A Novel Periodic Structure for Suppression of GHz Simultaneous Switching Noise Coupling Using LTCC Technology

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***Abstract*—There are several components which are designed for suppressing simultaneous switching noise coupling such as power bridge, ferrite bead, and π filter, but all of them are suffered from limited bandwidth. To solve this problem, a novel structure in LTCC technology is proposed. After appropriately designing the band gap, the noise beyond the ferrite bead limit could be suppressed by this structure. The structure is composed of three unit cell, and its size is 1.2mm×3.8mm×0.728mm. The stop band is from 2GHz to 5.5GHz and is validated both by simulation and experiment. Over 40dB noise reduction could be achieved by this structure.**

Key words: LTCC, power integrity

I. Introduction

Simultaneously switching noise (SSN) or Ground bounce noise (GBN) is becoming a major concern in high speed digital circuit [1] as the transient speed of IC becomes faster. The switching noise propagates through the entire power planes, and the analog circuit may not work well due to such kind of noise coupling. In order to isolate power noise effectively, dividing the power plane into power islands is usually employed. The power island are connected with a narrow neck, or conducting bridge. The noise propagation is preventing from this conducting bridge by varying the length, width and location to have the high impedance at high frequencies and low impedance at DC. [2] In addition to bridge, ferrite bead also has the same effect. At the low frequencies, power and reference plane could be viewed as a shunt capacitor on both side of bead. The π filter is formed and could be used to filter noise. However, the π filter failed at high frequency due to the distributed resonances of the power planes. To overcome this obstacle, the shunt capacitor in the π filter is characterized by lumped capacitors and has been studied in [3]. But this method suffers from limited bandwidth in noise reduction because of the equivalent series inductance (ESL) for capacitor and the saturation of frequency response for ferromagnetic material.

In this work, a novel structure for SSN coupling suppression in LTCC technology is proposed. The structure is composed of shunt multilayer capacitor and series transmission line periodically. The rejection band can be predicted using the periodic structure boundary. After appropriately designing the band gap, the noise beyond the ferrite bead limit could be suppressed by this structure. Over 40dB noise reduction could be achieved by this structure.

II. Design concept

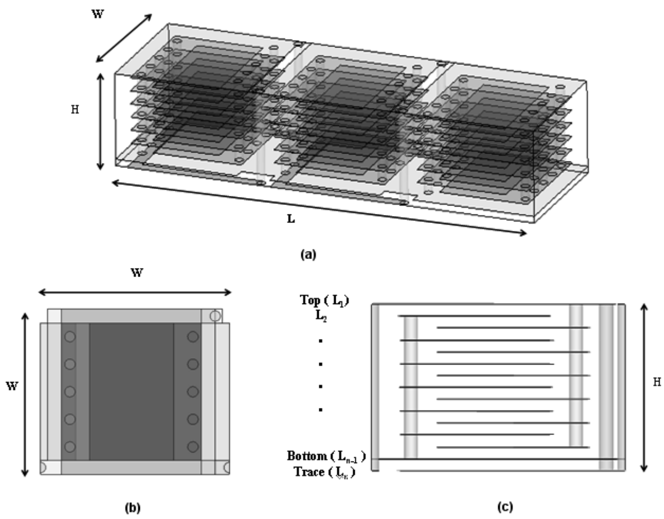

Fig. 1 (a) Proposed structure (b) Top view (c) Side view

Based on the concept of π filter as mentioned before, shunt capacitor and series inductance form a filter to impede noise. With the increasing clock frequencies of digital circuits, the range of noise frequency is from dc to several gigahertz. The noise range is so wide that we desire to have the wilder stop band bandwidth and more stop bands. Periodic structures support slow-wave propagation, and have stop band characteristics similar to those of filters. Besides, the band gap would appear periodically when using the transmission line in the periodic structure design. Under the consideration above, a novel structure is proposed as shown in Fig. 1. The unit cell of structure is composed of shunt multilayer capacitor and series transmission line. Three unit cells cascade periodically to form the structure. In the Fig. 1, part (a) is the proposed structure, its size is W mm×L mm×H mm. Top view of the structure is shown in the part (b), the area of unit cell of structure is W mm × W mm. Total number of layers n and height H is denoted in the part (c). The power at the top layer L_1 for different cells is connected by via and the transmission line at the bottom layer L_n under the ground layer L_{n-1}. The corresponding geometrical parameters for this structure are denoted by (W, L, H, n). An example of design parameter is (W, L, H, n) = (1.2mm, 3.8mm, 0.728mm, 14) with 3.2mm long transmission line with ⊏ shape.

III. Theoretical Model And Stop Band Prediction

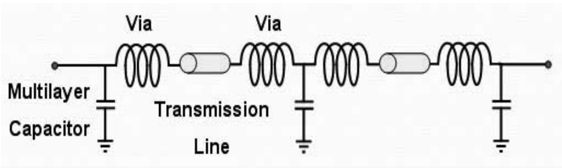

Fig. 2 Simple modeling of the proposed structure

As shown in Fig. 2, a simple model is proposed. The lump capacitor denotes unit cell of multilayer capacitor and the value is given by the parallel-plate equation $C = N\varepsilon_0\varepsilon_r A/d$ .The connection between unit cell and unit cell is described by via and the transmission line whose impedance is decided by the commercial tool Tx-Line Fig. 3 shows the insertion loss $|S_{21}|$ from simple modeling and full-wave simulation tool HFSS. As can be seen, the modeling is not valid because it can't predict the mode at about 6 GHz and the mode of lower frequency shift. To correct this problem, the multilayer capacitor of unit cell should not be viewed as a lump capacitor anymore. The modeling of multilayer capacitor is modified and is shown in Fig. 4. π model is used for each plane. L_P is an inductance resulted by the loop of the Layer p plane and the ground at the bottom, and the capacitance between Layer p and Layer $p+1$ is denoted by C_{PP+1}. The most important thing is that the mutual inductance between layer and layer has been taken into account [4]. In this way, significantly better consistency between modified modeling and HFSS could be seen in Fig.3, the modeling is effective now and could be used to analyze in the following.

In order to efficiently predict the band gap, the analysis of infinite periodic structure is necessary. Assuming that the structure in infinitely long or perfectly matched at the end (hence, no reflections), invoking Floquet's theorem, for the cell of the structure we have

$$\begin{bmatrix} V_n \\ I_n \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_{n+1} \\ I_{n+1} \end{bmatrix} = \begin{bmatrix} V_{n+1}e^{\gamma d} \\ I_{n+1}e^{\gamma d} \end{bmatrix} \quad (1)$$

The ABCD matrix in (1) is the matrix of unit cell which is composed of 14 layers capacitor, via and transmission line. The dispersion relation can be calculated by setting the determinant of the coefficient matrix equal to zero. The calculated dispersion diagram for the structure is shown in Fig.5. It is shown that the first stop band is from 2 GHz to 5.5GHz.

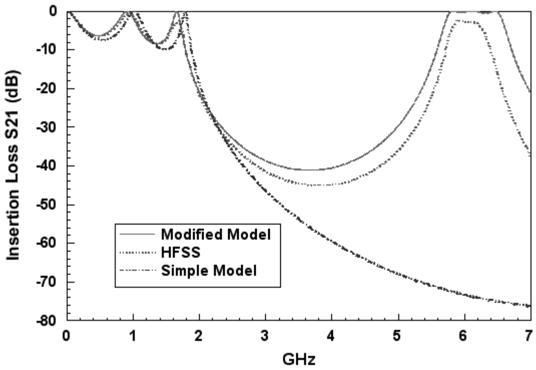

Fig. 3 Insertion loss of simple, modified modeling and HFSS

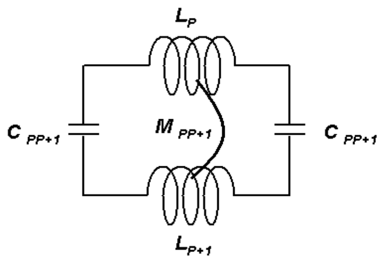

Fig. 4 π model for the plane of multilayer capacitor

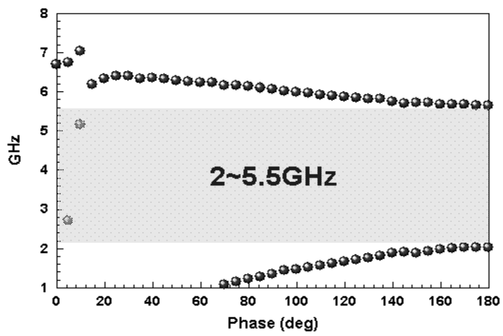

Fig. 5 Dispersion diagram for the proposed structure

IV. PI Performance And Co-Simulation

Exploring the performance of structure at high frequencies, LTCC process with relative permittivity 7.8, relative permeability 1, and dielectric loss tangent 0.005 is used. A test sample with the same geometrical parameters as mentioned before is fabricated. Good consistency is seen in Fig. 6 which shows the measured and simulated result for |S21|. The bandwidth is defined as the frequency range in which |S21|<-

25dB. It is observed that the stop band is between 2 to 5.5 GHz which agrees with the dispersion diagram as shown in Fig. 5. At least 25 dB of SSN suppression can be achieved within the stop band in the designs.

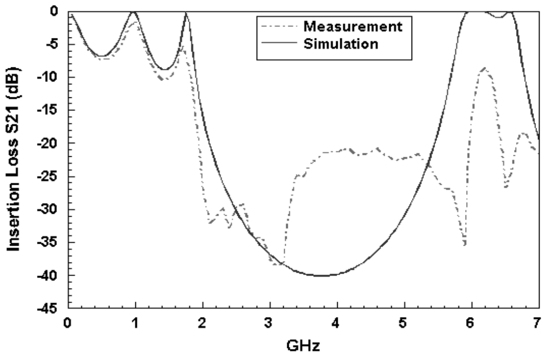

Fig. 6 Measured and simulated |S21| for the proposed structure.

The noise suppression capability is also verified in the frequency domain. A chip circuit LNA and package co-simulation environment is established as shown in Fig. 7. Instead of stable power voltage 1.8V, a clock swings from 1.6V to 2V is used to simulation 4.6 GHz SSN or GBN. The C-band LNA is designed in TSMC 0.18um with the resistance load 50 Ohm, and its input signal is a 5 GHz sin wave with amplitude 0.01V. The DC power is connected to the LNA through a device under test (DUT). There are three cases for DUT. One is the reference case that no circuit is used to impede power noise. Another is the proposed structure. The third is a π filter, which the modeling method of ferrite bead is from [5], and the equivalent model of both two capacitors GRM0335C1E120JD01 are released by MURATA. Fig. 8 shows the LNA output signal spectrum transformed from transient simulation in ADS. For the reference case, the power of noise is -30dBm. Because the noise frequency 4.6 GHz is close to the 5 GHz input signal for LNA, it may not work normally. It is obvious that about 40dB suppression is achieved by the proposed structure as the π filter does nothing. The suppressive ability is better than π filter at GHz frequencies.

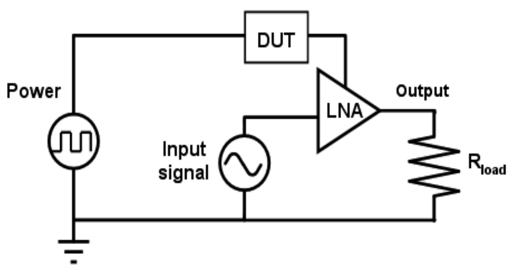

Fig. 7 Model for chip circuit LNA and package co-simulation.

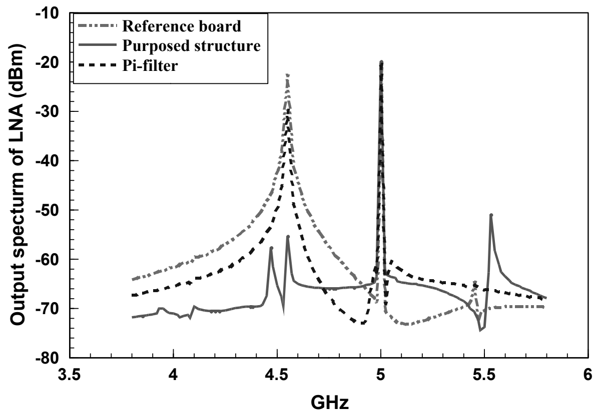

Fig. 8 Simulated output spectrum for the operated LNA with 4.6 GHz power noise

V. Conclusion

In this paper, a design for GHz SSN coupling suppression is proposed and has been implemented in LTCC technology. Compared to the ferrite bead, higher frequencies noise could be suppressed by the proposed structure. The equivalent lumped model is also established. Good agreement is seen between the modeling, simulation, and measurement. The suppressive ability is also verified in the frequency domain. In the chip-package co-simulation, over 40dB noise suppression on the C-band LNA output has been seen for the proposed structure.

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