Reflection and transmission of line-source excited pulsed EM fields at a thin, high-contrast layer with dielectric and conductive properties

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Title and affiliation

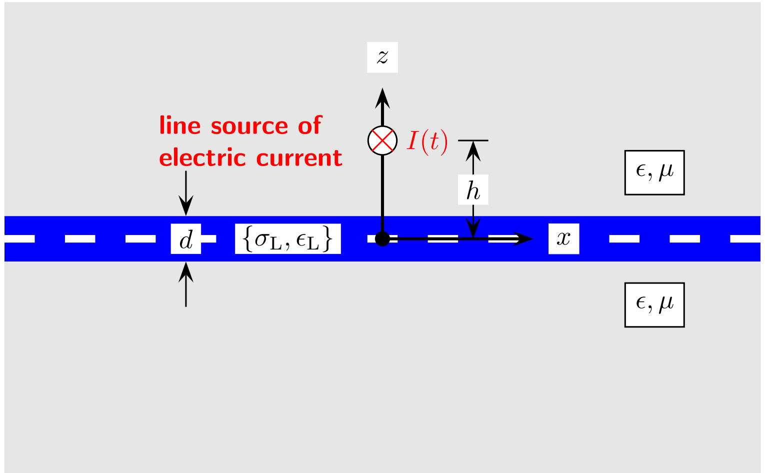
SYNOPSIS:

- Problem formulation
- Method of (analytical) solution (Generalized Cagniard-DeHoop method)
- Illustrative numerical results
- Application to signal integrity analysis in pulsed-field EM radiative inter- and intra-device signal transfer

AIM OF THE RESEARCH:

- Studying methods for characterizing pulsed-field EM radiative signal transfer in inter- and intra-microelectronic circuits/devices through the time-domain analysis of appropriate model configurations
- Analyzing the signal integrity associated with the signal transfer in such configurations
- Developing the basis for appropriate time-domain EM Interference regulations pertaining to pulsed-field inter- and intra-microelectronic circuits/devices signal transfer
- Constructing analytical results for the benchmarking of the relevant EM computational procedures

MODEL CONFIGURATION: • Line-source of electric current excited thin, high-contrast layer with dielectric and conductive properties



- $G_L = \lim_{d \downarrow 0} \int_{z=-d/2}^{d/2} \sigma_L(z) dz$ (thin-sheet conductance)
- $C_L = \lim_{d \downarrow 0} \int_{z=-d/2}^{d/2} \epsilon_L(z) dz$ (thin-sheet capacitance)

Model configuration

2D MAXWELL FIELD EQUATIONS:

- $\{H_x, E_y, H_z, J_y\}(x,z,t)$; $\partial_y = 0$

- $$\begin{bmatrix} 0 & -\partial_z & 0 \\ \partial_z & 0 & -\partial_x \\ 0 & \partial_x & 0 \end{bmatrix} \begin{bmatrix} H_x \\ 0 \\ H_z \end{bmatrix} - \epsilon\,\partial_t \begin{bmatrix} 0 \\ E_y \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ J_y \\ 0 \end{bmatrix}$$

- $$\begin{bmatrix} 0 & -\partial_z & 0 \\ \partial_z & 0 & -\partial_x \\ 0 & \partial_x & 0 \end{bmatrix} \begin{bmatrix} 0 \\ E_y \\ 0 \end{bmatrix} + \mu\,\partial_t \begin{bmatrix} H_x \\ 0 \\ H_z \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

THIN-SHEET BOUNDARY CONDITIONS:

- $E_y(x,z,t)\Big|_{z=-d/2}^{z=d/2} = 0$
- $H_x(x,z,t)\Big|_{z=-d/2}^{z=d/2} = (G_\mathrm{L} + C_\mathrm{L}\,\partial_t)\,E_y(x,0,t)$

2D Maxwell field equations

FIELD EXCITATION (ELECTRIC-CURRENT LINE SOURCE):

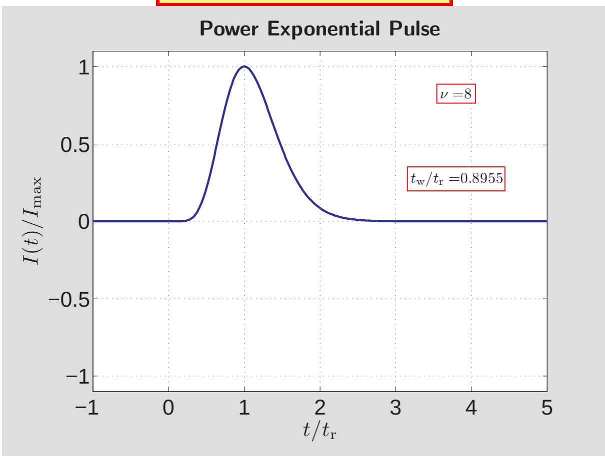
- $J_y(x,z,t) = I(t)\delta(0,h)$
- $I(t) =$ source signature

POWER EXPONENTIAL PULSE (3-PARAMETER UNIPOLAR PULSE):

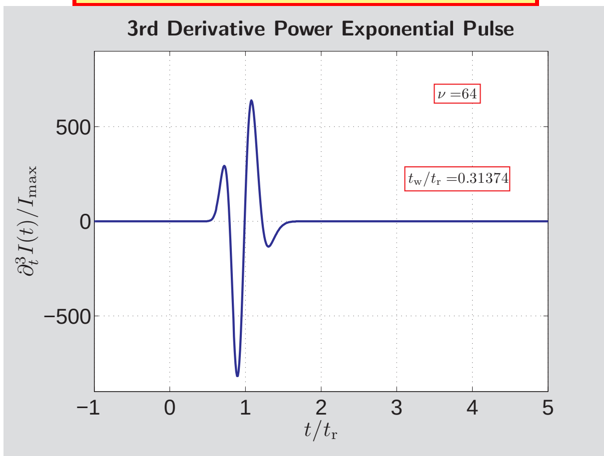
$$I(t) = I_{\max}\left(t/t_{\mathrm{r}}\right)^{\nu} \exp\left[-\nu\left(t/t_{\mathrm{r}} - 1\right)\right] H(t)$$

- $I_{\max}$ = pulse amplitude | t_{r} = pulse rise time | ν = pulse rising power

Model pulse



Typical digital pulse



Field excitation

- **TOTAL FIELD** $\{H_x, E_y, H_z\} =$
- **INCIDENT FIELD** $\{H^{\mathrm{i}}_x, E^{\mathrm{i}}_y, H^{\mathrm{i}}_z\} +$
- **SCATTERED FIELD** $\{H^{\mathrm{s}}_x, E^{\mathrm{s}}_y, H^{\mathrm{s}}_z\}$

CAGNIARD-DEHOOP METHOD

• Time Laplace transformation ($\hat{\cdot}$)	$\hat{\partial}_t = s$	$s \in \mathbb{R}, s > 0$
• Waveslowness representation ($\tilde{\cdot}$)	$\tilde{\partial}_x = -\mathrm{i}\alpha s$	$\alpha \in \mathbb{R}$
• Cagniard-DeHoop representation	$\mathrm{i}\alpha = p$	$p \in \mathbb{C}$
waveslowness domain $\{p, z, s\}$	$\longmapsto$	**spacetime domain** $\{x, z, \tau\}$
• Cagniard-DeHoop contour deformation	$p \to \overline{p}(x, z, \tau)$	$\tau = \text{time} \in \mathbb{R}$

• INCIDENT FIELD:

- $\tilde{E}^{\rm i}_y(p,z,s) = \mu\, s\, \hat{I}(s)\ \tilde{G}^{\rm i}(p,z,s)$
- $$\tilde{G}^{\rm i}(p,z,s) = \frac{\exp[-s\gamma(p)|z-h|]}{2\,s\,\gamma(p)}$$
  - $\gamma(p) = (1/c^2 - p^2)^{1/2} \quad c = (\epsilon\mu)^{-1/2} \quad \mathrm{Re}[\gamma(p)] \geq 0$

    (slowness-domain propagation coefficient)

• SCATTERED FIELD:

- $\tilde{E}^{\rm s}_y(p,z,s) = \mu\, s\, \hat{I}(s)\ \tilde{S}_{\rm L}(p,s)\ \tilde{G}^{\rm s}(p,z,s)$
- $$\tilde{G}^{\rm s}(p,z,s) = \frac{\exp[-s\gamma(p)(h+|z|)]}{2\,s\,\gamma(p)}$$

  $\tilde{S}_{\rm L}(p,s)$ = slowness-domain scattering coefficient layer

• INCIDENT FIELD:

- $$\hat{E}^{\rm i}_y(x,z,s) = \mu\, s\, \hat{I}(s)\, \frac{1}{2\pi {\rm i}} \int_{p=-{\rm i}\infty}^{{\rm i}\infty} \frac{\exp\{-s[px+\gamma(p)|z-h|]\}}{2\,s\,\gamma(p)} {\rm d}p$$
- $p \rightarrow p^{\rm i}(x,z,\tau)\ :\ p^{\rm i}x + \gamma(p^{\rm i})|z-h| = \tau$ | • $T^{\rm i} \leq \tau < \infty$ (CdH-path)
- $$\hat{E}^{\rm i}_y(x,z,s) = \mu\, s\, \hat{I}(s) \int_{\tau=T^{\rm i}}^{\infty} \exp(-s\tau) \frac{1}{2\pi(\tau^2 - T^{\rm i2})^{1/2}}\, {\rm d}\tau$$
- $T^{\rm i} = (x^2 + |z-h|^2)^{1/2}/c$ (arrival time)

• SCATTERED FIELD:

- $$\hat{E}^{\rm s}_y(p,z,s) = \mu\, s\, \hat{I}(s)\, \frac{1}{2\pi {\rm i}} \int_{p=-{\rm i}\infty}^{{\rm i}\infty} S_{\rm L}(p,s) \frac{\exp\{-s[px+\gamma(p)(h+|z|)]\}}{2\,s\,\gamma(p)} {\rm d}p$$
- $p \rightarrow p^{\rm s}(x,z,\tau)\ :\ p^{\rm s}x + \gamma(p^{\rm s})(h+|z|) = \tau$ | • $T^{\rm s} \leq \tau < \infty$ (CdH-path)
- $$\hat{E}^{\rm s}_y(p,z,s) = \mu\, s\, \hat{I}(s) \int_{\tau=T^{\rm s}}^{\infty} \exp(-s\tau) {\rm Re}[\tilde{S}_{\rm L}(p^{\rm s},s)]\, \frac{1}{2\pi(\tau^2 - T^{\rm s2})^{1/2}}\, {\rm d}\tau$$
- $T^{\rm s} = (x^2 + (h+|z|)|^2)^{1/2}/c$ (arrival time)

Field expressions (time Laplace-transform domain)

• INCIDENT FIELD:

• $E_y^{\mathrm{i}}(x,z,t) = \mu\,\partial_t I(t) \overset{(t)}{*} \left[\dfrac{1}{2\pi(\tau^2 - T^{\mathrm{i}2})^{1/2}}\right] H(t - T^{\mathrm{i}})$

• SCATTERED FIELD:

• $$E_y^{\mathrm{s}}(x,z,t) = \mu\,\partial_t\, I(t) \overset{(t)}{*} \Bigg[-\frac{1}{2\pi(t^2 - T^{\mathrm{s}2})^{1/2}} + \int_{\tau=T^{\mathrm{s}}}^{t} K_{\mathrm{L}}(\tau, t-\tau)\frac{1}{2\pi(\tau^2 - T^{\mathrm{s}2})^{1/2}}\mathrm{d}\tau\Bigg] H(t - T^{\mathrm{s}})$$

• $K_{\mathrm{L}}(\tau,t) = \mathrm{Re}\big[\beta_{\mathrm{L}}(p^{\mathrm{s}})\exp\{-[\beta_{\mathrm{L}}(p^{\mathrm{s}}) + G_{\mathrm{L}}/C_{\mathrm{L}}]t\}\big]H(t)$

• $\beta_{\mathrm{L}}(p^{\mathrm{s}}) = \dfrac{2\,\gamma(p^{\mathrm{s}})}{\mu C_{\mathrm{L}}}$

$\overset{(t)}{*} =$ time convolution

Field expressions (time domain)

ILLUSTRATIVE NUMERICAL RESULTS

CONCLUSION:

- Closed-form analytical field expressions facilitate quantifying the sensitivity of the pulse shape of the scattered field to the different configurational parameters
- The constructed time-domain algorithm can serve as a tool towards the study of the signal integrity related to the source/receiver signal transfer in configurations with thin, highly contrasting layers with conductive and capacitive properties
- Further research ⟹ extension to the corresponding 3D (point-source excited) model, with particular application to inter- and intra-device radiative transfer of digital signals