A High-Q Millimeter-Wave Air-Lifted Cavity Resonator on Lossy Substrates

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***Abstract*—In this letter, a 3-D high-quality-factor millimeter-wave cavity resonator is integrated on the lossy soda-lime glass substrate utilizing surface micromachining technologies. With a height of 300 μm, the air-lifted cavity features a measured Q of at least 219 at 30 GHz, demonstrating an improvement by almost an order of magnitude with respect to respective planar resonators on the same substrate. The 3-D cavity is monolithically integrated on the top of the substrate, with its side walls consisting of two rows of metalized pillars, while a weak coupling excitation scheme is used to extract the quality factor. This high performance cavity can be easily integrated with other monolithic integrated circuits and planar mm-wave components in multilayer modules.**

***Index Terms*—Cavity resonator, coplanar waveguide (CPW), micromachining technology, millimeter (MM) wave.**

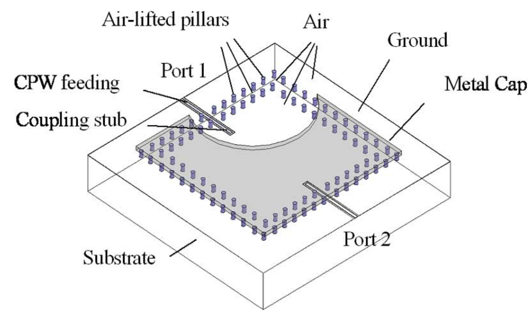

Fig. 1. Schematic illustration of the proposed structure (part of the cap removed deliberately to reveal the inside of the cavity).

I. Introduction

HIGH-Q resonators are widely used in the design of high-selectivity filters and diplexers. However, the conventional resonators made in the form of metallic rectangular or cylindrical waveguides [1] are bulky and not allowing for an easy integration with the monolithic integrated circuits. High-Q planar resonators are also extensively used due to their simplicity and the low fabrication cost [2], but usually requires high-ε_r and low loss substrates. In the past several years, several 3-D high-Q cavity resonators have been implemented using either bulk micromachining technologies or standard printed circuit board (PCB) drilling processes [3], [4], offering the advantage of the simple integration with other components on the same substrate. However, these cavity resonators require a substrate which should be low loss and easily micro-machined by either dry/wet etching or drilling, thus limiting their applications. The stereo-lithography method has also been explored and used to form more complicated 3-D structures [5]. It builds both the substrate and elevated parts layer by layer, using the same type of resin. This is a good technique for forming standalone complicated structures but selectively metalizing the surface of the 3-D structure requires laser ablation, posting a challenge for certain applications.

In this letter, a 30 GHz rectangular "elevated" cavity resonator was designed, fabricated and characterized on a lossy soda-lime glass. It demonstrates a measured quality factor of at least 219 by utilizing the surface micromachining technology. Furthermore, this quality factor can be easily controlled by adjusting the height of the cavity from several micron up to 1 $\sim$ 2 mm in the fabrication process.

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II. Proposed Structure and the Design Considerations

Fig. 1 shows the proposed high-Q cavity resonator. The four side walls are composed of two rows of metallized pillars with air gaps between them. The pillar fences instead of solid walls are used due to the fabrication feasibility concern, which is discussed later in this letter. When the diameter of the pillars and the pitch between the pillars satisfies the rule suggested in [6], the pillar fence will block the outgoing electromagnetic waves inside the cavity and will act effectively as four solid metal walls. The bottom wall is the metallization on top of the soda-lime glass substrate. This configuration offers two advantages: first, it allows for the easy integration of the resonator with other planar microwave components [coplanar waveguide (CPW)-fed components] located on the substrate surface; secondly, this metallized ground blocks most undesired substrate effects such as the dielectric loss and the frequency dispersion. In Fig. 1, the top cap is partially removed deliberately to reveal the side wall detail and the feeding scheme which is used to determine the resonator quality factor.

In our work, a square cavity with a height of 300 μm was designed to resonate at 30 GHz with the dimensions shown in Table I. The dimensions of a solid wall square cavity resonating at 30 GHz were first chosen, then they were transformed into the dimensions of the pillar fence cavity using the following equation reported in [7]:

$$W_{eff} = W - D^2/0.95b \tag{1}$$

TABLE I
PHYSICAL DIMENSIONS OF THE PILLAR FENCE CAVITY

	length	width	height	pillar diameter	pitch
Units(μm)	7120	7120	300	160	600

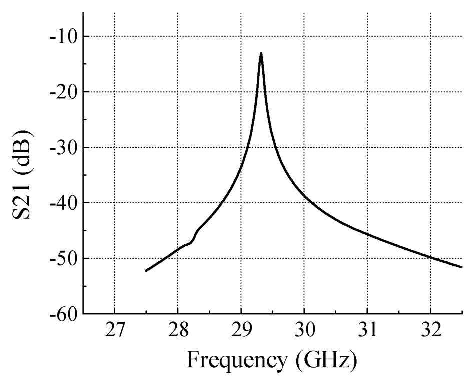


Fig. 2. Simulated port 1 → 2 power transmission in the weak-coupling scenario.

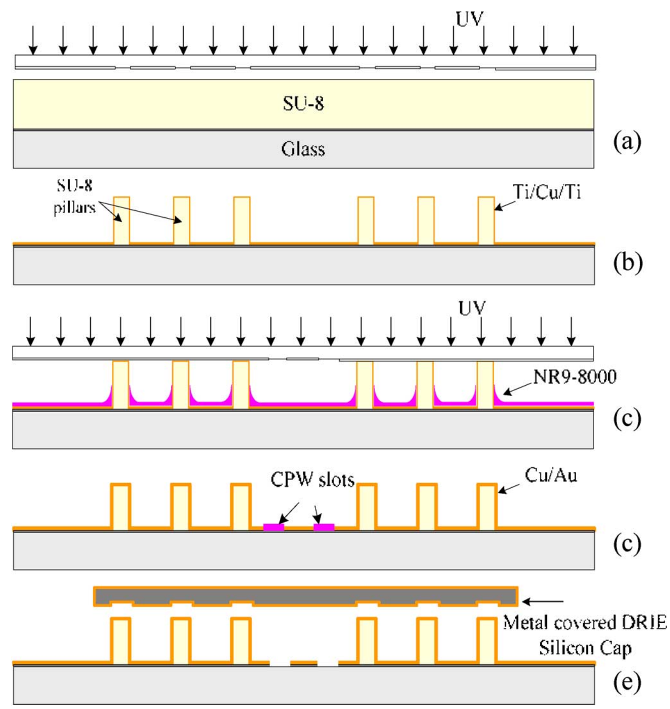


Fig. 3. Fabrication steps for the proposed cavity resonator.

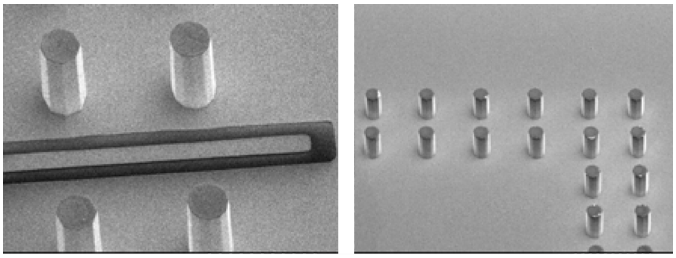
where W_{eff} is the effective width of the cavity and W is the measured distance between the centers of inner pillars on the two sides. D is the diameter of the pillar and b is the pitch between two adjacent pillars in the same row. An open-end CPW stub is inserted into the air cavity through the gap between two adjacent pillars to excite the cavity mainly by electrical coupling. This feeding scheme is for the sole purpose of determining the quality factor of the cavity, as it introduces a weak coupling mechanism. To accommodate the CPW inserting into the cavity, the pitch between the pillars along the middle line is increased to facilitate the fabrication. This moves the equivalent electrical wall outward and causes the frequency to shift downwards. The resonating frequency can be easily tuned back to 30 GHz by optimizing the pillars positions. Since we are focusing on concept proofing in this letter, no further optimization was performed for retuning.

For the conventional solid sidewall cavity with this height, the quality factor can be calculated as 607 at 30 GHz, only considering conductor loss. However, the blockage from the pillars is not perfect and the inserted open-end CPW stub inside the cavity couples some electromagnetic energy into the substrate, thus introducing additional loss. These effects degrade the cavity quality factor and were taken into account by using the finite element method (FEM)-based Ansoft HFSS 10.1 full-wave simulation, which also helps optimize the positions of the cylindrical pillars. The simulated weak coupling response is given by Fig. 2. By considering the conductor/dielectric loss, as well as the radiation leakage from the feeding line, an unloaded Q of 280 is observed in simulation.

III. Detailed Fabrication Steps

A specific type of soda-lime glass (Telic Co.) was chosen as the substrate to validate the proposed concept. The soda-lime glass is not optimized for high frequency applications since it has numerous impurities. The CPW line attenuation was extracted up to 110 GHz and it gives a 2.45 dB/cm attenuation at 30 GHz. This high dielectric loss severely degrades the performance of planar or in-substrate cavities. As mentioned earlier, using solid metal side walls is not feasible in the fabrication; plating the metal up to several hundred microns takes extremely long time and is costly. Instead, the metal-coated epoxy core conductor concept [8] is used. Even so, the solid polymer wall approach is still unfavorable since the epoxy core chosen to build the pillars is the negative tone photo-definable epoxy, Microchem SU-8, whose thermal property is not the same as the substrate. When there is a long SU-8 wall on the substrate, the accumulated tension will cause severe delamination, thus damaging the structure. On the contrary, the individual pillar only has a limited foot-print and has a very good mechanical adhesion to the substrate.

Fig. 3 details the fabrication process steps: a thin Ti layer was sputtered to improve the SU-8 adhesion to the glass. A 300 μm negative photo-definable epoxy SU-8 2075 was dispensed and patterned to define the mold of the pillar fences. Ti/Cu/Ti was then sputtered as the seed layer to cover the pillars, as well as the substrate in a conformal manner. Negative photo-resist NR9-8000 was coated and patterned in a noncontact way to cover the CPW slot region, preventing the metal coverage on the slot in the following electroplating step. Electroplating of copper and gold to cover the sidewall of the pillars and the exposed feeding structures. Rows of grooves were etched into a silicon wafer at the exactly same position of the pillar fences. This piece of silicon wafer was metalized to be used as a top cap of the cavity, by flipping the silicon wafer and latching the released structure into the pre-defined grooves. The top piece was bonded with the pillars using silver epoxy.



(a) (b)

Fig. 4. (a) The SEM picture of the coupling by an open-end CPW stub and (b) the SEM picture of the pillar fences for the cavity side wall.

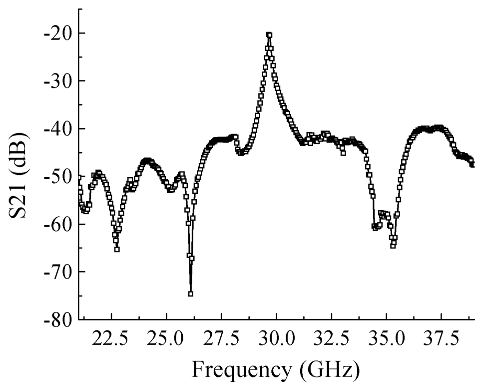


Fig. 5. Measured cavity performance for the proposed cavity resonator.

TABLE II
COMPARISON OF THE SIMULATED AND MEASURED CAVITY PERFORMANCES

	f_{res}	S12 (dB)	Unloaded Q
Simulation	29.23 GHz	-12.6	280
Measurement	29.65 GHz	-20.27	> 219

IV. MEASUREMENT RESULTS

The fabricated prototype (Fig. 4) was characterized by a two-port Agilent 8510C vector network analyzer with a probe station. The reference plane was set to be located at the outer surface of the rear pillar fences. The weak-coupled cavity resonates at 29.65 GHz with a 3-dB bandwidth from 29.6 to 29.75 GHz (Fig. 5). The peak coupling level from port 1 to port 2 is -20.27 dB. Using the equations in [3], the loaded Q_l is calculated as 197.7 and unloaded Q_u is calculated to be 218.9.

The reason for getting a value lower than the one of a conventional solid wall cavity, with the same dimensions and resonating frequency, is mainly due to the loss from the inserted open-end CPW short stub. By using the excitation described in Section II, even if the insertion loss of the line itself could be calibrated out by moving the reference plane into the cavity to the end of the CPW stub, the perturbation introduced by the lossy CPW stub could not be isolated from the intrinsic cavity performance. The total response looking into the reference point will be the combination of the cavity resonator itself, whose intrinsic quality factor could be even higher, plus the lossy part of the series resonating stub. Non-uniform metal coverage for the vertical structures in the sputtering and electro-plating step caused an anisotropic deposition profile and a thinner coverage of the pillar bottom, which introduced more conductor loss. This might help explain the discrepancy between the simulation and the measurement.

However, a planar CPW or microstrip resonator on the same substrate and at the same frequency would have a Q equal to 23.2 according to

$$Q \approx \frac{\beta}{2\alpha} = \frac{\pi}{\lambda_e \cdot \alpha} \qquad (2)$$

where α is the line attenuation and is measured to be as 2.45 dB/cm at 30 GHz and converted to 28.21 Np/m to be used in the (2). β is the propagation constant of the line and λ_e is the guided wavelength. Comparing 23.2 with the value of 219, it can be easily seen that the Q of the proposed resonator is significantly increased by almost an order of magnitude. The comparison of simulations and measurements is listed in Table II.

V. CONCLUSION

In this letter, a 3-D high Q millimeter-wave air-lifted cavity resonator has been developed on a lossy soda-lime glass substrate. With a height of 300 μm, it demonstrates a measured Q of at least 219 at 30 GHz, featuring almost an order of magnitude improvement in comparison to planar resonators on the same lossy material. The resonator is monolithically integrated on the top of the substrate using the surface micromachining technology, making the cavity easy to be integrated with other RF and millimeter-wave components and modules, while being almost substrate-independent.

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