Design and manufacturing of X-Band tunable micro-cavity resonator in MEMS technology

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***Abstract* — This paper presents the design modeling and hardwire prototypes fabrication of a X-band tunable cavity resonator based on MEMS technology. Brass metallic cavities with inner post have been thermo-compressive bonded on a silicon substrates having 4 MEMS varactors based on toggle mechanism. The tunable resonator was simulated in ANSYS® HFSS full wave environment, resulting in a continuous tuning range of 22% with an unloaded quality factor (Q) in the range of 80-180 and a very small volume of 3.2x3.2x1.4 mm^3. Preliminary experimental results are presented. The measurements on "hardwired prototypes" result in a maximum unloaded quality factor (Q) of 80 and tuning range of 14%, centered at the frequency of about 9GHz. The main responsible of the lower measured quality factor, respect to the simulated one, was found to be the additional losses in the silicon substrate.**

I. Introduction

MEMS technology has already demonstrated its successful employment for the design and realization of high-Q components and high-reconfigurable circuits [1]. LC tank resonators are key components in many electronic circuits as Voltage Controlled Oscillators (VCO), where they are employed as narrowband selective network. LC tank resonators can be realized by combining a MEMS capacitors (varactors or switches) and a planar [2] or micro-machined inductor [3], or fixed MIM capacitor with switched inductance [4]. The micro-machined inductor quality factor is the bottle-neck of the overall quality factor of the LC tank [5]. For application higher than 10 GHz, the inductive transmission line [6] or cavity resonators [7] are preferable for high Q-factor.

In order to keep a high Q factor, the integration of RF-MEMS varactors with micro-cavity resonators appears to be an attractive solution to achieve wide band, low loss and continuous tuning. Recently, micro-cavity resonators integrated with MEMS systems have demonstrated very high performance [8]. A capacitive post-loaded evanescent mode resonator offers the potential for high tunability.

In this paper, a MEMS tunable micro-cavity resonator is presented. It is based on a metallic evanescent mode cavity loaded with a fix inner post and 4 tunable MEMS varactors. The resonator has very compact geometry (3.2x3.2x1.4mm^3) and has coplanar accesses.

The integration of a metallic micro-cavity onto a planar substrate and fabrication improvements for increasing the bonding pressure of the cavity onto the silicon wafer, are also presented.

II. Design

Fig.1 illustrates the tunable LC resonator, which is made by assembling a brass cavity on a 450µm thick HR Silicon substrate, where 4 MEMS varactors are built. The brass cavity is thermo-compressive bonded at 200°C onto the planar substrate (Fig. 1b). The square metallic post has been machined at the center of the cavity and is bonded on a round metallic pad, providing a fixed capacitance (C_0) between the post and the coplanar ground shield (Fig. 1c). The 4 MEMS varactors are radially located at the same distance from the center of the metallic post and can be modeled as a tunable capacitance (C_{v_MEMS}) in shunt configuration with respect to the fixed capacitance C_0 (Fig. 1c).

The metal cavity has access holes for the feeding CPW lines. The input and output coplanar waveguide lines are electrically coupled (C_{acc}) to the E-field where it is maximum. The cavity dimensions are 3.2x3.2x1.4 mm^3.

A. FEM modeling

The device has been modeled in ANSYS® HFSS environment. The resonance frequency of the proposed tunable cavity can be approximated by:

$$F_{res} \approx \frac{1}{2\pi\sqrt{L_0\left(C_0 + C_{v\_MEMS}\right)}} \tag{1}$$

where, L_0 mainly accounts for inductive contribution of the feeding CPW lines and C_{v_MEMS} and C_0 and are the capacitances of the MEMS varactors and of the metallic central post. The latter indeed provides a fixed capacitive load (C_0) to the cavity, down-shifting its resonance frequency and consequently allowing for a reduced cavity dimensions with respect to the unloaded cavities. The four MEMS varactor ensure the continuous tuning of the LC resonator since every MEMS varactor allows for a continuous capacitance tuning ratio of 2.5 in the range 35fF and 90fF.

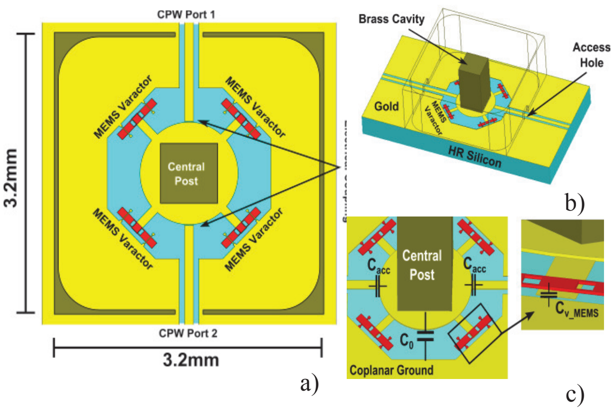


Fig. 1. Cavity resonator: a) Top view; b) 3D-model; c) Zoom of MEMS toggle varicap.

Simulated resonance frequency (F_{res}) as a function of the post height and size is reported in Fig. 2a and Fig. 2b for the two limit cases: when all the MEMS switches are in up-state or in down state.

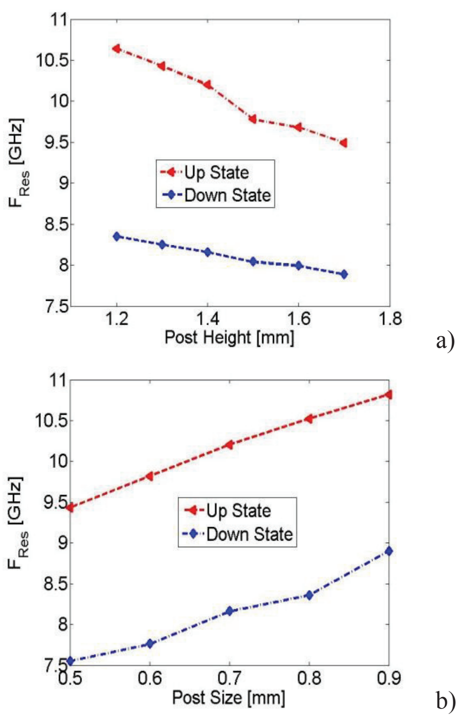


Fig. 2. Simulated resonance frequency as function of a) Post height and b) Post size.

The simulated transmission parameter as a function of the position of the MEMS varactors is presented in Fig. 3a, showing an overall tuning range of about 22%, from 8GHz to 10.2GHz. The equivalent circuit in Fig. 3b, was used to fit the simulation results reported in Table I. The losses, due to the dissipative contributions, were modeled as R_0.

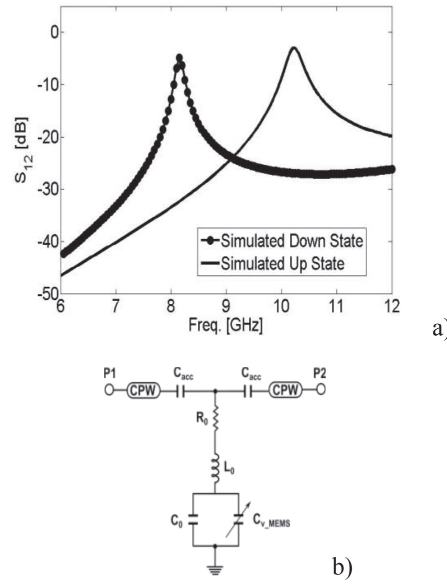


Fig. 3. a) Simulation results: transmission parameter as function of the varactor tuning; b) equivalent RLC circuit.

The theoretical quality factor (Q) was calculated by using the -3dB technique [9], resulting in a value of about 180 and 80 in up-state and down-state, respectively.

TABLE I
Simulated parameters for LC cavity resonator

RLC	*Up-State*	*Down-State*
R_0 [Ω]	*5.8*	8
L_0 [nH]	*24*	24
C_0 [pF]	*2.2*	2.2
C_{v_MEMS} [fF]	*65*	260
Q	*180*	80
F_{Res} [GHz]	*10.2*	8
Tuning Range	22%	

III. Fabrication of Hardwired Prototype

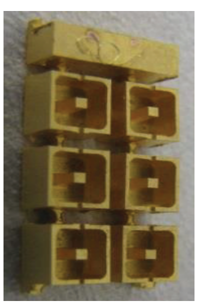
Two hardwired prototypes were manufactured in FBK foundry. The capacitance (C_{v_MEMS}) of the MEMS varactors has been realized considering its equivalent up-state (A2 prototype) and down-state (A1 prototype) values, (Fig. 4a and Fig. 4b). These structures were fabricated in a simple one mask process on 525µm thick HR Silicon substrate A 300 nm thick SiO_2 isolation layer was first obtained by thermal oxidation and then a seed-layer for electrochemical Au deposition, consisting of 2.5nm/25nm/2nm thick Cr/Au/Cr layer, was deposited by e-gun evaporation. The chromium layers acts as adhesion layer, the first for Au on oxide, the second for the photoresist over Au. The test structures were defined using a 7µm thick resist. After a short exposure to an oxygen plasma at 80˚C and the upper chromium layer removal, a 3µm thick gold layer was selectively grown in a commercial gold cyanide bath (Aurolyte CN 200 from Atotech). After the plating process the resist mask was removed with a solvent and the seed layer was removed by wet etch.


a)

b)

Fig. 4. Manufactured prototype: a) A2, equivalent up-state and b) A1, equivalent down-state cavity resonator.

The cavities were fabricated by milling a 2.7 mm thick brass plate. Brass has been chosen for its good electrical conductance and relative easy machining properties. The machining of the cavities has been done with the aid of a small precision CNC mill using 1mm diameter end mills. After some tests, the cutting parameters were optimized to obtain a smooth surface and a control of depth and lateral dimensions better than 10µm and a few tens of microns respectively. The precision of lateral dimensions can be still slightly improved by compensating tool deformation during the milling. In order to improve the electrical surface conductivity the machined brass cavities were gold plated (Fig. 5a). The cavities have been cleaned with solvents and wet-etched to remove the surface oxide. About 2µm gold layer was electrodeposited in a gold cyanide bath using a simple laboratory set-up and a current density of 3mA/cm^2.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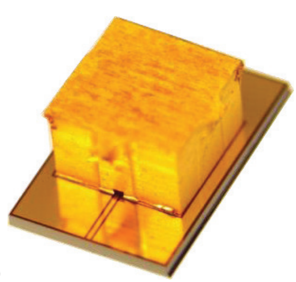
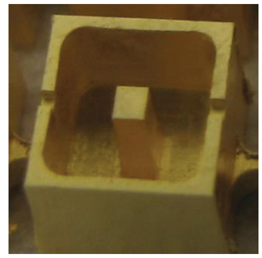

b)

Fig. 5. Manufactured prototype: a) gold plated cavities and b) assembled cavity resonator.

The metal cavities were joined to the test structures by gold-to-gold thermo-compression using a semi-auto TRESKY T3000 FC3 die bonder. The cavities were aligned, pressed on top of the test chips and heated at the bonding temperature of 200°C. The relatively low temperature was chosen to be compatible with MEMS varactors. In the first test, a load of 400gr was applied for 45min in a nitrogen atmosphere. The assembled cavity resonator is shown in Fig. 5b. A shear force of 5.2 N was required to detach the metal cavity, but inspection of the separated surfaces revealed that the bonding was not uniform and the centre post did not touch the substrate. A second generation of hardwired prototypes (B1 and B2) were fabricated using higher bonding pressure The applied force was increased up to 2 kg and the design of the cavity was modified in order to reduce the bonding area. Moreover, the force was applied by using a rigid interposer in order to have a more uniform load distribution and reduce the cavity deformations. Fig. 6a and Fig 6b show the first and the second cavity generation, respectively. As prototype A1 and A2, B1 and B2 refer to equivalent down-state and up-state cavity resonator.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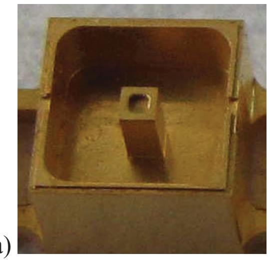
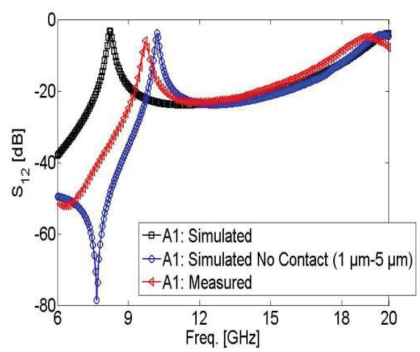

b)

Fig. 6. Manufactured cavity: a) first generation and b) second generation prototype.

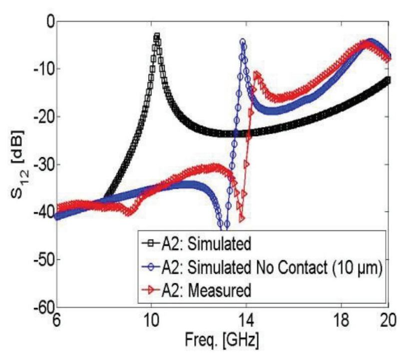
IV. Experimental results

A. First generation cavity (A1 and A2 prototypes)

Measured and simulated transmission parameters are shown in Fig. 7. Note that the measured resonance frequency of both prototypes (red lines), are higher than the simulated ones (black lines). Post simulations in HFSS considering an air-gap of about 1µm-10µm between the metallic post and the silicon substrate confirmed that this behavior is mainly due to the missing contact between the post and the substrate.



a)



b)

Fig. 7. Comparison between measured (red line), simulated (black line) and post-simulation (blue line) results for a) A1 and b) A2 prototypes.

B. Second generation cavity (B1 and B2 prototypes)

The measurements were repeated on B1 and B2 prototypes (Fig. 8a). In this case, a better agreement between measured and simulated transmission parameters was obtained, thanks to the correct post to substrate bonding of the second generation prototypes.

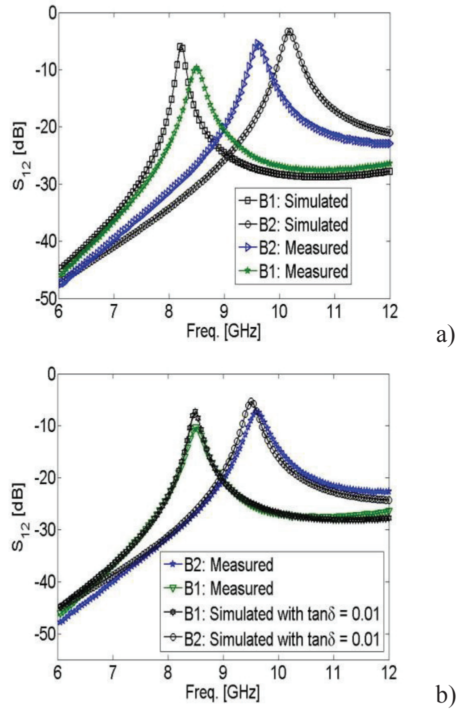


Fig. 8. Comparison between a) measured and simulated results, b) measured and post-simulation results for B1 and B2 prototypes.

However, the measured tuning range was reduced from the simulated value of 22% to the measured value of 14% and the measured quality factor (Q) was 80 for the up-state and 60 for down-state, lower than the corresponding simulated values of 180 and 80.

It was then found that this was due to the higher loss in the silicon substrate. The wafer used for this realization indeed presented an higher conductivity with respect to standard HR Si substrates and this affected the resonator loss as well as the tuning range. This was confirmed by post- simulation results (Fig. 8b) and the fabrication of a new prototype on the correct substrate is ongoing. The measured and simulated parameters are summarized in Table II.

TABLE II
Measured and simulated parameters for LC cavity resonator (B1 and B2 prototypes)

Parameter	*B2*		*B1*	
	Sim.	***Meas.***	***Sim.***	***Meas.***
R_0 [Ω]	*5.2*	7	*8*	10.2
L_0 [nH]	*24*	25	*24*	25
C_0 [pF]	*2.2*	2.3	*2.2*	2.3
$C_{v\ MEMS}$ [fF]	*65*	75	*260*	290
Q	*180*	80	*80*	60
F_{Res} [GHz]	*10.2*	9.8	*8*	8.2

V. CONCLUSION

This paper presented the design of a MEMS tunable micro-cavity resonator based on evanescent mode cavity loaded with a fixed metallic post and 4 tunable MEMS varactors. Measurement results on "hardwired prototypes" simulating the up and down state of the varactors demonstrated a tuning range of 14%, an unloaded quality factor of about 80, and very compact dimensions (3.2x3.2x1.4mm^3).

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