A Hybrid Micromachined High -Q Cavity Resonator at 5.8 GHz

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***Abstract*-A novel hybrid micromachined resonator with high quality factor and small size at 5.8GHz is presented. The design of the resonator is based on a micromachined cavity filled with a high dielectric constant material. Energy is coupled into the cavity from input and output microstrip lines via slots. It is shown experimentally that the limiting factor in achieving a higher Q with the given dielectric materials is the dielectric loss. This resonator provides a low cost, minimum size and compact solution for the fabrication of planar, narrow-band filters and diplexers in modern wireless communication systems.**

I. INTRODUCTION

Microwave and millimeter-wave components for wireless communication systems and radars are traditionally built with waveguide technology that offers low-loss and high quality factor (Q) circuits at the price of large size and weight, high cost, incompatibility with monolithic circuits and increased fabrication complexity especially at higher frequencies. Realization of these components in planar form is generally avoided due to the low quality factor and higher losses of those circuits that are caused by the presence of the substrate material. However, with the recent developments in microwave micromachining it is now possible to make microstrip or CPW line resonators suspended on membrane [1], cavity propagating or evanescent mode resonators [2]-[3], as well as dielectric resonators [4] that offer low-loss, high-Q and narrow bandwidth and can be monolithically integrated with other passive components and active devices on a single chip. This paper focuses on the demonstration of a high-Q loaded cavity micromachined resonator at 5.8GHz with minimum size.

II. CAVITY RESONATOR WITH AN ε_r=10.8

Based on previous work on micromachined resonators [2], a 17.47mm x 8.78mm x 0.92mm propagating-mode cavity was designed to resonate at 5.8GHz. The resonant frequency (f_{res}) of the cavity is evaluated by the following equation [5]:

$$f_{res} = \frac{c}{2\pi\sqrt{\varepsilon_r}}\sqrt{(\frac{m\pi}{a})^2 + (\frac{n\pi}{b})^2 + (\frac{o\pi}{d})^2} \quad (1)$$

where a is the width, b the height and d the length of the cavity.

The first resonant mode (TE_{101}) is at 5.81GHz if the cavity is filled with a dielectric of relative permittivity 10.8, such as Rogers Duroid. The corresponding cavity filled with air needs to have a size of 5cm x3cm x 0.93mm, for the first mode to resonate at the same frequency. The interest of loading the cavity with a dielectric material for size reduction is therefore evident. In addition, the dielectric material can serve as a host for other structures and devices inside the cavity.

Feeding of the cavity is achieved via coupling slots with two microstrip lines that have characteristic impedance of 50 Ω. Built on Duroid substrate (10.8), each end of the line is designed to provide a short circuit at the location of the slots. For this reason quarter wavelength stubs that extend beyond the center of the slots are used. This produces a minimum electric field and a maximum magnetic field parallel to the slots, which couples the energy in the cavity.

Since at 5.8 GHz, the wavelength in the feed substrate is 1.57cm, the two open stubs are too long relative to the distance between the two slots. For this reason it is necessary to bend them with an angle-to-width ratio of 1.8 [5] and avoid parasitic coupling between the lines. A solution with short-circuited stubs that implements via holes is also possible, in order to realize the feed for a smaller geometry [6].

The rectangular slots, 3.48mm x 340µm, are located a quarter cavity length away from the edges. Choosing this position results in a compromise between the insertion loss (S_{21}) and the resonant frequency (f_{res}). For slots closer to the cavity edge, S_{21} improves while f_{res} shifts lower. When the slots are closer to the cavity center, f_{res} shifts higher and the direct coupling between the lines increases to give a poor S_{21}. A schematic of the resonator can be seen in Fig. 1.

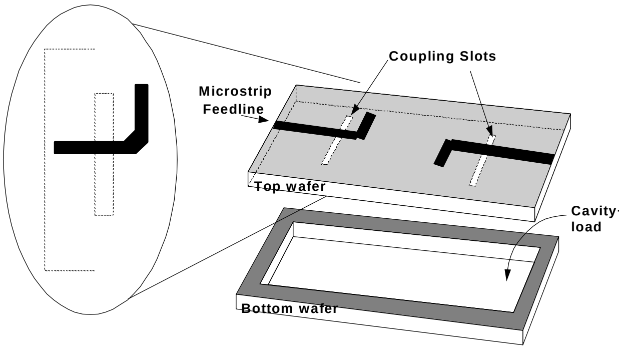

Fig. 1 A micromachined resonator with a cavity filled with dielectric material.

The theoretical quality factor for a rectangular cavity is given by [5]:

$$Q_c = \frac{(kda)^3 b\eta}{2\pi^2 R_m (2a^3 b + 2d^3 b + a^3 d + d^3 a)} \quad (2)$$

where $R_m = \frac{1}{\sigma\delta_s} = \sqrt{\frac{\pi . f_{res} . \mu}{\sigma}}$, k is the wave number, η the wave impedance and $\sigma = 3.8x10^7\ S/m$.

Based on (2), Q_c is evaluated to be $Q_c = 717$.

Taking into account the dielectric losses of the Duroid material, $\tan(\delta) = 0.0023 = (Q_d)^{-1}$, we get:

$$\frac{1}{Q_u} = \frac{1}{Q_c} + \frac{1}{Q_d} \quad (3) \quad \Rightarrow Q_u = 270$$

It is evident that dielectric losses dominate in the evaluation of the quality factor. A material with a smaller loss, such as Alumina, would be preferred.

The resonator was simulated using Ansoft's High Frequency Structure Simulator 7.0 (HFSS). Once the geometry is drawn, boundaries are characterized. Ground and microstrip lines are modeled as Perfect Electric Conductor (PEC) whereas the slots are Perfect Magnetic Conductors. Using the finite element method, the geometry is discretized and meshed with tetrahedras near the resonant frequency. Optimization is then performed to get the correct length of the open stubs taking into account the fringing fields at the end. A stub length of 4.59mm gives a minimum loss of 1.83 dB at 5.73 GHz and a 90MHz bandwidth.

The fabrication was separated into two different substrates that were bonded together. The top substrate was made of Duroid material that was 635μm thick. The bottom substrate was an aluminum block containing the cavity. Standard lithographic techniques were used for circuit fabrication. Alignment marks and screw locations were used for accurate positioning. A 50 Ω microstrip thru line was also fabricated in order to de-embed the loss due to the microstrip lines and the connectors. The bottom part of the resonator was fabricated using Electrical Discharge Machining (EDM) for accurate fabrication of the cavity particularly in the corners where it is necessary to achieve proper electrical continuity. For better results, the dielectric material was glued inside the cavity with silver epoxy (highly conductive). The block also contained the marks for alignment with the top wafer. Twelve screws and a clamp were used to ensure good bonding between the two pieces.

The assembled filter was characterized using an HP8510 vector network analyzer. The network analyzer was calibrated (SOLT) and the S-parameters for the resonator/filter were measured. Measured and simulated results can be seen in Fig.2 and Fig.3. The loss was measured to be 2.2 dB at 5.525 GHz (microstrip and connectors losses de-embedded). The bandwidth was 137.5 MHz or 2.48%. The differences between simulations and measurements are due to the imperfect bonding between the two wafers, the ground/cavity surface roughness and the tolerances in the Duroid dielectric constant and loss.

In order to measure more accurately the quality factor, a top wafer with narrow coupling slots was fabricated to achieve a weak coupling of the resonator.

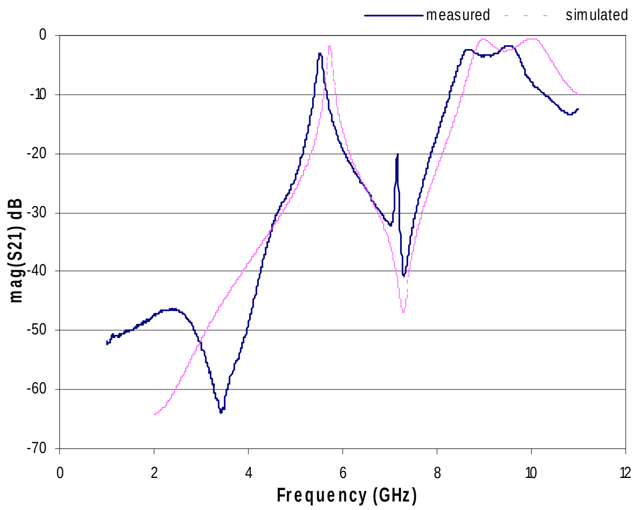

Fig. 2 Measured and simulated insertion loss for the ε_r=10.8 resonator.

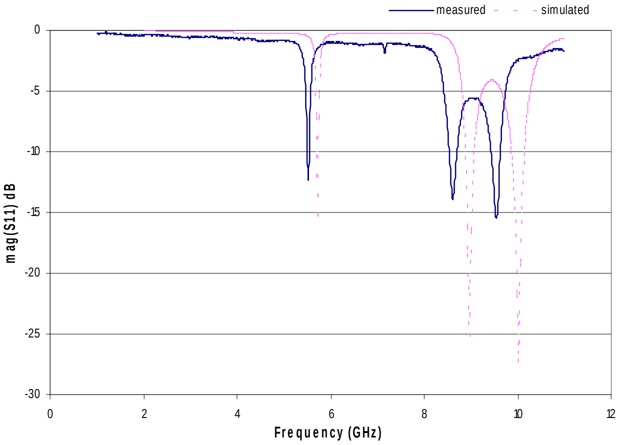

Fig. 3 Measured and simulated return loss for the ε_r=10.8 resonator.

As seen in Fig.4, the peaks get sharper and the loss increases. The bandwidth was measured to be 28.6 MHz at 5.68 GHz and the insertion loss was 17 dB. The loaded quality factor Q_L is:

$$Q_l = \frac{f_o}{\Delta f} = 199 \quad (4)$$

The external Q_e can be found from [2]:

$$S_{21}(dB) = 20\log(\frac{Q_l}{Q_e}) \ (5) \quad \Rightarrow Q_e = 1407$$

The unloaded Q_u is then evaluated by

$$\frac{1}{Q_l} = \frac{1}{Q_u} + \frac{1}{Q_e} \quad (6) \quad \Rightarrow Q_u = 232$$

Measured and theoretical results for the unloaded quality factor agree well. The small difference is due to the factors explained previously. It is expected that fabrication of the hybrid resonator in silicon (Si) with more accurate techniques, better wafer bonding and smoother cavity walls will further reduce the loss and enhance the resonator performance.

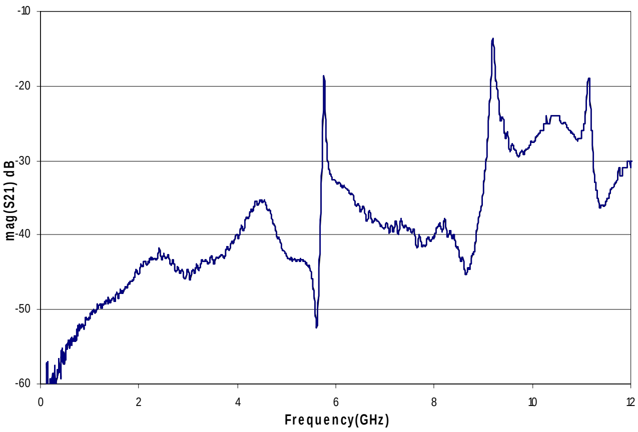

Fig. 4 Weak coupling response of the ε_r=10.8 resonator.

III. CAVITY RESONATOR WITH AN ε_r=9.5

In order to further reduce the loss, the cavity of section II was filled with 0.92 mm thick Alumina (ε_r=9.5) that had a tanδ=0.0003. Measured results in Fig. 5 show an insertion loss of 0.8 dB at 6.26 GHz and a bandwidth of 2.48%. The frequency shift is explained by the difference of permittivity and the non-optimized stub design. It is evident that by comparing with the previous results, an order of magnitude reduction in tanδ resulted in 1.4 dB loss reduction.

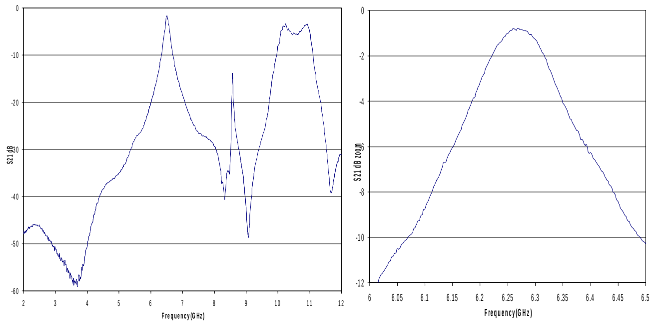

Fig. 5 Measured insertion loss for the Alumina resonator.

IV. CAVITY RESONATOR WITH AN ε_r=70 BST

In order to further reduce the size of the resonator, a material with a higher dielectric constant, such as Barium Strontium Titanate (BST), can be used. Based on a ceramic with ε_r=70 a new cavity was designed to resonate at 5.8 GHz. Such a resonator is achieved with a size of 7mm x 3.5mm x 0.25mm. The theoretical quality factor, given by (2), is Q_c=211.6 and when the dielectric loss (tanδ=0.0024) is taken into account equation (3) yields Q_u=140.3.

The top wafer was fabricated with short-circuited stubs and via-holes to maximize the magnetic field at the slot location and minimize the direct coupling between the two microstrip lines [6]. In order to accurately measure the quality factor of this new resonator, the input microstrip lines were mismatched relative to the 50 Ω source and connectors. For this reason, the two lines were designed for a higher characteristic impedance (narrower widths). Measured results with the HP8510 network analyzer are shown in Fig. 5, where it can be seen that the loss is around 30dB.

The bandwidth was measured to be 47 MHz at 5.82 GHz. The unloaded Q is then evaluated from equations (4)-(6) to be 124. Theory and measurement agree with an 11.5% error. The lower quality factor of this resonator, when compared to the resonator of section II, is due to the smaller height of the cavity (0.25mm instead of 0.93mm) which is dictated by the thickness of the available ceramic material.

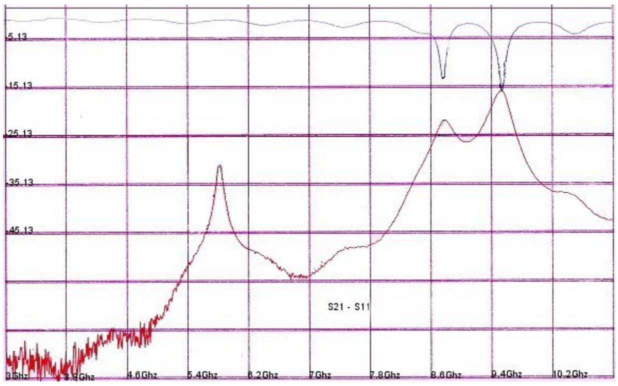

Fig. 6 Weak coupling response of the ε_r=70 resonator.

V. SI MICROMACHINED RESONATOR

A simulation using Si (ε_r=11.7) substrate instead of Duroid and the ceramic with ε_r=70 was performed, and results are shown in Fig.6. The Si resonator can be fabricated using high accuracy fabrication techniques such as cavity micromachining by a laser system, IR alignment and gold plating. Good bonding can also be achieved by attaching the ceramic below the top wafer and evaporating gold on it. Fabrication of the Si resonator is currently under way.

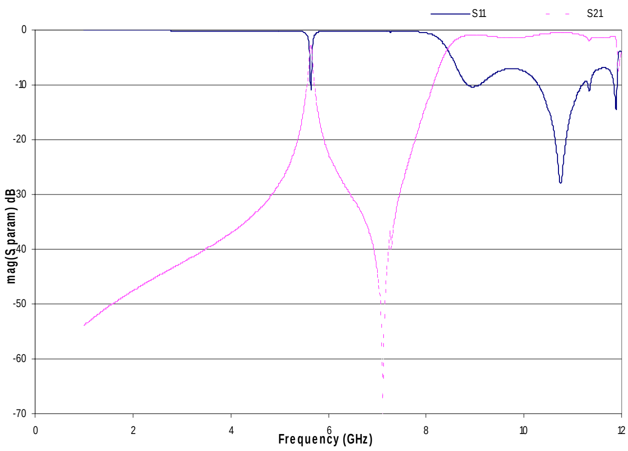

Fig. 7 Simulated results for a Si micromachined resonator with an LTCC dielectric.

VI.CONCLUSIONS

Two hybrid cavity micromachined resonators have been fabricated and tested. The first resonator had a size of 17.47mm x 8.78mm x 0.93mm and a dielectric load of ε_r=10.8. It exhibited a loss of 2.2 dB and a bandwidth of 137.5 MHz (2.48%) at 5.525 GHz, while its unloaded quality factor was measured to be 232 at 5.68 GHz. When the same cavity was filled with Alumina the bandwidth remained the same, but the loss was reduced to 0.8 dB at 6.26 GHz. The second resonator had a smaller size of 7mm x 3.5mm x 0.25mm and an ε_r=70. Its unloaded quality factor was found to be 124 at 5.82 GHz.

Both of these examples show the potential of using loaded micromachined resonators for the fabrication of **very small size**, low-loss and narrow-band planar filters and multiplexers at frequencies around 5.8 GHz. Clearly, the limiting factor for achieving even higher Q values is the dielectric loss of the material filling the cavity. Even with these limitations, the resonators presented herein exhibit a relatively high-Q for their small size, when compared with other planar structures.

Efforts are currently under way for the fabrication of these resonators in Si substrate with ceramic materials that have lower loss. An additional advantage of these resonators, apart from the minimum size, is the capability to include other devices or structures inside the cavity.

VII. ACKNOWLEDGEMENTS

This work was supported by the NSF-S/IUCRC Center for Low Power Electronics (CLPE) under Grant #EEC-9523338 and by Motorola, Semiconductor Products Sector.

VII. REFERENCES

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