Estimating Radiated Emissions from Heatsinks on Printed Circuit Boards above 1 GHz

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***Abstract*—Above 1 GHz, heatsinks on printed circuit boards are often large enough compared to a wavelength to be efficient antennas. Tall heatsinks can radiate like monopole antennas, while short, wide heatsinks can radiate like patch antennas. This paper investigates the development of closed form expressions for estimating the maximum possible radiated emissions from a heatsink based on the heatsink size and the maximum voltage observed between the heatsink and the printed circuit board power planes.**

Keywords-heatsink; EM radiation; maximum emissions estimate

I. INTRODUCTION

Large VLSI components being clocked at frequencies above 1 GHz require heatsinks of significant size in order to ensure reliable operation. Time-varying currents drawn from the circuit board through the inductance of the interconnections result in an $L\text{-}\delta i/\delta t$ voltage that appears between the heatsink and the power planes of the circuit board [1]. Since most heatsinks are made of materials that are good electrical conductors, this voltage is capable of driving the heatsink relative to the circuit board like an antenna. At low frequencies, where the heatsink is small relative to a wavelength, the emissions resulting from this phenomenon are usually negligible. However, at frequencies above 1 GHz, most heatsinks are no longer small relative to a wavelength, and it is possible for them to radiate efficiently at frequencies where a resonance is excited.

Calculating the precise levels of radiated emissions from a heatsink on an actual printed circuit board is neither possible nor desirable. Even if the precise nature of the VLSI components driving the heatsink could be determined, small variations in the heatsink geometry and its proximity to the board and other objects could have a profound influence on the radiated emissions at frequencies near resonance. In fact, at the frequencies of greatest interest (i.e. near resonance), the calculated field strengths would be the most susceptible to error. For this reason, engineers concerned with potential interference problems are not interested in determining the exact levels of radiated emissions for a precisely defined geometry. Instead, it is much more useful to obtain an accurate estimate of the maximum radiated emissions that is independent of small variations in the geometry or the influence of nearby components.

This paper presents a method for estimating the maximum possible radiated emissions for a heatsink with given maximum dimensions driven by a known voltage relative to a printed circuit board. Although, the voltage between a heatsink and a printed circuit board is difficult to predict from pure simulations, it can be easily obtained by measurements of the VLSI component and is relatively independent of the specific circuit board or heatsink geometry used for the measurement.

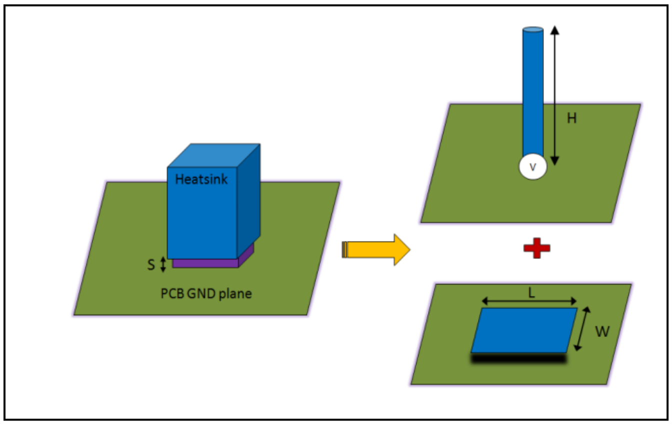

Figure 1. Heatsink viewed as the superposition of a monopole and patch antenna.

II. HEATSINKS AS MONOPOLES

The radiation from tall, thin heatsinks above a circuit board can be equated to the radiation from thick monopole antennas. The maximum radiated emissions from a monopole are well known. The relationship between the maximum radiated electric field and the maximum current on the monopole can be expressed as [2]

$$E_{\max} = \frac{\eta_o I_o}{2\pi r} \text{ , at } \theta = \frac{\pi}{2} \cdot \qquad (1)$$

The relationship between the maximum voltage at the monopole input and the input current at resonance is $V_{max} = I_o \times R_{res}$, where I_o is the input current and R_{res} is the input impedance of the monopole at resonance. Thus the ratio of the maximum radiated electric field to the maximum voltage at the feeding port for the resonant monopole is

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$$\frac{|E|_{\max}}{|V|_{\max}} = \frac{\eta_o}{2\pi r R_{res}} = \frac{120\pi}{2\pi r R_{res}} = \frac{60}{r R_{res}}\,. \qquad (2)$$

At frequencies much lower than the first monopole resonance, the input impedance is mostly capacitive and thus inversely proportional to frequency. The feed voltage to this stub monopole is also inversely proportional to frequency if the feeding current is constant. At the same time, the maximum radiated field is proportional to frequency for a short monopole with a constant feed current [2]. Thus the ratio of $|E|_{max}$ to $|V|_{max}$ is proportional to the square of the frequency. An expression for the maximum possible radiated emissions at low frequencies can be written as

$$\frac{|E|_{\max}}{|V|_{\max}} = \left(\frac{f}{f_{1st}}\right)^2 \frac{60}{r R_{res}}\,. \qquad (3)$$

The first monopole resonance occurs when the heatsink is approximately one quarter-wavelength tall. Closed-form expressions for the input impedance of a monopole at resonance available in the literature (e.g. [2]) and extensive simulations by the authors indicate that the minimum input resistance of an antenna radiating like a monopole at resonance is approximately 36-40 ohms regardless of the specific dimensions of the antenna. Setting R_{res} to 36 ohms in (2) provides an equation for the maximum possible radiated emissions from a heatsink radiating like a monopole at a given distance and for a given input voltage.

III. HEATSINKS AS PATCH ANTENNAS

For heatsinks where the length and/or width of the heatsink is not short relative to a wavelength, the heatsink can radiate like a microstrip patch antenna. The cavity formed between the circuit board and the bottom of the heatsink can become resonant at certain frequencies resulting in relatively efficient radiation. This phenomenon has been investigated extensively in the literature. The maximum voltage along the cavity apertures is available from the transfer impedance formula for a TM_z 2D cavity. Expressions for the maximum radiated emissions resulting from the cavities formed between PCB power planes are derived in [3] and [4].

When applying the expressions in [3] and [4] to heatsinks, the length L and the width W of the heatsink need to be extended to consider the edge effects. The extension is approximately that of the spacing [5] [6]. So,

$$L_{eff} = L + 2S \;\; ; \;\; W_{eff} = W + 2S\,. \qquad (4)$$

where L_{eff} and W_{eff} are the effective length and width of the cavity, respectively.

For a 2D cavity with two identical plates, the maximum radiated E field is developed in [3] and [4]. However, when the 2D cavity is formed by a plate (L×W) over a relatively large electrically conductive ground, the reflected E field from this ground must be taken into account. Thus the maximum radiated E field from such a cavity should be doubled. This results in an expression for the maximum radiated electric field from a short, wide heatsink radiating like a patch antenna,

$$|E|_{\max} = 2\frac{k\eta S I_{in}}{4\pi r} = \frac{k\eta S I_{in}}{2\pi r}\,, \qquad (5)$$

where k is the free space wave number, η is the free space intrinsic impedance, I_{in} is the noise source current, and r is the distance from the source.

The voltage along the edges of the cavity is approximately constant for any given frequency below the 1st resonance, and can be derived from the cavity transfer impedance formula as, [3] [4]

$$|V|_{\max} = \frac{\eta S I_{in}}{LWk}\,. \qquad (6)$$

Thus the $|E|_{\max}$ to $|V|_{\max}$ ratio is,

$$\frac{|E|_{\max}}{|V|_{\max}} = \frac{k^2 LW}{2\pi r}\,. \qquad (7)$$

For a resonant cavity, the far-field radiated emissions from the $TM_{mn\ (m\neq 0\ \&\ n\neq 0)}$ are usually weaker than the nearby $TM_{m0\ (m\neq 0)}$ or $TM_{0n\ (n\neq 0)}$ modes [2] [7]. Thus only the latter modes are considered in the ratio estimation. For frequencies above the 1st cavity resonance, the ratio can be obtained by calculating $|E|_{\max}$ from the far-field formula and getting $|V|_{\max}$ from the transfer impedance formula. For frequencies around the TM_{m0} mode of the cavity, the ratio is,

$$\frac{|E_{m0}|_{\max}}{|V_{m0}|_{\max}} = \frac{mkW}{\pi r}\,. \qquad (8)$$

This formula is derived following the same steps presented in [3] [4]: Calculate the maximum radiated E field from the PCB power bus radiation formula and the maximum voltage around the cavity using the 2D cavity transfer impedance formula.

Similarly for frequencies near the TM_{0n} mode, the ratio is

$$\frac{|E_{0n}|_{\max}}{|V_{0n}|_{\max}} = \frac{nkL}{\pi r}\,. \qquad (9)$$

To determine the connection point between the expression that is only valid at low frequencies (7) and the expression that is valid at high frequencies (8), the cavity transfer impedance formula is used. At the lower frequencies, the cavity can be approximately represented as a capacitor. By equating the lower frequency input impedance to that of the first cavity resonance (TM_{10}), the connection point between the two expressions occurs when,

$$k = \frac{\pi}{\sqrt{3}L} \approx \frac{2}{L} \quad . \tag{10}$$

For a normal cavity configuration without special structures that favor higher-order TM_{m0} or TM_{0n} modes, the maximum radiated emissions will not exceed the emissions occurring at the TM_{01} mode [7]. So for frequencies above this mode, the maximum radiated emissions expression can be simplified as

$$\frac{|E|_{\max}}{|V|_{\max}} = \frac{|E_{01}|_{\max}}{|V_{01}|_{\max}} = \frac{k_{01}L}{\pi r} = \frac{1}{r}\frac{L}{W} \quad , \tag{11}$$

where $k_{01}=2\pi/2W$ is the free space wave number at the TM_{01} resonance.

To take into account the possible wide bandwidth of the TM_{01} mode, the connection frequency is shifted lower by averaging the resonant frequencies of the TM_{01} mode and the highest TM_{m0} mode, which is no higher than the TM_{01} mode [7]. Thus this connection frequency is determined as

$$k = \left(\frac{\pi}{W} + \frac{\pi p}{L}\right)/2 \quad . \tag{12}$$

where *p* is the integer part of L/W. The final formula for the cavity is,

$$\left.\frac{|E|_{\max}}{|V|_{\max}}\right|_{PATCH} = \begin{cases} \dfrac{k^2 LW}{\pi r} \,, & k \le \dfrac{2}{L} \\ \dfrac{kW}{\pi r} \,, & \dfrac{2}{L} < k \le \left(\dfrac{\pi}{W} + \dfrac{\pi p}{L}\right)/2 \\ \dfrac{L}{rW} \,, & k > \left(\dfrac{\pi}{W} + \dfrac{\pi p}{L}\right)/2 \end{cases} \quad . \tag{13}$$

IV. COMPARISON OF MAXIMUM EMISSIONS ESTIMATE TO SIMULATIONS

An estimate for the maximum radiated emissions for four heatsinks was derived by combining equations (2) and (13) in order to account for both monopole and patch-mode emissions. Each heatsink had a length of 90 mm and a width of 64 mm. The results are indicated by the dashed lines in Figures 2 - 4. The first geometry investigated was a heatsink with negligible height. Figure 2 shows both the maximum emissions estimate and the actual emissions obtained from a full-wave [8] simulation with the heatsink driven by an ideal current source located close to the center. Since the zero-height heatsink is essentially a patch antenna, it is not surprising that the actual emission peaks come very close to the maximum emissions estimate at several frequencies.

Figure 3 shows similar results obtained for a heatsink with a height of 10 mm. In this case, the actual radiation peaks are still below the maximum emissions estimate, but are within a few dB at a couple of frequencies.

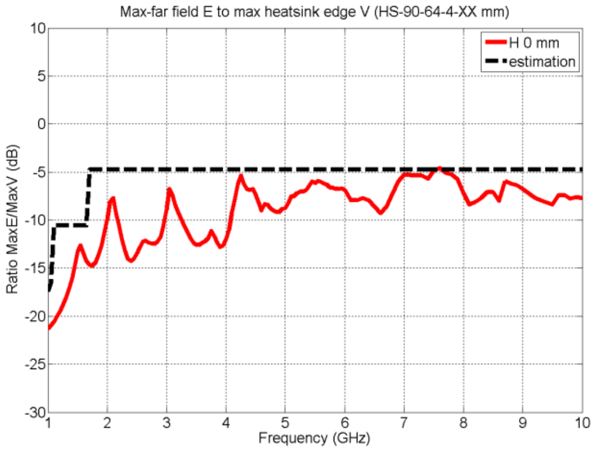

Figure 2. Maximum emissions estimate and actual emissions from a 90-mm x 64-mm patch antenna.

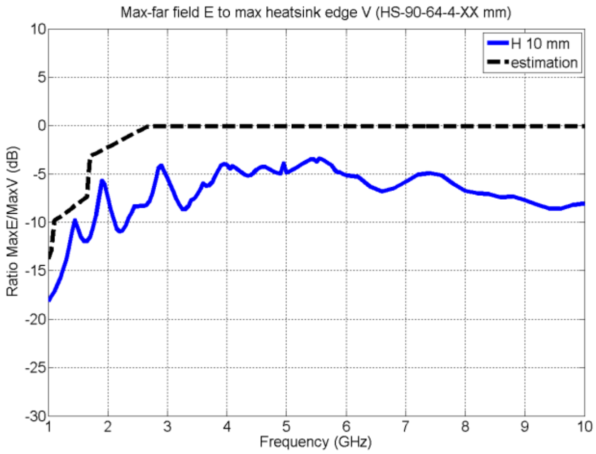

Figure 3. Maximum emissions estimate and actual emissions from a 90-mm x 64-mm x 10-mm heatsink.

Figures 4 and 5 show the results obtained when the height of the heatsink was increased to 40 mm and 100 mm respectively. In both cases, the peaks in the emissions are below the maximum emissions estimate even though some of the peaks are within a few dB.

In addition to the results shown here, the authors have evaluated heatsink geometries of different sizes and cross-sections and have yet to observe radiated emissions higher than predicted by the maximum emissions estimate obtained by combining equations (2) and (13). A more complete set of results will be provided in the first author’s dissertation when it is completed.

V. CONCLUSIONS

Although further development and validation of this technique is required, a maximum emissions estimate for heatsink-PCB configurations has been derived by viewing the radiation source as being a combination of resonant-monopole and resonant-patch antennas. The estimate relates the maximum possible radiated emissions to the maximum voltage observed between the heatsink and the circuit board. Maximum emissions estimates like this can be used to determine whether a particular source-antenna structure might possibly cause a radiated emissions problem.

Direct radiation from the heatsink-PCB structure is just one way that a heatsink can contribute to radiated emissions from an electronic device. Previous work has shown that heatsinks can drive the interior resonances of a shielded enclosure [9], or couple to cables attached to a circuit board resulting in radiated emissions from the cables [10].

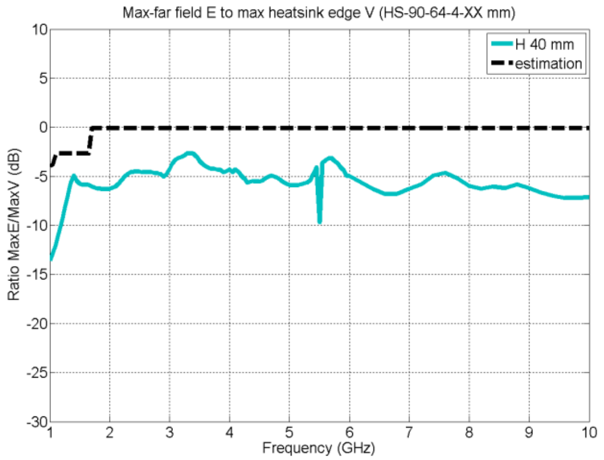

Figure 4. Maximum emissions estimate and actual emissions from a 90-mm x 64-mm x 40-mm heatsink.

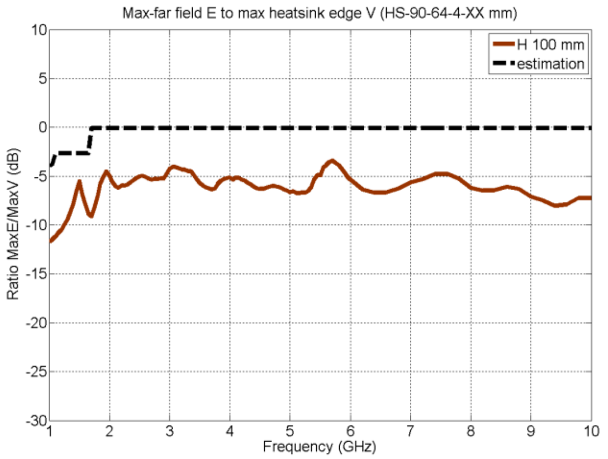

Figure 5. Maximum emissions estimate and actual emissions from a 90-mm x 64-mm x 100-mm heatsink.

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