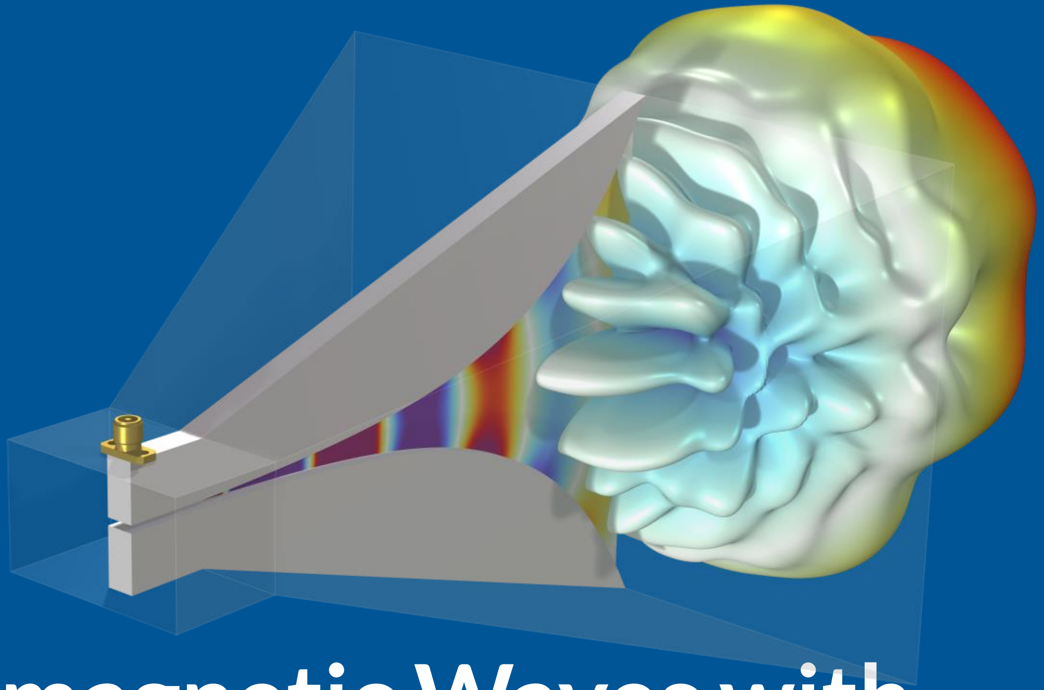
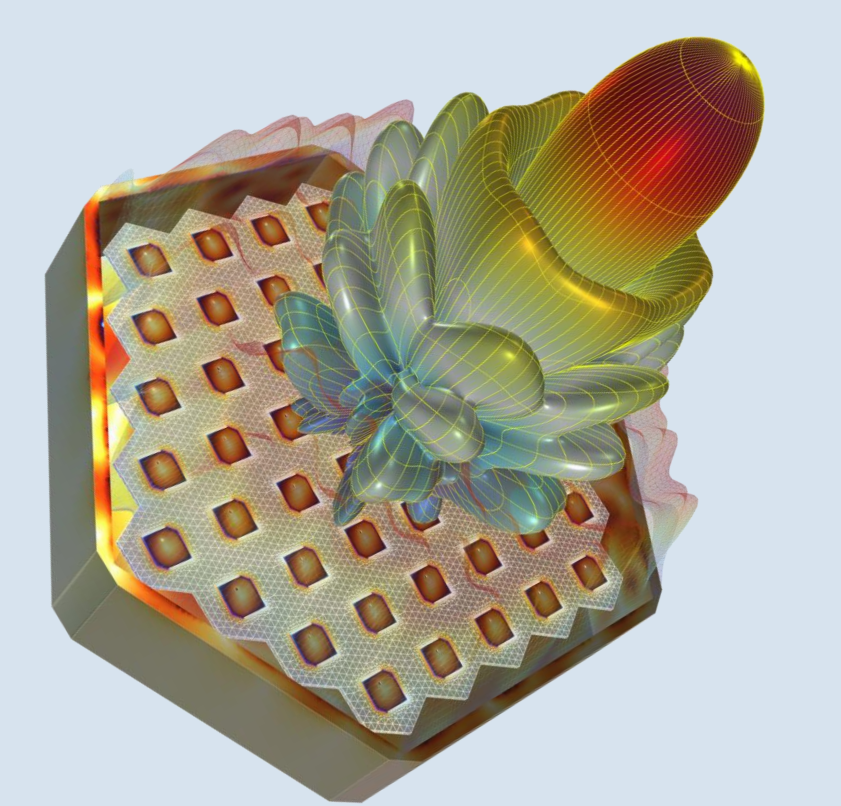


Modeling Electromagnetic Waves with COMSOL Multiphysics®

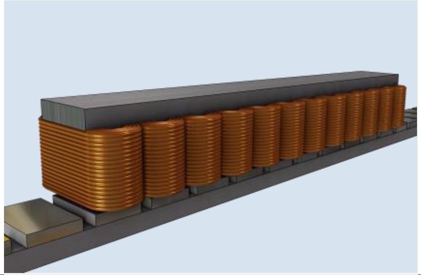
Linus Andersson
COMSOL


Circularly polarized antenna array.

Modeling Electromagnetic Waves with COMSOL Multiphysics®

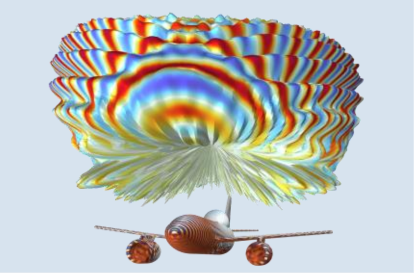
COMSOL Multiphysics® offers functionality for modeling electromagnetic waves from low RF frequencies up to optics and beyond.

Overview of Electromagnetics Modeling



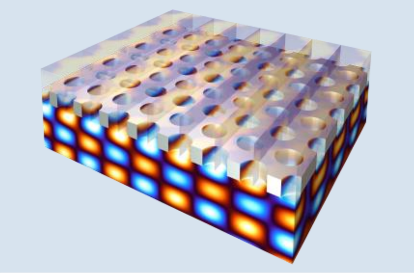
AC/DC Module

- Low frequency
- Power engineering
- Electromechanics
- Inductors, resistors, and capacitors
- Joule heating and induction heating



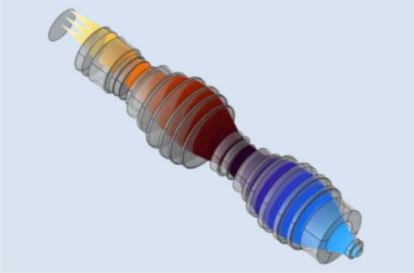
RF Module

- Wave propagation
- RF and mmWave engineering
- Antennas and radar cross sections (RCSs)
- Waveguides, filters, and couplers
- Microwave heating



Wave Optics Module

- Wave propagation
- Optical devices
- Optical beams and scattering
- Waveguides, gratings, and lasers
- Laser heating



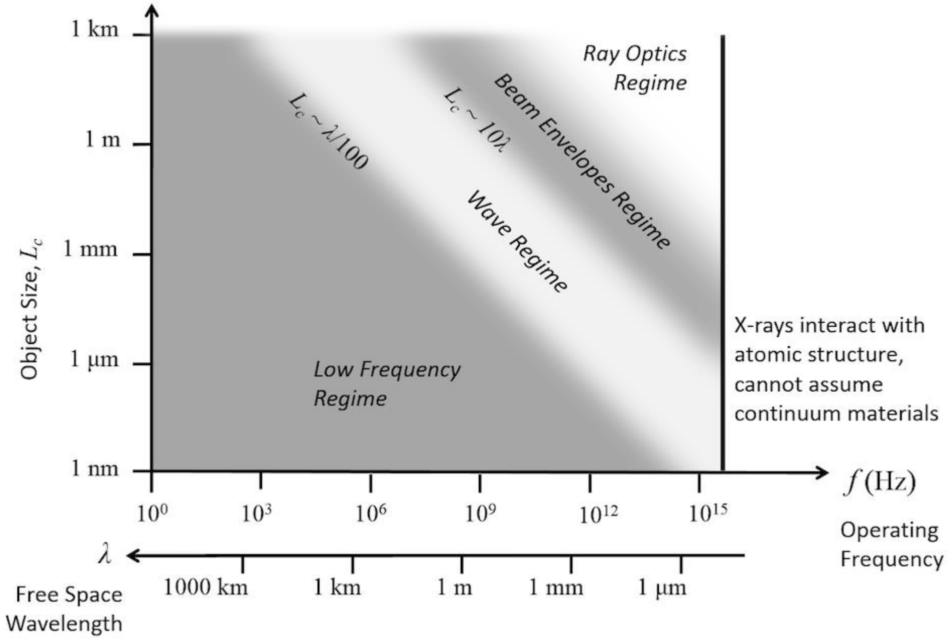
Ray Optics Module

- Ray propagation
- Optically large systems
- Refraction and diffuse and specular reflection
- Cameras, lasers, and spectrometers
- STOP* analysis

* STOP = structural-thermal-optical performance

Object Size Versus Wavelength

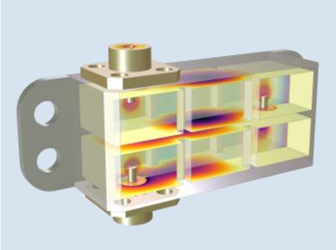
- RF and wave optics models predominantly fall in the wave regime, where the device size is about $\lambda/100$ to $10\ \lambda$.
- Devices that are smaller in terms of the wavelength can be modeled with the quasistatic formulations in the AC/DC Module.
- Devices that are large in a known direction of propagation benefit from beam envelopes, available in the Wave Optics Module.
- Systems that are large enough that diffraction can be neglected are modeled with the Ray Optics Module.



The wavelength should be considered with respect to device size.

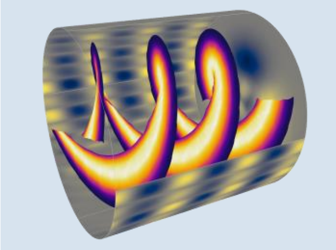
WAVE OPTICS MODULE

The Electromagnetic Waves Interfaces



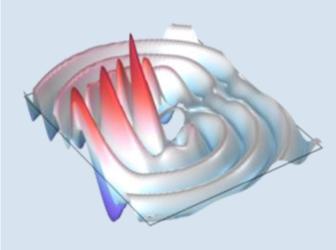
Frequency Domain

- Frequency domain
- Helmholtz equation
- General purpose on wavelength scale
- Mode analysis
- Scattering
- Periodic problems



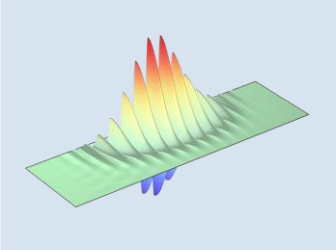
Beam Envelopes

- Frequency domain
- Helmholtz-like envelope equation
- Large domains
- Requires wave vector guess
- Wave propagation
- Gaussian beams



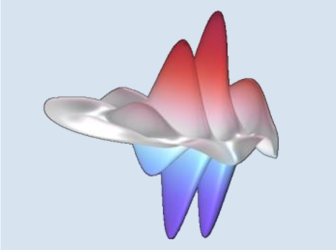
Boundary Elements

- Frequency domain
- Helmholtz equation with homogeneous materials
- Boundary element method
- No domain mesh
- Scattering



Transient

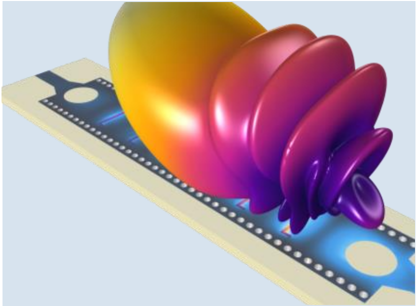
- Time domain
- Implicit time-stepping
- General purpose on wavelength scale
- Dispersive materials and devices
- Nonlinear optics



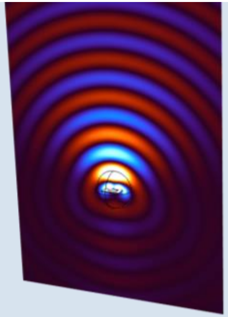
Time Explicit

- Time domain
- Explicit time-stepping
- Scales better than transient interface
- Scattering

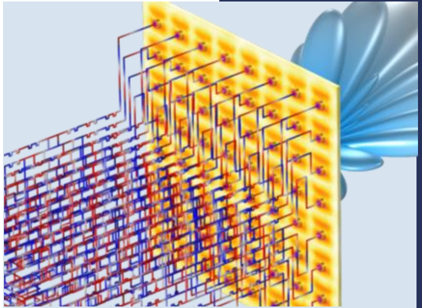
Frequency Domain Modeling



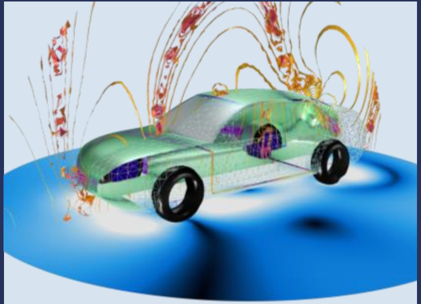
A substrate-integrated waveguide slot antenna model.



Electric field from a patch antenna, modeled with FEM and BEM.



A 64 x 64 Butler matrix connected to an 8 x 8 microstrip patch antenna array.



An automotive electromagnetic interference–electromagnetic compatibility (EMI–EMC) model.

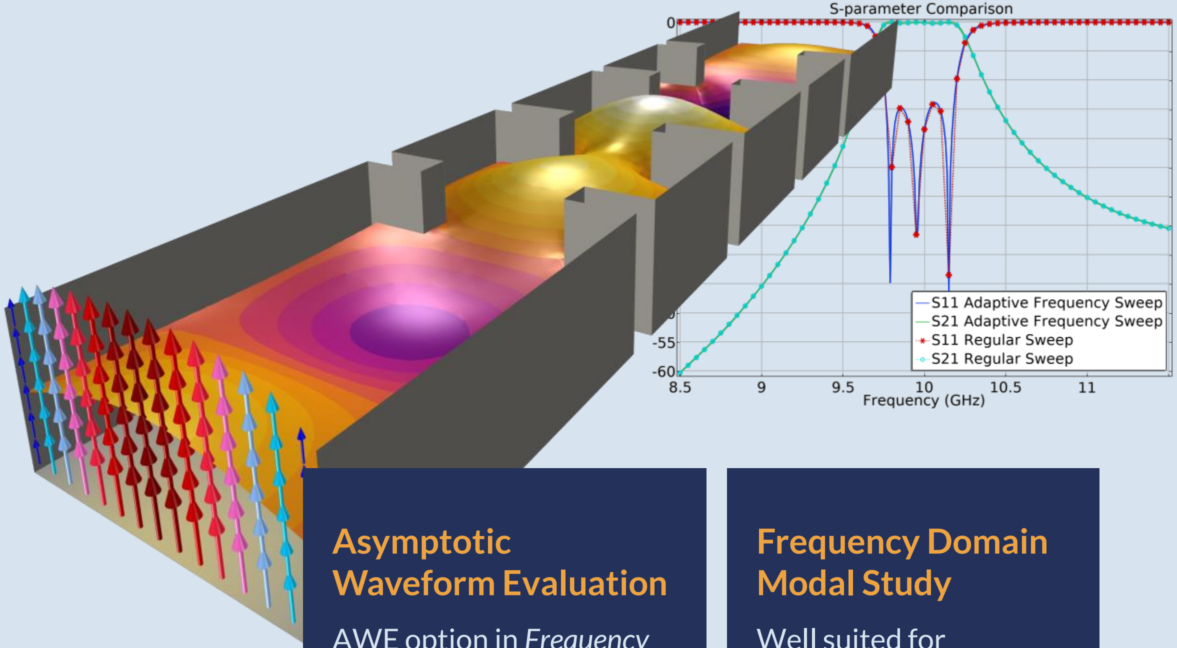
Sinusoidally driven models with linear media are preferably solved in the frequency domain using the finite element method (FEM) or boundary element method (BEM).

For resonances, an *Eigenfrequency* study type is available.

FEATURE OVERVIEW

Model Order Reduction

- Reduced-order modeling techniques
- Fast analysis with a very fine frequency step
- Orders of magnitude faster compared to regular frequency sweeps



Waveguide iris filter.

Asymptotic Waveform Evaluation

AWE option in *Frequency Domain* study and *Adaptive Frequency Sweep* study based on a slowly varying scalar value

Frequency Domain Modal Study

Well suited for bandpass-filter-type devices based on eigenfrequency analysis

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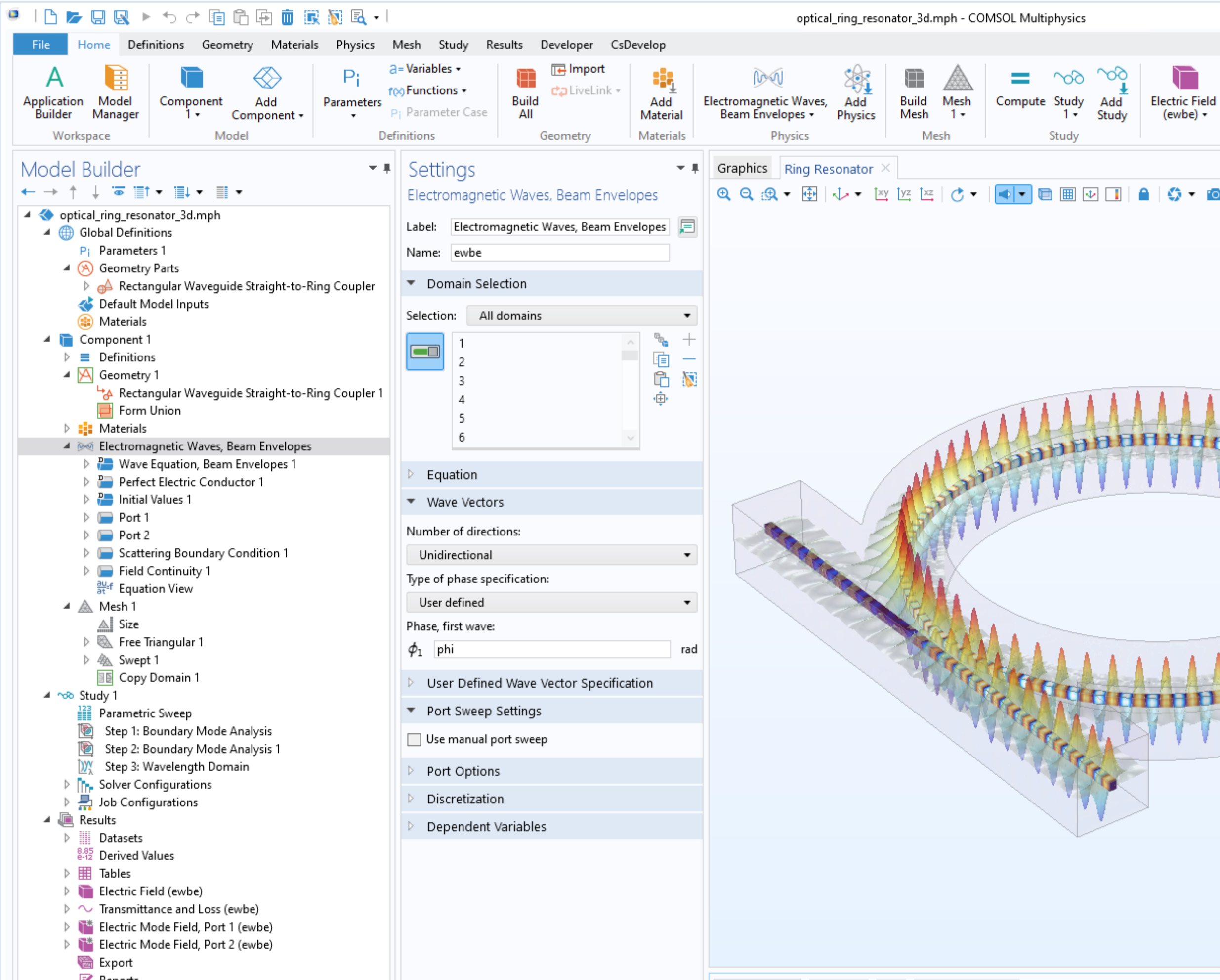
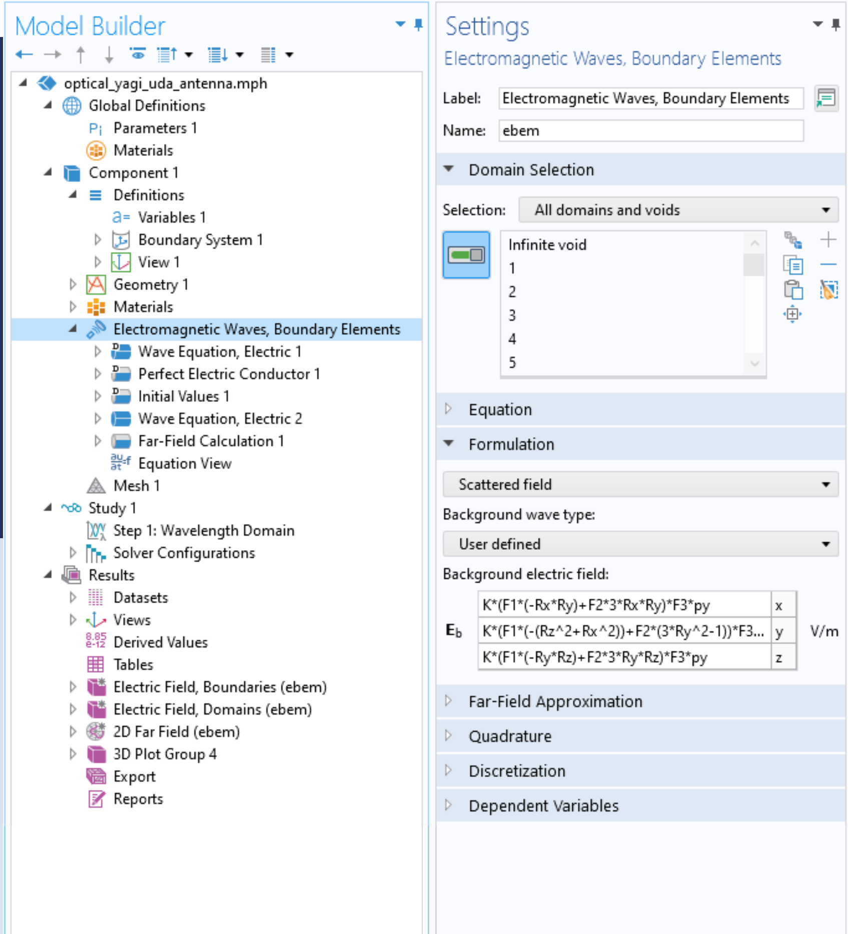
Electromagnetic Waves, Beam Envelopes

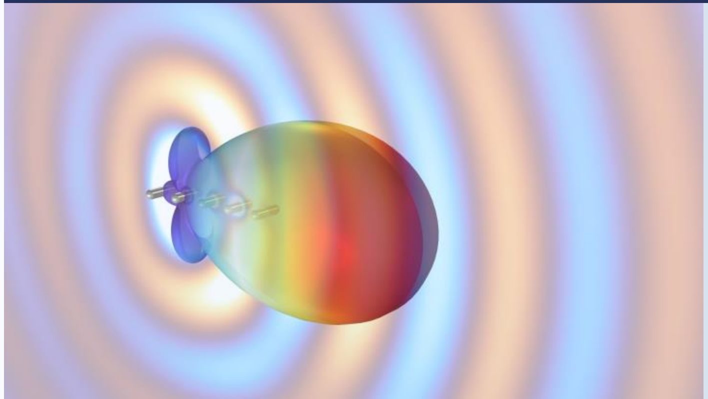
- Solves for slowly varying field envelopes, allowing a very coarse mesh. Use for problems much larger than the wavelength, like propagation in optical waveguides or Gaussian beam propagation.
- Includes similar features as the Electromagnetic Waves, Frequency Domain interface.



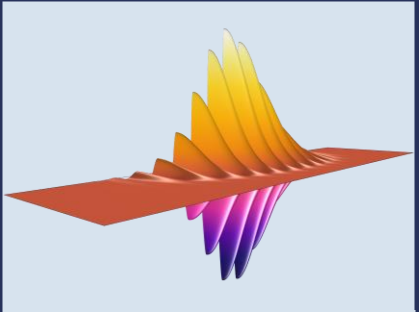
Electromagnetic Waves, Boundary Elements

When modeling using the Boundary Element Method (BEM), only boundary meshing is needed. Each dielectric domain must have homogeneous material properties. This approach is advantageous when objects have relatively small boundaries and are far apart.

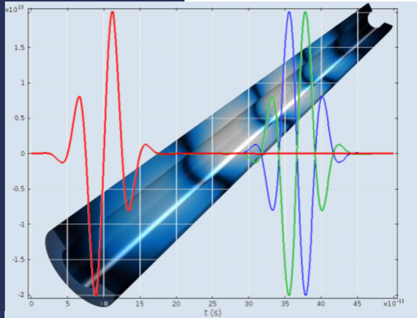




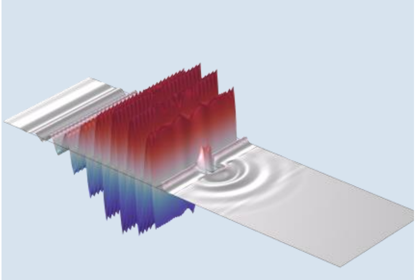
Transient Modeling



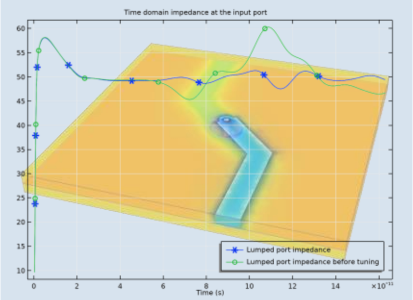
Second-harmonic generation.



Coaxial cable transient.



Dispersive materials.



Time-domain reflectometry (TDR) analysis.

- Electromagnetic wave propagation in media and structures when a time-domain solution is required:
  - Nonsinusoidal waveforms
  - Nonlinear media and harmonic generation
- Simulate broadband behavior and fast Fourier transform (FFT) to the frequency domain

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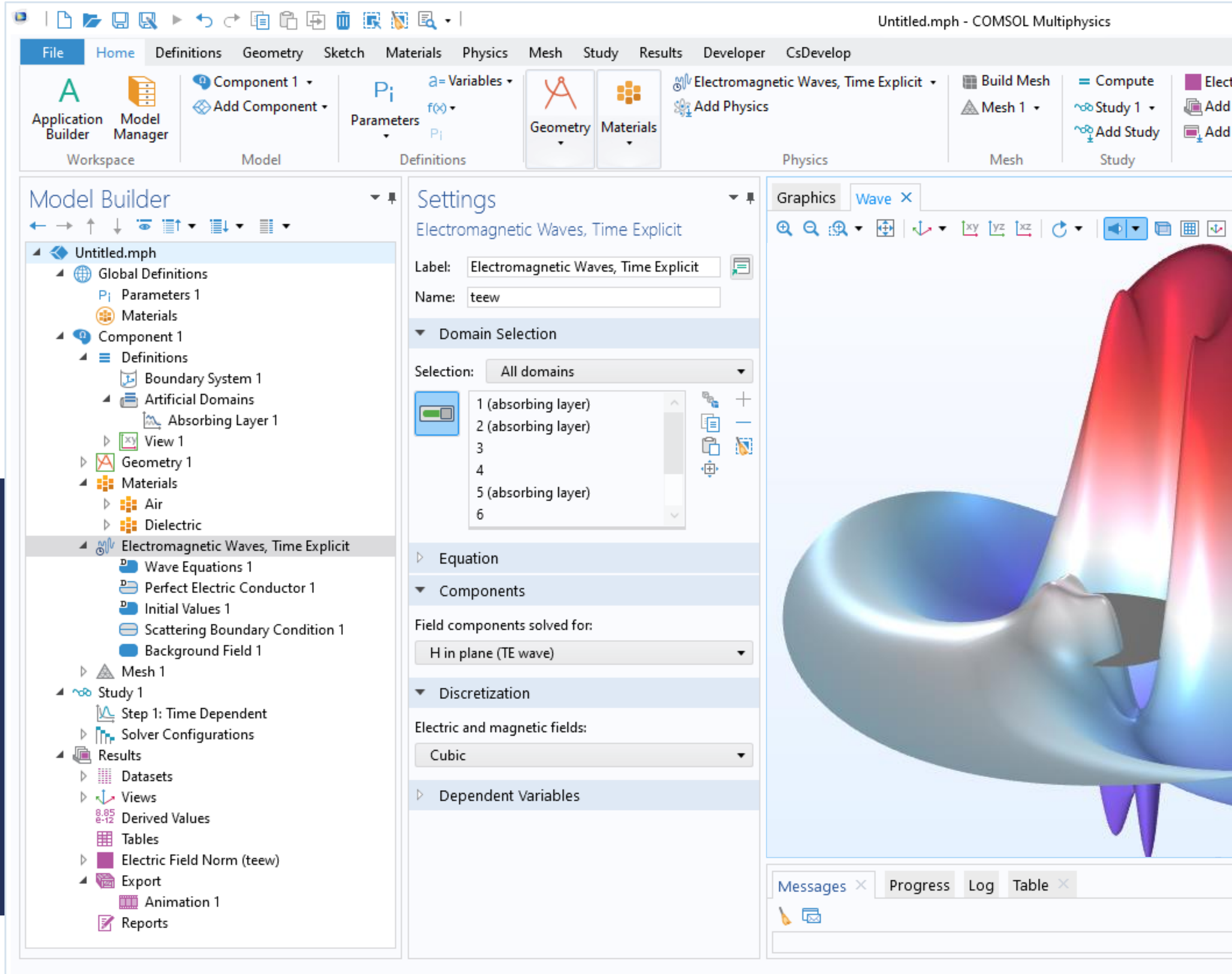
Electromagnetic Waves, Time Explicit



Lean on Memory

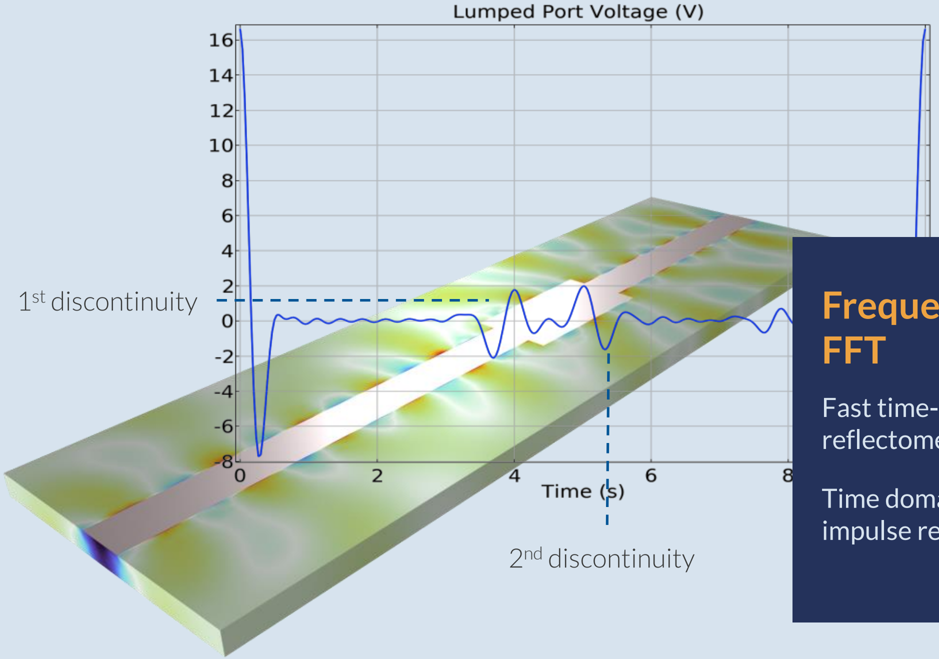
Use discontinuous Galerkin formulation and explicit time stepping. Scales better than Electromagnetic Waves, Transient for very large problems.

Scattering Problems

Excite using Background field and absorb waves using Absorbing layer

FEATURE OVERVIEW

Data Transformation



TDR of a defective microstrip line.

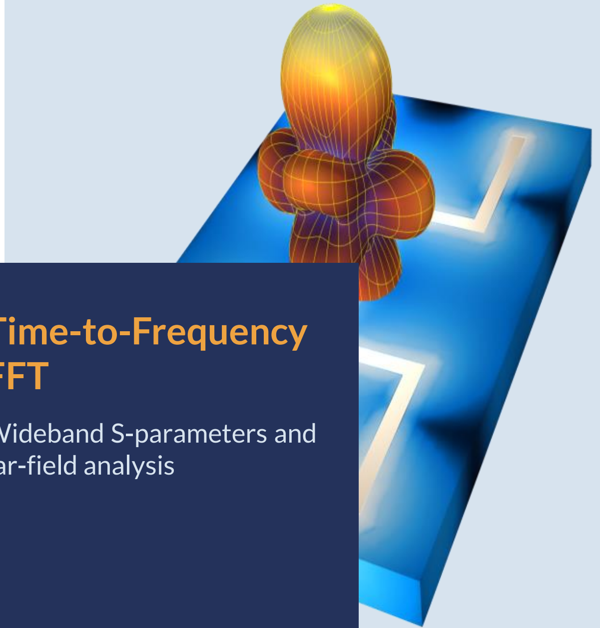
Frequency-to-Time FFT

Fast time-domain reflectometry (TDR) analysis

Time domain bandpass impulse response of a device

Time-to-Frequency FFT

Wideband S-parameters and far-field analysis



Printed dual-band antenna strip and far-field radiation pattern at the second resonance.

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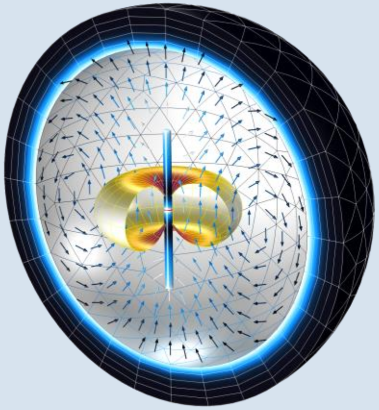
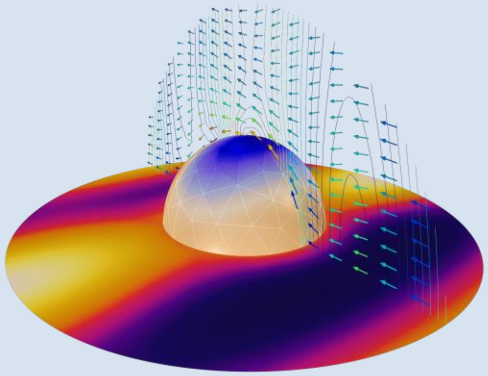
FEATURE OVERVIEW

Domain Conditions

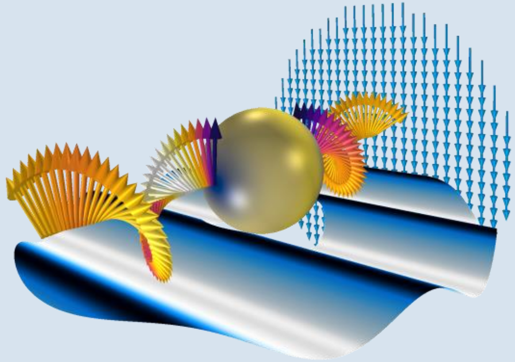
- Media are fully user-definable and can be anisotropic, lossy, dispersive, and dependent on other solution variables such as temperatures or deformations
- *Background Field* excitation for scattering problems
- *Perfectly Matched Layer* for modeling free space for antenna applications



Half-wave dipole antenna, surrounded by a perfectly matched layer.



Perfect electric conductor (PEC) sphere illuminated by a background plane wave.



Circularly polarized background field in a 2D axisymmetric model.

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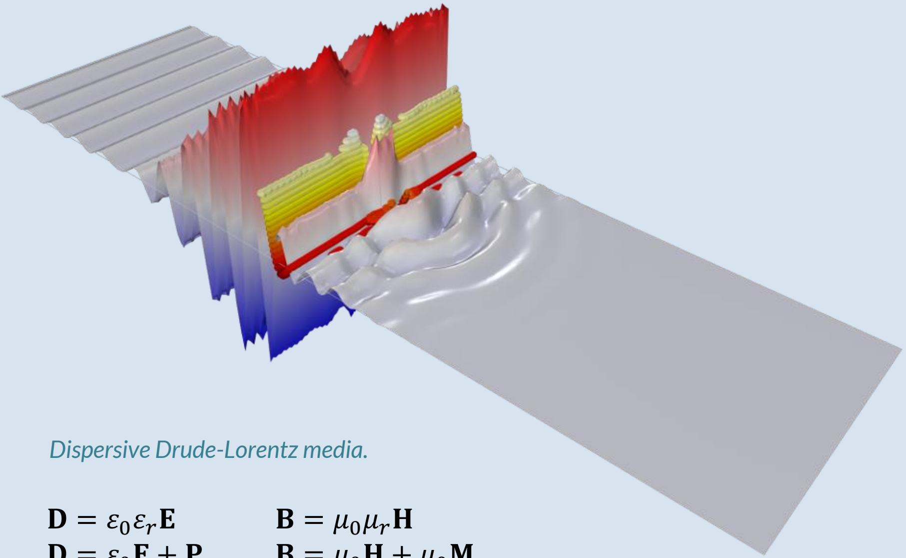
FEATURE OVERVIEW

Material Models



Dispersive Drude-Lorentz media.

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

$\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P}$ $\mathbf{B} = \mu_0 \mathbf{H} + \mu_0 \mathbf{M}$

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

Electric Displacement Field Model

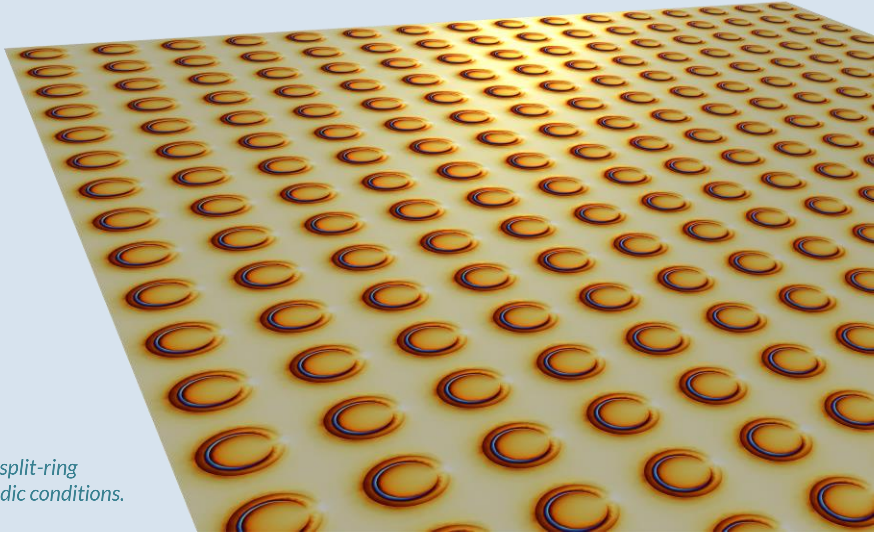
- Frequency domain: relative permittivity, refractive index, loss tangent, dielectric loss, Drude-Lorentz, Debye, and Sellmeier dispersion model
- Time domain: relative permittivity, refractive index, polarization, remanent electric displacement, and Drude-Lorentz dispersion model

Magnetic Constitutive Relation

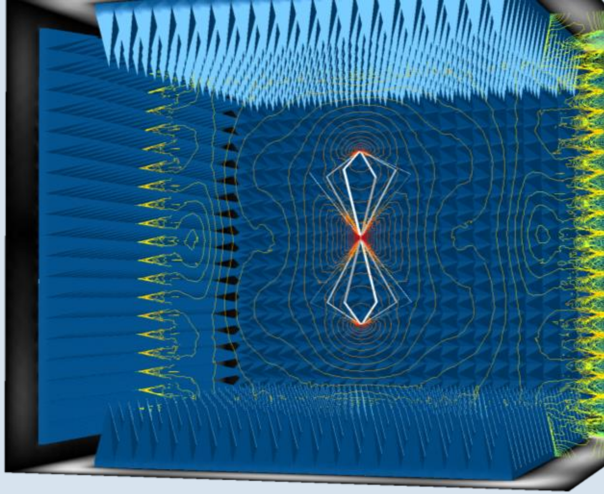
- Frequency domain: relative permeability, and magnetic losses
- Time domain: remanent flux density and magnetization

Material properties

- Constant or nonlinearly dependent upon the fields: isotropic, diagonal, or fully anisotropic
- Bi-directionally coupled to any other physics, and fully user-definable



Array view of complimentary split-ring resonator modeled with periodic conditions.

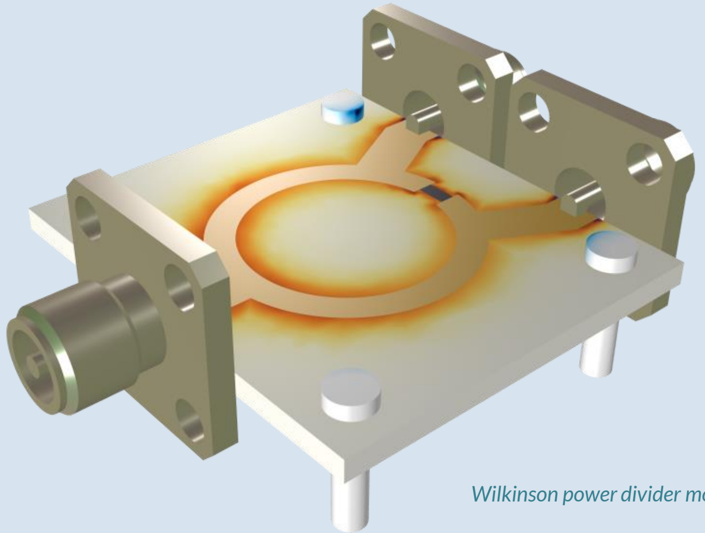


Biconical antenna in an anechoic chamber.

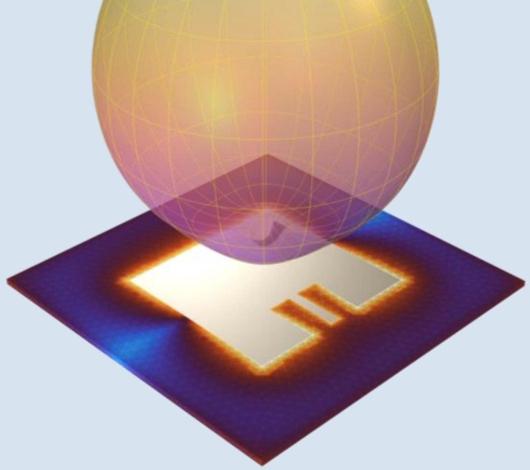
FEATURE OVERVIEW

Boundary Conditions

- Voltage source, current source, and 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
- Waveguide ports
- Electromagnetic wave excitations
- Absorbing (radiating) boundaries



Wilkinson power divider modeled with lossy boundaries.



Microstrip patch antenna with perfect electric conductor.

FEATURE OVERVIEW

Conductive Geometries

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

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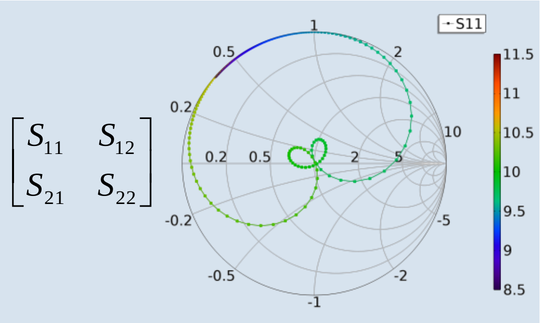
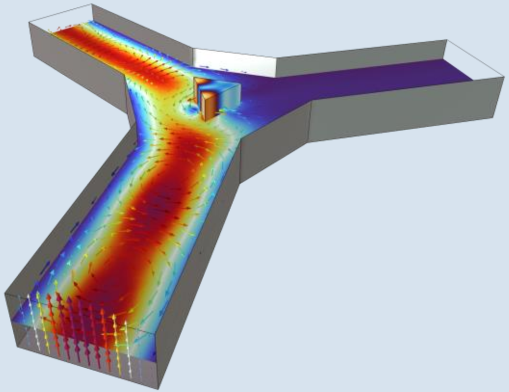
FEATURE OVERVIEW

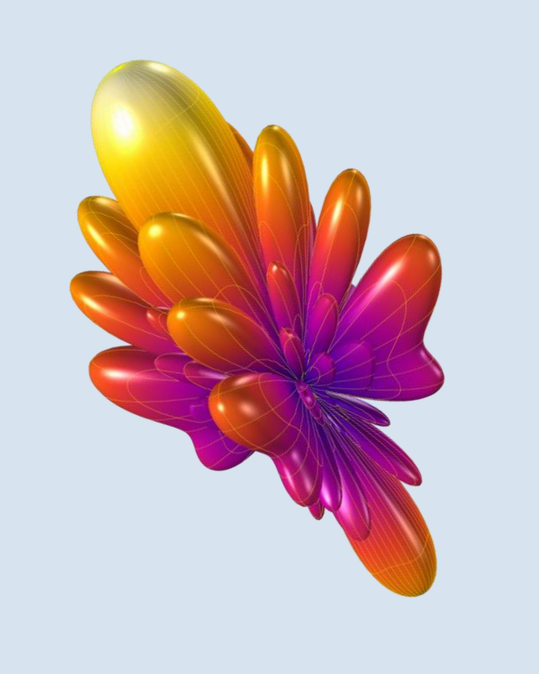
Data Extraction

- S-parameters
- Impedance and admittance
- Smith plot
- Touchstone file export
- Specific absorption rate (SAR)
- Far-field radiation patterns

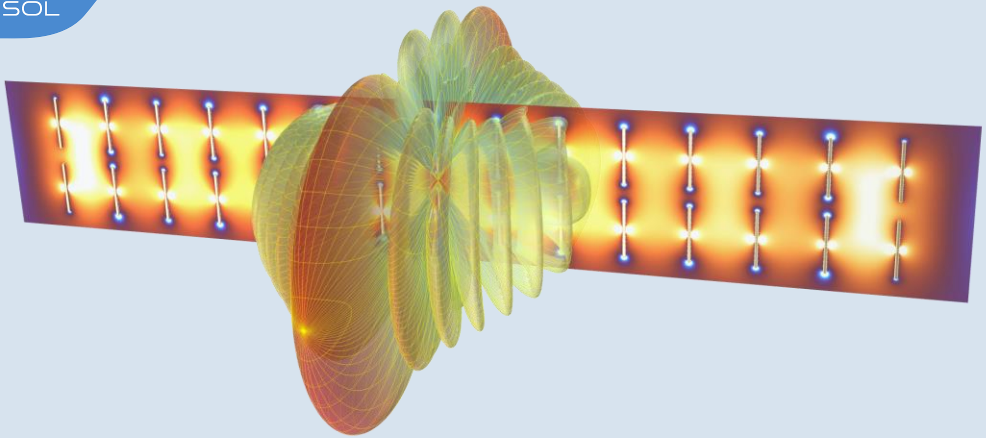


#GHz S MA R 50
3.0 0.05891382818518446 -67.81516360926776 0.92591813283265
0.03776297940906947 -16.65230114328461 0.05886362720383
0.9259141903749271 -128.9688561486247 0.037748966602644

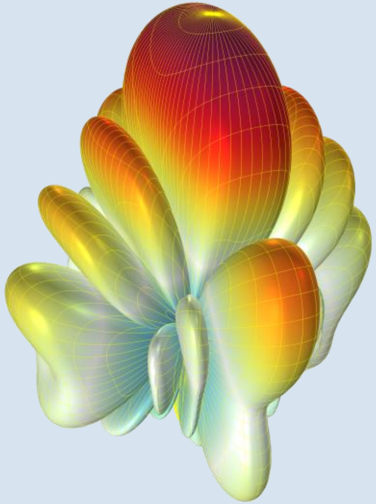




Upper left: Smith plot. Lower left: ferrite circulator. Top right: antenna array radiation pattern.



15x2 half-wave dipole antenna array modeled with the boundary element method.



Easy antenna array evaluation using array dataset.

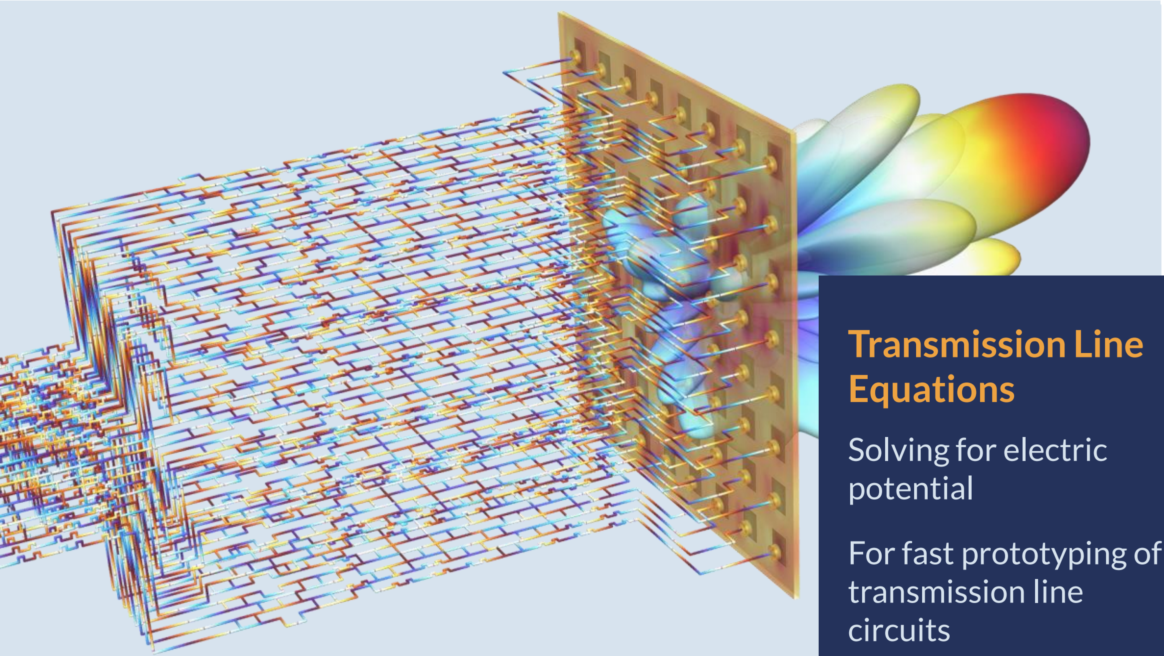
FEATURE OVERVIEW

Antenna Arrays

Moderately sized arrays can be modeled by drawing and exciting the entire array, using lumped ports with different phases. BEM can be advantageous.

Alternatively, model a single unit cell with periodic conditions and use an *Array Factor* dataset to extract the far field for an array of any size.

Additional Formulations

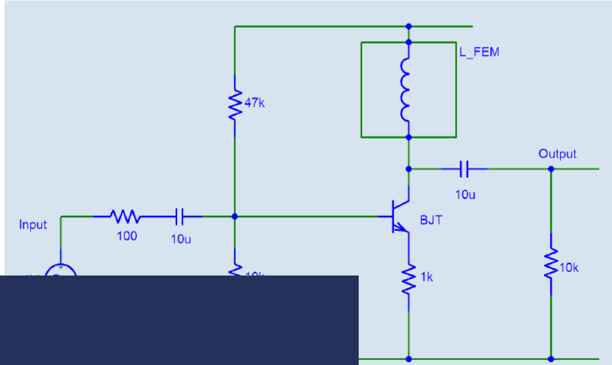


64 x 64 Butler matrix connected to 8 x 8 microstrip patch antenna array.

Transmission Line Equations

Solving for electric potential

For fast prototyping of transmission line circuits

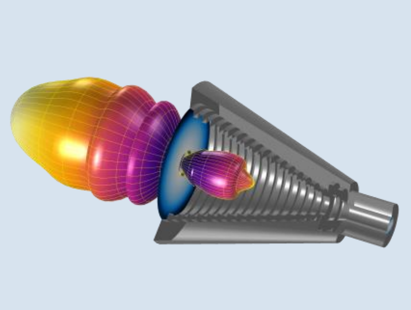


Electric Circuits

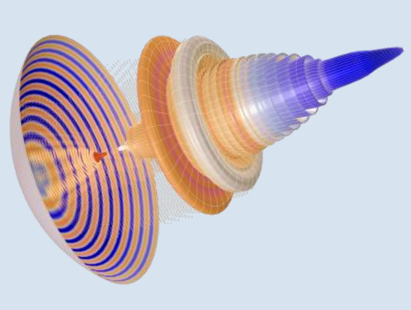
Model a lumped system of circuit elements and couple to the finite element model

FEATURE OVERVIEW

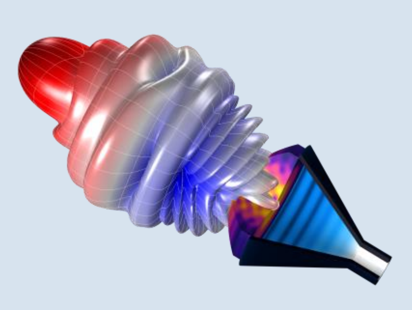
Axisymmetric Modeling



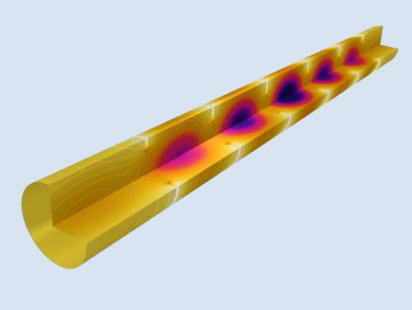
Corrugated horn antenna.



Dish reflector antenna.



Conical lens antenna.



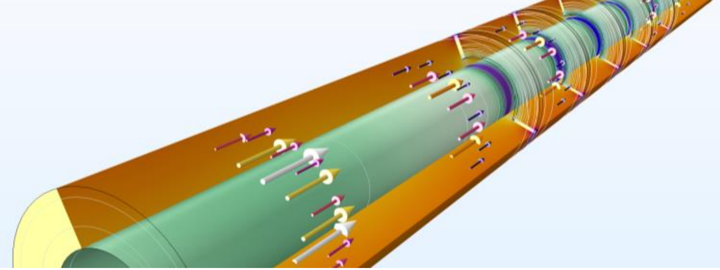
Circular waveguide filter.

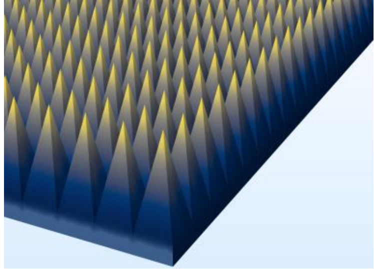
- Efficient body-of-revolution formulation for axisymmetric structures
- Fast modeling
- Possible to extract 3D results out of 2D axisymmetric simulations

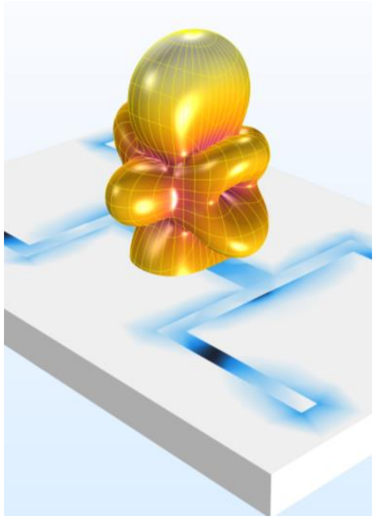
Application Library

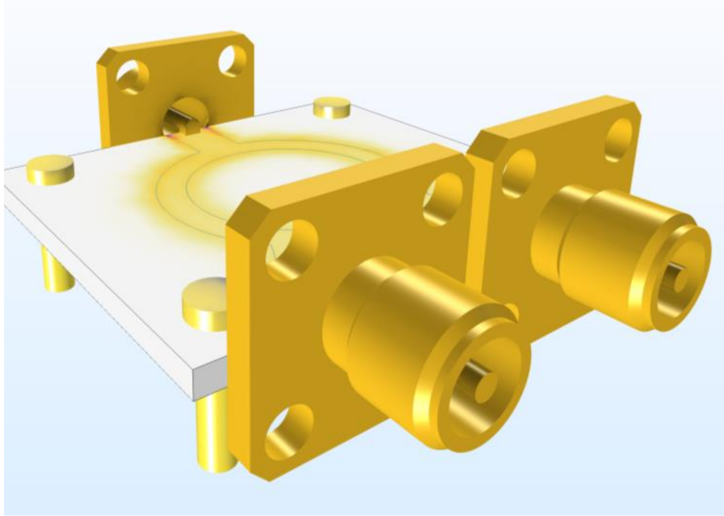
Tutorial models:

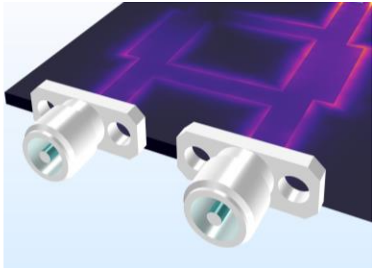
- More than 30 antenna models
- Couplers and power dividers
- EMI/EMC applications
- Ferrimagnetic devices
- Filters
- Gratings and Metamaterials
- Microwave heating
- Nonlinear Optics
- Scattering and RCS
- Transmission lines and waveguides
- Verification examples

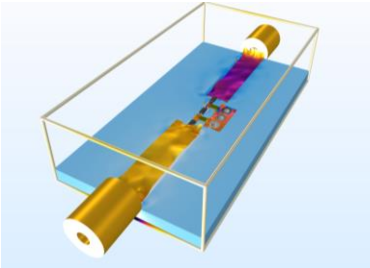










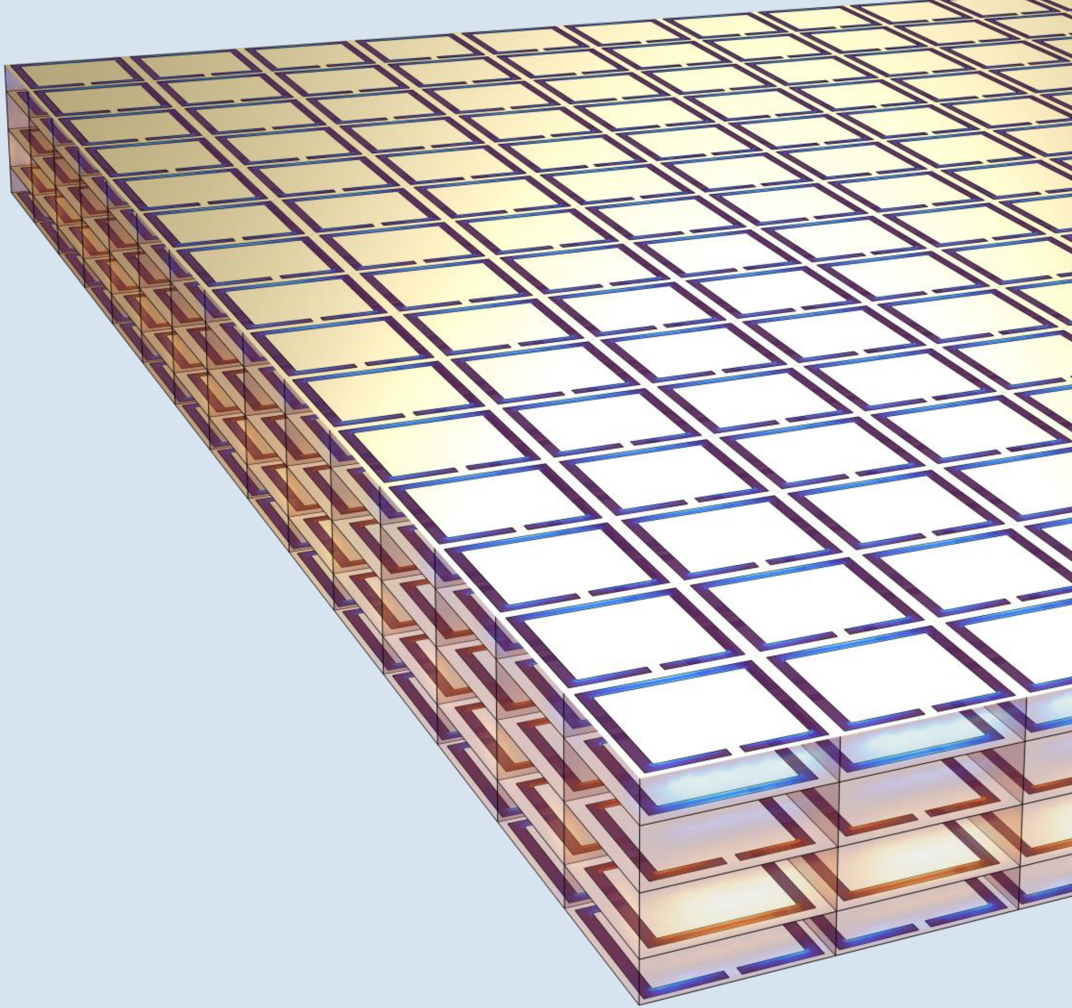


Periodic Structures

- Any structure that repeats in one, two, or all three dimensions can be treated as periodic
- Analyze a single unit cell with Floquet periodic boundary conditions:

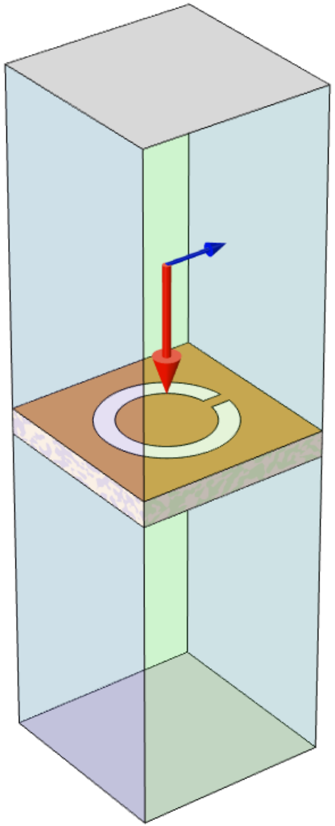
$$\mathbf{E}_d = \mathbf{E}_s \exp(-i\mathbf{k}_F \cdot (\mathbf{r}_d - \mathbf{r}_s))$$

- Typical examples:
  - Optical gratings
  - Frequency selective surfaces
  - Electromagnetic band gap structures
  - Metamaterials



Driven Periodic Problems

- Ports
  - Excitation
  - Absorption of radiation
    - Add as many as required to absorb all outgoing radiation
- Periodic, diffraction order, and orthogonal polarization ports represent plane waves propagating in the directions of the diffraction orders
  - Respect Floquet periodicity
- Periodic conditions constrain the field to fulfill Floquet periodicity

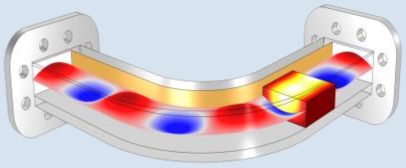


Top Ports
- Periodic port, excitation
- Orthogonal polarization port
- Diffraction order ports

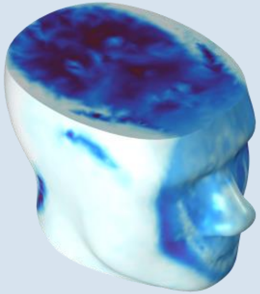
Periodic Conditions
- Left
- Right
- Back
- Front

Bottom Ports
- Periodic port, listener
- Orthogonal polarization port
- Diffraction order ports

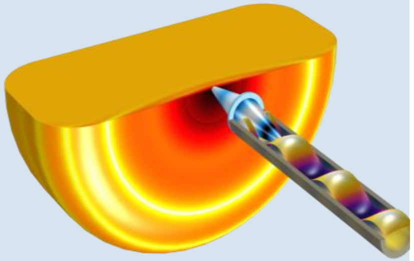
Microwave Heating



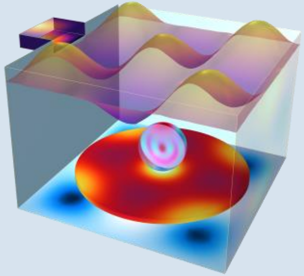
Heating of a dielectric block.



Specific absorption rate (SAR) in a human brain.



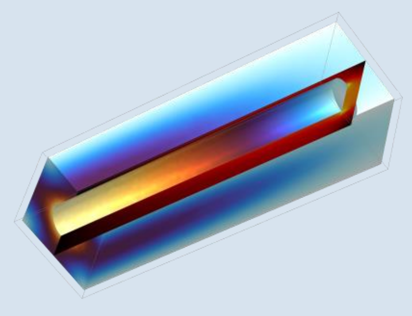
Conical dielectric probe.

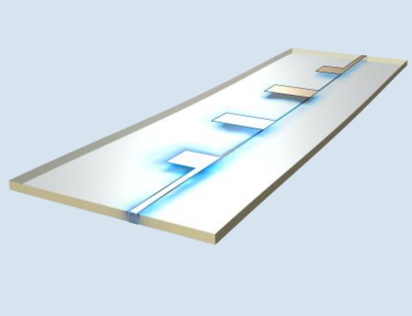


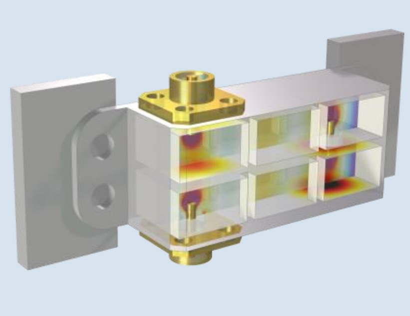
Microwave oven.

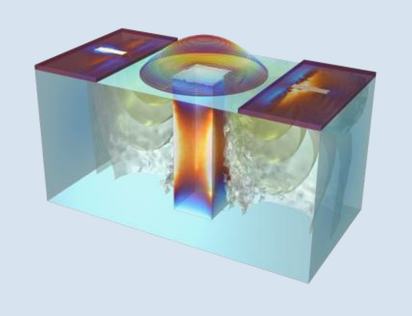
- Model heat transfer, with the electromagnetic losses as a heat source.
- *Frequency-Stationary* and *Frequency-Transient* study types handle bidirectionally coupled models, in which the electromagnetic material properties depend on the temperature.

Structural Deformations in EM Devices

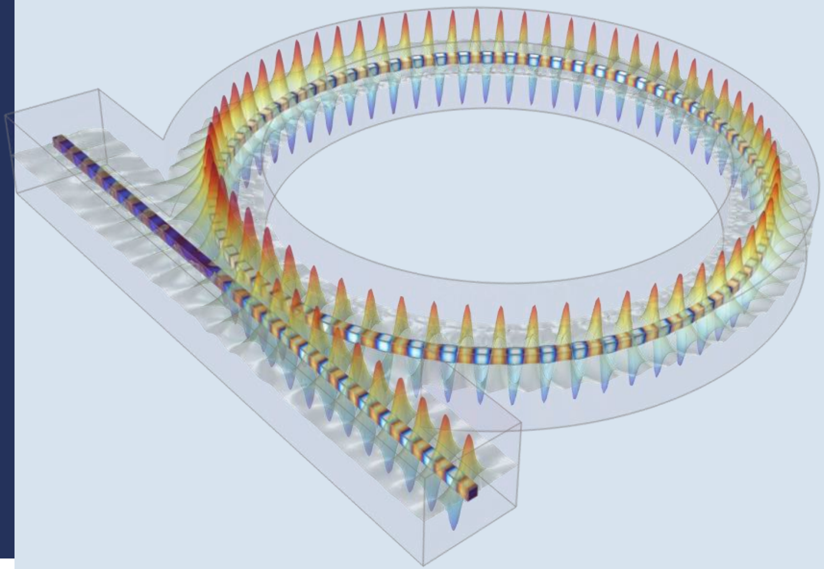

Thermal drift in a cavity filter.


Deformed PCB lowpass filter.


Thermostructural effects.


Piezoelectric tunable cavity filter.

- Model how structural deformations affect performance.
- For a narrow-band device, even a comparatively moderate thermal deformation may significantly shift the resonance. This is accurately modeled by combining structural mechanics, heat transfer, a moving mesh in the air/vacuum, and electromagnetic waves.



Optical ring resonator.

Conclusion

Used together, COMSOL Multiphysics® and the RF Module or the Wave Optics Module provide an all-in-one simulation environment with capabilities well suited for simulating electromagnetic waves. Electromagnetic properties can be considered alone or together with other physics such as heat transfer and structural mechanics.