# PCB Board Design Considerations for Impedance Control and Optimal Signal Integrity in High Speed Digital and RF Systems

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**Abstract**
For the electronics on PCB's, dielectric materials provide not only material and media support for the high-speed digital and RF systems, but also electrical performance. Impedance control and signal integrity have become increasingly important in high frequency applications, while trends in electronic industry continue to drive high-speed digital, RF and microwave systems for high-density integration, high system performance and high power operations over a wide range of operating temperatures. Microstrip and stripline are widely used in the high data rate and high frequency circuitry designs because they can be easily and cost-effectively fabricated with high performance, planar PCB laminates for various applications. To obtain optimal signal/power transmission, signal integrity and low signal distortion, certain controlled impedance (typically 50Ω) is very important to minimize impedance mismatching and power reflection. In practical designs, characteristic impedance of transmission lines is a complex function of substrate dielectric properties and physical structures, such as dielectric constant ($\varepsilon_r$), trace width ($W$) and substrate thickness ($h$ or $b$), or even metal strip thickness ($t$). However, when designers come to selecting the proper PCB laminates for their designs, there is lack of design tools for them to quantitatively evaluate the target board materials in terms of impedance control to effectively compare their temperature performance in terms of key PCB material properties, such as dielectric constant thermal stability and substrate thermal expansion. In this paper, based on the practical design equations for microstrip and stripline circuitry and using the Taylor series expansion (e.g. ΔZ=dZ/dk*Δk+dZ/dW*ΔW+dZ/dh*Δh+dZ/dt*Δt) for linear approximation of multiple-variable functions (e.g. Z0=Z(k,W,h,t)), analytic design equations for evaluating the transmission line impedance variations from its board dielectric and dimensional change have been developed. Additionally, these analytic design tools can also be readily applied to evaluate the variations of planar transmission lines for practical design and PCB fabrication impedance control with the board material's dielectric constant and dimensional stability resulting from substrate tolerances (i.e. laminate DK and thickness tolerance) and PCB processing (such as trace etching resolution, multilayer thickness and etc.).
***Index Terms* —** PCB design, Stripline, Microstrip, Impedance control, Signal integrity, Laminates, RF systems.

**Introduction**
Electrical phase stability and impedance control have become increasingly important in high frequency applications, while trends in electronic industry continue to drive high-speed digital, RF and microwave systems for high-density integration, high system performance and high power operations over a wide range of operating temperatures [1][2]. Ideal dielectric substrate materials for these challenging applications are highly expected to posses not only desirable electrical properties, such as dielectric temperature stability, dielectric constant consistency and low loss tangent, but also excellent thermal and mechanical properties, such as thin cores for multilayer capability, dimensional stability and low rates of thermal expansion, excellent thickness tolerance and high thermal conductivity (W/m·K). There has been increased focus on material technology development with high frequency substrates to create materials that are dimensionally stable and temperature stable (electrically and mechanically), maintain excellent tolerances (thickness and dielectric constant) and have improved thermal properties over wider temperature swings. Meanwhile, for practical considerations and sometimes for cost concerns over the premium for advanced board materials, robust designs and fabrication processes are also expected to have the capability to accommodate various tolerances and imperfections of board materials as well as PCB processing variations.

Derived from the design formulas for microstrip and stripline circuitry, this paper presents practical tools for RF designers to quantitatively evaluate PCB board materials in terms of impedance and phase angle control to effectively compare their temperature performance based on key PCB material properties, such as thermal coefficient of dielectric constant (i.e. TCEr) and thermal expansion (i.e. CTE). These analytic design tools can also be readily applied to evaluate the variations of planar transmission line impedance and frequency/phase stability with the board material's dielectric constant and dimensional stability resulting from substrate tolerances (i.e. laminate DK and thickness tolerance) and PCB processing control (such as trace etching resolution, multilayer thickness and etc.).

**Transmission Line Characteristic Impedance Variations**
Microstrip and stripline transmission lines are widely used in the high frequency circuitry designs with planar, high performance RF laminates.
To obtain optimal RF power transmission and low signal distortion, certain controlled impedance (typically 50Ω) is very important to minimize impedance mismatching and power reflection. In practical designs, characteristic impedance of

transmission lines is a complex function of substrate dielectric properties and physical structures, such as dielectric constant ($\varepsilon_r$), trace width ($W$) and substrate thickness ($h$ or $b$), or even metal strip thickness ($t$). If ignoring strip thickness effects, Figure 1 shows the relationships between size of design (line width and substrate thickness) and laminate DK for 50Ω stripline and microstrip lines (based on design formulas in [3]). It shows that higher substrate DK leads to smaller RF signal traces and miniaturized structures, while thicker substrate of fixed DK makes 50Ω transmission line wider for desired applications. Given a design with a specific DK value, there is a fixed ratio for line width and substrate thickness for fixed impedances.

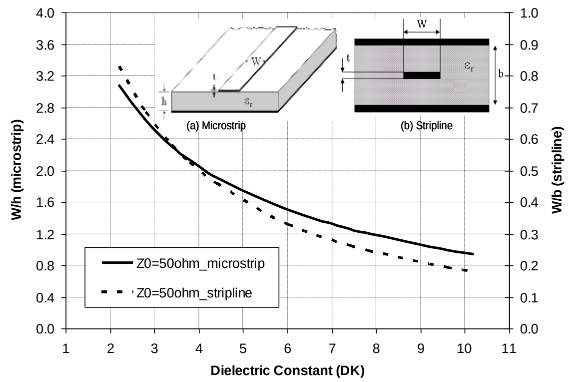


**Figure 1 - The relationships between size of design and laminate DK for 50Ω stripline and microstrip lines.**

In the theory of error propagation analysis, Taylor series expansion is very useful for linear approximation of the characteristic impedance variations for these planar transmission lines due to the small changes for the aforementioned variables of dielectric constant, trace width, substrate thickness and metal strip thickness, as shown in (1) and (2) with Δ representing the small changes.

$$Z_0 = Z_0(\varepsilon_r, W, h, t) \quad (1)$$

$$\Delta Z_0 \approx \frac{\partial Z_0}{\partial \varepsilon_r}\Delta\varepsilon_r + \frac{\partial Z_0}{\partial W}\Delta W + \frac{\partial Z_0}{\partial h}\Delta h + \frac{\partial Z_0}{\partial t}\Delta t \quad (2)$$

The impedance control analysis will initially be carried out for microstrip and stripline based on their design formulas [3] without considering trace metal thickness effect, and later, the effect of finite trace thickness will be studied for comparison.

### A. Microstrip Lines

For microstrip line, the characteristic impedance with infinite thin conductor can be calculated as follows based on its dimensions shown in Figure 1 (a).

$$Z_0 = \begin{cases} \dfrac{60}{\sqrt{\varepsilon_e}}\ln\left(8h/W + 0.25W/h\right) & \text{for W/h} \le 1 \\ \dfrac{120\pi}{\sqrt{\varepsilon_e}\left[W/h + +1.393 + 0.667\ln\left(W/h + 1.444\right)\right]} & \text{for W/h} \ge 1 \end{cases} \quad (3)$$

$$\text{where} \qquad \varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\frac{1}{\sqrt{1 + 12h/W}} \quad (4)$$

If defining $r = h/W$, and working on the following Taylor series expansions readily generated from (1) and (2),

$$\begin{cases} Z_0 = Z_0(\varepsilon_e, r) & \Delta Z_0 \approx \dfrac{\partial Z_0}{\partial \varepsilon_e}\Delta\varepsilon_e + \dfrac{\partial Z_0}{\partial r}\Delta r \\ \varepsilon_e = \varepsilon_e(\varepsilon_r, r) & \Delta\varepsilon_e \approx \dfrac{\partial \varepsilon_e}{\partial \varepsilon_r}\Delta\varepsilon_r + \dfrac{\partial \varepsilon_e}{\partial r}\Delta r \\ r = r(h, W) & \Delta r \approx \dfrac{\partial r}{\partial h}\Delta h + \dfrac{\partial r}{\partial W}\Delta W \end{cases} \quad (5)$$

then, by some simplifying operations or mathematical arrangement, impedance variations from its variables will be

$$\Delta Z_0 \approx \frac{\partial Z_0}{\partial \varepsilon_e}\frac{\partial \varepsilon_e}{\partial \varepsilon_r}\Delta\varepsilon_r + \left(\frac{\partial Z_0}{\partial \varepsilon_e}\frac{\partial \varepsilon_e}{\partial r} + \frac{\partial Z_0}{\partial r}\right)\frac{\partial r}{\partial h}\Delta h + \left(\frac{\partial Z_0}{\partial \varepsilon_e}\frac{\partial \varepsilon_e}{\partial r} + \frac{\partial Z_0}{\partial r}\right)\frac{\partial r}{\partial W}\Delta W \tag{6}$$

thus, for $W/h \le 1$ (narrow trace case), it obtains

$$\frac{\Delta Z_0}{Z_0} \approx -\frac{1}{2}\frac{1}{\left(\sqrt{1+12r}-1\right)/\left[\left(1+\sqrt{1+12r}\right)\varepsilon_r\right]+1}\frac{\Delta\varepsilon_r}{\varepsilon_r} + \left(\frac{1}{2\varepsilon_e}\frac{3(\varepsilon_r-1)r}{\sqrt{(1+12r)^3}} + \frac{8r-0.25/r}{(8r+0.25/r)\ln(8r+0.25/r)}\right)\left(\frac{\Delta h}{h}-\frac{\Delta W}{W}\right) \tag{7}$$

and, for $W/h \ge 1$ (wide trace case), similarly it yields

$$\frac{\Delta Z_0}{Z_0} \approx -\frac{1}{2}\frac{1}{\left(\sqrt{1+12r}-1\right)/\left[\left(1+\sqrt{1+12r}\right)\varepsilon_r\right]+1}\frac{\Delta\varepsilon_r}{\varepsilon_r} + \left(\frac{1}{2\varepsilon_e}\frac{3(\varepsilon_r-1)r}{\sqrt{(1+12r)^3}} + \frac{1+0.667/(1/r+1.444)}{r[1/r+1.393+0.667\ln(1/r+1.444)]}\right)\left(\frac{\Delta h}{h}-\frac{\Delta W}{W}\right) \tag{8}$$

For simplicity, coefficients for the variables can be defined as follows and this kind of designation will also be used for latter cases when applicable.

$$\frac{\Delta Z_0}{Z_0} \approx ZC_{DK}\cdot\frac{\Delta\varepsilon_r}{\varepsilon_r} + ZC_h\cdot\frac{\Delta h}{h} + ZC_W\cdot\frac{\Delta W}{W} \tag{9}$$

where: $ZC_{DK}$ = contribution coefficient of $\varepsilon_r$ (DK) change;
$ZC_h$ = contribution coefficient of $h$ (thickness) change;
$ZC_W$ = contribution coefficient of $W$ (width) change.

Thus,

$$ZC_{DK} = -\frac{1}{2}\frac{1}{\left(\sqrt{1+12r}-1\right)/\left[\left(1+\sqrt{1+12r}\right)\varepsilon_r\right]+1} \tag{10}$$

$$ZC_h = -ZC_W = \begin{cases} \frac{1}{2\varepsilon_e}\frac{3(\varepsilon_r-1)r}{\sqrt{(1+12r)^3}} + \frac{8r-0.25/r}{(8r+0.25/r)\ln(8r+0.25/r)} & (\mathrm{W/h} \le 1) \\ \frac{1}{2\varepsilon_e}\frac{3(\varepsilon_r-1)r}{\sqrt{(1+12r)^3}} + \frac{1+0.667/(1/r+1.444)}{r[1/r+1.393+0.667\ln(1/r+1.444)]} & (\mathrm{W/h} \ge 1) \end{cases} \tag{11}$$

Now these coefficients can be readily plotted in Figure 2 relevant to substrate dielectric constant (DK) for a 50Ω microstrip line. As shown above, once microstrip line is designed with specific characteristic impedance on certain DK substrate with a fixed *h/W* ratio, the coefficients of DK, board thickness (*h*) and trace width (*W*) contributing to impedance variation are also fixed. For low DK laminates, variations from *h* and *W* to impedance control are relatively more significant than the fluctuation of DK because of higher module of their contribution coefficients at lower DK's. With the increase of substrate's DK, the contributions of these variables to microstrip impedance variation will closely follow those trends for stripline, which will be discussed as follows.

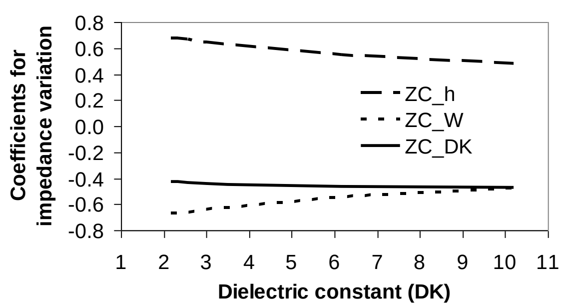


**Figure 2 - The relationships to substrate DK of the coefficients of DK, thickness (*h*) and trace width (*W*) contributing to impedance variations in 50Ω microstrip lines of infinite thin conductor.**

### B. Stripline Transmission Lines

The closed-form expressions of characteristic impedance for stripline (see Figure 1 (b)) with a zero strip thickness are [3]

$$Z_0 = \begin{cases} \dfrac{30\pi}{\sqrt{\varepsilon_r}} \dfrac{1}{W/\mathrm{b} + 0.441} & \text{for W/b} > 0.35 \\ \dfrac{30\pi}{\sqrt{\varepsilon_r}} \dfrac{1}{W/\mathrm{b} - (0.35 - W/\mathrm{b})^2 + 0.441} & \text{for W/b} < 0.35 \end{cases} \tag{12}$$

Using similar Taylor series expansions as for microstrip lines, it readily yields,

$$ZC_{DK} = -\frac{1}{2} \tag{13}$$

$$ZC_b = -ZC_W = \begin{cases} \dfrac{W/b}{W/b + 0.441} & (\text{W/b} > 0.35) \\ \dfrac{W/b[1 + 2(0.35 - W/b)]}{W/b - (0.35 - W/b)^2 + 0.441} & (\text{W/b} < 0.35) \end{cases} \tag{14}$$

The contribution coefficients of DK, board thickness (*b*) and strip width (*W*) to impedance variations of 50Ω stripline can also be plotted with the DK values of substrates in practical designs as shown in Figure 3. Similarly, for stripline impedance control with low DK substrates, the contributions to impedance change due to changes of board thickness and strip width are larger than the change of DK because of the differences among their contribution coefficients. For DK contribution, its coefficient is constant at -0.5, which is also approached by microstrip when its substrate DK increases. As expected, the contributions from board thickness and trace width variations are at the same scale but with opposite signs for ZC_*b* and ZC_*W* which agree with the microstrip case too.

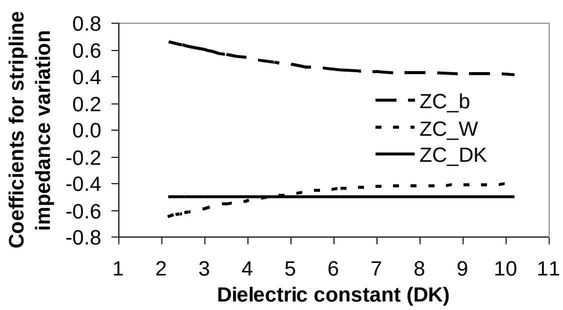


**Figure 3 - Impedance variation's coefficients of DK, *b* and *W* in 50Ω striplines of zero strip thickness and the trends with substrate DK.**

**Impedance Control in Planar Transmission Lines**

For impedance control, it is shown that the contributions to impedance variations come from the known dimensional parameters (*h* or *b* and *W*) and DK for stripline and microstrip lines. The changes for circuit dimensions and DK may be due to substrate product tolerances on thickness and DK, inherent effects of TCEr and CTE of laminates/traces in critical RF applications over wide temperature swings, and even impacts from PCB processing such as trace etching resolution and etc.

From discussions above, it is known that trace width and board thickness have opposite influences on impedance and lead to compensate each other if they have the same direction of change. Meanwhile, board DK has an opposite contribution to impedance against thickness, and this effect could be used to optimize circuit design and/or fabrication while selecting proper board materials with proper tolerances. For example, in microstrip design, a slightly higher DK could be offset by a thicker board. However, the worst case scenario is a thinner board or panel location of higher DK against a thicker board or panel location of smaller DK.

Figure 4 also shows that substrate thickness (as well as trace width while with opposite signs) in microstrip has a slightly bigger influence on impedance than in stripline because of its effect on microtrip effective dielectric constant.

Impedance control over temperatures is also critical for system performance over operating temperature swings such as in impedance matching networks. Figure 5 shows the TDR (time-domain reflectometer) test results for the impedance drifts of 50Ω microstrip lines on two PCB boards from 23°C to 125°C. These lines have the same board DK, thickness and trace width, except for different board thermal properties. Instead of those shown in Table 1, the high TC DK3.5 material also has higher thermal conductivity and lower loss tangent than the alternative DK3.5 laminate, with additional benefits of better thermal management and lowering board temperature. With no significant CTE differences for these DK3.5 laminates, it shows that TCEr affects dramatically the drifts of impedance.

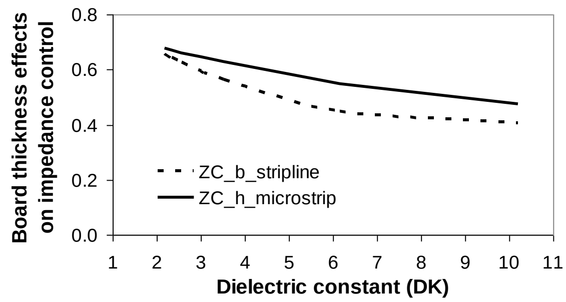


**Figure 4 - Comparison of substrate thickness effects on impedance variations in 50Ω stripline and microstrip lines.**

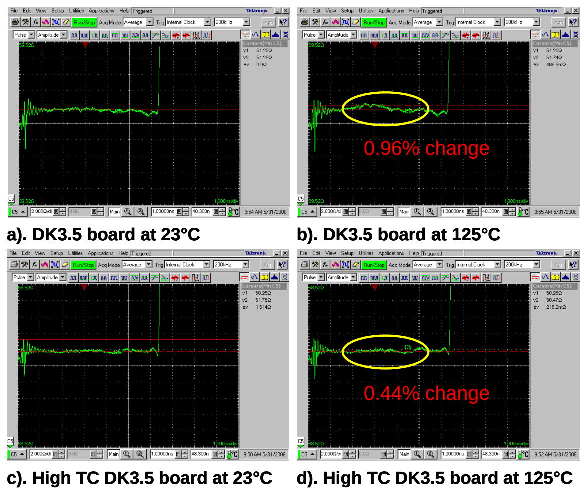


**Figure 5 - TDR tests of 50Ω microstrip line impedance changes over temperatures on RF laminate boards with different thermal conductivities and TCEr.**

Table 1 also compares the TDR test results with the estimates from the analytical tools developed here using board thermal properties. It shows the same trend for impedance drift over temperatures. In the calculation, the values of CTEx and CTEy of the laminates are used for metal trace expansion in the width and length directions, while the CTEz for board thickness expansion. However, according to the IPC standard test method [4], the laminate's TCEr could be affected by the influences of material CTE and modulus when under pressure (e.g. the standard clamp force is 4.45 ± 0.22 kN) and temperatures, while in microstrip model, there is no pressure or modulus effect.

**Table 1 - Drift of characteristic impedance and resonance frequency of microstrip lines and resonators for typical RF laminates from 23°C to 125°C, and selectively compared with TDR test on 50Ω microstrip lines.**

| PCB Laminates | DK | Df | Thermal properties, ppm/°C | | | | % of shift, from 23 to 125°C | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | TCEr | CTEx | CTEy | CTEz | $Z_0$ | $Z_0$-TDR | $f_0$ |
| Low DK laminate | 2.17 | 0.0009 | -160 | 25 | 34 | 252 | 2.26 | - | 0.82 |
| Stable, high performance | 2.94 | 0.0012 | -9 | 8 | 8 | 20 | 0.12 | - | 0.05 |
| Typical DK3.5 | 3.50 | 0.0030 | -55 | 5 | 9 | 35 | 0.44 | 0.96 | 0.28 |
| High TC laminate | 3.50 | 0.0020 | -9 | 7 | 7 | 23 | 0.14 | 0.44 | 0.05 |
| High TC laminate | 6.15 | 0.0020 | -75 | 9 | 9 | 35 | 0.50 | - | 0.38 |
| High DK laminate | 10.2 | 0.0023 | -380 | 8 | 10 | 20 | 1.89 | - | 1.94 |
| Halogen free, low loss | 3.70 | 0.0045 | 75 | 14 | 16 | 20 | -0.30 | - | -0.38 |
| FR-4 | 3.90 | 0.020 | 250 | 15 | 16 | 75 | -0.77 | - | -1.28 |

Table 1 also shows modeling results from the analytical tools developed in this paper for some RF laminates based on PTFE/Fiberglass composites and thermoset PCB materials. Traditional PTFE/Fiberglass-based materials, with low or high DK, show relatively high impedance drift potentially if under temperature due to high TCEr and/or CTE values.
With specially engineered ceramic fillers, thermal properties of ceramic filled PTFE/Fiberglass composites can be significantly improved, and thus, it improves the temperature stability of impedance and frequency/phase (which will be discussed later). Compared to typical FR-4, the halogen-free, low loss thermoset material shows excellent impedance and frequency stability over temperature in addition to its enhanced performances, such as lower dielectric loss and higher Tg (i.e. 205°C by DSC).

**Metal Strip Thickness Effects**

In previous discussions, the strip for stripline and microstrip lines has been considered as either zero thickness or infinite thin conductor. If considering a finite strip thickness ($t$) for microstrip lines, similar design formulas to (3) can be used to calculate the characteristic impedance while substituting the following $\frac{1}{r'}$ for $\frac{1}{r}=\frac{W}{h}$ in (3) when applicable [5].

$$\frac{1}{r'}=\begin{cases}\frac{W}{h}+\frac{1.25}{\pi}\frac{t}{h}\left(1+\ln\frac{4\pi W}{t}\right) & W/h\le 1/(2\pi)\\ \frac{W}{h}+\frac{1.25}{\pi}\frac{t}{h}\left(1+\ln\frac{2h}{t}\right) & W/h\ge 1/(2\pi)\end{cases} \tag{15}$$

While for the effective dielectric constant, it also has

$$\varepsilon_e=\frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\mathrm{F}\left(\frac{\mathrm{W}}{h}\right)-\frac{\varepsilon_r-1}{4.6}\frac{t/h}{\sqrt{W/h}} \tag{16}$$

$$\mathrm{F}\left(\frac{\mathrm{W}}{h}\right)=\begin{cases}\frac{1}{\sqrt{1+12\,h/W}}+0.04\left(1-\frac{W}{h}\right)^2 & W/h\le 1\\ \frac{1}{\sqrt{1+12\,h/W}} & W/h\ge 1\end{cases} \tag{17}$$

Using the same principles as shown in (5) and previous derivations, the perturbations of characteristic impedance due to the changes of dielectric properties and dimensions for microstrip lines with finite strip thickness can be calculated as follows. Some derivatives in (18) take the forms developed from (3) and some are based on the formulas of (15), (16) and (17) as shown in (19). For simplicity, the specific details about these derivatives are not shown, but they can be readily achieved without much burden if desired.

$$\Delta Z_0\approx\frac{\partial Z_0}{\partial\varepsilon_e}\left(\frac{\partial\varepsilon_e}{\partial\varepsilon_r}\Delta\varepsilon_r+\frac{\partial\varepsilon_e}{\partial h}\Delta h+\frac{\partial\varepsilon_e}{\partial W}\Delta W+\frac{\partial\varepsilon_e}{\partial t}\Delta t\right)+\frac{\partial Z_0}{\partial r'}\left(\frac{\partial r'}{\partial h}\Delta h+\frac{\partial r'}{\partial W}\Delta W+\frac{\partial r'}{\partial t}\Delta t\right) \tag{18}$$

$$\begin{cases}Z_0=Z_0(\varepsilon_e,r') & \Delta Z_0\approx\frac{\partial Z_0}{\partial\varepsilon_e}\Delta\varepsilon_e+\frac{\partial Z_0}{\partial r'}\Delta r'\\ \varepsilon_e=\varepsilon_e(\varepsilon_r,h,W,t) & \Delta\varepsilon_e\approx\frac{\partial\varepsilon_e}{\partial\varepsilon_r}\Delta\varepsilon_r+\frac{\partial\varepsilon_e}{\partial h}\Delta h+\frac{\partial\varepsilon_e}{\partial W}\Delta W+\frac{\partial\varepsilon_e}{\partial t}\Delta t\\ r'=r'(h,W,t) & \Delta r'\approx\frac{\partial r'}{\partial h}\Delta h+\frac{\partial r'}{\partial W}\Delta W+\frac{\partial r'}{\partial t}\Delta t\end{cases} \tag{19}$$

Figure 6 shows the comparison of strip thickness effects (with "$t$" designated in the legends) on the contribution coefficients to impedance drifts in microstrip lines. It is shown that using the strip as infinite thin conductor in the evaluation of impedance and frequency shift may *not* deviate a meaningful comparison.

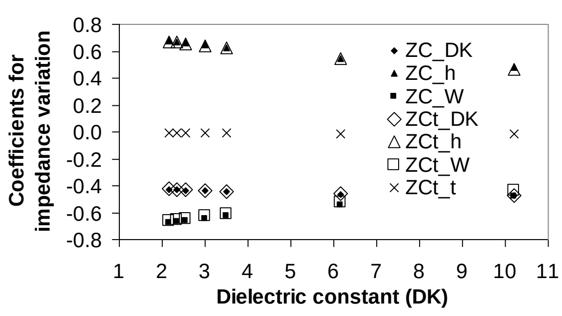


**Figure 6 - Comparison of the conductor thickness effects on impedance variation coefficients in microstrip lines.**

**Frequency and Phase Stability**

Dimension and DK changes in RF designs will definitely affect the performance of RF systems since at a specific frequency, physical circuit elements are designed with specific electrical lengths or phase angles, which will be changed if the dimensions and DK change over temperature. As circuits are designed around a specific frequency, so physical circuit elements are designed around specific electrical lengths; these are measured by phase angle. Where temperature affects dielectric constant and mechanical dimensions, phase angle values of the circuit elements are also affected. Dielectric constant across temperature needs to be consistent to avoid phase stability issues. For antenna designs, a significant shift in resonance frequency and bandwidth roll off at specific frequencies, results in lower gain performance. While for bandpass filters under the influence of DK changes, the center frequency also shifts and could render the design out of specs. Using the same principle of Taylor series expansion, the effects of those parameters ($\varepsilon_r$, $W$, $h$ or $b$, and $t$) similarly involved could be readily developed for resonant structures. However, due to mathematical involvement and potential paper space, this topic will be devoted to another future paper for detailed discussions. In this paper, the relationship between frequency or phase stability and dielectric constant drift will be *approximately* illustrated in the following equations ($x$ represents the small change of DK due to varying TCEr and CTE, while $l$ is physical length of circuit elements) as follows [6].

$$\text{Frequency} \quad f = \frac{v_p}{\lambda} = \frac{c_0}{\lambda\sqrt{\varepsilon_r}} \tag{20}$$

$$\text{Phase} \quad \phi = \frac{l}{\lambda} \cdot 2\pi = \frac{2\pi \cdot f \cdot l \cdot \sqrt{\varepsilon_r}}{c_0} \tag{21}$$

It mathematically approximates $\sqrt{1+x} \approx 1 + \frac{x}{2}$ and $\frac{1}{\sqrt{1+x}} \approx 1 - \frac{x}{2}$ if $|x| \ll 1$, when there is a small variation of dielectric constant DK, i.e. $\varepsilon_r' = (1+x) \cdot \varepsilon_r$

$$f' = \frac{1}{\sqrt{1+x}} \cdot f \approx \left(1 - \frac{x}{2}\right) \cdot f \tag{22}$$

$$\phi' = \sqrt{1+x} \cdot \phi \approx \left(1 + \frac{x}{2}\right) \cdot \phi \tag{23}$$

Approximately, frequency or phase shift over temperature swing is close to half of the amount of DK drift or change. As shown in Table 1, traditional PTFE/Fiberglass-based materials of low or high DK and FR-4 show relatively high frequency shifting over temperatures because of high TCEr values. PTFE/Fiberglass composites with specially engineered ceramic fillers and the halogen-free, low loss thermoset which have improved DK temperature stability show significant enhancement of frequency stability over temperatures.

**Conclusions**

This paper presents analytic methods for RF designers to quantitatively evaluate and properly select board materials, while understanding the relationships of planar transmission line impedance and frequency/phase stability with the material's dielectric constant and dimensional stability resulting from substrate tolerances, thermal properties and processing variations. TDR test under thermal conditions has shown that the temperature stability of dielectric constant and reduced thermal expansion in RF/Microwave laminates provide greater stability of electrical phase or electrical length and impedance control over temperatures in high frequency circuit elements that phase shifts and impedance mismatches will greatly affect the performance, such as the impedance matching networks in power amplifiers. For simplicity and quick estimates, using these analytical tools without considering strip thickness may not significantly affect the comparisons for selection of RF laminate materials. For thermal expansion rates of typical materials used in electronics, the ideal case would be to select materials with a low TCEr to control both impedance and resonance frequency for RF and high speed digital designs.

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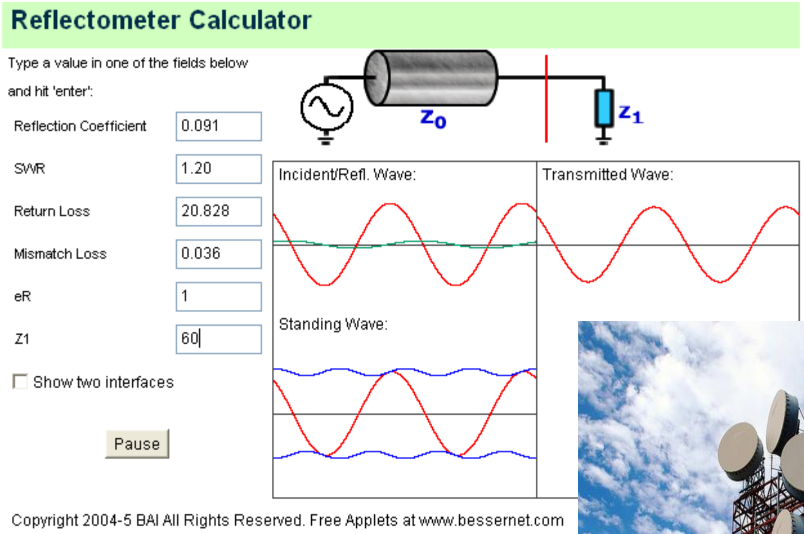
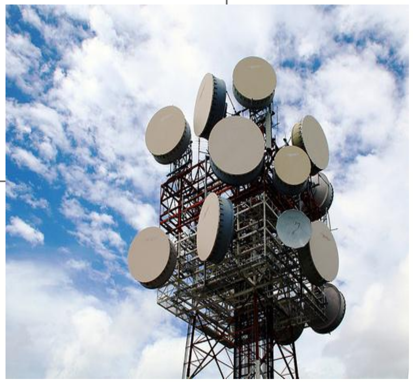
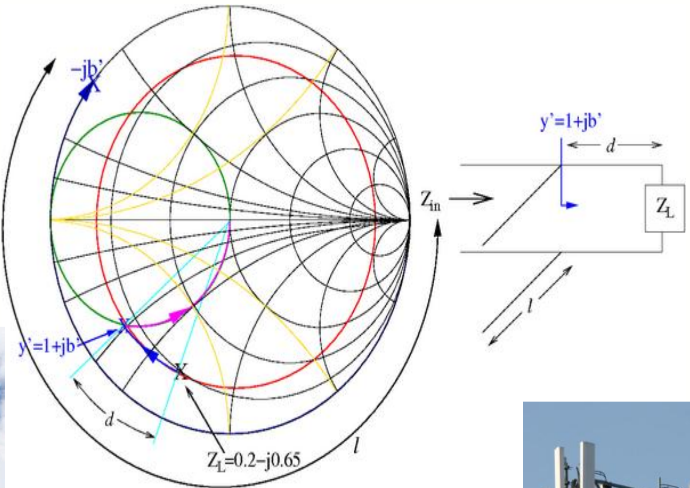
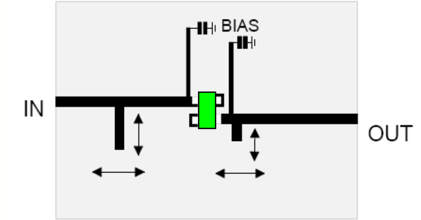
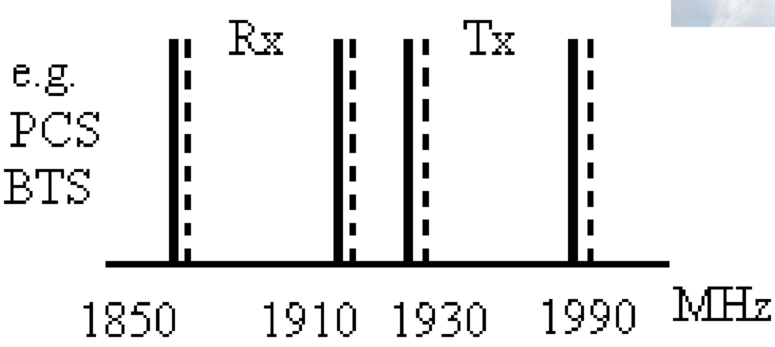
# Importance of Frequency/Phase Stability and Impedance Control





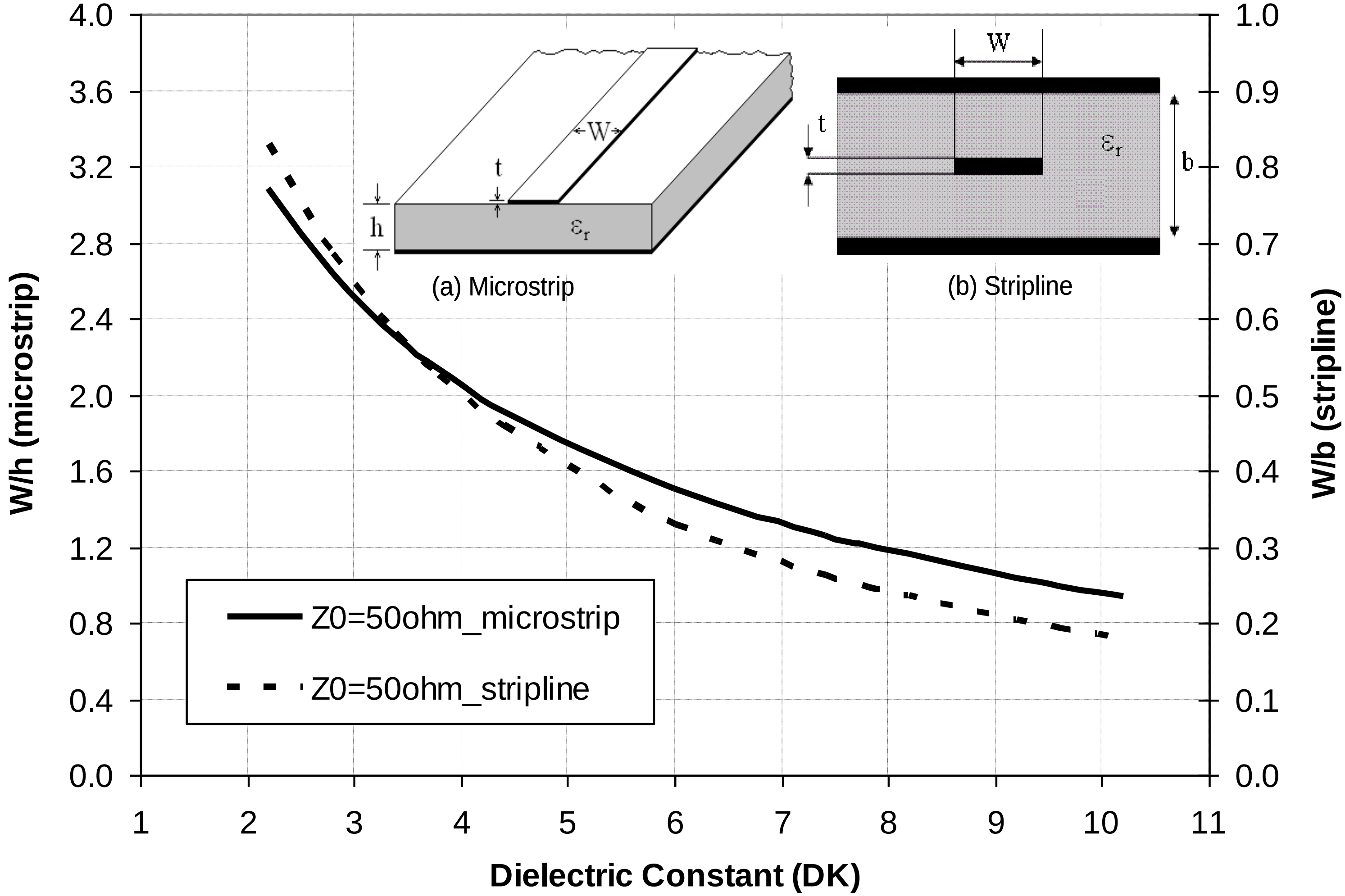




**If 0.2% shift of frequencies,**

**PCS BTS Rx: 0.2%x1880=3.76MHz (6.3% of Rx Band)**

**PCS BTS Tx: 0.2%x1960=3.92MHz (6.5% of Tx Band)**

# Microstrip and Stripline: Design Size vs. DK



# Taylor Series Expansions

$$Z_0 = Z_0\left(\varepsilon_r, W, h \text{ or } b\right)$$

**Taylor Series:**

$$\Delta Z_0 \approx \frac{\partial Z_0}{\partial \varepsilon_r}\Delta\varepsilon_r + \frac{\partial Z_0}{\partial W}\Delta W + \frac{\partial Z_0}{\partial h}\Delta h \quad (\text{or } \frac{\partial Z_0}{\partial b}\Delta b)$$

**With defining:**

$$\Delta x = x - x_0$$

$$\frac{\Delta Z_0}{Z_0} \approx ZC_{DK} \cdot \frac{\Delta\varepsilon_r}{\varepsilon_r} + ZC_W \cdot \frac{\Delta W}{W} + ZC_h \cdot \frac{\Delta h}{h}$$

***ZC_DK*** **= contribution coefficient of** ***εr*** **(DK) change;**

***ZC_W*** **= contribution coefficient of** ***W*** **(trace width) change;**

***ZC_h*** **= contribution coefficient of** ***h*** **(board thickness) change.**

# Theory of Error Propagation

**Microstrip:**

$$Z_0 = \begin{cases} \dfrac{60}{\sqrt{\varepsilon_e}} \ln\left(8h/W + 0.25W/h\right) & \text{for W/h} \le 1 \\ \dfrac{120\pi}{\sqrt{\varepsilon_e}\left[W/h + +1.393 + 0.667\ln\left(W/h + 1.444\right)\right]} & \text{for W/h} \ge 1 \end{cases}$$

$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\frac{1}{\sqrt{1 + 12h/W}}$$

$$r = h/W$$

$$\begin{cases} Z_0 = Z_0(\varepsilon_e, r) \\ \varepsilon_e = \varepsilon_e(\varepsilon_r, r) \\ r = r(h, W) \end{cases}$$

$$\Delta Z_0 \approx \frac{\partial Z_0}{\partial \varepsilon_e}\Delta\varepsilon_e + \frac{\partial Z_0}{\partial r}\Delta r$$

$$\Delta\varepsilon_e \approx \frac{\partial \varepsilon_e}{\partial \varepsilon_r}\Delta\varepsilon_r + \frac{\partial \varepsilon_e}{\partial r}\Delta r$$

$$\Delta r \approx \frac{\partial r}{\partial h}\Delta h + \frac{\partial r}{\partial W}\Delta W$$

$$\Delta Z_0 \approx \frac{\partial Z_0}{\partial \varepsilon_e}\frac{\partial \varepsilon_e}{\partial \varepsilon_r}\Delta\varepsilon_r + \left(\frac{\partial Z_0}{\partial \varepsilon_e}\frac{\partial \varepsilon_e}{\partial r} + \frac{\partial Z_0}{\partial r}\right)\frac{\partial r}{\partial h}\Delta h + \left(\frac{\partial Z_0}{\partial \varepsilon_e}\frac{\partial \varepsilon_e}{\partial r} + \frac{\partial Z_0}{\partial r}\right)\frac{\partial r}{\partial W}\Delta W$$

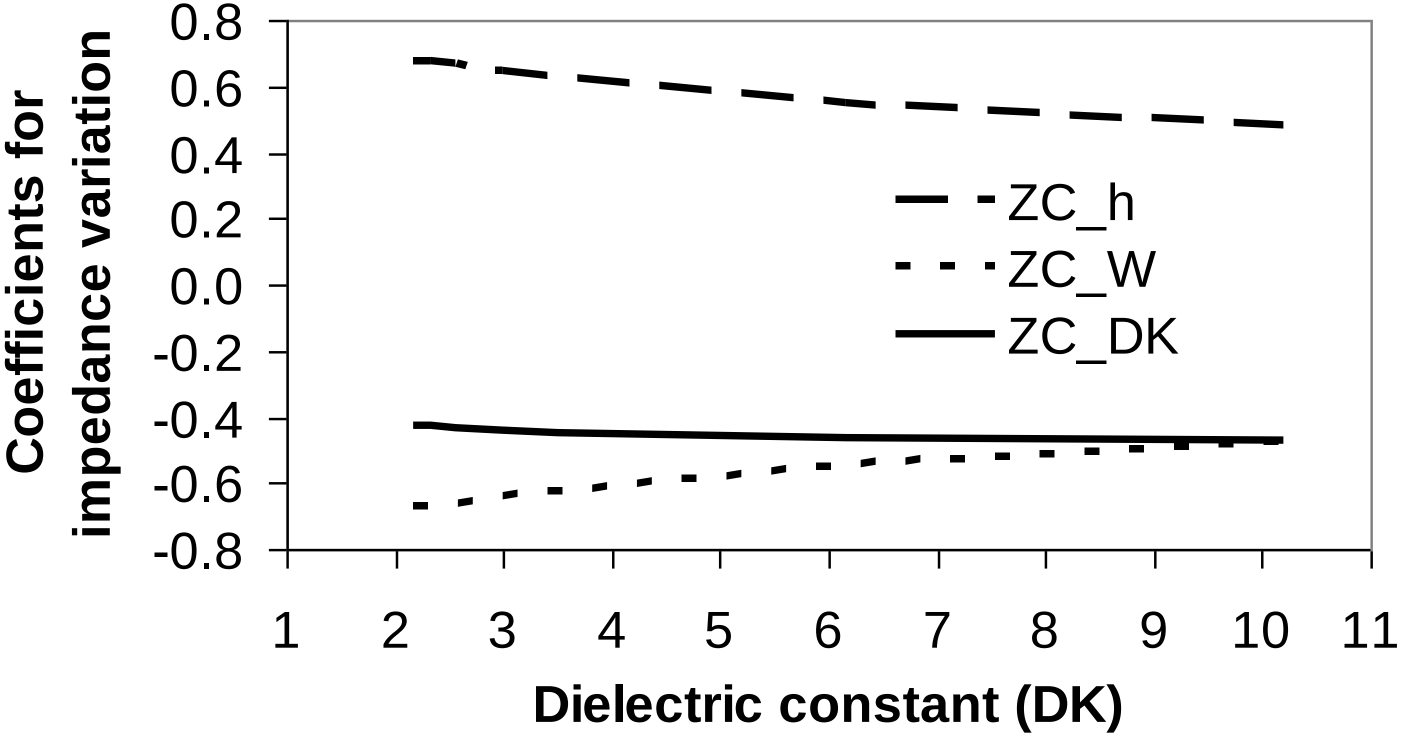
# Impedance Variations in Microstrip

$$\frac{\Delta Z_0}{Z_0} \approx ZC_{DK} \cdot \frac{\Delta \varepsilon_r}{\varepsilon_r} + ZC_W \cdot \frac{\Delta W}{W} + ZC_h \cdot \frac{\Delta h}{h}$$

$$ZC_{DK} = -\frac{1}{2}\frac{1}{\left(\sqrt{1+12r}-1\right)\Big/\left[\left(1+\sqrt{1+12r}\right)\varepsilon_r\right]+1}$$

$$ZC_h = -ZC_W = \begin{cases} \dfrac{1}{2\varepsilon_e}\dfrac{3(\varepsilon_r-1)r}{\sqrt{(1+12r)^3}} + \dfrac{8r-0.25/r}{(8r+0.25/r)\ln(8r+0.25/r)} & (\mathrm{W/h} \le 1) \\ \dfrac{1}{2\varepsilon_e}\dfrac{3(\varepsilon_r-1)r}{\sqrt{(1+12r)^3}} + \dfrac{1+0.667/(1/r+1.444)}{r[1/r+1.393+0.667\ln(1/r+1.444)]} & (\mathrm{W/h} \ge 1) \end{cases}$$

# Impedance Variations in Microstrip



# Impedance Variations in Stripline

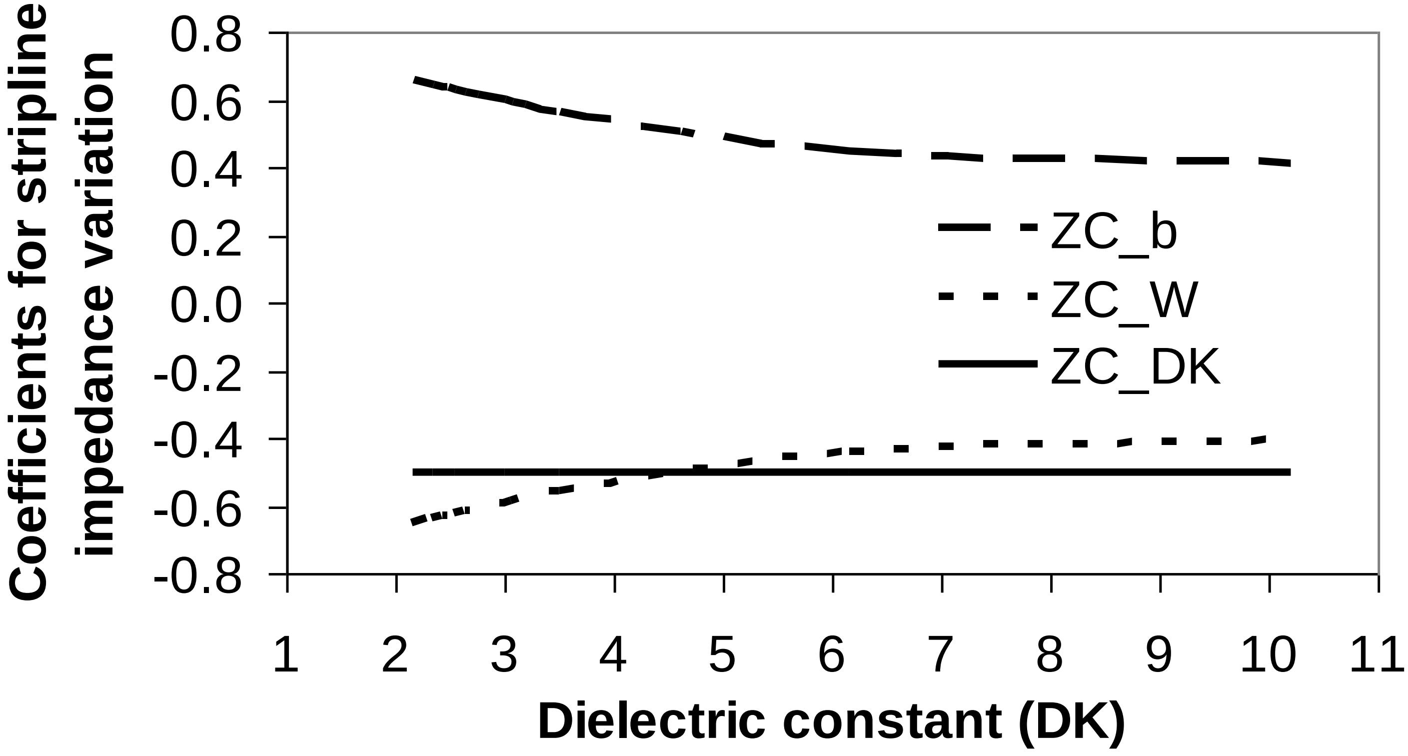
$$Z_0 = \begin{cases} \dfrac{30\pi}{\sqrt{\varepsilon_r}} \dfrac{1}{W/\mathrm{b} + 0.441} & \text{for W/b} > 0.35 \\ \dfrac{30\pi}{\sqrt{\varepsilon_r}} \dfrac{1}{W/\mathrm{b} - (0.35 - W/\mathrm{b})^2 + 0.441} & \text{for W/b} < 0.35 \end{cases}$$

$$\frac{\Delta Z_0}{Z_0} \approx ZC_{DK} \cdot \frac{\Delta\varepsilon_r}{\varepsilon_r} + ZC_W \cdot \frac{\Delta W}{W} + ZC_b \cdot \frac{\Delta b}{b}$$

$$ZC_{DK} = -\frac{1}{2}$$

$$ZC_b = -ZC_W = \begin{cases} \dfrac{W/b}{W/b + 0.441} & (\text{W/b} > 0.35) \\ \dfrac{W/b[1 + 2(0.35 - W/b)]}{W/b - (0.35 - W/b)^2 + 0.441} & (\text{W/b} < 0.35) \end{cases}$$

# Impedance Variations in Stripline

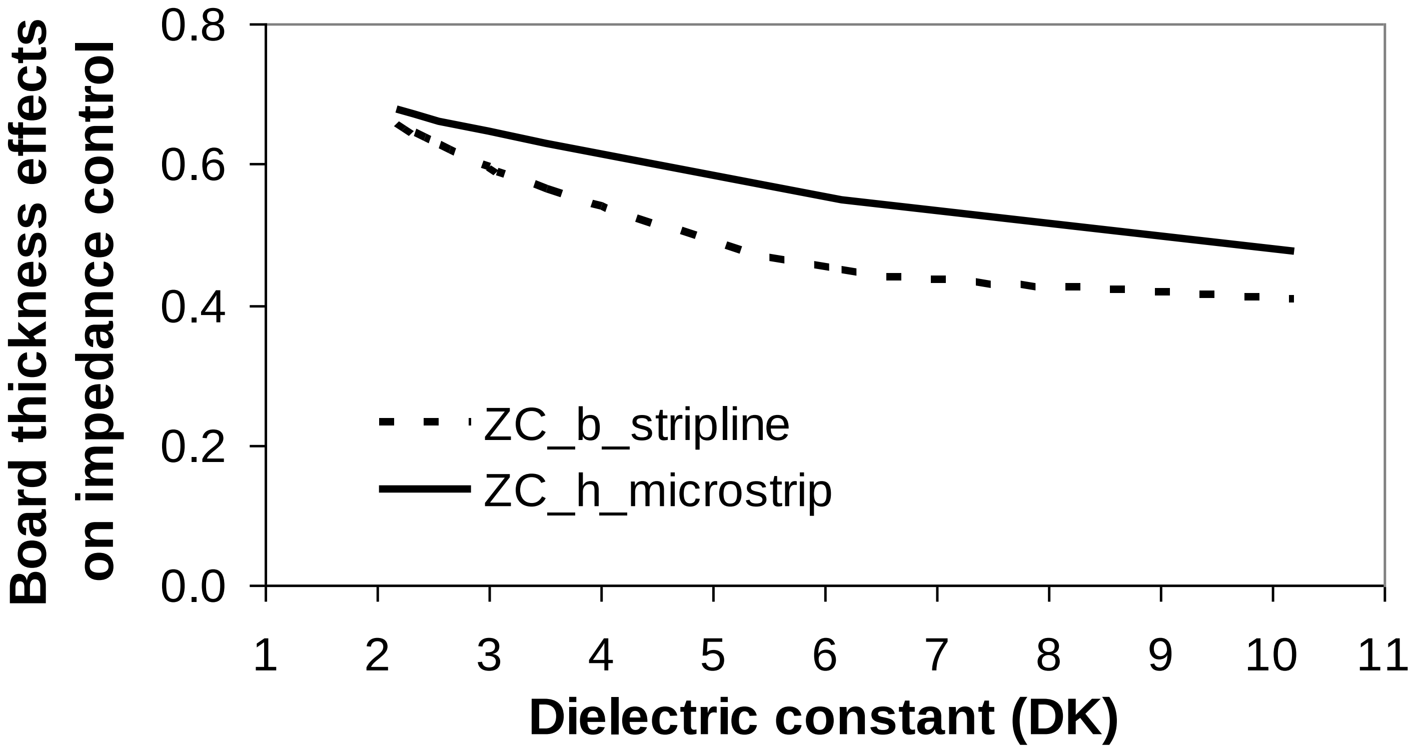


# Impedance Control in Microtrip and Stripline

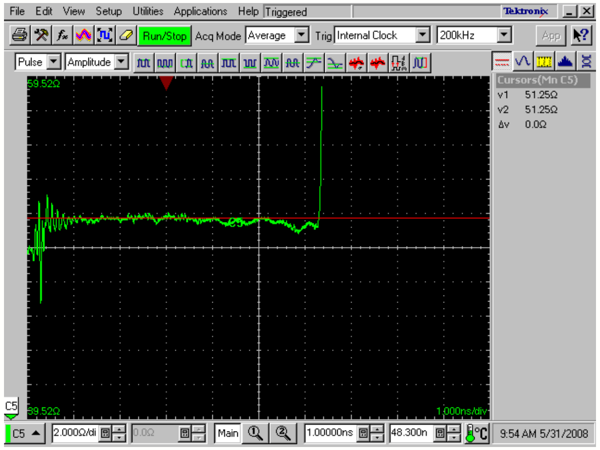
- Dielectric Constant (DK) coefficient has a negative sign, thus, while DK increases, transmission line characteristic impedance decreases.
- Trace width and board thickness have opposite influences on impedance and lead to compensate each other if they have the same direction of change.
- Board DK has an opposite contribution to impedance against thickness too, and this effect could be used to optimize circuit design and/or fabrication while selecting proper board materials with proper tolerances.

**Worst case scenario:** **a thinner board or panel location of higher DK against a thicker one of smaller DK.**

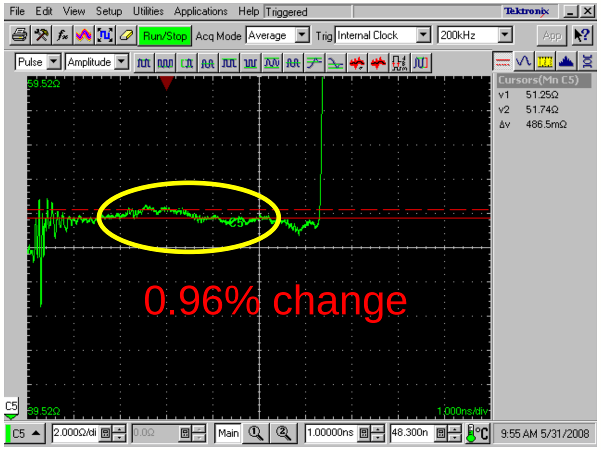
# Different Board Thickness Effects on Microstrip and Stripline



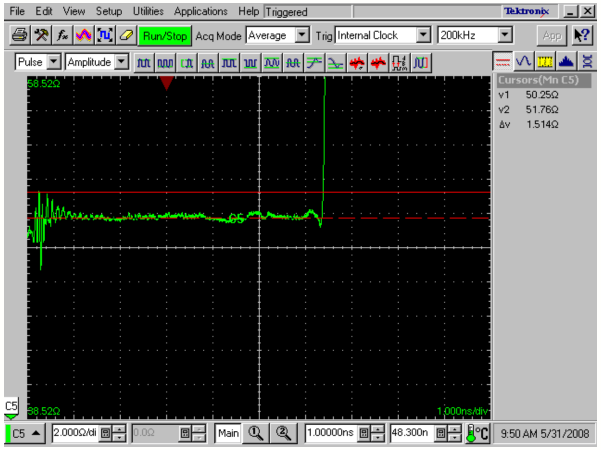
# Impedance Drift over Temperatures



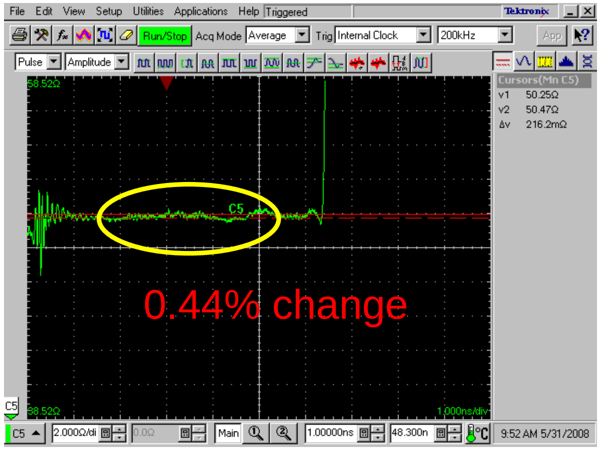

a). DK3.5 board at 23°C




b). DK3.5 board at 125°C




c). High TC DK3.5 board at 23°C

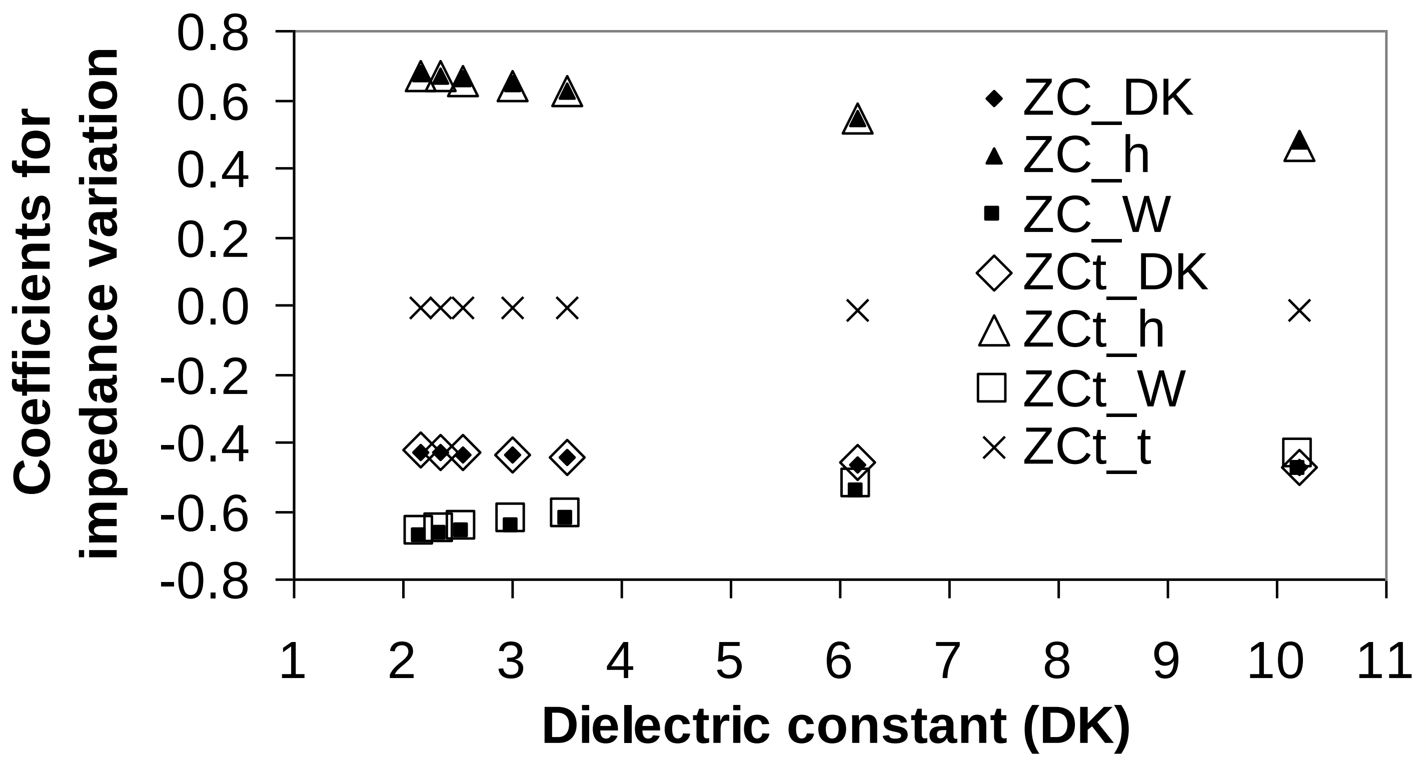



d). High TC DK3.5 board at 125°C

# Impedance and Frequency Shift over Temperatures

| PCB Laminates | DK | Df | Thermal properties, ppm/°C | | | | % of shift, from 23 to 125°C | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | TCEr | CTEx | CTEy | CTEz | $Z_0$ | $Z_0$-TDR | $f_0$ |
| Low DK laminate | 2.17 | 0.0009 | -160 | 25 | 34 | 252 | 2.26 | - | 0.82 |
| Stable, high performance | 2.94 | 0.0012 | -9 | 8 | 8 | 20 | 0.12 | - | 0.05 |
| Typical DK3.5 | 3.50 | 0.0030 | -55 | 5 | 9 | 35 | 0.44 | 0.96 | 0.28 |
| High TC laminate | 3.50 | 0.0020 | -9 | 7 | 7 | 23 | 0.14 | 0.44 | 0.05 |
| High TC laminate | 6.15 | 0.0020 | -75 | 9 | 9 | 35 | 0.50 | - | 0.38 |
| High DK laminate | 10.2 | 0.0023 | -380 | 8 | 10 | 20 | 1.89 | - | 1.94 |
| Halogen free, low loss | 3.70 | 0.0045 | 75 | 14 | 16 | 20 | -0.30 | - | -0.38 |
| FR-4 | 3.90 | 0.020 | 250 | 15 | 16 | 75 | -0.77 | - | -1.28 |

# Metal Strip Thickness Effect on Microstrip



# Frequency and Phase Stability

Frequency $f = \frac{v_p}{\lambda} = \frac{c_0}{\lambda\sqrt{\varepsilon_r}}$

Phase $\phi = \frac{l}{\lambda} \cdot 2\pi = \frac{2\pi \cdot f \cdot l \cdot \sqrt{\varepsilon_r}}{c_0}$

$$\varepsilon_r^{'} = (1 + x) \cdot \varepsilon_r$$

If |x|<<1

$$\sqrt{1+x} \approx 1 + \frac{x}{2} \qquad \frac{1}{\sqrt{1+x}} \approx 1 - \frac{x}{2}$$

$$f^{'} = \frac{1}{\sqrt{1+x}} \cdot f \approx \left(1 - \frac{x}{2}\right) \cdot f \qquad \phi^{'} = \sqrt{1+x} \cdot \phi \approx \left(1 + \frac{x}{2}\right) \cdot \phi$$

# Impedance and Frequency Shift over Temperatures

| PCB Laminates | DK | Df | Thermal properties, ppm/°C | | | | % of shift, from 23 to 125°C | | |
|---|---|---|---|---|---|---|---|---|---|
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| High TC laminate | 6.15 | 0.0020 | -75 | 9 | 9 | 35 | 0.50 | - | 0.38 |
| High DK laminate | 10.2 | 0.0023 | -380 | 8 | 10 | 20 | 1.89 | - | 1.94 |
| Halogen free, low loss | 3.70 | 0.0045 | 75 | 14 | 16 | 20 | -0.30 | - | -0.38 |
| FR-4 | 3.90 | 0.020 | 250 | 15 | 16 | 75 | -0.77 | - | -1.28 |

# Conclusion

- To properly select PCB board materials for right applications, we need to understand the relationships of impedance and frequency stability with the material's dielectric constant and dimensional stability resulting from substrate tolerances, thermal properties and processing variations
- TDR test has shown that improved temperature stability of dielectric constant and reduced thermal expansion in RF/Microwave laminates provide greater stability of frequency or electrical phase and impedance control over temperatures in high frequency circuits.
- For simplicity and quick estimates, using the analytical tools in this paper neglecting strip thickness may *not* significantly affect the comparisons for selecting proper RF laminate materials.
- For thermal expansion rates of typical materials used in electronics, the ideal case would be to select materials with a low TCEr to control both impedance and resonance frequency for RF and high speed digital designs.

# THANK YOU!

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