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A PCB NOISE ANALYSIS REGARDING EMP PENETRATION USING AN ELECTROMAGNETIC TOPOLOGY METHOD

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Abstract—The usability of the EMT (Electromagnetic Topology) method is discussed and verified in this paper. The EMT results are compared to the results from a 3D fullwave electromagnetic solver. The electromagnetic wave shows a very fast rise time in the EMP (Electromagnetic Pulse) signal; the SUT (System Under Test) is a simple PCB strip line model. The resistances of the loads attached to each side of the strip line were $1\,\mathrm{M\Omega}$ and $50\,\Omega$. We then obtained the noise voltages occurring in each load when being penetrated by an EMP. We also discuss the frequency sweeps used to obtain the resonant frequencies of the model. The results agree well with those from the CST Microwave Studio. The EMT method would be more accurate if the dielectric tangent loss and copper loss are considered.

1. INTRODUCTION

Modern electronic systems are very robust in regards to EMP (Electromagnetic Pulse) attacks because these electronic systems operate at low voltages and low power, and have very high transistor integration and high clock frequencies. However, studies on the hazardous effect of EMP on electronic devices or an EMP generating apparatus still need to be performed [1–8]. If an undesired amount of high level noise penetrates the electronic systems, they suffer from hazardous malfunctions or permanent physical destruction. Therefore, appropriate protections are essential in modern electronic systems.

The most important element of electric/electronic systems is the Integrated Circuit (IC). An IC is basically mounted directly on the

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PCB (Printed Circuit Board) or uses a socket. When external high power electromagnetic waves occur, due to the resulting over voltages and over currents generated in the IC, electronic systems can operate abnormally. In [9], it was found that laptop computers malfunctioned due to an external impulse noise of 2 kV/m.

We analyzed the EMP (Electromagnetic Pulse) interaction problem in electronic/electric systems through experiment and computer simulation. It is possible to estimate the susceptibility of an SUT (System Under Test) attacked by EMP penetration using various measurement equipment. It is also possible to predict the results of an experiment with full wave computational calculation method algorithms, such as FDTD (Finite Difference Time Domain), FEM (Finite Element Method), FIM (Finite Integration Method), MoM (Method of Moment), etc. Computer simulations are preferable because real world experiment facilities (EMP Simulators, Open Area Sites) are very expensive.

An electromagnetic wave incident induces noise voltage and noise current into the circuit structures when the wave penetrates the SUT (System Under Test). This is called 'electromagnetic coupling'. The penetration and coupling mechanism can be analyzed using transmission line theory with first/second telegrapher differential equations [10]. Therefore, if the SUA (System Under Attack) is regarded as a circuit constructed with transmission lines and loads, we can calculate the induced voltage/current noise using multi-conductor transmission line and coupling theory.

This EMT (Electromagnetic Topology) method was suggested by Baum, Liu and Tesche in the 1970s. The EMT can be built upon BLT (Baum-Liu-Tesche) formalism [10]. It is comparable to an onion's many layers being decomposed into their smaller fundamental parts. Similarly the selected system is decomposed into volumes and surfaces from the highest level to the lowest level each volume consisting of many paths that the external noise penetrates through.

The '**path**' that the noise goes through is divided into two categories. The first is the conduction path; the second is the radiation path. The conduction path consists of conductive metal wires, PCB strip lines, electric cables, antennas, metal structures, and metal sheets through which EMP noise can propagate through in the form of voltages and currents. The radiation path describes the way that the electromagnetic wave moves through the free spaces, cavities and apertures. If an external EMP noise is generated, the noise penetrates into the system through the radiation paths. When an electromagnetic wave touches the conductive metals or wires, electromagnetic coupling occurs. The electromagnetic coupling is a phenomenon of the electromagnetic wave. An energy transformation into electrical energy in the form of voltages and currents occurs.

Volumes are covered by surfaces except for the highest level volume. The 'surface' is defined as the electromagnetic energy barriers of metal sheets and metal cases. In contrast, the surface apertures are essentially made up of ventilation, visual ports, windows, doors and other functions. Therefore, the surfaces cannot be perfect electromagnetic barriers. An externally generated EMP noise generates overvoltage and current noise in conductors; the conductors are connected to the fundamental elements of the system. The overvoltage and current noise result in dangerous malfunctions or destruction to the fundamental elements of the system.

The EMT method reflects this penetration process, so we can calculate the electromagnetic penetration faster than is possible using the MoM, FDTD, and FEM techniques. The EMT method does not need a great amount of computation resources relative to the MoM, FDTD, FEM techniques. Whereas these techniques calculate all of the system elements, in the EMT method, we calculate only the conduction/radiation noise paths using RF transmission theory. In the case of both large structures (ships, airplanes, aircraft, bombers, automobiles, etc.) and simple structures, the EMP method is more easily applied than the previous methods. Many reports show that the EMT method gives good results in the SUTs of basic cavities, bombers, missiles, etc. [11–13].

The purpose of this paper is to show application possibility of EMT method on PCB strip line and comparison between EMT calculation code and an electromagnetic analysis tool using FIM algoritm. The EMP penetration of a simple PCB strip line on an FR-4 PCB structure was studied as it applies to the EMT method. The EMP waveform is an electromagnetic wave with an ultra fast rise time impulse that results in hazardous effects to a system. We show the results from the time domain voltage noise and a frequency sweep. These results are then compared to the results from commercial full wave electromagnetic simulation software programs.

2. THE NUMERICAL CALCULATION SETUP

2.1. The EMT Method

The EMT method expresses the electromagnetic paths (radiation paths) and voltage/current paths (conduction paths) as 'tubes'. In Figure 1, the solid and dotted lined tubes represent the conduction paths and radiation paths, respectively. The electromagnetic penetration path is known as the 'PoE (Point of Entry)'. Windows,

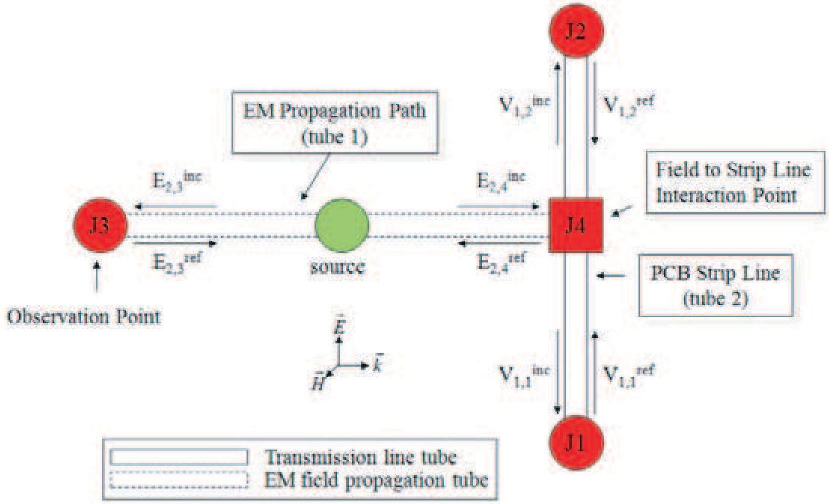

Figure 1. The EMT energy flow diagram.

gaskets, ducts and honeycombs are all radiation noise PoEs. Metal wires, power/communication cables, pipes, and antennas make up the conduction noise PoEs.

All systems consist of these elements. However, some of these elements are not hazardous PoEs, whereas dangerous PoEs invoke a negative EMP resistance to a system. We express the EMT method regarding these electromagnetic/voltage/current energy flows as EMT energy flow diagrams. The EMT energy flow diagram is shown in Figure 1.

The terminals seen in Figure 1 are called 'junctions' (J_1, J_2, J_3, and J_4). The junctions are each terminal loads attached to energy flow paths. J_4 in Figure 1 is the termination of the radiation path (tube 2) coupling interaction between the electromagnetic waves in the conduction path. J_1 and J_2 are terminals in the conduction path (tube 1), they can be either passive elements (R, L, C) or active elements (diodes, transistors, AMPs etc.). The EMP incident is reflected by the transmission line structure; it results in a scattered electromagnetic wave propagating towards J_3. The green circle in the middle of tube 2 attached to J_3 and J_4 is the EMP source. It shows that the EMP source generates an electromagnetic wave to the system.

We use the EMT method to convert this diagram into complex matrix forms. If the system is complex, possessing many tubes, junctions, and interactions, the matrix becomes an n-dimensional matrix (super matrix). The mathematical calculations for the matrix are found in (1) to (3). This set of equations is referred to as BLT formalism. $[W^{(S)}]$ is any source on a tube, $[I]$ is the unit matrix, $[S]$ is the scattering matrix, and $[\Gamma]$ is the propagation matrix. All of the matrixes are super matrixes (matrix of matrixes). $[W(0)]$ represents the electric field, magnetic field, voltage, and current at J_1, $[W(L)]$ represents of the same things for J_2.

$$[W(0)] = ([I] - [S][\Gamma])^{-1}[S][\Gamma]\left[W^{(S)}\right] \tag{1}$$

$$[W(L)] = [\Gamma][W(0)] + \left[W^{(S)}\right] \tag{2}$$

$$([I] - [S][\Gamma])[W(0)] = [S]\left[W^{(S)}\right] \tag{3}$$

2.2. The PCB Model

The PCB model used for the analysis is shown in Figures 2 and 3. The PCB consists of dielectric media and copper plates on the top and bottom of the dielectric media. The bottom copper plate is normally used as an electrical ground plane and the upper copper plate has specific RF functions controlled by a desired pattern (strip lines). The electric field generated by the upper strip line creates a quasi TEM because the dielectric constants of the dielectric media and air are different. Therefore, we obtained the equivalent RF circuit of this PCB structure and calculated the effective relative permittivity and characteristic impedance. The effective relative permittivity and characteristic impedance equations are found in (4) to (6) [14]. In this study, the dielectric loss and copper loss are neglected. The PCB model specifications are listed in Table 1. The PCB dielectric is FR-4 ($\varepsilon_r = 4.9$) and 1 ounce (35 µm) of copper plates were used. The dielectric loss was neglected in this paper to make the calculation simpler.

$$\varepsilon_{r,eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + 12\frac{h}{w}\right)^{-0.5} \tag{4}$$

$$Z_C = \frac{60}{\sqrt{\varepsilon_{r,eff}}}\log\left(\frac{8h}{w} + \frac{w}{4h}\right) \quad \text{at } \frac{w}{h} \leq 1 \tag{5}$$

$$Z_C = \frac{120\pi}{\sqrt{\varepsilon_{r,eff}\left[w/h + 1.393 + 0.667\log(w/h + 1.444)\right]}} \quad \text{at } \frac{w}{h} > 1 \tag{6}$$

The loads attached to each side of the PCB strip line have been considered. Functional semiconductors are commonly connected to sockets on a PCB. Therefore, we used the equivalent impedance of a

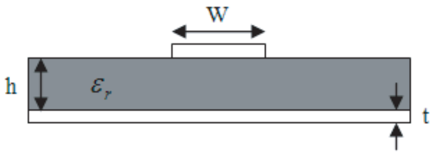

Figure 2. The PCB strip line.

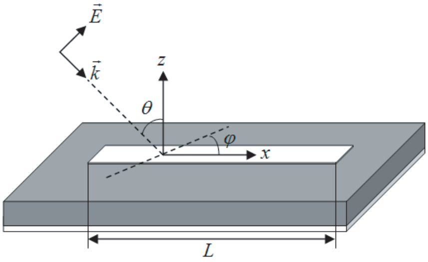

Figure 3. The electromagnetic wave.

Table 1. The PCB model specifications.

Specifications	Symbols	Values	
Width of strip line	**W**	2 mm	
Length of strip line	**L**	6 cm	
PCB dielectric thickness	**h**	1.5 mm	
relative permittivity	ε_r	4.9	FR-4
Copper plate thickness	**t**	35 µm	1 ounce

HCT04 CMOS inverter. The input impedance of this IC is very large and the output impedance is small. Load 1 (input) is 1 MΩ and Load 2 (output) is 50 Ω. These loads were attached to each side of the strip line and are connected to the bottom ground plane.

2.3. The EMP Waveform

The EMP waveform has been defined for calculation. An EMP possessing an electric field E_0 having the incident angles θ and φ was considered, as shown in Figure 3. The EMP waveform can be expressed by a double exponential function [12], as shown in (7). Heaviside complex functions can be used because of the errors of the differential process found at $t = 0$. However, the EMT calculation is a numerical analysis; a double exponential function is enough for our study. The EMP wave is assumed to be plane wave in a far field region from an EMP generating source.

$$E(t) = E_0 k \left(e^{-\alpha t} - e^{-\beta t}\right) \tag{7}$$

The EMP expression in (7) consists of the desired peak value E_0, time constants α and β, and the compensation constant k. α and β

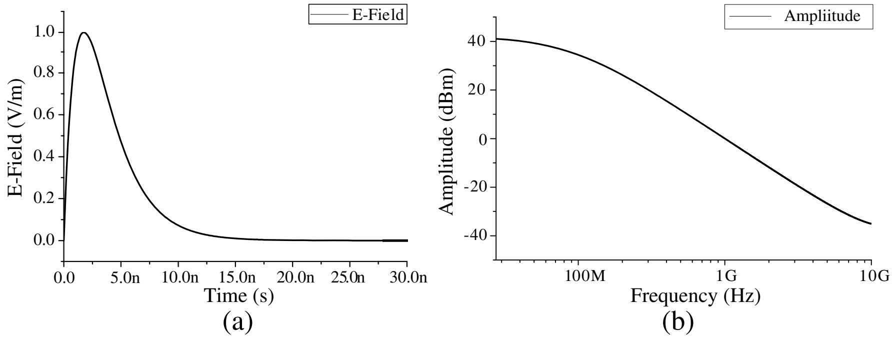

Figure 4. The EMP noise impacting the strip line characterisitics. (a) The EMP waveform time domain. (b) The EMP waveform spectrum.

determine the rise time t_r and the FWHM (Full With Half Maximum) t_{FWHM} of the EMP wave form [16]. However, the relationship of α-β and t_r-t_{FWHM} is complicated and has a nonlinear characteristic [17, 18]. The determination of α-β from t_r-t_{FWHM} is quite difficult. Although a rough approximation method exists, it is a rule of thumb method and so does not have a good accuracy ($\beta = 1/t_r$, $\alpha = 1/t_{\text{FHHM}}$).

Magdowski and Vick have studied this problem; they improved the method of how to directly find the t_r-t_{FWHM} from α and β. The equation fits well to all of our ranges [19]. Therefore in this paper, we will use the Magdowski method. In the method, two assumptions exist:

$$\lambda = \beta/\alpha \tag{8}$$

$$\mu = t_{\text{FWHM}}/t_r \tag{9}$$

λ and μ of are ratios of the each parameters, the purpose of λ and μ is to make each parameters dependently. The EMP waveform used has a very fast t_r of 1 ns; the peak value is normalized. The IEC standard nuclear generated HEMP (High Altitude EMP) specifies a $t_r = 2.5$ ns, a $t_{\text{FWHM}} = 23$ ns, and a peak electric field 50 kV/m [15]. But a system generated or intentional EMP is more hazardous than a nuclear generated EMP, because it has a faster rise time and higher frequency spectrum range. Electromagnetic waves of around 1 GHz cause more hazardous effects on electronic systems, such as laptop computers, PCs, motors, ships, airplanes, etc. [20]. A 1 GHz t_r has effective cut off frequencies of about 1 ns. The EMP wave form used in this study and its Fourier spectrum are shown in Figure 4; the parameters from (7) are listed in Table 2.

Table 2. The EMP specifications.

Specifications	Symbols	values
Peak *E-field*	E	1 V/m
Compensation constant	k	1.05
Time constant 1	α	7.88×10^8
Time constant 2	β	4.02×10^8
Polarization angle	γ	0°
incident angle 1	Θ	0°
Incident angle 2	φ	0°

3. THE NUMERICAL CALCULATION RESULTS

3.1. The Comparison of the Results to the CST Microwave Studio Findings

A full wave electromagnetic wave analysis tool, CST MWS (Microwave Studio), was used to compare and verify the results of the EMP method used in this study. CST MWS has been certified in regards to its performance and accuracy in a variety of literature [21]. We used the CST MWS Finite Integration Method (FIM) [22]. A 3-dimensional structure, as shown in Figure 5, was constructed in order to solve the model; the model is equivalent to the EMP model seen in Table 1. The incident characteristics of the EMP and the EMP waveform are the same as seen in Table 2.

3.2. The EMT Results

The EMP penetration and interaction on the PCB model was analyzed using the EMT method. Figures 6 and 7 show the voltages for the $50\,\Omega$ input and $1\,\mathrm{M}\Omega$ output, respectively. As shown in the figures, the noise adopts a ringing damped sinusoidal wave; the frequencies fit with the resonant frequencies of the model. Although the EMP is an ultra wideband signal in the range of hundreds of MHz, the resonant frequencies are the only ones to penetrate into the SUT. The other frequency elements are cut off. This is similar to dipole antenna theory; all of the metal structures, even the metal plane, perform as RF filters. Notably, the frequencies at around 1 GHz have the most effect on electronic systems This phenomenon is known as Baum's law [20].

The EMT noise result on the $50\,\Omega$ load was 2.5×10^{-4} V; the corresponding CST MWS result was 3.5×10^{-4} V. The error is 28% as shown in Figure 6. The EMT noise voltage on the $1\,\mathrm{M}\Omega$ load was

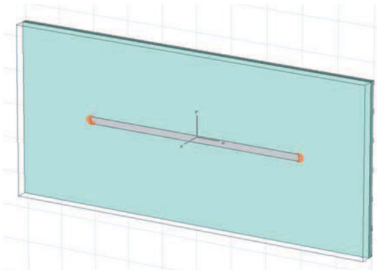

Figure 5. The CST microwave studio 3D model.

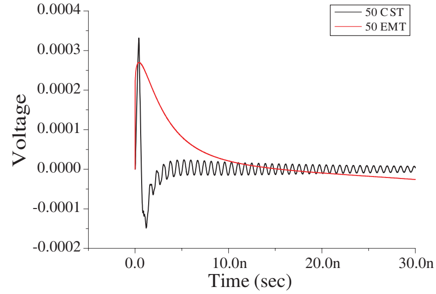

Figure 6. The EMP noise on the $50\,\Omega$ load.

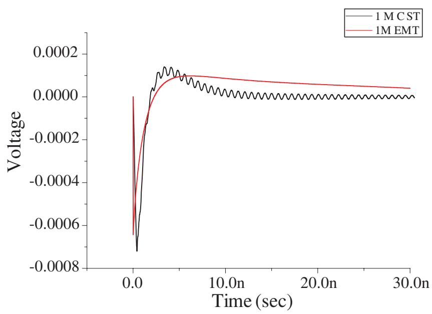

Figure 7. The EMP noise on the $1\,\mathrm{M}\Omega$ load.

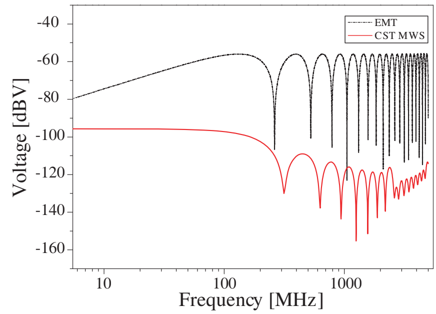

Figure 8. The frequency sweep voltage noise on the $50\,\Omega$ load.

-6.0×10^{-4} V; the corresponding CST MWS result was -7.0×10^{-4} V. The error is 14% as shown in Figure 7. Calculation time was 1sec for the EMT method using MATLAB and 15 sec in the CST MWS (Intel Dual core E8200 2.66 GHz/2.66 GHz CPU, 4 GB RAM, Windows 7 32 Bit).

The noise is very small in the range of 10^{-4} V when a 1 V/m EMP is used. However, an EMP signal is normally a few kV/m to hundreds of kV/m, so the noise can cause dangerous malfunctions in electronic elements. However, the relationship between the noises on two loads is nonlinear in regards to the resistance of the two loads. The noise voltage on the $1\,\mathrm{M}\Omega$ load doubles that on the $50\,\Omega$ load. The ratio of resistances of the two loads is 2,000 (absolute value). This phenomenon has also been reported in [23]. The fluctuations in Figures 6 and 7 exist in CST MWS results. The fluctuation might be due to accuracy problem of FIM method.

Figure 8 shows the frequency sweep model using the two numerical

Table 3. The resonant frequencies of the two numerical solutions.

Resonance Frequencies [MHz]			
No.	EMT	CST Microwave Studio	Error (%)
1	265.1	309.51	14.34
2	526.75	627.02	15.99
3	789.85	940.2	15.99
4	1056.03	1270.22	16.86
5	1320.38	1569.39	15.86
6	1567.39	1868.14	16.09
7	1832.32	2181.13	15.99
8	2120.26	2596.33	18.33
9	2356.76	2860.25	17.60
10	2596.33	3151	17.60
Average Error			16.46

methods. The external electromagnetic source is not an EMP waveform but a normalized sinusoidal waveform. The noise on the loads is also sinusoidal. The resonant frequencies are the elements penetrating into the systems, not the blocked frequency elements.

As shown in Figure 8, the voltage noise seen by the EMT method is higher than that found for the CST MWS. This may be caused by lack of concern for both the tangent loss of the FR-4 and the copper loss of the strip line. The two losses are not considered in the EMT method whereas the CST MWS automatically calculates them. The lower levels seen in Figures 6 and 7 are also caused by this reason. More accurate studies need to be developed

Table 3 lists the resonant frequencies. The resonant frequency error has a minimum of 14.34%, a maximum of 18.33%, and an average of 16.46%. Therefore the results of EMT method are similar to the CST MWS method.

4. CONCLUSION

In this study, the EMT method used to predict EMP penetration into electronic systems is discussed. The results from the EMT method were similar to those found for full wave electromagnetic wave solvers. The EMT method needs less computer memory and less calculation time than these full wave solvers. In addition, the EMT method reflects penetration process, so one can calculate electromagnetic penetrations faster than the MoM, FDTD, FEM methods. The EMT method gives us good results in the SUTs of basic cavities, bombers, missiles, etc.

The results of the EMT method are slightly different from the results of the CST MWS because the EMT method does not consider dielectric loss and copper loss. The EMT method will give a better accuracy when the dielectric loss and copper loss are considered, so additional studies need to be performed. Therefore, we will continue our studies regarding EMT calculation for cavities and apertures.

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