# Skin-Effect Modeling of Image Plane Techniques for Radiated Emissions from PCB Traces

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**Abstract:** This paper uses high frequency skin effect models to characterize the current density concentration on PCB traces and then uses image plane techniques to reduce radiated emissions. The signal trace is divided into four rectangular segments based on current density concentrations and radiated emission levels are investigated by placing image planes parallel to each segments. For thick flat parallel conductors of several skin thickness, when the separation between the signal trace and ground plane is very small, the high frequency current flow is within the inner surfaces of signal trace and ground plane and sides of the signal trace. The amount of current flow on the top of the signal trace is very small and the image plane above the signal trace has little effect on radiated emissions. The radiated emission levels are measured for different trace and image plane thickness and separations and results are presented.

## I. INTRODUCTION

Most printed circuit board (PCB) designs use strip line or microstrip line structures in order to reduce high frequency radiated emissions. A strip line consists of a strip signal conductor centered in a dielectric medium between two conducting planes. The conducting plane in a PCB must be either power or ground. The microstrip line is a strip signal conductor separated from a ground or power plane by a dielectric. Microstrip structures can be implemented on a single power or ground layer which is cheaper than strip line. Implementing microstrips on outer layers of the PCB lend to easy circuit adjustments after circuit has been fabricated. Due to the presence of air and dielectric interface, an improperly designed microstrip not only radiates but also has potential for crosstalk. For a narrow microstrip in which the trace width (w) is very small compared to the dielectric height (h), the fields are distributed around the strip similar to any isolated conductor [1]. The dielectric discontinuity due to the air-dielectric interface on the microstrip excites the current flowing on top and sides of the microstrip into higher order radiating modes. High frequency current distributions on the strip and ground plane of a microstrip have been studied by several authors [2,3]. When w>h, most of the strip current flows on the bottom and sides of the strip and the ground return current flows on the top of ground plane. The width of the ground current spreads beyond the strip width w is shown in Figure 1 and 3. When w>>h the current distribution tends to concentrate on the bottom of the strip and above the ground plane similar to a pulse[3]. The width of the current distribution on the strip and ground plane almost equals w. When w/h is large, the upper part of the strip should act as electromagnetic shield. If the thickness of the strip is increased further, shielding effectiveness also increases.

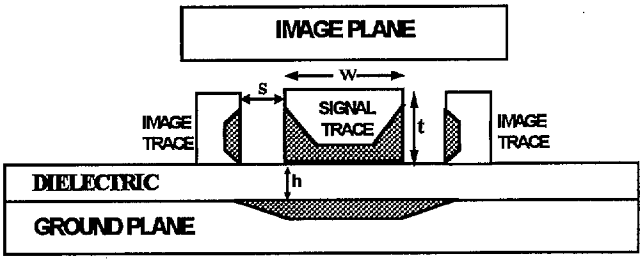

Figure 1. HIGH FREQUENCY CURRENT DENSITY CONCENTRATION ON THICK SIGNAL TRACE, IMAGE TRACES, AND GROUND PLANE

The parallel side image traces to the signal trace (see Figure 1), also known as guard traces, tend to be more effective as the image traces are moved closer to the signal trace and grounded to the ground plane. The side image traces must be placed such that it covers the ground plane spread current that extends beyond w.

Most papers, to author's knowledge, on skin effect theory, address the circuit performance issues, such as crosstalk, power loss and do not address radiated emissions problems. The radiated emissions on microstrip structures have been studied by several authors using image plane theory. Radiated emissions were reduced effectively by reducing the circuit inductance by the method of images [4]. This paper investigates the following:

(1) identifies skin effect current distributions around the traces and ground plane and by varying the conductor thickness, the radiated emissions are investigated.

(2) identifies skin effect current distributions around the traces and ground plane for different conductor thickness and by placing grounded image traces at sides of the signal trace, the radiated emissions are investigated.

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(3) identifies skin effect current distributions around the traces and ground plane for different conductor thickness and by placing grounded image traces at the sides of the signal trace at different separation distance, the radiated emissions are investigated.

(4) identifies skin effect current distributions around the traces and ground plane at different w/h ratios and radiated emissions are investigated for the following experimental configurations:

a. without image traces on the sides of the signal trace.
b. ungrounded image traces on either side of the signal trace.
c. grounded image traces on either side of the signal trace.
d. grounded image trace on either side of the signal trace and an isolated ground plane on the top of the signal trace.

## II. BASIC ASSUMPTIONS

Due to the presence of the air-dielectric interface in microstrip structures, the field distribution at very high frequencies, tends to become a non-TEM mode. Over most of the operating frequency range ($w << \lambda_0$), the longitudinal components of the fields in dominant mode is negligibly smaller than the transverse component. In this paper, field distribution similar to TEM or quasi-TEM mode is assumed. The ground plane is very large compared to the dimensions of microstrip. Any anomalous skin effect due to very low temperatures and high frequency is ignored.

## III. IMAGE PLANE THEORY

The image plane theory is based on cancellation of two fields of equal magnitude but opposite phase. For a PCB trace, the opposing field could be either from a return current trace or plane or from an isolated image plane An isolated ground plane acts as imaginary return current plane and does not contain return current. For effective cancellation of differential fields, the location, phase, and intensity of the oppositely directed field are important. For the same physical locations, the return trace or plane is only half the distance from the signal trace as compared to an isolated image plane. Therefore, when the opposing field is from a parallel return trace or ground plane, the field cancels more effectively.

## IV. SKIN EFFECT MODEL

At high frequencies, current distribution over the cross section of isolated flat conductors is confined to the outer surfaces due to skin effect. The current distribution of an isolated conductor was examined by several authors in detail [5,6,7]. When two conductor planes are parallel to one another and carry currents of equal density in opposite directions and the separation between them is very small, the magnetic field between the conductors adds, and those outside them cancels. Figure 2 illustrates magnetic field distribution for an odd mode coplanar microstrips. In this illustration, the image effect of ground plane has been ignored for simplicity. The magnetic field created by the microstrips are oppositely directed and therefore, they add between the strips and cancel outside the strips. As the spacing (s) between the strips becomes very small, more fields will effectively add between the conductors and cancel outside the conductors.

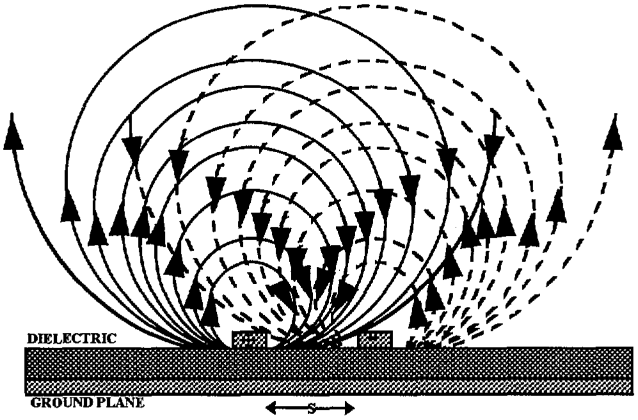

Figure 2. MAGNETIC FIELD DISTRIBUTION FOR A COPLANAR MICROSTRIPS.

For a microstrip structure, it is assumed that all flux lines after extending indefinitely laterally within the space between the strip and ground plane, self close by returning in the space outside the strip and ground plane. The field intensity between the strip and ground plane is high and most current flows on the inner sides of the strip and ground plane. The intensity of field outside the strip and ground plane is very small and constitutes small currents. If w/h is large, the leakage field outside the strip and ground plane is similar to a solenoid, where if the length of the solenoid is greater than the diameter, the field is assumed to be zero at external points near the center axis of the solenoid[1].

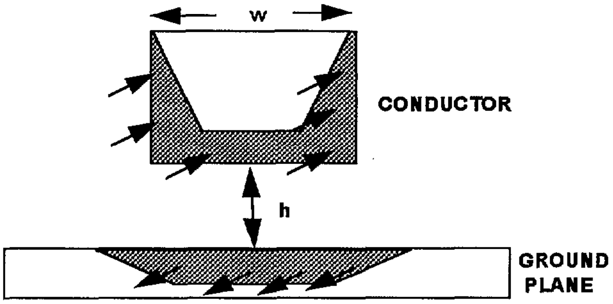

Figure 3. CONCENTRATION OF CURRENT DENSITY DISTRIBUTION OF A CONDUCTOR ABOVE GROUND PLANE FOR h < w

For a microstrip structure, it has been shown by Faraji-Dana and Chow [5] and recently by Moongilan [1] that as the ratio of trace width (w) and height of the trace (h) assumes large values ($w//h \to \infty$), there is higher concentration of current distribution on the top of the ground plane and the bottom and sides of the trace conductor where the inductance and therefore impedance is very small; and negligibly small current flow on the top of the trace conductor (see Figure 3). Faraji-Dana et al. have indicated that even for a small value of w/h = 0.1, relative current concentration of 3 % to 4% was measured at the center part of the lower side of the trace as compared to the upper side depending on the conductivity of the material, cross sectional area, and frequency. The redistribution current, due to interaction of magnetic fields of neighboring conductors, is also known as the proximity effect. For thick parallel traces, the total inductance is the sum of the external or circuit inductance plus the internal inductance [8].

$$L_T = L_{ex} + L_{in} = \mu\,\frac{h}{w} + 2\,\frac{1}{\omega\delta\sigma w} \qquad (1)$$

where

$\mu$ = permeability

$\omega = 2\pi f$

f = frequency in Hz.

$$\delta = \text{skin depth} = \left(\frac{1}{\pi f \mu \sigma}\right)^{1/2}$$

$\sigma$ = DC conductivity of the material.

The total series resistance

$$R = 2\,\frac{1}{\delta\sigma w} \qquad (2)$$

The surface impedance ($Z_S$) per unit length is obtained as the voltage drop per unit length on the surface divided by the total current enclosed. It should be noted that skin depth $\delta$ is a point where the current penetration depth drops to 1/e or 38.8 percent of its amplitude at the surface. But the definition of surface impedance appears as if current is uniformly distributed over the thickness $\delta$. If the w/h is very large, the magnetic field external to conductors must be zero. In equation (1) external inductance is negligible [6]. Therefore, from (1) and (2)

$$Z_S = R + j\,\omega L = \frac{1+j}{\delta\sigma w}$$

$$= (1+j)\,\frac{1}{w}\left(\frac{\pi f \mu}{\sigma}\right)^{1/2} \quad \Omega/\text{m} \qquad (3)$$

The equation (3) shows that wider conductors, independent of h, will provide lower $Z_s$ and spread current distribution widely into a thinner layer. As illustrated in Figure 2 for coplanar microstrips, if w is fixed and h is decreased, more current concentrates at the inner surfaces of the conductors due to the large concentration field within the surfaces and small concentration at the outer surfaces. Equation (3), based on w/h approaching infinity may not be physically realizable. It can be concluded that an increase of w results in lower current concentration and lower $Z_S$ values. A decrease of h results in higher current concentration and an increase of $Z_S$. In a microstrip structure when w/h is small, the ground current spreads widely under the strip and as w/h increases, ground current spread decreases and tightly follows the trace width w with higher concentration [3].

Horton et al. have proved that the power loss or attenuation per unit length of microstrip does not change appreciably for trace thickness (t)/skin depth ($\delta$) > 2 for any w/h > 2 [9]. i.e. when $t/\delta > 2$ for all w/h > 2, the power loss is independent of $t/\delta$ and decreases as w/h increases. Therefore, wider strips must distribute current concentration as a finite thinner layer and must be at the bottom of the strip and top of the ground plane. This shows that for thicker conductors the upper part of the conductor must act effectively as electromagnetic shielding. When w/h is large, the current concentrates at the bottom of the strip, and the return current spread on the ground plane is equal to width of the trace [3]. Therefore, high frequency return current tends to tightly follow the signal trace. This implies that high frequency current does not follow the least resistive path but follows the least inductive path. If the current returns by any other path, then the total loop area between signal and return current will be larger. Larger loop area produces larger inductance.

## V. EXPERIMENTAL RESULTS

In order to prove both image plane techniques and skin effect models, several radiated emissions investigations were performed and are described in this section. For each investigation, a 10 x 8 inch ground plane and a 9 inch long and 10 mils wide signal trace was used. A battery powered 60 MHz clock was used as signal source. The impedance of the each trace was measured with time domain reflectometer and terminated with a resistance equal to the characteristic impedance. The radiated emissions from the clock and battery interconnection and clock board to experimental board were reduced by shielding the clock board and filtering the power leads using bulk ferrite beads. The ground plane and image traces were connected through plated-through vias at every 3 inches. The radiated emission measurements were performed at an open area test site at a 3 m distance. The following cases were investigated:

1. The effect of signal trace thicknesses (0.7, 1.4, and 2.8 mils) on skin effect current and the performance of the ground plane as image plane on radiated fields. The results are presented in Figure 4.
2. The effect of parallel grounded image traces placed at 10 mils distance on either side of the signal trace (see Figure 1) for various signal, and ground trace thicknesses (0.7, 1.4, and

2.8 mils). The ground plane and image traces were connected through plated-through vias at every 3 inches The results are presented in Figure 5.

3. The effect of parallel grounded image traces placed at 20 mils distance on either side of the signal trace (see Figure 1) for various signal, and ground trace thicknesses (0.7, 1.4, and 2.8 mils). The results are presented in Figure 6.

4. The dielectric thickness was increased from 3 to 12 mils and the following were investigated: (a) the effect of the ground plane as image plane for signal trace and ground plane thickness of 1.4 mils. (b) then parallel ungrounded image traces on either side of the signal trace was analyzed for signal, and ground trace thicknesses of 1.4 mils (c) then parallel grounded image traces on either side of the signal trace was analyzed for signal and ground trace thicknesses of 1.4 mils.(d) Analysis was also performed with a third image plane on top of the signal trace (see Figure 1). This image plane was simulated using 1 inch wide copper tape. This tape was isolated from ground plane. The results are presented in Figure 7.

## VI. CONCLUSIONS

For a thick flat microstrip structure, when the separation between the signal trace and ground plane is very small, the high frequency current flows on the bottom and sides of the signal trace and the top of the ground plane. The amount of current flow on the top of the signal trace is very small. Therefore:

- for the same w/h ratio, thicker traces produced lower radiated emission levels because the thicker conductor top surface offered more shielding to the signal currents.
- grounded side image traces, placed at closer separation distance from the signal trace, produced lower radiated emission levels compared to grounded side image traces placed at larger separation distances. The return current distribution on the ground plane decreases as a function of perpendicular distance from the trace. Therefore smaller and widely spread return current flows on the side image traces placed at larger separation distance result in less field interaction between signal trace and image traces. This resulted in higher radiated emission levels for larger separation distance.
- thicker image and signal traces produced lower radiation levels compared to thinner traces. The thicker image and signal traces offered more shielding. Image traces thicker than the signal trace produced lower radiated emissions. This was simulated using copper tapes. Data is not reported in this paper. Using current technology, traces with different thicknesses can't be cheaply fabricated on the same PCB layer.
- ungrounded image traces produced higher radiation levels compared to grounded image traces. For an ungrounded image trace, the effective image is twice the actual distance, therefore, field interaction was not as effective as grounded image traces.
- image traces on the sides of the signal trace and image plane (ground plane) below the signal trace reduced the radiated emission levels. An isolated ground plane on the top of the signal trace did not produce a significant reduction in radiated emissions, since current on the top of the image and traces were vanishingly small.

Grounding the top image plane makes microstrip line look like a strip line, and therefore invalidates the skin effect theory indicated in this paper because skin current tends to flow equally on all sides of the signal trace. For the test set up with side image traces at 10 mils separation distance and 3 mil dielectric thickness, the characteristic impedances measured were 30Ω, 28Ω, and 25Ω for trace thicknesses of 0.7 mils, 1.4 mils and 2.4 mils respectively. For the test set up with side image traces and 12 mil dielectric thickness, the characteristic impedance measured was 75Ω for a trace thickness of 1.4 mils. By judiciously selecting dielectric material with lower permittivity(ε), the trace impedance can be increased and radiation levels also can be reduced.

## VII. REFERENCES

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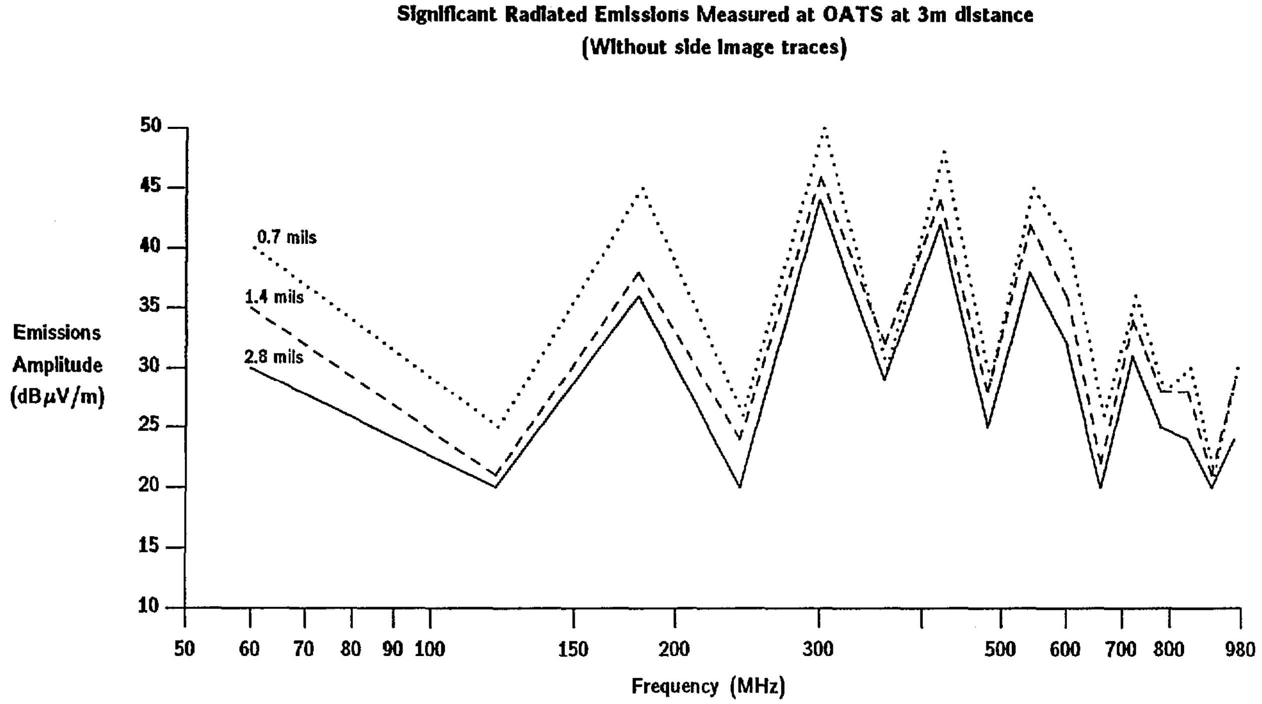
Significant Radiated Emissions Measured at OATS at 3m distance
(Without side image traces)

Figure 4. Radiated emission levels for signal trace thicknesses of 0.7, 1.4, and 2.8 mils, trace width of 10 mils and dielectric (εr=4.2) thickness of 3 mils.

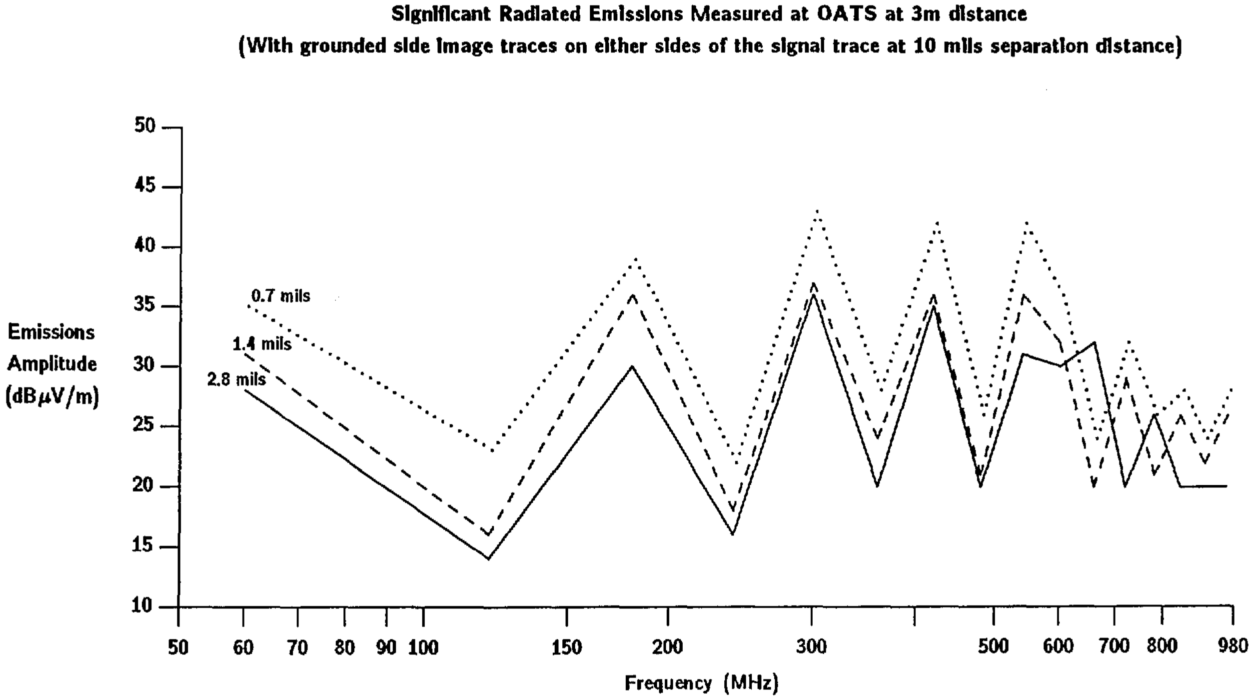
Significant Radiated Emissions Measured at OATS at 3m distance
(With grounded side image traces on either sides of the signal trace at 10 mils separation distance)

Figure 5. Radiated emission levels for signal and ground trace thicknessses of 0.7, 1.4, and 2.8 mils, trace width of 10 mils, with grounded side image trace at 10 mils separation distance and dielectric (εr=4.2) thickness of 3 mils.

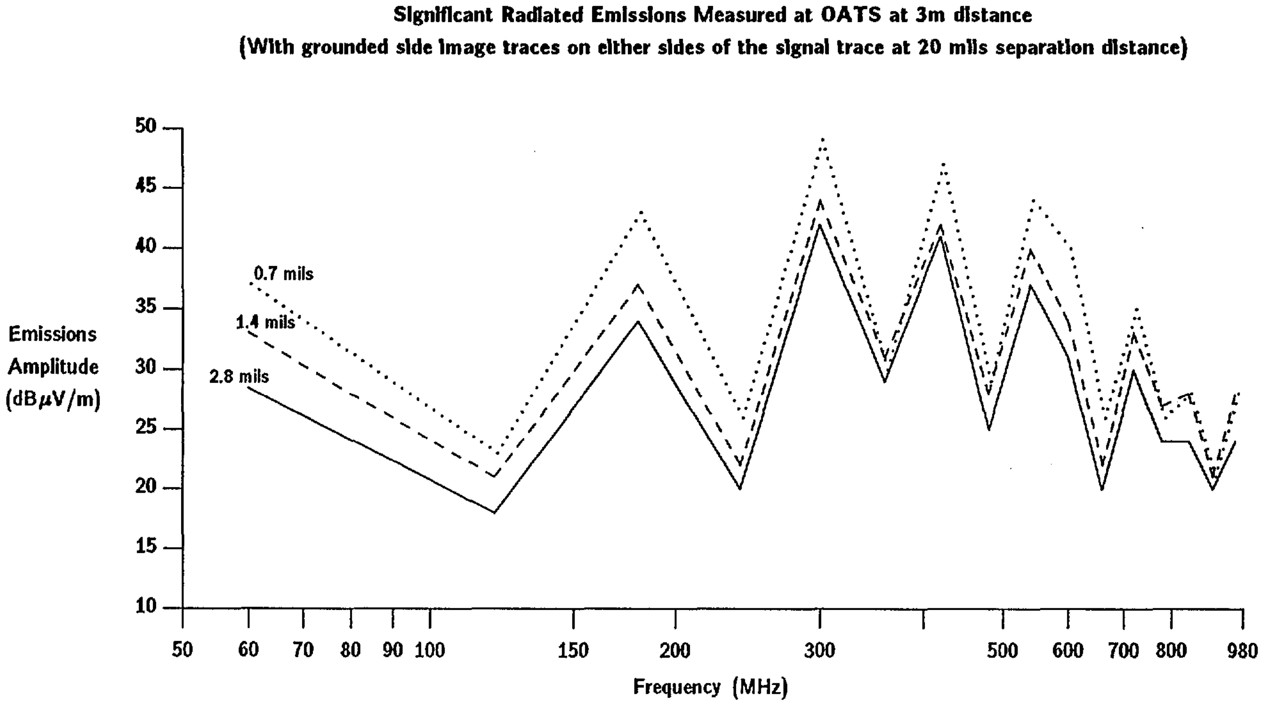

Figure 6. Radiated emission levels for signal and ground trace thicknessses of 0.7, 1.4, and 2.8 mils, trace width of 10 mils, trace separation distance of 20 mils and dielectric ($\epsilon r$=4.2) thickness of 3 mils.

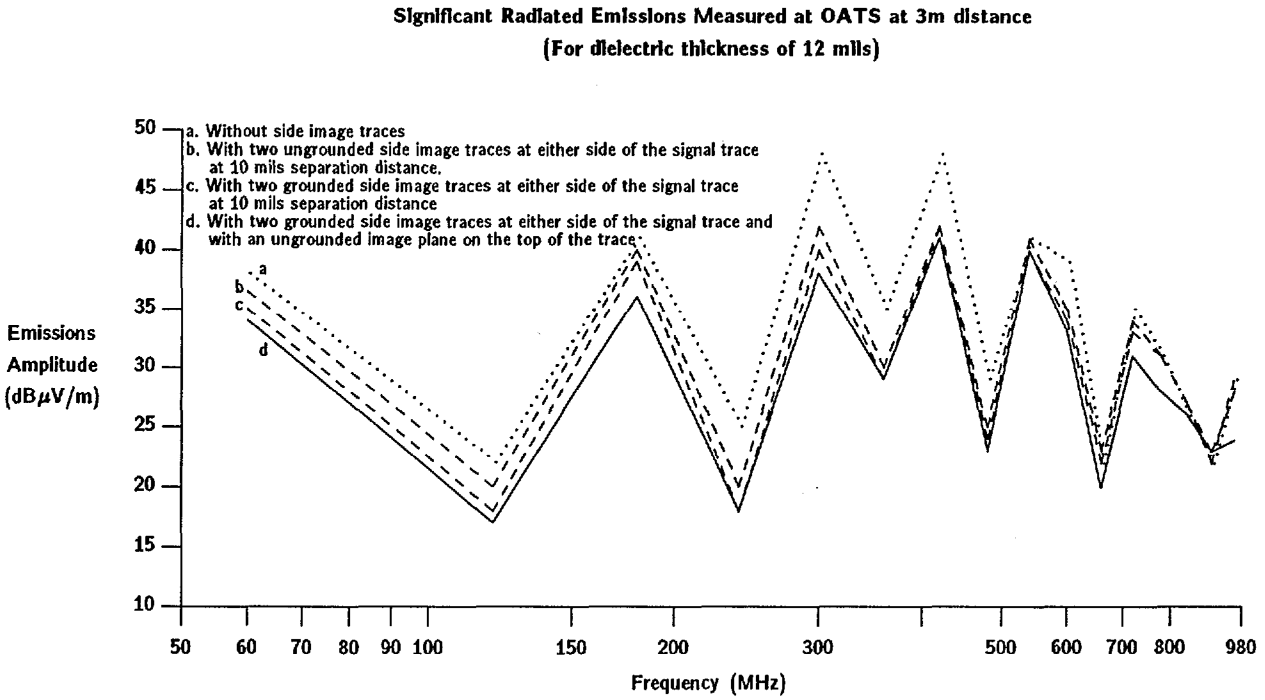

Figure 7. Radiated emission levels for signal and ground trace thicknessses of 1.4 mils, trace width of 10 mils and dielectric ($\epsilon r$=4.2) thickness of 12 mils (a) Without side image traces (b) With ungrounded side image traces (c) With grounded side image traces (d) With grounded side image traces and ungrounded image plane on top of the signal and image traces.