an open-ended stub to perform the frequency shift. A two-pole tunable filter with a 13% relative bandwidth has been designed, fabricated, and measured. The center frequency can be switched from 18.5 to 21.05 GHz with low return losses (less than 15 dB) and low insertion losses (3.5 dB).**

***Index Terms*—Filters, microelectromechanical systems (MEMS).**

I. Introduction

THE recurring demand for ever more flexible and sophisticated, compact, and low-power wireless systems has generated the need for technological solutions that can dramatically reduce manufacturing cost, size, weight, improve performance, and battery life [1]. Tunable systems are, therefore, receiving an increasing attention since this is an elegant way to meet a great part of these requirements. For instance, tunable systems avoid the repetition of front-end radio structures for multistandard applications, or they can add flexibility to present analog front-ends in a wide range of applications.

In existing systems, tuning is obtained using lumped components such as MESFETs, varactors, or p-i-n diodes in conjunction with passive components [2], [3]. Filters are among the components that did receive much attention since they are very sensitive to loss. Semiconductor-based tunable filters have important insertion-loss level, low isolation, electrical power consumption, and overall degraded performances compared with fixed frequency filters. Moreover, loss compensation circuits usually add noise to the filter and can cause instability of the component.

Recent developments in microelectromechanical systems (MEMS) have made possible the design of tunable filters and are expected to bring a new interest to these components[4]–[7]. Indeed, MEMS offer low losses, near-zero power consumption, and they can be monolithically integrated with conventional microwave integrated circuit (MIC) passive fabrication techniques.

This paper presents an original tunable interdigital coplanar waveguide (CPW) filter with tapped feed line input/output. Tuning is achieved using surface micromachined cantilever variable capacitors with electrostatic actuation, which will be described below.

The CPW filter design and structure will be presented next, as well as specific aspects of MEMS microwave simulation. Finally, measured performances will be presented and discussed.

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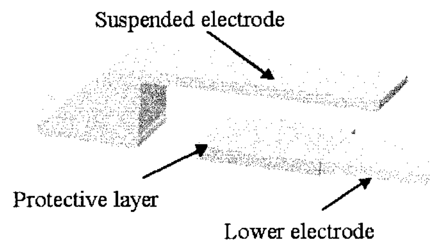

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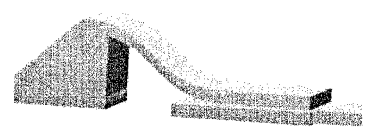


(b)

Fig. 1. Drawing of a MEMS capacitive cantilever switch. (a) In the off state. (b) In the on state.

II. MEMS Design and Fabrication

A. MEMS Description

A MEMS series capacitive cantilever-type switch is shown in Fig. 1.

This component presents a movable metallic membrane suspended above a lower electrode, forming a capacitor between these two conductors. In the up state the capacitance $C\text{off}$ is small, since air is separating the two electrodes [see Fig. 1(a)]. The varactor value is controlled by the distance between the two electrodes. By applying a dc-bias voltage, the upper membrane is deflected by the electrostatic force down to the opposite electrode: the gap is reduced and the capacitance is increased. If the applied voltage becomes higher than the cantilever pull-in voltage, the suspended membrane snaps down to the lower electrode [see Fig. 1(b)]. The resulting capacitance increases sharply, its value ($C\text{on}$) depends on surface roughness of the upper membrane and the dielectric constant of the insulating layer.

There are two ways to use these cantilevers as variable capacitors: either the capacitance is changed using the "stable" region (before pull-in) or the cantilever is used as a switch, with high

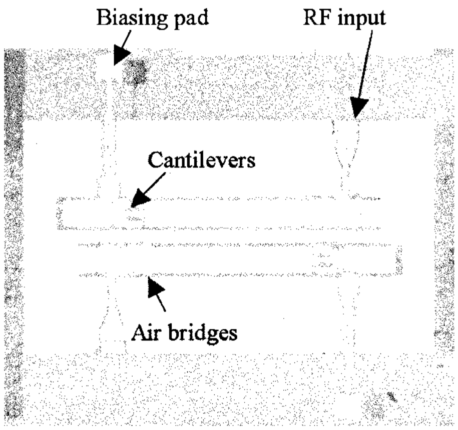


Fig. 2. Microphotograph of the fabricated filter.

ratio between the up and down states. We did use this approach in this study since it presents several advantages. Indeed, the capacitance can be switched between two well-defined values, it is insensitive to vibration or noise, and the tuning range is only limited by the on-to-off capacitance ratio of the MEMS cantilever. Such MEMS variable capacitors can be decoupled by an appropriate fixed-series capacitor (or open-ended line section) that will allow to control capacitance variation and to minimize its impact on loss [8]. Since MEMS have large on-to-off ratios, a decoupled MEMS varactor can still achieve relatively large frequency variations with low losses. At last, digital-like implementations have been demonstrated [6] and allow fine-tuning performance.

B. Fabrication

MEMS fabrication starts with the deposition of a 300-A/9000-A Ti/Au evaporated layer, on a 1-mm-thick fused silica substrate. An evaporated layer is chosen since it offers a very smooth surface that improves the capacitive contact quality. This Ti/Au layer is patterned and an SiCr resistive layer is evaporated and patterned.

This layer will be used for the integration of biasing resistors. Next, a 1500-A-thick alumina layer is deposited using a pulsed laser deposition system and lifted off. Using the appropriate deposition parameters, very smooth dielectric layers can be obtained at room temperature with this technique. This insulating layer prevents direct contact between the first and second metal layers (Fig. 1) and can also be used as an insulating layer in metal–insulator–metal (MIM) capacitors.

Next, a 2.8-μm-thick sacrificial layer is spun and patterned onto the wafer. A second layer of 50-A/1000-A Ti/Au layer is evaporated and gold is electroplated up to 3 μm.

After this last metal layer has been patterned, the sacrificial layer is removed and the component is released, using a CO2 critical point drying system. A microphotograph of the fabricated filter is shown Fig. 2.

In this process, the typical ratio between the capacitance in the up state and the down state is around 20, the capacitance increases from 40 fF to approximately 800 fF for a cantilever capacitor, as used below. Typically measured pull-down voltages are between 60 and 70 V because of the initial height and short length of the cantilevers (Fig. 3).

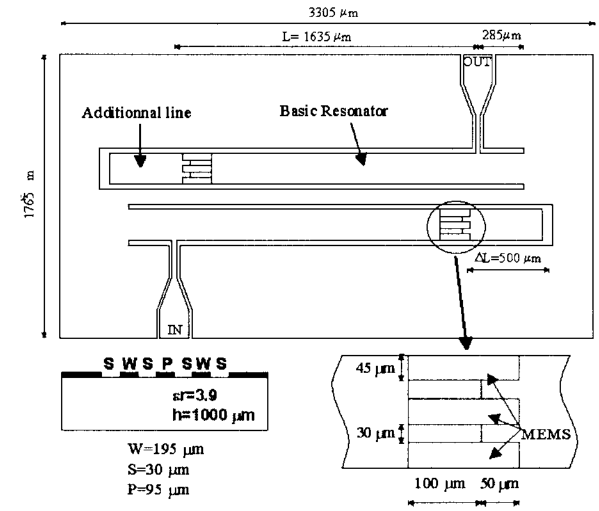


Fig. 3. Interdigital coplanar second-order filter. Connection between the two lines is performed with three MEMS cantilevers. The required mode filter bridges are not shown in this figure.

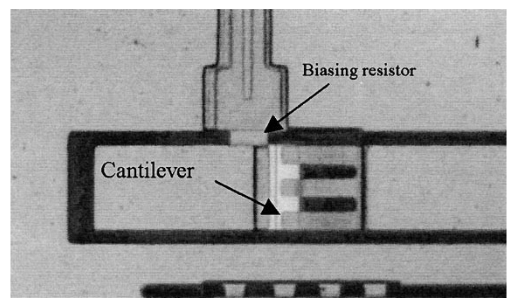


Fig. 4. Close-up view of the MEMS area.

III. Tunable Filter Design and Structure

Generally, the response of a passive filter is optimal at a given frequency. However, tuning the center frequency implies a variation of one or more of the filter component parameters (such as electrical lengths) that can affect electrical characteristics (matching, insertion losses, bandwidth, etc.). To limit the effects of tuning on filter performances, its structure has to be carefully selected.

Interdigital filter structures exhibit a good tolerance concerning center frequency variations [9]. A CPW implementation is shown Figs. 2 and 3. This two-pole filter is made of two quarter-wavelength CPW resonators, terminated by MEMS cantilevers. These cantilevers are used as variable series capacitors between the resonator and the additional open-ended short transmission-line section.

When the cantilevers are moved down, the center frequency shifts since the capacitive part of the resonators is changed. The cantilevers are actuated by applying a voltage between the additional line section and the resonators. A high-value SiCr resistor is used to decouple RF from the biasing network. This network passes under the CPW ground plane to minimize the perturbation on the circuit. (Fig. 4)

It can be seen in Fig. 2 that air bridges have been added to this structure since the tapped feed-line excitation scheme makes the structure highly nonsymmetrical. Electromagnetic simulations have shown that currents are very high on these bridges and

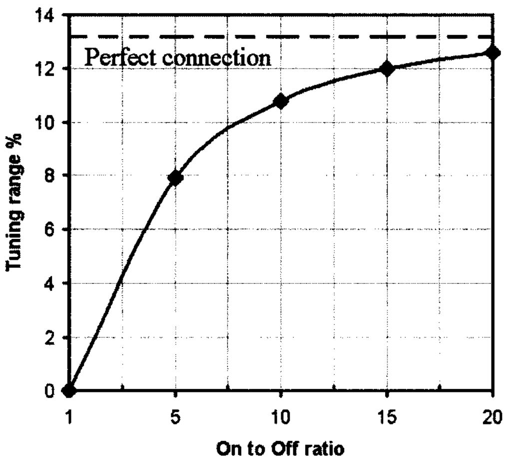


Fig. 5. Computed frequency variation versus on-to-off ratios of the MEMS varactors for the geometry Fig. 3. The performance of a perfect series connection is shown via the dashed line.

that their number have a significant impact on losses and center frequency.

The two-pole filter was designed using Agilent Momentum in the strip simulation mode. Our objective was to be as close as possible to a Chebyshev filter with 0.1-dB ripple for both states. Therefore, the filter has been first optimized for an IF of 20 GHz with 10% fractional bandwidth to minimize variation and mismatch between the two center frequencies resulting from changes in the capacitance values. The resonator length is $L = 1635$ μm and the additional coplanar line section length is $\Delta L = 500$ μm.

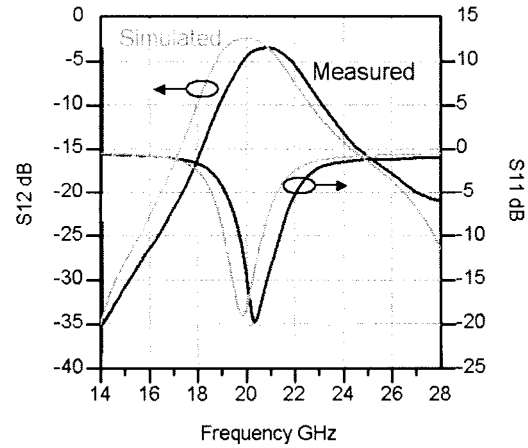
Each resonator is ended by three MEMS cantilevers, 150-μm long, suspended 50 μm over the extra resonator section. We use three cantilevers in parallel for two reasons. First, this type of fork-like design eases the release process of the structures. The second reason is that, in this design, only the tip of the cantilever is used as a capacitor, that is to say, each cantilever has a small capacitance value. In the end, the three fingers in parallel forms a capacitor with a low series resistance regarding the capacitance and reduce loss in the circuit.

MEMS were taken into account in the full-wave simulations using vias and strip metallization. The on and off states were simulated using two different heights in the substrate definition so that both air bridges and cantilevers can be taken into account. In order to check the influence of on-to-off capacitance ratio on the filter tuning performances, we did simulate the frequency shift versus on-to-off ratios using Momentum. The results are reported in Fig. 5. It can be seen that an on-to-off ratio higher than 20 approaches the frequency shift obtained by direct connection between the resonator and line sections (in that case, 13.2%).

IV. Measurements

Measurements were done using an HP 8510C network analyzer and a cascade probe station. Calibration was done using a short-open-line-thru (SOLT) procedure.

Simulated and measured S-parameters are presented in Fig. 6. Good agreement is shown between simulated and measured data. In the simulations, the metallic losses are taken into account assuming gold conductivity of $3.9^E 7$ S $\cdot$ m-1, but radiation losses also have a significant contribution. Therefore, measured data exhibit higher losses than simulation. Still, the level of losses is low and out-of-band rejection is relatively large. Also, there is a frequency shift between simulations and measurements and this is due to the difficulty to estimate properly the influence of air bridges at the input of the structure since their shape is not perfectly flat, as it is assumed in the simulations.



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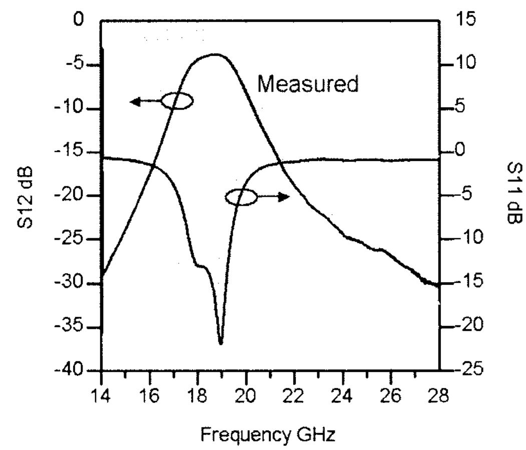

(b)

Fig. 6. Simulated and measured responses of the tunable filter. (a) Switches up. (b) Switches down.

In the up state [see Fig. 6(a)], the measured center frequency is 21.05 GHz. The 3-dB fractional bandwidth is around 14%, which is equivalent to an absolute bandwidth of 2.9 GHz, and measured insertion losses are 3.5 dB. Return losses are better than 15 dB.

When the switches are down, the center frequency is shifted down to 18.5 GHz [see Fig. 6(b)]. The 3-dB fractional bandwidth is increased to 13%, which is equivalent to an absolute bandwidth of 2.4 GHz. Measured insertion losses are 3.8 dB, while return losses are approximately 12 dB. This small increase in insertion-loss level can be explained by this change in return loss.

The measured tuning range is 2.55 GHz, at a center frequency of 19.77 GHz, which is equivalent to 12.8% relative frequency shift. This frequency shift corresponds to an on-to-off ratio of approximately 20, which is in good agreement with the plot shown in Fig. 5. and typical on-to-off variations obtained on this process.

The simulations were done using this ratio, and it can be seen that the frequency shift is also well predicted.

V. Conclusions

A second-order millimeter-wave tunable bandpass filter has been designed, fabricated, and measured. MEMS elements are monolithically implemented on the filter resonators and they are used as on–off switches between each resonator and an additional line. This filter has demonstrated that low-insertion losses, good rejection, and large tuning range can be achieved using MEMS fabrication techniques. This kind of component will be useful for the integration of multiband low-noise and low-power receivers.

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