ABSTRACT

This paper investigates the Electromagnetic (EM) radiated emissions in multilayer Printed Circuit Boards (PCB's) with respect to the decoupling and intrinsic board capacitances of power distribution. Extensive measurements are performed and a simplified mathematical model is developed to estimate these emissions. The problem of the AI-noise is also addressed and is presented in a companion paper [1].

INTRODUCTION

The switching currents and the emissions arising from them in multilayer PCBs, are difficult to describe accurately, as they require detailed parameterisation of both the electrical and physical characteristics of the PCB. In [1] a circuit model was developed for the switching noise. Approaches taken to reduce the radiated emissions are broadly in line with those taken to reduce DI-noise. The principal sources of emission can be grouped as due to:

1 Current loops arising from the components and loads and their connections to power and ground supplies. Decoupling capacitors, where present, also create current loops, as do the interconnection signal lines which drive the components (differential mode radiation).

2 If radiation due to the interconnections are minimized, the voltage gradient between power planes can give rise to strong radiated emissions when resonances of the PCB occur. This is particularly evident in the case of an I/O cable attached to the PCB (common mode radiation).

The main objective is to have a well-designed board which will limit the impulsive noise present and number of decoupling capacitors and hence their associated emissions.

TEST SET-UP DESCRIPTION

In order to investigate the various design choices available in multilayer PCBs two similar boards were constructed [1]. The first board was made using a standard lay-up (S1D), Fig. 1a, while the second utilised Buried Capacitance Technology (BC) which maximises the intrinsic capacitance of the power distribution planes and minimize the parasitic inductance, Fig 1b. Note that the BC is a 6-layer board, and is so called because of the interplane capacitance of the buried Vcc and Gnd layers. The board capacitance of the standard lay-up was 6 nF, whereas the distributed capacitance of the BC board was 124nF. This valuable increase is possible due to a special type of laminate which permits the Vcc and Gnd planes to be placed close together, and can significantly reduce the need for discrete decoupling capacitors. It should also be noted that the effective frequency range of a real decoupling capacitor is limited by its self-resonance caused by the inductance present in its leads: above this frequency the impedance is inductive. The interplane capacitance has a greatly extended frequency of operation due to the extremely low value of inductance of the power and ground planes. An actual board will have many resonances associated with the board capacitance and the decoupling and power-supply bulk capacitances. The presence of the lead inductances shift the resonance frequencies and reduce the effectiveness of the decoupling capacitors in reducing emissions [3].

On both PCBs the same functions are implemented with identical layout, as illustrated in Fig. 2. Each of the eight outputs of the fifteen components (74AC244) were loaded by 56 pF in parallel with 255 Ω [1]. A representative diagram of the associated current loops is given in Fig. 3. Note that the loop is formed by the electrical signal path. In the case of multilayer boards with power distributed by equipotential planes, the loop area depends less on the physical placing of components and capacitors than in the case of boards in which the power is not distributed by planes. In multilayer boards this loop typically will have a reduced area, and the currents due to the high frequency switching currents can be considerably reduced with respect to PCB without power planes.
A series of emission measurements were made on the two boards. A total of 24 ports of the components U5, U7 and U9 were switched simultaneously. For a standard board a comparison was made between the cases without decoupling capacitors and with 100 nF PTH capacitors inserted close to each of the 15 components. In order to measure the emissions from the board only, attention was paid to the type of power supply. Switching power supplies have significant EM emissions, and therefore the boards were powered by a battery pack. The component buffers were switched using a 8 MHz shielded oscillator which was itself powered by an internal battery (see Fig. 7). Some preliminary tests were performed in a 3m semi-anechoic chamber. The antenna was placed at 3 m, Fig. 8. The boards were rotated 360° around their vertical axis in steps of 45°. Little variation in the radiated field strength was noted as the radiation pattern was more or less circular. The boards were then placed in the position indicated in Fig. 8.
The Fig. 4–5–6 show the emissions with the antenna in horizontal and vertical positions for the three cases of: the standard board without and with decoupling capacitors and the buried capacitance board, respectively.

**Standard Board without decoupling capacitors:**

In Fig.s 4a, 4b the emission level reaches 55 dBμV/m for the horizontally polarised field and 60 dBμV/m for the vertically polarised field. The horizontal emission profile displays a certain uniformity in the frequency range 50–250 MHz, while peaks at 40 MHz and 48 MHz are evident for the vertical field measurement. The emissions are between 40 dBμV/m and 60 dBμV/m up to 500 MHz.

**Standard Board with decoupling capacitors:**

With a 100 nF placed near each of the 15 components on the standard board, the same procedure as above was followed. The results are shown in Fig. 5a, 5b. Comparing the two sets of graphs (Fig. 4 & 5), a slight reduction in the emissions is noted for the board having decoupling capacitors. In detail, comparing Fig. 4b with Fig. 5b (antenna in vertical position), it can be observed as emissions up to 40 MHz get lower, while frequencies near 100 MHz get higher. In fact the dynamic behaviour of the Vcc noise in the case of standard board with decoupling is faster than that without decoupling as during the L to H switch frequency oscillation turns from 25 MHz to 50 MHz [1]. Another reason is that the PTH capacitors have an associated inductance of the order of...
5 nH which reduces the effectiveness of the action of the capacitances in lowering emissions in the high frequency region [3].

**Buried Capacitance Board:**

The same measurement was performed with the buried capacitance board and in this case the reduction of the emission is more evident (Fig. 6a, b, c). This is due to the fact that the distributed decoupling capacitances have a negligible inductance. The emission profile varies between 20 dBuV/m and 55 dBuV/m with an average around 40 dB. The peak of emissions near 150 MHz (Fig. 6b) is due to the resonance of the board, and this was confirmed by calculating the impedance of the board vs frequency [4].

**Comments**

For the set-up in question the emissions are principally of the differential-mode type, as there are no cables attached and the power supply is a battery. For the vertically polarised electric field it can be seen that the emissions from the buried capacitance board are generally lower (6 - 20 dBuV/m) than for the other two cases. For the horizontally polarised electric field the emissions are lower for some frequency ranges. It can also be seen that the presence of decoupling capacitors on the standard board does not significantly reduce emissions. This can be explained by the fact that, in this case, the interplane capacitance of the standard board is sufficient to supply the required switching currents, that the action of the decoupling capacitors is delayed by parasitic inductances [3] and that the loop current in the active components is nearly affected by the kind of filtering. In addition, the loop area associated with the decoupling capacitors is much smaller than that associated with the components. Hence, the differential emissions due to the decoupling capacitors' loops are less significant than the emissions due to the components' loops and the board's voltage gradient (∆Ve). The last being dominant only for resonance frequencies. This does not necessarily mean that the decoupling capacitors serve no purpose as far as emitted radiation is concerned, as the efficiency of decoupling is strongly affected by its ESL (Equivalent Series Inductance). Besides, considering that there is more noise present on the board without decoupling capacitors [1], with respect to the standard board, they may be of use in the case of common mode emissions.

**PCB with a wire attached**

In order to further investigate this point, the set-up was modified by the attachment of a wire to the ground plane of both boards. The wire was extended horizontally for 1.1 m and was not terminated at the far end, Fig. 9. Such an arrangement can be used to produce a large common mode component in the emissions. The results, Fig. 10, 11, 12 show a marked increase in the emissions near 72 MHz. This frequency corresponds to the 1/4 resonance of the wire length and is due to common mode radiation. This is more evident from Fig. 13 where the peak emission profile for standard board with and without decoupling and BC board are overlaid. Again, the buried capacitance board has lower emission levels. For the standard board the difference in emissions with and without the decoupling capacitors is very small, indicating that in this set-up the decoupling capacitors have little influence on the emitted fields due to the high inductance of the decoupling capacitors. This behaviour can be explained looking at Fig. 11 of [1], where the power-noise in the case of standard board, with and without decoupling, and BC board for 24 simultaneous switching (U5-7-9) is shown. In case of BC the AI-noise is negligible and emissions in Fig. 6a are similar to those in Fig. 12. With standard board (with and without decoupling), the noise is evident and its spectra has components able to feed the attached cable in resonance conditions, and this is clear looking at Fig. 13.
Modeling

A simplified approach was used to model the emissions from the current loops only. For this purpose the case of standard board with decoupling was selected. In fact in this case emissions caused by the voltage gradient between the power planes has insignificant effect because the resonance of the filtered PCB is under 30MHz. The signal propagation on the boards has been extensively dealt with in [1], and from the resulting time–domain simulations accurate descriptions of the currents flowing in the the power supply, and decoupling and load capacitors are known. The contributions to the emissions of each of these loops can be calculated by the method of Hertzian dipoles. In fact, a reduced formulation for the maximum differential mode electric fields emitted (in the measured direction) from a loop is [2]:

$$|E_m| = C |I_D| f^2 A \cdot r \quad [V/m]$$

where:
- $I_D$: differential current flowing in the loop
- $A$: loop area
- $f$: frequency
- $r$: distance to the antenna
- $C$: constant $= 1.316 \times 10^{-14}$

For the case of the standard board with decoupling capacitors, the currents (obtained from a circuit analysis program) flowing in the power supply and decoupling loops were transformed into the frequency domain (Fig. 15). The emissions were then calculated using the above formula and summed using superposition for the three active AC244 (see U5, U7 and U9 Fig. 2). Because the interconnecting tracks were minimized, the radiated emission profile is dominated by the currents on the loop illustrated in Fig. 14 and used for the calculations.

Fig. 14: Main loops radiation from 20-pin chip

Fig 16 shows a comparison between the measured and calculated fields for horizontal polarisation. The contribution from capacitor radiation area can be neglected (Fig. 15). While the model used for the electric field is very simple it is interesting to note the correspondence between the measured and calculated emission profiles.

For the case of an I/O cable attached to a PCB, a simple wire antenna model can be used where the voltage source is the $\Delta I$–noise of the PCB [5].
CONCLUSIONS

Some emission measurements were performed on two test boards to determine the effectiveness of **buried capacitance** technology in reducing emissions from multilayer PCBs, with respect to a standard lay-up. The measurements show that using this approach radiation is considerably reduced for both cases of differential and common mode radiation. Additionally, in this test case the inclusion of PTH decoupling capacitors on a standard board had little impact on the emitted fields due to the high (several nH) inductance of the leads. The emissions due to the principal current loops present on a PCB were identified and represented by a simplified radiation model which has some correlation with the measured electric field. Aside from signal integrity issues, the buried capacitance approach has advantages in reducing emissions from multilayer PCBs due to the very low associated inductances (less than 1nH). For the same reason, a useful reduction in emission from PCBs could be obtained using SMD decoupling capacitors.

REFERENCES


