Multifunctional Substrates for High-Frequency Applications

Xun Gong, *Student Member, IEEE*, William J. Chappell, *Member, IEEE*, and Linda P. B. Katehi, *Fellow, IEEE*

***Abstract*—A substrate that is designed to suppress parasitic modes while at the same time provides high-Q filtering capability is presented. High-density circuits require the integration of multiple functions in very limited space. More specifically, with the design of three-dimensional (3-D) circuits, parasitic effects caused by the excitation of surface waves result in a serious degradation of performance and impose limitations on circuit density and performance. Herein, an effort is presented to use advanced design concepts to enable embedded functionality within a substrate. The presented substrate geometries can easily be extended to 3-D to allow for the development of system-in-a-package which incorporates a high-Q filter bank to provide effective frequency selectivity. To demonstrate this concept, resonators and filters in LTCC are designed, fabricated and measured. Resonators in LTCC with unloaded Q up to 428 were measured. A narrow-band 2-pole filter is realized to show that a function of a relatively high-Q can be incorporated into the packaging. The 2.28% filter has an insertion loss of 1.7 dB due to the low loss nature of the design. Simulation and measurement of the structures are presented with good agreement achieved.**

***Index Terms*—Cavity resonators, low-temperature co-fired ceramics (LTCC), multifunctional, narrow bandpass filters, periodic structure, reduced size.**

I. Introduction

As an ideal material for vertical circuit integration, LTCC has received much interest for many years [1]. But utilizing this material for high-Q resonators and filters is still a challenging problem. Critical front-end elements, such as narrow bandpass filters and low phase noise oscillators, are inhibited by the low quality factor of resonators when embedded inside the packaging material. However, the goal of creating high-Q resonators and filters inside the packaging to help enable the system-in-a-package concept is still appealing as it will further enhance the integration concepts such as that shown in Fig. 1. Traditionally, LTCC resonators and filters are realized by lumped elements or stripline [2], [3]. The quality factor is limited due to the energy leakage by surface wave modes and/or the relatively crowded current distribution. For example a typical half wavelength microstrip resonator has an unloaded $Q <= 200$ at 8 GHz [4]. In this paper, a resonator formed by periodic vias which is consistent with standard LTCC fabrication procedure is presented. The resonators, shown in Fig. 1, allow a means of creating the proper tradeoff between size and unloaded Q to maximize this relation for a given material property.

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X. Gong is with the Radiation Laboratory, Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI 48109-2122 USA.

W. J. Chappell and L. P. B. Katehi are with the Department of Electrical and Computer Engineering, Birck Nanotechnology Center, Purdue University, West Lafayette, IN 47906 USA.

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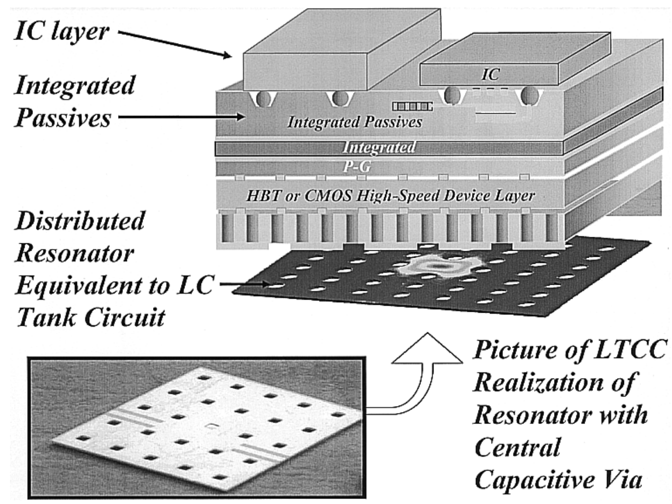

Fig. 1. Picture of proposed system in a package concept with high Q resonant layer formed by periodic via.

In a previous development, a resonator has been created by removing a single via in a periodic array of vias. The periodic array of vias provides virtual inductive walls thus allowing for the creation of a resonance while prohibiting excitation of surface waves in the substrate. The implementation of this resonator in LTCC material is the topic of Section II. These resonators were fabricated using Harris Corp.'s LTCC fabrication facility and measured results indicate a Q up to 428 at 7.73 GHz utilizing this resonator concept in a 16 layer tape cast substrate. As a further advancement, a method of reducing the size of the structure has been developed [5]. Instead of removing the central via, the central via can be reduced in height, creating a capacitive loading which reduces the resonant frequency. Section IV discusses the performance of these capacitively loaded resonators. The high-Q concept is further developed in Section V by showing the extension of a single resonator into a narrow bandpass filter that can be embedded inside packaging. The measured insertion loss of the 2.28% filter is only 1.7 dB due to the high-Q nature of the constituent resonators.

II. Embedded Resonance From Periodic Vias

The first task was to create a resonator out of a periodic array of vias. By fully removing one of the periodic vias or creating a capacitive post, a resonator can be created. Since the current in the resonator is not crowded, a relatively high Q can be achieved

$$\frac{1}{Q_{\text{UNLOADED}}} = \frac{1}{Q_{\text{METAL}}} + \frac{1}{Q_{\text{DIELECTRIC}}} + \frac{1}{Q_{\text{LEAKAGE}}}. \quad (1)$$

The loss that determines the unloaded Q of the resonator is composed of three factors: metal loss, dielectric loss, and leakage loss through the periodic vias. Since the three factors are in parallel, the lowest Q value dominates. The effect of each loss mechanism is determined by full-wave FEM simulations (Ansoft HFSS) in which only one loss factor at a time was accounted. The unloaded Q of each individual simulation corresponds to the numerical value of each loss mechanism.

The leakage loss is the energy that escapes through the EBG lattice due to the finite number of elements in the periodic array. For a via width to period ratio of 25%, two periods surrounding the removed via gives a $\mathrm{Q}_{\mathrm{LEAKAGE}} > 20\,000$, which is much larger than that of the other two loss factors. The $\mathrm{Q}_{\mathrm{METAL}}$ is directly related to the volume of the resonator. If the resonator were made electrically larger to achieve a $\mathrm{Q}_{\mathrm{METAL}}$ that is high enough, the unloaded Q would then be dominated by the $\mathrm{Q}_{\mathrm{DIELECTRIC}}$. One way to do this is to store the fields in an electrically thick substrate. This trend is seen in Fig. 2 which is a plot of the relevant Q terms versus substrate thickness. $\mathrm{Q}_{\mathrm{DIELECTRIC}}$ is simply the inverse of the loss tangent of the material.

For most LTCC materials, $\mathrm{Q}_{\mathrm{DIELECTRIC}}$ is between 100 and 1000. For the Ferro A6-M product that was used in this fabrication, the loss tangent is quoted by the manufacturer to be 2.6e-3 corresponding to a $\mathrm{Q}_{\mathrm{DIELECTRIC}}$ of 384, though this varies slightly depending on the fabrication conditions, with reports ranging as low as 1e-3 (implying a dielectric Q of 1000) [4]. Through correlation with our measurements, we estimated the loss tangent to be 1.82e-3, which gives a $\mathrm{Q}_{\mathrm{DIELECTRIC}}$ of 550. It is this loss of the LTCC material that limits the performance of the resonant components embedded in the packaging.

III. Capacitive Post in Otherwise Periodic Vias

Instead of removing the central via, a reduced height via is used to create a capacitance in the center of the resonant region. The capacitive perturbation to the cavity lowers the resonant frequency. A large-scale model of this resonator has previously been shown to prove the concept of size reduction without a large sacrifice in Q [5]. The amount of resonant frequency reduction relative to a noncapacitively loaded cavity can be up to an order of magnitude. The reduction in electrical size reduces $\mathrm{Q}_{\mathrm{METAL}}$, but has only a marginal detrimental effect on the unloaded Q because it is still dominated by the dielectric loss. This effect is shown in the bottom graph of Fig. 2 for a resonator with a substrate that is 8 layers thick (29.6 mils). This figure also shows the overall effect on the resonant frequency. By adjusting the post height, the optimal size reduction of a resonator can be determined for a given material property. The exact point at which the tradeoff of size versus Q is optimal depends on the application. This investigation proved a means from which the tradeoff could be created.

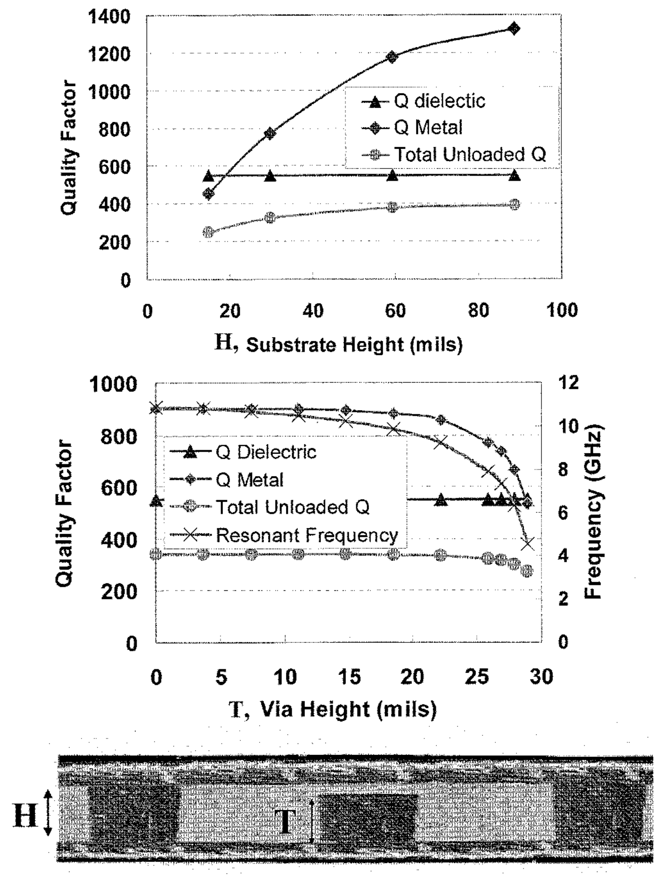

Fig. 2. The effect of substrate height, H, and capacitive post height, T, on quality factor. Bottom: cross section view of a substrate with a reduced height via.

IV. Resonator Results and Discussion

Ferro A6-M LTCC material was used to fabricate designs that were simulated by Ansoft HFSS, utilizing the periodic via concept. The external feeding of the resonators is achieved by matching the magnetic field of short-ended CPW lines to that of the natural resonant mode of the defect resonator (Fig. 1). External Q is controlled by adjusting the length of CPW lines into the resonators, or in other words, by changing the amount of magnetic field coupling. The thickness of each layer was 3.7 mils after sintering. A 50 mil punch was used to provide 41.17 mil vias after sintering. The period of vias was compensated such that it was 160 mils by 160 mils post firing. Due to the shrinkage of the LTCC material, there was an 8% variation in via size and 1% variation in period.

Fig. 3 shows the measured and simulated response of resonators for an 8 layer substrate (29.6 mils). Using the equation, $Q_u = Q_L/(1 - |S_{21}|)$, the quality factor of resonator could be extracted. The measured Q value was found to be close to the eigenvalue solution from the full wave simulation. This correlation was tabulated for multiple substrates' heights (8- and 16-layer substrates) and various capacitive via heights, with the highest measured unloaded Q of 428, as shown in the Table I below.

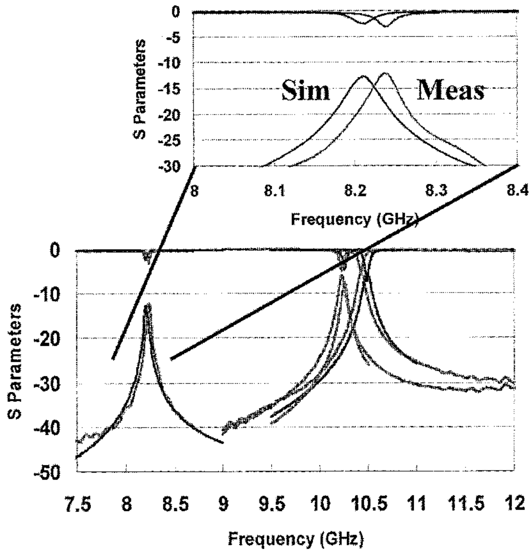

Fig. 3. Measured and simulated response of resonators (from right to left: removed via, 4 and 7 layer via).

TABLE I
MEASURED Q VALUE

Center Post/ Substrate Height (mils)	Res. Freq. Reduction (%)	Eigen Sol. Unloaded Q	Extracted Unloaded Q
0/29.6	0	321	300
14.8/29.6	2	320	336
25.9/29.6	22	303	334
0/59.2	0	385	380
51.8/59.2	27	351	428

The largest reduction in resonant frequency was from 10.43 GHz to 7.73 GHz (a 27% reduction) for a capacitive via created from 14-layers out of a 16-layer substrate. The finished substrates were then coated in standard post-fired thick silver film from Ferro using screen printing techniques. In the simulation, the A6 was assumed to have a dielectric constant of 5.65 and a loss tangent of 1.82e-3.

V. Embedded Multipole Filter

A two-pole filter was created by placing two capacitive vias 87.5% through the substrate two periods away from each other (Fig. 4). Using the reduced height via as a resonator instead of removing the via completely reduced the resonant frequency from 10.43 GHz to 8.16 GHz. The via sizes and period were chosen to provide a 2% bandwidth. The length of CPW lines were adjusted to provide a critical external coupling. The resulting filter response was shown in Fig. 4 which compared a simulation with measurements of the fabricated filter. The bandwidth of the measured filter was 2.28%, which was slightly larger than the 2.0% designed bandwidth. The variation in bandwidth is hypothesized to be the result from the shrinkage of the via, particularly the via separating the two capacitive posts. The measured insertion loss was 1.7 dB while the simulation indicated that 2.3 dB insertion loss for this filter was expected. This favorable response came from the slightly larger bandwidth of the filter, and possible variation of dielectric loss which might be better than the value used in simulation.

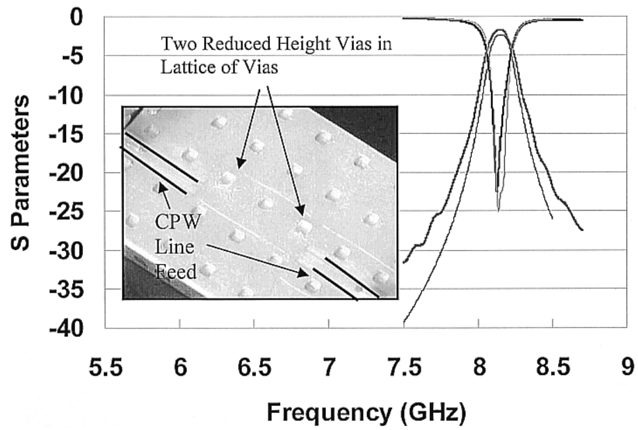

Fig. 4. Two-pole filter with 1.7 db IL and 2.28% BW.

VI. Conclusions

A multifunctional package has been presented to provide high-Q frequency selectivity using periodic vias by standard LTCC fabrication procedure. Unloaded Q's up to 428 were measured. A size reduction of 27.8% was achieved with a partially removed via. A multipole filter was created by coupling two capacitive post resonators together and showed good insertion loss (1.7 dB) for a narrow bandwidth (2.28%). The resulting structures are consistent with standard LTCC fabrication procedure and therefore can be easily integrated with other circuits to form three-dimensionally integrated, high performance systems.

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