A Micromachined High-Q X-Band Resonator

John Papapolymerou, Jui-Ching Cheng, Jack East, *Member, IEEE*, and Linda P. B. Katehi, *Fellow, IEEE*

***Abstract*—This letter presents a new structure which can be used as a microwave high-Q resonator for the development of narrow-band low-loss filters in a planar environment. The resonator is made of a low-loss micromachined cavity which is easy to integrate with monolithic circuits. Compared to conventional metallic resonators, the performance of this resonator is similar, but the weight and size are significantly reduced.**

I. Introduction

CONVENTIONAL microwave high-Q resonators made by metallic rectangular or cylindrical waveguides are heavy in weight, large in size, and costly to manufacture. Furthermore, they do not allow for an easy integration with monolithic integrated circuits.

With the maturity of micromachining techniques in fabricating microwave circuits, it is now possible to make miniature silicon micromachined waveguides or cavities [1]–[4] as building blocks for the development of high-Q bandpass filters. The quality factor that can be achieved with this technique is much higher than the quality factor of traditional microstrip resonators either printed on a dielectric material or suspended in air with the help of a dielectric membrane [5]. A possible high-Q filter geometry is shown in Fig. 1, consisting of input and output microstrip lines and rectangular cavities on different dielectric layers. The cavities are made by Si micromachining and are metallized by conventional techniques. Coupling between the cavities and microstrip lines is achieved via the slots etched at appropriate locations with respect to the microstrip lines. Coupling between cavities is controlled by the size, position, and orientation of the corresponding coupling slots. The vertical stacking of the cavities greatly reduces the occupied area when multiple cavities are needed for filter design.

In the following sections, a micromachined resonator is analyzed and built. The theoretically calculated results are compared to measurements. The Q of the resonator is computed and compared to the Q of conventional metallic and planar resonators.

II. Theoretical Analysis

A hybrid technique [6] that combines the method of moments (MoM) and the finite-element method (FEM) is used in the theoretical analysis. This technique primarily uses the method of moments to analyze the open part of the structure and the FEM to compute the fields inside the cavity. The two techniques are coupled at the slot surface. Due to the flexibility of FEM, the shape of the cavity is not restricted to be rectangular and the cavity can be filled with complex material. The procedure of applying this technique is briefly described in the next paragraph. The exact formulation will not be shown here, since it is similar to the one presented in [6].

Manuscript received January 21, 1997. This work was supported by the Army Research Office (MURI Program) under Contract DAAH-04-96-1-0001.

The authors are with the Department of Electrical Engineering and Computer Science, The University of Michigan, Ann Arbor, MI 48019-2122 USA.

Publisher Item Identifier S 1051-8207(97)03854-3.

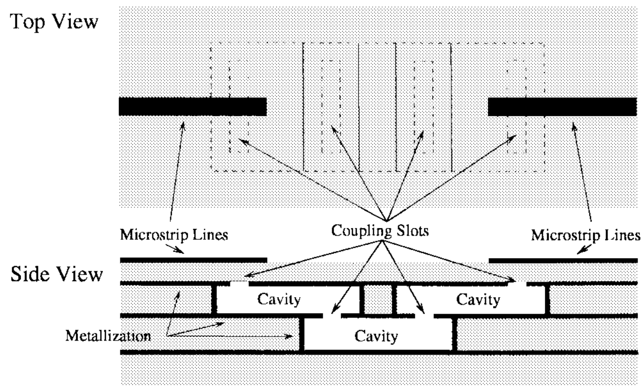

Fig. 1. The structure of the proposed micromachined bandpass filters.

Fig. 2 shows a cavity coupled by two microstrip lines through two slots. By using the equivalence principle, the slots can be replaced by perfect electric conductors with equivalent magnetic currents flowing above their surface at the location of the slots. In this way, the cavity and the microstrip lines are separated by the ground plane of the microstrip lines. The field inside or outside the cavity can be represented as an integral of the unknown equivalent current sources dot-multiplied by the dyadic Green's function. By enforcing the continuity of tangential magnetic fields across the slots and using Galerkin's method, a matrix equation linking the unknown current distribution on the microstrip lines and field distribution on the slots is derived. The finite element technique applied in the cavity links the fields on the two slots through an FEM matrix. This hybrid technique reduces to a matrix equation which is then solved to compute the unknown current and field distributions.

III. Fabrication

The X-band resonator is fabricated using standard micromachining techniques. For the circuit shown in Fig. 2 two silicon wafers, 500-μm thick, with 1.45-μm thermally grown oxide deposited on both sides are used. To measure the resonator with on-wafer probing, a coplanar waveguide (CPW)-to-microstrip transition is incorporated to provide a matched transition to the feeding lines. The ground of the CPW and the microstrip are set at an equal potential with the implementation of via holes. The characteristic impedance of

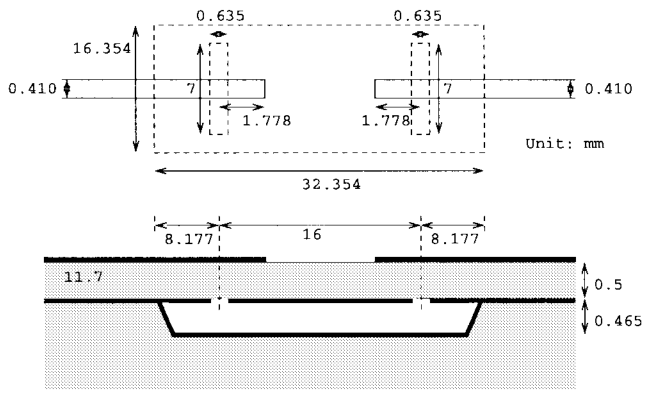

Fig. 2. An X-band micromachined resonator.

both the CPW and microstrip is 50 Ω. The two microstrip lines are gold electro-plated with a total thickness of 7.5 μm in order to minimize losses. Infrared alignment is used in order to correctly align the two slots on the back of the wafer with the microstrip lines printed on the other side.

The cavity is fabricated on a second wafer by using chemical anisotropic etching (EDP or TMAH) until a depth of about 465 μm is achieved. Once the wafer is etched, it is metallized with a total thickness of 2 μm. The two wafers are then bonded together with silver epoxy that is cured at 150 °C. The alignment between the two wafers is achieved by opening windows on the top wafer during the etching process to align to marks that are placed on the second wafer.

IV. Computed and Measured Results

A resonator with the dimensions shown in Fig. 2 is built and the S-parameters are measured and compared with the computed results. The reference planes for the measurement are at the middle of the slots and de-embedding is achieved using a thru-reflect-line (TRL) calibration with the standards fabricated on the same wafer. Computed and measured results can be seen in Fig. 3. Note that although the cavity is not rectangular, we find that the first resonant frequency is very close to that of a rectangular cavity of similar size. The small difference (1%) in the center frequency is partly due to the finite accuracy in modeling the nonvertical slopes of the cavity and partly to the inherent numerical error of our simulation technique. Fig. 4 shows the z-component electric field density on the bottom of the cavity at the resonant frequency (10.4 GHz). The field pattern also matches quite well to that of the first resonant mode of a rectangular cavity of the similar size. The figure is drawn according to the physical dimension of the cavity. The two coupling slots are located at 1/4 and 3/4 of the length of the cavity as indicated in the figure.

In order to evaluate the unloaded Q (Q_u) of the cavity the losses due to the excess length of the lines from the reference planes, which is needed to tune the slots, must be removed. For this reason the ohmic loss on the feeding lines is found from the TRL standards and is used to compute the loss on the two open end stubs extending beyond the center of the slots. For the measured results shown in Fig. 3 this loss has already

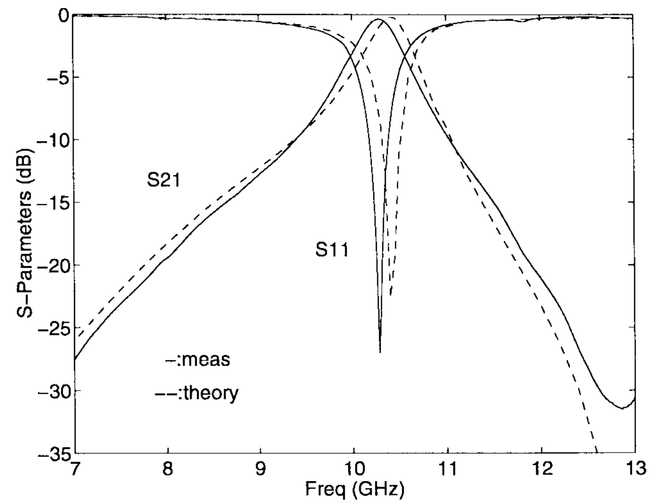

Fig. 3. Measured and theoretical S-parameters for the resonator of Fig. 2.

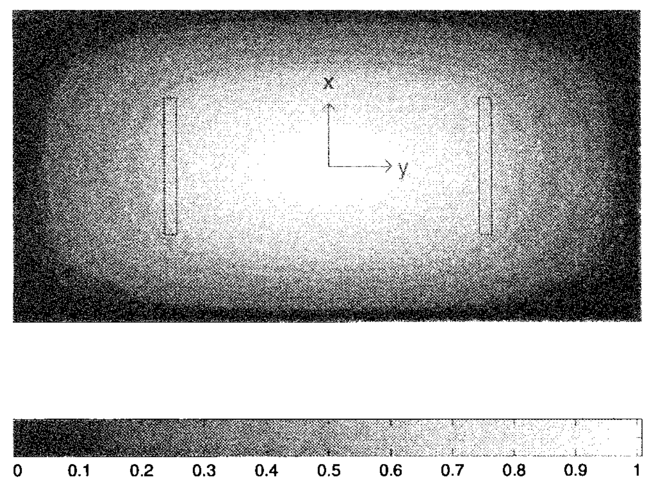

Fig. 4. Computed z-component of the electric field density on the bottom of the cavity.

been de-embedded. The loaded Q (Q_l) of the cavity defined as

$$Q_l = \frac{f_o}{\Delta f_{3-\mathrm{dB}}} \tag{1}$$

where $f_o = 10.285$ GHz is the resonant frequency and $\Delta f_{3-\mathrm{dB}} = 0.5$ GHz is the 3-dB bandwidth, is found equal to 20.57. The external Q of the resonator Q_e, which includes the input–output loading effects, can be found from [5]

$$S_{21}\,(\mathrm{dB}) = 20\log_{10}\left(\frac{Q_l}{Q_e}\right) \tag{2}$$

where S_{21} was measured to be 0.36 ± 0.04 dB. The error is attributed to calibration accuracy and fabrication tolerances. Equation (2) gives $Q_e = 21.44 \pm 0.1$. Knowing Q_e and Q_l we can find Q_u from the known relation

$$\frac{1}{Q_l} = \frac{1}{Q_u} + \frac{1}{Q_e}. \tag{3}$$

Using the above definitions and the measured results, Q_u is found to be equal to 506 ± 55 and is very close to the

TABLE I
COMPARISON OF MEASURED Q FOR SEVERAL RESONATORS AT X-BAND

type		size (mm x mm x mm)	Q_u
non-planar	metal (rectangular)	19.8x22.9x10.2	8119
	metal (rectangular)	16x32x0.465	526
planar	micromachined cavity	16x32x0.465	506
	membrane-microstrip	5.3x7.1x0.35	234
	microstrip	2.65x3.55x0.5	125

theoretical value of 526 for a metallic cavity with the same dimensions [7].

The advantages of the proposed micromachined cavity are made clear by the comparisons of Table I (for the first cavity see [8]). As seen by this table, the micromachined cavity has a Q similar to a metallic waveguide cavity with the same dimensions, but it has the advantage of maintaining a planar form that allows for easy integration with microwave integrated circuit (MIC) and monolithic MIC (MMIC) structures. Despite its planar character, the micromachined cavity has a Q that is four times higher than that of traditional microstrip resonators ($Q_u = 125$).

V. CONCLUSION

In this letter, a new resonator structure consisting of input and output microstrip lines and micromachined rectangular cavities is presented. The use of Si micromachining enables the integration of a cavity resonator with microstrip components without affecting the planar character of the circuit. The size and weight of this component is significantly reduced compared to conventional resonators made by metallic cavities, while demonstrating an increased quality factor when compared with other planar resonators. We should note here that this high-Q resonator can be used as a basic element in the design and fabrication of high-Q bandpass filters.

REFERENCES

[1] R. F. Drayton and L. P. B. Katehi, "Microwave characterization of microshield lines," in *Dig. 40th ARFTG Conf.,* Orlando, FL, Dec. 1992.

[2] ——, "Experimental study of micromachined circuits," in *Dig. 1993 Int. Symp. Space Terahertz Tech.,* Los Angeles, CA, Mar. 1993.

[3] ——, "Micromachined circuits for MM-wave applications," in *Dig. 1993 Euro. Microwave Conf.,* Madrid, Spain, Sept. 1993.

[4] R. F. Drayton, T. M. Weller, and L. P. B. Katehi, "Development of miniaturized circuits for high-frequency applications using micromachining techniques," *Int. J. Microcirc. Elec. Packaging,* vol. 3, 1995.

[5] C. Y. Chi, "Planar microwave and millimeter-wave components using micromachining technologies," Ph.D. dissertation, Univ. of Michigan, Ann Arbor, 1995.

[6] J. Cheng, N. I. Dib, and L. P. B. Katehi, "Theoretical modeling of cavity-backed patch antennas using a hybrid technique," *IEEE Trans. Antennas Propagat.,* vol. 43, pp. 1003–1013, Sept. 1995.

[7] R. E. Collin, *Foundations for Microwave Engineering.* New York: McGraw-Hill, 1966, pp. 322–325.

[8] K. Chang, *Handbook of Microwave and Optical Components-Volume I.* New York: Wiley, 1989, pp. 196–199.