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Design and Implementation of the Embedded Capacitance Layers for Decoupling of Wireless Sensor Nodes

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Abstract

In this paper, the embedded capacitance material (ECM) is fabricated between the power and ground layers of the wireless sensor nodes, forming an integrated capacitance to replace the large amount of decoupling capacitors on the board. The ECM material, whose dielectric constant is 16, has the same size of the wireless sensor nodes of 3cm*3cm, with a thickness of only 14µm. Though the capacitance of a single ECM layer being only around 8nF, there are two reasons the ECM layers can still replace the high frequency decoupling capacitors (100nF in our case) on the board. The first reason is: the parasitic inductance of the ECM layer is much lower than the surface mount capacitors'. A smaller capacitance value of the ECM layer could achieve the same resonant frequency of the surface mount decoupling capacitors. Simulation and measurement fit this assumption well. The second reason is: more than one layer of ECM material are utilized during the design step to get a parallel connection of the several ECM capacitance layers, finally leading to a larger value of the capacitance and smaller value of parasitic. Characterization of the ECM is carried out by the LCR meter. To evaluate the behaviors of the ECM layer, time and frequency domain measurements are performed on the power-bus decoupling of the wireless sensor nodes. Comparison with the measurements of bare PCB board and decoupling capacitors solution are provided to show the improvement of the ECM layer. Measurements show that the implementation of the ECM layer can not only save the space of the surface mount decoupling capacitors, but also provide better power-bus decoupling to the nodes.

Introduction

Noise on the power bus caused by a rapid current change is a common problem in high speed PCB design [1]. Decoupling capacitors are commonly used to mitigate the power supply noise. Typically the surface mount (SMT) capacitors are used for decoupling. The huge amounts of the SMT capacitors not only take up circuit space but also increase the design difficulty and unreliability. Moreover, the working frequency of the SMT capacitors is limited due to the parasitic inductance brought by the interconnection.

Embedded capacitance could be an effective alternative to the discrete decoupling capacitors [2] [3]. This method makes full use of the power and ground planes of the PCB to form an embedded capacitance [4]. To improve the capacitance density, the thickness of the dielectric material is decreased and the high dielectric constant material is selected [5]. There are many publications to characterize the impedance and other parameters of the PCB with embedded capacitance [6] [7] and its applications [8] [9]. However, there are very few applications to use the embedded capacitance material in the wireless sensor network node communication, which operates on radio frequency (RF) and has a critical requirement of circuit space. This paper aims to characterize the PCB board with embedded capacitance material, and implement a RF communication system on this board. Finally the performance of the embedded capacitance is examined by the measurements of time and frequency domains of a working wireless sensor node.

Principle of the Embedded Capacitance Material (ECM)

For ordinary PCB, the discrete surface mount capacitors are used for power supply noise decoupling. Noise caused by other circuit elements is shunted through the capacitor, reducing the effect they have on the rest of the circuit. The working principle of discrete decoupling capacitor, connected between the power (red in Fig.1) and ground (blue in Fig.1) layers, is shown in the top part of Fig.1.

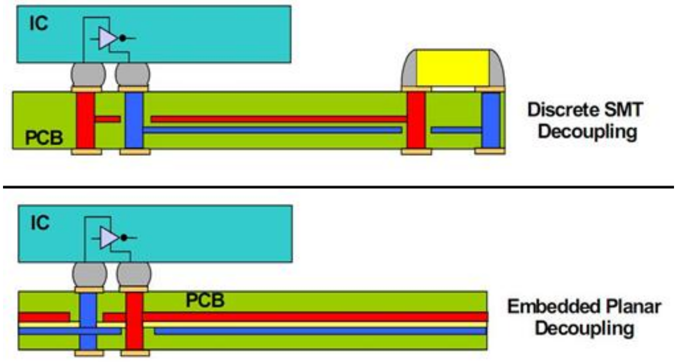

Fig. 1. Top: Discrete surface mount capacitor for decoupling
Bottom: Embedded planar capacitor for decoupling

The idea of embedded planar decoupling is illustrated in the bottom part of Fig.1. The dielectric constant material (yellow in Fig.1) forms parallel plate capacitor with the help of the conducting layers (power and ground). Fig.2 shows a typical structure of a parallel plate capacitor. So the embedded capacitance provided by this method potentially can be used for decoupling and replace the discrete decoupling capacitors.

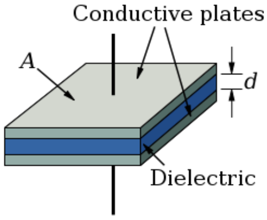

Fig. 2. Parallel plate capacitor model

However, the application of the embedded capacitance was limited due to its low value of capacitance for ordinary PCB boards. The following formula provides a fast to calculate the capacitance of a planar plate capacitor:

$$C = \frac{\varepsilon_r \varepsilon_0 A}{d} \qquad (1)$$

Where ε_0 is the permittivity of free space, ε_r the relative permittivity of the dielectric material or the dielectric constant of the material, A the area and d is the distance between two plates.

Take a FR4 (dielectric constant=4) PCB board of size 3cm by 3cm and thickness of 1mm for example, the capacitance of the embedded layers is as low as hundreds of pF only. Usually the level of several tens or hundreds of nF of capacitance is required for the microcontrollers and radio chips power supply decoupling purpose.

From the formula (1), it is obvious that there are two ways to increase the capacitance. One is decreasing d, another is increasing ε_r. The embedded capacitance material (ECM) implements both two ways by building a 14 μm thick layer of ceramic-filled epoxy(C-Ply, whose dielectric constant is 16) sandwiched between two layers of copper foil. Capacitance density of 1.0 nF/cm^2 is achieved. This level of capacitance density is useful for high speed digital, signal filter designs and power supply decoupling.

Design of the WSN mote with ECM layers

A wireless sensor network (WSN) consists of spatially distributed autonomous sensors to cooperatively monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutants. In addition to one or more sensors, each node in a sensor network is typically equipped with a radio transceiver or other wireless communications device, a small microcontroller, and an energy source.

There are strong needs to miniaturize the WSN nodes in lots of application such as medical and house monitoring. Usually there are lots of decoupling capacitors in the WSN nodes for the power supply of the micro-controllers and radio chips, which becomes a limit factor of integration and optimization of the motes. The WSN nodes used in this paper are the Tyndall 25mm motes, which operates in the ISM frequency band with an ultra-low power micro-controller. The Tyndall mote with embedded capacitance material aims to utilize the advanced dielectric technology to replace the discrete decoupling capacitors finally.

Since there were existing designs for the Tyndall motes on PCB board with the traditional FR4 substrate, a re-design was not required but a convert method from PCB board to ECM design should be developed. Notice that every power pad of the decoupling capacitors had nearby vias to the power plane and the ground pads were shorted to the common ground on the component layer, the embedded capacitance could take effect with the help of these two pads.

Thus the simplest way to convert the design would be just remove the discrete surface mount components and keep the pads on the board. This method provides a fast and reliable approach to design ECM boards for WSN applications. However, in the future development, the space of the discrete capacitors saved should be fully used to place other components or routines to get the purpose of miniaturization.

Not only the PCB layout and component placement, but also the board layer stackup should be re-considered. Fig.3 gives the details of the layer stackup. The two rectangles present two layers of the ECM material, formed by GND, PWR and ECM dielectric.

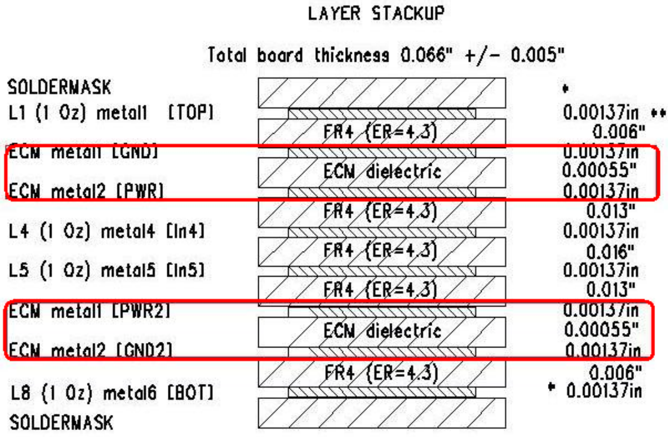

Fig. 3. Layer stackup of the WSN mote with ECM layers

Calculation result of a single ECM layer using form (1) is around 5nF. The reason to put two ECM layers is to improve the value of the embedded capacitance because capacitors in parallel would result in a larger capacitance. Thus the total capacitance of the ECM structure should be the level of 10nF.

Characterization of the ECM boards

The ECM boards were fabricated with the new design done in the previous chapter. Characterization of the bare ECM boards is then performed to make comparison with traditional PCB boards.

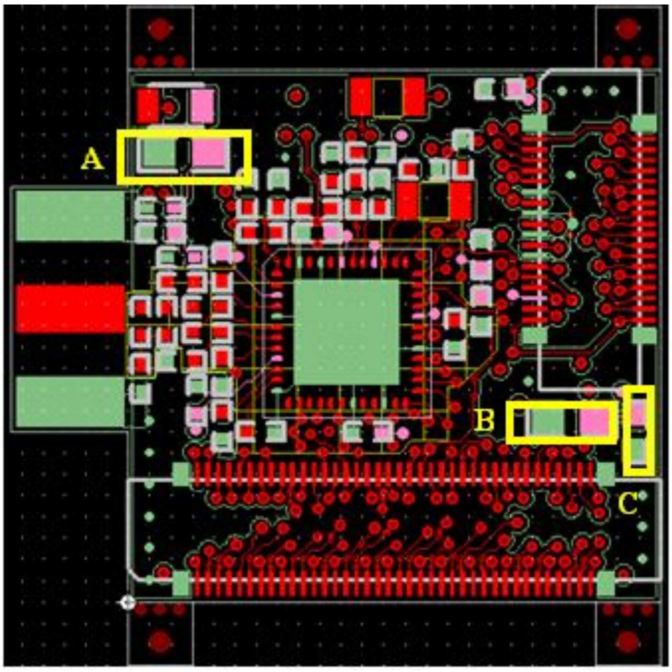

Fig. 4. Layout view for the board characterization

Fig.4 shows the board layout to be tested, where pink areas are the power pads, green the ground connection and red the signal connection. All the decoupling capacitors should be placed between pink (power) and green (ground) pads.

Three test points, named as A, B and C in Fig.4, were selected to perform characterization of the bare boards. LCR meter was used to measure the capacitance and the parasitic inductance of the boards. Fig.5 illustrates the equivalent circuits of the parameters measured.

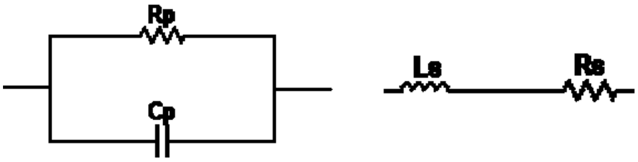

Fig. 5. Equivalent circuits of the capacitance and inductance measurements by the LCR meter.

Fig.6 provides Cp measurements of the ECM and ordinary PCB boards. It is clear that ECM provides higher density of capacitance than FR4 PCB. The capacitance of the ECM board is 10nF below 5MHz, which matches the previous calculation well. At the frequency range of 5 to 15MHz, the capacitance value drops dramatically, which indicates the working frequency is approaching the material's resonant frequency.

Thus from the Fig.6, the resonant frequency is close to 20MHz since at that frequency the capacitance decreases to pF level. There is no need to work at higher frequency because above the resonant frequency the capacitor is working as inductive component rather than capacitive.

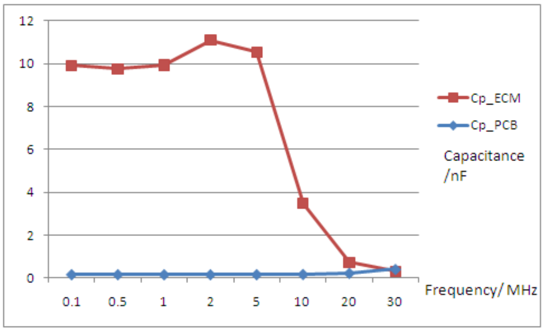

Fig. 6. Measurements of Cp for ECM and PCB boards

Fig.7 shows Rp measurements. Rp represents the level of leakage and should be as large as possible. Rp of both boards drop to a low level of tens of ohm above 20MHz, which means not suitable for working at higher frequency than 20MHz.

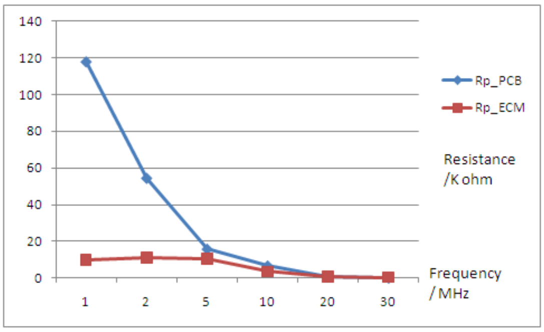

Fig. 7. Measurements of Rp for ECM and PCB boards

Fig.8 shows Ls measurements of the LCR meter. Ls represents the parasitic inductance and should be as small as possible. Ls of both boards are of the value of several nH. Combined with the results of Fig.6, we can conclude that ECM provides much higher capacitance than PCB board, without bringing large parasitic inductance like surface mount capacitors.

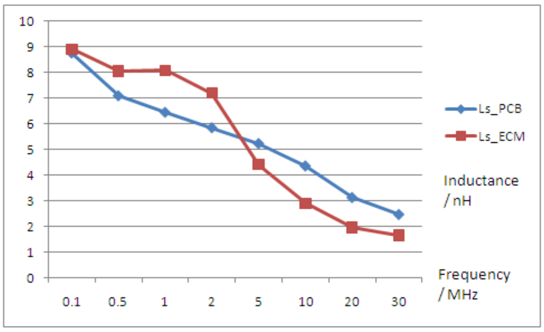

Fig. 8. Measurements of Ls for ECM and PCB boards

Fig.7 shows Rs measurements. Rs should be as small as possible since Rs is parallel with Ls. Rp of both boards keep at a rather low level of 0.1 – 0.2 ohm.

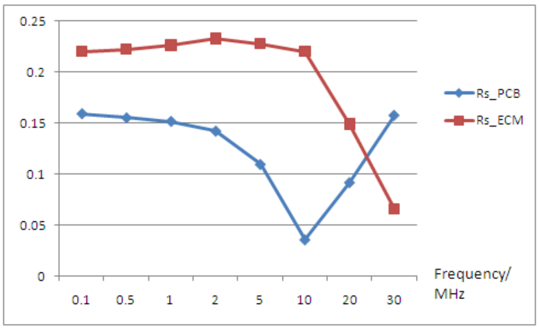

Fig. 9. Measurements of Rs for ECM and PCB boards

Measurements of the WSN motes

In this chapter, electrical measurements are carried out for the Tyndall WSN motes. Fig.10 is the mote to be tested of power noise. The red rectangles present the surface mount decoupling capacitors replaced by the ECM layers. Lot of circuit space is saved and the electrical connection is simplified.

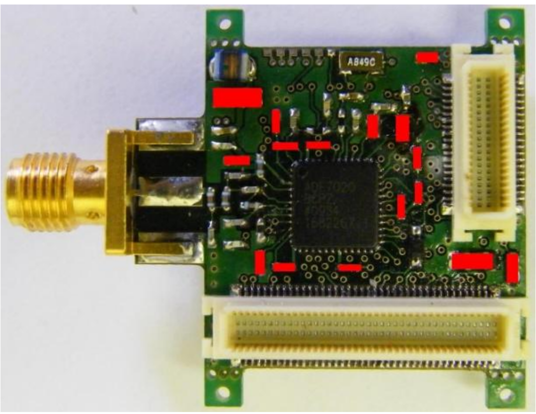

Fig. 10. Tyndall 25mm mote

To show the performance of decoupling, measurements of power supply noise of the time and frequency domains are provided.

In Fig.11, the black curve is the time domain measurement of power noise of the ordinary PCB mote without any decoupling capacitors mounted. The noise peak can reach as high as 50mV and will bring in uncertainty and instability to the circuits.

The blue curve shows the measurement of the PCB board with SMT capacitors. The peak value is reduced to 15mV, which means a big improvement of the power noise.

Thirdly the red curve is for the ECM board. The peak value and average value are even smaller than the blue curve, which indicates the ECM board has the best performance in power supply decoupling.

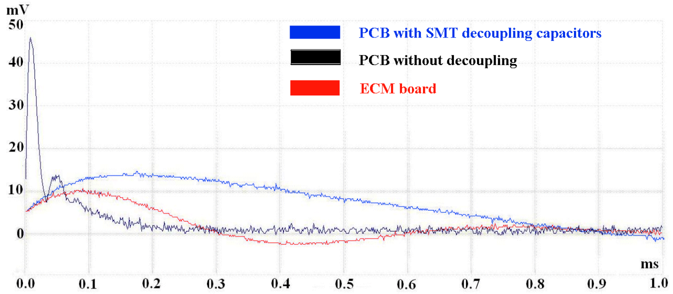

Fig. 11. Time domain measurements of the power noise

Frequency domain measurements are also carried out. In Fig.12, the black curve is the frequency domain measurement of power noise of the ordinary PCB mote without any decoupling capacitors mounted. The noise below 2.5MHz of the black curve is higher than the two others.

The blue curve shows the measurement of the PCB board with SMT capacitors, while the red curve is for the ECM board. It is difficult to compare the blue and red curves. However, both boards work better than the PCB without decoupling.

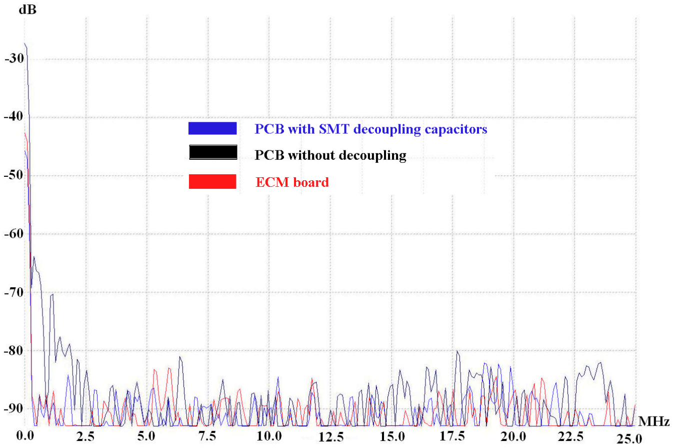

Fig. 12. Frequency domain measurements of the power noise

Based on the observation of time and frequency domains, ECM provides great improvement of power noise from PCB without decoupling and is slightly better than the SMT decoupling solution.

Conclusions

In this paper, the principle of the embedded capacitance material (ECM) is presented and its application in power noise decoupling is studied. A fast and reliable method to convert traditional PCB design to the ECM structure is provided. After fabrication, characterization of the bare ECM board is carried out to compare with the bare PCB board, showing the ECM has much higher capacitance density and can provide a capacitance value of 10pF for decoupling for 3cm by 3cm WSN motes. Finally the measurements, both in time and frequency domains, of the working WSN motes with different boards prove that the ECM can provide better decoupling effect than the SMT decoupling capacitors.

Acknowledgments

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