PCB's top ground plane and its effect on a microstrip line's characteristic impedance

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Title-3

Introduction

When designing microstrip circuits, several precautions have to be taken to ensure proper grounding and transmission line impedance. The structure shown in Figure 1 was analyzed while varying the substrate thickness, h, the gap between the microstrip line and top layer ground plane, G, and the relative dielectric constant of the substrate, ε_r . Two questions are addressed in this study; does the impedance stay fairly constant from IF to RF frequencies, and what effect does the gap between the microstrip line and the top ground plane have on the transmission line's characteristic impedance, Z_0?

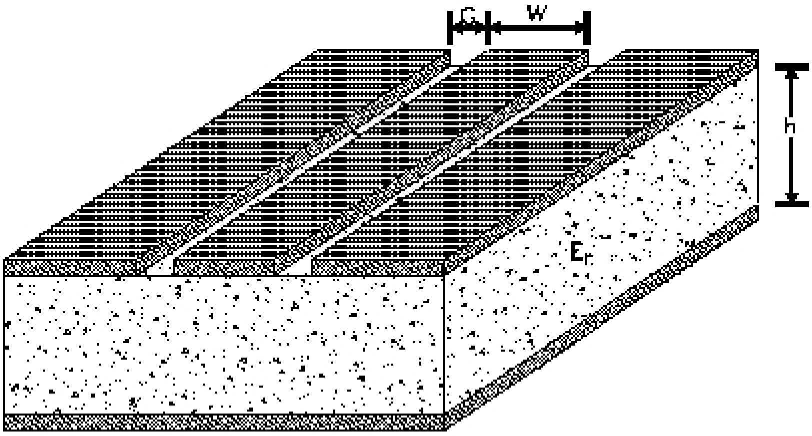

Figure 1 A typical microstrip line scenario.

Frequency dependence of a microstrip line with a top ground plane

The first case investigated had the following parameters:

$$h = 10 \text{ mils}$$
$$\varepsilon_r = 3.8$$
$$W = 20 \text{ mils}$$

The parameters given above should correspond to a microstrip line with characteristic impedance, Z_0 of 50 Ω. Figure 2 shows the relationship between the transmission line's characteristic impedance, Z_0 , and the operating frequency. The lowest frequency analyzed in this study was 100 MHz. The variation of Z_0 between 100 MHz and 2 GHz is only 0.7 Ω, which is negligible for most practical applications. The 0.7 W change in the transmission line's impedance would result in a VSWR of 1.014, or a reflection coefficient S_{11} of -43.2 dB. However, when the gap G in Figure 1 is varied from 10 mils to 40 mils (0.5 to 2 times the microstrip line width, W) the change in characteristic impedance Z_0 is 1.9 Ω. The largest variation in Z_0 occurs when the gap, G, becomes significantly smaller than the line's width, hence resulting in coplanar waveguide mode.

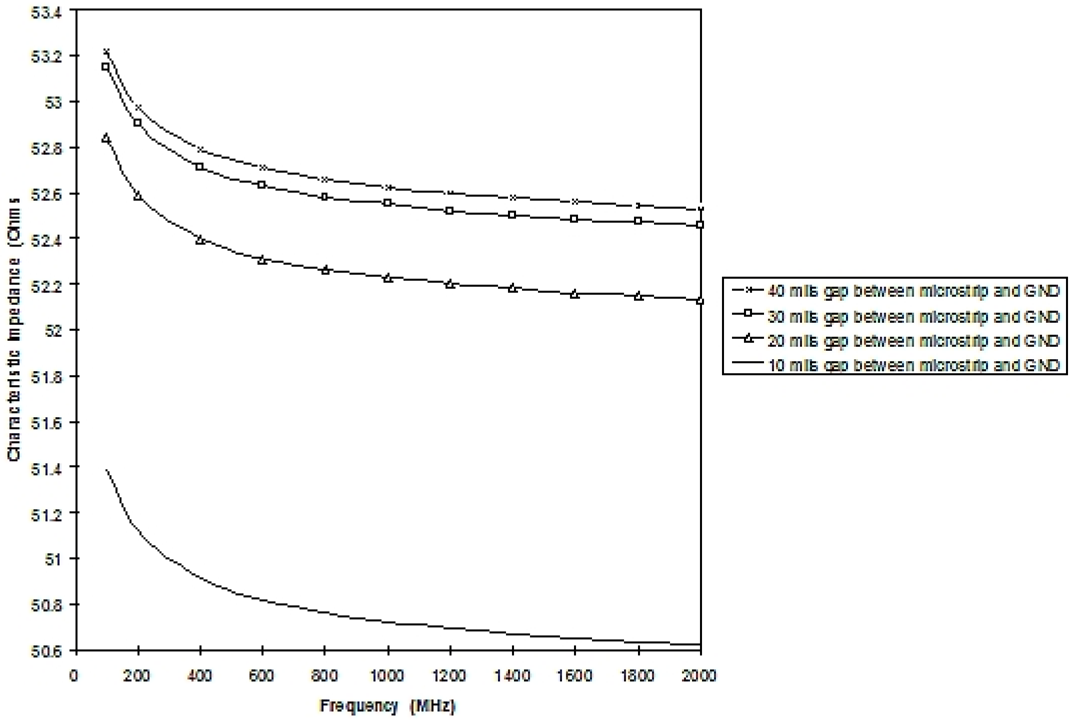

Figure 2. Microstrip impedance as a function of frequency for different PCB top-layer ground gaps for a thin PCB substrate (10 mils).

The second case analyzed had the following parameters:

$$
\begin{aligned}
h &= 60 \text{ mils} \\
\varepsilon_r &= 3.8 \\
W &= 20 \text{ mils}
\end{aligned}
$$

Here, the substrate's thickness, h, was increased from 10 mils to 60 mils. This case had higher transmission line impedance since more of the field lines are concentrated in the substrate and the effective dielectric constant is somewhat higher, which is shown in Figure 3.

The characteristic impedance varies from 78 Ω to 104 Ω when the gap G is varied from 10 mils to 40 mils. Therefore, varying the gap, G, between the microstrip line and the top ground plane has a greater effect on varying the desired transmission line impedance than the variation caused by increasing frequency of operation.

For example, the characteristic impedance Z_0 of the transmission line differs by 26.5 Ω at 2 GHz when a gap of 10 mils is compared to a gap of 40 mils.   This great variation will result in a substantial VSWR and correspondingly bad return loss.

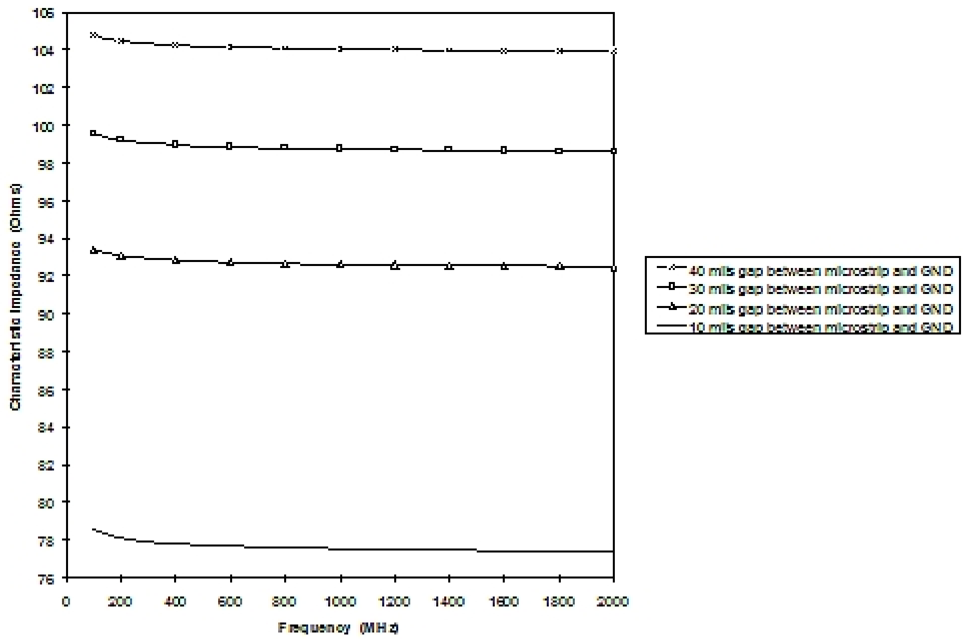

Figure 3. Microstrip impedance as a function of frequency for different PCB top-layer ground gaps for a thin PCB substrate (60 mils).

The effect of the gap

The effect of the gap between the microstrip line and the top ground plane

Generally, practical circuit designs require a top ground plane for both convenience when using shunt components and for shielding. The factors to keep in mind are the spacing between the microstrip line and the top ground plane G, the printed circuit board layer substrate's height h, and the relative dielectric constant of the substrate itself ε_r.

The microstrip line width is also important to keep in mind when the width becomes narrow. A narrow transmission line width results in more of the electric field lines being concentrated in the air above the substrate, making the effective dielectric constant more susceptible to variations in the gap G. Hence, the impedance of the line is more susceptible to variations in the gap, G.

As seen in Figures 4, 5, and 6 is that the change in characteristic impedance Z_0 is greater for thicker substrates when the gap G is varied. A thicker PCB layer substrate h results in a larger variation in characteristic impedance Z_0 when the gap G is varied.

The illustration of this is shown in figures 4, 5 and 6 where the PCB substrate had a relative dielectric constant of ε_r=3.8 and the frequency of simulation was 1 GHz. The figures 4, 5 and 6 have the same y-axis range of the characteristic impedance Z_0 (Δ=85 Ω). It can clearly be seen that the least variation as a function of the top layer ground spacing to microstrip line, G, occurs with thinner substrates, which also corresponds to the use of higher effective dielectric constant material.

For best performance, an empirical design equation is proposed (1). This is based on interpolating figures 4, 5, and 6

$$G = 15 \cdot h + \frac{h}{W} + \frac{20}{\varepsilon_r} \qquad (1)$$

where G is the gap between the microstrip line and the top ground plane, W is the width of the microstrip line, ε_r is the relative dielectric constant of the substrate, and h is the thickness of the substrate. The rule of thumb in designing the transmission line is to space the top ground plane gap G at least 1.5 times the substrate height h away from the microstrip line.

When using shunt components, the best case is clearly the use of a thinner substrate, where the characteristic impedance of the microstrip line stays relatively constant over a wide range of gap widths. This is important because if there are components going to ground the impedance of the transmission line would change significantly when the ground plane has to be drawn closer to the microstrip for the components (such as 0201 or 0402).

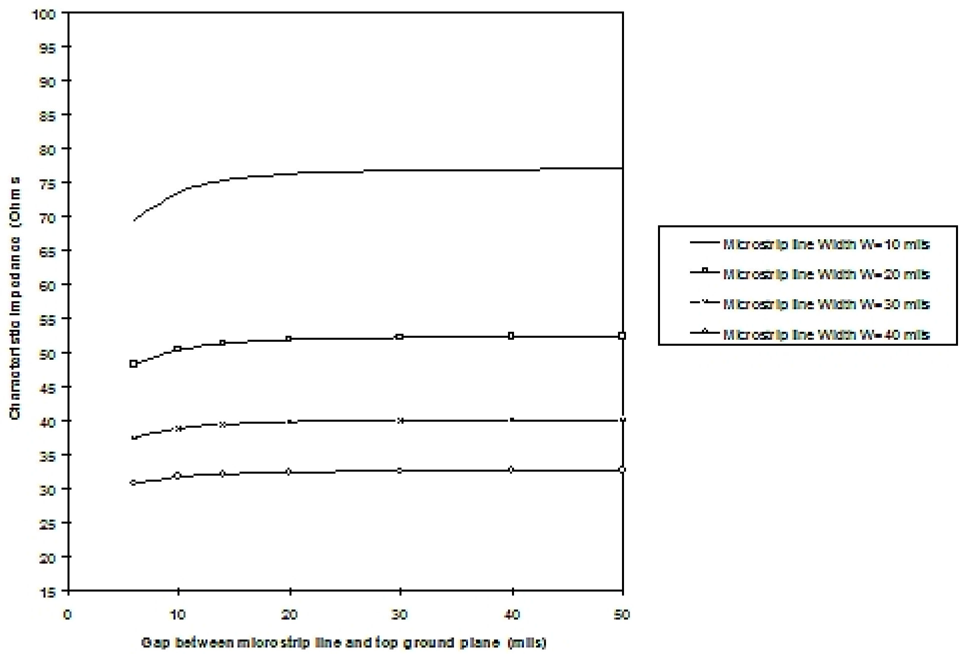

Figure 4. Microstrip impedance as a function of top-layer ground plane gap for different microstrip line widths (substrate thickness h = 10 mils and ε_r=3.8).

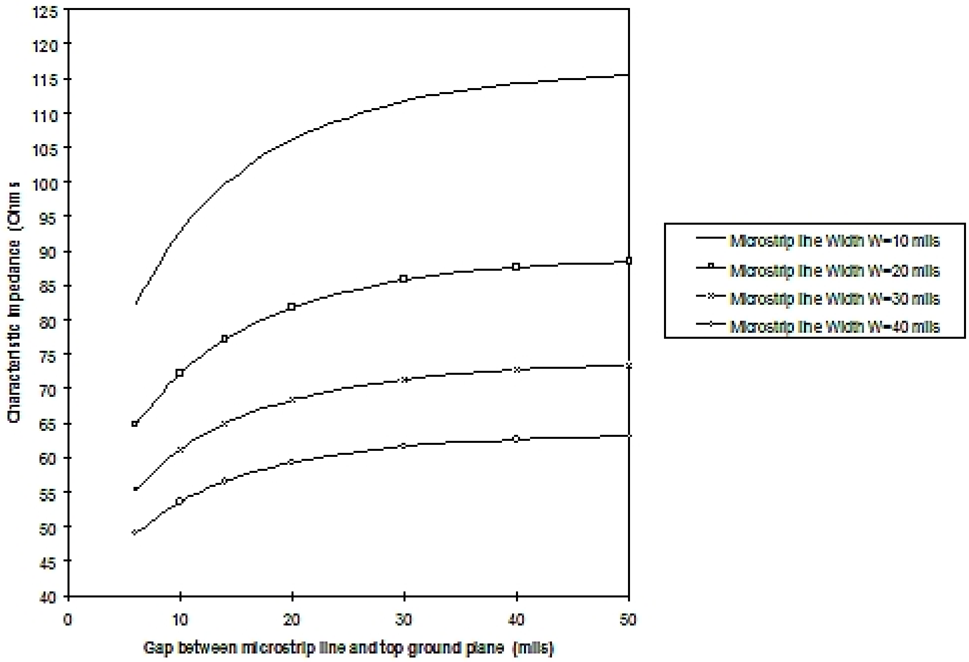

Figure 5. Microstrip impedance as a function of top-layer ground plane gap for different microstrip line widths (substrate thickness h = 30 mils and ε_r=3.8).

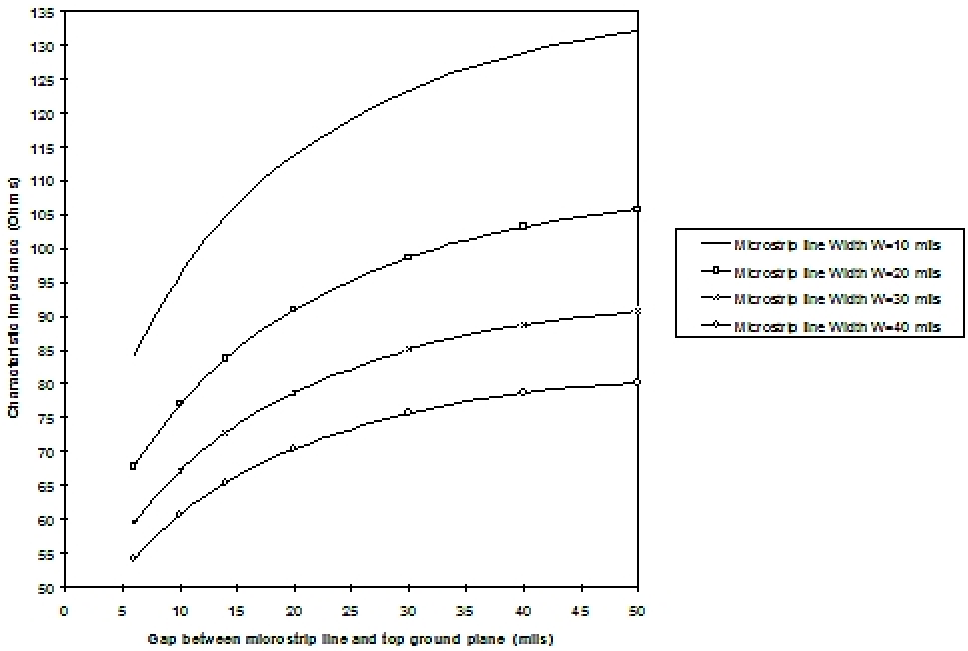

Figure 6. Microstrip impedance as a function of top-layer ground plane gap for different microstrip line widths (substrate thickness h = 60 mils and ε_r=3.8).

Conclusion

Conclusion

The characteristic impedance of a microstrip transmission line structure becomes very sensitive to changes in the gap between the microstrip line and the top ground plane when thicker substrates or narrower microstrip widths are used. In order to keep a relatively constant characteristic impedance the effective dielectric constant should be kept as close to the relative dielectric constant as possible.

This minimizes the concern in choosing the correct gap G, as the choice is less critical for thinner dielectric substrates than for thicker dielectric substrates. With thinner dielectric substrates, the variation of the gap will not cause significant change in microstrip line impedance for different line widths. For thicker substrates, the gap between the top-layer ground plane and the microstrip line need to be large to ensure proper impedance that it becomes impractical with respect to denser populated boards or having shunt elements (which results in having varying gap widths).

The variation of the characteristic impedance from 100 MHz to 2 GHz was 0.7 Ω, for a microstrip line of width 20 mils on a substrate with $\varepsilon_r = 3.8$ and substrate height of 10 mils. This is typically insignificant for most 50 Ω systems. However, the impedance of the microstrip line had an exponential increase at frequencies below 200 MHz. Even with an exponential increase in Z_0 at lower IF frequencies the impedance would not likely change more than up to 10% at the most.

Appendix

Figures A1, A2, A3, and A4 were obtained to determine the sensitivity of the transmission line with respect to the gap between the microstrip line and the top ground plane for different relative dielectric constants. All four figures had the same substrate thickness h=60 mils. The transmission line widths investigated were 10, 20, 30, and 40 mils. The figures A1, A2, A3, and A4 all have the same delta y-axis range (110 Ω) in order to better illustrate the variations in characteristic impedance Z_0.

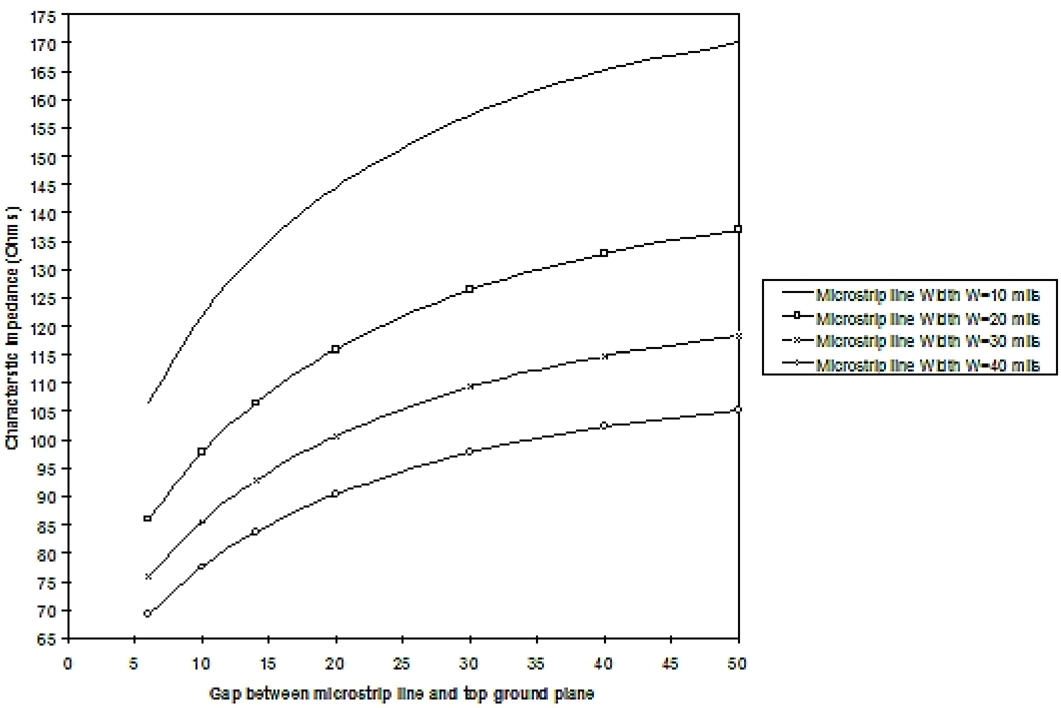

Figure A1. Characteristic impedance as a function of top-layer ground plane gap for different microstrip line widths (substrate thickness h = 60 mils and ε_r=2).

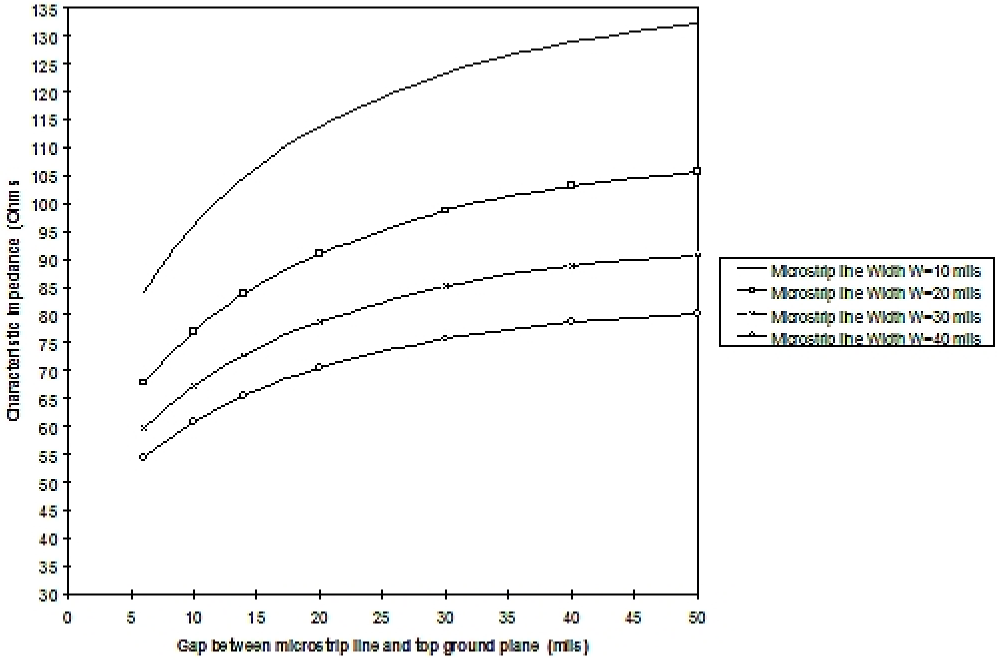

Figure A2. Characteristic impedance as a function of top-layer ground plane gap for different microstrip line widths (substrate thickness h = 60 mils and ε_r=3.8).

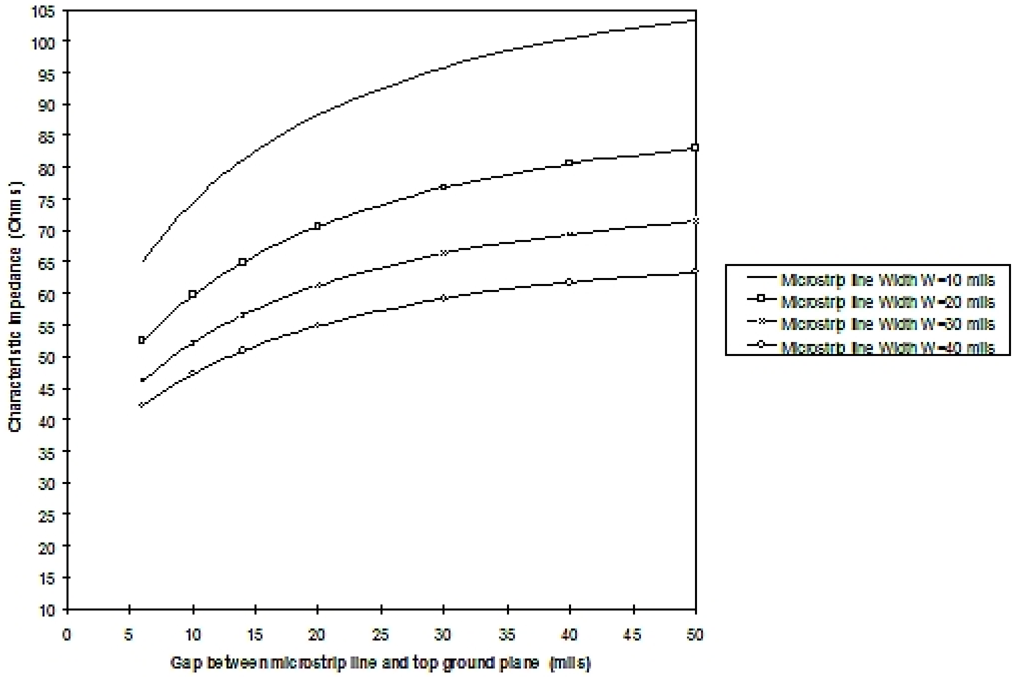

Figure A3. Characteristic impedance as a function of top-layer ground plane gap for different microstrip line widths (substrate thickness h = 60 mils and ε_r=7).

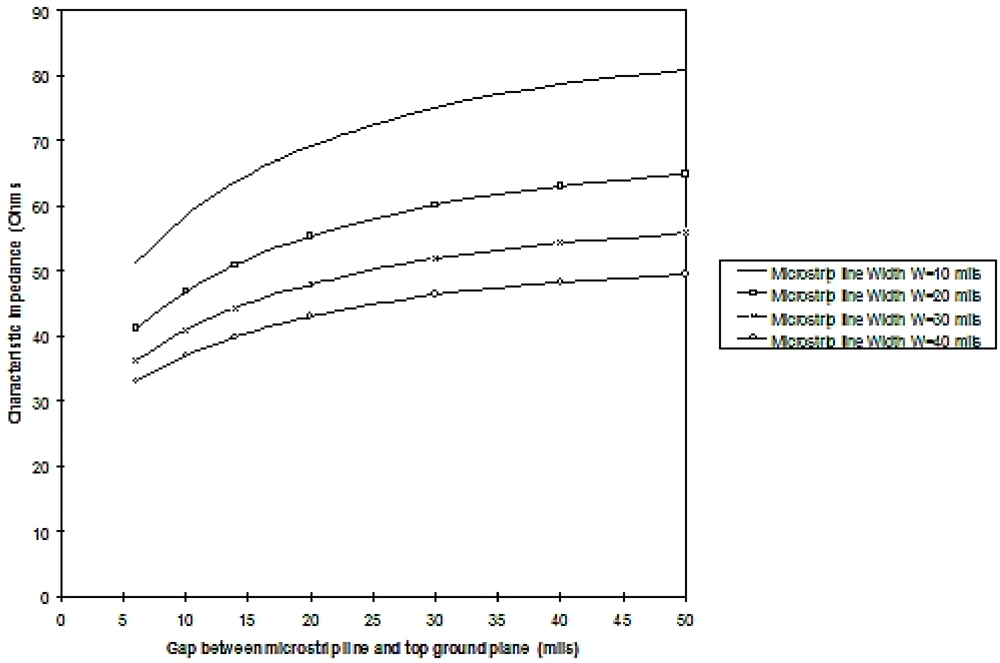

Figure A4. Characteristic impedance as a function of top-layer ground plane gap for different microstrip line widths (substrate thickness h = 60 mils and ε_r=12).

About the author

Arild Kolsrud has worked at Lucent/Bell Labs, Texas Instruments and Qualcomm. He has a Bachelor's and Master's degree in electrical engineering from Texas A&M University in RF/Microwave. He is also the author of six technical papers and holds seventeen patents.