High-Q LTCC Resonators For Millimeter Wave Applications

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Abstract — **This paper examines millimeter wave LTCC waveguide resonators and proposes a design strategy for obtaining high-Q factors using a number of loss-reduction and feeding techniques. The modeling and simulation methodology employed has been confirmed through a baseline LTCC resonator design, showing excellent agreement between measurements and predictions. An optimum design was then carried out which yielded an unloaded Q over 1000 at Ka-band, the highest value ever reported for a standard LTCC process.**

I. Introduction

The increasing popularity of millimeter wave (mm-wave) applications has created many challenges for interconnect and packaging technologies. Cofired ceramics have found emerging acceptance in the packaging of microwave integrated circuits due to the ability of fabricating planar microwave structures and embedding passive elements within the laminations of the package. Low temperature cofired ceramics (LTCC) combine the beneficial electrical properties of ceramics at mm-wave frequencies with a precise control of the dielectric thickness.

High-Q resonators are required in mm-wave applications such as LANs, point to point communications and automotive radar. In addition, large volume production, miniaturization and low assembly costs are key requirements. LTCC is a promising technology for embedding the resonator with the MMIC chips [1]-[3]. The implementation of a resonator in LTCC using rows of vias as sidewalls was initially presented in [4]. However it has vias with staggered locations in each layer instead of stacked vias through all the layers. It also suffers from a complex excitation technique and was designed using a planar electromagnetic simulator. All of these drawbacks resulted in a low Q (only ~150) at 5.8 GHz.

Despite the importance of achieving compact, mass producible high-Q resonators at higher frequencies, very little has been published in this area and, to our knowledge, nothing in LTCC. The idea of using via posts to form a resonator is used in [5] to implement a Duroid substrate-integrated waveguide (SIW) having a Q above 500 at 21 GHz. Also, via posts have been used to form photonic band gap (PBG) resonators in Duroid substrates with Q above 700 at 9 GHz [6]. Although these values of Q are impressive, Duroid is not a packaging technology. It is therefore important to investigate LTCC high-Q resonators.

This paper reports on the achievement of a high-Q resonator (Q~1000) in an LTCC environment. A number of Q-enhancing techniques are described along with various excitation techniques. To validate the process, a mm-wave LTCC resonator was designed, fabricated and tested. Excellent agreement between measurements and analytical predictions was obtained.

II. Design of LTCC Waveguide Resonators

The design of LTCC waveguide resonators closely follows that of conventional dielectric filled rectangular waveguide resonators. For a ceramic filled resonator with via walls, the resonant frequency can be obtained based on the effective cavity dimensions proposed by Cassivi et al [5] and the use of rectangular waveguide design equations. However, 3D EM simulations are more suitable to explore complex laminated structures with different excitation techniques. The designs in this paper make use of CST MICROWAVE STUDIO, which is based on the Finite Integration Technique (FIT) [7].

A. Baseline Design

As a basic reference design, a two-port probe-fed LTCC resonator was designed, implemented and measured. A 3D model was built for this rectangular resonator using rows of vias as sidewalls and two metallic covers. Commercial DuPont 943 LTCC material was chosen, having a loss tangent that increases from 0.0026 to 0.0036 over the 26-45 GHz range. Figure 1 presents its layout with the following parameters:

a = 3000 μm (vertical dimension)
b = 600 μm (resonator height, six layers of fired tape)
d = 7600 μm (horizontal dimension)
r = 100 μm (via radius)
p = 600 μm (via pitch)
t = 8 μm (thickness of metal traces)

Each port is excited with a via probe beneath the center conductor of the CPW contact pads.

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This structure is designed to resonate at around 28, 35 and 40GHz according to the excitation of higher order modes (namely; TE103, TE104, and TE105). The quality factor is calculated for each mode, where unloaded quality factor Q_o includes dielectric, conductor, and radiation losses as in Equation 1.

$$\frac{1}{Q_o} = \frac{1}{Q_c} + \frac{1}{Q_d} + \frac{1}{Q_r} \qquad (1)$$

It was found that if the spacing between the vias within the via-walls is less than one tenth of the guided wavelength, radiation losses will be small and the effect of Q_r is negligible [1].

B. Fabrication, Measurements, and Discussion

This LTCC resonator was fabricated by VTT Electronics, Finland, and tested on a microwave probing station connected to a network analyzer. The measured S21 parameter is shown in Fig.2, while Table I compares the predicted and the experimental results, where Q_o has been extracted from the loaded Q measurements as in [8].

It can be seen from Table I that excellent agreement between measured and simulated results has been achieved. This validates our modeling and simulation methodologies for LTCC resonators. The Q values obtained are relatively low and Section III discusses ways to improve performance.

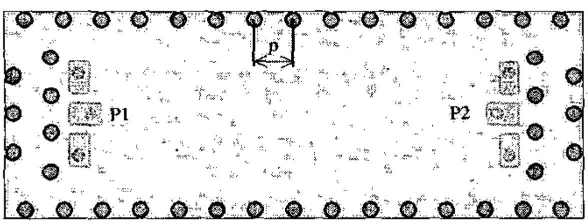

Fig. 1. Baseline 2-port Probe-Excited LTCC Resonator.

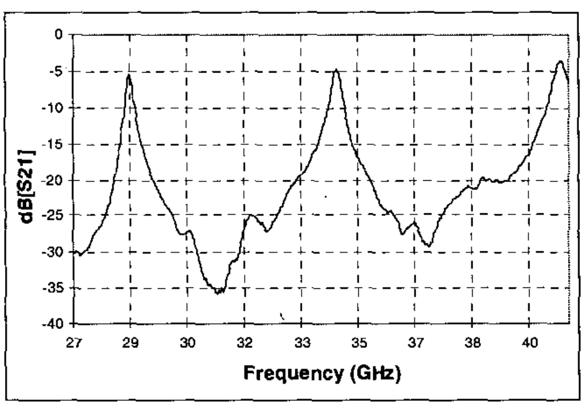

Fig. 2. Measured S21 in dB, for the baseline resonator.

TABLE I
MEASURED VERSUS SIMULATED RESULTS OF THE BASELINE RESONATOR

	Measured		Predicted	
Mode	f_o	Q_o	f_o	Q_o
TE_{103}	28.58	294	28.44	280
TE_{104}	34.44	270	34.22	257
TE_{105}	40.79	254	40.4	242

III. PROPOSED Q ENHANCEMENT TECHNIQUES

The following techniques are proposed to maximize the quality factor of LTCC resonators.:

1) Increasing the height, b, of the resonator will increase the resonator volume and hence increase its Q. It is therefore recommended to include as many layers as possible in the resonator. Altering b does not affect the resonance frequency.

2) Using a ceramic material with the lowest possible loss tangent will obviously increase Q_d and hence the overall Q. The limiting case of this is to put an air cavity inside the LTCC resonator, which will reduce the dielectric losses dramatically. The resonator must then be redesigned in order to obtain the same resonant frequency due to the change in the dielectric constant. A typical LTCC resonator having Q=600 at 20GHz can exhibit a Q of 1000 when it is redesigned and resimulated with an appropriate air filling.

3) Double rows of staggered vias can be used as sidewalls in order to minimize the resonator radiation loss. This technique is particularly useful for high-Q air-filled structures where Q_r is no longer negligible.

4) To obtain a high loaded quality factor Q_L, the coupling between the resonator and its feed line should be sufficiently weak. In this case Q_L may approach Q_o. For LTCC resonators, some possible excitation techniques and their effect on Q_L are as follows:

A. Probe Excitation

A probe may be simply made of a via through only one layer of LTCC, as shown in Fig.3(a). For loose coupling, it is recommended that the probe be away from the maximum of the electric field of the desired mode of resonance.

B. Loop Excitation

Loop coupling may be employed in LTCC as shown in Fig. 3(b). The size and location of the loop with respect to the H field determine the degree of coupling. The construction shown in Figure 3(b) is chosen to give a small amount of coupling for high Q_L.

C. Excitation Using Center Strip of a CPW

Figure 3(c) shows a novel excitation using the center strip of a CPW. The strip is straight and longitudinal but closer to one wall. The entire cavity is excited by the TEM wave of the strip.

The advantage of this method is that MMIC chips in neighboring cavities may be connected easily and with minimal discontinuity to the resonator. Also, tuning of resonance modes using the strip width and length is much easier than with loops or probes because they are constrained by the via diameter and the constant layer thickness.

A potential disadvantage of CPW strip excitation is the excitation of a radial-like mode inside the resonator, which can resonate close to the fundamental TE101 mode. This mode is shown in Fig.3(c) and can be tuned out with proper care by the designer.

The above points show there are many factors, which should be taken into consideration to obtain a high-Q LTCC resonator.

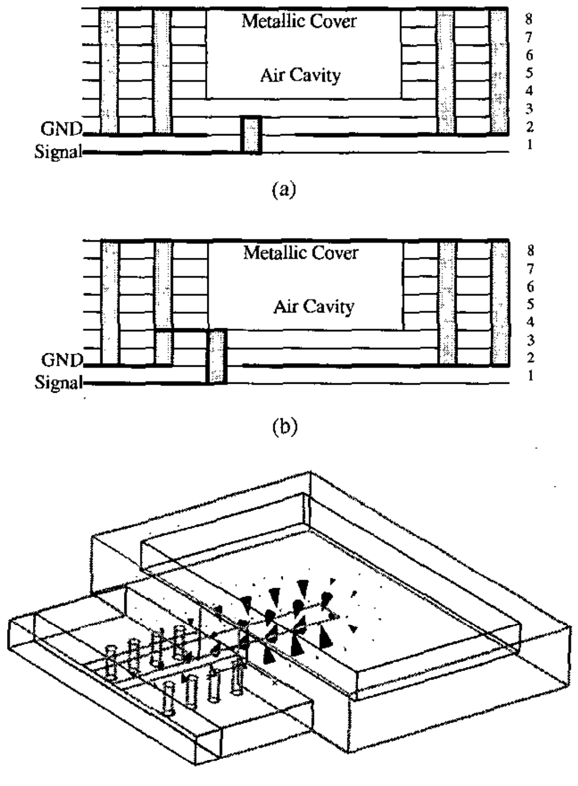

Fig. 3. Possible excitation techniques for LTCC Resonators: (a) Probe Excitation, (b)Loop Excitation, and (c)A proposed center strip of a CPW.

IV. Novel High-Q LTCC Resonator

Based on the preceding discussion, an optimum design has been carried out. The Ferro A6-S LTCC tape system was selected, having ε_r=6.2, and tanδ=0.0013, which is one of the lowest loss LTCC materials. Both the dielectric constant and the loss tangent are confirmed by measurements up to 40GHz. The module thickness was taken to be 0.8 mm, which corresponds to 8 LTCC layers of 100 µm each. The number of layers was chosen to be only 8 as a compromise between low cost and high Q.

As shown in Fig. 4, a microstrip-connected probe feed is used to excite the resonator from the backside metal in order to reserve as many layers as possible for the resonator height b. In this case, the optimized resonator dimensions are: a = 8mm, b = 0.7mm, d = 9.9mm, r = 75µm, and p = 0.4mm, with an air cavity of 7mmx9mm.

Double staggered via rows are used as sidewalls to increase Q but they are omitted from Fig.4 for clarity. For each layer, the catch pads of vias are connected with a strip line to enhance the conductive surface of the sidewalls by about 8%. An air cavity is also created inside the resonator as shown in Fig.5. The predicted and measured resonant frequencies as well as the Q values are reported in Table II.

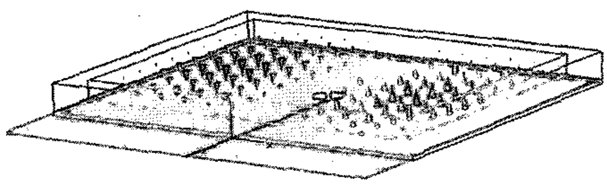

Fig. 4. The optimized Hi-Q LTCC Resonator with probe feed.

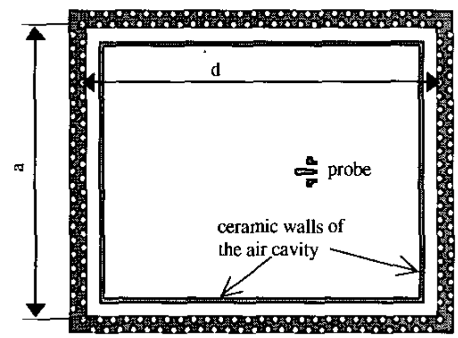

Fig. 5. Layout of an LTCC Resonator with double staggered via walls and Air Cavity.

It is clear that very high-Q values (>1000) have been achieved. In fact, this LTCC resonator is believed to be the first design showing such a high Q in a standard LTCC process for mm-wave applications. The LTCC air cavity resonator shown in Fig. 5 is fabricated and its experimental results are shown in Fig.6. While agreement with predicted values is excellent for the TE102 mode, noisy measurement results prevented certain resonance modes from being observed (TE_{201}, TE_{202}) or did not allow their Q values to be extracted with high accuracy (TE_{101} and TE_{103}) [9].

TABLE II

MEASURED VERSUS SIMULATED Q VALUES FOR LTCC RESONATOR WITH AIR CAVITY

	Measured		**Predicted**	
Mode	f_o	Q_o	f_o	Q_o
TE_{101}	19.81	1206*	20.276	1022
TE_{102}	28.672	1102	29.053	1054
TE_{201}	---	---	32.586	1013
TE_{202}	---	---	37.653	982
TE_{103}	38.674	844*	38.26	886

* Uncertain result due to noisy measurement.

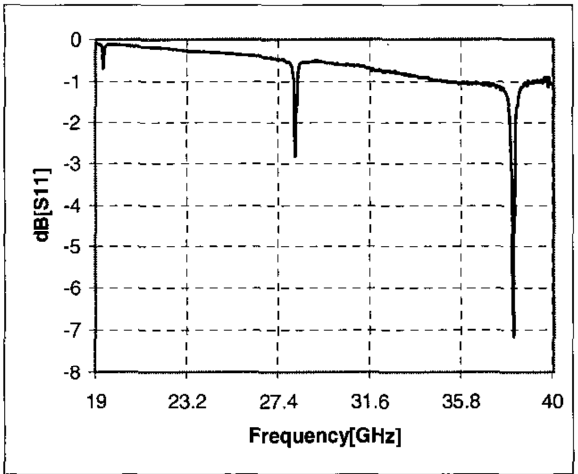

Fig.6. Measured S11 in dB for the LTCC Resonator with air cavity shown in Fig.5.

V. CONCLUSION

In this paper, high-Q LTCC resonators have been investigated for mm-wave applications. Our modeling and simulation methodology has been experimentally validated through a baseline LTCC resonator design at millimetric frequencies. A design strategy for obtaining high Q-factors has been proposed, which includes the insertion of air cavities and novel excitation structures. Based on these techniques, an optimum LTCC resonator design was carried out which yielded an unloaded Q over 1000 at Ka band - the highest ever reported value for a standard LTCC process. Excellent agreement between measurements and analytical predictions was obtained.

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