Signal Integrity Journal
Signal Integrity · Power Integrity · EMC/EMI

High-Speed Digital Field Visualization of Currents and Crosstalk

Yuriy Shlepnev – Simberian Inc.

Simberian
Electromagnetic Solutions

Presented at Signal Integrity webinar on August 15, 2017

Dr. Yuriy Shlepnev

Simberian Inc.

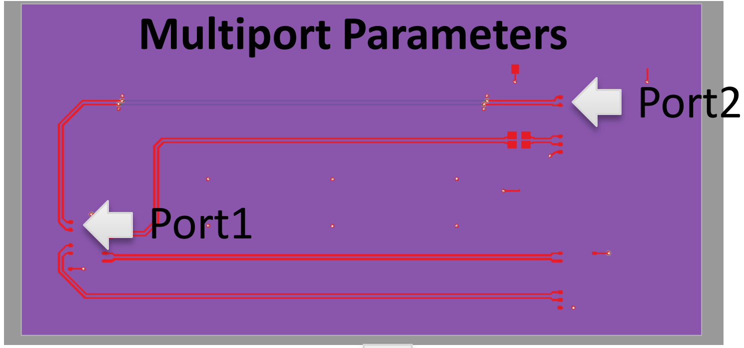
Yuriy Shlepnev is President and Founder of Simberian Inc., where he develops Simbeor electromagnetic signal integrity software. He received M.S. degree in radio engineering from Novosibirsk State Technical University in 1983, and the Ph.D. degree in computational electromagnetics from Siberian State University of Telecommunications and Informatics in 1990. He was principal developer of electromagnetic simulator for Eagleware Corporation and leading developer of electromagnetic software for simulation of signal and power distribution networks at Mentor Graphics. The results of his research are published in multiple papers and conference proceedings.

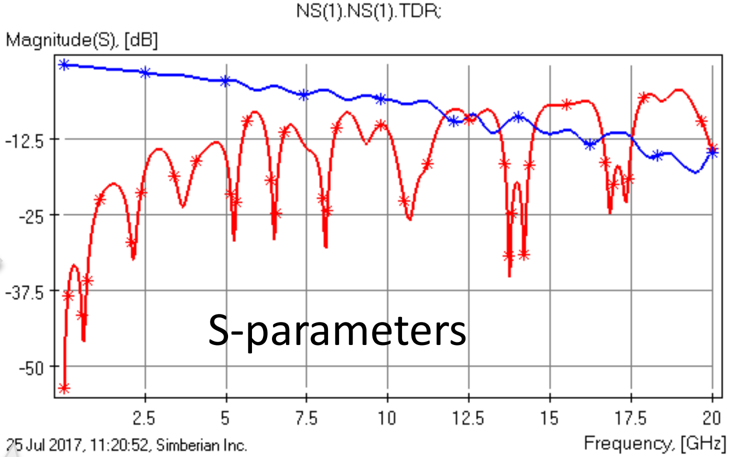
Outline

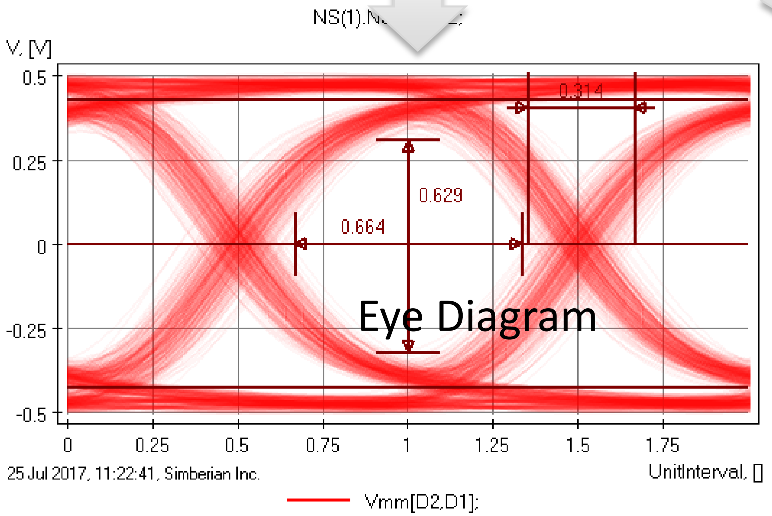
- Introduction
- Electromagnetic field visualization basics
- Current crowding, skin-effect, power flow
- Cross-talk microstrips and strips
- Cross-talk in vias
- Conclusion

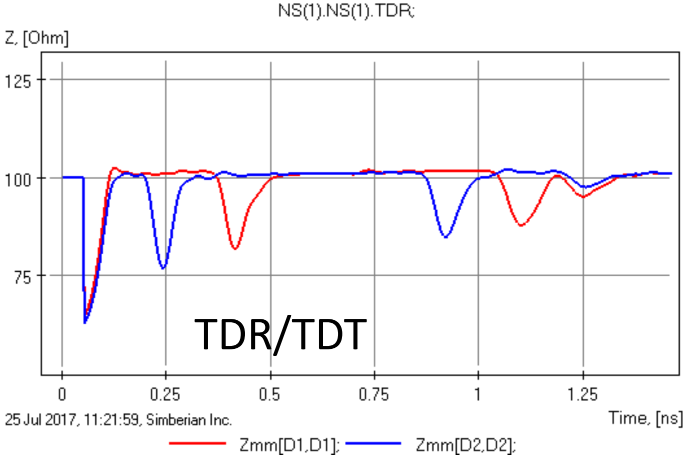
PCB/Packaging interconnects: multiport or black-box description

Compute and measure Multiport Parameters



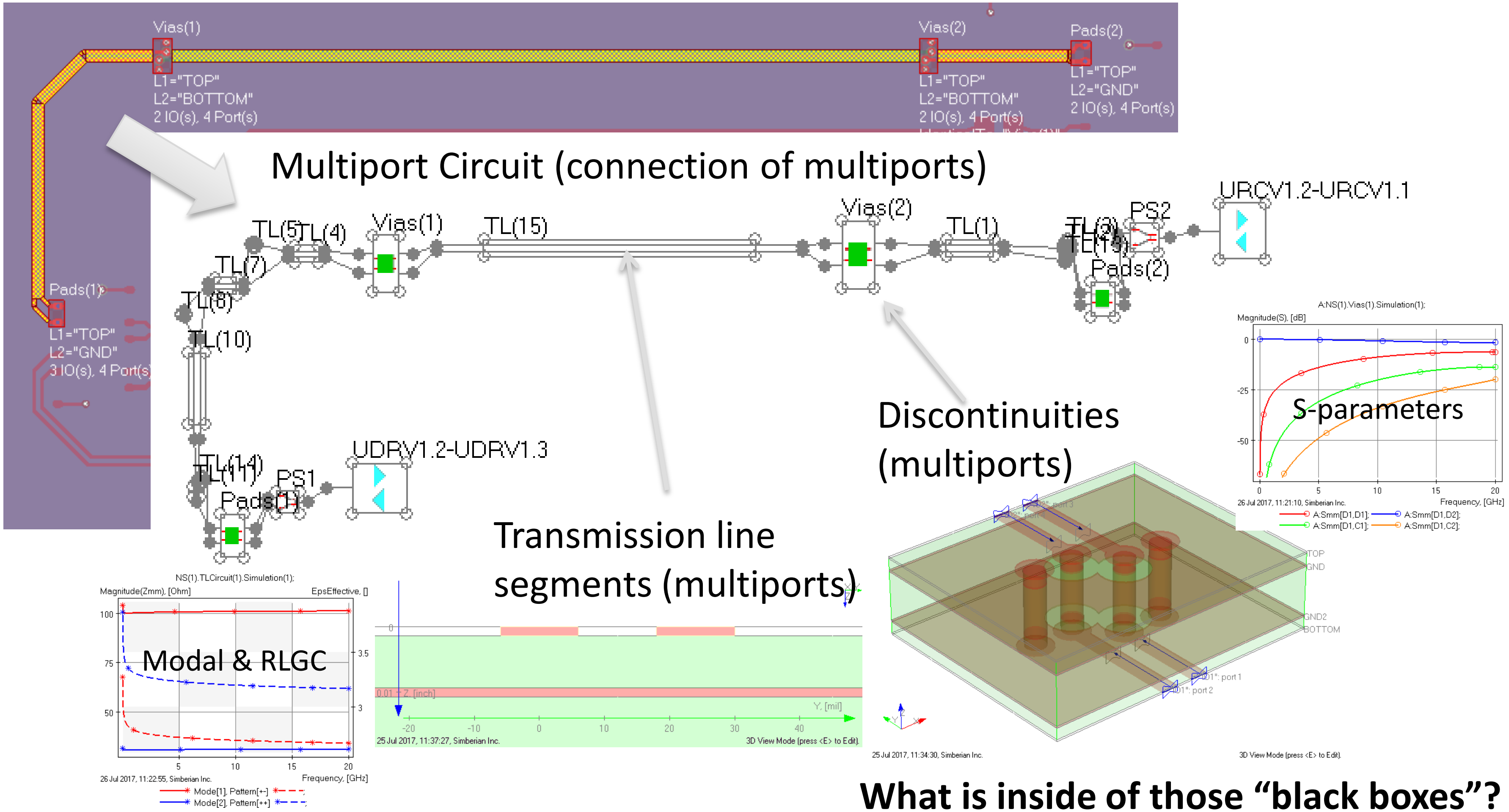






Let's take closer look at how we usually model it…

Analysis – more “black boxes”



Multiport Circuit (connection of multiports)

Discontinuities (multiports)

S-parameters

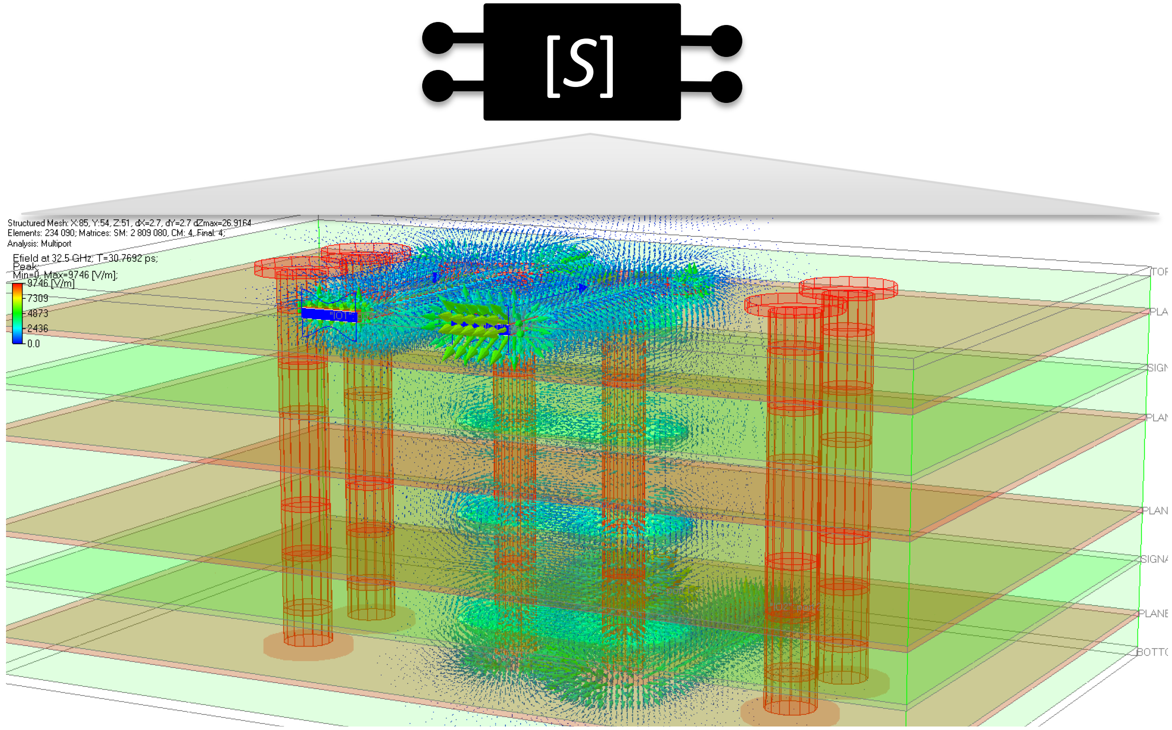
Transmission line segments (multiports)

Modal & RLGC

What is inside of those “black boxes”?

See more at Y. Shlepnev, “Decompositional Electromagnetic Analysis of Digital Interconnects”, IEEE Int. Symp. on Electromagnetic Compatibility (EMC2013), Denver, CO, 2013, p.563-568.

“Black box” contains fields



```
Structured Mesh: X:85, Y:54, Z:51, dX=2.7, dY=2.7 dZmax=26.9164
Elements: 234 090; Matrices: SM: 2 809 080, CM: 4, Final: 4;
Analysis: Multiport
Efield at 32.5 GHz; T=30.7692 ps;
Peak:
Min=0, Max=9746 [V/m];
```

Looking at the S-parameters/TDR/TDT/eye we see just the tip of an ICEBERG!

What we do not usually see contains a lot of information that is almost never “measured”, but is critical to revealing “How interconnects work”

Electric and magnetic fields, current densities, power flow density…

Fields are described by Maxwell's equations

$$\oiint \bar{D}\cdot d\bar{s} = \iiint \rho_{free}\cdot dv$$

$$\oiint \bar{B}\cdot d\bar{s} = 0$$

Gauss's laws

Continuity (Kirchhoff's current law)

$$\oiint \bar{J}_{free}\cdot d\bar{s} = -\frac{\partial}{\partial t}\iiint \rho_{free}\cdot dv$$

$$\oint \bar{H}\cdot d\bar{l} = \frac{\partial}{\partial t}\iint \bar{D}\cdot d\bar{s} + \iint \bar{J}_{free}\cdot d\bar{s}$$

Ampere's law

$$\oint \bar{E}\cdot d\bar{l} = -\frac{\partial}{\partial t}\iint \bar{B}\cdot d\bar{s}$$

Faraday's law (Kirchhoff's voltage law)

$$\bar{D} = \varepsilon_0\bar{E} + \bar{P}$$

$$\bar{B} = \mu_0\left(\bar{H} + \bar{M}\right)$$

$$J_{free} = \sigma\bar{E}$$

Fields in materials

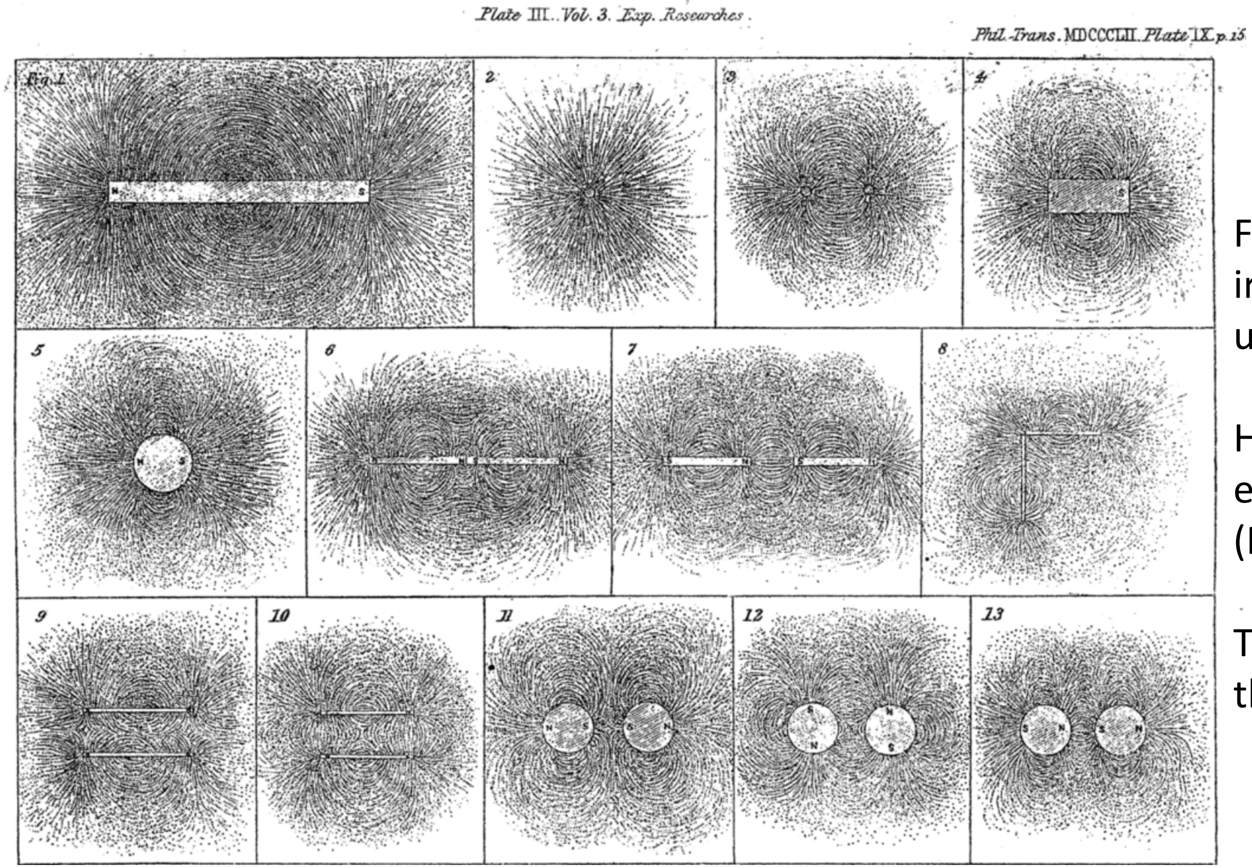
Plus material equations and boundary conditions….

$\bar{E}$ - Electric Intensity (V/m)
$\bar{H}$ - Magnetic Intensity (A/m)
$\bar{D}$ - Electric Flux (Coulomb/m^2)
$\bar{B}$ - Magnetic Flux (Tesla or Weber/m^2)
ρ_{free} - Free Charge Density (Coulomb/m^3)
$\bar{J}_{free}$ - Free Current Density (A/m^2)

$\bar{P}$ - Polarization (Coulomb/m^2)
$\bar{M}$ - Magnetization (A/m)

Very complicated to say the least ☺
Visual Computational Electromagnetics may be helpful tool to understand…

Field visualization in 19th century



Faraday visualized fields with the iron fillings and almost never used equations;

He discovered and described electromagnetic induction (Faraday's law) using words only;

That leaded to the discovery of the Maxwell's equations…

Michael Faraday, Experimental Researches in Electricity, 1855

EM fields visualization – 70s & 80s

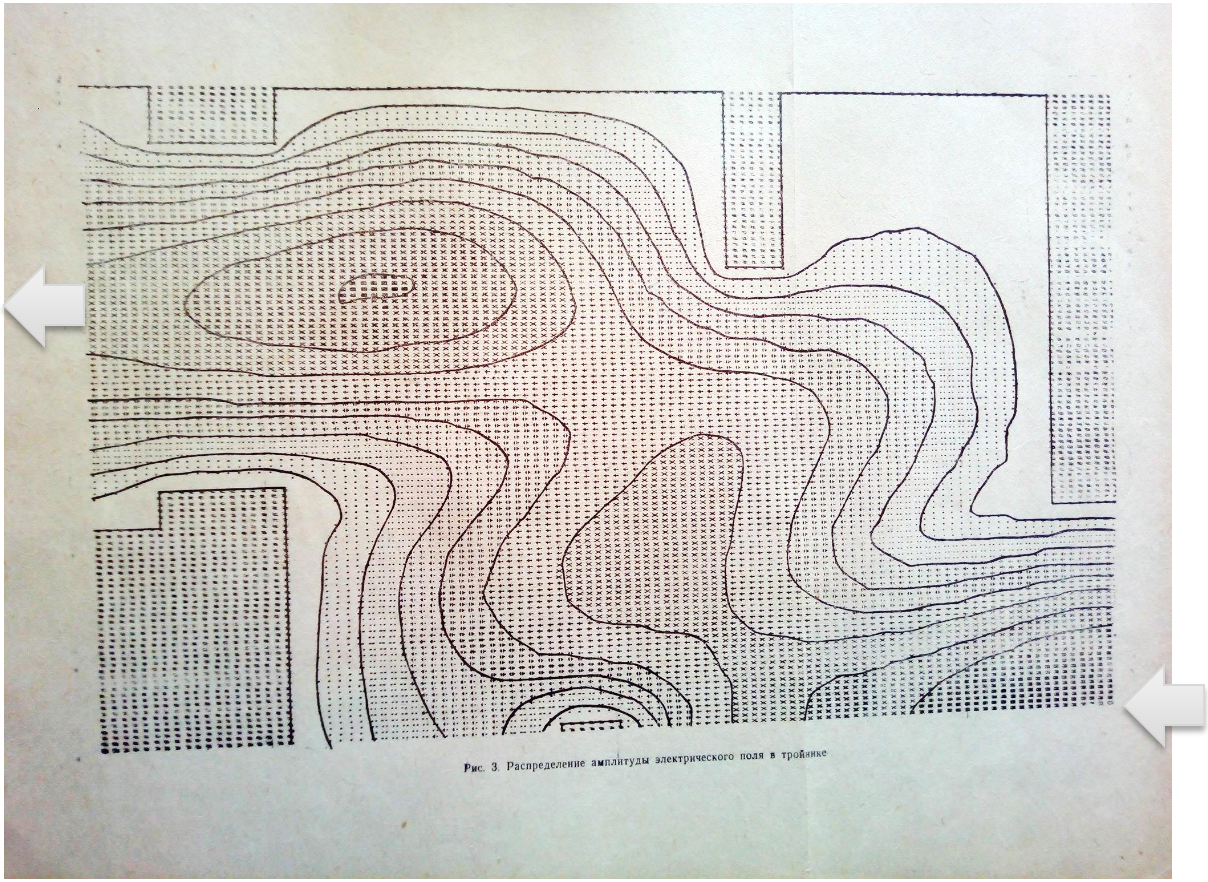


Рис. 3. Распределение амплитуды электрического поля в тройнике

Use of printers:
Electric Field in rectangular waveguide T-junction

Print out from VOLNA software of B.V. Sestroretzkiy, V.M. Seredov, N.A. Sadovnikov, МНИИП (now Corporation Vega)

TE_{10} wave

EM fields visualization – 70s & 80s

Electric fields in microstrip line on magnetized ferrite substrate computed with Minimal Autonomous Blocks (Treftz's finite elements)

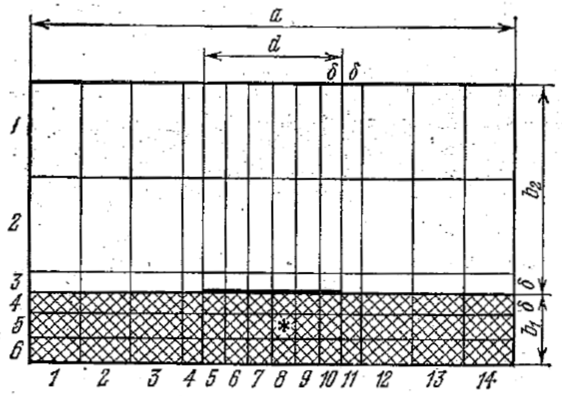


Рис. 4.22. Разбиение поперечного сечения при построении структуры полей: $a = 3{,}5$ мм, $d = 1$ мм, $b_1 = 0{,}5$ мм, $b_2 = 1{,}5$ мм, $\delta = 0{,}15$ мм.

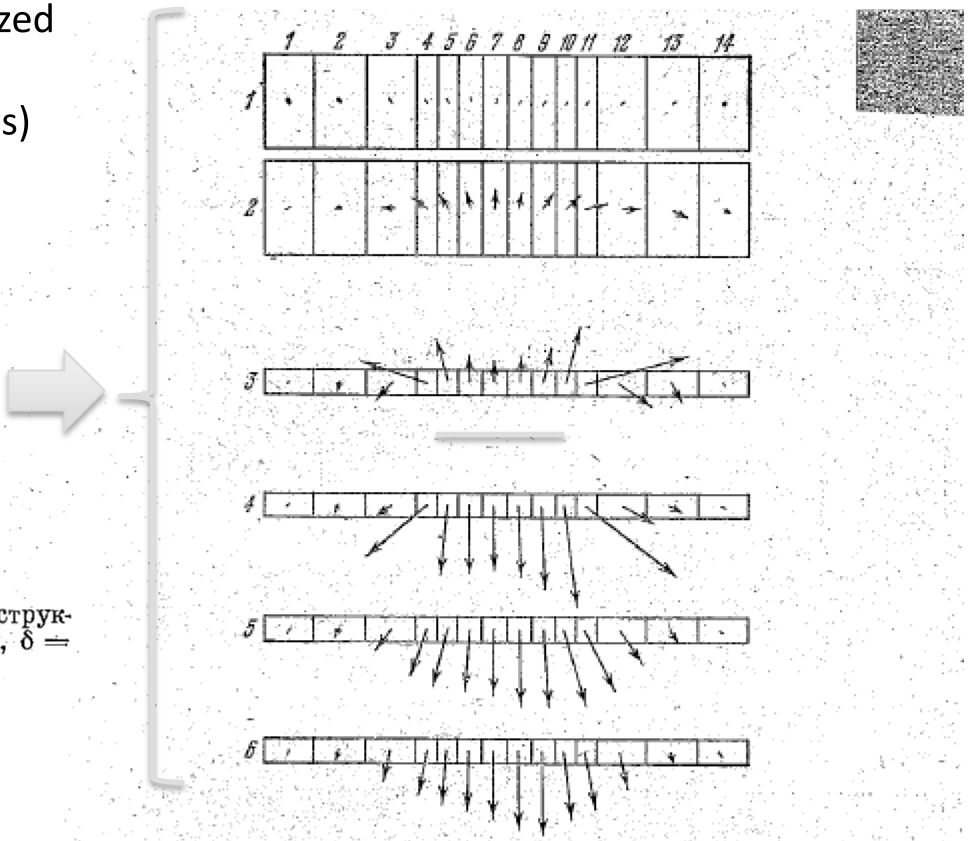
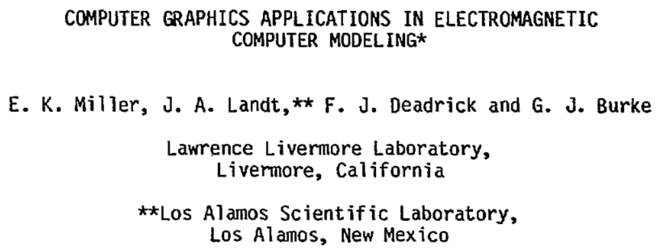


Рис. 4.27. Система направленных отрезков, характеризующих поперечное электрическое поле на всех МАБ поперечного сечения прежней полосковой линии (нормально намагниченная ферритовая подложка).

From В.В. Никольский, Т.И. Никольская, Декомпозиционный подход к задачам электродинамики, Наука, 1983, с. 176-181.

EM fields visualization – 70s & 80s



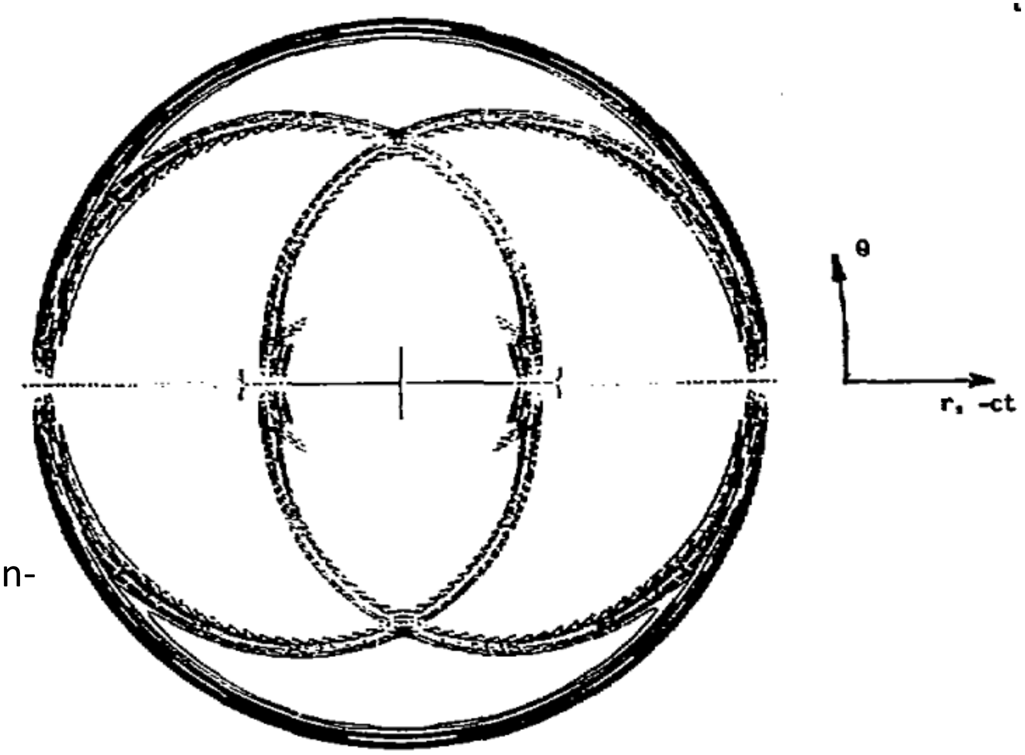
COMPUTER GRAPHICS APPLICATIONS IN ELECTROMAGNETIC
COMPUTER MODELING*

E. K. Miller, J. A. Landt,** F. J. Deadrick and G. J. Burke

Lawrence Livermore Laboratory,
Livermore, California

**Los Alamos Scientific Laboratory,
Los Alamos, New Mexico

IEEE Antennas and Propagation Society International Symposium, 1981, p. 634-637.

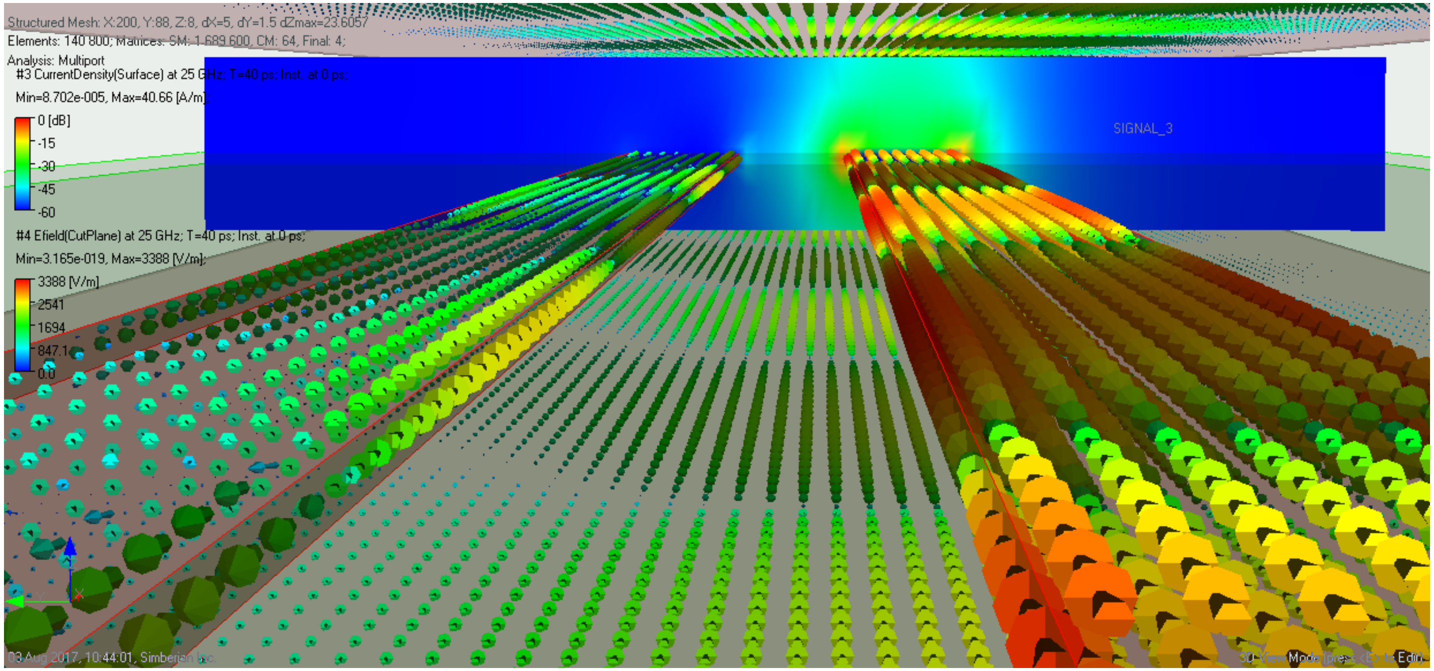


Far-field space-time contour plot for a Gaussian-pulse excitation of a center-fed dipole, 1981

Mostly use of plotters and printers until 90s …

90s and 2000s - gaming changed everything…

Personal computers and console video games took a great graphical leap forward in the 2000s, becoming able to display graphics in real time computing that had previously only been possible pre-rendered and/or on business-level hardware (https://en.wikipedia.org/wiki/Computer_graphics).



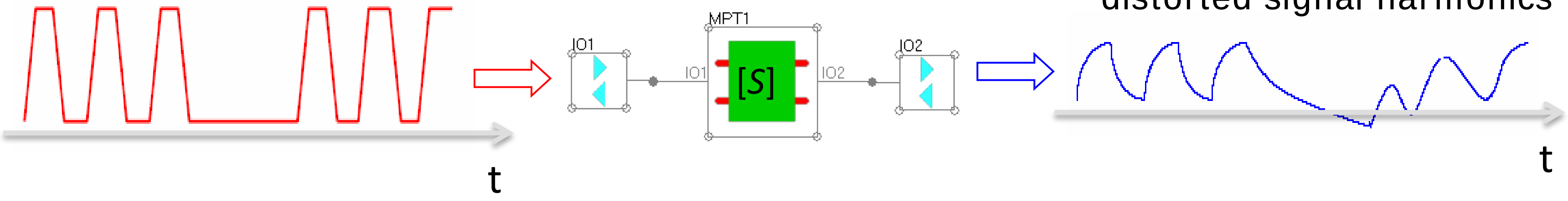
```
Structured Mesh: X:200, Y:88, Z:8, dX=5, dY=1.5 dZmax=23.6057
Elements: 140 800; Matrices: SM: 1 689 600, CM: 64, Final: 4;
Analysis: Multiport
  #3 CurrentDensity(Surface) at 25 GHz; T=40 ps; Inst. at 0 ps;
  Min=8.702e-005, Max=40.66 [A/m];
  #4 Efield(CutPlane) at 25 GHz; T=40 ps; Inst. at 0 ps;
  Min=3.165e-019, Max=3388 [V/m];
03 Aug 2017, 10:44:01, Simberian Inc.
3D View Mode (press <E> to Edit)
```

Surface current density and electric field in strip lines computed and visualized in Simbeor software

Time and Frequency Domains

Signal -> Harmonics

Response -> superposition of distorted signal harmonics



Signal degradation in interconnects are caused by dielectric and conductor loss and dispersion, high-frequency non-TEM wave dispersion, effect of discontinuities (ISI or multiple reflection) and radiation; **The best way to model those effect is in the FREQUENCY DOMAIN (our focus);**

All fields, currents and power are real parts of time-harmonic complex vectors

$$\mathrm{Re}\left[\vec{F}_0\left(\bar{r}\right)\cdot e^{i\omega t}\right] \qquad \mathrm{Re}\left[\vec{P}_0\left(\bar{r}\right)\cdot e^{i2\omega t}\right]$$

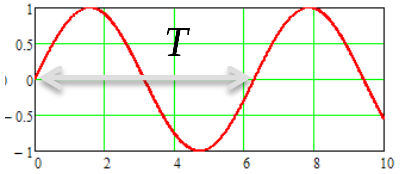
Excitation – single frequency sinusoidal voltage sources

$$V\left(t\right)=V_0\cdot\sin(\omega t+\varphi)$$

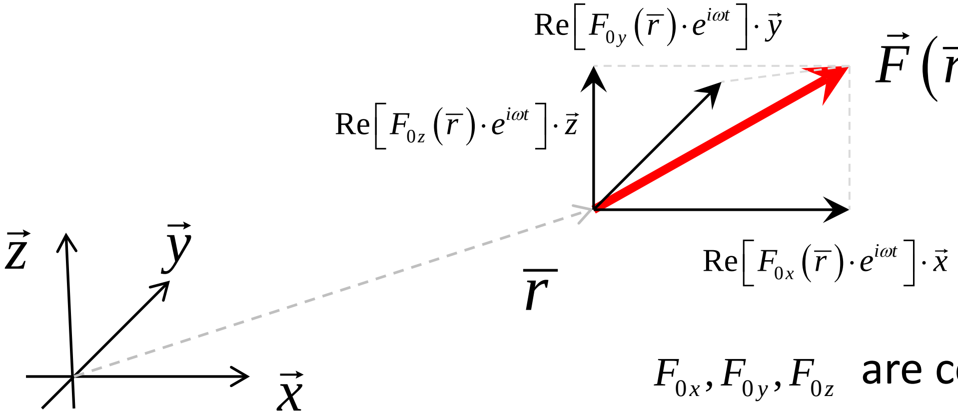
$$\omega = 2\pi\cdot f = \frac{2\pi}{T}$$

frequency

period



Time-harmonic vector fields



$\vec{F}\left(\overline{r},t\right)$ Instantaneous field value: amplitude and direction are periodic functions of time

F_{0x}, F_{0y}, F_{0z} are complex numbers

$$\vec{F}\left(\overline{r},t\right)=\mathrm{Re}\left[\vec{F}_0\left(\overline{r}\right)\cdot e^{i\omega t}\right]=\mathrm{Re}\left[F_{0x}\left(\overline{r}\right)\cdot e^{i\omega t}\right]\cdot\vec{x}+\mathrm{Re}\left[F_{0y}\left(\overline{r}\right)\cdot e^{i\omega t}\right]\cdot\vec{y}+\mathrm{Re}\left[F_{0z}\left(\overline{r}\right)\cdot e^{i\omega t}\right]\cdot\vec{z}$$

Peak value: $\vec{F}_{peak}\left(\overline{r}\right)=\vec{F}\left(\overline{r},t_{peak}\right)\quad\left|\vec{F}\left(\overline{r},t_{peak}\right)\right|\geq\left|\vec{F}\left(\overline{r},t\right)\right|,\ 0\leq t<T$

Average value (for power flow): $\vec{P}_{average}\left(\overline{r}\right)=\dfrac{1}{T}\displaystyle\int_0^T\vec{P}\left(\overline{r},t\right)\cdot dt$

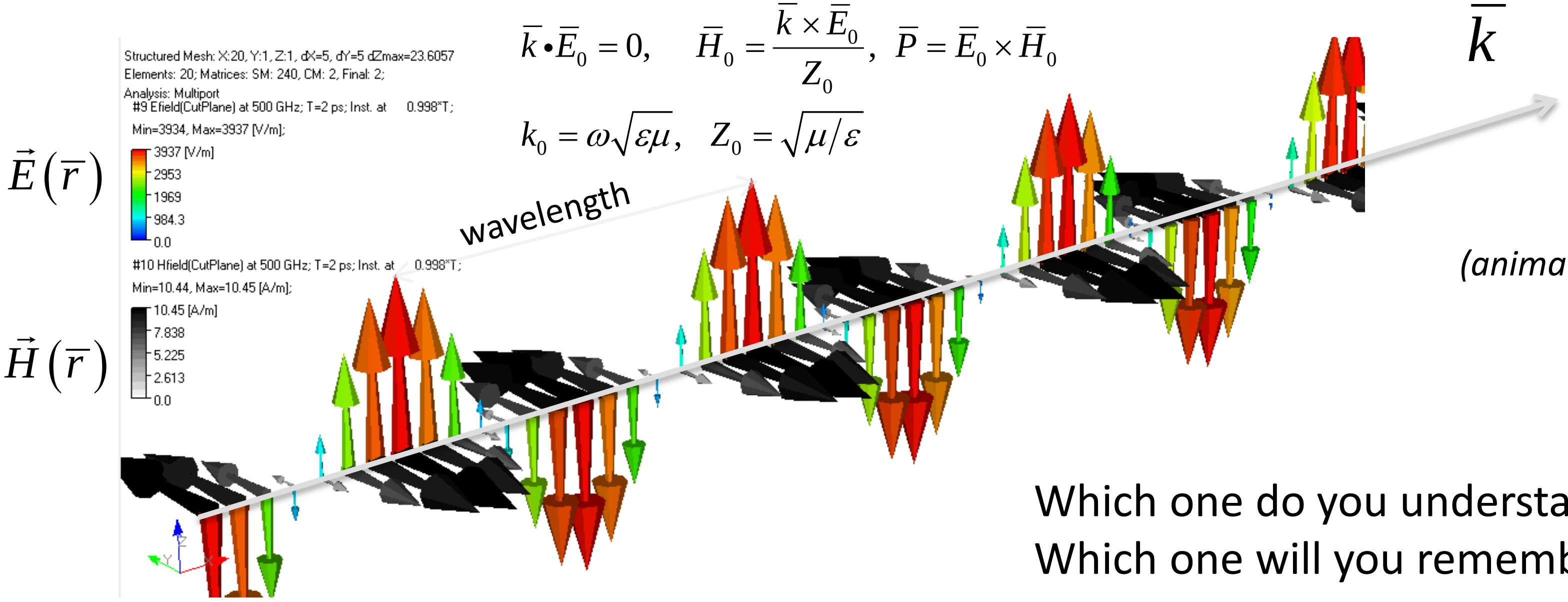
Equations or Pictures

Plane wave solution

$$\begin{pmatrix} \vec{E}(\bar{r}) \\ \vec{H}(\bar{r}) \end{pmatrix} = \begin{pmatrix} \bar{E}_0 \\ \bar{H}_0 \end{pmatrix} \cdot e^{-ik_0 \bar{k} \bullet \bar{r}}, \ \bar{r} \in \Omega_p$$

$$\bar{k} \bullet \bar{E}_0 = 0, \quad \bar{H}_0 = \frac{\bar{k} \times \bar{E}_0}{Z_0}, \ \bar{P} = \bar{E}_0 \times \bar{H}_0$$

$$k_0 = \omega\sqrt{\varepsilon\mu}, \quad Z_0 = \sqrt{\mu/\varepsilon}$$



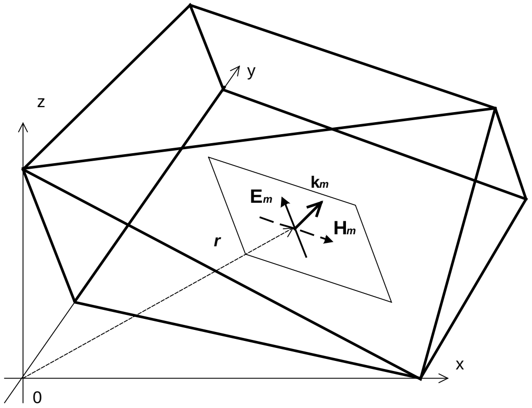
Structured Mesh: X:20, Y:1, Z:1, dX=5, dY=5 dZmax=23.6057
Elements: 20; Matrices: SM: 240, CM: 2, Final: 2;
Analysis: Multiport
#9 Efield(CutPlane) at 500 GHz; T=2 ps; Inst. at 0.998*T;
Min=3934, Max=3937 [V/m];
3937 [V/m]
2953
1969
984.3
0.0
#10 Hfield(CutPlane) at 500 GHz; T=2 ps; Inst. at 0.998*T;
Min=10.44, Max=10.45 [A/m];
10.45 [A/m]
7.838
5.225
2.613
0.0

(animated)

Which one do you understand?
Which one will you remember?

Richard Feynman: *Dirac said that to understand a physical problem means to be able to see the answer without solving equations. Maybe he exaggerated; maybe solving equations is experience you need to gain understanding. But until you do understand, you're just solving equations.* - 1979

Field modeling technique: Trefftz Finite Elements



Element interior fields (exact solution of Maxwell's equations):

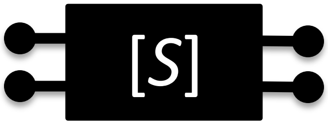
$$\begin{pmatrix}\vec{E}(\bar{r})\\ \vec{H}(\bar{r})\end{pmatrix} = \sum_{m=1}^{N_{\text{int}}}\left[A_m^{+}\cdot\begin{pmatrix}\bar{E}_{0m}\\ -\bar{H}_{0m}\end{pmatrix}\cdot e^{ik_0\bar{k}_m\bullet\bar{r}} + A_m^{-}\cdot\begin{pmatrix}\bar{E}_{0m}\\ \bar{H}_{0m}\end{pmatrix}\cdot e^{-ik_0\bar{k}_m\bullet\bar{r}}\right],\quad \bar{r}\in\Omega_p$$

$$\bar{k}_m\bullet\bar{E}_{0m}=0,\qquad \bar{H}_{0m}=\frac{\bar{k}_m\times\bar{E}_{0m}}{Z_0},\quad k_0=\omega\sqrt{\varepsilon\mu},\quad Z_0=\sqrt{\mu/\varepsilon}$$

Projection on boundaries

$$\bar{b}_{el}=\left[S_{el}\right]\cdot\bar{a}_{el}$$

S-parameters of Trefftz element



$$\bar{b}=\left[S\right]\cdot\bar{a}$$

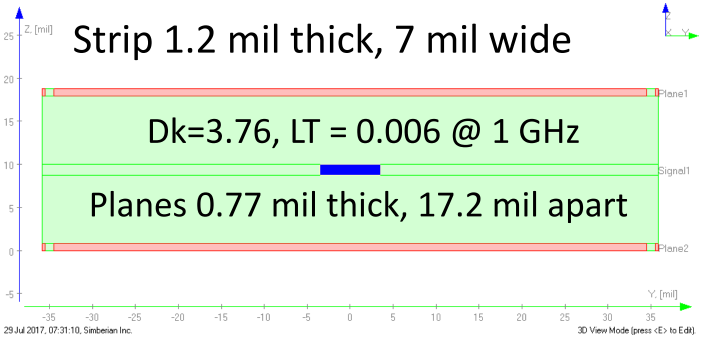
S-parameters of structure

1. *V.V. Nikol'skii, T.I. Lavrova, "The method of minimum autonomous blocks and its application to waveguide diffraction problems," Radio Engineering & Electronic Physics, vol. 23, no. 2, p.1-10, 1978.*

2. *V.V. Nikol'skii, T.I. Nikol'skaia, Decompositional approach to electromagnetic problems. Moscow: Nauka, 1983 (in Russian).*

3. *Y.O. Shlepnev, Trefftz finite elements for electromagnetics. - IEEE Trans. on Microwave Theory and Techniques, vol. MTT-50, pp. 1328-1339, May, 2002.*

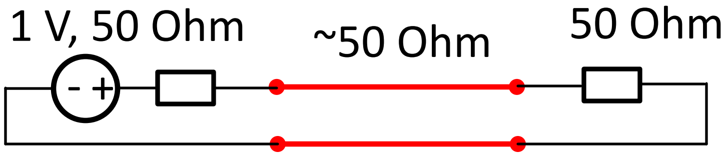
Fields and currents in strip line



Strip 1.2 mil thick, 7 mil wide

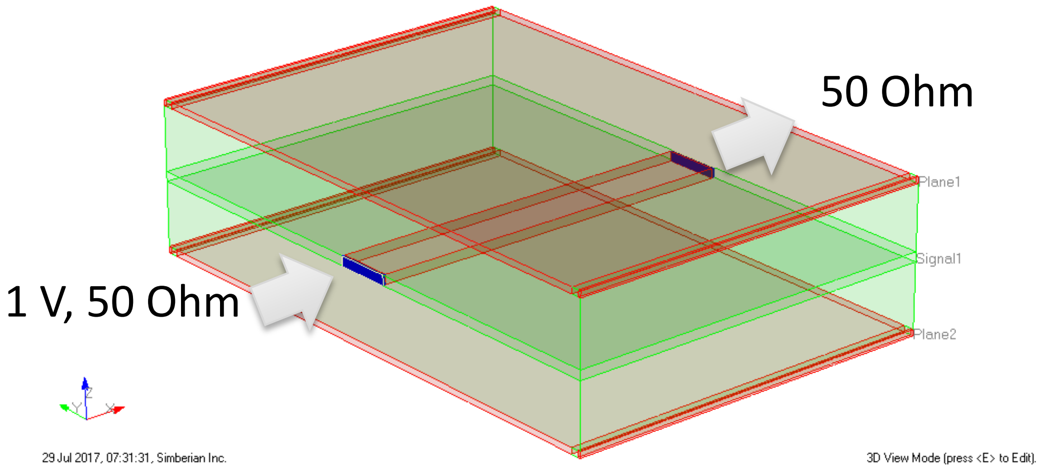
Dk=3.76, LT = 0.006 @ 1 GHz

Planes 0.77 mil thick, 17.2 mil apart



Vpeak ~ 0.5 V

Ipeak ~ 0.01 A



50 Ohm

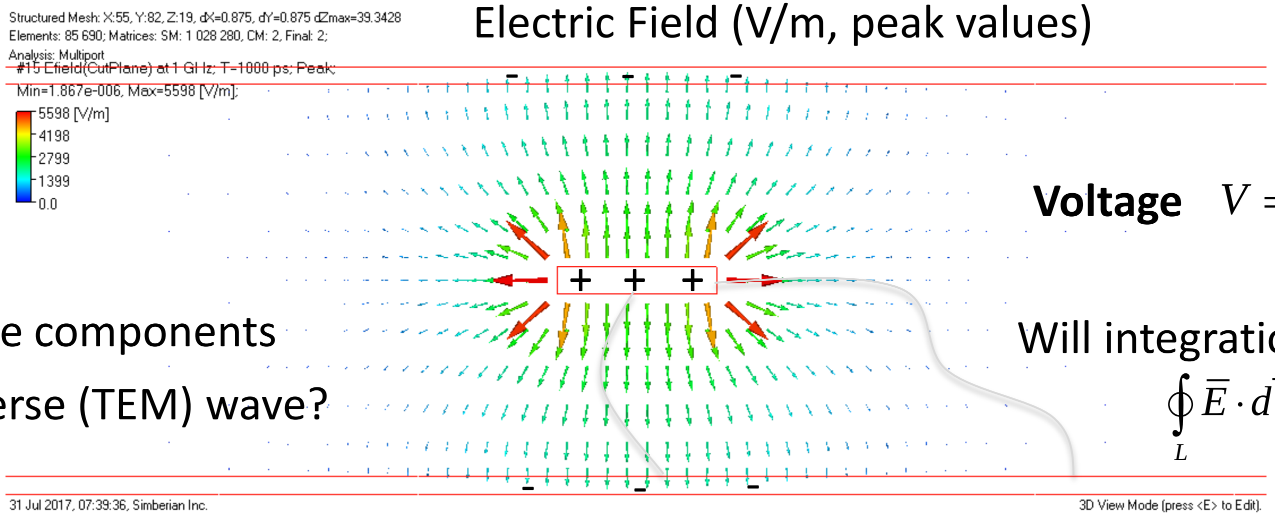
1 V, 50 Ohm

Modal and RLGC(f) parameters are extracted from the analysis of small segment in Simbeor for analysis of traces with arbitrary length

Example from demo-video #2016_03: **How Interconnects Work™**: EM field, current and power flow in strip line

Electric Field at 1 GHz

Electric Field (V/m, peak values)



Structured Mesh: X:55, Y:82, Z:19, dX=0.875, dY=0.875 dZmax=39.3428
Elements: 85 690; Matrices: SM: 1 028 280, CM: 2, Final: 2;
Analysis: Multiport
#15 Efield(CutPlane) at 1 GHz; T=1000 ps; Peak;
Min=1.867e-006, Max=5598 [V/m];

31 Jul 2017, 07:39:36, Simberian Inc.

$\overline{E}$

Transverse components

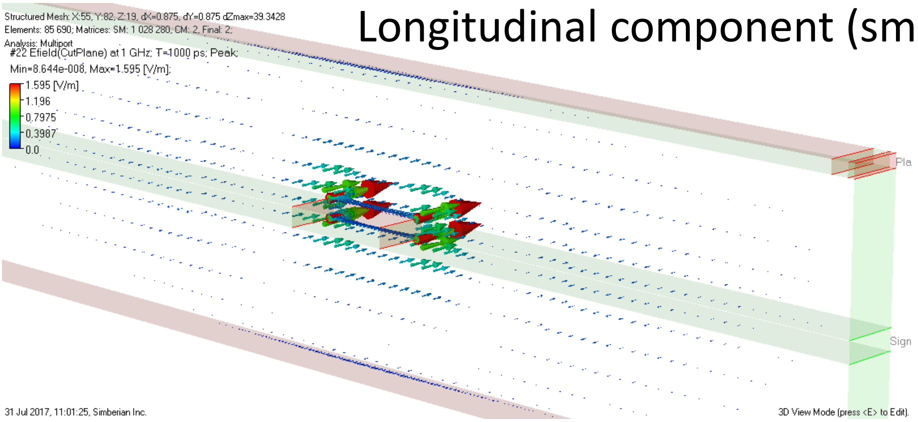
Is it transverse (TEM) wave?

Voltage $V = \int_{sig}^{ref} \overline{E} \cdot d\overline{l} \approx 0.5V$

Will integration path matter?

$$\oint_L \overline{E} \cdot d\overline{l} = -i\omega\mu \iint_S \overline{H} \cdot d\overline{s}$$

Longitudinal component (small)



Structured Mesh: X:55, Y:82, Z:19, dX=0.875, dY=0.875 dZmax=39.3428
Elements: 85 690; Matrices: SM: 1 028 280, CM: 2, Final: 2;
Analysis: Multiport
#22 Efield(CutPlane) at 1 GHz; T=1000 ps; Peak;
Min=8.644e-008, Max=1.595 [V/m];

31 Jul 2017, 11:01:25, Simberian Inc.

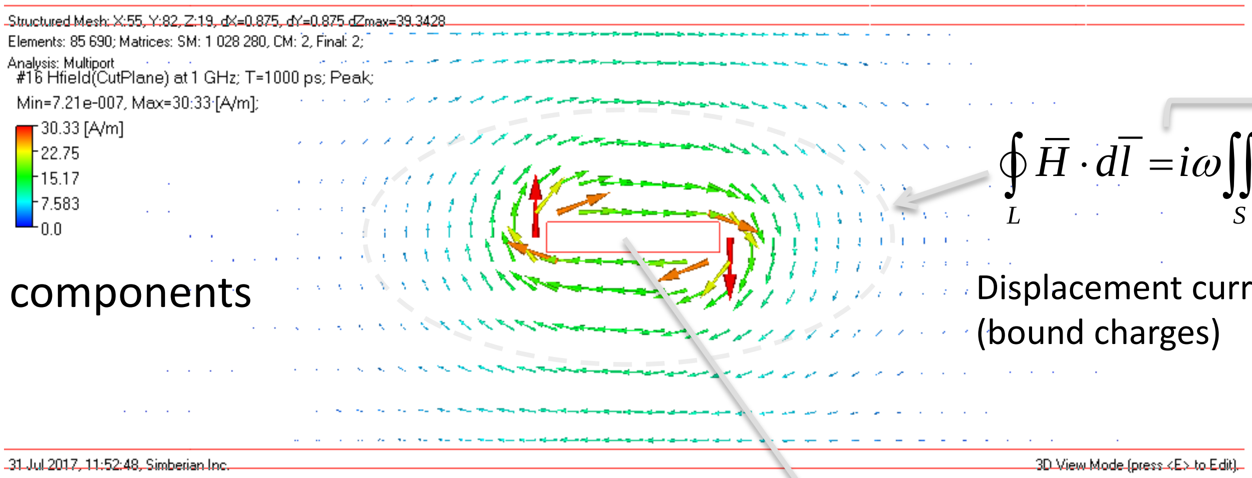
E_x

Hint: No longitudinal components only without losses in conductor and dielectric

Magnetic Field at 1 GHz

Magnetic Field (A/m, peak values)

$\overline{H}$



Structured Mesh: X:55, Y:82, Z:19, dX=0.875, dY=0.875 dZmax=39.3428
Elements: 85 690; Matrices: SM: 1 028 280, CM: 2, Final: 2;
Analysis: Multiport
#16 Hfield(CutPlane) at 1 GHz; T=1000 ps; Peak;
Min=7.21e-007, Max=30.33 [A/m];

Transverse components

Currents

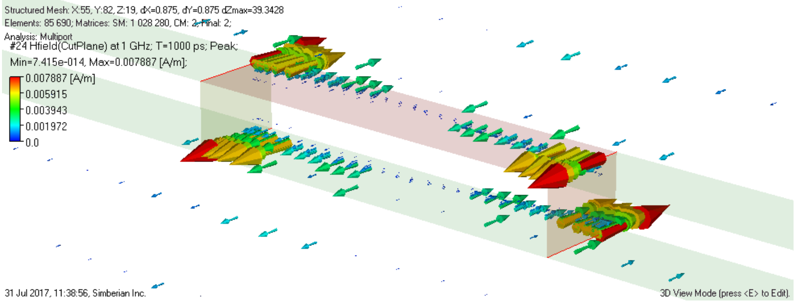
$$\oint_L \overline{H}\cdot d\overline{l} = \overbrace{i\omega\iint_S \overline{D}\cdot d\overline{s} + \iint_S \overline{J}_{free}\cdot d\overline{s}}^{\textbf{Currents}}$$

Displacement current (bound charges)

Conduction current (free charges)

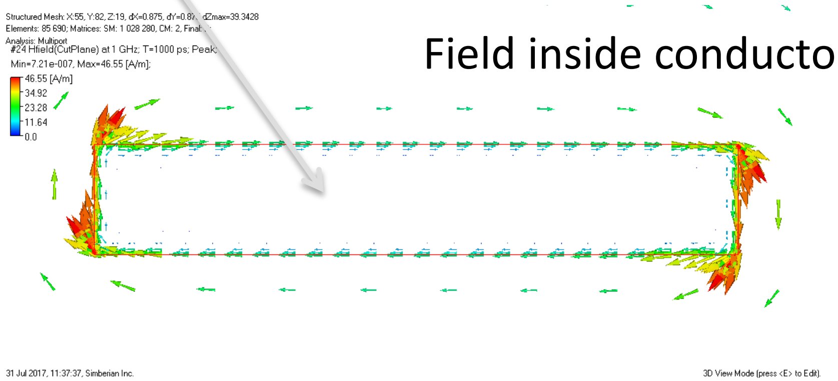
Longitudinal component (small)

H_x



Structured Mesh: X:55, Y:82, Z:19, dX=0.875, dY=0.875 dZmax=39.3428
Elements: 85 690; Matrices: SM: 1 028 280, CM: 2, Final: 2;
Analysis: Multiport
#24 Hfield(CutPlane) at 1 GHz; T=1000 ps; Peak;
Min=7.415e-014, Max=0.007887 [A/m];

$\overline{H}$



Structured Mesh: X:55, Y:82, Z:19, dX=0.875, dY=0.875 dZmax=39.3428
Elements: 85 690; Matrices: SM: 1 028 280, CM: 2, Final: 2;
Analysis: Multiport
#24 Hfield(CutPlane) at 1 GHz; T=1000 ps; Peak;
Min=7.21e-007, Max=46.55 [A/m];

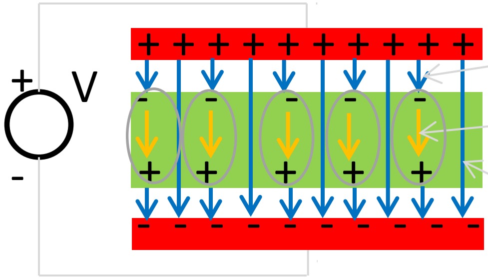
Field inside conductor

Currents in Ampere’s law

$$\oint_L \overline{H}\cdot d\overline{l} = i\omega\iint_S \overline{D}\cdot d\overline{s} + \iint_S \overline{J}_{free}\cdot d\overline{s}$$

Displacement in vacuum and polarization currents

$$\overline{D} = \varepsilon_0\overline{E} + \overline{P} \qquad \overline{P} = f\left(\overline{E},\overline{\mathrm{H}},\mathrm{T},\mathrm{F},\ldots\right)$$



$\overline{E}$ electric field in vacuum

$\overline{P}$ **polarization**

$\overline{E}_{dia}$ **smaller** electric field in dielectric

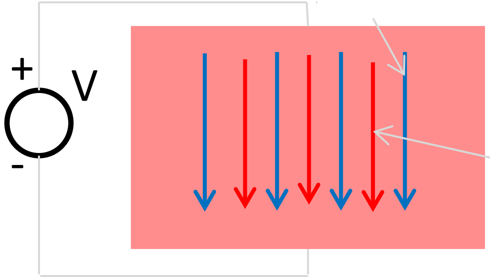
Polarization [Coulomb/m^2] is displacement of charges **bound to atoms**, molecules, lattices, boundaries,… described **by material (constitutive) equations** (LTI):

$$\overline{D} = \varepsilon_0\overline{E} + \overline{P} = \varepsilon_0\varepsilon(\omega)\overline{E}$$

Conduction current (A/m^2)

$$J_{free} = f\left(\overline{E},\mathrm{T},\ldots\right)$$

$\overline{E}$ electric field



J_{free} current

Translational motion of free charges in electric field described by the **Ohm’s law** (LTI):

$$J_{free} = \sigma\left(\omega\right)\overline{E}$$

σ - bulk conductivity, Siemens/m

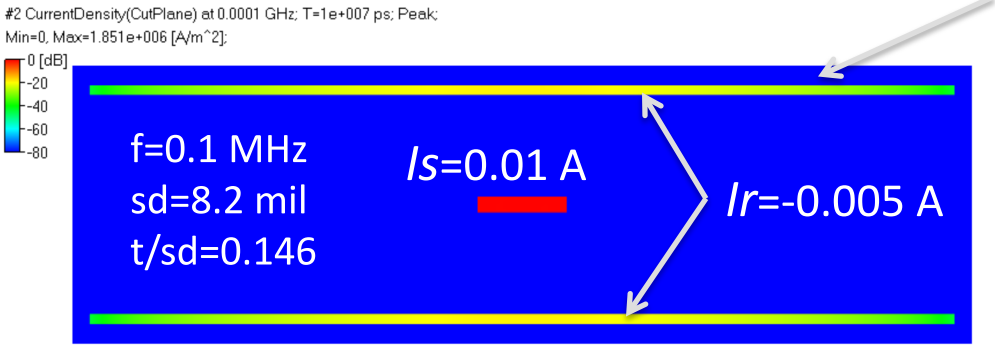
See more in the “Material World…” tutorial, DesignCon 2016 at www.simberian.com

Current density in strip line: current crowding

$$I = \iint_S \overline{J}_{free} \cdot d\overline{s}$$

Almost uniform distribution through thickness, both in planes and strip

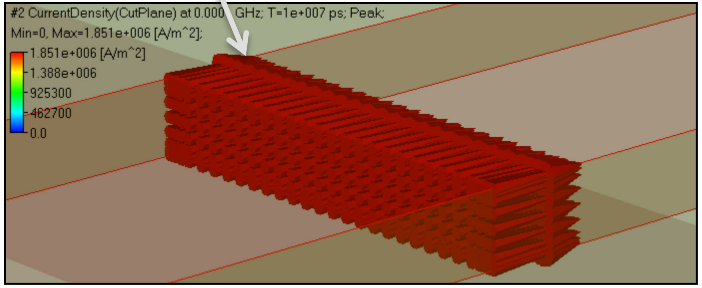
J_{dB}


#2 CurrentDensity(CutPlane) at 0.0001 GHz; T=1e+007 ps; Peak;
Min=0, Max=1.851e+006 [A/m^2];

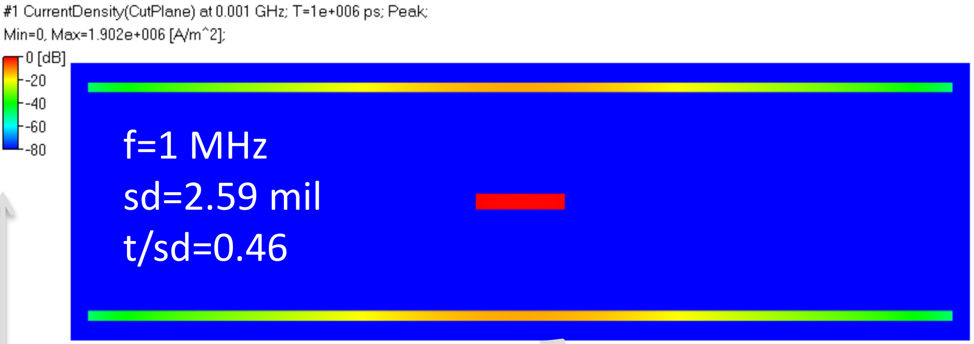
f=0.1 MHz
sd=8.2 mil
t/sd=0.146

Is=0.01 A

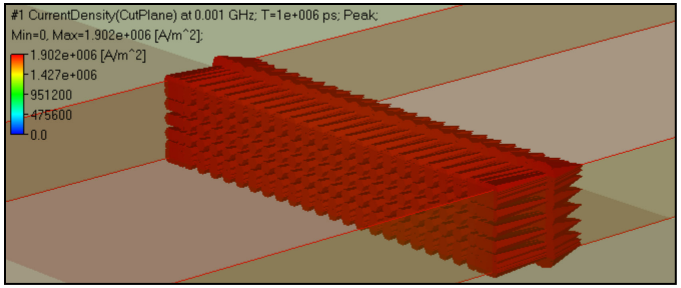
Ir=-0.005 A



J_{dB}


#1 CurrentDensity(CutPlane) at 0.001 GHz; T=1e+006 ps; Peak;
Min=0, Max=1.902e+006 [A/m^2];

f=1 MHz
sd=2.59 mil
t/sd=0.46



$$J_{dB} = 20 \cdot \log_{10}\left(\frac{|J|}{|J_{\max}|}\right) \ [dB]$$

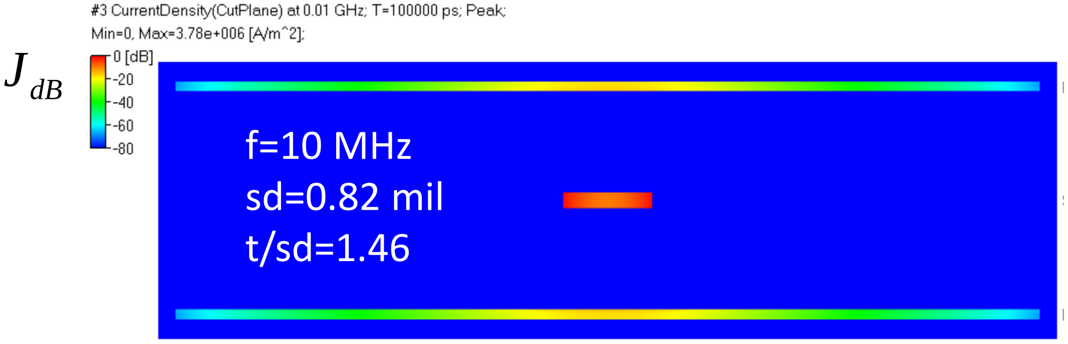
Concentration of current below the strip at higher frequency

Strip width 7 mil, t=1.2 mil, planes 0.77 mil; Peak values are shown; sd is skin depth;

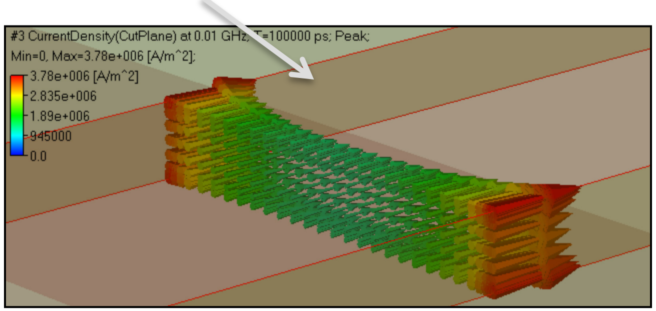
Current density in strip line: transition to skin-effect

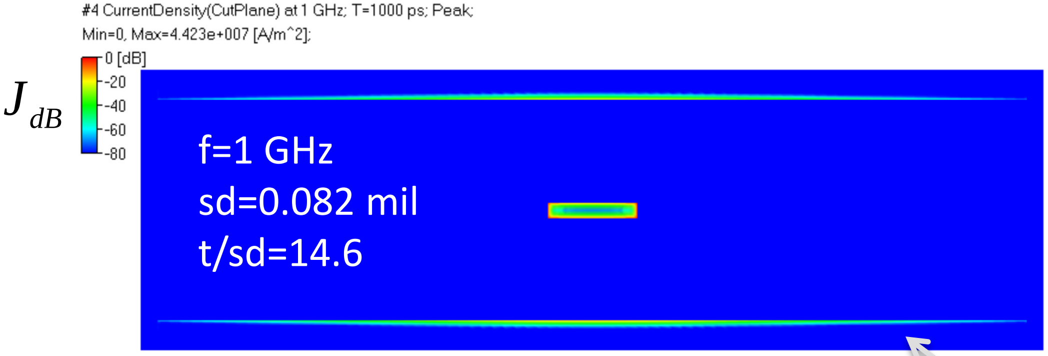
$$I = \iint_S \overline{J}_{free} \cdot d\overline{s}$$

Non-uniform current distribution - onset of the skin-effect in strip

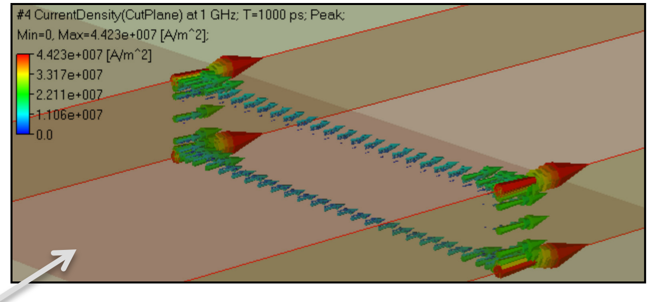


f=10 MHz
sd=0.82 mil
t/sd=1.46





f=1 GHz
sd=0.082 mil
t/sd=14.6



Strip width 7 mil, t=1.2 mil, planes 0.77 mil;
Peak values are shown; sd is skin depth;

Current flow in thin layer at 1 GHz (typical PCB)

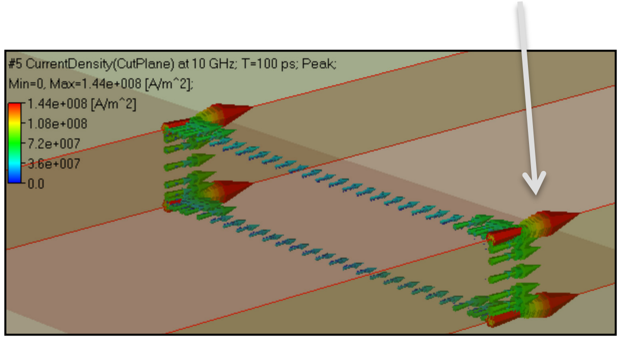
Current density in strip line: well-developed skin-effect

$$I = \iint_S \overline{J}_{free} \cdot d\overline{s}$$

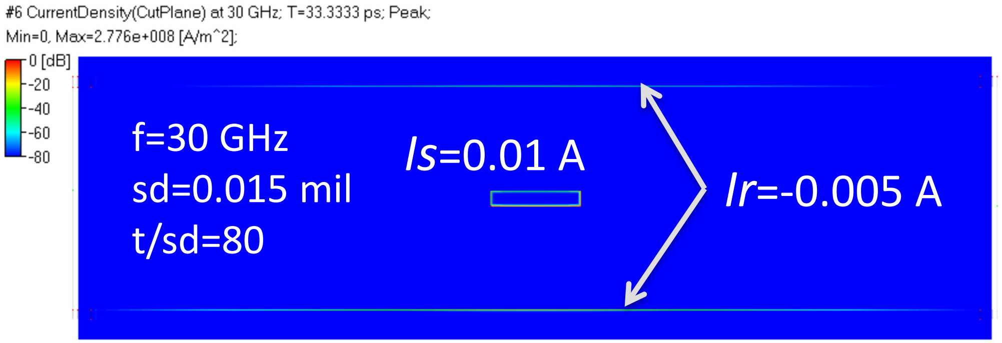
Current flow in very thin layer of conductor, higher currents at the edges

J_{dB}

f=10 GHz
sd=0.026 mil
t/sd=46.15



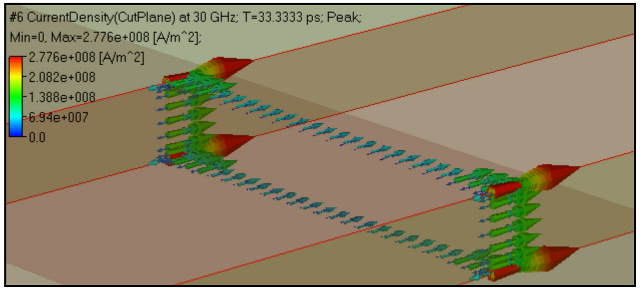
J_{dB}



f=30 GHz
sd=0.015 mil
t/sd=80

Is=0.01 A

Ir=-0.005 A

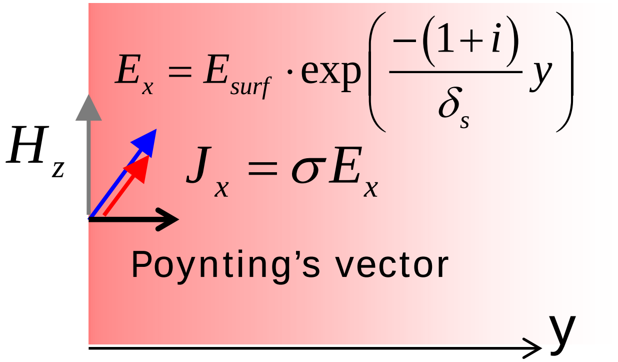


Maximal currents are at the edges – the edge singularity at high frequencies

Strip width 7 mil, t=1.2 mil, planes 0.77 mil;
Peak values are shown; sd is skin depth;

Skin depth and reversal of current

Plane-wave solution inside conductor

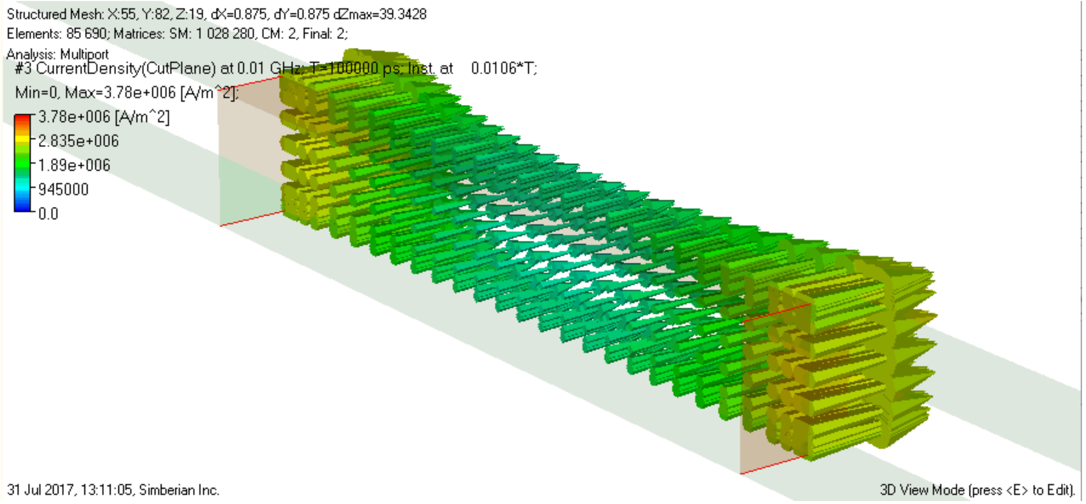


$$E_x = E_{surf} \cdot \exp\left(\frac{-(1+i)}{\delta_s} y\right)$$

$$J_x = \sigma E_x$$

$$\delta_s = \frac{1}{\sqrt{\pi f \mu \sigma}}$$ Skin depth

Current density in strip at 10 MHz (sd = 0.82 mil)

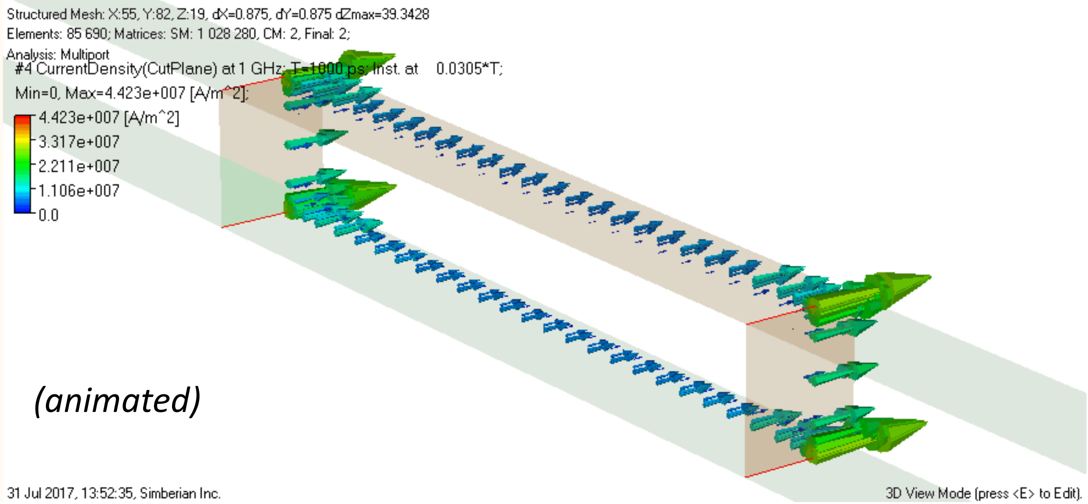


Structured Mesh: X:55, Y:82, Z:19, dX=0.875, dY=0.875 dZmax=39.3428
Elements: 85 690; Matrices: SM: 1 028 280, CM: 2, Final: 2;
Analysis: Multiport
#3 CurrentDensity(CutPlane) at 0.01 GHz; T=100000 ps; Inst. at 0.0106*T;
Min=0, Max=3.78e+006 [A/m^2];

31 Jul 2017, 13:11:05, Simberian Inc.

3D View Mode (press <E> to Edit).

Current density in strip at 1 GHz (sd = 0.082 mil)



Structured Mesh: X:55, Y:82, Z:19, dX=0.875, dY=0.875 dZmax=39.3428
Elements: 85 690; Matrices: SM: 1 028 280, CM: 2, Final: 2;
Analysis: Multiport
#4 CurrentDensity(CutPlane) at 1 GHz; T=1000 ps; Inst. at 0.0305*T;
Min=0, Max=4.423e+007 [A/m^2];

(animated)

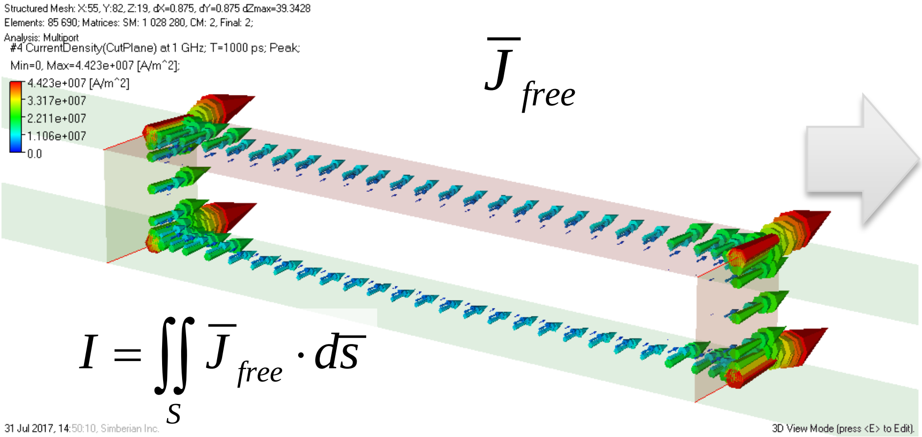
31 Jul 2017, 13:52:35, Simberian Inc.

3D View Mode (press <E> to Edit).

Surface current density

Current density (A/m^2)

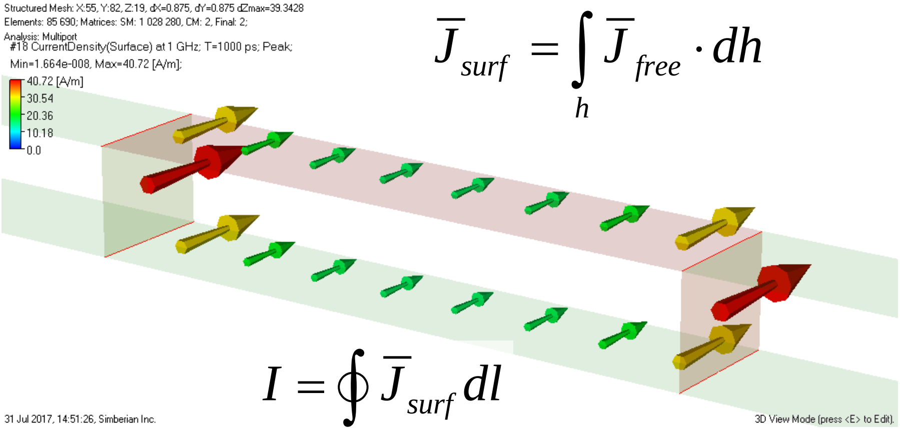
Surface current density (A/m)



```
Structured Mesh: X:55, Y:82, Z:19, dX=0.875, dY=0.875 dZmax=39.3428
Elements: 85 690; Matrices: SM: 1 028 280, CM: 2, Final: 2;
Analysis: Multiport
 #4 CurrentDensity(CutPlane) at 1 GHz; T=1000 ps; Peak;
 Min=0, Max=4.423e+007 [A/m^2];
31 Jul 2017, 14:50:10, Simberian Inc.
3D View Mode (press <E> to Edit).
```

$$\overline{J}_{free}$$

$$I = \iint_S \overline{J}_{free} \cdot d\overline{s}$$

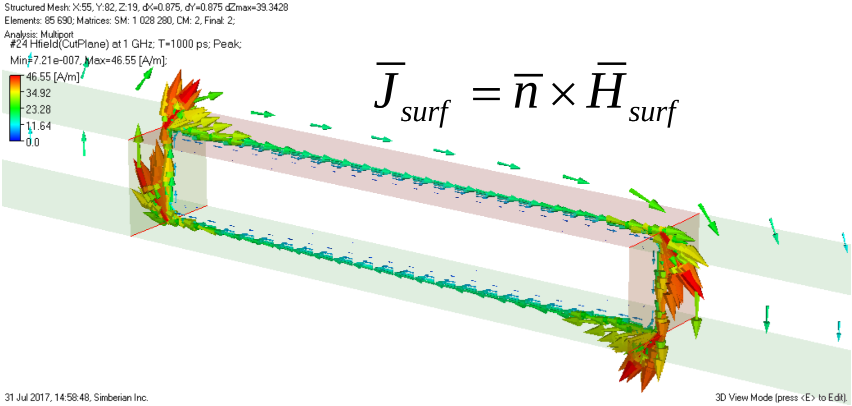


```
Structured Mesh: X:55, Y:82, Z:19, dX=0.875, dY=0.875 dZmax=39.3428
Elements: 85 690; Matrices: SM: 1 028 280, CM: 2, Final: 2;
Analysis: Multiport
 #18 CurrentDensity(Surface) at 1 GHz; T=1000 ps; Peak;
 Min=1.664e-008, Max=40.72 [A/m];
31 Jul 2017, 14:51:26, Simberian Inc.
3D View Mode (press <E> to Edit).
```

$$\overline{J}_{surf} = \int_h \overline{J}_{free} \cdot dh$$

$$I = \oint_L \overline{J}_{surf} dl$$

$$\overline{H}$$



```
Structured Mesh: X:55, Y:82, Z:19, dX=0.875, dY=0.875 dZmax=39.3428
Elements: 85 690; Matrices: SM: 1 028 280, CM: 2, Final: 2;
Analysis: Multiport
 #24 Hfield(CutPlane) at 1 GHz; T=1000 ps; Peak;
 Min=7.21e-007, Max=46.55 [A/m];
31 Jul 2017, 14:58:48, Simberian Inc.
3D View Mode (press <E> to Edit).
```

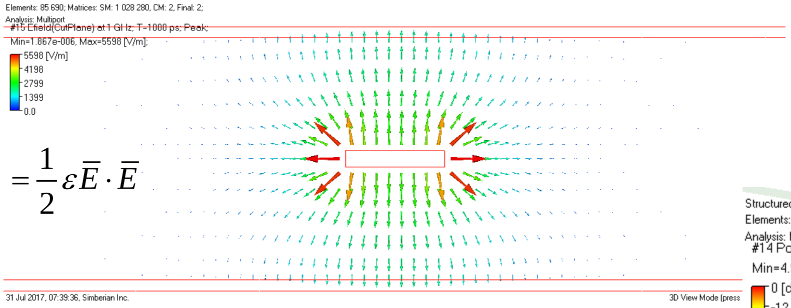
$$\overline{J}_{surf} = \overline{n} \times \overline{H}_{surf}$$

Magnetic field intensity -> current in circuit theory

Power flow density at 1 GHz

Poynting vector is energy passing through unit area in 1 sec

$\overline{E}$

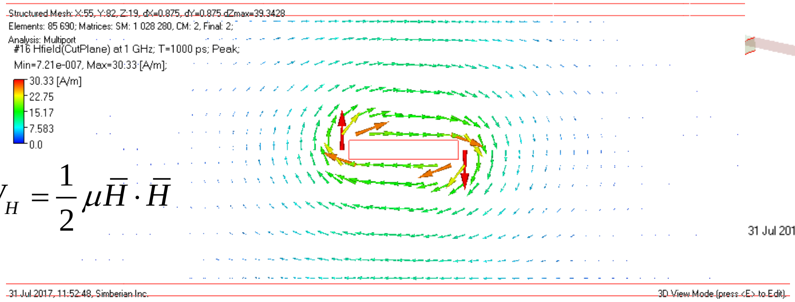


Structured Mesh: X:55, Y:82, Z:19, dX=0.875, dY=0.875 dZmax=39.3428
Elements: 85 690; Matrices: SM: 1 028 280, CM: 2, Final: 2;
Analysis: Multiport
#15 Efield(CutPlane) at 1 GHz; T=1000 ps; Peak;
Min=1.867e-006, Max=5598 [V/m];

$$W_E = \frac{1}{2}\varepsilon \overline{E}\cdot\overline{E}$$

$$\overline{P}_{flow} = \overline{E}\times\overline{H}$$ W/m^2

$\overline{H}$



Structured Mesh: X:55, Y:82, Z:19, dX=0.875, dY=0.875 dZmax=39.3428
Elements: 85 690; Matrices: SM: 1 028 280, CM: 2, Final: 2;
Analysis: Multiport
#16 Hfield(CutPlane) at 1 GHz; T=1000 ps; Peak;
Min=7.21e-007, Max=30.33 [A/m];

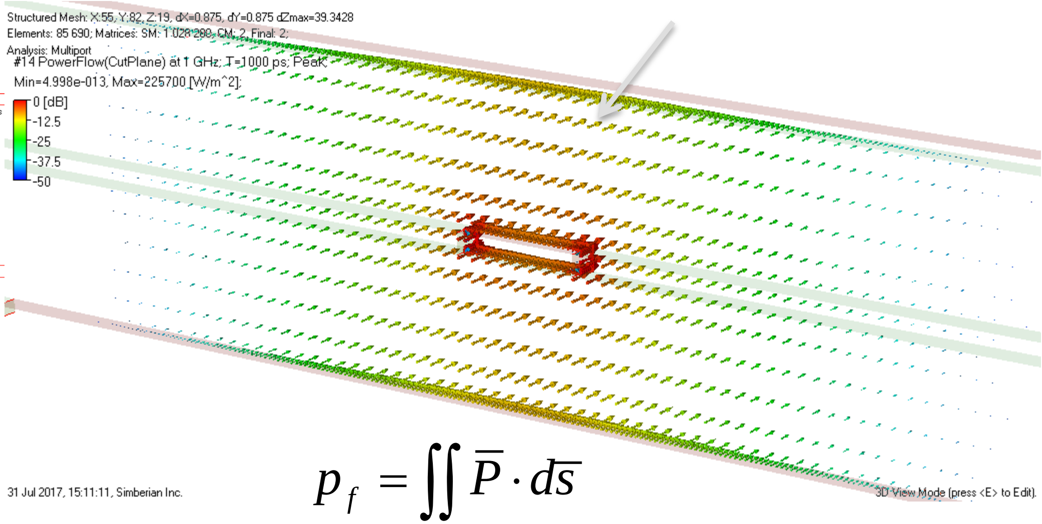
$$W_H = \frac{1}{2}\mu \overline{H}\cdot\overline{H}$$

$$\overline{P}_{average} = \frac{1}{2}\overline{E}\times\overline{H}^*$$

$$P_{dB} = 10\cdot\log_{10}\left(\frac{\left|P_{flow}\right|}{\left|P_{\max}\right|}\right)[dB]$$

Longitudinal component outside of conductors dominates

P_{dB}



Structured Mesh: X:55, Y:82, Z:19, dX=0.875, dY=0.875 dZmax=39.3428
Elements: 85 690; Matrices: SM: 1 028 280, CM: 2, Final: 2;
Analysis: Multiport
#14 PowerFlow(CutPlane) at 1 GHz; T=1000 ps; Peak;
Min=4.998e-013, Max=225700 [W/m^2];

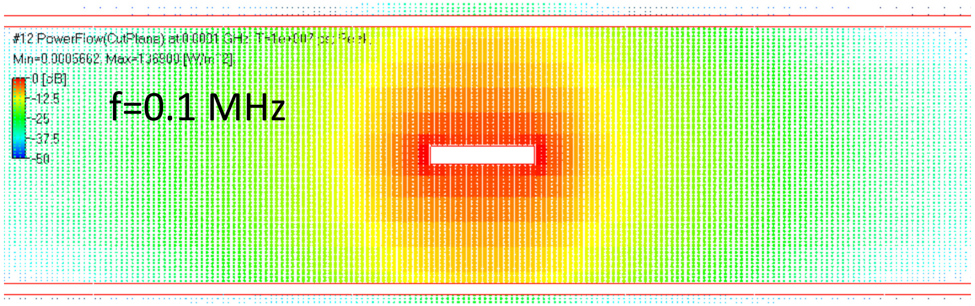
$$p_f = \iint_S \overline{P}\cdot d\overline{s}$$

$p_f = v\cdot i$ - circuit theory

Power flow in strip line

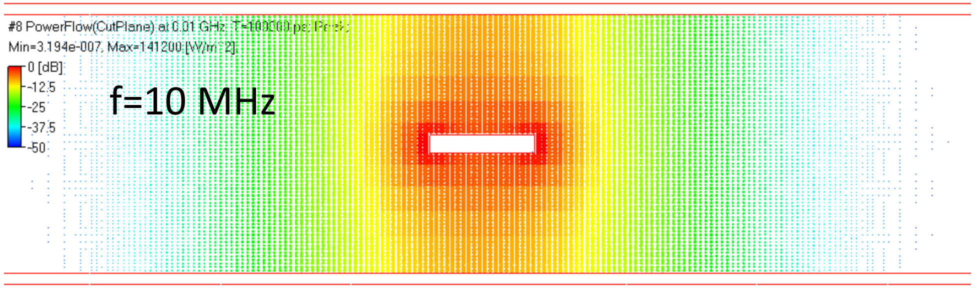
Peak value of power flow density [W/m^2]

$\overline{P}_{dB}$

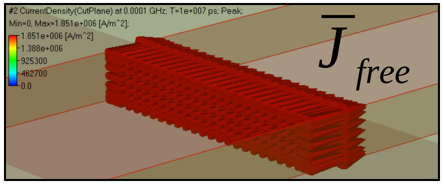


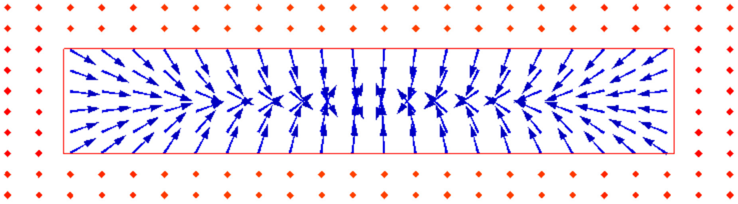
More power flows along the line closer to strip edges at higher frequency

$\overline{P}_{dB}$

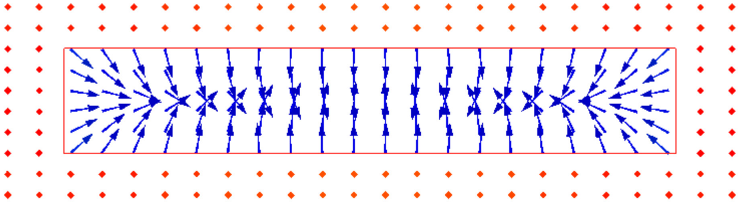


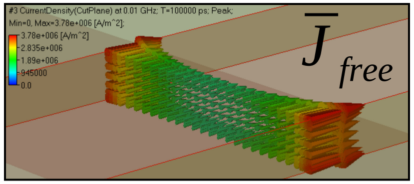
Conductor interior





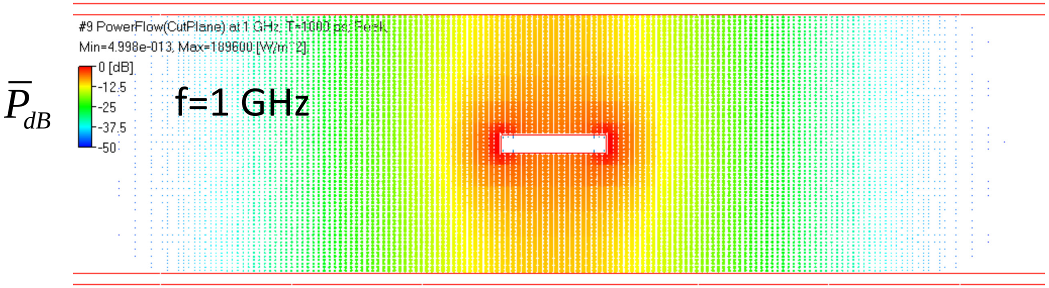
Conductor absorbs power



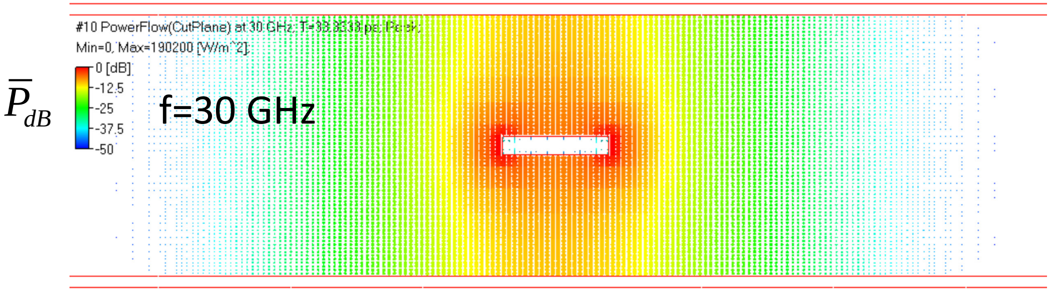


Power flow in strip line

Peak value of power flow density [W/m^2]

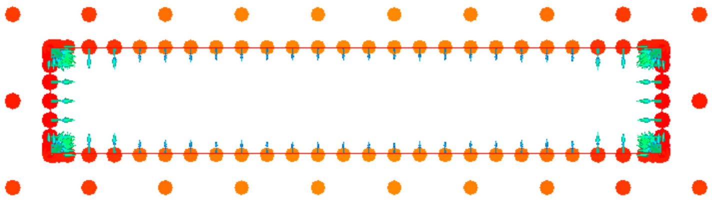


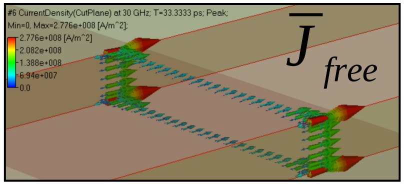
Power flow concentration near the strip edges continues as frequency rises



$$\oiint_S \overline{P}_{flow} \cdot d\overline{s} + \frac{d}{dt}\iiint_V (W_E + W_H) \cdot dv + \iiint_V P_d \cdot dv = 0$$

Conductor interior absorbs more power (30 GHz), scaled arrows in dB

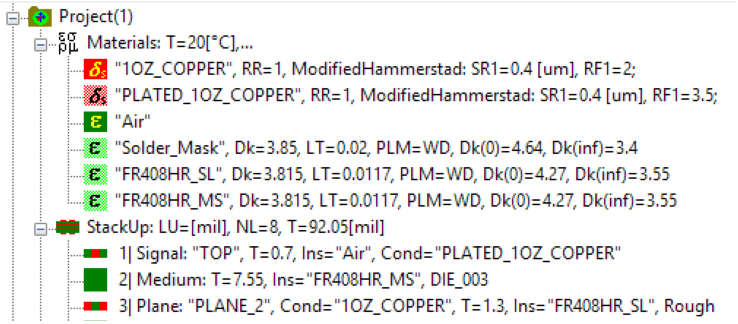




Energy passing through conductor boundary is absorbed by the conductor

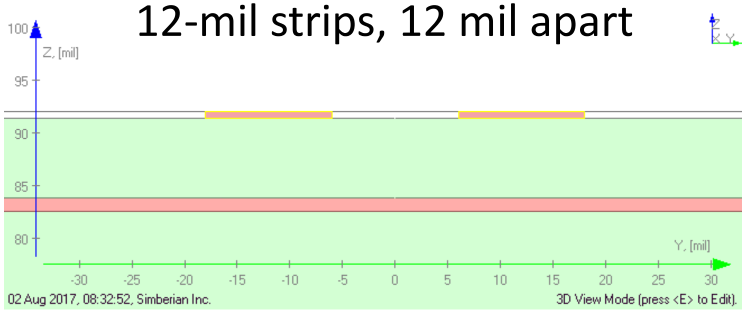
$$P_d = \sigma \overline{E} \cdot \overline{E}$$

Cross-talk in microstrips



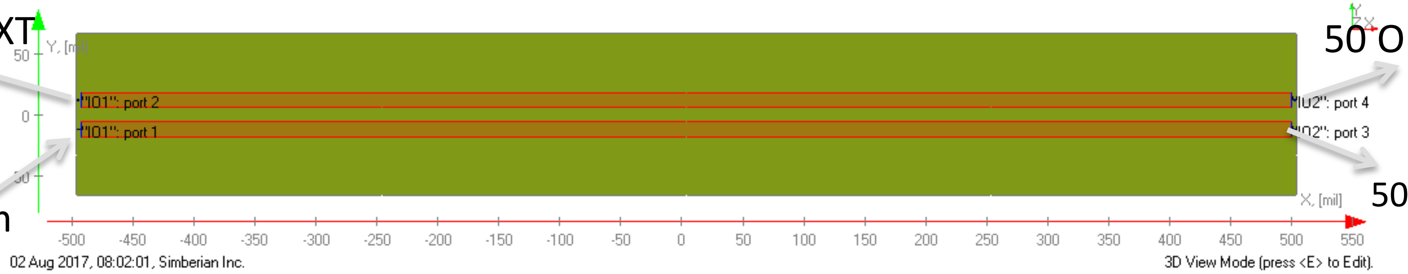
Project(1)
- Materials: T=20[°C],...
  - "1OZ_COPPER", RR=1, ModifiedHammerstad: SR1=0.4 [um], RF1=2;
  - "PLATED_1OZ_COPPER", RR=1, ModifiedHammerstad: SR1=0.4 [um], RF1=3.5;
  - "Air"
  - "Solder_Mask", Dk=3.85, LT=0.02, PLM=WD, Dk(0)=4.64, Dk(inf)=3.4
  - "FR408HR_SL", Dk=3.815, LT=0.0117, PLM=WD, Dk(0)=4.27, Dk(inf)=3.55
  - "FR408HR_MS", Dk=3.815, LT=0.0117, PLM=WD, Dk(0)=4.27, Dk(inf)=3.55
- StackUp: LU=[mil], NL=8, T=92.05[mil]
  - 1| Signal: "TOP", T=0.7, Ins="Air", Cond="PLATED_1OZ_COPPER"
  - 2| Medium: T=7.55, Ins="FR408HR_MS", DIE_003
  - 3| Plane: "PLANE_2", Cond="1OZ_COPPER", T=1.3, Ins="FR408HR_SL", Rough

12-mil strips, 12 mil apart



50 Ohm, NEXT

50 Ohm, FEXT



1 V, 50 Ohm

50 Ohm, Through

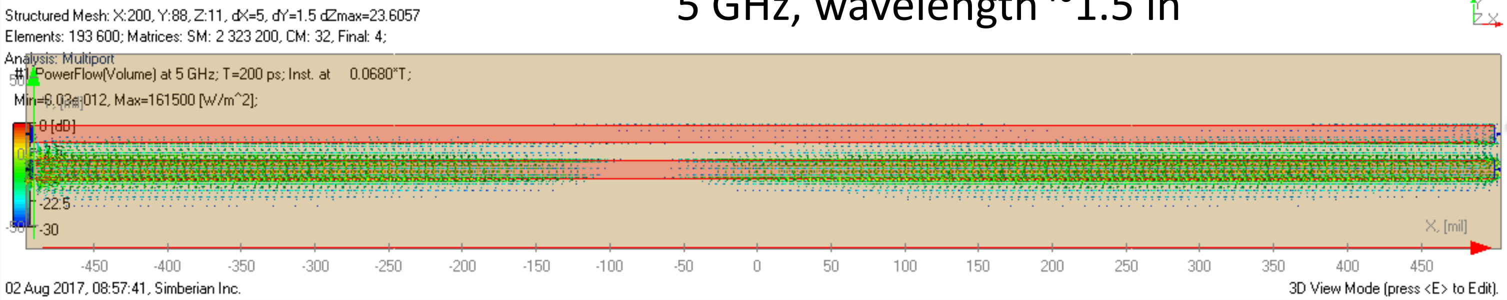
NEXT: Near-End Crosstalk

FEXT: Far-End Crosstalk

Power flow density in microstrips

5 GHz, wavelength ~1.5 in

$\overline{P}_{dB}$

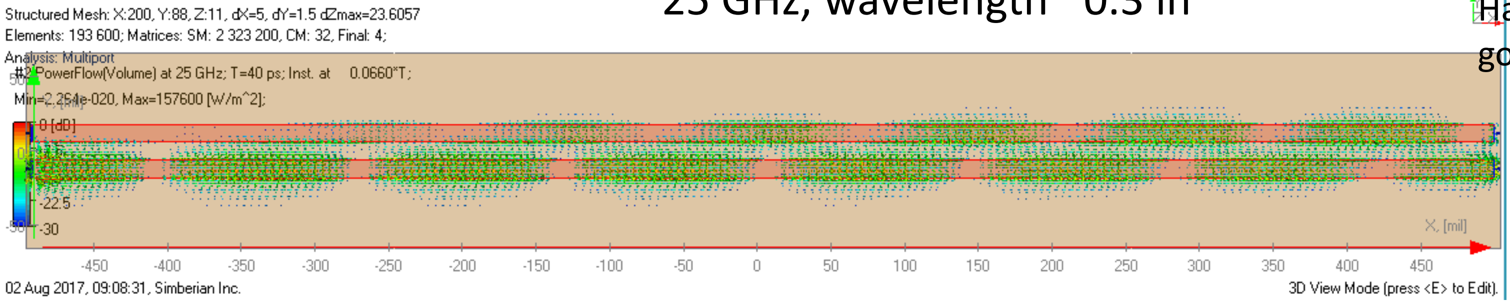


Structured Mesh: X:200, Y:88, Z:11, dX=5, dY=1.5 dZmax=23.6057
Elements: 193 600; Matrices: SM: 2 323 200, CM: 32, Final: 4;
Analysis: Multiport
#1 PowerFlow(Volume) at 5 GHz; T=200 ps; Inst. at 0.0680*T;
Min=6.03e-012, Max=161500 [W/m^2];
02 Aug 2017, 08:57:41, Simberian Inc.
3D View Mode (press <E> to Edit).

Small FEXT

25 GHz, wavelength ~0.3 in

$\overline{P}_{dB}$

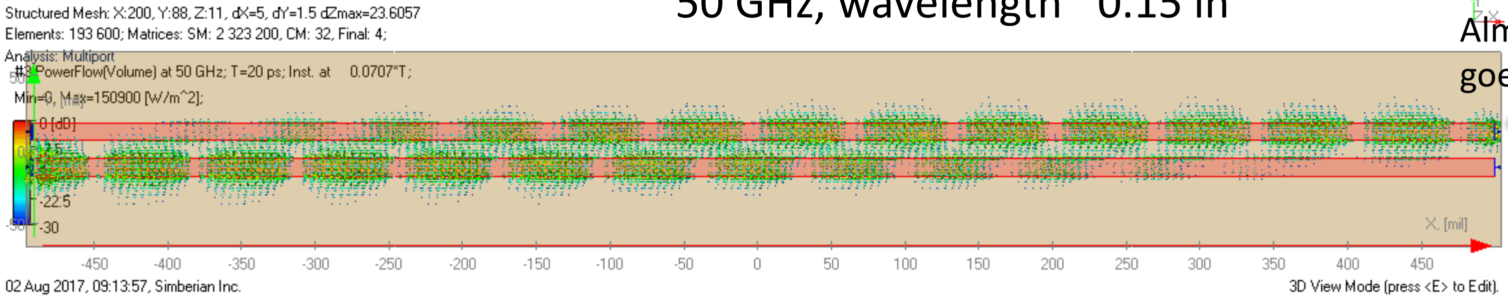


Structured Mesh: X:200, Y:88, Z:11, dX=5, dY=1.5 dZmax=23.6057
Elements: 193 600; Matrices: SM: 2 323 200, CM: 32, Final: 4;
Analysis: Multiport
#2 PowerFlow(Volume) at 25 GHz; T=40 ps; Inst. at 0.0660*T;
Min=2.264e-020, Max=157600 [W/m^2];
02 Aug 2017, 09:08:31, Simberian Inc.
3D View Mode (press <E> to Edit).

Half of power goes into FEXT

50 GHz, wavelength ~0.15 in

$\overline{P}_{dB}$



Structured Mesh: X:200, Y:88, Z:11, dX=5, dY=1.5 dZmax=23.6057
Elements: 193 600; Matrices: SM: 2 323 200, CM: 32, Final: 4;
Analysis: Multiport
#3 PowerFlow(Volume) at 50 GHz; T=20 ps; Inst. at 0.0707*T;
Min=0, Max=150900 [W/m^2];
02 Aug 2017, 09:13:57, Simberian Inc.
3D View Mode (press <E> to Edit).

Almost all power goes into FEXT

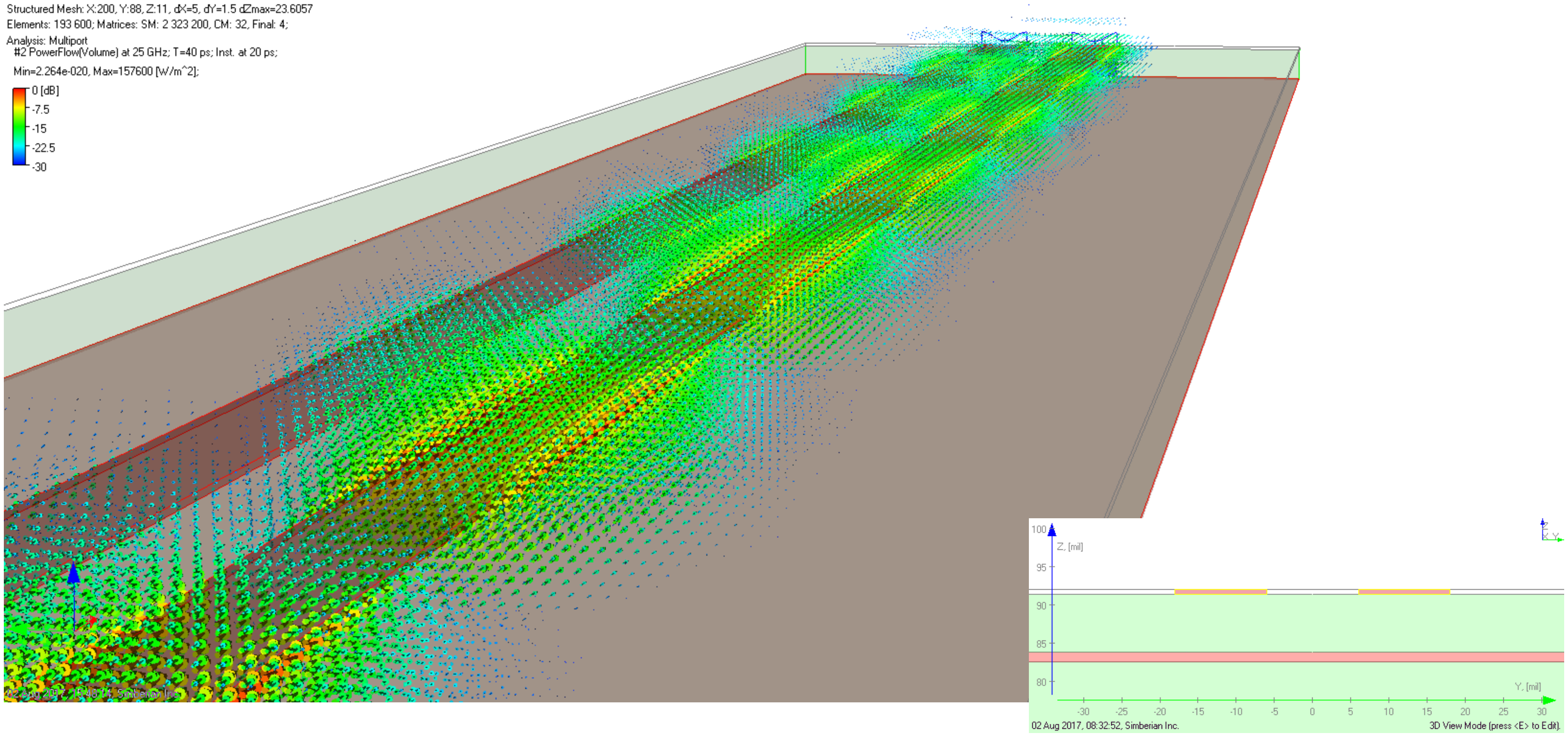
What if segment length is 5 inch? *(animated)*

Power flow density in microstrip

25 GHz, wavelength ~0.3 in

Instantaneous at 20 ps

$\overline{P}_{dB}$



Structured Mesh: X:200, Y:88, Z:11, dX=5, dY=1.5 dZmax=23.6057
Elements: 193 600; Matrices: SM: 2 323 200, CM: 32, Final: 4;
Analysis: Multiport
#2 PowerFlow(Volume) at 25 GHz; T=40 ps; Inst. at 20 ps;
Min=2.264e-020, Max=157600 [W/m^2];

02 Aug 2017, 08:32:52, Simberian Inc.

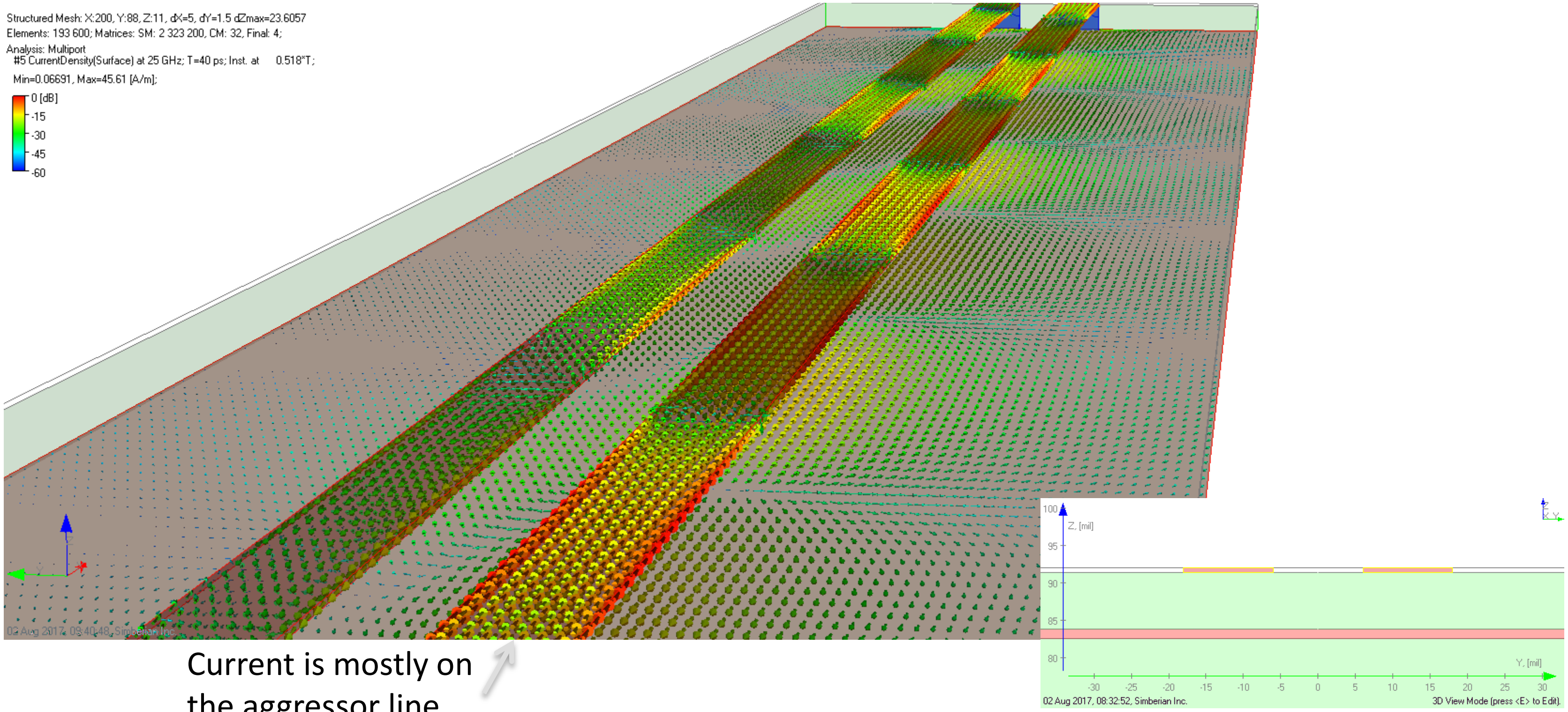
3D View Mode (press <E> to Edit).

Surface current density in microstrip

25 GHz, wavelength ~0.3 in
Instantaneous at 20 ps

Almost identical currents
in opposite directions

$\overline{J}_{surf}, dB$



Structured Mesh: X:200, Y:88, Z:11, dX=5, dY=1.5 dZmax=23.6057
Elements: 193 600; Matrices: SM: 2 323 200, CM: 32, Final: 4;
Analysis: Multiport
#5 CurrentDensity(Surface) at 25 GHz; T=40 ps; Inst. at 0.518*T;
Min=0.06691, Max=45.61 [A/m];

02 Aug 2017, 08:40:48, Simberian Inc.

02 Aug 2017, 08:32:52, Simberian Inc.

3D View Mode (press <E> to Edit).

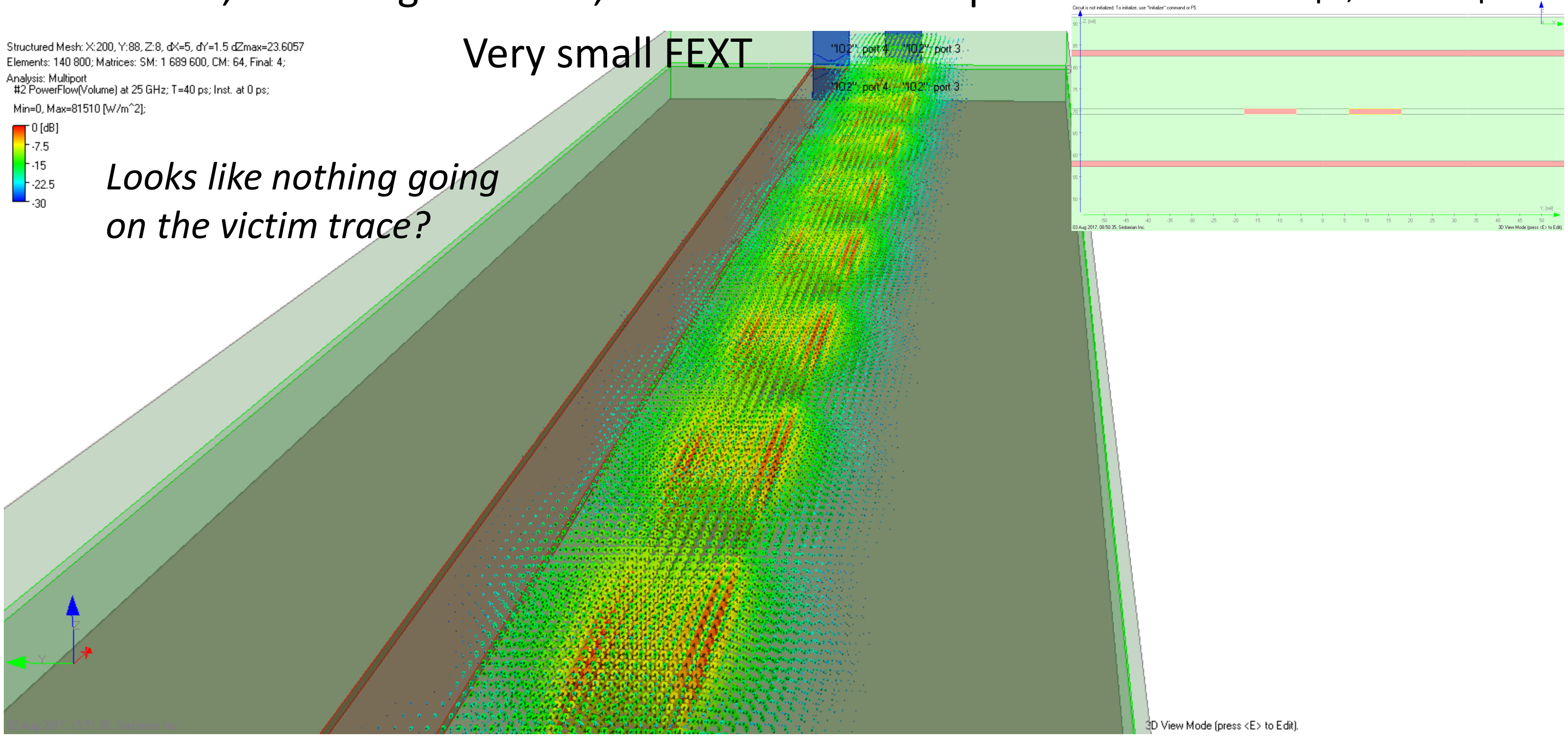
Current is mostly on
the aggressor line

See more at demo-video #2016_11: **How Interconnects Work™**: Crosstalk power flow in microstrip lines

Power flow density at strip lines

25 GHz, wavelength ~0.3 in, Instantaneous at 0 ps

12-mil strips, 12 mil apart



Structured Mesh: X:200, Y:88, Z:8, dX=5, dY=1.5 dZmax=23.6057
Elements: 140 800; Matrices: SM: 1 689 600, CM: 64, Final: 4;
Analysis: Multiport
#2 PowerFlow(Volume) at 25 GHz; T=40 ps; Inst. at 0 ps;
Min=0, Max=81510 [W/m^2];

Circuit is not initialized. To initialize, use "Initialize" command or F5.

03 Aug 2017, 08:50:35, Simberian Inc.

3D View Mode (press <E> to Edit).

$\overline{P}_{dB}$

Very small FEXT

Looks like nothing going on the victim trace?

Very small NEXT

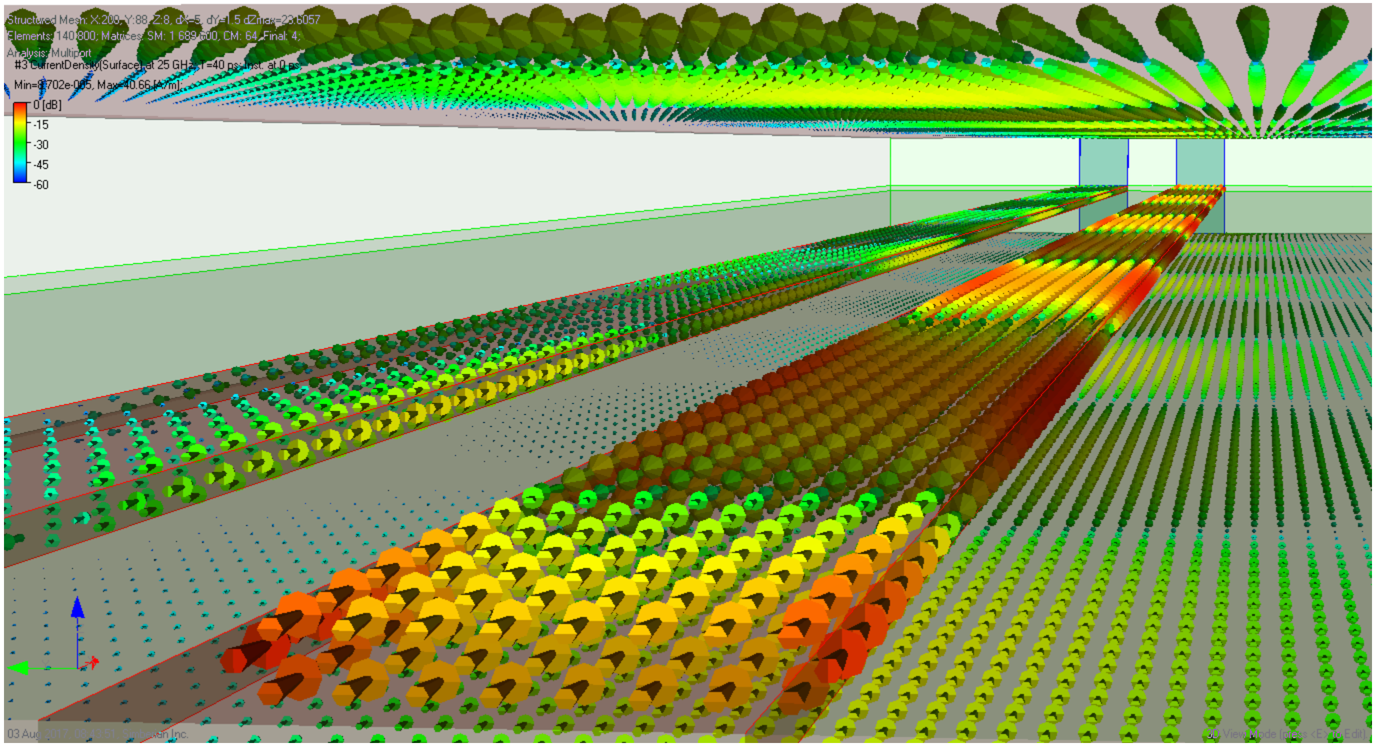
1 V, 50 Ohm

See more at demo-video #2016_11: **How Interconnects Work™**: Crosstalk power flow in microstrip lines

Surface current density in strip lines

25 GHz, wavelength ~0.3 in, Instantaneous at 0 ps

$\overline{J}_{surf}$, dB



```
Structured Mesh: X:200, Y:88, Z:8, dX=5, dY=1.5 dZmax=23.6057
Elements: 140 800; Matrices: SM: 1 689 600, CM: 64, Final: 4;
Analysis: Multiport
#3 CurrentDensity(Surface) at 25 GHz; T=40 ps; Inst. at 0 ps;
Min=8.702e-005, Max=40.66 [A/m];
```

1 V, 50 Ohm

Hint: superposition of even and odd modes

See more at demo-video #2016_11: **How Interconnects Work™**: Crosstalk power flow in microstrip lines

Cross-talk in differential vias

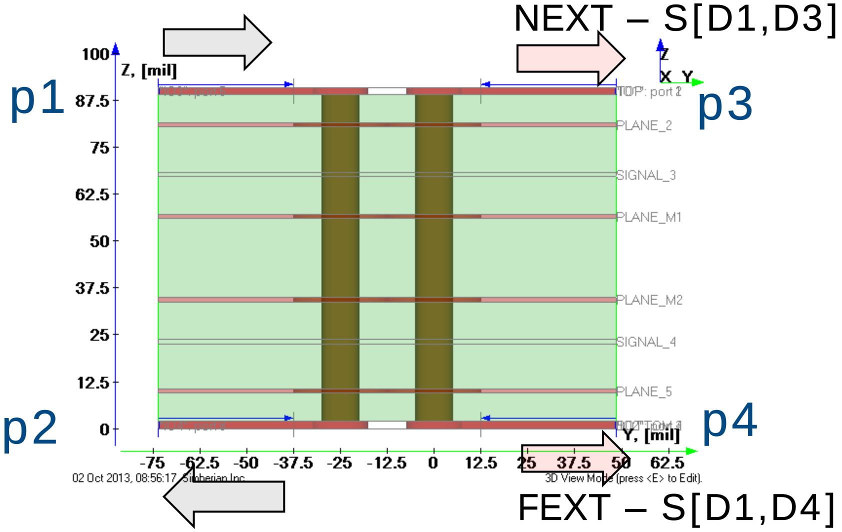
Two coupled differential vias in a 120 x 120 mil area caged with PEC wall

Vias are 30 mil apart, antipad 25x55 mil, traces 8 mil MSL, 8 mil separation;

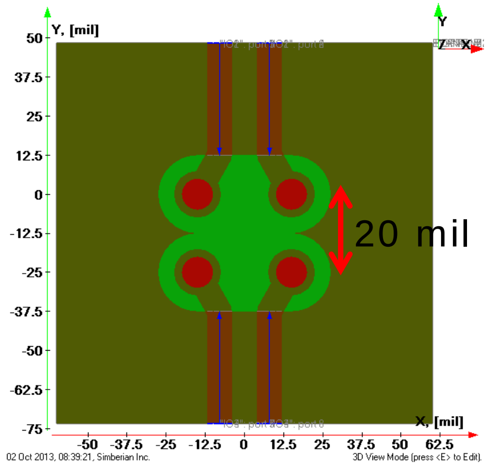
The first cage resonance is at about 12 GHz (half wavelength in dielectric)

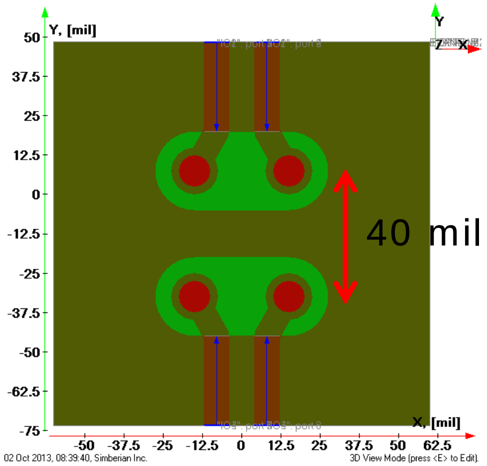
Stackup from CMP-28 board, Wild River Technology http://wildrivertech.com

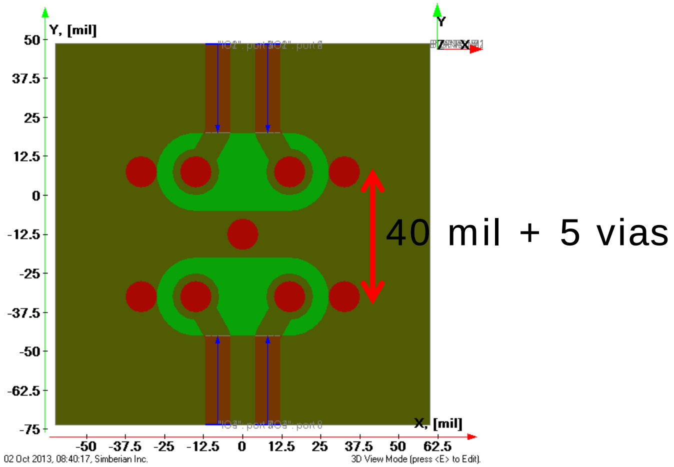
See more at App Note #2013_06 at http://www.simberian.com/AppNotes.php



Three cases:

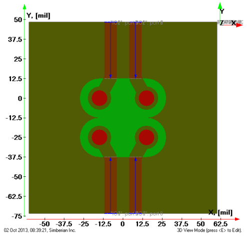




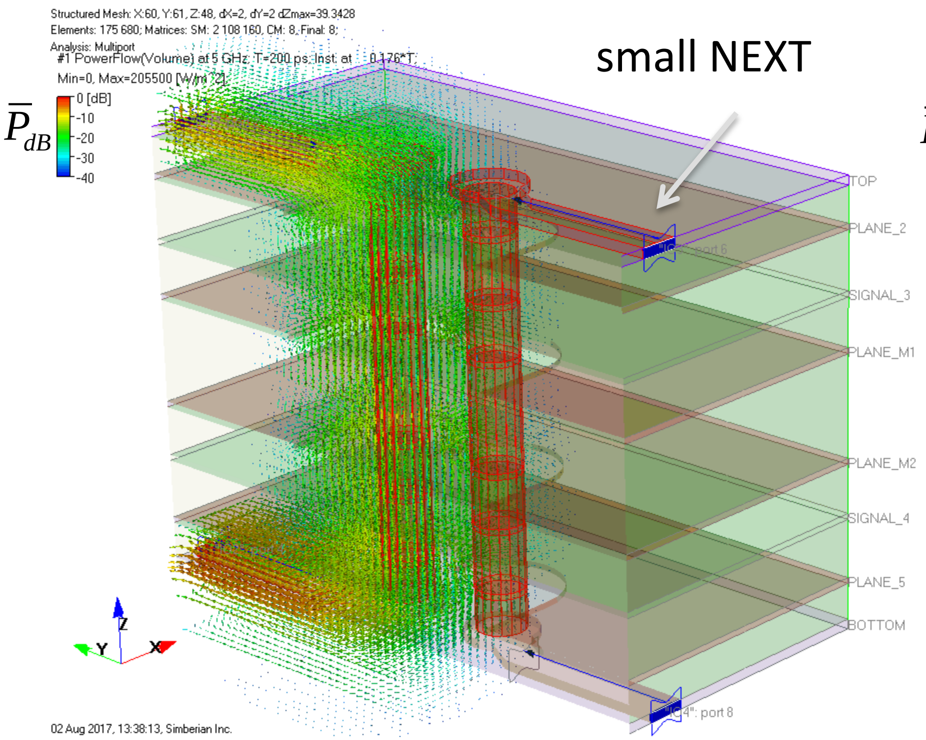


Power flow density in closely spaced differential vias

(animated)



5 GHz

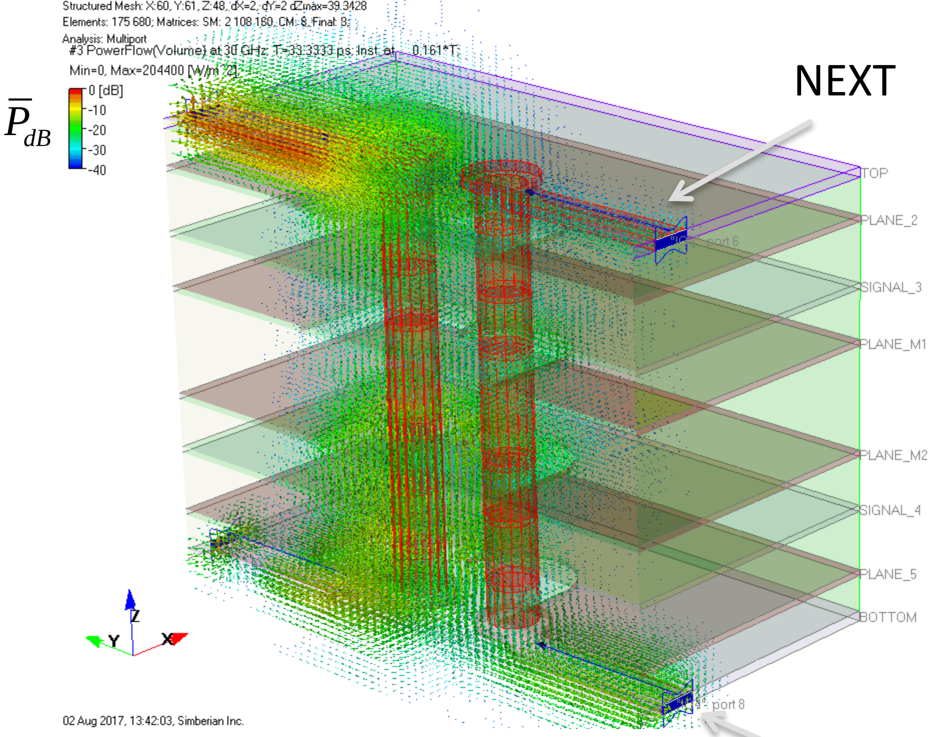


Structured Mesh: X:60, Y:61, Z:48, dX=2, dY=2 dZmax=39.3428
Elements: 175 680; Matrices: SM: 2 108 160, CM: 8, Final: 8;
Analysis: Multiport
#1 PowerFlow(Volume) at 5 GHz, T=200 ps, Inst. at 0.176*T;
Min=0, Max=205500 [W/m^2]

02 Aug 2017, 13:38:13, Simberian Inc.

small NEXT

30 GHz



Structured Mesh: X:60, Y:61, Z:48, dX=2, dY=2 dZmax=39.3428
Elements: 175 680; Matrices: SM: 2 108 160, CM: 8, Final: 8;
Analysis: Multiport
#3 PowerFlow(Volume) at 30 GHz, T=33.3333 ps, Inst. at 0.161*T;
Min=0, Max=204400 [W/m^2]

02 Aug 2017, 13:42:03, Simberian Inc.

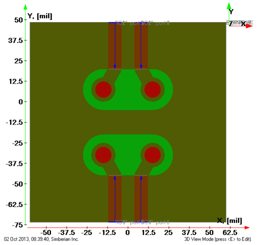
NEXT

FEXT

Differential excitation, half of the structure is shown

Power flow density in 40-mil separated differential vias

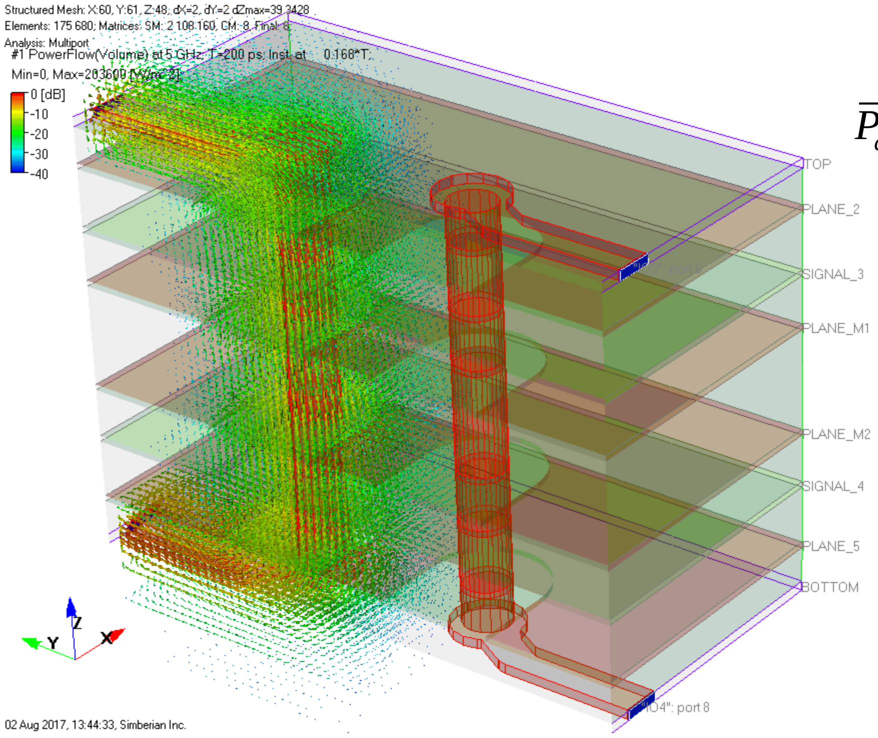
(animated)



5 GHz

30 GHz

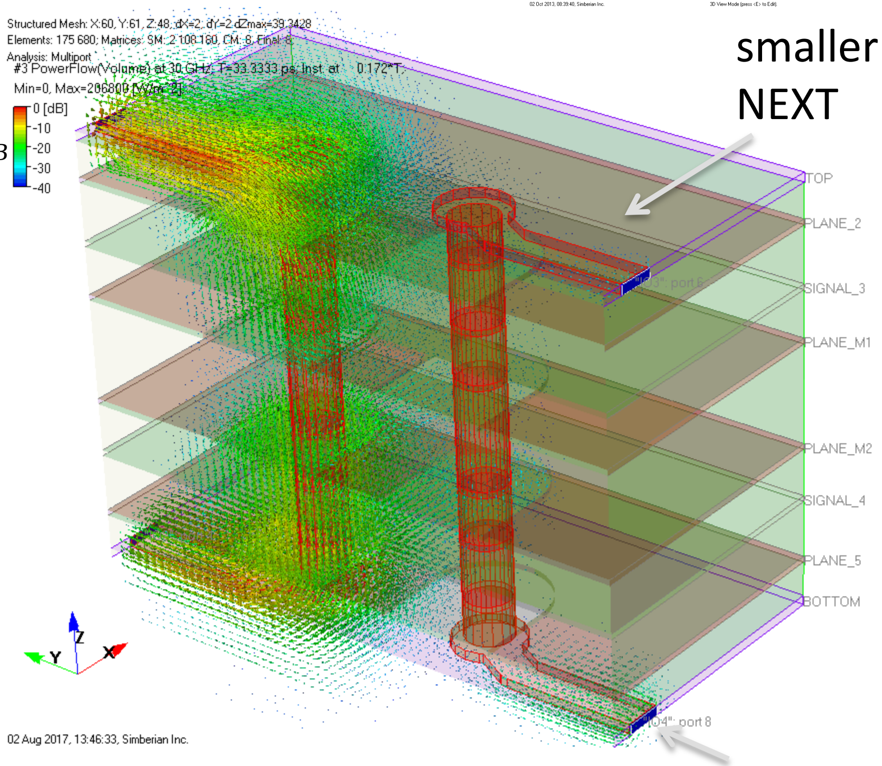
$\overline{P}_{dB}$



Structured Mesh: X:60, Y:61, Z:48, dX=2, dY=2 dZmax=39.3428
Elements: 175 680; Matrices: SM: 2 108 160, CM: 8, Final: 8;
Analysis: Multiport
#1 PowerFlow(Volume) at 5 GHz; T=200 ps; Inst. at 0.168*T;
Min=0, Max=203600 [W/m^2];

02 Aug 2017, 13:44:33, Simberian Inc.

$\overline{P}_{dB}$



Structured Mesh: X:60, Y:61, Z:48, dX=2, dY=2 dZmax=39.3428
Elements: 175 680; Matrices: SM: 2 108 160, CM: 8, Final: 8;
Analysis: Multiport
#3 PowerFlow(Volume) at 30 GHz; T=33.3333 ps; Inst. at 0.172*T;
Min=0, Max=206800 [W/m^2];

02 Aug 2017, 13:46:33, Simberian Inc.

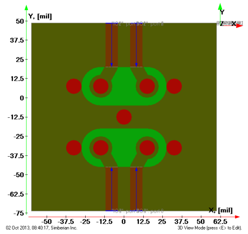
smaller NEXT

smaller FEXT

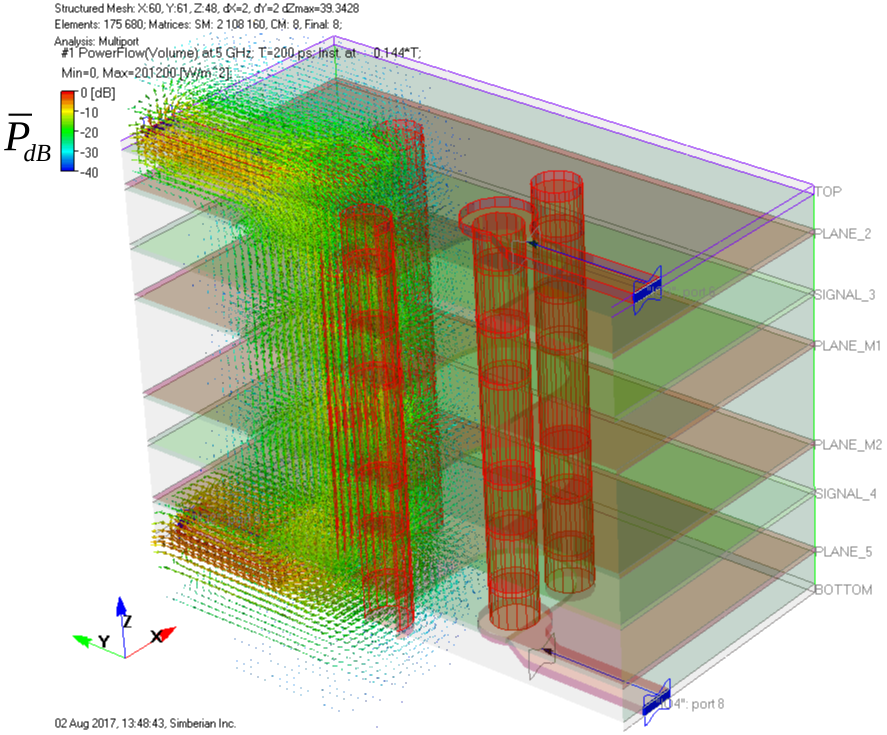
Differential excitation, half of the structure is shown

Power flow density in differential vias with stitching vias

(animated)



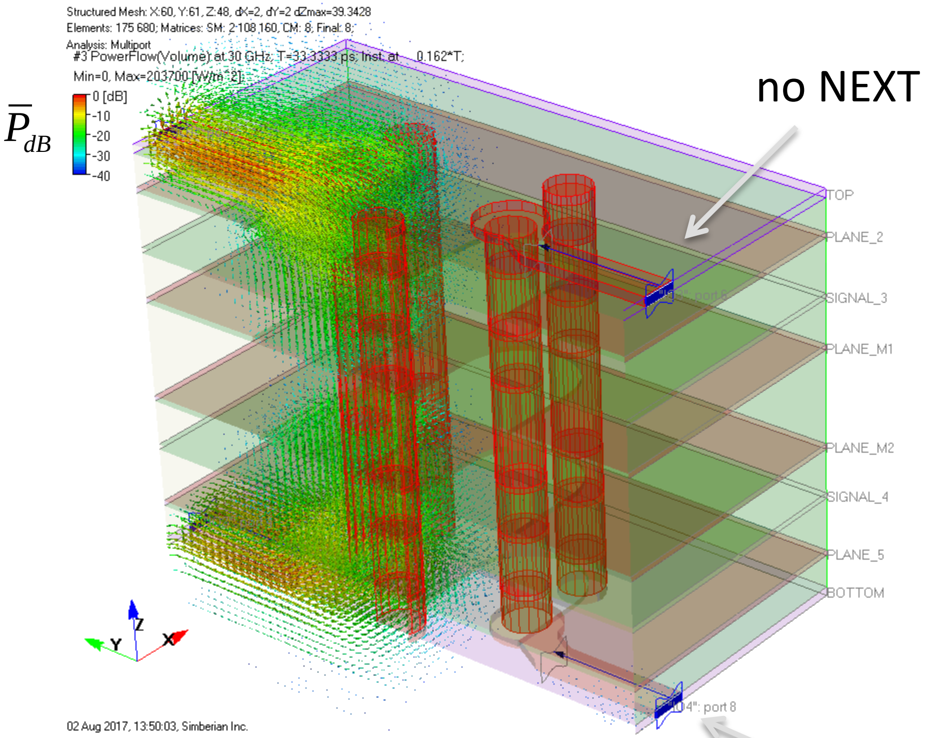
5 GHz



Structured Mesh: X:60, Y:61, Z:48, dX=2, dY=2 dZmax=39.3428
Elements: 175 680; Matrices: SM: 2 108 160, CM: 8, Final: 8;
Analysis: Multiport
#1 PowerFlow(Volume) at 5 GHz; T=200 ps; Inst. at 0.144*T;
Min=0, Max=201200 [W/m^2];

02 Aug 2017, 13:48:43, Simberian Inc.

30 GHz



Structured Mesh: X:60, Y:61, Z:48, dX=2, dY=2 dZmax=39.3428
Elements: 175 680; Matrices: SM: 2 108 160, CM: 8, Final: 8;
Analysis: Multiport
#3 PowerFlow(Volume) at 30 GHz; T=33.3333 ps; Inst. at 0.162*T;
Min=0, Max=203700 [W/m^2];

02 Aug 2017, 13:50:03, Simberian Inc.

no NEXT

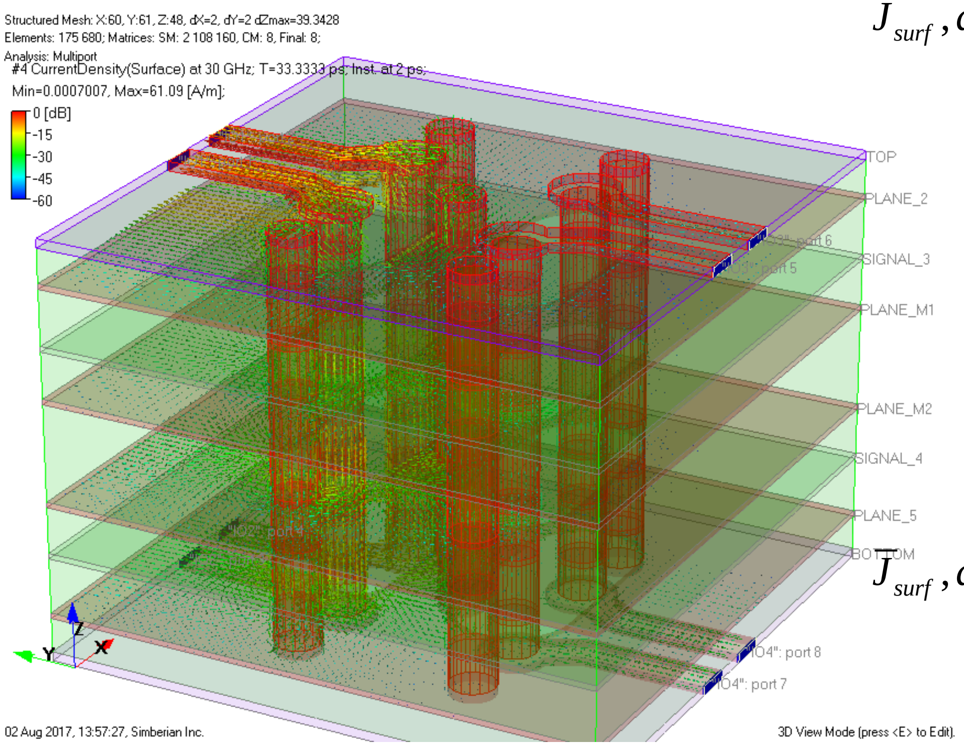
Very small FEXT

Differential excitation, half of the structure is shown

Surface current density on planes and vias

Instantaneous current density at 30 GHz, t=2ps

$\overline{J}_{surf}, dB$

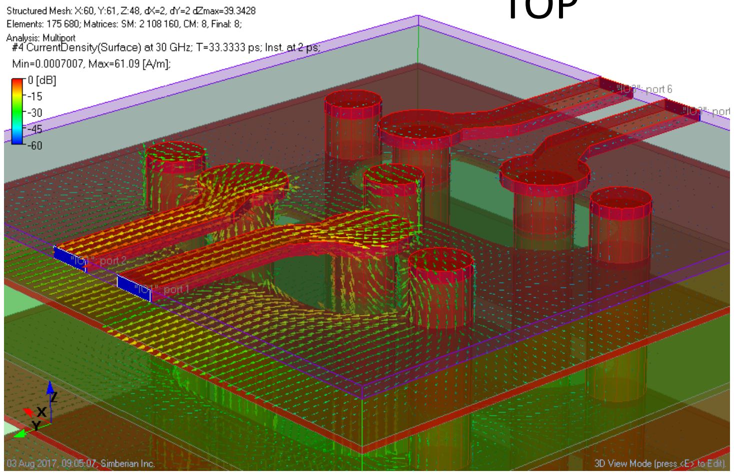


Structured Mesh: X:60, Y:61, Z:48, dX=2, dY=2 dZmax=39.3428
Elements: 175 680; Matrices: SM: 2 108 160, CM: 8, Final: 8;
Analysis: Multiport
#4 CurrentDensity(Surface) at 30 GHz; T=33.3333 ps; Inst. at 2 ps;
Min=0.0007007, Max=61.09 [A/m];

02 Aug 2017, 13:57:27, Simberian Inc.
3D View Mode (press <E> to Edit).

TOP

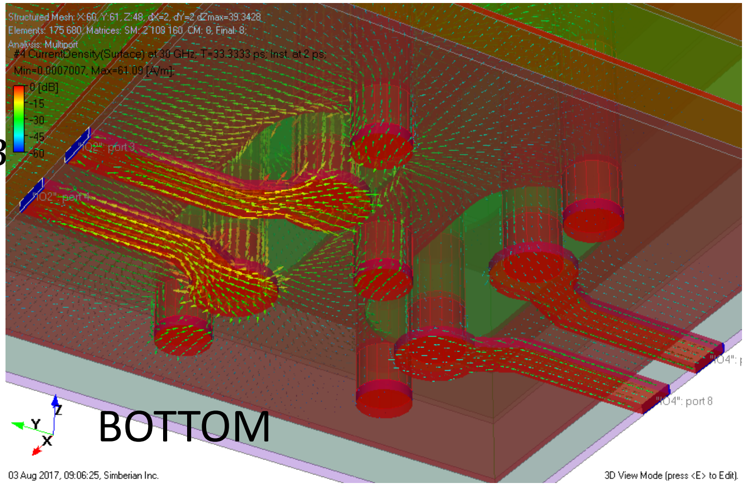
$\overline{J}_{surf}, dB$



Structured Mesh: X:60, Y:61, Z:48, dX=2, dY=2 dZmax=39.3428
Elements: 175 680; Matrices: SM: 2 108 160, CM: 8, Final: 8;
Analysis: Multiport
#4 CurrentDensity(Surface) at 30 GHz; T=33.3333 ps; Inst. at 2 ps;
Min=0.0007007, Max=61.09 [A/m];

03 Aug 2017, 09:05:07, Simberian Inc.
3D View Mode (press <E> to Edit).

$\overline{J}_{surf}, dB$



Structured Mesh: X:60, Y:61, Z:48, dX=2, dY=2 dZmax=39.3428
Elements: 175 680; Matrices: SM: 2 108 160, CM: 8, Final: 8;
Analysis: Multiport
#4 CurrentDensity(Surface) at 30 GHz; T=33.3333 ps; Inst. at 2 ps;
Min=0.0007007, Max=61.09 [A/m];

BOTTOM

03 Aug 2017, 09:06:25, Simberian Inc.
3D View Mode (press <E> to Edit).

More visualization at www.simberian.com…

- #2017_02: **How Interconnects Work™**: Microstrip over meshed reference plane in flex interconnects, 16 min
- #2016_13: **How Interconnects Work™**: Crosstalk power flow in differential vias, 10 min
- #2016_12: **How Interconnects Work™**: Crosstalk power flow in single-ended vias, 11min
- #2016_11: **How Interconnects Work™**: Crosstalk power flow in microstrip lines, 12min
- #2016_10: **How Interconnects Work™**: Coaxial connector launch localization, 10 min
- #2016_09: **How Interconnects Work™**: Power flow in coaxial connector launch, 16 min
- #2016_08: **How Interconnects Work™**: EM fields, surface current and power flow in single-ended vias - with and without stubs, 15 min
- #2016_07: **How Interconnects Work™**: Conductor roughness part 2 - modelling with Roughness Correction Coefficients, 16 min
- #2016_06: **How Interconnects Work™**: EM fields and power flow in differential vias, 16 min
- #2016_05: **How Interconnects Work™**: Currents and power flow in differential vias, 10 min
- #2016_04: **How Interconnects Work™**: Conductor roughness modeling with Effective Roughness Dielectric, 10 min
- #2016_03: **How Interconnects Work™**: EM field, current and power flow in strip line, 10 min
- #2016_02: **How Interconnects Work™**: Skin-effect in microstrip line - current density, 10 min
- #2016_01: **How Interconnects Work™**: Skin-effect in microstrip line - EM fields and current density, 17 min

Conclusion

- Usefulness of visualization
    - Better understand or electromagnetics
    - Better understanding of “How interconnects work”
    - Troubleshooting problem setup and software
- Simbeor electromagnetic signal integrity software (Simbeor THz version 2017.02) is used for all computations and visualization plots

See more at app notes and demo-videos of “How Interconnects Work” at http://www.simberian.com