A Novel High-Q_u Octave-Tunable Resonator with Lumped Tuning Elements

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***Abstract*—This paper presents a novel design of high-quality factor (Q_u) continuously-tunable resonator compatible with standard PCB fabrication technology. The proposed resonator is tuned by lumped element varactors placed on the top surface of a substrate-integrated evanescent-mode cavity, thus significantly reducing the complexity of integration without sacrificing Q_u. The proposed design approach is compatible with a variety of tuning elements, including solid-state, ferroelectric, and RF-MEMS varactors. A tunable resonator with solid-state varactors is demonstrated to validate this design approach. The resonator surpasses the state-of-the-art with a frequency tuning range of 0.5–1.2 GHz (tuning ratio of $2.4:1$) and Q_u of 82–197. An RF-MEMS varactor enabled tunable resonator based on the same design further shows Q_u of 240 at 6.6 GHz.**

***Index Terms*—tunable resonator, tunable filter, MEMS**

I. Introduction

Tunable filters are critical components for future reconfigurable wireless systems [1]. Recently, there has been much development in low-loss highly-tunable filters using highly-loaded evanescent-mode (EVA) resonant cavities [2]–[4]. For example, an EVA cavity resonator with SOI based RF-MEMS tuners was demonstrated with an unloaded quality factor Q_u of 650–300 at 5–1.9 GHz [3]. An alternative design integrates discrete RF-MEMS capacitive switches inside the resonant cavity and achieves a Q_u of 500–300 for 5.58–4.07 GHz [4]. While both approaches achieve high Q_us that are not possible with planar tunable filters, sophisticated fabrication and integration techniques are needed to assemble these filters.

This paper presents a novel substrate-integrated high-Q_u tunable resonator design that utilizes planar lumped tuning elements, such as solid-state and discrete RF-MEMS varactors. The proposed design overcomes the above mentioned integration difficulty and is fully compatible with standard PCB manufacturing processes while maintaining high Q_u. Compared with [5] in which RF-MEMS switches are used to switch amongst vertical posts in the cavity, the proposed tunable resonator achieves continuous tuning over more than an octave frequency range. Such resonators are suitable for the realization of low-loss tunable filters and low phase-noise tunable oscillators.

II. Design

The proposed design structure is illustrated in Fig. 1-a. In a conventional EVA resonator design, frequency tuning is achieved by changing the gap between the capacitive loading post and cavity top wall. This is modeled by changing the effective capacitance, C_{post} Fig. 1-b. To achieve the desired capacitance value, vertical alignment with a precision of well below 1 μm is required. We realize that this capacitance may well be achieved using lumped elements placed on the top surface of the cavity. To this end, the metallic post in the center of the cavity is directly connected to a pad on the top wall of the cavity, which is separated from the rest of the cavity ceiling by an air gap Fig. 1-a. Lumped-element varactors can be placed across the air gap using standard surface mount (SMT) technology. By changing the capacitance, C_{tune}, the resonant frequency of the cavity is changed.

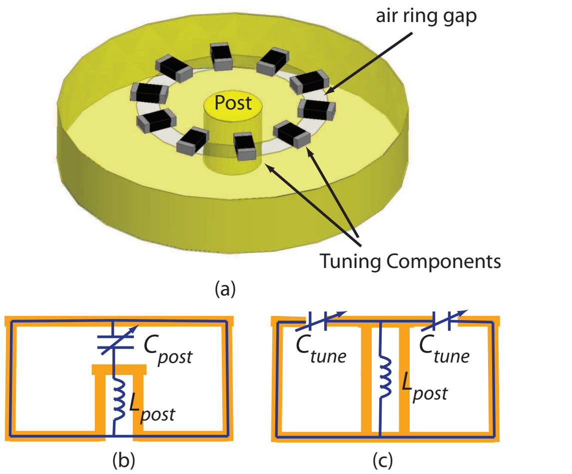

Fig. 1. Schematic of proposed resonator design: (a) PCB with generalized varactor as tuning elements; (b) equivalent circuit model for previous cavity; (c) equivalent circuit model for the proposed air ring gap cavity.

The proposed design has several inherent benefits.

(a) The most attractive feature of the proposed resonator is the flexibility in choosing various types of tuning components.
(b) By transitioning from a vertical to horizontal gap for the highly-concentrated electric field, the initial starting frequency and tuning range is primarily determined by the tuning element as opposed to the precision assembly, thus allowing much improved repeatability.
(c) The resonator is integrated in industry-standard PCB substrate with commercially-available tuning components facilitating high-volume manufacturing, ease of integration with other RF front-end components, and lower fabrication

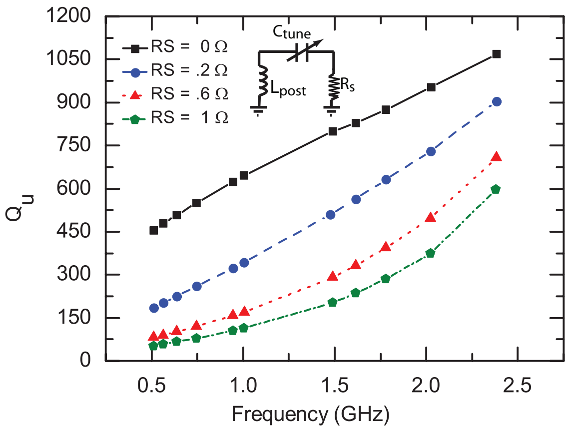

Fig. 2. HFSS ANSYS simulation of the resonator Q_u with various R_s of the tuning components.

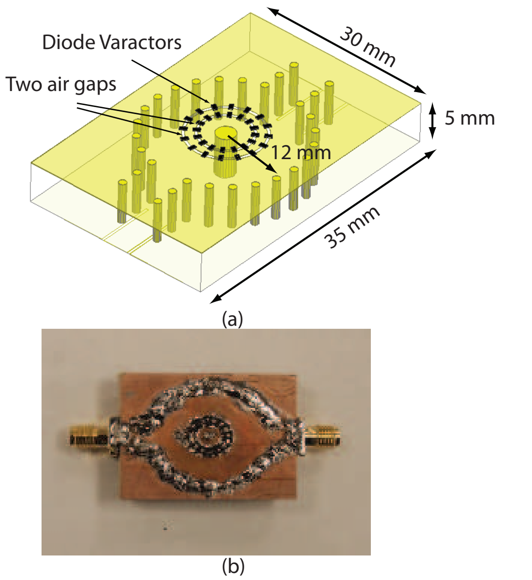

Fig. 3. (a) Designed two ring air gap resonator (b) Fabricated resonator.

cost. Compared with planar designs, such as microstrip resonators/filters, the proposed design retains the high Q_u of cavity resonators.

Full wave electromagnetic simulation software, ANSYS HFSS, is used to study the impact of the loss of the tuning components on the resonator Q_u. "Lumped RLC" boundary condition is used to model lumped element varactors with both a C_{tune} and a R_s value, which represent the finite Q of the varactor. Fig. 2 shows the simulated Q_u with C_{tune} from 0.1–5.5 pF and R_s of 0.2–1 Ω with a total of 20 tunable components. The dimensions of the resonant cavity are 12 mm cavity radius, 0.4 mm post radius, and 5 mm substrate thickness.

Conceptually, the Q_u of the resonator depends on the Q of the tuning component and Q of the cavity. The intrinsic Q of the cavity is shown in the curve with $R_s = 0$. For low-Q tuning components, such as solid-state varactors, the Q_u of the resonator is primarily limited by the Q of the varactor. On the other hand, tunable components with lower R_s ($.2 - .4$ Ω), such as RF-MEMS varactors, can achieve much higher Q_u. For example, simulation shows that a resonator with a varactor of $R_s = 1$ Ω and $C_{tune} = 1.5$ pF resonates at 1 GHz with a Q_u of 104, whereas the Q_u would be 323 with $R_s = .2$ Ω.

III. Experimental Validation

A. Solid State Tuners

In order to validate the proposed design, a solid state varactor tunable resonator was fabricated on Rogers TMM3 substrate based on the structure presented in Fig. 1-a. Copper pins were inserted in vias created in TMM3 substrates in order to make the cavity. Ideally, only one ring gap is necessary, but in order to bias the varactors, a structure with two rings is required Fig. 3. In order to avoid current crowding, the air gap is populated with as many varactors as possible. To get frequency tuning in the desired range, each air ring gap has 16 Skyworks Solution's SMV1405-040LF diode varactors, with a total of 32 varactors for the resonator. The cavity dimensions were optimized using ANSYS HFSS: 12 mm cavity radius, 0.4 mm post radius, and 5 mm substrate thickness. Fig. 4 shows the measured frequency tuning range and the extracted Q_u for the resonator. The resonator is intentionally weakly coupled so that Q_u extraction can be achieved with high accuracy. A measured Q_u of 197–82 from 1.2–0.5 GHz (tuning ratio of $2.4:1$) with a maximum bias of 31 V is demonstrated. The measured Q_u is within 22% of the eigenmode simulation results (Fig. 4). To the best of the authors' knowledge, this is the highest Q_u reported for this frequency range using commercially-available solid state varactors.

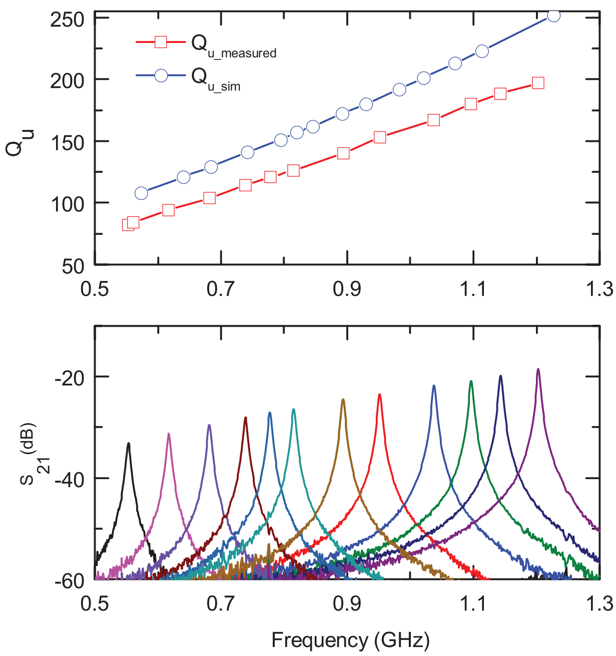

Fig. 4. Measured results of tunable resonator using solid state varactors.

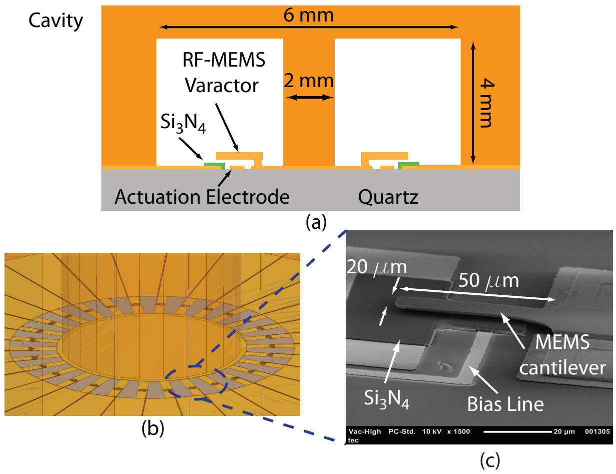

Fig. 5. 3D schematic of the proposed tunable resonator architecture loaded with RF-MEMS tuning elements. (a) Profile view of entire resonator. (b) Broad angle view of model with several MEMS tuner elements. (c) SEM image of actual RF-MEMS tuner element.

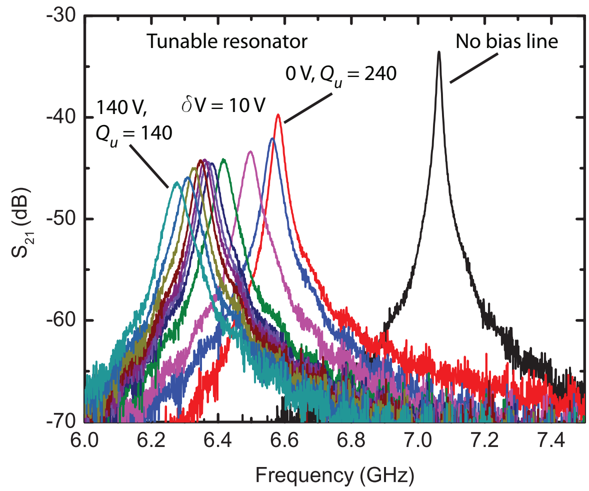

Fig. 6. Measured RF-performance of the tunable resonator with RF-MEMS capacitive switches.

B. RF-MEMS Tuners

As discussed in Section II, the Q_u of the resonator can be improved significantly by improving the Q of the varactor. To demonstrate this, an RF-MEMS tunable resonator is designed and fabricated.

Fig. 5 shows the complete resonator topology with the RF-MEMS tuners. The resonator is formed by bonding a machined metallic cavity with a quartz substrate on which RF-MEMS varactors are fabricated. The following dimensions are chosen for the cavity for a $Q_u > 700$, post diameter of 2 mm, the cavity radius of 6 mm, and cavity height of 4 mm. The air gap is defined by a photolithographic process and is loaded with RF-MEMS varactors to achieve frequency tuning. The tunable resonator is designed for 6–7 GHz. The capacitance required to achieve this tuning range is 78–57 fF. To obtain the up-state capacitance of 57 fF with 30 beams, an overlap area of 20×13 μm^2 and an initial gap height of 1.5 μm are required. The required thickness of the Si_3N_4 dielectric is 200 nm. Because the skin depth of gold is 1.24–0.88 μm from 6–7 GHz, the beams are designed to be at least 2 μm such that the Q_u is not severely degraded. The width and length of the cantilever beam are 20 μm and 50 μm respectively, resulting in a spring constant of 68 N/m and a pull down voltage of 88 V.

Fig. 6 shows the measured frequency tuning and the Q_u of the resonator. A Q_u of 240–140 from 6.6–6.25 GHz is demonstrated for a bias voltage under 140 V. The tuning and Q_u are lower than the simulation results (Q_u of 880–350 for 7–6 GHz). The analog tuning after pull-down is achieved by a zipping actuation. The reduced frequency range is mainly attributed to the surface roughness of the Si_3N_4, which results in a reduction of the effective permittivity. Additionally, it is difficult to assess if all the beams have actuated because a single common actuation electrode is used. This issue can be solved by using separate hold-down electrodes under each beam. The reduction in Q_u is mainly attributed to RF energy leakage through the bias line. In the fabricated device, the width of the high-impedance bias line is reduced by 230% from its designed value because of a severe undercutting in the metal etching process. Full-wave simulation shows 50% reduction in Q_u when undercutting is taken into consideration. This is also evidenced by measurement of a control resonator without biaslines Fig. 6, exhibiting only 34% reduction in Q_u compared to simulation. Nevertheless, the measured results of this prototype devices demonstrates the concept and potential of the proposed design approach.

IV. Conclusion

This paper presents a novel design of a continuously tunable resonator that is compatible with standard PCB fabrication technology. The frequency tuning is achieved by lumped element varactors placed on the top surface of a substrate-integrated evanescent-mode resonator. The design approach is validated by experimental results. Proof-of-concept demonstration devices surpasses the state-of-the-art in terms of Q_u and tuning range.

References

[1] G. M. Rebeiz, K. Entesari, I. C. Reines, S. Park, M. A. El-Tanani, A. Grichener and A. R. Brown, "Tuning in to RF MEMS," *IEEE Microwave Theory and Tech.*, vol. 10, no. 6, pp. 381−389, Sept. 2009.

[2] H. Joshi, H. H. Sigmarsson, D. Peroulis, and W. J. Chappell, "Highly loaded evanescent cavities for widely tunable high-Q filters," in *2007 IEEE MTT-S Int. Microw. Symp. Tech. Dig.*, Jun. 2007, pp. 2133−2136.

[3] X. Liu, L. P. B. Katehi, W. J. Chappell and D. Peroulis, "High-Q tunable microwave cavity resonators and filters using SOI-based RF MEMS tuners," *J. Microelectromech. Syst*, vol. 19, no. 4, pp. 774−784, Aug. 2010.

[4] S.-J. Park, I. Reines, C. Patel and G. M. Rebeiz, "High-Q RF-MEMS 4−6 GHz tunable evanescent-mode cavity filter," *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 2, pp. 381−389, Feb. 2010.

[5] V. Sekar, M. Armendariz, K. Entesari, "A 1.2-1.6-GHz Substrate-Integradeted-Waveguide RF MEMS Tunable Filter," *IEEE Trans. Microw. Theory Tech.*, vol. 59, no. 4, pp. 866−876, Feb. 2011.