# Worst-Case Coupled Voltage Analysis of the Printed Circuit Board Traces

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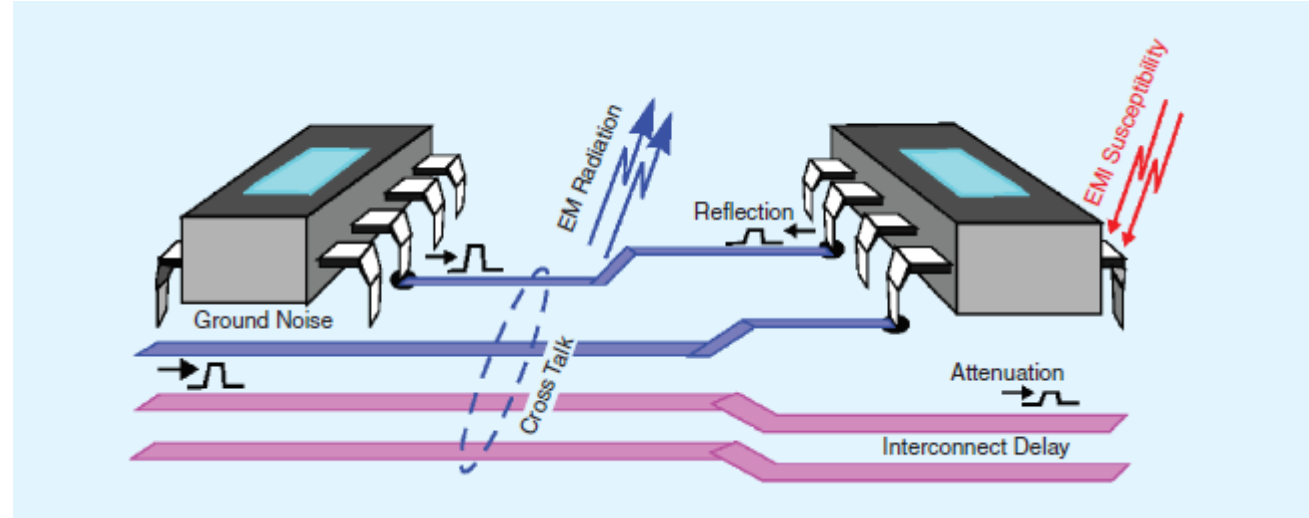2. Missouri Institute of Defense and Energy, Kansas City, Missouri, USA

https://www.raspberrypi.org/products/raspberry-pi-3-model-b-plus/
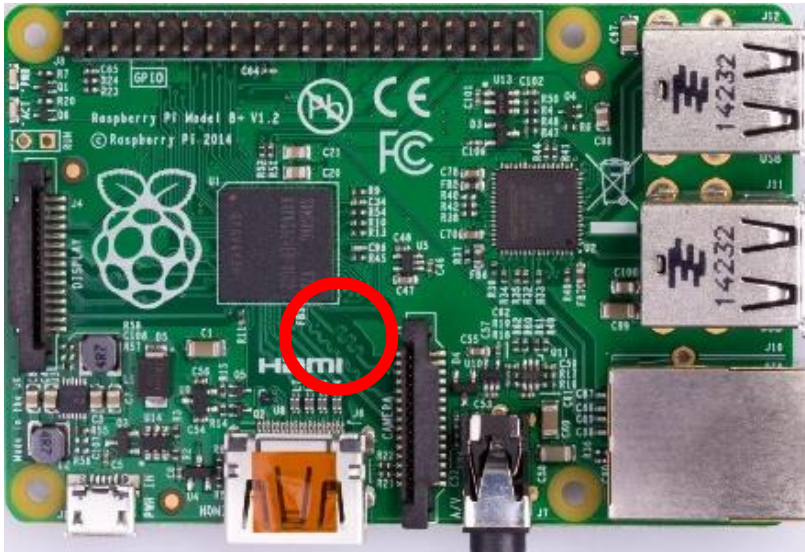


*Fig Source: High-speed interconnect modeling by R. Achar*

➢ Goal: To study electromagnetic (EM) coupling to PCB traces under influence of external incident electric field.

➢ Usually, traces come in as differential pairs. This reduces crosstalk.

➢ These traces take various shapes depending on the their start and end position on the PCB.

➢ Four types of loads are possible in a realistic PCB – open, short, matched, and non-linear.

Many parameters affect the EM coupling to PCB traces, some of which are:

➢ Trace length, trace width, trace shape, incidence angle $(\gamma, \theta, \alpha)$, dielectric permittivity, dielectric thickness, operating frequency, load and source impedance etc.

➢ In this work, we have focused on studying worst-case voltage (WCV) coupled to PCB traces for different trace and incident electric field parameters.

# External electromagnetic field coupling to PCB Traces
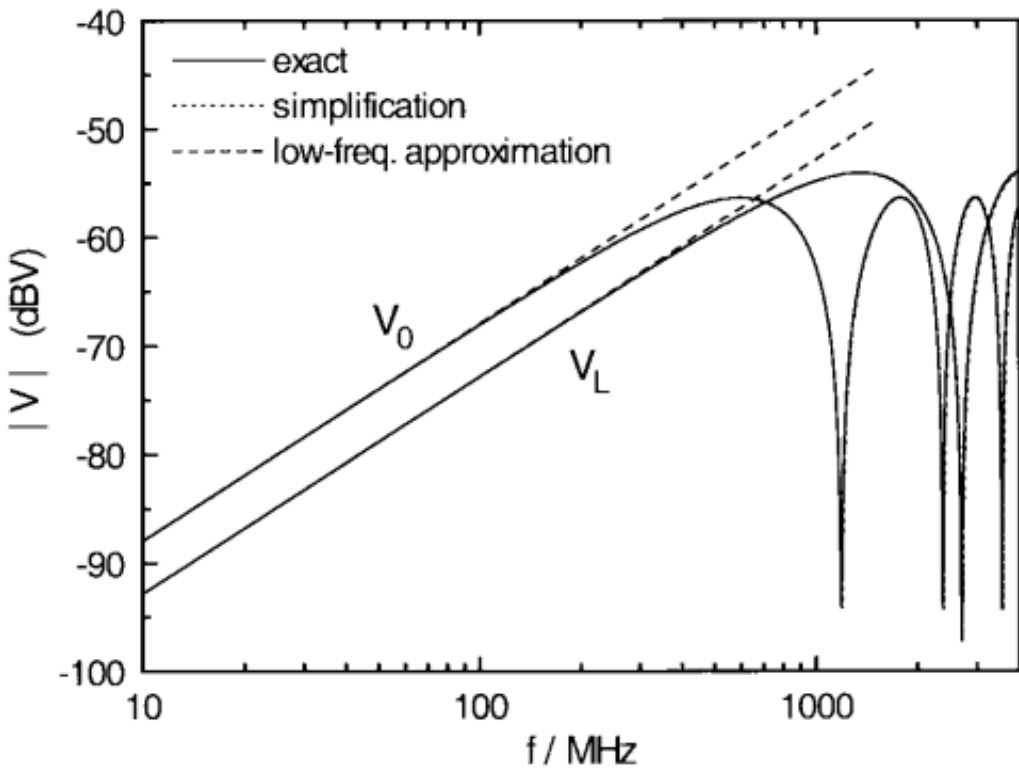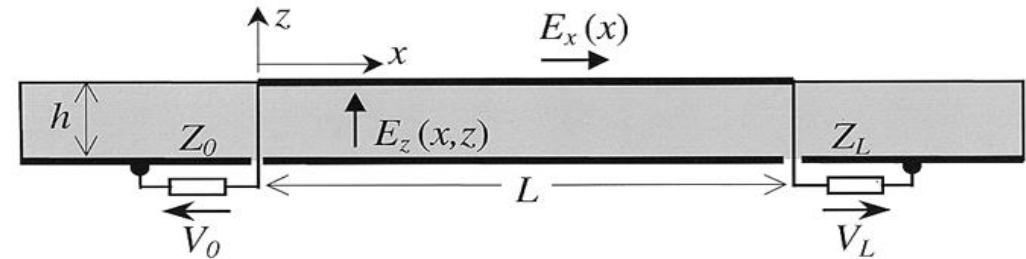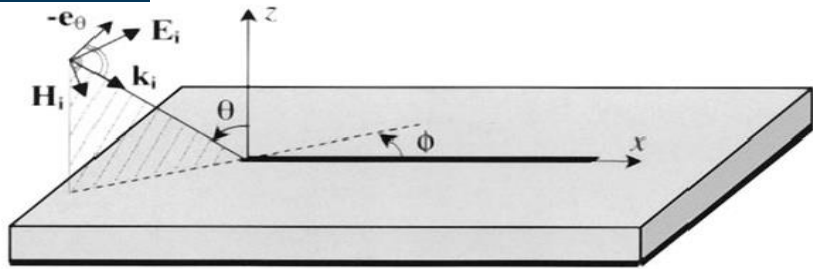




> The "**exact**" coupled load-voltage to a PCB trace above an **infinite ground** plane due to an incident plane wave can be calculated using the Baum-Liu-Tesche (BLT) formulation [1]. The BLT formulation accounts for both horizontal electric field on the substrate surface and vertical electric field in the substrate layer:

$$V_{0,L} \cong \mp E_i \frac{e^{j\beta(x_{2,1}-L)}}{2} \frac{e^{j(\mp\beta-k_x)L}-1}{j(\mp\beta-k_x)}\left(f_x(\theta,\phi,\gamma) - j(\mp\beta-k_x)f_z(\theta,\phi)\frac{1-e^{-jk_{2z}h}}{jk_{2z}}\right)$$

> When the substrate thickness, $h$, is much smaller than the wavelength, λ, the $e^{-jk_{2z}2h}$ term can be approximated using two-term Taylor series expansions leading to the "simplification"

> When the length L << λ, the same approximation can be applied for the other exponential terms leading to the "low-freq approximation" technique.

[1]. M. Leone and H. L. Singer, "On the coupling of an external electromagnetic field to a printed circuit board trace," *IEEE Trans. on Electromag. Comp.*, vol. 41, no. 4, pp. 418-424, Nov. 1999.
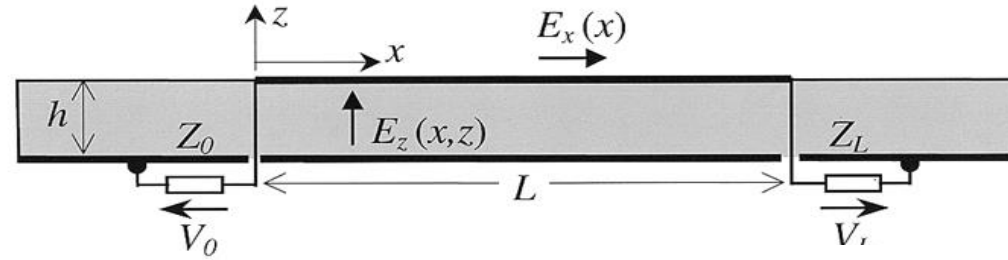
Result from Paper [1]

Verified Fig. 6 from [1]
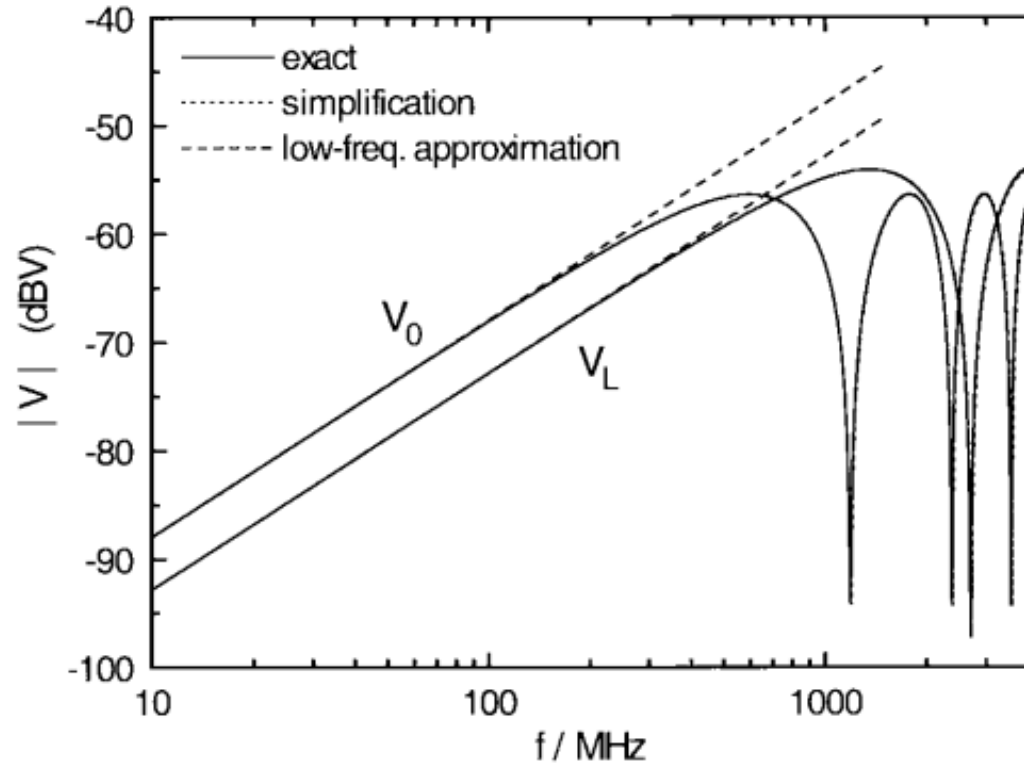
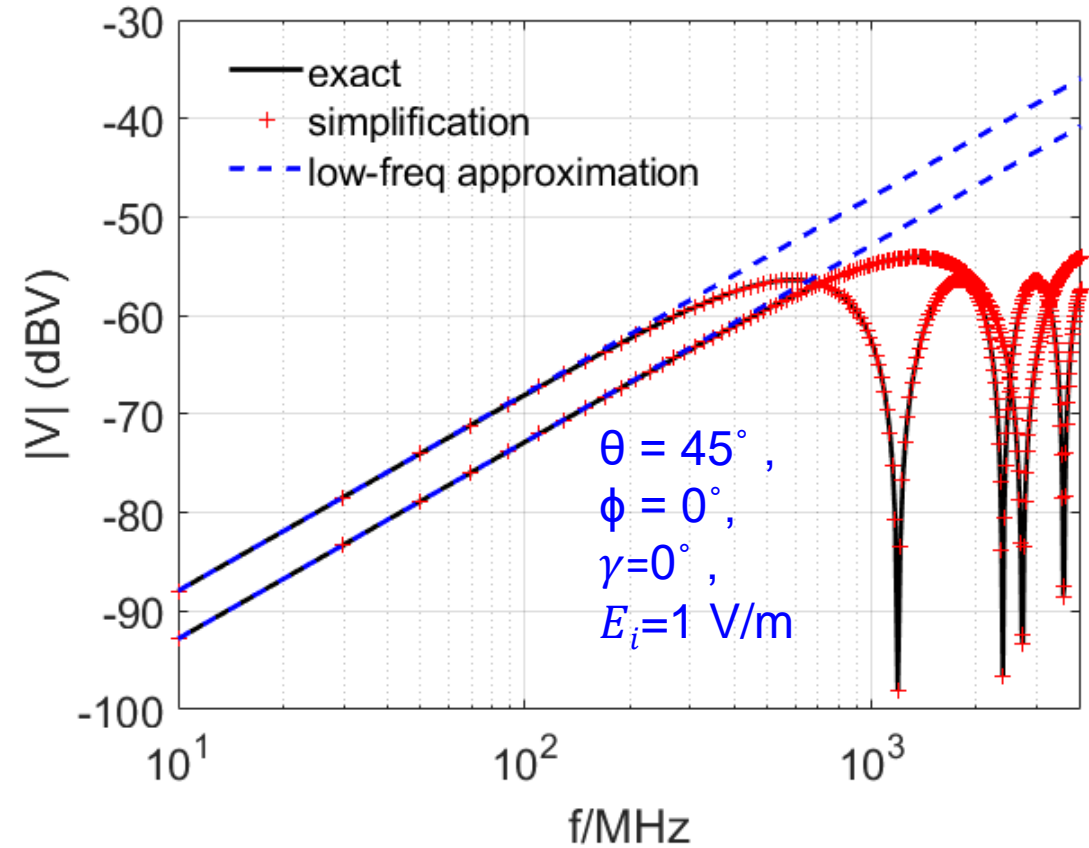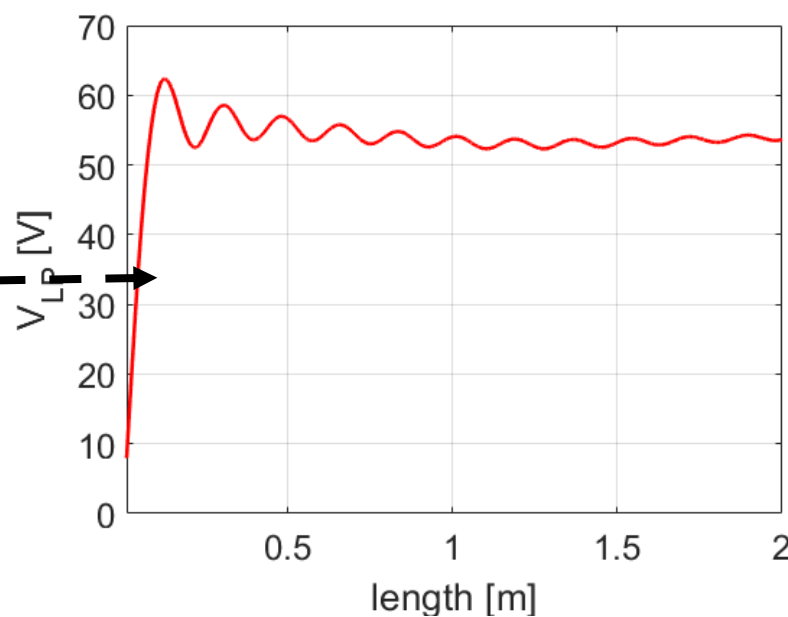Verification of $V_{0,L}$ using MATLAB

$\theta = 45°$,
$\phi = 0°$,
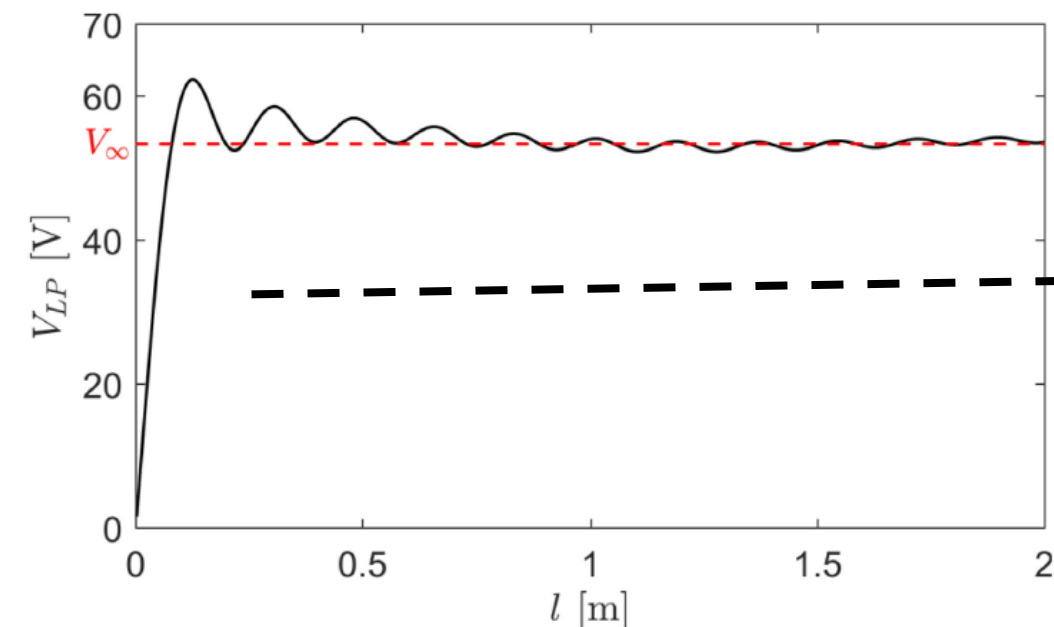$\gamma = 0°$,
$E_i = 1$ V/m
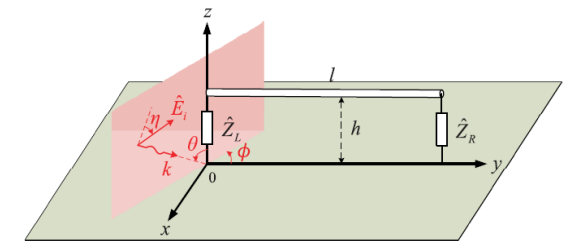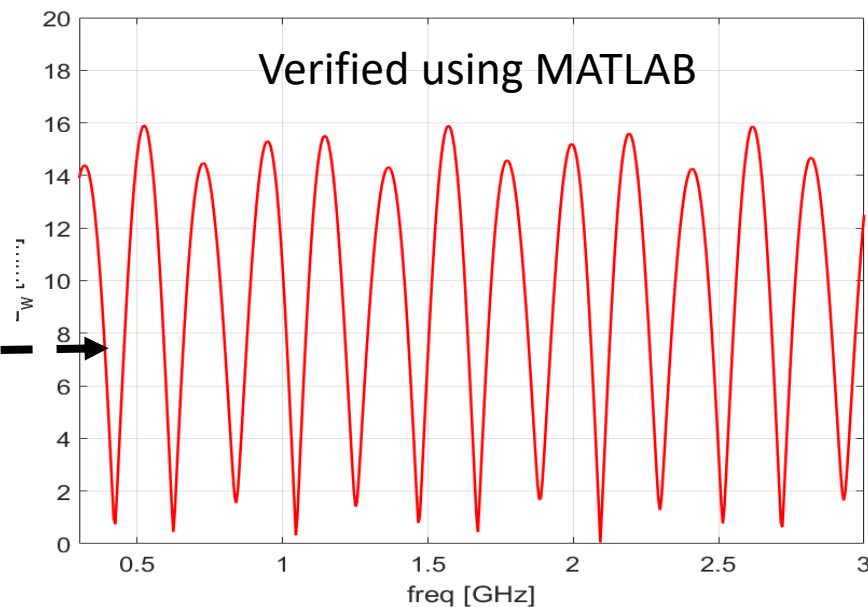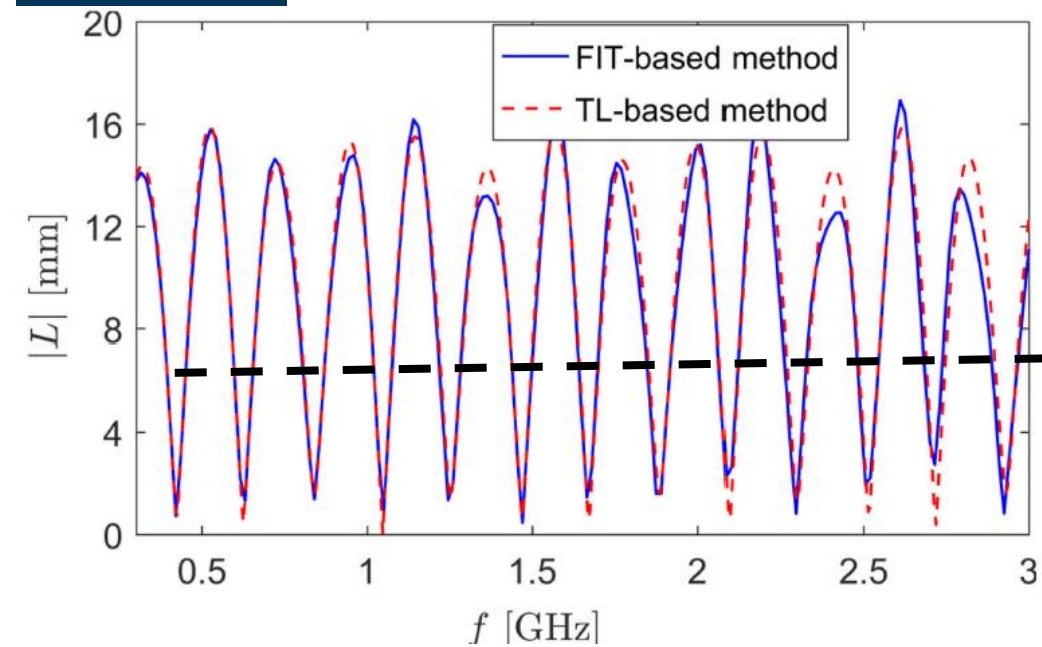
Fig. 6. Comparison of the exact (36), simplified (43), and the low-frequency responses (49) for a practical example ($\theta = 45°$, $\phi = \gamma = 0°$, and $E_i = 1$ V/m).

[1]. M. Leone and H. L. Singer, "On the coupling of an external electromagnetic field to a printed circuit board trace," *IEEE Trans. on Electromag. Comp.*, vol. 41, no. 4, pp. 418-424, Nov. 1999.

## FEKO vs Exact ($V_{0,L}$) comparison and verification
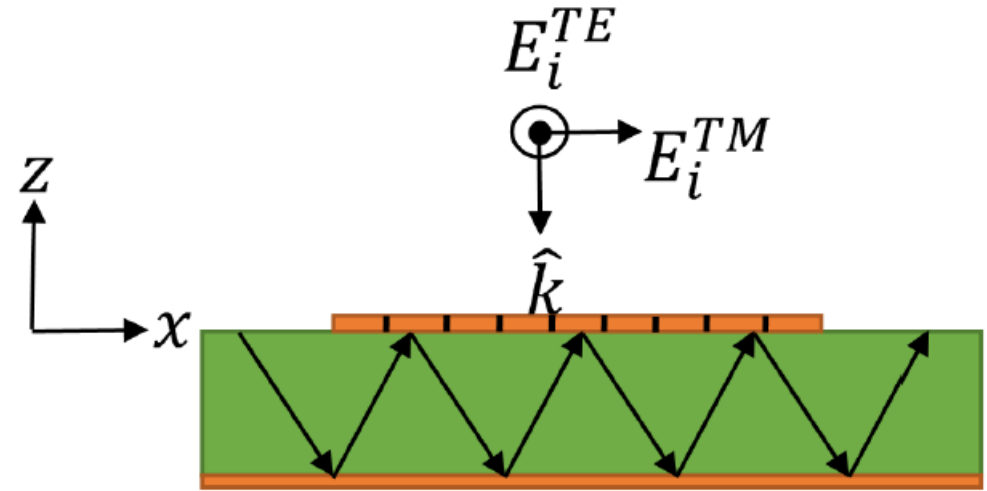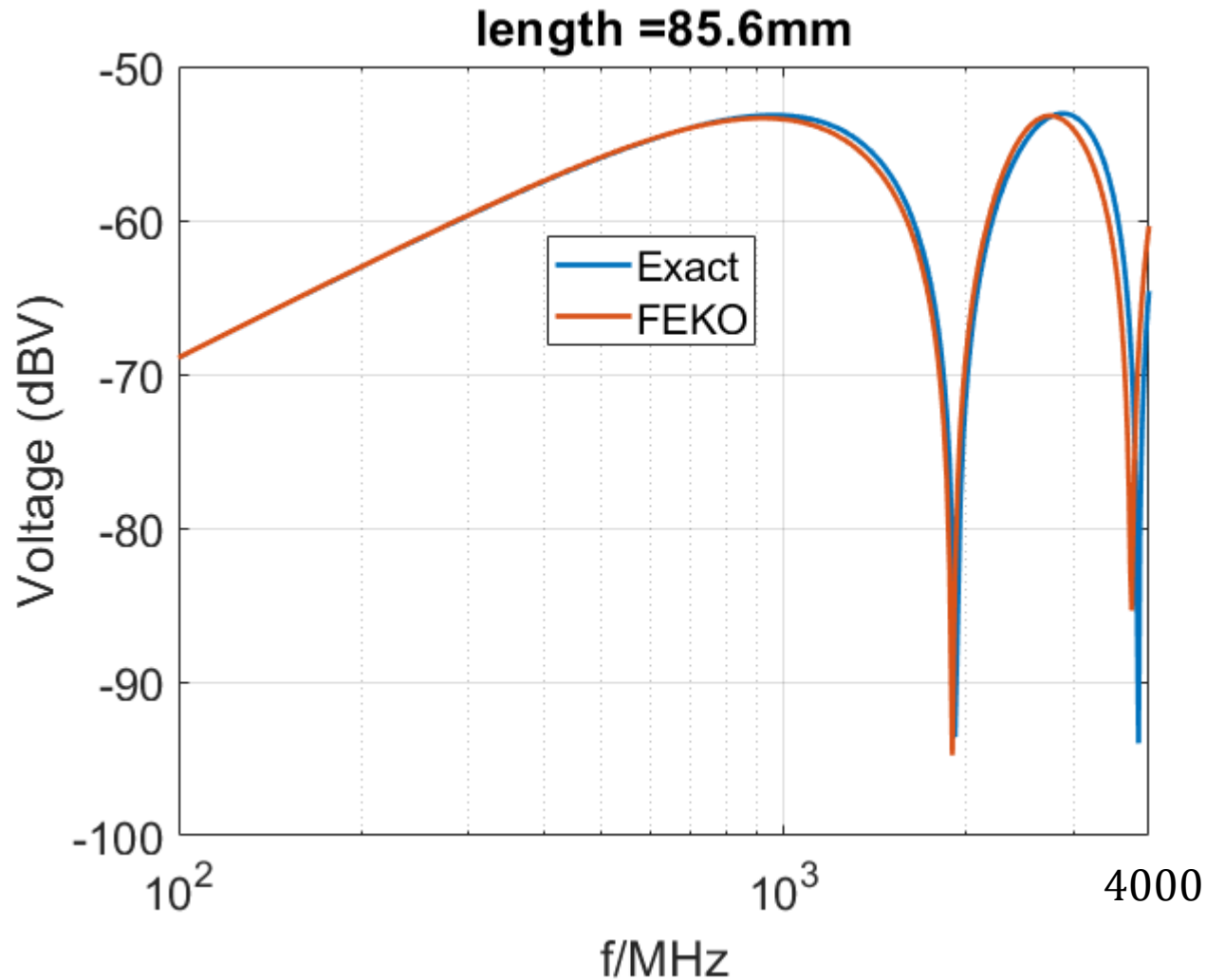


**PCB input parameters:**

- $f_L$ (lower frequency) = 0.1 GHz
- $f_U$ (upper frequency) = 4 GHz
- $\epsilon_r$ (dielectric permittivity) = 4.4
- W (trace width) = 3.81752 mm (50 ohms)
- h (dielectric thickness) = 2 mm
- $\theta = \phi = \gamma = 0°$

[1]. M. Leone and H. L. Singer, "On the coupling of an external electromagnetic field to a printed circuit board trace," *IEEE Trans. on Electromag. Comp.*, vol. 41, no. 4, pp. 418-424, Nov. 1999.

Verified using MATLAB

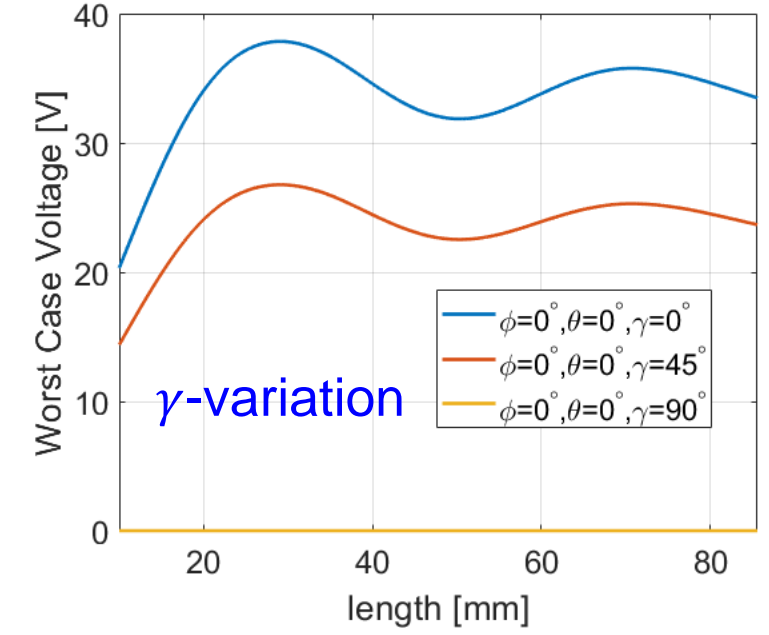$$WCV = \sqrt{\frac{Z_0 E}{\pi} \int_{f_1}^{f_2} |L_0(f)|^2 df}$$

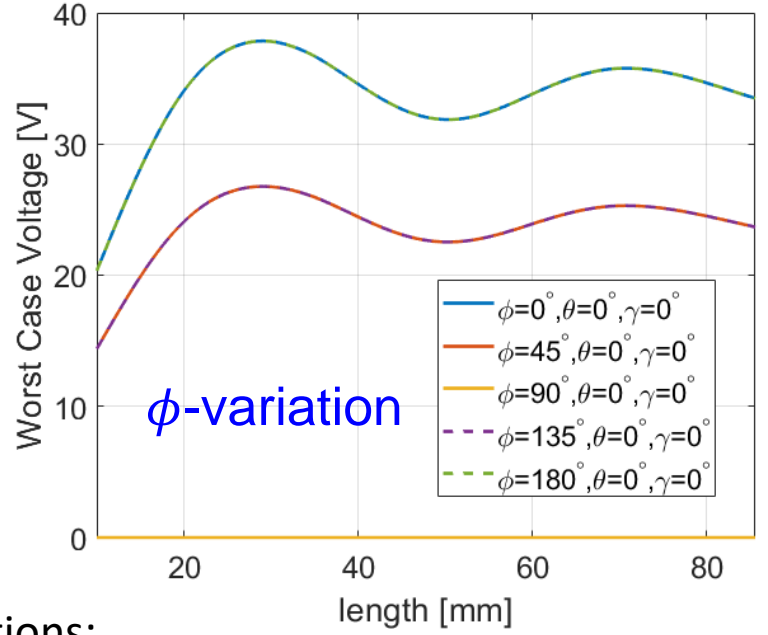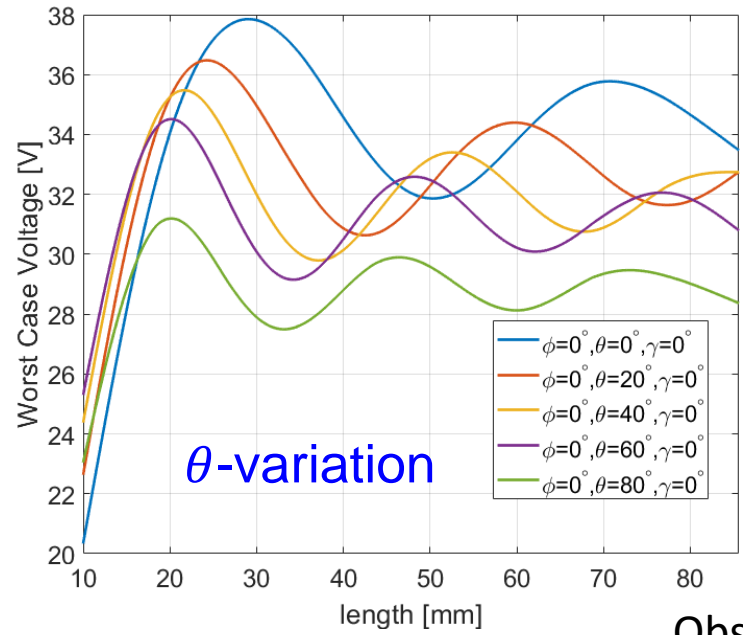$$L_0(f) = \frac{V_{LP}(f)}{E_i}$$
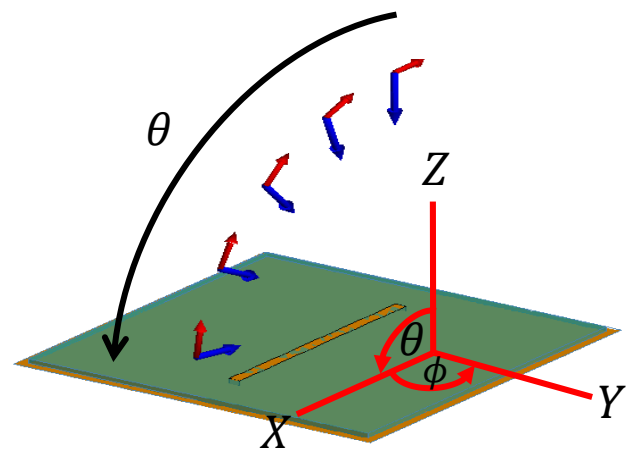
Frequency dependent load voltage

$E_i$ (Incident field strength ) = 1 V/m

$$Z_0 = \sqrt{\mu_0/\varepsilon_0}$$

$E$ (energy density)= 1 m**J**/m²

[2]. T. Liang, G. Spadacini, F. Grassi and S. A. Pignari, "Coupling of Wideband Radiated IEMI to Cables Above Ground," in *IEEE Transactions on Electromagnetic Compatibility*, vol. 62, no. 2, pp. 589-597, April 2020.
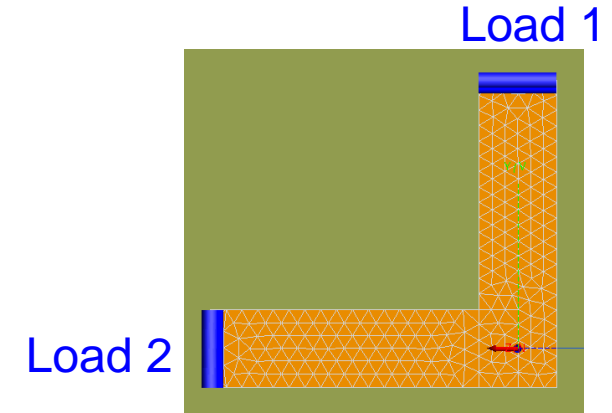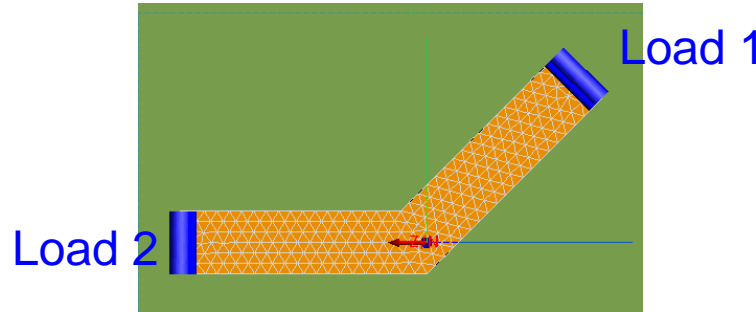
Observations:

> In this slide, we have shown the WCV (calculated using WCV equation shown in slide 6) for a straight PCB trace using $V_0$ for different $\theta, \phi, \gamma$ values. In $\theta$-variation, we can notice that as the value of $\theta$ increases, the peak WCV shifts left i.e., to smaller trace lengths.

> Whereas with $\phi$-variation, the WCV at an oblique angle reduces 1/3rd of parallel case (i.e., E-field parallel to trace length). Similar observation with $\gamma$-variation.

PCB input parameters:

❑ $f_L$ (lower frequency) = 0.1 GHz
❑ $f_U$ (upper frequency) = 4 GHz
❑ $\epsilon_r$ (dielectric permittivity) = 4.4
❑ W (trace width) = 3.81752 mm (50 ohms)
❑ h (dielectric thickness) = 2 mm

Load 2 — Load 1 (straight trace)


Load 1 — Load 2 (45° trace)
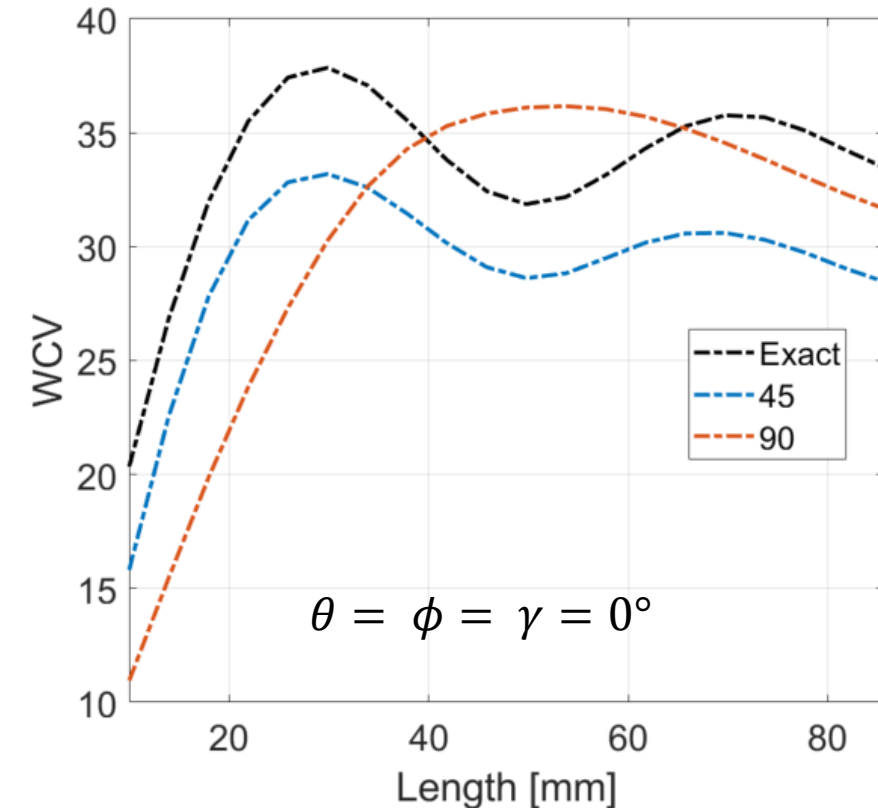

Load 1 — Load 2 (90° trace)

## Load 1



$$\theta = \phi = \gamma = 0°$$

Legend:
- Exact
- 45
- 90

Axes: WCV vs Length [mm]

## Load 2



$$\theta = \phi = \gamma = 0°$$

Legend:
- Exact
- 45
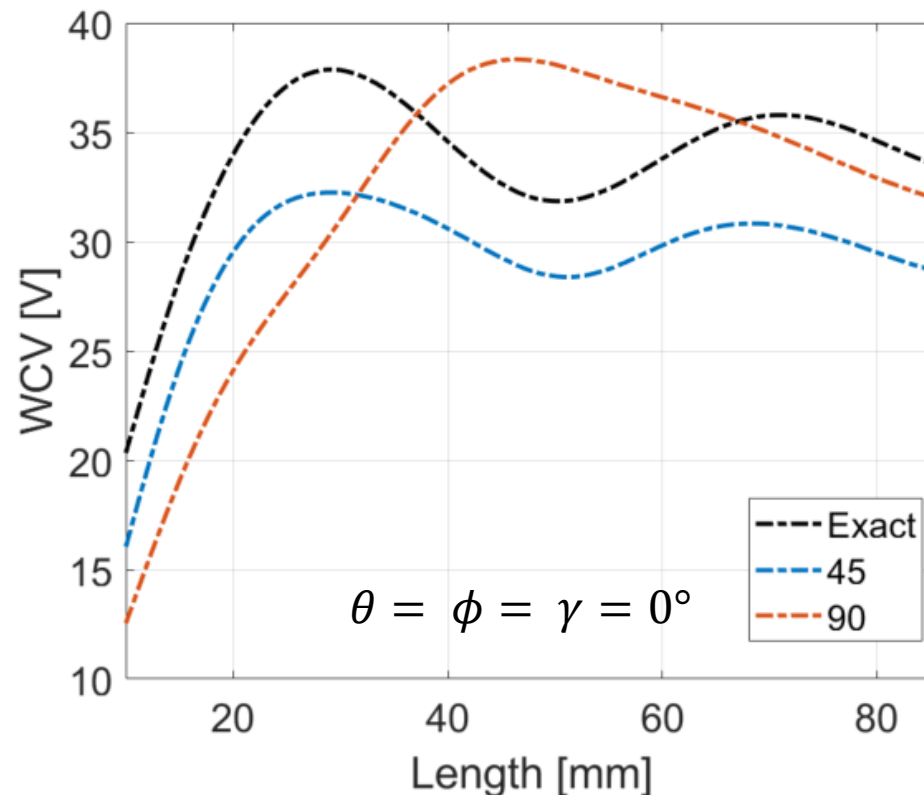- 90

Axes: WCV [V] vs Length [mm]
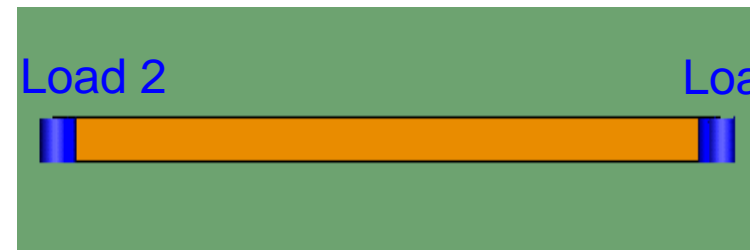
## Observations:

➢ The load voltage for straight trace was calculated from $V_0$ shown in slide 3, whereas for non-straight traces, the load voltage is obtained from commercial EM simulator Altair FEKO.

➢ Load 1 and load 2 shows no significant difference except for 90° trace

➢ 90° trace yields higher WCV when the length of trace is exactly half the length of the board.

➢ No significant difference in the WCV pattern between straight (exact) and 45° trace except lower amplitude for the latter shape.

➢ Until the end of the presentation, only load 1 WCV results will be shown unless otherwise specified.
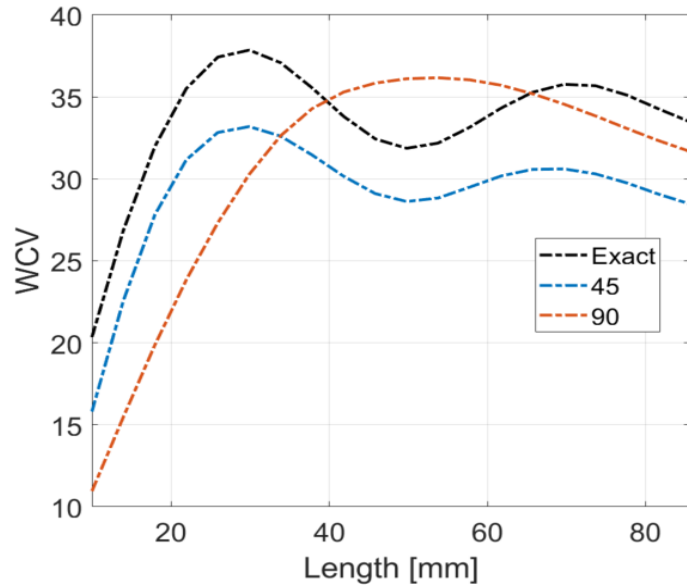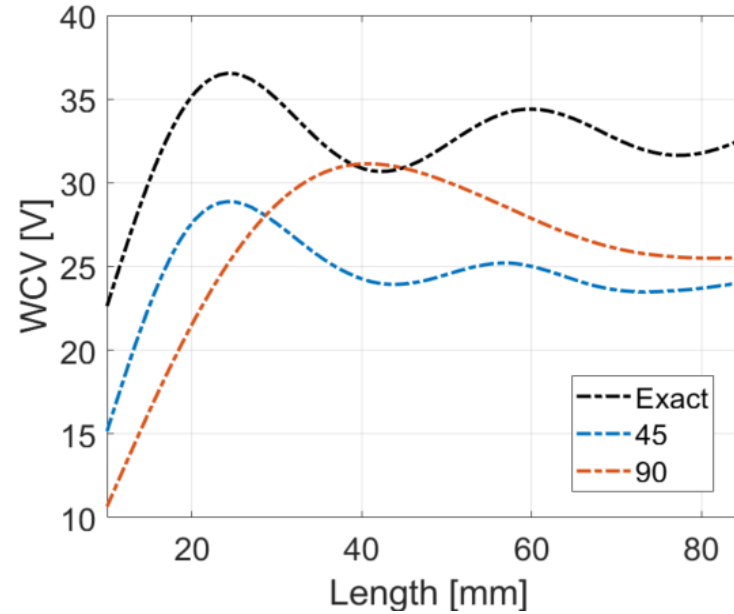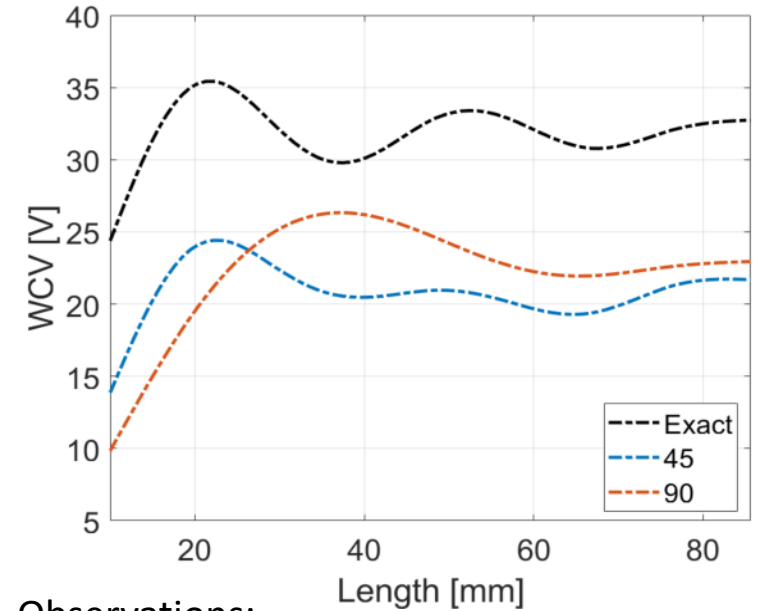
$\theta = \phi = \gamma = 0°$

$\theta = 20°, \phi = 0°, \gamma = 0°$

$\theta = 40°, \phi = 0°, \gamma = 0°$

$\theta = 60°, \phi = 0°, \gamma = 0°$
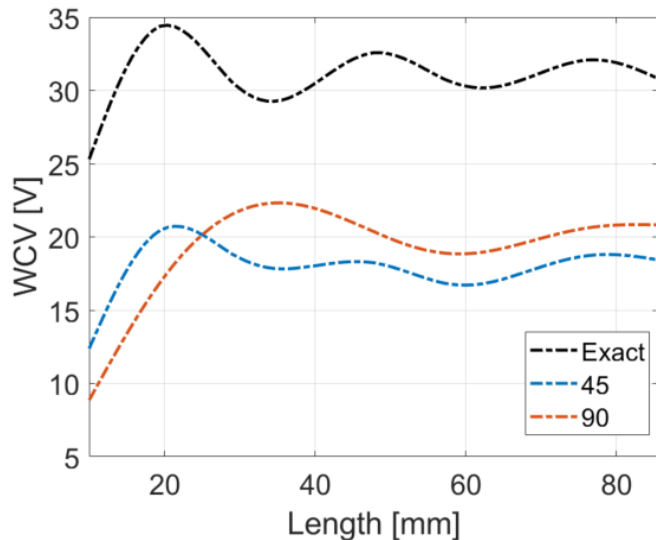
$\theta = 80°, \phi = 0°, \gamma = 0°$
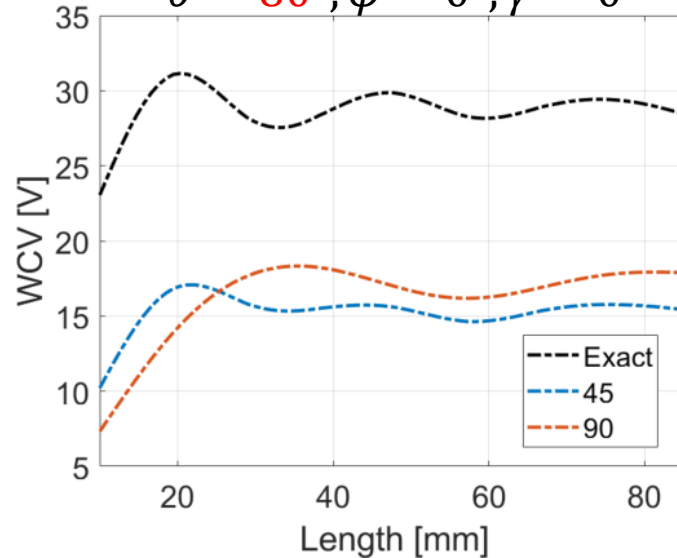
Observations:

- In this slide, $\theta$ incident angle has been changed from 20° to 80° to observe the change in the WCV as the trace length changes for three different trace shapes.

- The straight (exact) trace does not change by much as $\theta$ increases, however, 45° and 90° almost reduces by 1/3$^{rd}$ at $\theta$ = 80° when compared to $\theta$ = 0°. We did not choose $\theta$ = 90° since the PCB is backed by a rectangle shaped ground plane. At this angle, the coupling between trace and incident field is ideally zero or practically insignificant.

$\theta = \phi = \gamma = 0°$



$\theta = 0°, \phi = 30°, \gamma = 0°$



$\theta = 0°, \phi = 60°, \gamma = 0°$



$\theta = 0°, \phi = 90°, \gamma = 0°$
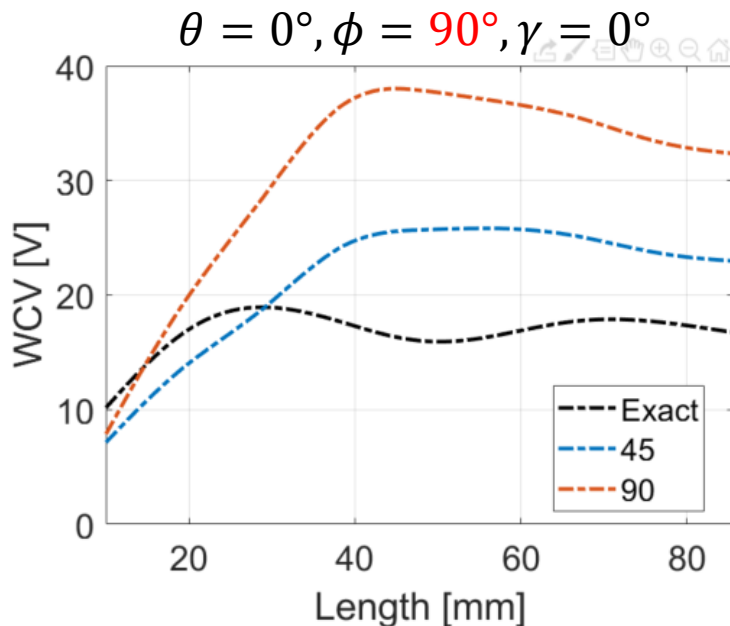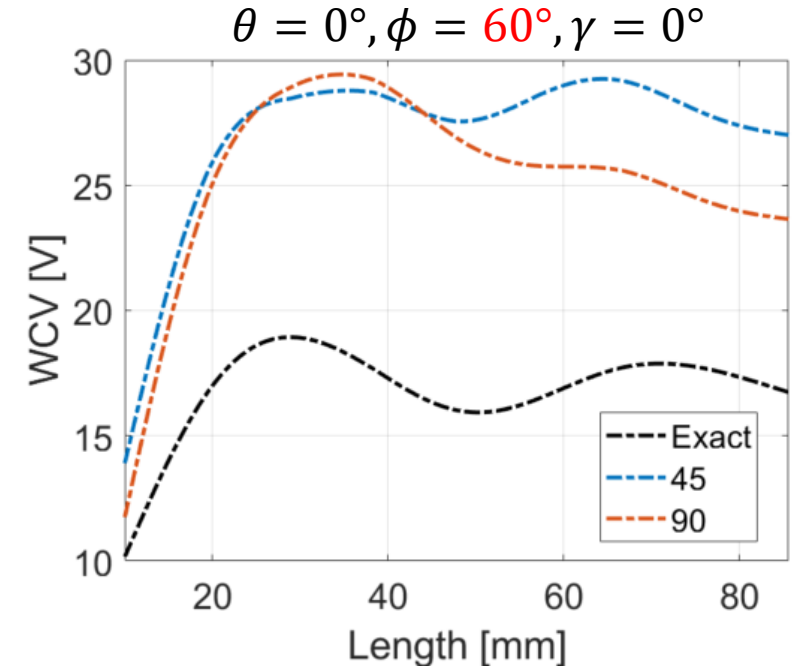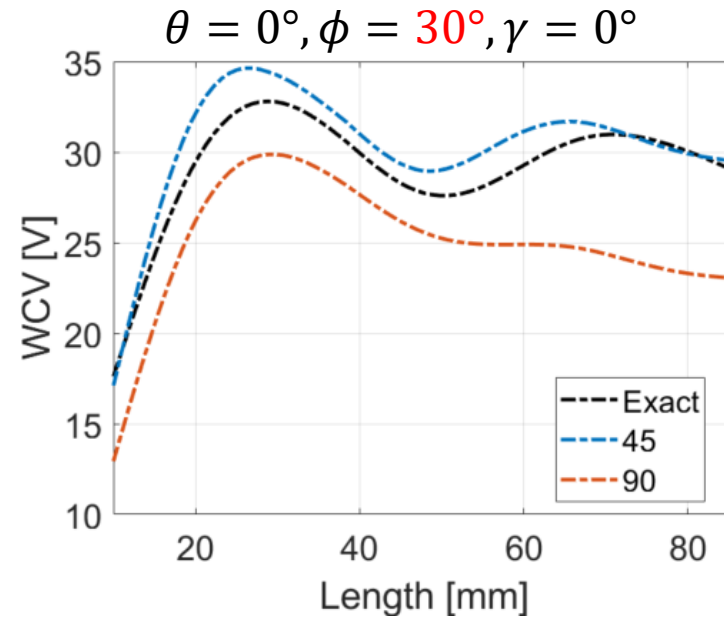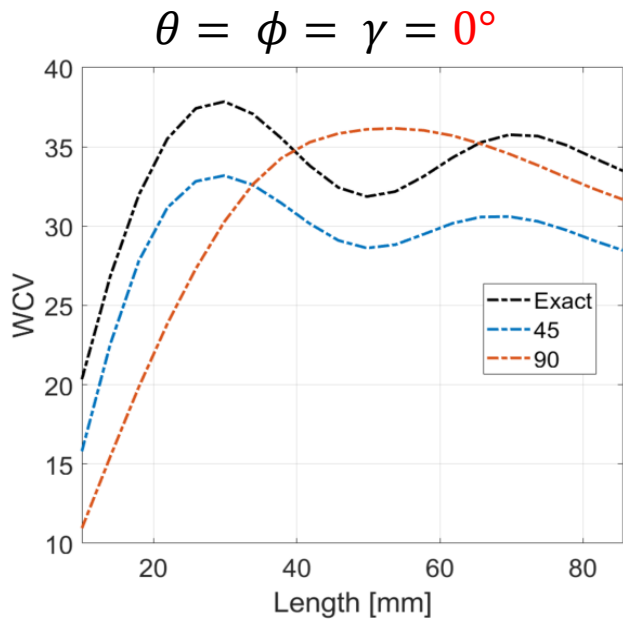
## Observations:

- In this slide, we show the WCV with change in trace length between three trace shapes and for different $\phi$ values. The $\phi$ rotation occurs perpendicular to the axis with the length of the trace.

- As $\phi$ changes from 0° to 90°, the straight trace couples less due to the E-field direction changing from parallel to trace length to perpendicular to trace length. Very less coupling occurs when $\phi$ = 90°. The level of coupling also depends on the width of the trace.

- The 45° trace shows a mixed behavior. We can expect the 45° trace to couple maximum at an oblique angle (i.e., at $\phi$ = 45°) and then to reduce with further increase in $\phi$ value.

- The 90° couples maximum when the $\phi$ incident angle is either at 0° or 90° and expect to have less coupling at oblique and acute angles.

- The WCV from $\gamma$ variation can be predicted easily based on $\phi$ variation results since the former is associated with change in polarization angle.

$\theta = \phi = \gamma = 0°$

$\theta = \phi = \gamma = 0°$
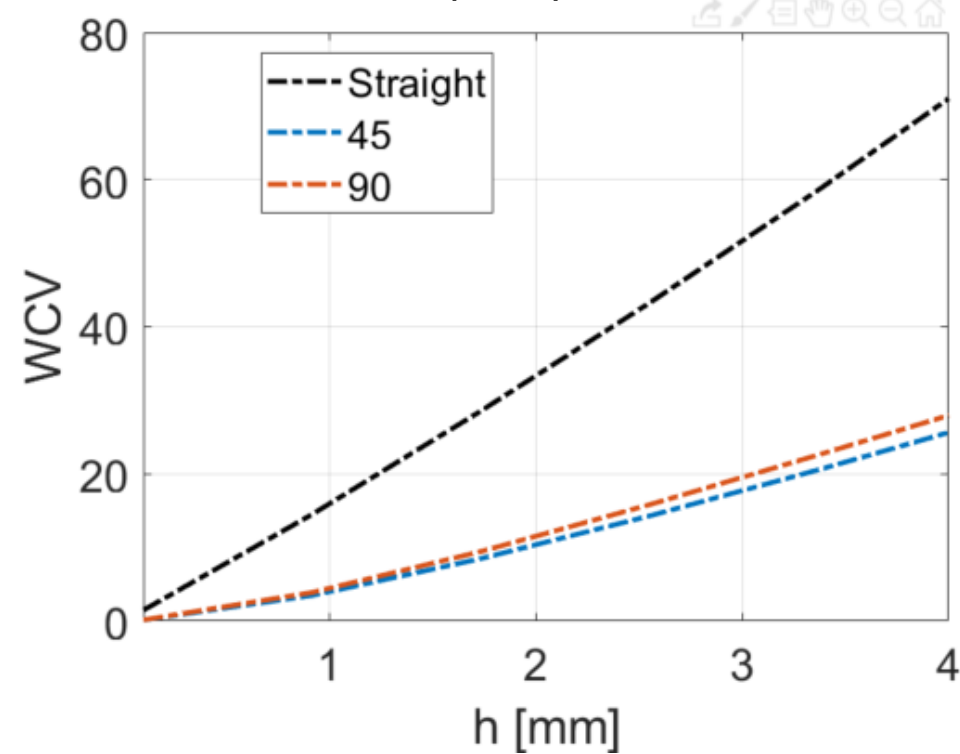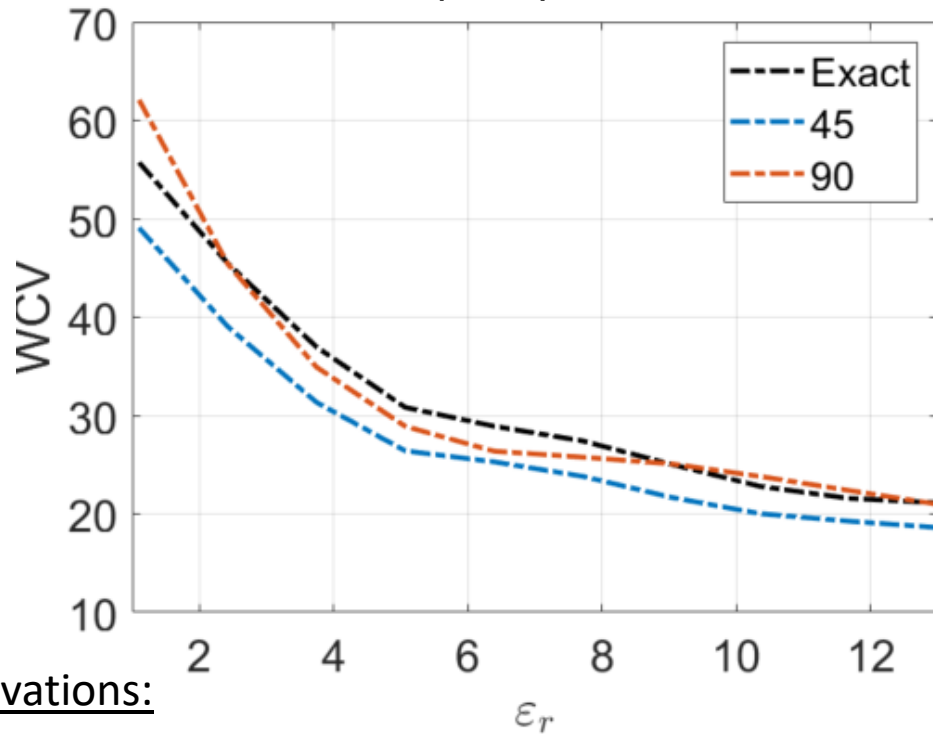
## Observations:

➤ Left figure shows WCV calculated over a range of dielectric permittivity for three different trace shapes. The length of the trace (85.6 mm), width (3.81752 mm), frequency range (0.1 to 4 GHz), dielectric thickness (2 mm) at normal incidence have been chosen. Right figure shows WCV calculated over a range of dielectric thickness. In this case, all parameters remain same and a certain dielectric permittivity (4.4).

➤ In both figures, change in dielectric permittivity or thickness leads to change in trace impedance. In our simulations and calculations, the load and source impedances have been matched to the trace impedance. For example, if trace impedance equals 65 ohms, we have adjusted our load and source impedances to be 65 ohms, which satisfies the matched load condition.

➤ In the left figure, the WCV shows from three trace shapes a $1/r^2$ behavior and the difference between them is insignificant. It is also evident that 45° trace always stays below straight trace, whereas 90° slowly oscillates between other two trace shape outputs. This tells us that choosing a higher dielectric permittivity might be advantageous to avoid unintentional coupling.

➤ In the right figure, the WCV linearly increases as the value of dielectric thickness increases. It is known that thicker substrates generate higher order TE and TM modes, thus leading to higher levels of EM field coupling due to multiple resonances. The multiple resonances leads to increased chance of radiation, which always couple to external EM field if the field carries multiple frequencies in its pulse. Therefore, the objective should always be to keep the thickness as small as possible.

## Change in load impedance
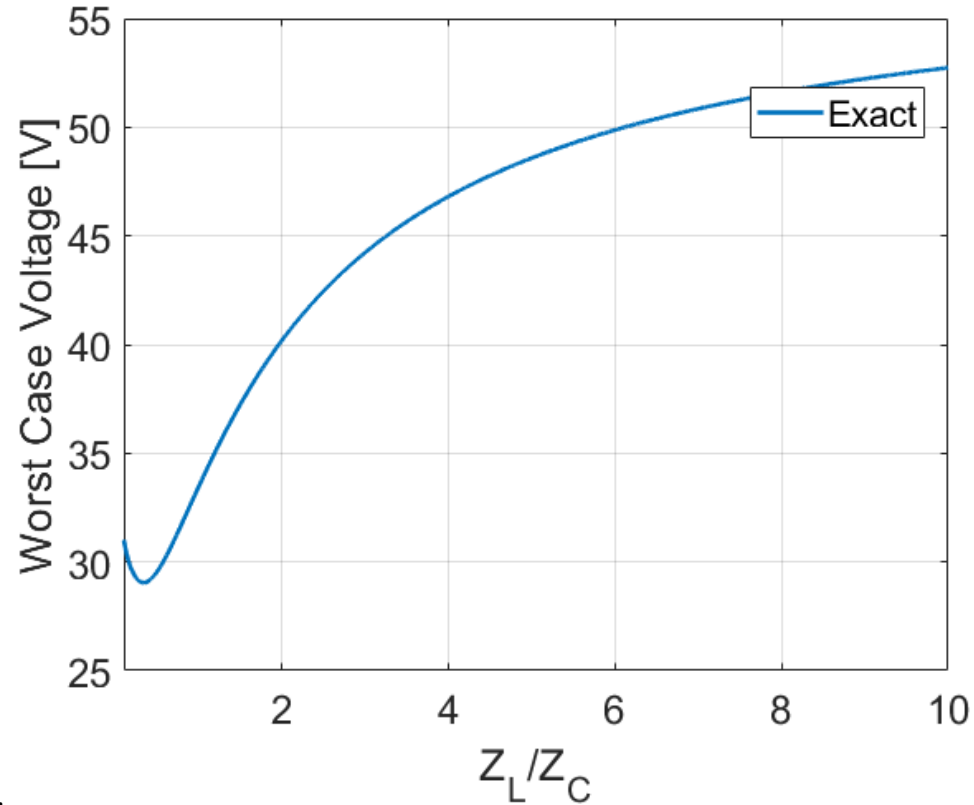
## Change in source impedance
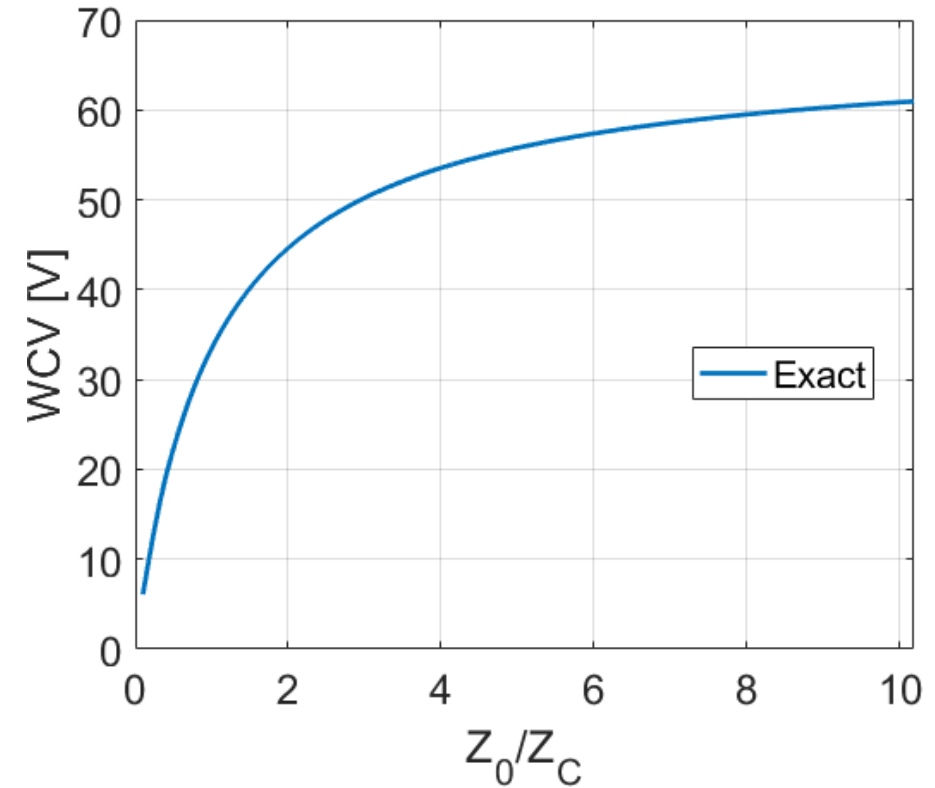
## Observations:

- In this slide, we have calculated WCV for a straight trace with 50 ohm trace/characteristic impedance ($Z_C = 50 \, \Omega$) and varied the load and source impedance as a function of $Z_C$. In both outputs, we are calculating WCV from $V_0$.

- In the left figure, the minimum WCV occurs when load impedance is properly matched ($Z_L = Z_C$). Both sides to this condition, the reflections increases which leads to increased chance of coupling.

- However, in the right figure, we do not notice the increasing trend before the matched condition ($Z_0 < Z_C$). This is because the reflections from this port will end up at the other end and gets absorbed by the matched condition ($Z_L = Z_C$).

- For 45° and 90° traces, similar outputs can be expected.

$\theta = \phi = \gamma = 0°$
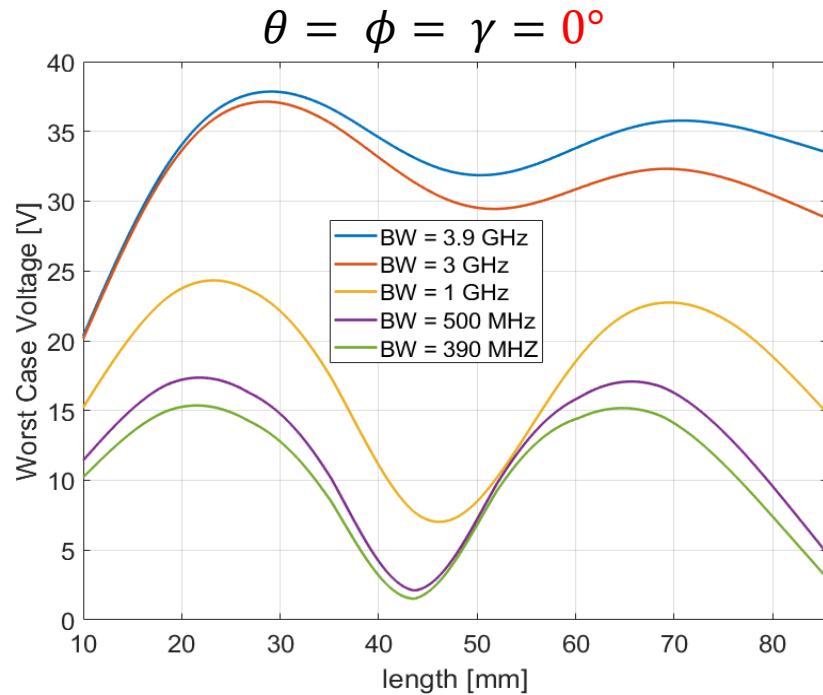


**Bandwidth Division**

$$b_r = \frac{f_U}{f_L}$$

$b_r \leq 1.01$------hypoband

$1.01 \leq b_r \leq 3$-------mesoband

$3 \leq b_r \leq 10$-------sub-hyperband

$b_r \geq 10$-------hyperband

BW = 3.9 GHz ($b_r$ = 40)

BW = 3 GHz ($b_r$ = 4)

BW = 1 GHz ($b_r$ = 1.33)

BW = 500 MHz ($b_r$ = 1.1429)

BW = 390 MHz ($b_r$ = 1.1080)

Observations:

➤ In the above result, the bandwidth is varied by keeping $f_U$ fixed at 4 GHz, while $f_L$ is varied. For example, a bandwidth of 3 GHz implies $f_L$ = 1 GHz and $f_U$ = 4 GHz.

➤ It is known that hyperband in time domain implies a short rise time pulse, whereas hypoband implies conventional CW signal, depending on the actual frequency content.

➤ In our results, we can notice that hyperband packs more energy within the pulse and thus leads to higher WCV values than the hypoband which shows minimum coupling.

➤ In converse, since hypoband packs fewer frequencies, only certain trace lengths could couple to external field.

BW = 390 MHz
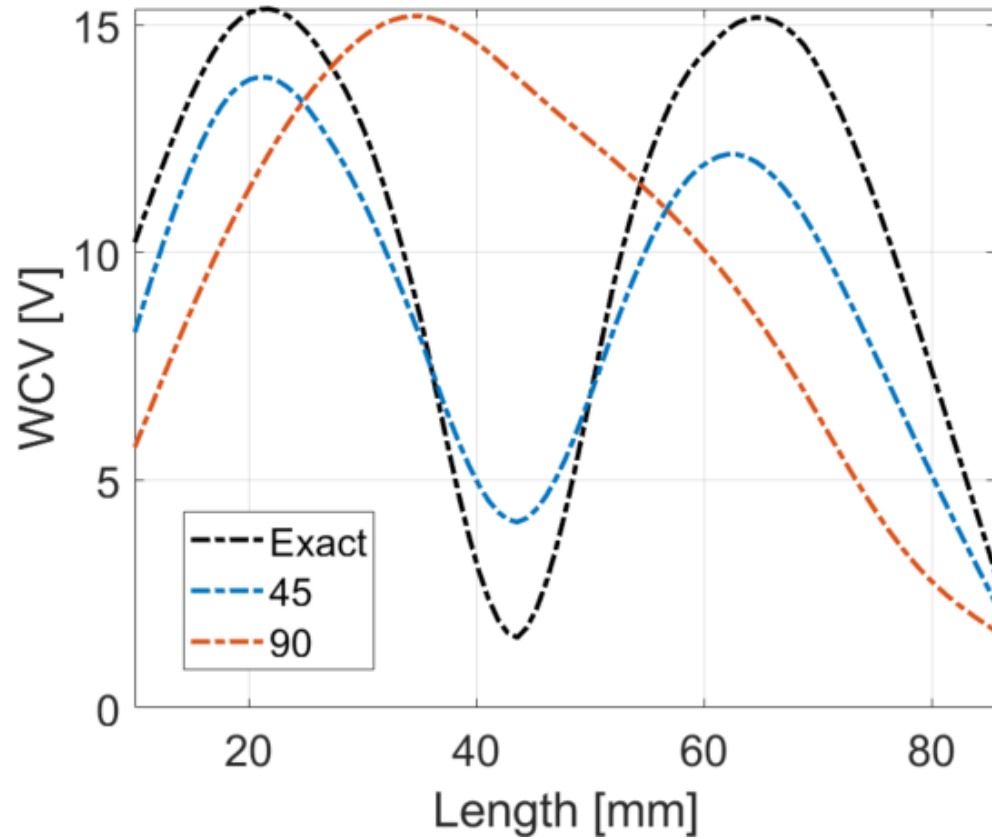
BW = 2 GHz
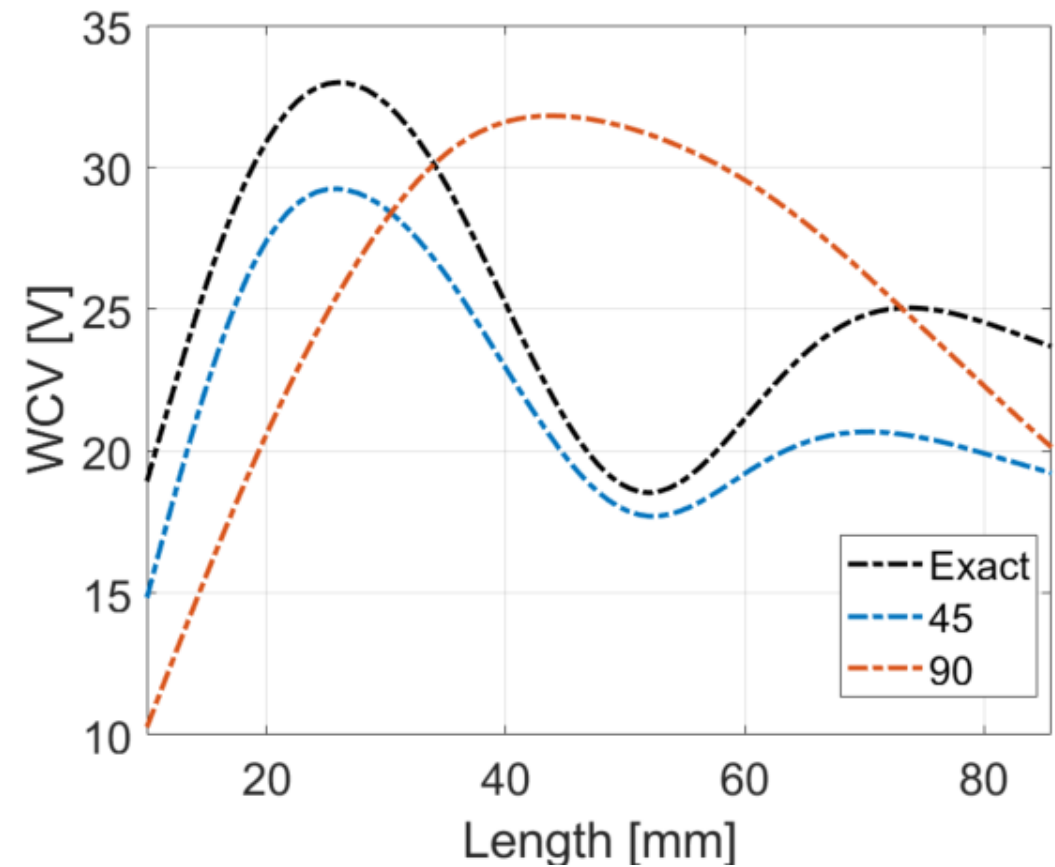


Observations:

➢ 45° and 90° traces shows similar behavior as explained for a straight trace in the previous slide.

➤ Worst-case coupled voltage is a useful method to understand maximum and minimum coupling scenarios for a given trace configuration.

➤ $\theta, \phi, \gamma$ variation has showed a similar behavior for the three trace configurations.

➤ In our study, we observed that on average straight trace couples more to the incident E-field than a trace with 45° bend.

➤ Trace length plays a crucial role in determining the amount of energy coupled to a particular load.

➤ 90° degree bent trace couples more when the trace length is approximately equal to one half of the board size. It is advised to keep 90° as small as possible in order to lessen external field coupling.

➤ Moreover, variation with substrate thickness, relative permittivity of substrate, source and load impedance, yielded a predictive output.

➤ Similarly, bandwidth variation has shown an estimated response i.e., the sharper the pulse the higher the chance of coupling due to wide bandwidth nature of sharp pulses.

THANK YOU

Dear session chairs and readers, please feel free to email or call if there are any questions, comments, and suggestions related to this work.

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