Investigating and visualising emission from PCB structures.

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The output of a near-field scanner is associated to relevant circuit current levels. Both differential-mode and common-mode effects are then distinguished, by considering fields from appropriate simple test pieces.

Introduction.

Have you considered how fields from signal and return current routes on your PCB layout actually appear? Electromagnetic near-field scanners are commercially available that enable the distribution of the source of unwanted electromagnetic emission to be practically traced on circuit structures. They can function in slightly different ways, but are useful in that they provide a powerful visual image. The subtle changes in circuit near-field emission may be analyzed, which has a relationship to the ultimate Electromagnetic Compatibility (EMC) of equipment. Any type of practical close proximity measurement, will however to some extent be intrusive and will have an effect on the near-field evaluation result.

Resultant spatial scans of field distribution often need interpretation. The aim of this work using an Emscan 2.21, was to explore effects and correlate relevant current levels on circuit layouts, with the viewed colour contour representation of scanner output voltage. The value of high frequency current has a relationship to consequential far-field emission. The Emscan machine will sense the net magnetic near-field emission from high frequency current. Consideration may therefore need to be given to the topology of the circuit under investigation, as conductors differentially mutually coupled, might be expected to indicate a lower sensed level than isolated conductors. The level of current flowing on PCB ground is of particular interest, as it has a relationship to the radiated common-mode emission from attached cables.

Description of the Emscan scanner.

The Emscan 2.21 scanner consists of a plate onto which the circuit under test is placed. The plate has an array of 1280 vertically defined pickup loops formed in a multilayer PCB. These are arranged in a 0.3 inch by 0.3 inch pitch, 45 degree herringbone pattern. Each loop may be addressed and sensed in turn by DC biasing a series diode on or off, via control and sense tracks that are buried within the mulitlayer PCB. A ground layer 0.125 inch (3.2 mm) below the top surface of the plate, through which the loops are defined, isolates their connecting traces. Output from the Emscan scanner plate is measured at each selected frequency, by a spectrum analyzer with 30 dB pre-amplifier. The whole scanning and image processing process is controlled by software running on a PC.

Differential and common-mode currents.

Differential signals can produce direct loop emission from the PCB circuit. Ground voltage gradients, generated from the differential-mode return currents passing over a finite impedance path, can drive low level common-mode currents of microamps. This can cause excitation of cables attached to circuit ground and common-mode emission, which is an effect of great concern with equipment EMC. [1,2,3,4]. Figure 1 depicts this effect.

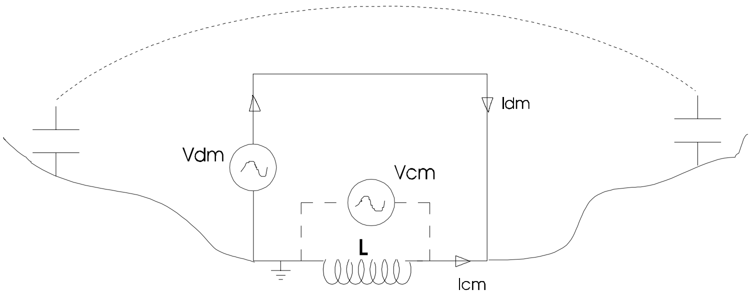


Figure 1. Mechanisim for generation of current driven common-mode emission.

It is possible to establish by calculation, the range of interest, for both low level common-mode current and differential-mode current, from some basic considerations that follow. It is also desirable to be able to quantify from scans, the low level of differential-mode return current over areas of PCB ground, which generates common-mode currents. This distribution can often be observed, where an effective return path does not exist.

Relationship of common-mode current on a cable to far-field emission.

The radiated emission electromagnetic field strength limit in Standards at 3 m distance up to 230 MHz, is 40 dBuVm^{-1} or 100 uVm^{-1}.

If the cable attached is assumed to be resonant; the equation to determine the electromagnetic emission from a resonant dipole is:

$$E = \frac{60I}{r} \quad \text{Volts metre}^{-1} \qquad (1)$$

where: I = current in Amperes
r = distance in metres

So at 3 m measurement distance the current required to reach limit is,

$$I = \frac{100\text{uVm}^{-1}}{20} = 5\text{ uA} \qquad (2)$$

But field strength measurement is normally carried out on an OATS over a ground plane with an in phase intentional reflection that can add a factor of 6 dB or 2 times. So only 2.5 uA of current on a cable is required to reach 100 uVm^{-1} field strength limit . (Note: For radiated emission measurement with multiple cables attached, consideration must be given to their resultant interaction).

The limit for permitted common-mode interference current on a cable is then rounded up to 3 uA.

Relationship of differential-mode current to far-field emission.

Differential-mode radiated emission from a loop (allowing for OATS measurement in-phase reflection) may be calculated from;

$$E = \frac{2.63 \times 10^{-14} * f^2 * I * A}{r} \quad \text{Volts metre}^{-1} \qquad (3)$$

where: f = frequency in Hertz
I = current in Amperes
A = loop area in metres^2
r = distance in metres

So the current for permitted interference can be calculated from;

$$I = \frac{E * r}{2.63 \times 10^{-14} * f^2 * A} \qquad (4)$$

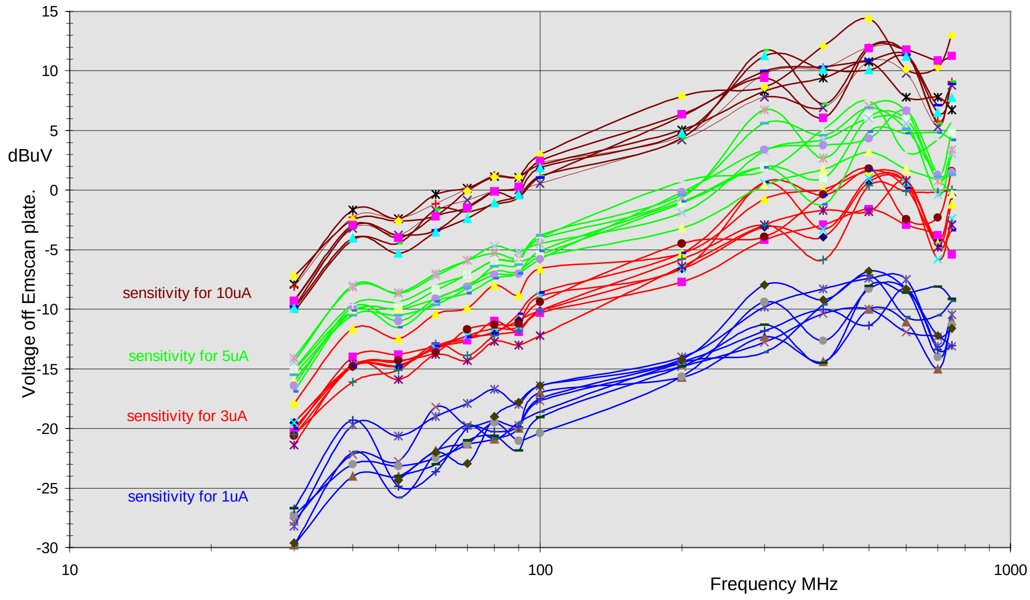
As an example, at 100 MHz with 3 m measurement distance for a small 10 cm^2 PCB trace loop (32 mm by 32 mm) this current would be 1.14 mA.

Note: The calculation neglects the effects of mutual coupling of loop fields and the consequence on far-field emission.

Calibration of Emscan output against set current.

In order to calibrate the scanner output value against a known set current, a calibration jig, consisting of a 3 mm wide by 8 mm long isolated trace, between two connectors was produced. Positioned on the surface of sensing plate the jig adds 5 nH of inductance, in series with the signal source system 50 Ohm characteristic impedance and has a VSWR at 750 MHz of 1.8:1. The scanner output response against frequency, for current levels from a RF sine wave generator, was measured for eight cells diagonally across the sensing plate, and is plotted as Figure 2.

Figure 2. Emscan 2.21 measured sensitivity for 1 to 10 uA on isolated trace at d < 2.5 mm.



From these results, an averaged Transfer Impedance value (referred to 1 Ohm) against frequency, was produced, see Figure 3. This may be used with scanner measured voltage level, to generally determine the current level on an isolated trace to +/- 2.5 dB.

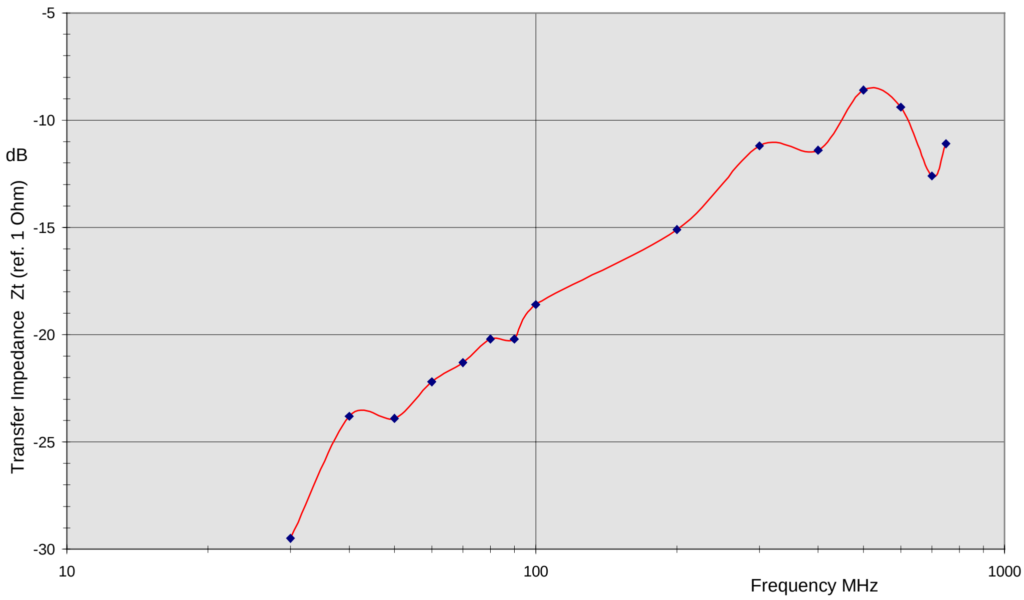
Figure 3, produced using: $Zt(\text{db ref. 1 Ohm}) = V_{emscan}\text{dBuV} - I\,\text{dBuA}$ (3)

where: Zt is Transfer Impedance in dB referred to 1 Ohm.

V_{emscan}dBuV is voltage measured.

I dBuA is current.

Figure 3. Emscan 2.21 Transfer Impedance Zt, for isolated trace at d < 2.5 mm.



The PCB test pieces.

Two types of PCB structure are of interest to investigate and lend themselves to effective practical analysis using a scanning machine; single-sided and double-sided with ground plane. Both are extensively used in high volume manufacture, which dictates that for EMC, effective layout is utilised to negate the need for additional components and shielding.

Test pieces were produced with 1.6 mm thickness PCB using the two types of construction. These were terminated microstrip and coplanar transmission lines, with a characteristic impedance of 50 Ohms and which enable a known differential current to be set. Dimensions are shown in Figure 4.

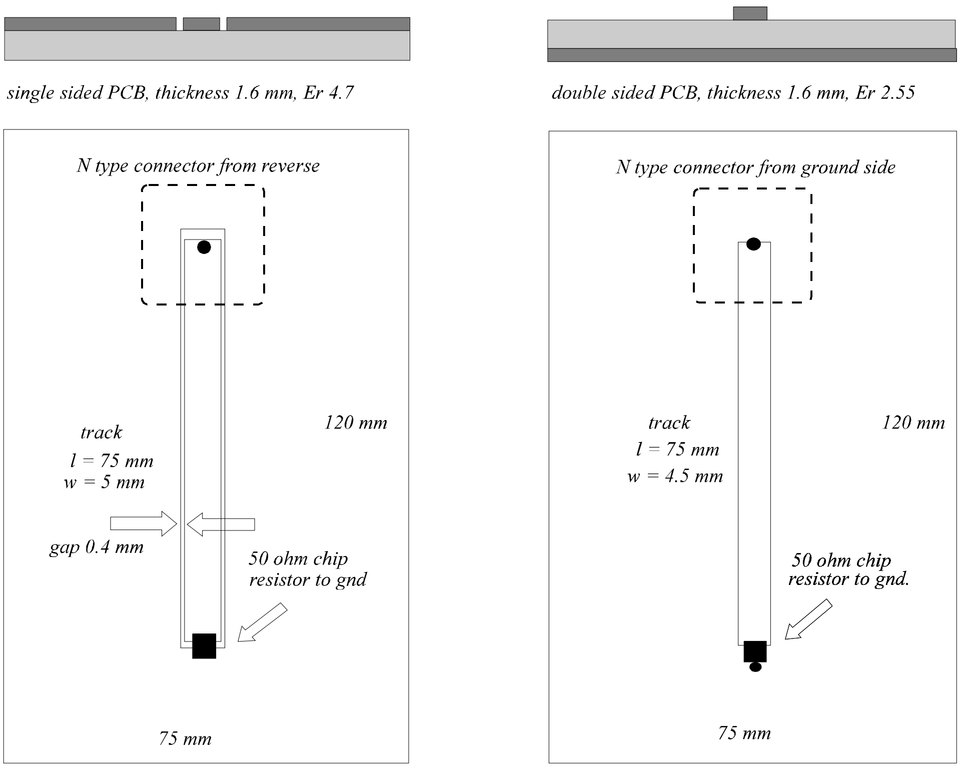


Figure 4. Coplanar and microstrip test pieces

Applying the test pieces.

To prevent ambient pickup on the PCB under test or the attached cables, which would affect results, scans of low amplitude level were performed in a screened room.

The test pieces were placed on the scanner as shown in Figure 5. The input impedance change, at the chosen test frequency of 100 MHz, when placed on the sensing plate is minimal, (mismatch is <1.2:1 VSWR on plate). Input feed cable ground was returned to the scanner plate RF connection ground and a current probe was used to measure the common-mode current on the coaxial input feed cable. The feed cable from the RF sine wave generator was routed in this way to ensure a consistent common-mode return path.

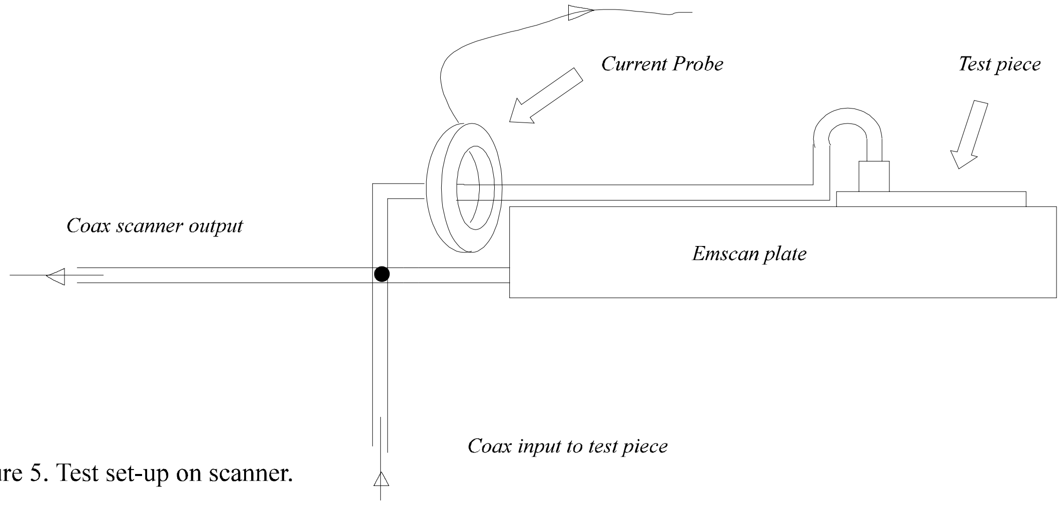


Figure 5. Test set-up on scanner.

The common-mode current level on the feed cable, was found to be influenced when the cable and test pieces were placed trackside down on the scanner plate. This image plane effect must be due to capacitive coupling between PCB track, scanner plate ground and PCB ground, and was found to vary with PCB geometry and frequency [5,6,7]. Therefore the common-mode current levels, sensed on cables attached to PCB's placed on the scanner plate, cannot be directly related by measured value to any far field emission results. It is nevertheless desirable and useful, to visualise the generation and distribution of common-mode effects, for consideration during subsequent layout investigations focused on differential sources.

In the investigations using the test pieces, differential currents were initially applied at a low level (i.e. 3 uA), to avoid sensing any associated common-mode currents.

Investigation using microstrip structure.

The magnetic flux associated with the microstrip structure is depicted in Figure 6. The differential ground return current is forced to return preferentially on the inside surface under or close to the signal track, due to the skin effect and because mutual coupling between signal and return magnetic fields, creates a lowest inductance or impedance path. The magnetic field is more intense and uniform in this space. The corresponding opposing fields outside of the trace position are however not copositioned, (distance is dependant on dielectric thickness) so there is still a small net field.

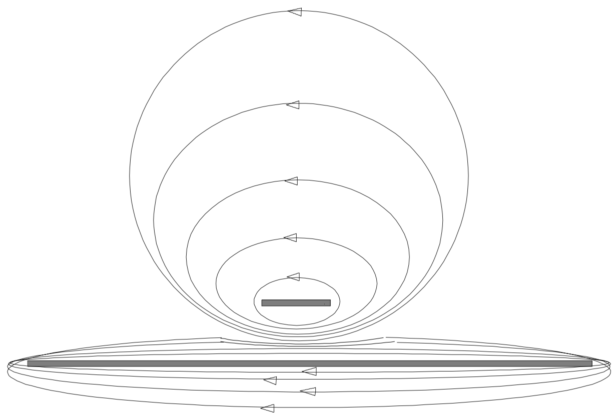


Figure 6 . Magnetic flux lines around trace and finite plane.

Figure 7 shows the sensed magnetic near-field emission on the trace side of the test piece at 100 MHz from a 3 uA differential-mode set current. Compared to the isolated trace result, the scanner response from close to the surface of the microstrip line, appears to be only very slightly reduced (if reduced at all) by the mutual coupling between magnetic fields from forward and return currents. In fact what's viewed is considered to be chiefly the field from between the trace and ground plane.

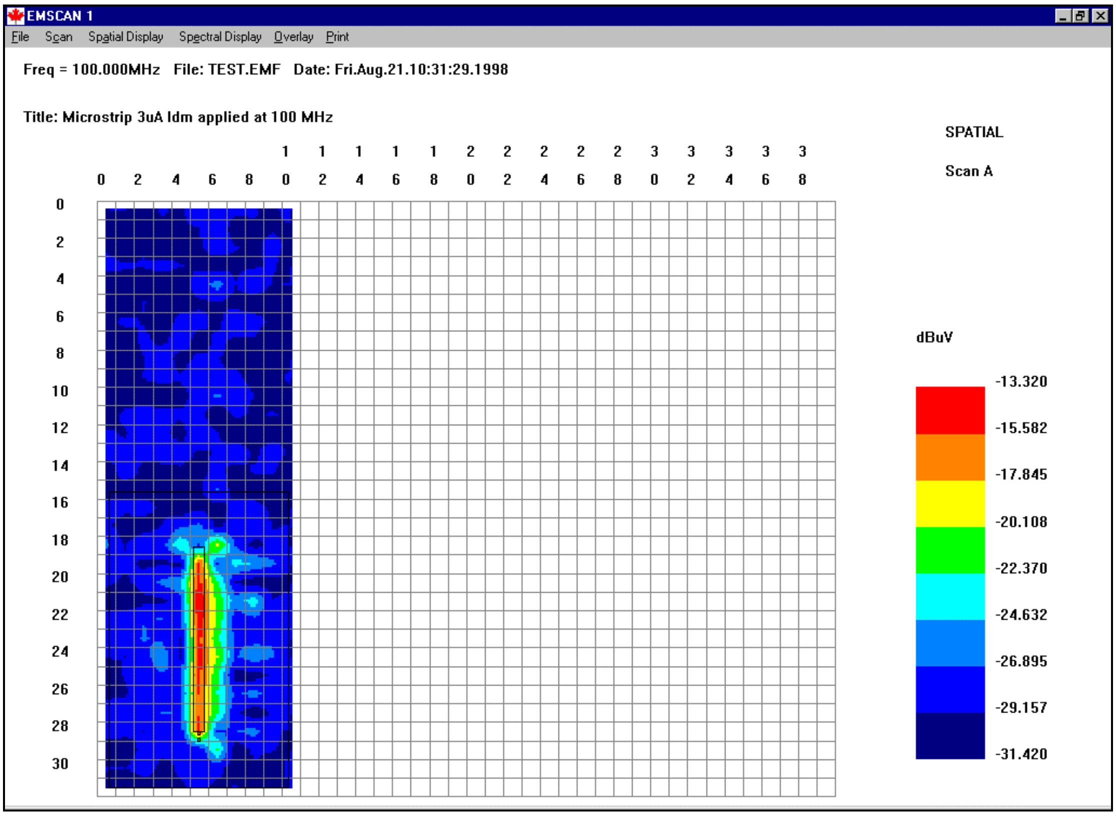


Figure 7. Microstrip line 3 uA Idm at 100MHz.

The differential-mode current applied to the test piece was increased, so that a 3 uA common-mode current was set on the feed cable, measured with a current probe. Figure 8 shows the field sensed from the 3 uA common-mode current on the feed cable positioned along column 5 of the scanner plate. Its association to the residual field distribution over the topside of the PCB ground can also be seen. This field on the topside of the PCB ground is formed by the combination of differential return current flowing over the finite impedance of the ground plane and the resultant lower level common-mode current.

It is possible to view just the common-mode field component, corresponding to that from the feed cable, on the reverse ground side of the microstrip test piece and this is shown in Figure 9.

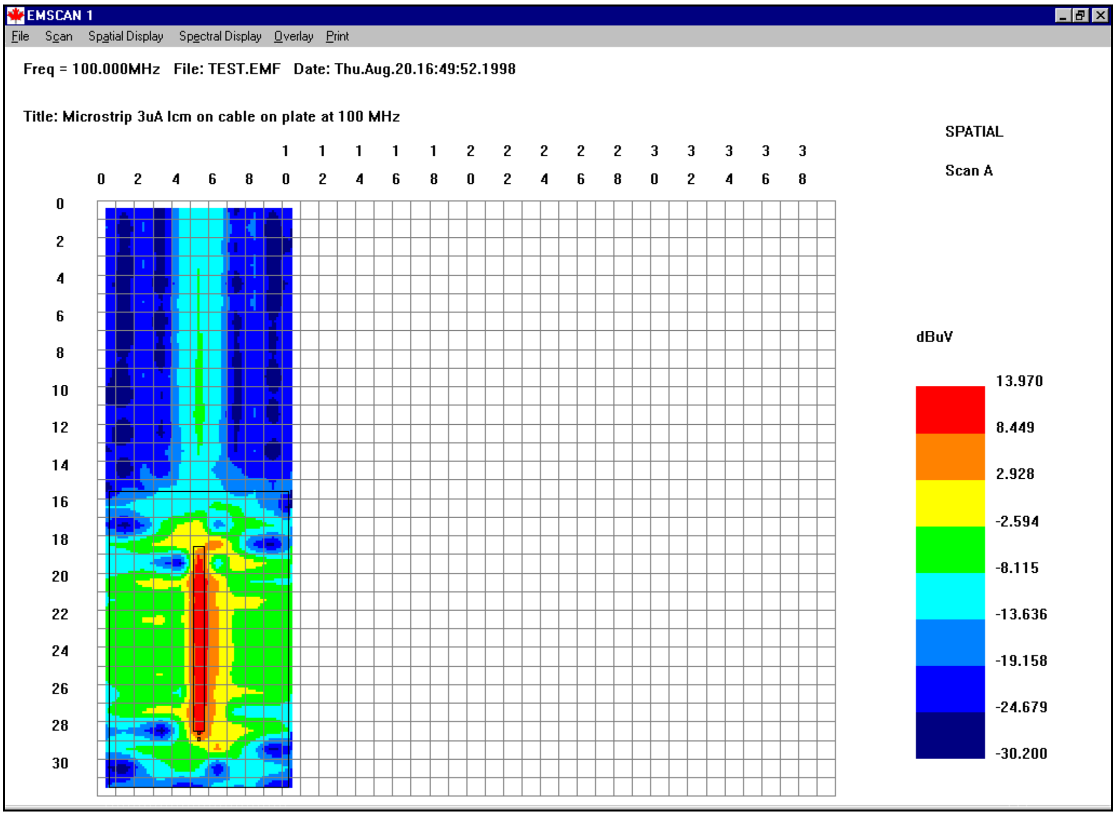


Figure 8. Microstrip line top side, 3 uA Icm on attached cable at 100 MHz

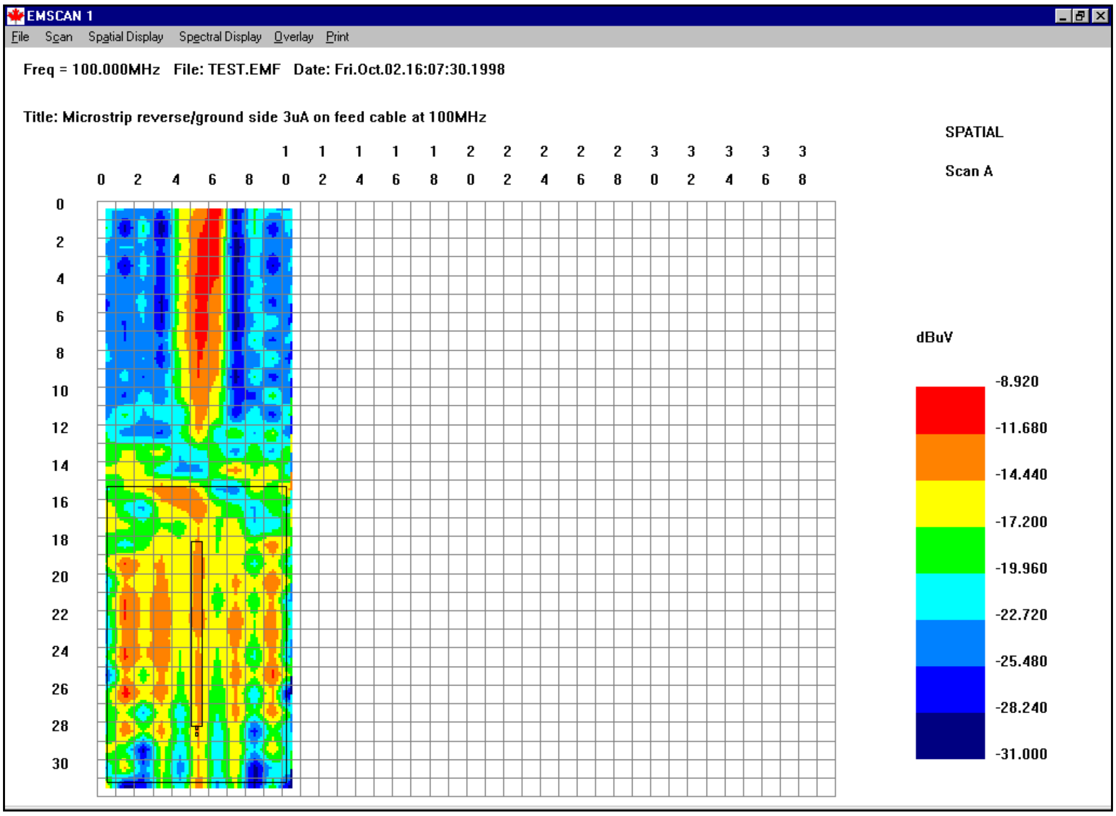


Figure 9. Microstrip reverse side, 3 uA Icm on attached cable at 100 MHz

Investigation using coplanar trace structure.

The magnetic flux associated with the coplanar structure is depicted in Figure 10. Signal return currents on the ground would be expected to preferentially return on the edge closest to the trace, being the lowest inductance or impedance path due to mutual coupling. With this structure the gap between trace and ground can be made smaller than the PCB thickness. The magnetic field in this space is more intense and uniform. The corresponding opposing fields outside of this location are however not copositioned (distance is dependant on gap width and trace width) so there will be a small net field.

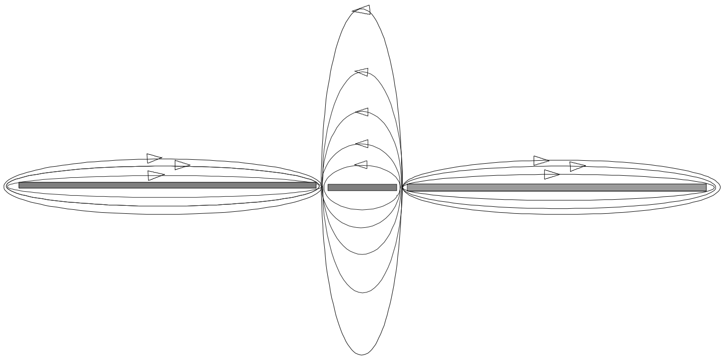


Figure 10. Magnetic flux lines around trace and return path.

Figure 11 shows the sensed magnetic near-field emission from the test piece at 100 MHz from a 3 uA differential-mode set current. The field level sensed close to the surface of the trace, compares to the level from the microstrip line and isolated trace. Again this is considered to be chiefly the field from between the trace and ground plane.

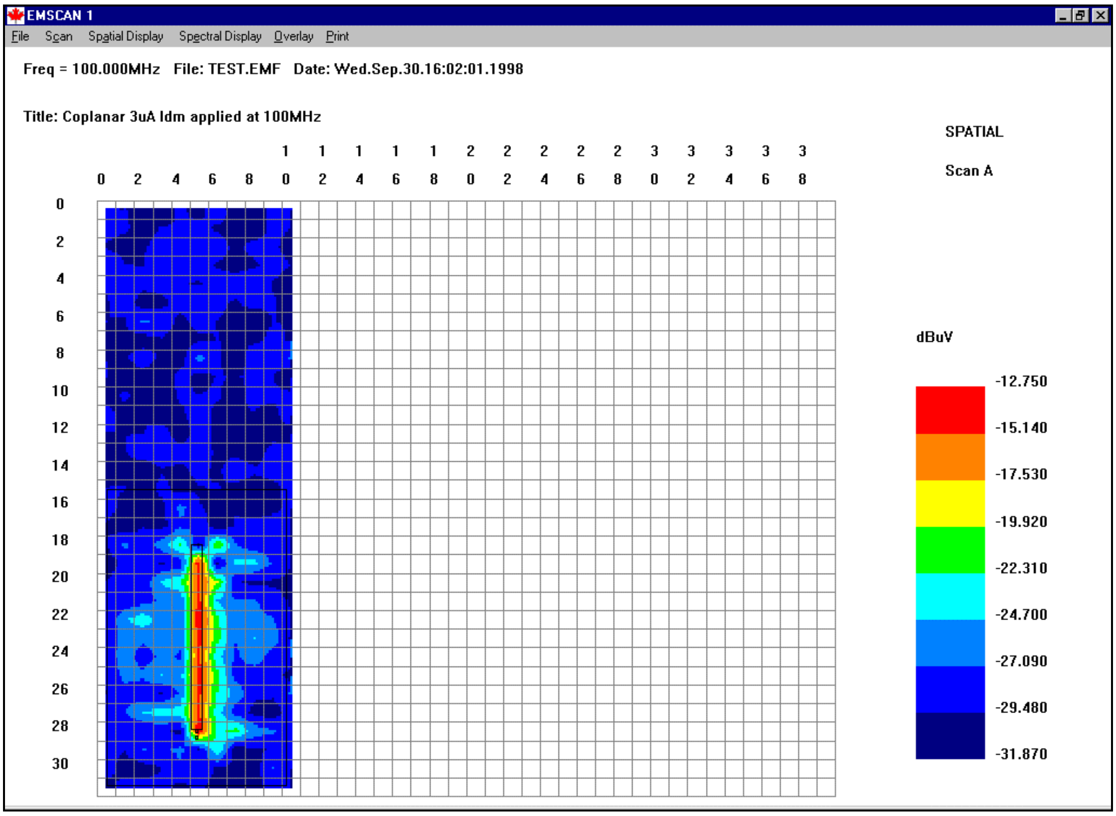


Figure 11 Coplanar trace, 3 uA Idm at 100 MHz

The differential-mode current was then increased, so that a 3 uA current was set on the feed cable, measured with a current probe. Figure 12 shows the field sensed from the common-mode current on the feed cable positioned along column 5 of the scanner plate. Compared to the microstrip test piece, a higher level of differential-mode current was required and this difference is attributed to test piece geometry and the image plane effect. Differential return current routing which occurs preferentially close to the trace is highlighted.

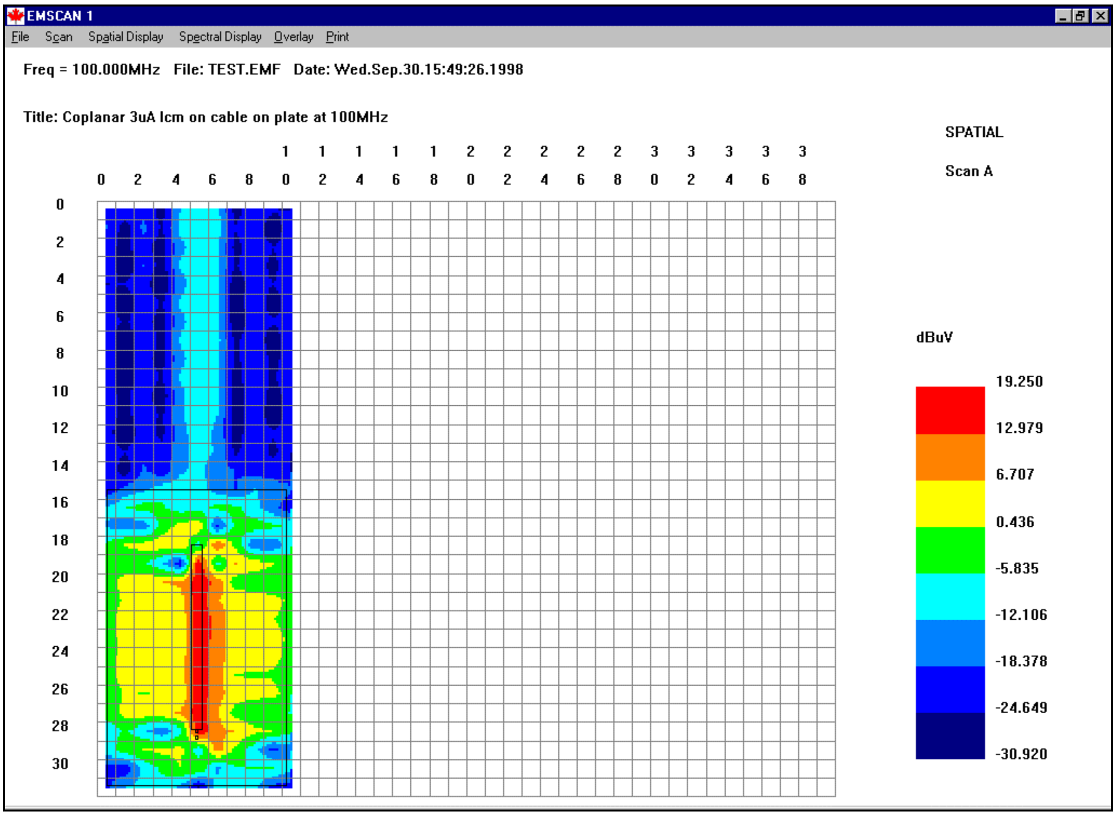


Figure 12 Coplanar trace, 3 uA Icm on attached cable at 100 MHz

Conclusions.

Correlation of near-field scanner output against current at a fixed distance, has been accomplished and effects explored. The value and distribution of differential-mode currents, on single and double sided PCB trace geometries, may be determined down to 1 uA from near-field spatial scan levels and calibration data. This could provide a useful benchmarking test for design comparison. At a set current the field sensed from the test-piece traces or space between trace and ground, was not found to be greatly reduced by mutual coupling cancellation effects, which are assumed to occur at a greater distance away. To provide an acceptable relationship between determined current and differential-mode loop far-field emission, it may be therefore necessary to also consider a reducing influence factor dependant on trace geometry.

The generation of common-mode current on ground has been viewed but distribution can be masked by higher level differential return currents. The position of a PCB with respect to reference ground, e.g. the Emscan plate, can have an influence on the common-mode emission level, which varies with frequency. Common-mode current levels from cables attached to the PCB, should therefore be measured in the required circuit operating location using a current probe.

Although this work has been undertaken on a particular type of scanner, it is anticipated that the approach and findings could be applied to other models and types.

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