COMSOL MULTIPHYSICS

RF MODULE

REFERENCE GUIDE

VERSION 3.4

COMSOL

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RF Module Reference Guide

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CONTENTS

Chapter 1: Introduction

Chapter 2: The Application Modes

Chapter 3: Programming Reference

Chapter 4: Function Reference

1

Introduction

The RF Module 3.4 is an optional package that extends the COMSOL Multiphysics™ modeling environment with customized user interfaces and functionality optimized for the analysis of electromagnetic waves. Like all modules in the COMSOL family it provides a library of prewritten ready-to-run models that make it quicker and easier to analyze discipline-specific problems.

This particular module solves problems in the general field of electromagnetic waves, such as RF and microwave applications, optics, and photonics. The application modes included here are fully multiphysics enabled, making it possible to couple them to any other physics application mode in COMSOL Multiphysics or the other modules. For example, to analyze stress-optical effects in a waveguide, you would first do a plane strain analysis using the Structural Mechanics Module followed by an optical mode analysis show the resulting split of the fundamental modes.

The underlying equations for electromagnetics are automatically available in all of the application modes—a feature unique to COMSOL Multiphysics. This also makes nonstandard modeling easily accessible.

The documentation set for the RF Module consists of two printed books, the *RF Module User's Guide* and the *RF Module Model Library*, and this *RF Module*

Reference Guide. All three books are available in PDF and HTML versions from the COMSOL Help Desk. This book contains reference information such as application mode implementation details, information about command-line programming, and details about the command-line functions that are specific to the RF Module (for example, a function for S-parameter extraction).

Typographical Conventions

All COMSOL manuals use a set of consistent typographical conventions that should make it easy for you to follow the discussion, realize what you can expect to see on the screen, and know which data you must enter into various data-entry fields. In particular, you should be aware of these conventions:

- A **boldface** font of the shown size and style indicates that the given word(s) appear exactly that way on the COMSOL graphical user interface (for toolbar buttons in the corresponding tooltip). For instance, we often refer to the **Model Navigator**, which is the window that appears when you start a new modeling session in COMSOL; the corresponding window on the screen has the title **Model Navigator**. As another example, the instructions might say to click the **Multiphysics** button, and the boldface font indicates that you can expect to see a button with that exact label on the COMSOL user interface.
- The names of other items on the graphical user interface that do not have direct labels contain a leading uppercase letter. For instance, we often refer to the Draw toolbar; this vertical bar containing many icons appears on the left side of the user interface during geometry modeling. However, nowhere on the screen will you see the term “Draw” referring to this toolbar (if it were on the screen, we would print it in this manual as the **Draw** menu).
- The symbol **>** indicates a menu item or an item in a folder in the **Model Navigator**. For example, **Physics>Equation System>Subdomain Settings** is equivalent to: On the **Physics** menu, point to **Equation System** and then click **Subdomain Settings**. **COMSOL Multiphysics>Heat Transfer>Conduction** means: Open the **COMSOL Multiphysics** folder, open the **Heat Transfer** folder, and select **Conduction**.
- A `Code` (monospace) font indicates keyboard entries in the user interface. You might see an instruction such as “Type `1.25` in the **Current density** edit field.” The monospace font also indicates COMSOL Script codes.
- An *italic* font indicates the introduction of important terminology. Expect to find an explanation in the same paragraph or in the Glossary. The names of books in the COMSOL documentation set also appear using an italic font.

2

The Application Modes

The Application Mode Variables

The application modes in the RF Module define a large set of variables. The purpose of this reference chapter is to list all the variables that each application mode define. Other information, like the theoretical background for the application mode, can be found in chapter "The Application Modes" on page 105 of the *RF Module User's Guide*.

The *Application Mode Variables* section lists all variables that are available in postprocessing and when formulating the equations. You can use any function of these variables when postprocessing the result of the analysis. It is also possible to use these variables in the expressions for the physical properties in the equations.

The application mode variable tables are organized as follows:

- The **Name** column lists the names of the variables that you can use in the expressions in the equations or for postprocessing. The indices *i* and *j* (using an italic font) in the variable names can mean any of the spatial coordinates. For example, E*i* means either Ex, Ey, Ez in 3D when the spatial coordinates are x, y, and z. In 2D axisymmetry E*i* stands for either Er or Ez. The variable names of vector and tensor components are constructed using the names of the spatial coordinates. For example, if you use x1, y1, and z1 as the spatial coordinate names, the variables for the vector components of the electric field are Ex1, Ey1, and Ez1.

  In a COMSOL Multiphysics model, the variable names get an underscore plus the application mode name appended to the names listed in the tables. For example, the default name of the Electrostatics application mode is emes. With this name the variable for the x component of the electric field is Ex_emes.
- The **Analysis** column specifies for which type of analysis the variable is defined. The available analysis types are, for example, static, transient, harmonic, and eigenfrequency. The available analysis types are application-mode dependent. Some variables are defined differently depending on the analysis type, and others are only available for some analysis types.
- The **Constitutive Relation** column indicates the constitutive relation for which the variable definition applies. The abbreviations used are defined in the table below.

ABBREVIATION	CONSTITUTIVE RELATION
epsr	$\mathbf{D} = \varepsilon_0\varepsilon_r\mathbf{E}$
P	$\mathbf{D} = \varepsilon_0\mathbf{E} + \mathbf{P}$

ABBREVIATION	CONSTITUTIVE RELATION
`Dr`	$\mathbf{D} = \varepsilon_0\varepsilon_r\mathbf{E} + \mathbf{D}_r$
`mur`	$\mathbf{B} = \mu_0\mu_r\mathbf{H}$
`M`	$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$
`Br`	$\mathbf{B} = \mu_0\mu_r\mathbf{H} + \mathbf{B}_r$

- The **Material Parameters** column appears in the tables for the electromagnetic waves application modes. It indicates if the refractive index n or the relative permeability ε_r, the conductivity σ, and the relative permeability μ_r are used as material parameters in the expression for the variable.
- The **Description** column gives a description of the variables.
- The **Expression** column gives the expression of the variables in terms of other physical quantities. In these expressions, the subscripts i and j of vector and tensor components stand for one of the spatial coordinates. For example, E_i is either E_x, E_y, or E_z. When two equal subscripts appear in an expression this implies a summation. For example $\sigma_{ij}E_j = \sigma_{ix}E_x + \sigma_{iy}E_y + \sigma_{iz}E_z$.

Electromagnetic Waves

A number of variables and physical quantities are available for postprocessing and for use in equations and boundary conditions. They are all given in the tables below.

See page 6 for a description of the notation used in these tables. The *up* and *down* subscripts indicate that the variable should be evaluated on the geometrical up or down side of the boundary. A letter t in front of a vector quantity for a boundary variable means the tangential vector on boundaries.

Common Variables for the Application Modes

All the components of the electric and magnetic field quantities are available for postprocessing and for use in equations and boundary conditions. The different energy quantities are also available.

See page 6 for a description of the notation used in the tables.

APPLICATION SCALAR VARIABLES

The application-specific variables in this mode are given in the following table.

TABLE 2-1: COMMON APPLICATION MODE SCALAR VARIABLES

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
`lambda0`	harmonic, mode analysis, λ_0 is input	free space wavelength	λ_0
`lambda0`	harmonic, mode analysis, ν is input	free space wavelength	$\frac{1}{\nu\sqrt{\varepsilon_0\mu_0}}$
`lambda0`	eigenfrequency	free space wavelength	$2\pi/k_0$
`omega`	harmonic, mode analysis	angular frequency	$2\pi\nu$
`omega`	eigenfrequency	angular frequency	$\mathrm{Im}(-\lambda)$
`nu`	harmonic, mode analysis, λ_0 is input	frequency	$\frac{1}{\lambda_0\sqrt{\varepsilon_0\mu_0}}$
`nu`	harmonic, mode analysis, ν is input	frequency	ν

TABLE 2-1: COMMON APPLICATION MODE SCALAR VARIABLES

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
nu	eigenfrequency	frequency	$\frac{\omega}{2\pi}$
k0	harmonic, mode analysis, eigenfrequency	free space wave number	$\omega\sqrt{\varepsilon_0\mu_0}$
c0		speed of light	$\frac{1}{\sqrt{\varepsilon_0\mu_0}}$
epsilon0		permittivity of vacuum	ε_0
mu0		permeability of vacuum	μ_0
damp	eigenfrequency	damping coefficient	$\delta = \mathrm{Re}(\lambda)$
Qfact	eigenfrequency	quality factor	$\frac{\omega}{2\lvert\delta\rvert}$

APPLICATION SUBDOMAIN VARIABLES

The subdomain variables are given the table below. Note that depending on application mode some field components may be zero. Suitable simplifications are then made on constitutive relations and expressions.

TABLE 2-2: COMMON APPLICATION MODE SUBDOMAIN VARIABLES

NAME	ANALYSIS	MAT. PARAMS	CONST. REL.	DESCRIPTION	EXPRESSION
k	harmonic, mode analysis			wave number	$k_0\sqrt{\mu_r\left(\varepsilon_r - j\frac{\sigma}{\omega\varepsilon_0}\right)}$
k	eigenfrequency			wave number	$k_0\sqrt{\mu_r\varepsilon_r}$
c				phase velocity	$\frac{c_0}{\sqrt{\mu_r\varepsilon_r}}$
Z_wave				wave impedance	$c_0\mu_0\mu_r$
mur		n		relative permeability	1
mur*ij*		n		relative permeability, x_ix_j component	1

TABLE 2-2: COMMON APPLICATION MODE SUBDOMAIN VARIABLES

NAME	ANALYSIS	MAT. PARAMS	CONST. REL.	DESCRIPTION	EXPRESSION
mur		epsr	M	relative permeability	1
mur		epsr	mur, Br	relative permeability	μ_r
mur*ij*		epsr	mur, Br	relative permeability, x_ix_j component	μ_{rij}
mu				permeability	$\mu_0\mu_r$
mu*ij*				permeability, x_ix_j component	$\mu_0\mu_{rij}$
n		n		refractive index	n
n*ij*		n		refractive index, x_ix_j component	n_{ij}
n		epsr		refractive index	$\sqrt{\varepsilon_r}$
n*ij*		epsr		refractive index, x_ix_j component	$(\sqrt{\varepsilon_r})_{ij}$
epsilonr		n		relative permittivity	n^2
epsilonr*ij*		n		relative permittivity, x_ix_j component	$n_{ik}n_{kj}$
epsilonr		epsr	P	relative permittivity	1
epsilonr		epsr	epsr, Dr	relative permittivity	ε_r
epsilonr*ij*		epsr		relative permittivity, x_ix_j component	ε_{rij}
epsilon				permittivity	$\varepsilon_0\varepsilon_r$
epsilon*ij*				permittivity, x_ix_j component	$\varepsilon_0\varepsilon_{rij}$
sigma		n		electric conductivity	0
sigma*ij*		n		electric conductivity, x_ix_j component	0

TABLE 2-2: COMMON APPLICATION MODE SUBDOMAIN VARIABLES

NAME	ANALYSIS	MAT. PARAMS	CONST. REL.	DESCRIPTION	EXPRESSION
sigma		epsr		electric conductivity	σ
sigma*ij*		epsr		electric conductivity, x_ix_j component	σ_{ij}
delta	harmonic, mode analysis			skin depth	$\frac{1}{\omega\sqrt{\frac{1}{2}\mu\varepsilon\left(\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1\right)}}$
P*i*	transient	epsr	P	electric polarization, x_i component	P_i
P*i*	transient	epsr	Dr, epsr	electric polarization, x_i component	$D_i - \varepsilon_0 E_i$
Dr*i*	transient	epsr	epsr	remanent displacement, x_i component	0
Dr*i*	transient	epsr	P	remanent displacement, x_i component	P_i
Dr*i*	transient	epsr	Dr	remanent displacement, x_i component	D_{ri}
M*i*	transient	epsr	M	magnetization, x_i component	M_i
M*i*	transient	epsr	mur, Br	magnetization, x_i component	$\frac{B_i}{\mu_0} - H_i$
Br*i*	transient	epsr	mur	remanent flux density, x_i component	0
Br*i*	transient	epsr	M	remanent flux density, x_i component	$\mu_0 M_i$
Br*i*	transient	epsr	Br	remanent flux density, x_i component	B_{ri}

TABLE 2-2: COMMON APPLICATION MODE SUBDOMAIN VARIABLES

NAME	ANALYSIS	MAT. PARAMS	CONST. REL.	DESCRIPTION	EXPRESSION
E*i*	**E** dependent variable			electric field, x_i component	E_i
E*i*	**H** dependent variable			electric field, x_i component	$-\frac{j}{\omega\varepsilon_0}\left(\varepsilon_r - j\frac{\sigma}{\omega\varepsilon_0}\right)^{-1}_{ij}(\nabla\times\mathbf{H})_j$
E*i*	transient			electric field, x_i component	$-\frac{\partial A_i}{\partial t}$
normE				electric field, norm	$\sqrt{\mathbf{E}\cdot\mathbf{E}^*}$
D*i*				electric displacement, x_i component	$\varepsilon_{ij}E_j$
normD				electric displacement, norm	$\sqrt{\mathbf{D}\cdot\mathbf{D}^*}$
B*i*	**H** dependent variable			magnetic flux density, x_i component	$\mu_{ij}H_j$
B*i*	**E** dependent variable			magnetic flux density, x_i component	$\frac{j}{\omega}(\nabla\times\mathbf{E})_i$
B*i*	transient			magnetic flux density, x_i component	$(\nabla\times\mathbf{A})_i$
normB				magnetic flux density, norm	$\sqrt{\mathbf{B}\cdot\mathbf{B}^*}$
H*i*	**H** dependent variable			magnetic field, x_i component	H_i
H*i*	**E** dependent variable or transient			magnetic field, x_i component	$\mu^{-1}_{rij}B_j/\mu_0$
normH				magnetic field, norm	$\sqrt{\mathbf{H}\cdot\mathbf{H}^*}$
Weav	harmonic, mode analysis, eigenfrequency			time average electric energy	$\frac{1}{4}\mathrm{Re}(\mathbf{E}\cdot\mathbf{D}^*)$

TABLE 2-2: COMMON APPLICATION MODE SUBDOMAIN VARIABLES

NAME	ANALYSIS	MAT. PARAMS	CONST. REL.	DESCRIPTION	EXPRESSION
Wmav	harmonic, mode analysis, eigenfrequency			time average magnetic energy	$\frac{1}{4}\mathrm{Re}(\mathbf{B}\cdot\mathbf{H}^*)$
Wav	harmonic, mode analysis, eigenfrequency			time average total energy	$W_e^{\mathrm{av}} + W_m^{\mathrm{av}}$
Qav	harmonic, mode analysis, eigenfrequency			time average resistive heating	$\frac{1}{2}\mathrm{Re}(\sigma\mathbf{E}\cdot\mathbf{E}^* - j\omega\mathbf{E}\cdot\mathbf{D}^*)$
Po*i*av	harmonic, mode analysis, eigenfrequency			time average power flow x_i component	$\frac{1}{2}\mathrm{Re}(\mathbf{E}\times\mathbf{H}^*)_i$
normPoav	harmonic, mode analysis, eigenfrequency			time average power flow, norm	$\sqrt{\mathbf{S}^{\mathrm{av}}\cdot\mathbf{S}^{\mathrm{av}*}}$
We	transient			electric energy	$\frac{1}{2}(\mathbf{E}\cdot\mathbf{D})$
Wm	transient			magnetic energy	$\frac{1}{2}(\mathbf{B}\cdot\mathbf{H})$
W	transient			total energy	$W_e + W_m$
Q	transient			resistive heating	$\left(\sigma\mathbf{E} - \frac{\partial\mathbf{D}}{\partial t}\right)\cdot\mathbf{E}$
Po*i*	transient			power flow x_i component	$(\mathbf{E}\times\mathbf{H})_i$
normPo	transient			power flow, norm	$\sqrt{\mathbf{S}\cdot\mathbf{S}^*}$
dr_guess				default guess for width in radial direction	Δ_r
R0_guess				default guess for inner radius	R_0
S*i*				infinite element x_i coordinate	s_i

TABLE 2-2: COMMON APPLICATION MODE SUBDOMAIN VARIABLES

NAME	ANALYSIS	MAT. PARAMS	CONST. REL.	DESCRIPTION	EXPRESSION
Sd*i*_guess				default guess for width along x_i coordinate	Δ_i
dVol				Volume integration contribution	dV

APPLICATION BOUNDARY VARIABLES

The boundary variables are given in the table below.

TABLE 2-3: COMMON APPLICATION MODE BOUNDARY VARIABLES

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
normJs		surface current density, norm	$\sqrt{\mathbf{J}_s \cdot \mathbf{J}_s^*}$
nPoav		normal power flow	$\mathbf{n} \cdot \mathbf{S}^{\mathrm{av}}$
Qs	transient	surface resistive heating	$\mathbf{J}_s \cdot t\mathbf{E}$
Qsav	harmonic, eigenfrequency, mode analysis	time average surface resistive heating	$\frac{1}{2}\mathrm{Re}(\mathbf{J}_s \cdot t\mathbf{E}^*)$
deltabnd	harmonic, eigenfrequency, mode analysis, impedance cond.	skin depth	$\dfrac{1}{\omega\sqrt{\frac{1}{2}\mu\varepsilon\left(\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1\right)}}$
dVolbnd		Area integration contribution	dA

3D Electromagnetic Waves Application Mode

Below is the variables listed that differ from the list of common variables in "Common Variables for the Application Modes" on page 8. If you do not find a variable in the list below, it can be in the list of common variables. Note that no mode analysis is available for 3D Electromagnetic Waves.

APPLICATION SCALAR VARIABLES

No differences exist between the list of variables in "Application Scalar Variables" on page 8.

APPLICATION MODE SUBDOMAIN VARIABLES

No differences exist between the list of variables in “Application Subdomain Variables” on page 9.

APPLICATION BOUNDARY VARIABLES

The boundary variables are given in the table below.

TABLE 2-4: APPLICATION MODE BOUNDARY VARIABLES

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
`Js`*i*	**H** dependent variable	surface current density, x_i component	$-\mathbf{n}\times t\mathbf{H}$
`Js`*i*	**E** dependent variable, transient	surface current density, x_i component	$\mathbf{n}_{\mathrm{up}}\times(t\mathbf{H}_{\mathrm{down}}-t\mathbf{H}_{\mathrm{up}})$
`tH`*i*	**H** dependent variable	tangential magnetic field, x_i component	tH_i
`tH`*i*	**E** dependent variable or transient	tangential magnetic field, x_i component	$H_i-(\mathbf{n}\cdot\mathbf{H})n_i$
`normtH`		tangential magnetic field, norm	$\sqrt{t\mathbf{H}\cdot t\mathbf{H}^*}$
`tE`*i*	**E** dependent variable	tangential electric field, x_i component	tE_i
`tE`*i*	**H** dependent variable	tangential electric field, x_i component	$E_i-(\mathbf{n}\cdot\mathbf{E})n_i$
`tE`*i*	transient	tangential electric field, x_i component	$\frac{\partial}{\partial t}tA_i$
`normtE`		tangential electric field, norm	$\sqrt{t\mathbf{E}\cdot t\mathbf{E}^*}$

In-Plane Waves Application Mode

Below is the variables listed that differ from the list of common variables in “Common Variables for the Application Modes” on page 8. If you do not find a variable in the list below, it can be in the list of common variables. Note that no mode analysis is available for In-Plane Waves.

See page 6 for a description of the notation used in the tables.

APPLICATION SCALAR VARIABLES

No differences exist between the list of variables in "Application Scalar Variables" on page 8.

APPLICATION MODE SUBDOMAIN VARIABLES

The variables for hybrid-mode waves is simply the sum of the variable sets from TE waves and TM waves.

TABLE 2-5: APPLICATION MODE SUBDOMAIN VARIABLES, IN-PLANE TE WAVES

NAME	ANALYSIS	MAT. PARAMS	CONST. REL.	DESCRIPTION	EXPRESSION
Ez	harmonic, eigenfrequency			electric field, z component	E_z
Ez	transient			electric field, z component	$-\frac{\partial A_z}{\partial t}$
Bx	harmonic, eigenfrequency			magnetic flux density, x component	$\frac{j}{\omega}\frac{\partial E_z}{\partial y}$
By	harmonic, eigenfrequency			magnetic flux density, y component	$-\frac{j}{\omega}\frac{\partial E_z}{\partial x}$
Bx	transient			magnetic flux density, x component	$\frac{\partial A_z}{\partial y}$
By	transient			magnetic flux density, y component	$-\frac{\partial A_z}{\partial x}$

TABLE 2-6: APPLICATION MODE SUBDOMAIN VARIABLES, IN-PLANE TM WAVES

NAME	ANALYSIS	MAT. PARAMS	CONST. REL.	DESCRIPTION	EXPRESSION
Hz	harmonic, eigenfrequency			magnetic field, z component	H_z
Hz	transient			magnetic field, z component	$\mu_{rij}^{-1}\frac{B_z}{\mu_0}$

TABLE 2-6: APPLICATION MODE SUBDOMAIN VARIABLES, IN-PLANE TM WAVES

NAME	ANALYSIS	MAT. PARAMS	CONST. REL.	DESCRIPTION	EXPRESSION
Bz	harmonic, eigenfrequency			magnetic flux density, z component	μH_z
Bz	transient			magnetic flux density, z component	$\frac{\partial A_y}{\partial x} - \frac{\partial A_x}{\partial y}$

APPLICATION MODE BOUNDARY VARIABLES

The variables for hybrid-mode waves is simply the sum of the variable sets from TE waves and TM waves.

TABLE 2-7: APPLICATION MODE BOUNDARY VARIABLES, IN-PLANE TE WAVES

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
Jsz		surface current density, z component	$n_{\mathrm{xup}}(H_{\mathrm{ydown}} - H_{\mathrm{yup}}) - n_{y\mathrm{up}}(H_{x\mathrm{down}} - H_{x\mathrm{up}})$

TABLE 2-8: APPLICATION MODE BOUNDARY VARIABLES, IN-PLANE TM WAVES

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
Jsz	transient	surface current density, z component	$n_{\mathrm{xup}}(H_{\mathrm{ydown}} - H_{\mathrm{yup}}) - n_{y\mathrm{up}}(H_{x\mathrm{down}} - H_{x\mathrm{up}})$

Axisymmetric Waves Application Mode

Below is the variables listed that differ from the list of common variables in "Common Variables for the Application Modes" on page 8. If you do not find a variable in the list below, it can be in the list of common variables. Note that no mode analysis is available for Axisymmetric Waves.

See page 6 for a description of the notation used in the tables.

APPLICATION SCALAR VARIABLES

No differences exist between the list of variables in "Application Scalar Variables" on page 8.

APPLICATION MODE VARIABLES

The expressions for the refractive index and relative permittivity differ depending on which of the two is given as input in the equation.

The subdomain variables for axisymmetric TE and TM waves are given below in two tables. The variables for hybrid-mode waves is simply the sum of the two tables.

TABLE 2-9: APPLICATION MODE SUBDOMAIN VARIABLES, AXISYMMETRIC TE WAVES

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
`Ephidr`	harmonic, eigenfrequency	electric field divided by r	u
`Aphidr`	transient	magnetic potential divided by r	u
`Ephi`	harmonic, eigenfrequency	electric field, φ component	ru
`Ephir`	harmonic, eigenfrequency	electric field, r derivative of φ component	$r\frac{\partial u}{\partial r}+u$
`Ephiz`	harmonic, eigenfrequency	electric field, z derivative of φ component	$r\frac{\partial u}{\partial z}$
`Aphi`	transient	magnetic potential, φ component	ru
`Aphir`	transient	magnetic potential, r derivative of φ component	$r\frac{\partial u}{\partial r}+u$
`Aphiz`	transient	magnetic potential, z derivative of φ component	$r\frac{\partial u}{\partial z}$
`Aphit`	transient	magnetic potential, time-derivative of φ component	$r\frac{\partial u}{\partial t}$
`Ephi`	transient	electric field, φ component	$\frac{\partial A_\varphi}{\partial t}$
`Br`	harmonic, eigenfrequency	magnetic flux density, r component	$-\frac{j}{\omega}\frac{\partial E_\varphi}{\partial z}$

TABLE 2-9: APPLICATION MODE SUBDOMAIN VARIABLES, AXISYMMETRIC TE WAVES

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
Bz	harmonic, eigenfrequency	magnetic flux density, z component	$\frac{j}{\omega}\left(u+\frac{\partial E_{\varphi}}{\partial r}\right)$
Br	transient	magnetic flux density, r component	$-\frac{\partial A_{\varphi}}{\partial z}$
Bz	transient	magnetic flux density, z component	$u+\frac{\partial A_{\varphi}}{\partial r}$

TABLE 2-10: APPLICATION MODE SUBDOMAIN VARIABLES, AXISYMMETRIC TM WAVES

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
Hphidr	harmonic, eigenfrequency	magnetic field divided by r	u
Hphi	harmonic, eigenfrequency	magnetic field, φ component	ru
Hphir	harmonic, eigenfrequency	magnetic field, r derivative of φ component	$r\frac{\partial u}{\partial r}+u$
Hphiz	harmonic, eigenfrequency	magnetic field, z derivative of φ component	$r\frac{\partial u}{\partial z}$
Hphi	transient	magnetic field, φ component	$\mu_{rij}^{-1}\frac{B_j}{\mu_0}$
Bphi	harmonic, eigenfrequency	magnetic flux density, φ component	μH_{φ}
Bphi	transient	magnetic flux density, φ component	$\frac{\partial A_r}{\partial z}-\frac{\partial A_z}{\partial r}$

APPLICATION MODE BOUNDARY VARIABLES

The boundary variables for axisymmetric TE and TM waves are given below in two tables. The variables for hybrid-mode waves is simply the sum of the two tables.

TABLE 2-11: APPLICATION MODE BOUNDARY VARIABLES, AXISYMMETRIC TE WAVES

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
Jsphi		surface current density, φ component	$n_{z\text{up}}(H_{r\text{down}} - H_{r\text{up}}) - n_{r\text{up}}(H_{z\text{down}} - H_{z\text{up}})$

TABLE 2-12: APPLICATION MODE BOUNDARY VARIABLES, AXISYMMETRIC TM WAVES

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
Jsphi	transient	surface current density, φ component	$n_{z\text{up}}(H_{r\text{down}} - H_{r\text{up}}) - n_{r\text{up}}(H_{z\text{down}} - H_{z\text{up}})$

Perpendicular Waves Application Mode

Below is the variables listed that differ from the list of common variables in "Common Variables for the Application Modes" on page 8. If you do not find a variable in the list below, it can be in the list of common variables. Note that no harmonic or transient analysis is available for Perpendicular Waves.

See page 6 for a description of the notation used in the tables.

APPLICATION SCALAR VARIABLES

The application-specific variables in this mode are given in the following table.

TABLE 2-13: APPLICATION MODE SCALAR VARIABLES, PERPENDICULAR WAVES

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
beta	mode analysis	propagation constant	$\mathrm{Im}(-\lambda)$
beta	eigenfrequency	propagation constant	β
neff		effective mode index	β / k_0
dampz	mode analysis	attenuation coefficient	$\delta_z = \mathrm{Re}(-\lambda)$

TABLE 2-13: APPLICATION MODE SCALAR VARIABLES, PERPENDICULAR WAVES

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
dampz	eigenfrequency	attenuation coefficient	$\delta_z = \mathrm{Re}(j\beta)$
dampzdB		attenuation, dB scale	$20\delta_z \log e$

APPLICATION MODE SUBDOMAIN VARIABLES

The subdomain variables for TM waves, TE waves, Hybrid-mode waves H-field formulation, and Hybrid-mode waves E-field formulation are listed in four tables below in the given order.

TABLE 2-14: APPLICATION MODE VARIABLES, PERPENDICULAR TM WAVES

NAME	ANALYSIS	MAT. PARAMS	DESCRIPTION	EXPRESSION
Ex	mode analysis		electric field, x component	$\frac{j\beta}{(\sigma + j\omega\varepsilon)} H_y$
Ex	eigenfrequency		electric field, x component	$\frac{\beta}{\omega\varepsilon} H_y$
Ey	mode analysis		electric field, y component	$-\frac{j\beta}{(\sigma + j\omega\varepsilon)} H_x$
Ey	eigenfrequency		electric field, y component	$-\frac{\beta}{\omega\varepsilon} H_x$
Ez			electric field, z component	E_z
Hx	mode analysis		magnetic field, x component	$\frac{\sigma + j\omega\varepsilon}{k^2 - \beta^2} \frac{\partial E_z}{\partial y}$
Hx	eigenfrequency		magnetic field, x component	$\frac{j\omega\varepsilon}{k^2 - \beta^2} \frac{\partial E_z}{\partial y}$
Hy	mode analysis		magnetic field, y component	$-\frac{\sigma + j\omega\varepsilon}{k^2 - \beta^2} \frac{\partial E_z}{\partial x}$
Hy	eigenfrequency		magnetic field, y component	$-\frac{j\omega\varepsilon}{k^2 - \beta^2} \frac{\partial E_z}{\partial x}$

TABLE 2-15: APPLICATION MODE VARIABLES, PERPENDICULAR TE WAVES

NAME	ANALYSIS	MAT. PARAMS	DESCRIPTION	EXPRESSION
Hx			magnetic field, x component	$-\frac{\beta}{\omega\mu}E_y$
Hy			magnetic field, y component	$\frac{\beta}{\omega\mu}E_x$
Hz			magnetic field, z component	H_z
Ex			electric field, x component	$-\frac{j\omega\mu}{k^2-\beta^2}\frac{\partial H_z}{\partial y}$
Ey			electric field, y component	$\frac{j\omega\mu}{k^2-\beta^2}\frac{\partial H_z}{\partial x}$

TABLE 2-16: APPLICATION MODE VARIABLES, PERPENDICULAR HYBRID-MODE WAVES, MAGNETIC FIELD DEPENDENT VARIABLE

NAME	ANALYSIS	MAT. PARAMS	DESCRIPTION	EXPRESSION
Hz	two-component		magnetic field, z component	$-\frac{j}{\beta\mu_{rzz}}(\nabla_t \cdot \mu_{rt}\mathbf{H}_t)$
Hz	three-component formulation		magnetic field, z component	αh_z

TABLE 2-17: APPLICATION MODE VARIABLES, PERPENDICULAR HYBRID-MODE WAVES, ELECTRIC FIELD DEPENDENT VARIABLE

NAME	ANALYSIS	MAT. PARAMS	DESCRIPTION	EXPRESSION
Ez	two-component		electric field, z component	$-\frac{j}{\beta\varepsilon_{rzz}}(\nabla_t \cdot \varepsilon_{rt}\mathbf{E}_t)$
Ez	three-component formulation		electric field, z component	αe_z

APPLICATION BOUNDARY VARIABLES

The boundary variables for TM waves, TE waves, Hybrid-mode waves H-field formulation, and Hybrid-mode waves E-field formulation are listed in four tables below in the given order.

TABLE 2-18: APPLICATION MODE VARIABLES, PERPENDICULAR TM WAVES

NAME	DESCRIPTION	EXPRESSION
Jsz	surface current density, z component	$n_{x\mathrm{up}}(H_{y\mathrm{down}} - H_{y\mathrm{up}}) - n_{y\mathrm{up}}(H_{x\mathrm{down}} - H_{x\mathrm{up}})$

TABLE 2-19: APPLICATION MODE VARIABLES, PERPENDICULAR TE WAVES

NAME	DESCRIPTION	EXPRESSION
Jsx	surface current density, x component	$-n_y H_z$
Jsy	surface current density, y component	$n_x H_z$
Jsz	surface current density, z component	$n_y H_x - n_x H_y$

TABLE 2-20: APPLICATION MODE VARIABLES, PERPENDICULAR HYBRID-MODE WAVES, MAGNETIC FIELD DEPENDENT VARIABLE

NAME	DESCRIPTION	EXPRESSION
Jsx	surface current density, x component	$-n_y H_z$
Jsy	surface current density, y component	$n_x H_z$
Jsz	surface current density, z component	$n_y H_x - n_x H_y$

TABLE 2-21: APPLICATION MODE VARIABLES, PERPENDICULAR HYBRID-MODE WAVES, ELECTRIC FIELD DEPENDENT VARIABLE

NAME	DESCRIPTION	EXPRESSION
Jsx	surface current density, x component	$n_{y\mathrm{up}}(H_{z\mathrm{down}}-H_{z\mathrm{up}})$
Jsy	surface current density, y component	$-n_{x\mathrm{up}}(H_{z\mathrm{down}}-H_{z\mathrm{up}})$
Jsz	surface current density, z component	$n_{x\mathrm{up}}(H_{y\mathrm{down}}-H_{y\mathrm{up}})$ $-n_{y\mathrm{up}}(H_{x\mathrm{down}}-H_{x\mathrm{up}})$

Boundary Mode Analysis Application Mode in 3D

Below is the variables listed that differ from the list of common variables in “Common Variables for the Application Modes” on page 8. If you do not find a variable in the list below, it can be in the list of common variables. Note that only mode analysis is available for Boundary Mode Analysis in 3D.

See page 6 for a description of the notation used in the tables.

APPLICATION SCALAR VARIABLES

The application-specific variables in this mode are given in the following table.

TABLE 2-22: APPLICATION MODE SCALAR VARIABLES, BOUNDARY MODE ANALYSIS

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
beta		propagation constant	$\mathrm{Im}(-\lambda)$
neff		effective mode index	β/k_0
dampz		attenuation coefficient	$\delta_z=\mathrm{Re}(-\lambda)$
dampzdB		attenuation, dB scale	$20\delta_z\log e$

APPLICATION MODE BOUNDARY VARIABLES

The boundary variables for TM waves, TE waves, and Hybrid-mode waves are listed in three tables below in the given order.

TABLE 2-23: APPLICATION MODE VARIABLES, BOUNDARY MODE ANALYSIS, TM WAVES

NAME	MAT. PARAMS	DESCRIPTION	EXPRESSION
tE*i*		tangential electric field, x_i component	$\frac{j\beta}{(\sigma+j\omega\varepsilon)}(\mathbf{n}\times\mathbf{H}_t)_i$
En		electric field, normal component	je_n
tD*i*		tangential electric displacement, x_i component	εtE_i
Dn		electric displacement, normal component	εE_n
tH*i*		tangential magnetic field, x_i component	$\frac{\sigma+j\omega\varepsilon}{k^2-\beta^2}(\nabla_t\times\mathbf{n}E_n)_i$
tB*i*		tangential magnetic flux density, x_i component	μH_i

TABLE 2-24: APPLICATION MODE VARIABLES, BOUNDARY MODE ANALYSIS, TE WAVES

NAME	MAT. PARAMS	DESCRIPTION	EXPRESSION
tH*i*		tangential magnetic field, x_i component	$-\frac{\beta}{\omega\mu}(\mathbf{n}\times\mathbf{E}_t)_i$
Hn		magnetic field, normal component	jh_n
tB*i*		tangential magnetic flux density, x_i component	μH_i
Bn		magnetic flux density, normal component	μH_n
tE*i*		tangential electric field, x_i component	$\frac{j\omega\mu}{k^2-\beta^2}(\nabla_t\times\mathbf{n}H_n)_i$
tD*i*		tangential electric displacement, x_i component	εE_i

TABLE 2-25: APPLICATION MODE VARIABLES, BOUNDARY MODE ANALYSIS, HYBRID MODE WAVES

NAME	DEP. VAR.	MAT. PARAMS	DESCRIPTION	EXPRESSION
tH*i*	$\mathbf{H}$		tangential magnetic field, x_i component	th_i/β
tH*i*	$\mathbf{E}$		tangential magnetic field, x_i component	$-\frac{\beta}{\omega\mu}(\mathbf{n}\times\mathbf{E}_t)_i-\frac{j}{\omega\mu}(\nabla_t\times\mathbf{n}E_n)_i$
Hn	$\mathbf{H}$		magnetic field, normal component	jh_n/k_0
Hn	$\mathbf{E}$		magnetic field, normal component	$-\frac{j}{\omega\mu}\mathbf{n}\cdot(\nabla_t\times\mathbf{E}_t)$
tB*i*			tangential magnetic flux density, x_i component	μH_i
Bn			magnetic flux density, normal component	μH_n
tE*i*	$\mathbf{H}$		tangential electric field, x_i component	$\frac{\beta}{\omega\varepsilon_c}(\mathbf{n}\times\mathbf{H}_t)_i+\frac{j}{\omega\varepsilon_c}(\nabla_t\times\mathbf{n}H_n)_i$
tE*i*	$\mathbf{E}$		tangential electric field, x_i component	te_i/β
En	$\mathbf{H}$		electric field, normal component	$\frac{j}{\omega\varepsilon_c}\mathbf{n}\cdot(\nabla_t\times\mathbf{H}_t)$
En	$\mathbf{E}$		electric field, normal component	je_n/k_0
tD*i*			tangential electric displacement, x_i component	εE_i

Boundary Mode Analysis Application Mode in 2D

Below is the variables listed that differ from the list of common variables in "Common Variables for the Application Modes" on page 8. If you do not find a variable in the list below, it can be in the list of common variables. Note that only mode analysis is available for Boundary Mode Analysis in 2D.

See page 6 for a description of the notation used in the tables.

APPLICATION SCALAR VARIABLES

See the corresponding section for "Boundary Mode Analysis Application Mode in 3D" on page 24.

APPLICATION MODE BOUNDARY VARIABLES

The boundary variables for TM waves, and TE waves are listed in two tables below in the given order.

TABLE 2-26: APPLICATION MODE VARIABLES. BOUNDARY MODE ANALYSIS 2D TM WAVE.

NAME	SETTING	DESCRIPTION	EXPRESSION
tEx		tangential electric field, x component	$\frac{\beta n_y}{\varepsilon\omega - j\sigma} H_z$
tEy		tangential electric field, y component	$\frac{-\beta n_x}{\varepsilon\omega - j\sigma} H_z$
normtE		tangential electric field, norm	$\sqrt{\mathbf{E} \cdot \mathbf{E}^*}$
En		normal electric field	$\frac{-1}{\sigma + j\omega\varepsilon}(\nabla_T \times \mathbf{n} H_z)$
tDi		electric displacement, i component	εE_i
normtD		tangential electric displacement, norm	$\sqrt{\mathbf{D} \cdot \mathbf{D}^*}$
Dn		normal electric displacement	εE_n
Hz		magnetic field, z component	H_z

TABLE 2-27: APPLICATION MODE VARIABLES. BOUNDARY MODE ANALYSIS 2D, TE WAVE

NAME	SETTING	DESCRIPTION	EXPRESSION
tHx		tangential magnetic field, x component	$\frac{-\beta n_y}{\omega\mu} E_z$
tHy		tangential magnetic field, y component	$\frac{\beta n_x}{\omega\mu} E_z$
normtH		tangential magnetic field, norm	$\sqrt{\mathbf{H} \cdot \mathbf{H}^*}$
Hn		normal magnetic field	$\frac{j}{\omega\mu} \nabla_t \times \mathbf{n} E_z$
tB*i*		tangential magnetic flux density, xi component	$\mu t H_i$

TABLE 2-27: APPLICATION MODE VARIABLES. BOUNDARY MODE ANALYSIS 2D, TE WAVE

NAME	SETTING	DESCRIPTION	EXPRESSION
normtB		tangential magnetic flux density, norm	$\sqrt{\mathbf{B} \cdot \mathbf{B}^*}$
Bn		normal magnetic flux density	μH_n
Ez		electric field, z component	E_z

3

Programming Reference

The Programming Language

Earlier in this documentation, the examples use the COMSOL Multiphysics graphical user interface for solving problems with the RF Module. Although this user interface provides a convenient environment for modeling many problems, it can sometimes be useful to work with a programming tool.

For details on specific functions, see the *Command Reference*.

A summary of the application structure, and how application objects are used for a convenient transformation of application mode data to PDE and boundary coefficients, is presented in the following section.

The Application Structure

The process of performing a simulation using the application modes available through the RF Module includes the correct setup of the application structure. The application structure contains the necessary information for the model setup in several fields. This section describes the application structure in the context of the RF Module. See also the section “Application Structures” on page 56 in the *COMSOL Multiphysics Scripting Guide*. Most fields have corresponding entries in the FEM structure, described in the section “Specifying a Model” on page 9 in the *COMSOL Multiphysics Scripting Guide*. The following table gives an overview of the fields in the application structure.

FIELD	DESCRIPTION
`appl.mode`	Application mode class
`appl.dim`	Cell array of dependent variable names
`appl.sdim`	Cell array of spatial coordinates
`appl.border`	Assembly on interior boundaries; turn on/off assembly on interior boundaries
`appl.name`	Application mode name
`appl.var`	Cell array or structure with application-specific scalar variables.
`appl.assign`	Assigned variable names
`appl.assignsuffix`	Suffix to append to all application mode variable names

FIELD	DESCRIPTION
`appl.equ`	Structure containing domain properties
`appl.bnd`	Structure containing boundary conditions
`appl.edg`	Structure containing edge conditions
`appl.pnt`	Structure containing point conditions
`appl.prop`	Application mode specific properties

Most of these fields have default values and need not be specified when solving a problem using the programming language. The function `multiphysics` is used to transform the application structure data to the FEM structure to generate the complete set of equations. See the corresponding entry in the *Command Reference* for details.

The application mode specific names of the fields in the structures in the table above can be found in the chapter "Application Mode Programming Reference" on page 39.

APPLICATION MODE CLASS

The application modes are specified via a corresponding class name.

To specify the class, write the name of the class as a string, for example,

```
appl.mode.class='InPlaneWaves';
```

which specifies that the In-Plane Waves application mode will be used.

Some application modes, for example the In-Plane Waves application mode, can be used both for Cartesian and axisymmetric problems. The default is to use Cartesian coordinates. To specify an axisymmetric problem, use

```
appl.mode.type = 'AxisymmetricWaves';
appl.mode.type = 'axi';
```

DEPENDENT VARIABLES

The `dim` field in the application structure states the names of the dependent variables, and hence gives the dimension of the corresponding PDE system. If the `dim` field is missing, the corresponding standard names of the electromagnetic field quantities solved for are used. Note that in some axisymmetric modes, there is a variable transformation in the equations solved. In those modes, the default name of the dependent variable name has `dr` added to the name of the electromagnetic quantity, since the dependent variable is divided by r.

The default names of the dependent variables in the In-Plane Waves application mode is `'Ez'`.

You can set a new name of the dependent variable by typing

```
appl.dim = {'E'};
```

SPATIAL COORDINATES

The names of the spatial coordinates are given in `fem.sdim`. However, `fem.sdim` only gives the names of the spatial coordinates of the geometry: one variable in 1D, two variables in 2D, and three variables in 3D. To specify all three spatial coordinates, use `appl.sdim`. The additional spatial coordinates are used when giving names to vector component variables.

For example, in 2D Cartesian coordinates

```
fem.sdim = {'x1' 'y1'};
appl.sdim = {'x1' 'y1' 'z1'};
```

defines the spatial coordinates x_1, y_1, z_1.

In cylindrical coordinates

```
fem.sdim = {'r' 'z'};
appl.sdim = {'r' 'phi' 'z'};
```

defines the spatial coordinates r, φ, z.

The coordinates defined both in `fem.sdim` and `appl.sdim` should match.

APPLICATION NAME

This field is used for giving the application a name. If no name is specified, a default name is used.

```
appl.name = 'antenna';
```

APPLICATION MODE PROPERTIES

Some application modes define properties to, for example, specify which type of analysis to perform or which dependent variables to use. These are specified in the `appl.prop` structure. For example, the In-Plane Waves application mode defines the field `appl.prop.analysis`, which specifies if a transient, time-harmonic, or eigenfrequency analysis should be performed. For instance,

```
appl.prop.analysis = 'harmonic';
```

indicates time-harmonic analysis.

The default element type used for domains and boundaries can be specified in the `appl.prop.elemdefault` field. For example, you can write

```
appl.prop.elemdefault='Lag1';
```

to obtain linear Lagrange elements.

APPLICATION SCALAR VARIABLES

For scalar variables that are valid in the whole model, such as permittivity and permeability of vacuum and angular frequency, the values can be specified in the `appl.var` field. Note that only predefined variable names can be used in this field.

For the In-Plane Waves application mode, the variables can be set as

```
appl.var.epsilon0 = 1;
appl.var.mu0 = 1;
appl.var.nu = 100;
```

The `appl.var` field can also be specified as a cell array,

```
appl.var = {'epsilon0', 1, 'mu0', 1, 'nu', 100};
```

The default values in the In-Plane Waves application mode in the harmonic formulation are

```
appl.var.epsilon0 = 8.854187817e-12;
appl.var.mu0 = 4*pi*1e-7;
appl.var.nu = 1e9;
```

ASSIGNED VARIABLE NAMES

To avoid duplication of variable names, the `appl.assign` field can be used to state the relation between the assigned name of a variable that you can use in postprocessing and in the PDE and boundary coefficients, and the default name that is used in the COMSOL Multiphysics and RF Module algorithms. This field is hence only necessary when you solve a multiphysics problem where variable name conflicts may arise.

If you want to use the variable name `w` for the intrinsic variable `omega` in the Perpendicular currents quasi-statics mode, all you have to enter is

```
appl.assign.omega = 'w';
```

This can also be specified as a cell array,

```
appl.assign = {'omega' 'w'};
```

The odd entries in the `assign` field state the default application scalar variable names or the postprocessing variable names. These are listed in the subsection "Application Mode Variables" for each application mode in "The Application Mode Formulations" on page 106. The even entries in `appl.assign` are the variable names that you want to use for the physical entities when modeling.

There is also a field `appl.assignsuffix`, which can be used to add a suffix to the name of all application mode variables. Variables appearing in `appl.assign` will take the given assigned name, while the others will get the suffix added to their names.

DOMAIN PROPERTIES

The application structure field `appl.equ` is used for specifying electromagnetic properties that will be transformed into PDE coefficients. For example the In-Plane Waves application mode defines the fields

```
appl.equ.epsilonr
appl.equ.mur
appl.equ.sigma
appl.equ.n
appl.equ.matparams
appl.equ.magconstrel
appl.equ.elconstrel
appl.equ.P
appl.equ.Dr
appl.equ.Br
appl.equ.M
```

Now consider an example with two materials. To use other values than the default for the physical properties, enter them as follows.

Scalars such as `sigma` are given as a cell array with the values,

```
appl.equ.sigma={'5.9e7' '0'};
```

Vectors such as `M` are given as a nested cell array with the vector components as elements in the inner cell array,

```
appl.equ.M={{'0' '0'} {'0' '500'}};
```

In the 3D case, the vector has three components,

```
appl.equ.M={{'0' '0' '0'} {'0' '500' '0'}};
```

Tensors or matrix variables are given as cell arrays with the tensor components,

```
appl.equ.mur={{'1' '2'; '3' '4'} {'5' '6' '7' '8'}};
```

This example shows two ways of writing a 2x2 tensor. The first tensor is written row by row with a semicolon separating the rows,

$$\begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix}$$

while the second tensor is written column by column,

$$\begin{bmatrix} 5 & 7 \\ 6 & 8 \end{bmatrix}$$

There are a number of short-hand ways of writing a tensor. In 2D `{'1' '2'}` is a diagonal tensor

$$\begin{bmatrix} 1 & 0 \\ 0 & 2 \end{bmatrix}$$

`{'1' '2' '3'}` is a symmetric tensor

$$\begin{bmatrix} 1 & 2 \\ 2 & 3 \end{bmatrix}$$

and `{'1' '2' '3' '4'}` is the full tensor

$$\begin{bmatrix} 1 & 3 \\ 2 & 4 \end{bmatrix}$$

Similarly in 3D `{'1' '2' '3'}` is a diagonal tensor

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 3 \end{bmatrix}$$

`{'1' '2' '3' '4' '5' '6'}` is a symmetric tensor

$$\begin{bmatrix} 1 & 2 & 4 \\ 2 & 3 & 5 \\ 4 & 5 & 6 \end{bmatrix}$$

and `{'1' '2' '3' '4' '5' '6' '7' '8' '9'}` is the full tensor

$$\begin{bmatrix} 1 & 4 & 7 \\ 2 & 5 & 8 \\ 3 & 6 & 9 \end{bmatrix}$$

Constitutive Relations

In the static and quasi-static application modes three different constitutive relations between both the **D** and **E** fields and the **B** and **H** fields can be used. To specify which ones to use, use the fields `appl.equ.elconstrel` and `appl.equ.magconstrel`. Their values are listed in the table below.

CONSTITUTIVE RELATION	VARIABLE	VALUE
$\mathbf{D} = \varepsilon_0\varepsilon_r\mathbf{E}$	`elconstrel`	`epsr`
$\mathbf{D} = \varepsilon_0\mathbf{E} + \mathbf{P}$	`elconstrel`	`P`
$\mathbf{D} = \varepsilon_0\varepsilon_r\mathbf{E} + \mathbf{D}_r$	`elconstrel`	`Dr`
$\mathbf{B} = \mu_0\mu_r\mathbf{H}$	`magconstrel`	`mur`
$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$	`magconstrel`	`M`
$\mathbf{B} = \mu_0\mu_r\mathbf{H} + \mathbf{B}_r$	`magconstrel`	`Br`

Refractive Index and Relative Permittivity

The material data can be given either by the refractive index or the three properties relative permittivity, relative permeability and conductivity. To specify which of the two to use, use the field `appl.equ.matparams`. It takes the value `n` for refractive index and the value `epsr` for the other three properties. For example,

```
appl.equ.matparams = {'n' 'epsr'};
appl.equ.n = {'1.2' '1'};
appl.equ.epsilonr = {'1' '2'};
appl.equ.sigma = {'0' '1e4'};
appl.equ.mur = {'1' '1.1'};
```

specifies the refractive index $n = 1.2$ for the first domain and $\varepsilon_r = 2$, $\sigma = 10^4$ S/m, and $\mu_r = 1.1$ for the second one.

BOUNDARY CONDITIONS

The boundary conditions for the simulation is given in the `appl.bnd` field. First you have to select which type of boundary condition you want at each boundary. This is done using the field `appl.bnd.type`. Then some boundary conditions requires certain boundary variables to be set, unless the default value is sufficient. Note that not all types of boundary conditions require a boundary variable.

For example, the boundary variables defined by the In-Plane Waves application mode are

```
appl.bnd.type
appl.bnd.epsilonrbnd
appl.bnd.murbnd
appl.bnd.sigmabnd
appl.bnd.nbnd
appl.bnd.E0
appl.bnd.Esz
```

```
appl.bnd.portnr
appl.bnd.inport
appl.bnd.Pport
appl.bnd.rectmodetype
appl.bnd.usermodetype
appl.bnd.modespec
appl.bnd.betaTE
appl.bnd.betaTM
appl.bnd.modenum
appl.bnd.betaport
appl.bnd.nucutoff
appl.bnd.curofforbeta
appl.bnd.applmode
appl.bnd.wavetype
appl.bnd.srcpnt
appl.bnd.eta
appl.bnd.kdir
appl.bnd.nu0
appl.bnd.srctype
appl.bnd.Js0
appl.bnd.A0
appl.bnd.matparams
appl.bnd.H0
```

The variables are specified using the same form for scalars, vectors, and tensors as above for the subdomain variables.

DOMAIN GROUPS

Often you have a model with several subdomains having the same physical properties and many boundaries where you want to apply the same boundary condition. To simplify the notation, the index vectors in the fields `equ.ind` and `bnd.ind` are used. Consider this example:

```
appl.equ.sigma = {'5.9e7' '0'};
appl.equ.ind = [1 2 1 1 1];
```

Here you have five subdomains. Subdomain 2 is nonconducting, whereas the other four subdomains have the electric conductivity $5.9 \cdot 10^7$ S/m.

Here is another example where three different boundary conditions are applied to six boundaries:

```
appl.bnd.type = {'tH0' 'H' 'A'};
appl.bnd.A0 = {[] [] '100'};
appl.bnd.H0 = {[] {'10' '5'} []};
appl.bnd.ind = [1 2 2 2 3 3];
```

This specifies the magnetic field at boundaries 2, 3, and 4, the magnetic potential at boundaries 5 and 6 and electric insulation at boundary 1. Note that the perfect magnetic conductor condition does not need any boundary variable to be defined and that we have set the variables to an empty vector where the value is ignored.

There is an alternative syntax for the index vector using a cell array of numeric vectors instead of a single numeric vector as in the examples above. In this case the numeric vectors in the cell array list the domains having the same settings. For example,

```
appl.equ.ind = {[1 3 4 5] 2};
```

is equivalent to

```
appl.equ.ind = [1 2 1 1 1];
```

and

```
appl.bnd.ind = {1 [2 3 4] [5 6]};
```

is equivalent to

```
appl.bnd.ind = [1 2 2 2 3 3];
```

Application Mode Programming Reference

This reference chapter tabulates the application mode dependent fields of the application structure. For each application mode these are the following sections:

- *Dependent variables*, which gives the variables in `appl.dim`. In the COMSOL Multiphysics graphical user interface (GUI) you find these variables in the **Dependent variables** edit field in the Model Navigator.
- *Application mode class and name*, which specifies the values to use in `appl.mode` and gives the default value of `appl.name`. In the GUI, `appl.name` appears in the **Application mode name** edit field in the Model Navigator.
- *Scalar variables*, which specifies the variables in `appl.var`. The corresponding GUI dialog box is the **Application Scalar Variables** dialog box.
- *Properties*, which specifies all fields in `appl.prop`, for example which type of analysis to perform or which elements to use. In the GUI you find the properties in the **Application Mode Properties** dialog box.
- *Subdomain/Boundary/Edge/Point Variables*, which specifies the variables available in `appl.equ`, `appl.bnd`, `appl.edg`, `appl.pnt`. The GUI dialog boxes corresponding to these fields are the **Subdomain Settings**, **Boundary Settings**, **Edge Settings**, and **Point Settings** dialog boxes, respectively.
- *Boundary Conditions*, which specifies which type of boundary conditions are available and which boundary variables are significant for each boundary condition. In the user interface, the boundary condition types correspond to the items in the **Boundary condition** list in the **Boundary Settings** dialog box.

See also the chapter "The Programming Language" on page 30 for a general discussion of the various fields in the application structure.

DEPENDENT VARIABLES

FIELD	DEFAULT	DESCRIPTION
`appl.dim`	`{'Ex','Ey','Ez','Hx','Hy','Hz', 'Ax','Ay','Az','scEx','scEy', 'scEz','scHx','scHy','scHz', 'psi'}`	Electric and magnetic field, magnetic potential and divergence condition variable

All ten dependent variables have to be specified, including the seven that are not in use.

APPLICATION MODE CLASS AND NAME

FIELD	VALUE	DEFAULT
`appl.mode.class`	`ElectromagneticWaves`	
`appl.name`		rfw

SCALAR VARIABLES

FIELD	DEFAULT	DESCRIPTION
`appl.var.epsilon0`	`8.854187817e-12`	Permittivity of vacuum
`appl.var.mu0`	`4*pi*1e-7`	Permeability of vacuum
`appl.var.nu`	`1e9`	Frequency
`appl.var.lambda0`	`0.3`	Free space wavelength

PROPERTIES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.prop.analysis`	`harmonic | eigen | trans`	`harmonic`	Analysis type, harmonic propagation, eigenfrequency or transient propagation
`appl.prop.solvefor`	`E | H`	`E`	Which field to use as dependent variable, electric or magnetic
`appl.prop.inputvar`	`nu | lambda`	`nu`	Which property to use when characterizing the wave, the frequency or wavelength.

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.prop.eigtype`	`lambda | freq`	`freq`	Should the parameters to the eigenvalue solver be given in terms of the eigenvalue or the eigenfrequency. This property only applies when working in the user interface.
`appl.prop.divcond`	`on | off`	`off`	Divergence condition active or not.
`appl.prop.elemdefault`	`Vec1 | Vec2 | Vec3`	`Vec1`	Default element type, vector elements.

SUBDOMAIN VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.equ.sigma`	expression | cell array of expressions	0	Electric conductivity
`appl.equ.mur`	expression | cell array of expressions	1	Relative permeability
`appl.equ.epsilonr`	expression | cell array of expressions	1	Relative permittivity
`appl.equ.n`	expression | cell array of expressions	1	Refractive index
`appl.equ.matparams`	`n | epsr`	`epsr`	Indicates if the material is specified in terms of the refractive index or in terms of the permittivity, permeability, and conductivity.
`appl.equ.M`	cell array of expressions	0	`Magnetization`
`appl.equ.Br`	cell array of expressions	0	Remanent flux density
`appl.equ.P`	cell array of expressions	0	Electric polarization
`appl.equ.Dr`	cell array of expressions	0	Remanent displacement

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.equ.magconstrel`	`mur | M | Br`	`mur`	Magnetic constitutive relation
`appl.equ.elconstrel`	`epsr | P | Dr`	`epsr`	Electric constitutive relation

BOUNDARY VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.bnd.H0`	cell array of expressions	0	Magnetic field
`appl.bnd.Js0`	cell array of expressions	0	Surface current density
`appl.bnd.E0`	cell array of expressions	0	Electric field
`appl.bnd.A0`	cell array of expressions	0	Magnetic potential
`appl.bnd.eta`	expression	1	Surface impedance
`appl.bnd.Es`	cell array of expressions	0	Surface electric field
`appl.bnd.sigmabnd`	expression | cell array of expressions	0	Electric conductivity
`appl.bnd.murbnd`	expression cell array of expressions	1	Relative permeability
`appl.bnd.epsilonrbnd`	expression | cell array of expressions	1	Relative permittivity
`appl.bnd.nbnd`	expression | cell array of expressions	1	Refractive index
`appl.bnd.lrsource`	`E | H | EH`	`E`	Source field for the low-reflecting boundary condition, electric, magnetic, or general

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.bnd.mbsource`	`E	H`	`E`	Source field for the matched boundary condition, electric or magnetic
`appl.bnd.beta`	expression	`0`	Propagation constant
`appl.bnd.matparams`	`n	epsr`	`epsr`	Indicates if the material in the impedance boundary condition is specified in terms of the refractive index or in terms of the permittivity, permeability, and conductivity.
`appl.bnd.portnr`	expression	`1`	Port number.
`appl.bnd.inport`	`0	1`	`0`	Wave excitation at this port
`appl.bnd.modespec`	`userdef	rect	circular	coaxial	numeric`	`userdef`	Mode specification
`appl.bnd.rectmodetype`	`TE	TM`	`TE`	Mode type for rectangular port
`appl.bnd.usermodetype`	`TE	TM	TEM`	`TE`	Mode type for user defined mode
`appl.bnd.nummodetype`	`auto	TE	TM	TEM`	`auto`	Mode type for numeric port
`appl.bnd.modenum`	expression	`10`	Mode number for rectangular port
`appl.bnd.circmodenum`	expression	`11`	Mode number for circular port
`appl.bnd.nu0`	expression	`0`	Reference frequency
`appl.bnd.nucutoff`	expression	`0`	Cutoff frequency
`appl.bnd.cutofforbeta`	`cutoff	beta`	`beta`	Should the cutoff frequency of beta and nu0 be specified

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.bnd.applmode`	expression	`0`	The application mode to pick numeric data from
`appl.bnd.sparammethod`	`field | energy`	`field`	Method to calculate S-parameter output data
`appl.bnd.type`	string	`E0 | cont`	The type of boundary condition

`appl.bnd.type` takes the default value `E0` on exterior boundaries and `cont` on interior boundaries.

BOUNDARY CONDITIONS

DESCRIPTION	TYPE	APPLICABLE VARIABLES	VARIABLE DESCRIPTION
Magnetic field	H	H0	Magnetic field
Surface current	Js	Js0	Surface current density
Perfect magnetic conductor	H0		
Electric field	E	E0	Electric field
Magnetic potential	A	A0	Magnetic potential
Perfect electric conductor	E0		
Continuity	cont		
Low-reflecting	NR	H0 E0 lrsource	Magnetic field Electric field E/H/both as source
Matched boundary	M	E0 H0 beta mbsource	Electric field Magnetic field Propagation constant E or H as source
Impedance boundary condition	IM	Es matparams nbnd sigmabnd murbnd epsilonrbnd	Surface electric field Input parameters Refractive index Conductivity Relative permeability Relative permittivity
Transition boundary condition	sIM	Es eta	Surface electric field Surface impedance
Port	port	portnr inport modespec rectmodetype usermodetype nummodetype modenum nu0 nucutoff cutofforbeta applmode	Port number Wave excitation at port Mode specification Mode type for rect. Mode type for userdef Mode type for num. Mode number Reference frequency Cutoff frequency Cutoff or beta, nu0 Appl. mode with data

The **Type** column indicates the possible values for `appl.bnd.type`.

EDGE VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.edg.I0`	expression	`0`	Current
`appl.edg.type`	string	`cont`	The type of edge condition

EDGE CONDITIONS

DESCRIPTION	TYPE	APPLICABLE VARIABLES	VARIABLE DESCRIPTION
Current	`I`	`I0`	Current
Perfect electric conductor	`E0`		
Continuity	`cont`		

In-Plane and Axisymmetric Waves

DEPENDENT VARIABLES

Variables for In-Plane Waves.

FIELD	DEFAULT	DESCRIPTION
`appl.dim`	`{'Ez', 'Hz', 'Ax','Ay','Az'}`	Electric and magnetic field, z components and magnetic potential

Variables for Axisymmetric Waves.

FIELD	DEFAULT	DESCRIPTION
`appl.dim`	`{'Ephidr', 'Hphidr', 'Ar','Aphidr','Az'}`	Electric and magnetic field, φ components divided by r Magnetic potential vector φ component divided by r

All variables must be given, including the once that are not used when doing TE or TM wave analysis.

APPLICATION MODE CLASS AND NAME

Class and name for In-Plane Waves.

FIELD	VALUE	DEFAULT
appl.mode.class	InPlaneWaves	
appl.name		rfwe | rfwh | rfweh

Class and name for Axisymmetric Waves.

FIELD	VALUE	DEFAULT
appl.mode.class	AxisymmetricWaves	
appl.name		rfwe | rfwh | rfweh

The default for `appl.name` is `rfwe` for TE waves, `rfwh` for TM waves, and `rfweh` for hybrid waves.

SCALAR VARIABLES

FIELD	DEFAULT	DESCRIPTION
appl.var.epsilon0	8.854187817e-12	Permittivity of vacuum
appl.var.mu0	4*pi*1e-7	Permeability of vacuum
appl.var.nu	1e9	Frequency
appl.var.lambda0	0.3	Free space wavelength

PROPERTIES

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.prop.analysis	harmonic | eigen | trans	harmonic	Analysis type, harmonic propagation, eigenfrequency, transient propagation
appl.prop.field	TE | TM | TETM	TE	Which type of waves to handle, TE, TM, or hybrid waves
appl.prop.inputvar	nu | lambda	nu	Which property to use when characterizing the wave, the frequency or wavelength.

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.prop.eigtype`	`lambda | freq`	`freq`	Should the parameters to the eigenvalue solver be given in terms of the eigenvalue or the eigenfrequency. This property only applies when working in the user interface.
`appl.prop.elemdefault`	`Vec1 | Vec2 | Vec3 | Vec1_lag1 | Vec2_lag2 | Vec3_lag3 | Lag1 | Lag2 | Lag3 | Lag4 | Lag5`	`Vec2 | Vec2_lag2 | Lag2`	Default element type. Vector elements or Lagrange elements of order 1 to 5.
`appl.prop.weakconstr`	`off | ideal | non-ideal`	`off`	The type of weak constraints to use.

SUBDOMAIN VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.equ.sigma`	expression | cell array of expressions	0	Electric conductivity
`appl.equ.mur`	expression |cell array of expressions	1	Relative permeability
`appl.equ.epsilonr`	expression | cell array of expressions	1	Relative permittivity
`appl.equ.n`	expression | cell array of expressions	1	Refractive index
`appl.equ.matparams`	`n | epsr`	`epsr`	Indicates if the material is specified in terms of the refractive index or in terms of the permittivity, permeability, and conductivity.
`appl.equ.M`	cell array of expressions	0	Magnetization
`appl.equ.Br`	cell array of expressions	0	Remanent flux density

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.equ.P	cell array of expressions	0	Electric polarization
appl.equ.Dr	cell array of expressions	0	Remanent displacement
appl.equ.magconstrel	mur | M | Br	mur	Magnetic constitutive relation
appl.equ.elconstrel	epsr | P | Dr	epsr	Electric constitutive relation

BOUNDARY VARIABLES

FIELD	APPL. MODE	VALUE	DEFAULT	DESCRIPTION
appl.bnd.H0		cell array of expressions	0	Magnetic field
appl.bnd.Js0z	In-Plane	expression	0	Surface current density
appl.bnd.Js0phi	Axisymmetric	expression	0	Surface current density
appl.bnd.E0		cell array of expressions	0	Electric field
appl.bnd.A0		cell array of expressions	0	Magnetic potential
appl.bnd.eta		expression	1	Surface impedance
appl.bnd.Esz	In-Plane	expression	0	Surface electric field
appl.bnd.Esphi	Axisymmetric	expression	0	Surface electric field
appl.bnd.sigmabnd		expression | cell array of expressions	0	Electric conductivity
appl.bnd.murbnd		expression | cell array of expressions	1	Relative permeability
appl.bnd.epsilonrbnd		expression | cell array of expressions	1	Relative permittivity
appl.bnd.nbnd		expression | cell array of expressions	1	Refractive index

FIELD	APPL. MODE	VALUE	DEFAULT	DESCRIPTION
appl.bnd.lrsource		E | H | EH	E	Source field for the low-reflecting boundary condition, electric, magnetic, or general
appl.bnd.betaTE		expression	0	Propagation constant for TE waves
appl.bnd.betaTM		expression	0	Propagation constant for TM waves
appl.bnd.betaport		expression	0	Propagation constant in Port boundary condition
appl.bnd.matparams		n | epsr	epsr	Indicates if the material in the impedance boundary condition is specified in terms of the refractive index or in terms of the permittivity, permeability, and conductivity.
appl.bnd.portnr		expression	1	Port number.
appl.bnd.inport		0 | 1	0	Wave excitation at this port
appl.bnd.modespec	In-Plane	userdef | analytic | numeric	userdef	Mode specification
appl.bnd.modespec	Axisymmetric	userdef | cylindrical | coaxial | numeric	userdef	Mode specification
appl.bnd.rectmodetype		TE | TM	TE	Mode type for rectangular port
appl.bnd.usermodetype		TE | TM	TE	Mode type for user defined mode
appl.bnd.modenum		1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10	1	Mode number for analytic port
appl.bnd.nu0		expression	0	Reference frequency

FIELD	APPL. MODE	VALUE	DEFAULT	DESCRIPTION
`appl.bnd.nucutoff`		expression	`0`	Cutoff frequency
`appl.bnd.cutofforbeta`		`cutoff | beta`	`beta`	Should the cutoff frequency of beta and nu0 be specified
`appl.bnd.applmode`		expression	`0`	The application mode to pick numeric data from
`appl.bnd.type`		`string`	`E0 | cont`	The type of boundary condition

`appl.bnd.type` takes the default value `E0` on exterior boundaries and `cont` on interior boundaries.

BOUNDARY CONDITIONS

The variables `H0` and `E0` are always vectors of length 3, also in the TE and TM cases when not all vector components are used in the boundary conditions.

DESCRIPTION	APPL. MODE	WAVE TYPE	TYPE	APPLICABLE VARIABLES	VARIABLE DESCRIPTION
Magnetic field		TE	`H`	`H0` (in-plane components)	Magnetic field
Magnetic field		TM	`H`	`H0` (out-of-plane component)	Magnetic field
Magnetic field (exterior boundaries)		hybrid	`H`	`H0`	Magnetic field
Magnetic field (interior boundaries)		hybrid	`HH0`	`H0` (out-of-plane component)	Magnetic field
Surface current	In-Plane	TE, hybrid	`Js`	`Js0z`	Surface current density
Surface current	Axisymmetric	TE, hybrid	`Js`	`Js0phi`	Surface current density
Perfect magnetic conductor			`H0`		
Electric field		TE	`E`	`E0` (in-plane components)	Electric field
Electric field		TM	`E`	`E0` (out-of-plane component)	Electric field

DESCRIPTION	APPL. MODE	WAVE TYPE	TYPE	APPLICABLE VARIABLES	VARIABLE DESCRIPTION
Electric field (exterior boundaries)		hybrid	E	E0	Electric field
Electric field (interior boundaries)		hybrid	EE0	E0 (out-of-plane component)	Electric field
Magnetic potential		TE	A	A0 (out-of-plane components)	Magnetic potential
Magnetic potential		TM	A	A0 (in-plane component)	Magnetic potential
Magnetic potential		hybrid	A	A0	Magnetic potential
Perfect electric conductor			E0		
Electric and magnetic field		hybrid	EH	H0 E0 (out-of-plane components)	Magnetic field Electric field
Neutral		hybrid	n		
Continuity			cont		
Low-reflecting		TE	NR	E0 (out-of-plane component)	Electric field
Low-reflecting		TM	NR	H0 (out-of-plane component)	Magnetic field
Low-reflecting		hybrid	NR	H0 E0 lrsource	Magnetic field Electric field E/H/both as source
Matched boundary		TE	M	E0 (out-of-plane component) betaTE	Electric field Propagation constant
Matched boundary		TM	M	H0 (out-of-plane component) betaTM	Magnetic field Propagation constant

DESCRIPTION	APPL. MODE	WAVE TYPE	TYPE	APPLICABLE VARIABLES	VARIABLE DESCRIPTION
Matched boundary		hybrid	M	H0 (out-of-plane component) E0 (out-of-plane component) betaTE betaTM	Magnetic field Electric field propagation constant TE waves propagation constant TM waves
Impedance boundary condition			IM	Es matparams nbnd sigmabnd murbnd epsilonrbnd	Surface electric field Input parameters Refractive index Conductivity Relative permeability Relative permittivity
Transition boundary condition			sIM	Es eta	Surface electric field Surface impedance
Port			port	portnr inport modespec rectmodetype usermodetype modenum nu0 nucutoff cutofforbeta applmode	Port number Wave excitation at port Mode specification Mode type for analytic Mode type for userdef Mode number Reference frequency Cutoff frequency Cutoff or beta, nu0 Appl. mode with data
Axial symmetry			ax		

The **Type** column indicates the possible values for `appl.bnd.type`.

POINT VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.pnt.I0	expression	0	Current

DEPENDENT VARIABLES

FIELD	DEFAULT	DESCRIPTION
`appl.dim`	`{'Ex', 'Ey', 'Ez', 'Hx', 'Hy', 'Hz', 'ex', 'ey', 'ez', 'hx', 'hy', 'hz'}`	Electric and magnetic field.

All twelve variables must be given, including the ones that are not used. The table below shows which variables that are used in each equation:

FORMULATION	VARIABLES	DESCRIPTION
TE	`Hz`	Magnetic field, z component
TM	`Ez`	Electric field, z component
Three-component formulation, $\mathbf{H}$ dependent variable, mode analysis	`Hx, Hy, hz`	Magnetic field, in-plane components, $H_z = \alpha h_z$
Three-component formulation, $\mathbf{H}$ dependent variable, eigenfrequency	`Hx, Hy, hz`	Magnetic field, in-plane components, $H_z = \alpha h_z$
Two-component formulation, $\mathbf{H}$ dependent variable	`Hx, Hy`	Magnetic field, x and y components
Three-component formulation, $\mathbf{E}$ dependent variable, mode analysis	`Ex, Ey, ez`	Electric field, in-plane components, $E_z = \alpha e_z$
Three-component formulation, $\mathbf{E}$ dependent variable, eigenfrequency	`Ex, Ey, ez`	Electric field, in-plane components, $E_z = \alpha e_z$
Two-component formulation, $\mathbf{E}$ dependent variable	`Ex, Ey`	Electric field, x and y components

APPLICATION MODE CLASS AND NAME

FIELD	VALUE	DEFAULT
appl.mode.class	PerpendicularWaves	
appl.name		rfwev | rfwhv | rfwv

The default value for appl.name is rfwev for TE waves, rfwhv for TM waves, and rfwv for hybrid mode waves.

SCALAR VARIABLES

FIELD	DEFAULT	DESCRIPTION
appl.var.epsilon0	8.854187817e-12	Permittivity of vacuum
appl.var.mu0	4*pi*1e-7	Permeability of vacuum
appl.var.nu	1e9	Frequency
appl.var.lambda0	0.3	Free space wavelength
appl.var.beta	30	Propagation constant

PROPERTIES

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.prop.analysis	mode | eigen	mode	Analysis type, mode analysis or eigenfrequency
appl.prop.field	TE | TM | TETM	TETM	Which type of waves to handle, TE, TM, or hybrid waves
appl.prop.solvefor	E | H	H	Which field to use as dependent variable
appl.prop.comps	2 | 3	3	Which field components to use as dependent variables, in-plane or all three components
appl.prop.inputvar	nu | lambda	nu	Which property to use when characterizing the wave, the frequency or wavelength.

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.prop.eigtype	lambda | freq | propconst | modeind	modeind | freq	Should the parameters to the eigenvalue solver be given in terms of the eigenvalue or some other quantity. This property only applies when working in the user interface.
appl.prop.elemdefault	Vec1_lag1 | Vec2_lag2 | Vec3_lag3 | Lag1 | Lag2 | Lag3 | Lag4 | Lag5	Vec2_lag2 | Lag2	Default element type. Vector or Lagrange elements of order 1 to 5.

SUBDOMAIN VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.equ.sigma	expression | cell array of expressions	0	Electric conductivity
appl.equ.mur	expression | cell array of expressions	1	Relative permeability
appl.equ.epsilonr	expression | cell array of expressions	1	Relative permittivity
appl.equ.n	expression | cell array of expressions	1	Refractive index
appl.equ.matparams	n | epsr	epsr	Indicates if the material is specified in terms of the refractive index or in terms of the permittivity, permeability, and conductivity.

BOUNDARY VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.bnd.type`	string	`E0 | H0 | cont`	The type of boundary condition

`appl.bnd.type` takes the default value `E0` on exterior boundaries except in the two-component magnetic field formulation when it takes the default `H0`. On interior boundaries the default value is `cont`.

BOUNDARY CONDITIONS

DESCRIPTION	TYPE
Perfect magnetic conductor	`H0`
Perfect electric conductor	`E0`
Continuity	`cont`

The **Type** column indicates the possible values for `appl.bnd.type`.

Boundary Mode Analysis

DEPENDENT VARIABLES

FIELD	DEFAULT	DESCRIPTION
`appl.dim`	`{'en', 'hn', 'ex', 'ey', 'ez', 'hx', 'hy', 'hz'}`	Electric and magnetic field.

All eight variables must be given, including the ones that are not used.

APPLICATION MODE CLASS AND NAME

FIELD	VALUE	DEFAULT
appl.mode.class	BoundaryModeAnalysis	
appl.name		rfwb

SCALAR VARIABLES

FIELD	DEFAULT	DESCRIPTION
appl.var.epsilon0	8.854187817e-12	Permittivity of vacuum
appl.var.mu0	4*pi*1e-7	Permeability of vacuum
appl.var.nu	1e9	Frequency
appl.var.lambda0	0.3	Free space wavelength

PROPERTIES

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.prop.field	TE | TM | TETM	TETM	Which type of waves to handle, TE, TM, or hybrid waves
appl.prop.solvefor	E | H	H	Which field to use as dependent variable
appl.prop.inputvar	nu | lambda	nu	Which property to use when characterizing the wave, the frequency or wavelength.
appl.prop.eigtype	lambda | propconst | modeind	modeind	Should the parameters to the eigenvalue solver be given in terms of the eigenvalue or some other quantity. This property only applies when working in the user interface.
appl.prop.elemdefault	Vec1_lag1 | Vec2_lag2 | Vec3_lag3 | Lag1 | Lag2 | Lag3 | Lag4 | Lag5	Vec2_lag2 | Lag2	Default element type. Vector or Lagrange elements of order 1 to 5.

BOUNDARY VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.bnd.sigma`	expression	0	Electric conductivity
`appl.bnd.mur`	expression	1	Relative permeability
`appl.bnd.epsilonr`	expression	1	Relative permittivity
`appl.bnd.n`	expression	1	Refractive index
`appl.bnd.matparams`	`n | epsr`	`epsr`	Indicates if the material is specified in terms of the refractive index or in terms of the permittivity, permeability, and conductivity.

EDGE VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.edg.type`	string	`cont`	The type of edge condition

EDGE CONDITIONS

DESCRIPTION	TYPE
Perfect magnetic conductor	`H0`
Perfect electric conductor	`E0`
Continuity at interior edges	`cont`

The **Type** column indicates the possible values for `appl.edg.type`.

4

Function Reference

Summary of Commands

Commands Grouped by Function

S-Parameter Computation

FUNCTION	PURPOSE
`sparammeteratrix`	Compute the full S-parameter matrix using the port boundary conditions defined in the model.
`touchwrite`	File export to the Touchstone format

Purpose

Compute the full S-parameter matrix using the port boundary conditions defined n the model.

Syntax

```
S = sparametermatrix(fem,...)
```

Description

`S = sparametermatrix(fem,...)` computes the S-parameter matrix `S` from the model stored in the `fem` structure.

By default, `sparametermatrix` searches for all port boundary conditions and activates all of them, setting each port to input.

If the model in `fem` has `N` ports, `sparametermatrix` computes a `N`-by-`N` S-parameter matrix `S`. A parametric sweep results in a `N`-by-`N`-by-`M` matrix, where `M` is the number of parameters returned by the solver.

Table 4-1 contains the valid property/value pairs for the `sparametermatrix` function.

TABLE 4-1: VALID PROPERTY/VALUE PAIRS

PROPERTY NAME	PROPERTY VALUE	DEFAULT	DESCRIPTION
`Scale`	lin | db	`lin`	dB or linear scale

Solver is a string that states which solver to use. The default solver is `femlin`.

Property value pairs not recognized by `sparametermatrix` are passed on as solver parameters to the solver.

See Also

`femsolver`, `posteval`, `postint` (in the *COMSOL Multiphysics Command Reference*)

Purpose File export to the Touchstone format.

Syntax

```
ok = touchwrite(filename, freq, data, ...)
```

Description

`ok= touchwrite(filename, freq, data,...)` exports the frequency-dependent data from an S-parameter analysis stored in `freq` and `data` to a file named `filename`. The argument `data` is an `N`-by-`N`-by-`length(freq)` matrix, where `N` is the number of ports in the analysis. The function `sparametermatrix` can compute the S-parameter data.

Table 4-1 contains the valid property/value pairs for the `touchwrite` function.

TABLE 4-2: VALID PROPERTY/VALUE PAIRS

PROPERTY NAME	PROPERTY VALUE	DEFAULT	DESCRIPTION
`Format`	`DB | MA | RI`	`MA`	The format used for the complex notation in the file
`Frequnit`	`Hz | kHz | MHz | GHz`	`GHz`	The unit used for the frequency
`Parameter`	`S | Y | Z | H | G`	`S`	The parameter type stored in the `data` argument
`Zref`	double value	`50`	The reference impedance in ohms

The format can be specified as pairs of magnitude and angle (`MA`), magnitude in dB and angle (`DB`), or as real and imaginary parts (`RI`).

See Also `sparametermatrix`

INDEX