Engineering Notes

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Effective Electromagnetic Shielding in Multilayer Printed Circuit Boards

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Introduction

ELECTROMAGNETIC coupling of signals between conductors often poses problems in attaining electromagnetic interference (EMI) requirements. Many coupling problems manifest themselves as circuit dysfunctions which are readily resolved with shielded wire or filters at the equipment interface. However, an inevitable outgrowth of today's integrated circuit technology, which permits equipment to assume multifunction roles, is self-induced malfunctions. Elimination of these malfunctions, by after-the-fact EMI designs, is often complicated by increasing operational frequencies which tend to view conventional ground planes as high-impedance paths or semitransparent shields. These problems are most prevalent in motherboards or master interconnect boards which interface with both internal circuitry and the outside environment. Recent development of a 14-layer motherboard, for a prototype avionic system, exemplified these problems associated with self-induced malfunctions.

Description of Problem

Prototype motherboard development concepts were geared to minimizing board layers by creating data bus lines for common use within each of two microprocessor subsystems. Each data bus was independent of the other and yet had common access to scratch pad memory and discrete input/output cards. The resulting motherboard design contained several adjacent bus layers of parallel printed lines as illustrated in Fig. 1. Use of "full" V_{cc} and ground plane layers were incorporated to provide isolation between these processor buses and to provide returns for power and signals.

Problems began to manifest themselves when the bus drivers and receivers were activated. Each bus driver delivered a 3.5 V data train with 8-10 ns rise-times. These fast rise-times resulted in coupled amplitudes of 1.5 V peak-to-peak even with several intermediate ground layers. Since the bus receivers were designed utilizing leading- and trailing-edge triggering, the coupling noise was of sufficient amplitude and duration to cause unintentional receiver response. This response was revealed through false commands and loss of alteration of data.

Modifications of the ground plane layers and daughter card returns were made to assure adequate distributed bonds to the zero reference point (chassis ground) but to no avail. Voltage measurements, performed to evaluate ground plane effectiveness, not only demonstrated substantial potential gradients within the ground plane layer but showed voltage fluctuations on the same order of magnitude as the coupled noise. In addition, these ground plane anomalies were most prevalent where source lines crossed over the cutout area provided for each connector interface.

Analysis and Solution

Consider the axiom that electron or current flow follows the path of least resistance. In a two-wire transmission line, resistance at low frequencies is uniform throughout the cross-sectional area of each conductor. This uniform resistance and a negligible mutual inductance permit the repelling forces between like charges in each conductor to have a dominate influence resulting in a uniformly distributed current density within each wire. At higher frequencies, conductor resistance takes on the following definition:

$$R = l/(\pi a \delta \sigma)\,\text{ohms}$$

where a is the radius of the conductors, $\delta = 1/\sqrt{f\mu\sigma\pi}$ the skin depth, σ the conductivity of copper, μ the magnetic permeability of copper, and f the operating frequency under consideration. As frequency increases, resistance increases due to the effective reduction in cross-sectional area created by the decrease in skin depth. Concurrently, current density ceases to be uniform throughout each wire and tends to concentrate along the surface of the conductors.

As the distance between wires approaches the cross-sectional dimensions, the mutual inductance creates a reduction in apparent wire spacing as well as the total inductance. This mutual inductance allows the current distribution in each conductor to affect that distribution in the other conductor. The result is that current not only becomes confined to the surface of the conductor but is distributed around each axis according to the law of distribution of charges. In effect, current density in the two-wire system is a maximum at the closest points between the cross-sectional area of each wire.[1]

Extending this discussion to printed circuit conductors over a solid ground plane reveals the same basic responses in current behavior. At low frequencies, small resistances offered by the conductors result in a uniform current distribution. As frequencies increase, the mutual inductance

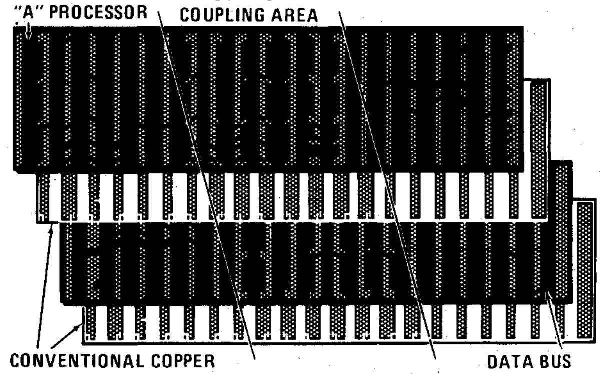

Fig. 1 Parallel data buses with conventional ground planes.

Received Nov. 10, 1981; revision received Aug. 20, 1982.

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and increasing resistance tend to localize current along the closest points between conductors.

Now, consider placing large apertures normal to this localized current flow as illustrated in Fig. 2. Each aperture produces a sudden discontinuity, increasing the complex resistivity ρ and local current density J at the point of interruption. These increases result in highly localized E fields ($E = J\rho$) which couple through the apertures to adjacent signal layers, degrading the effective shielding of the ground planes. In the design under study, 21 such connector apertures were utilized accounting for 40-50% of board area.

Further evaluations of coupling around an aperture revealed that length, number of apertures, and width, respectively, were the major contributing factors in degrading shielding effectiveness. Since the number and width of the connectors were fixed by the system design, the only available

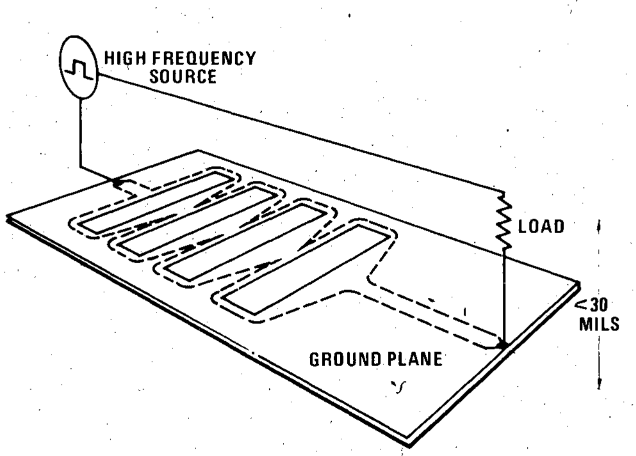

Fig. 2 Conventional ground plane design enhances aperture coupling.

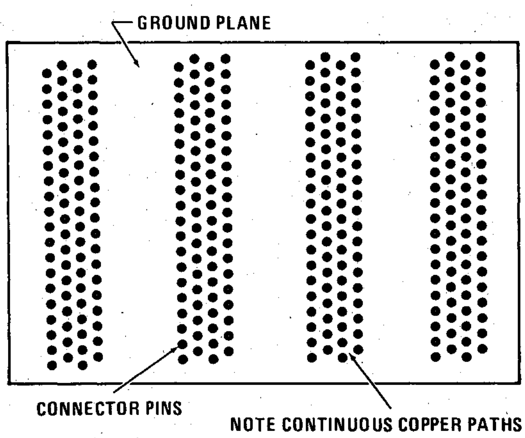

Fig. 3 An inverse dot matrix ground plane pattern.

alternative was altering the apparent length of the connector to provide a lower-impedance current return. Test results showed that interposing several distributed shorts across each aperture resulted in a significant increase in shielding effectiveness. However, the increased shielding effectiveness proved valid only when the transmitting and receiving lines were on opposing sides of the protective shorts.

Preliminary investigations of motherboard signal coupling showed only 7-12 dB of isolation provided through the ground plane layers. This isolation proved to be the typical line isolation of parallel lines within the same board layer. Attenuation, for a 2 mil copper plane at 100 MHz, should have been approximately 67 dB between adjacent signal layers based on the absorption loss equation

$$A = 3.34 \times 10^3 t\sqrt{f} \text{dB}$$

where t is the ground plane thickness in mils. Consequently, this ideal attenuation was set as the upper limit with 40 dB as the lower limit and desired goal in minimizing signal coupling.

Feasible implementation of the test results and analysis was in the form of an "inverse dot matrix" pattern, as presented in Fig. 3, which was applied to each ground and V_{cc} (5V) plane. This type of plane provided the closest approximation of a solid copper plane by reducing connector apertures to small insulating rings around each connector pin. A continuous path around each pin minimizes the resistivity and current bunching observed with sudden discontinuities, thus significantly reducing local E fields. Furthermore, return signals could now occupy the lower impendance area immediately below the signal source.

Test results on this motherboard showed coupled noise levels reduced to 0.01 V for greater than 48 dB of attenuation and as an added benefit, a reduction in line-to-line coupling within board layers by the same order of magnitude. These results and analysis indicate that the inverse dot matrix planes provide a most effective method of minimizing cross coupling between sets of high-speed TTL data lines.

Conclusion

Avoid the use of apertures in the ground planes of multilayer motherboards for accommodating connector terminals! Achieving the desired EMI requirements is nearly impossible in high-density printed circuit boards, which use large quantities of apertures without extensive and often unwanted line filtering and gross shielding. As in the case history described, the use of a dot matrix ground plane pattern around connector pins can be used to achieve improvements of 30-40 dB in signal isolation and decoupling without added components.

References

[1]Grover, F.W., "High Frequency Formulas," *Inductance Calculations, Working Formulas and Tables,* 2nd ed., D. Van Nostrand Co., Inc., New York, 1947, pp. 261-282.

A Practical Correlation Test for Cooperative Passive Optical Sensors

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Introduction

PASSIVE optical sensors are gaining increased attention for use in tracking systems, particularly for ballistic missile defense. Their inherent weakness is their inability to provide range data. It is generally accepted that this problem could be avoided if two sensors could observe the same object and then triangulate to obtain the needed range. The difficulty with this is the absence of a practical way to associate the observations between the two sensors when a large number of objects are observed. In other words, one must determine that a pair of observations from the separate sensors indeed correspond to observations of the same object. The conventional approach[1] to this problem is to first establish a track file with the individual sensors. This provides two sets of six-dimensional state estimates and associated uncertainty covariance matrices.

Received April 12, 1982; revision received Aug. 5, 1982.
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