RF simulations with COMSOL

ICPS 2017

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Types of Electromagnetics Modeling

Static — Low Frequency — Transient — High Frequency

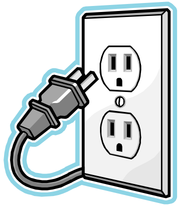
RF Module

AC/DC Module

Wave Optics Module

$$\frac{\partial \mathbf{E}}{\partial t} = 0$$

Electric and magnetic fields do not vary in time.



$$\mathbf{E}\sin(\omega t)$$

Fields vary sinusoidally in time, but there is negligible radiation.

$$\mathbf{E}(t)$$

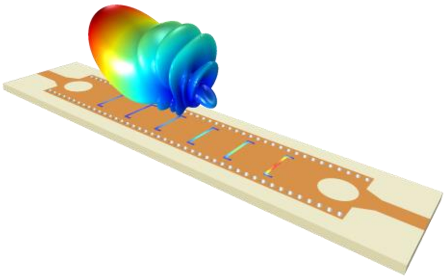
Fields vary arbitrarily in time, radiation may or may not be significant. Objects can be moving.

$$\mathbf{E}\sin(\omega t)$$

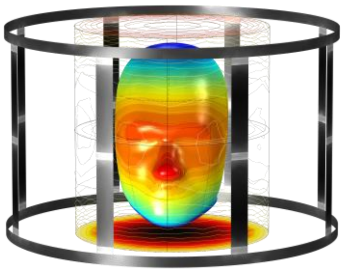
Fields vary sinusoidally in time, energy transfer is via radiation.

High Frequency Modeling

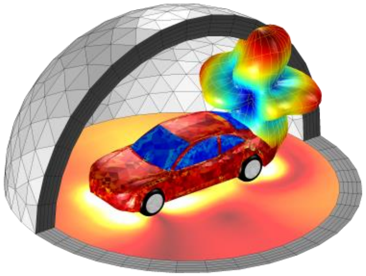
- Electromagnetic Waves formulation solves for the electric and magnetic fields with Frequency domain and Eigenfrequency (resonant mode) analysis



Substrate Integrated Waveguide Slot Antenna



MRI Birdcage Coil



Automotive EMI/EMC

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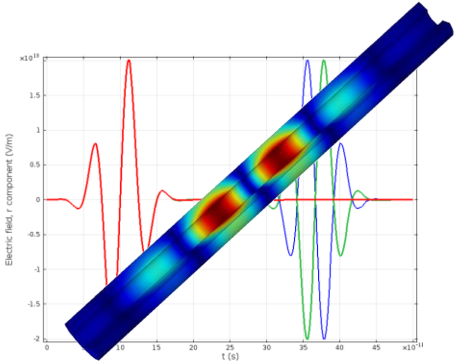
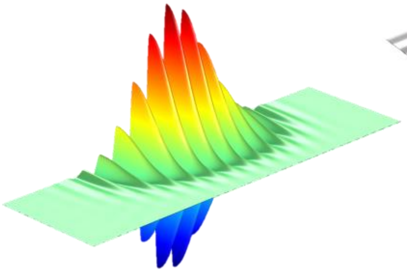
Transient Modeling

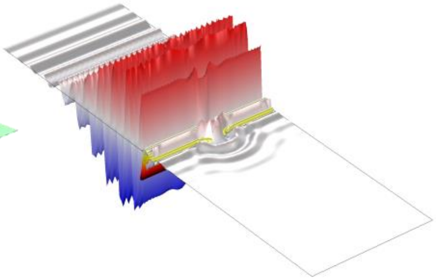
- Transient electromagnetics solves for nonlinear wave phenomena
- For transient phenomena such as signal propagation as a function of time



Coaxial Cable Transient



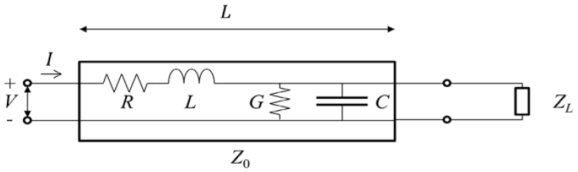
Second Harmonic Generation

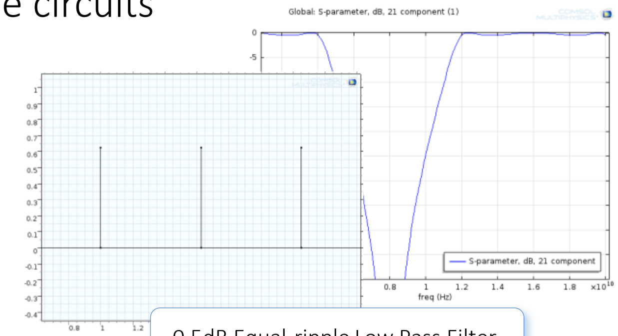


Dispersive Drude-Lorentz media

Additional Formulations: Transmission Line Equations

- The Transmission Line Equation formulation solves for the electric potential along transmission lines
- For fast prototyping of transmission line circuits





0.5dB Equal-ripple Low Pass Filter

Feature Overview: Material Models

- All material properties can be:
  - Constant or nonlinearly dependent upon the fields
  - Isotropic, Diagonal, or Fully Anisotropic
  - Real or complex properties (losses)
  - Bi-directionally coupled to any other physics, e.g. Temperature, Strain
  - Fully User-Definable
- RF Module supports loss tangents and dispersion models
  - Drude-Lorentz, and Debye dispersion

$$\mathbf{D} = \varepsilon_0 \varepsilon_r \mathbf{E}$$
$$\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P}$$
$$\mathbf{D} = \varepsilon_0 \varepsilon_r \mathbf{E} + \mathbf{D}_r$$

$$\mathbf{B} = \mu_0 \mu_r \mathbf{H}$$
$$\mathbf{B} = \mu_0 \mathbf{H} + \mu_0 \mathbf{M}$$
$$\mathbf{B} = \mu_0 \mu_r \mathbf{H} + \mathbf{B}_r$$

$$\mathbf{J} = \sigma \mathbf{E}$$

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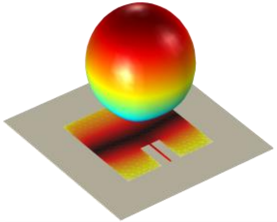
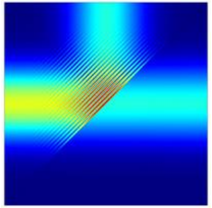
$$\mathbf{D} = \varepsilon_0 \varepsilon_r \mathbf{E} + \mathbf{D}_r \qquad \mathbf{B} = \mu_0 \mu_r \mathbf{H} + \mathbf{B}_r$$

Modeling of Conductive Geometries

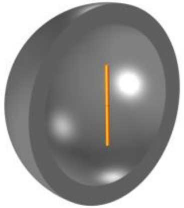
- Geometrically very thin, highly conductive, electrically thicker than skin-depth
  - Perfect Electric Conductor (PEC) Boundary Condition, lossless, non-penetrable
- Geometrically very thin, conductive, and lossy
  - Transition Boundary Condition, lossy, skin-depth dependent penetration, modeled in 2D
- Conductive, electrically much thicker than skin-depth
  - Impedance Boundary Condition, lossy, non-penetrable



Thin copper layer modeled as PEC at 1.6 GHz



Very thin silver layer modeled via Transition Boundary Condition at 428 THz



Copper rod represented by Impedance Boundary Condition

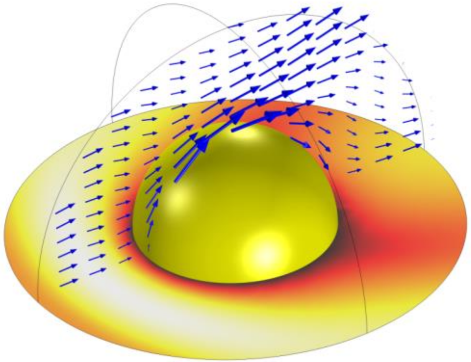
http://www.comsol.com/showroom/gallery/11742/
http://www.comsol.com/showroom/gallery/12621/
http://www.comsol.com/showroom/gallery/8715/

Feature Overview: Boundary Conditions

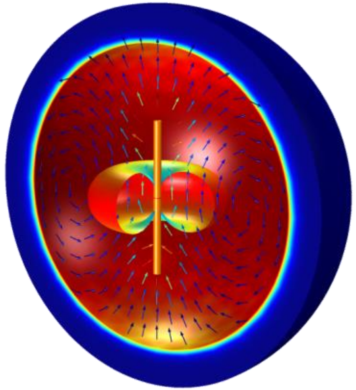
- Voltage source, Current source, & Insulating surfaces
- Thick volumes of electrically resistive, or conductive, material
- Thin layers of electrically resistive, or conductive, material
- Perfectly conducting boundaries
- Periodicity conditions
- Connections to external circuit models
- Lumped, Coaxial, and other Waveguide feeds
- Electromagnetic wave excitations
- Absorbing (Radiating) boundaries

Feature Overview: Domain Conditions

- Background Field excitation for scattering problems
- Perfectly Matched Layer for modeling of free space



PEC Sphere illuminated by a background plane wave



Half-wave dipole antenna, surrounded by Perfectly Matched Layer

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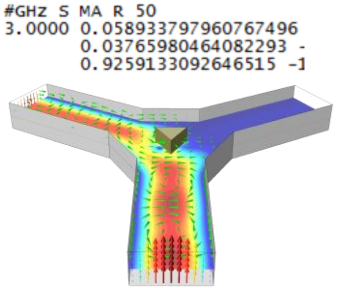
Feature Overview: Data Extraction

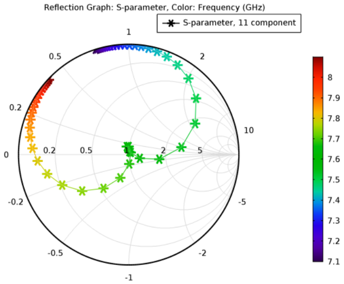
- Impedance, Admittance, and S-parameters
- Smith plot
- Touchstone file export
- Far-field plots for radiation

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}$$

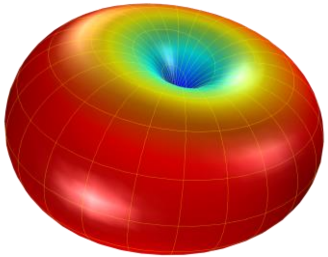
Lumped Parameters



Touchstone File Export



Smith Plot



Far-Field Radiation Pattern

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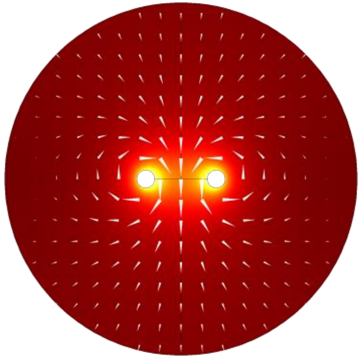
Waveguides and Transmission Lines

• Any structure that guides electromagnetic waves along its structure can be considered a waveguide • COMSOL can compute propagation constants, impedance, S-parameters	$\nabla\times\mu_r^{-1}(\nabla\times\mathbf{E})-k_0^2(\varepsilon_r-j\sigma/\omega\varepsilon_0)\mathbf{E}=\mathbf{0}$ $\mathbf{E}=\mathbf{E}(x,y)\exp(\lambda z)$ $\lambda=-j\beta-\delta_z$
• COMSOL also solves the time-harmonic transmission line equation for the electric potential for electromagnetic wave propagation along one-dimensional transmission lines.	$\frac{\partial}{\partial x}\left(\frac{1}{R+i\omega L}\frac{\partial V}{\partial x}\right)-(G+i\omega C)V=0$
Typical examples	Coaxial cable Optical fibers and waveguides

Impedance of a Parallel Wire Transmission Line

- The impedance of a parallel wire transmission line has an analytic solution
- A cross-sectional model is used to find the fields
- The transmission line is unshielded, so the fields extend to infinity, associated modeling issues are addressed
- The computed impedance agrees with the analytic solution

$$Z_{0,\text{ analytic}} = \frac{1}{\pi}\sqrt{\frac{\mu_0}{\varepsilon_0\varepsilon_r}}\operatorname{acosh}\left(\frac{r_d}{r_a}\right)$$



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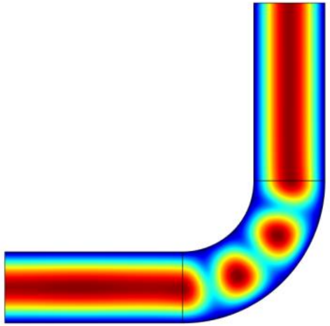
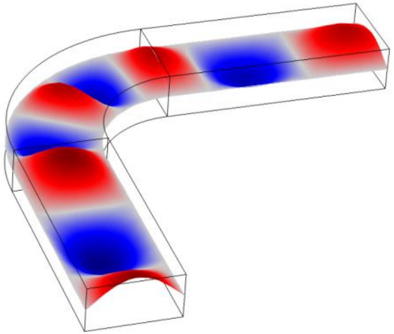
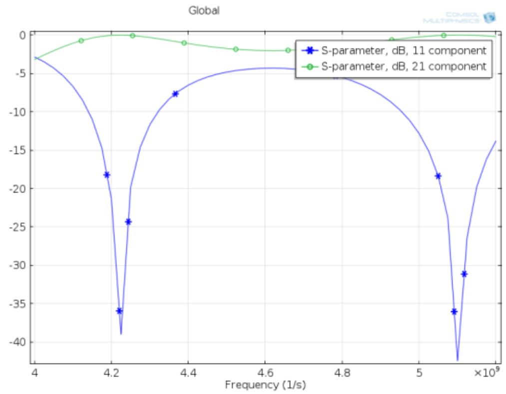
H-bend Waveguide 2D & 3D Model

- The transmission of a TE_{10} wave through a 90 ° bend in a waveguide is modeled







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Passive Devices Example Models

- Passive devices like couplers, power dividers, and filters can be realized by combining resonant structures and transmission lines. COMSOL calculates the fields distribution, impedance, and S-parameters

$$\nabla \times \mu_r^{-1}(\nabla \times \mathbf{E}) - k_0^2(\varepsilon_r - j\sigma/\omega\varepsilon_0)\mathbf{E} = \mathbf{0}$$

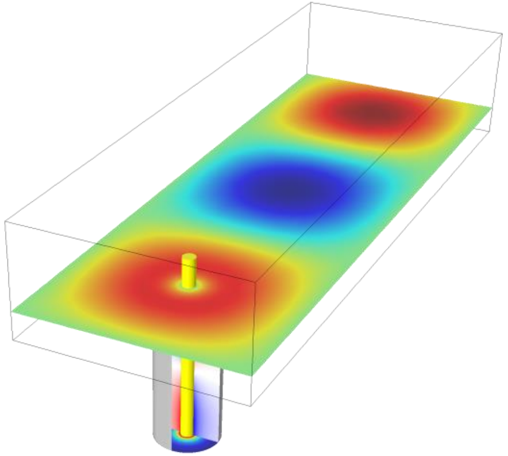
$$S = \begin{bmatrix} S_{11} & S_{12} & .. & S_{1n} \\ S_{21} & S_{22} & .. & . \\ : & : & :: & : \\ S_{n1} & . & .. & S_{nn} \end{bmatrix}$$

Typical examples	3dB Couplers and Power Dividers Band-pass Filters

COMSOL

Coaxial Cable to Waveguide Coupling

- A model of a coaxial cable feed that excites a propagating wave inside a rectangular waveguide
- S-parameters for transmission and reflection are computed



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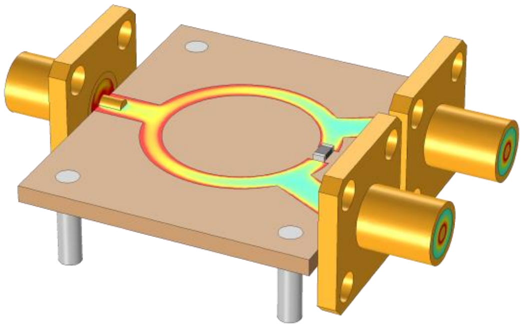
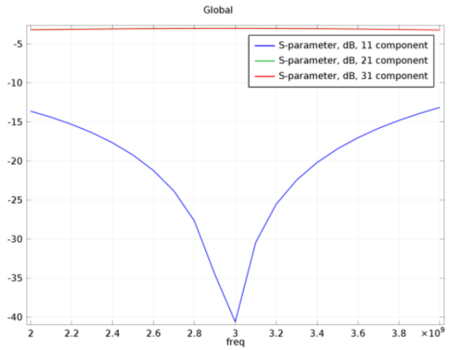
Wilkinson Power Divider

- A Wilkinson power divider is a three-port lossless device and outperforms a T-junction divider and a resistive divider
- Computed S-parameters show good input matching and -3 dB evenly split output
- 100 Ohm resistor modeled via lumped element feature





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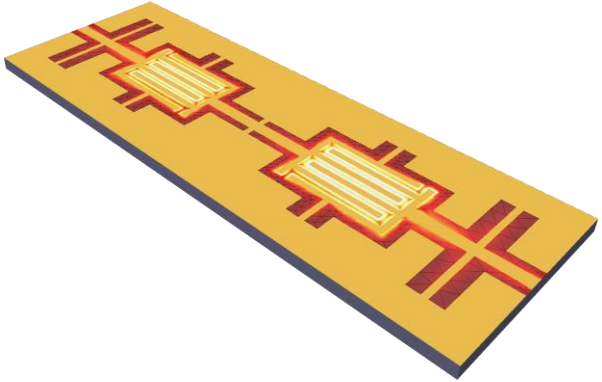
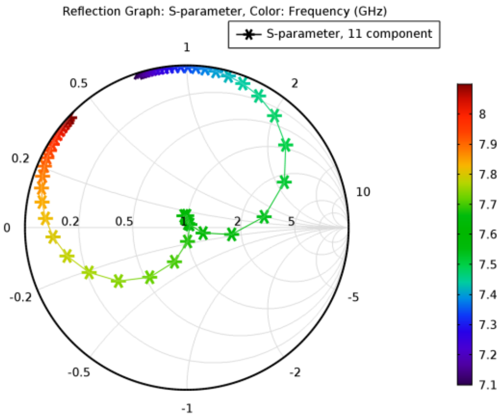
Coplanar Waveguide (CPW) Bandpass Filter

- Excite and terminate two slots equally using multi-element uniform lumped ports
- Combination of interdigital capacitors (IDCs) and short-circuited stub inductors (SSIs)





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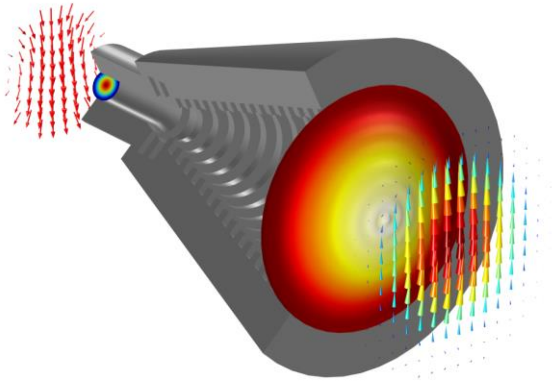
Antenna Example Models

• Antennas transmit and/or receive radiated electromagnetic energy. COMSOL can compute the radiated energy, far field patterns, losses, gain, directivity, impedance and S-parameters by solving the linear problem for the *E*-field	
$\nabla \times \mu_r^{-1}(\nabla \times \mathbf{E}) - k_0^2(\varepsilon_r - j\sigma/\omega\varepsilon_0)\mathbf{E} = \mathbf{0}$ $\mathbf{E}_{far} = -\frac{jk}{4\pi}\mathbf{r}_0 \times \int [\mathbf{n} \times \mathbf{E} - \eta \mathbf{r}_0 \times (\mathbf{n} \times \mathbf{H})] \exp(jk\mathbf{r} \cdot \mathbf{r}_0)\, dS$	
Typical examples	Microstrip Patch Antenna Vivaldi Antenna Dipole Antenna

Corrugated Circular Horn Antenna

- Designed using a 2D axisymmetric model
- Low cross-polarization at the antenna aperture by combining TE mode excited at the circular waveguide feed and TM mode generated from the corrugated inner surface



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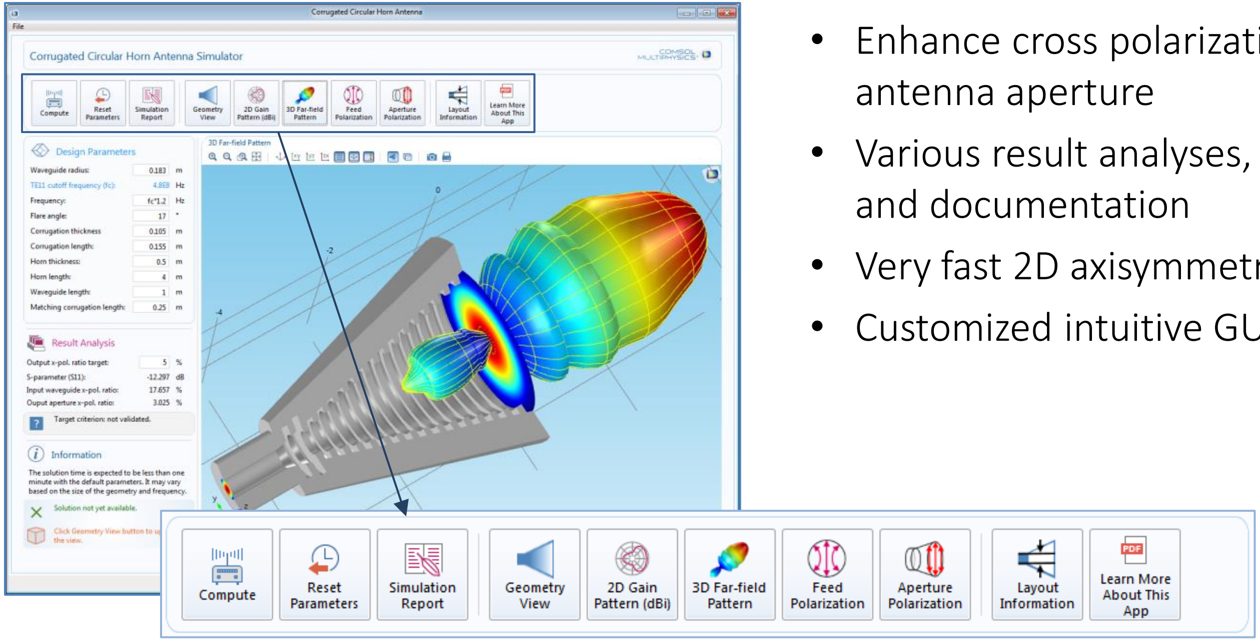
Corrugated Circular Horn Antenna Simulator



- Enhance cross polarization ratio at the antenna aperture
- Various result analyses, simulation report, and documentation
- Very fast 2D axisymmetric simulation
- Customized intuitive GUI

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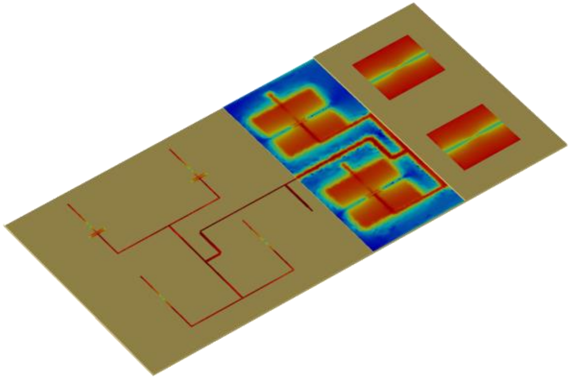
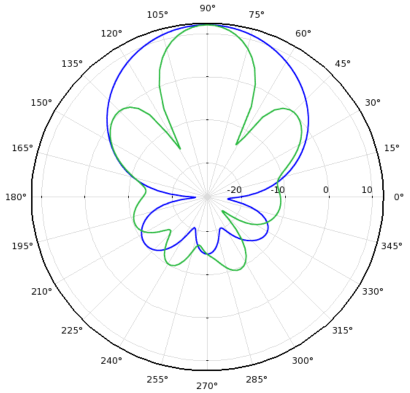
4 x 2 Microstrip Patch Antenna Array

- Slot-coupled 4x2 array of patch antennas
- Controlling the phase and magnitude assigned to each element can steer the beam
- Far-Field radiation pattern is computed





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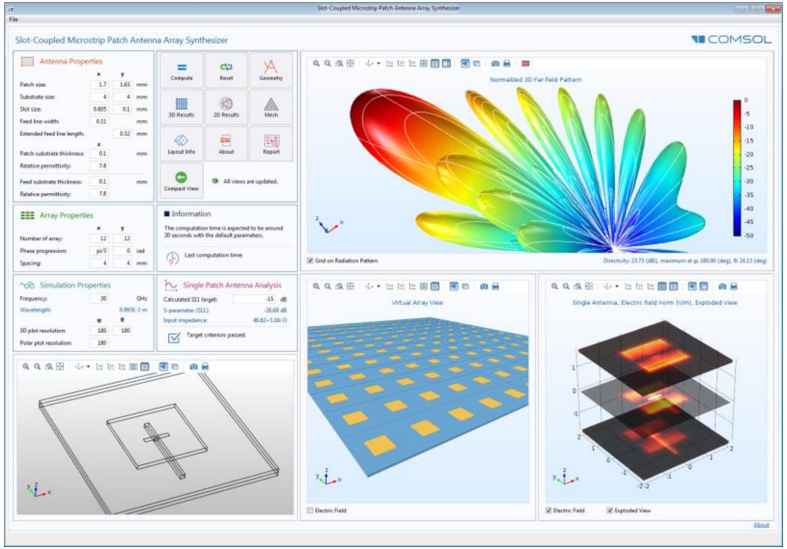
Slot-Coupled Microstrip Patch Antenna Array Synthesizer



- Single slot-coupled microstrip patch antenna fabricated on a multilayered low temperature co-fired ceramic (LTCC) substrate
- Far-field radiation pattern of the antenna array and directivity.
- Approximated by multiplying the array factor and the single antenna radiation
- Phased antenna array prototypes for 5G mobile networks

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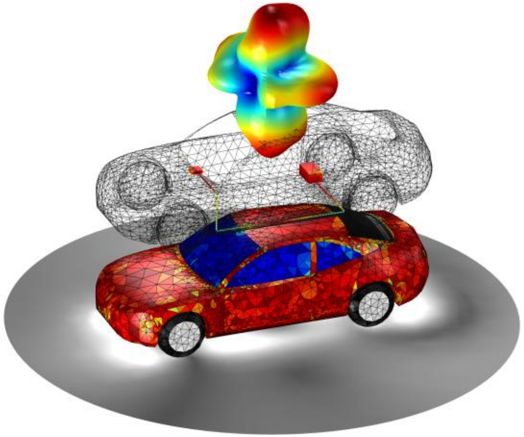
Car Antenna Effect on a Cable Harness

- Printed FM antenna on a real windshield
- Far-field pattern with a ground plane
- Electric field intensity affected on a cable harness



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Examples of Periodic Problems

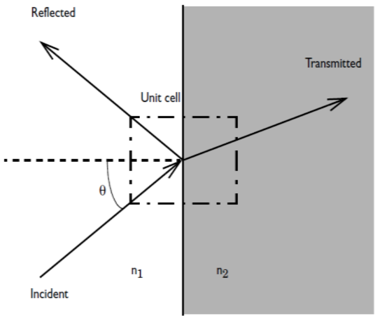
- Any structure that repeats in one, two, or all three dimensions can be treated as periodic, which allows for the analysis of a single unit cell, with Floquet Periodic boundary conditions

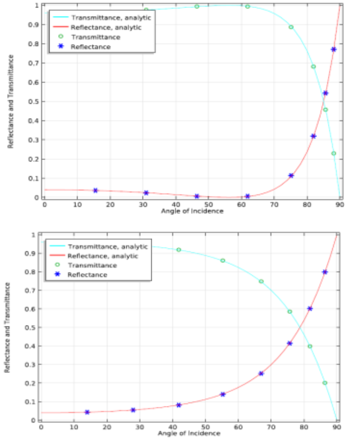
$$\mathbf{E}_d = \mathbf{E}_s \exp(-j\mathbf{k}_F \cdot (\mathbf{r}_d - \mathbf{r}_s))$$

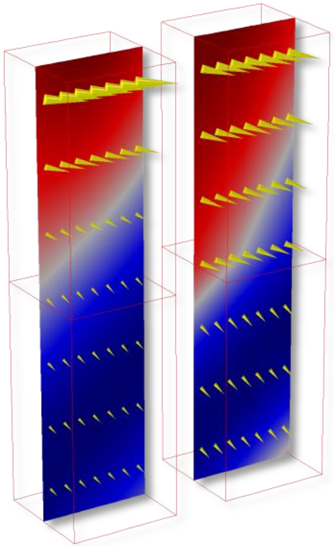
Typical examples	Optical Gratings Frequency Selective Surfaces Electromagnetic Band Gap Structures

Verification of Fresnel Equations

- TE- and TM-polarized light incident upon an infinite dielectric slab
- 3D model uses Floquet Periodicity
- Results agree with analytic solution







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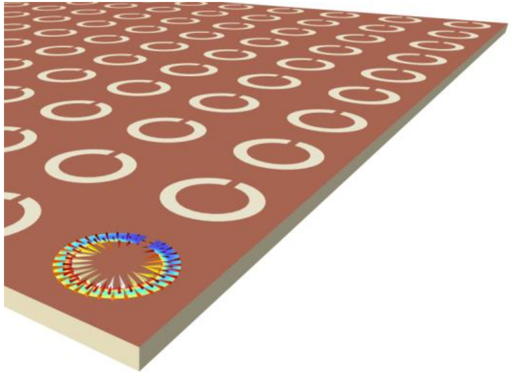
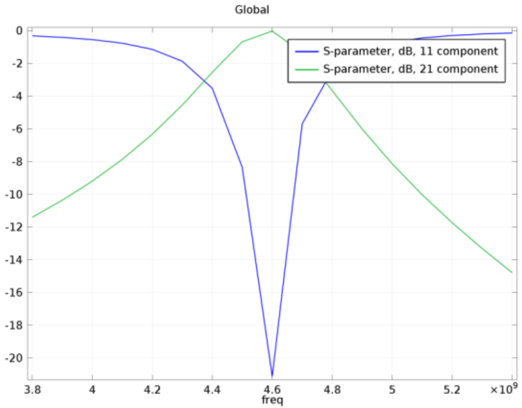
Frequency Selective Surface, CSRR

- One unit cell of the complementary split ring resonator (CSRR) with periodic boundary conditions to simulate an infinite 2D array
- Interior port boundaries combined with perfectly matched layer absorbing higher order modes





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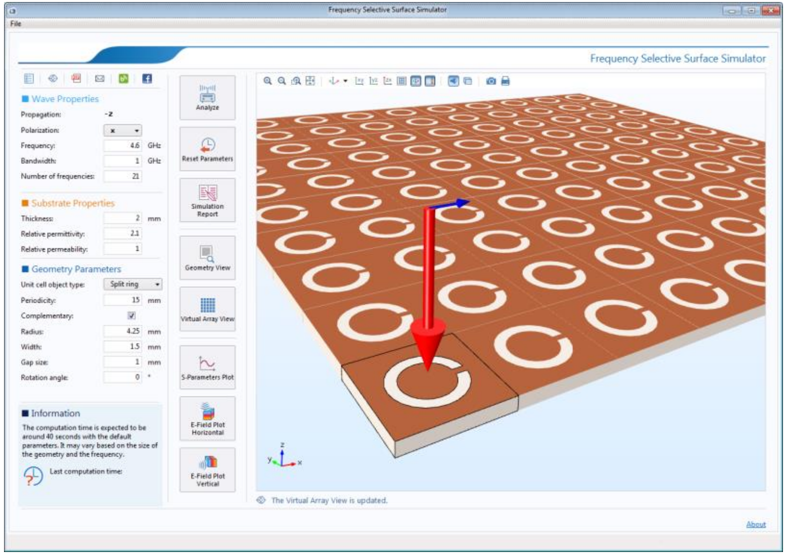
Frequency Selective Surface Simulator



- Periodic structures that generate a bandpass or a bandstop frequency response
- Built-in unit cell types: five popular FSS types, with two predefined polarizations and propagation at normal incidence
- The reflection and transmission spectra, the electric field norm on the top surface of the unit cell, and the dB-scaled electric field norm

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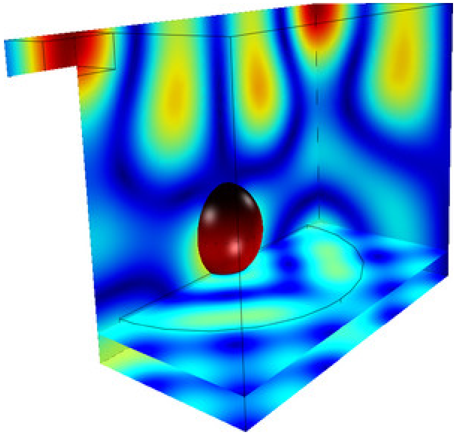
Electromagnetic Heating Examples

• An electromagnetic wave interacting with any materials will have some loss that leads to rise in temperature over time. Any losses computed from solving the electromagnetic problem can be bi-directionally coupled to the thermal equation	
$$\rho C_p \frac{\partial T}{\partial t} - \nabla \cdot \left(k \nabla T \right) = Q_{\substack{Electromagnetic \\ Losses}}$$	
Typical examples	Thermal Drift in a Microwave Filter Cavity Microwave Ovens Absorbed Radiation in Living Tissue Tumor Ablation

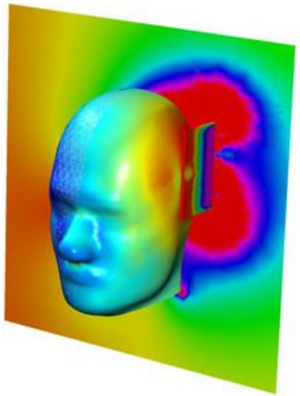
Potato in a Microwave Oven

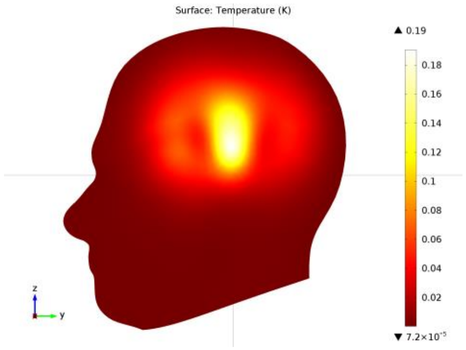
- A half-symmetry model of a potato in a microwave oven
- The electromagnetic fields are solved in the frequency domain
- The thermal problem is solved transiently



Absorbed Radiation (SAR) in the Human Brain

- A representative cell phone antenna is placed next to a head
- The dielectric properties of the head are from scan data
- Absorbed radiation and temperature rise is computed
- Pennes Bioheat equation models living tissue





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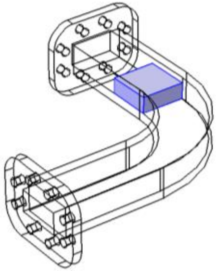
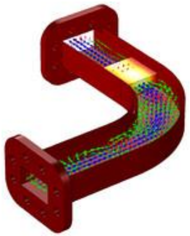
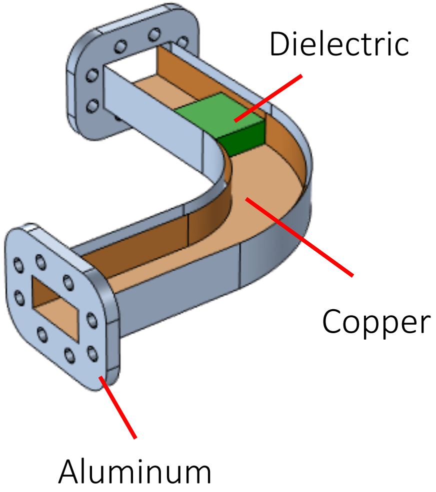
Live Demo

- EM heating of a lossy dielectric in a rectangular waveguide
- RF solved in frequency domain; HT solved in time domain







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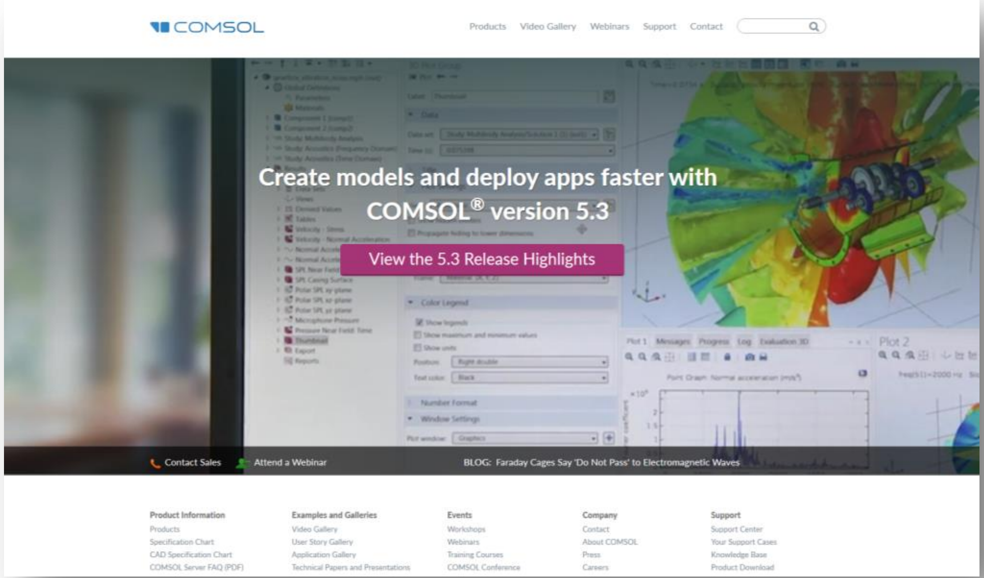

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