ELECTROMAGNETIC EMISSION FROM EDGE PLACED DIFFERENTIAL TRACES ON PRINTED CIRCUIT BOARD

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Abstract: Edge placement of a differential pair on the printed circuit board causes balance disruption, and resulting in electromagnetic (EM) emission. In this work, the emission from edge placed differential traces is numerically simulated and also measured. The simulation is based on the FDTD method. The field distribution is accurately snapped in the simulation and the emission characteristics are revealed. In the measurements, both the electric and magnetic fields are measured for several geometries. Finally, the common-mode inductance of edge placed differential pair is derived and the EM emission is further investigated.

Key words: Common-mode inductance, differential signaling, electromagnetic emission, FDTD method.

1. Introduction

Recent growth in high-end processor and moving multimedia data through local area network (LAN), mobile phone and satellite system has demanded data transfer in faster speed and with lower power system and noise. Comparing to the single trace, tightly spaced differential traces are highly resistant to external fields, reduce the common-mode (CM) radiation levels, and improve the signal integrity as well as dynamic range [1]-[3], thus are commonly adopted in LAN and other signal interconnections in high-speed digital systems. For obtaining the aforementioned signal transmission performance, however, the two lines in the differential pair should be perfectly balanced. Edge placement of a differential pair on the printed circuit board (PCB) causes balance disruption and creates common-mode currents, resulting in an increased electromagnetic (EM) emission. Therefore, it is necessary to quantify the electromagnetic emission from differential traces with edge placement on PCB to determine the routing possibility when the edge placement is not avoidable. In the first part of this work, the simulation of the EM emission from edge placed differential traces is reported. The simulation is based on the well-known FDTD method. The field distributions for the single-ended trace and the differential traces are compared based on the simulation results. Then the measured field distributions above the edge placed differential traces are reported. The emission due to common-mode currents on the PCB is one of the major reasons of electromagnetic interference in digital high-speed electronic equipment. The common-mode radiation is well known as caused by the parasitic ground plane inductance, or common-mode inductance, since a voltage drop across the inductance provides a noise source that can drive common-mode current on the external structure [4], [5]. Based on the closed-form expression of common-mode inductance for the single-ended trace on finite ground plane [6], [7], the common-mode inductance of edge placed differential pair on PCB is derived. Then the relationship of the common-mode inductance of differential pair with the offset of the trace pair from the board center, and with the board width/height ratio are reported and the EM emission due to the edge placement of the differential-pair is further investigated.

2. Simulation of the EM emission

The differential pair with edge placement on the PCB is shown in Fig. 1. The distance from the center of differential pair to the board center is denoted by \( s \), and we call it offset through this paper. The PCB board used in our simulation and measurement is the FR4 board having relative permittivity of 4.4. The height of the PCB is \( h = 1.6 \) mm and the width of the board is \( w = 32 \) mm. The pitch (center to center) distance of the two differential traces is \( \Delta s = 5 \) mm and the trace width is 3 mm. Since the ground plane is finite, thus in \( y \)-direction the FDTD computation domain is larger than the PCB board width. In \( z \)-
direction, the PCB board and the traces are terminated by the absorbing boundary. Thus both the fields above the PCB board and below it are calculated in the simulation. In our FDTD simulation, a grid of cell size of 0.4 x 0.5 x 1.0 mm and cell number of 30 x 84 x 108 are used, thus the geometry of the PCB structure is translated to a computation domain of 272 160 cells. The calculated $x$- and $y$-components of the magnetic fields in the cut-plane of 5-mm above the PCB are shown in Fig. 2. One can see the fields are mainly tied up to the two traces. This is because the differential lines have equal but opposite signals. Thus when the traces shifts to the edge, the fields are not affected too much. But when the offset is 11 mm, fields become asymmetric and imbalance in currents occurs on the traces. When this imbalance happens, the fringing fields may escape from the PCB and lead to EM emissions. For examining the fringing fields, the total magnetic fields in a transverse plane (cut-plane to the $z$-axis) are shown in Fig. 3 for different trace offsets. For comparison, the field for a single-ended trace is shown in Fig. 3 (d). The single-ended trace is the case by leaving only the right trace of the differential pair and offset is $s = 11$ mm. One can see no fringing field for the $s = 0$ case and even for the $s = 8$ mm case, it is still not obvious. When the offset is $s = 11$ mm, fringing fields for the differential pair are obvious but still lower than that of the single-ended trace.

Fig. 2. Simulation results of the magnetic field above the edge placed differential traces of different offsets: (a) $H_x$ and (b) $H_y$ for $s = 0$, (c) $H_x$ and (d) $H_y$ for $s = 8$ mm, and (e) $H_x$ and (f) $H_y$ for $s = 11$ mm.
Fig. 3. Simulation results of the magnitude of magnetic field in the transverse plane for edge placed differential traces of different offsets and single-ended line: (a) $s = 0$, (b) $s = 8$ mm, and (c) $s = 11$ mm for differential traces, and (d) for single-ended trace.

Fig. 4. Measured magnetic field above the edge placed differential traces of different offsets: (a) $|H_y|$ for $s = 0$, and (b) $|H_y|$ for $s = 11$ mm.

3. Measurement

The EM fields about 5-mm above the PCB board also measured. Field probes made of semi-rigid cable and controlled by computer are used to measure the corresponding field components. The data are recorded at intervals of 0.5 and 1 mm in $y$- and $z$-directions, respectively. An active balun is used to generate the differential signals. Limited by the bandwidth of the balun, the fields below 1.1 GHz are measured. Here only the $y$-components of the magnetic fields at 1 GHz for several test boards are shown in Fig. 4. Since the trace length is small compared to the wavelength at this frequency, the periodic variation is not visible in the figure. But the results are coincident with the simulations. Note that in Fig. 4, only the magnitude of the field is graphed but in Fig. 2 both the magnitude and the phase information are included. The imbalance of the fields above the two traces is obvious when $s = 11$ mm.
4. Common-mode Inductance

The common-mode inductance of the single trace generally defined as the ratio of the total magnetic flux penetrating the lower side of the ground plane to the amplitude of the current that produce this flux. The per-unit-length common-mode inductance of a single trace on PCB has been obtained as

\[
L_{CM}^{Single} = \frac{\mu_0}{\pi} \left[ \frac{2(s + jh)}{w} + \sqrt{\frac{(s + jh)^2}{w^2} + 1} \right]. \tag{1}
\]

If the currents on the differential traces are exactly 180° out of phase, the CM inductance for the differential pair with offset of \( s \) can be calculated

\[
\Delta L_{CM}^{diff}(s) = L_{CM}^{Single}(s + \Delta s/2) - L_{CM}^{Single}(s - \Delta s/2). \tag{2}
\]

Fig. 5 shows a comparison of the CM inductance of the single-ended trace with that of the differential pair for different ground plane widths. The height of the board is \( h = 1.6 \text{ mm} \), and the pitch distance for the differential pair is \( \Delta s = 5 \text{ mm} \). One can see while \( s/w \) is small, e.g., less than 0.3, the parasitic inductance for the differential pair is almost zero, but for the single-ended trace this inductance is about 0.04 nH/cm for \( w = 16 \text{ cm} \), i.e., \( w/h = 100 \). A significant increase is noticed for both the single trace and the differential pair when the trace offset from the center exceeds approximately 80% of the half-plane width, i.e., \( s/w > 0.4 \), but the parasitic inductance for the single trace is still much larger than that of the differential pair. The improvement of the differential pair over the single-ended trace on the EM emission level reduction is well supported by this result. Furthermore, for wide ground plane, the common-mode inductance of the differential pair is almost zero over a great part of \( s/w \) range. Thus if the edge placement of differential traces is not avoidable, a large ground plane is preferable for decreasing the CM inductance. It is well known that current through the CM inductance results in a voltage drop and results in EM emission. The driven voltage, known as common-mode noise source, is directly related to the CM inductance. Since edge placed differential traces results in an increase in the CM inductance, thus it also results in an increase in the electromagnetic emission.

5. Conclusion

Edge placement of differential traces on the PCB causes balance disruption and results in increase of electromagnetic emission. In this work, the EM emission from edge placed differential traces is numerically simulated and also measured. According to the field distribution snapped by FDTD simulation, the EM emission characteristics have been revealed. The simulation results have been confirmed by the measurements. Finally the common-mode inductance of edge-placed differential pair was derived and the EM emission mechanism was investigated.