Accurate Field Shape Model for Beam-Wave Interaction Simulation of Folded-Waveguide Traveling-Wave Tubes

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Session 2.3 - Traveling Wave Tubes - September 9, 2016

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Outline

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Challenges in Satellite Communication

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- Increasing number of services requiring high data rates

→ Use higher bands as carrier frequencies

→ Increased free-space and atmospheric loss

Images from "energyworx.com" and "a-read.com".

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The Traveling-Wave Tube Amplifier

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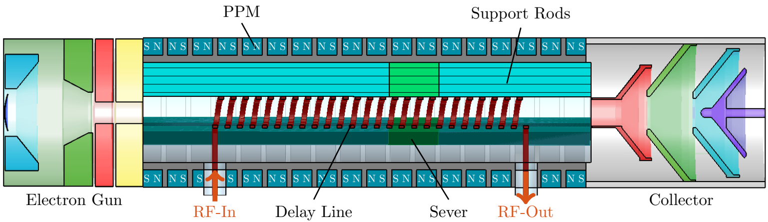

- Conversion of kinetic to RF energy
- State-of-the-art technology for satellite communication
- Thermal/mechanical limitations of commonly used helix delay lines above 40 GHz

The Folded-Waveguide Delay Line

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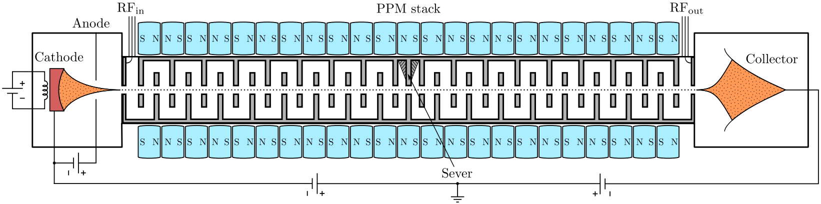
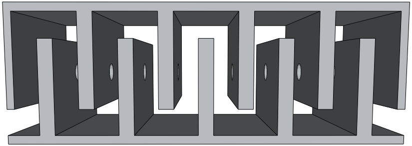


Pros and Cons

+ Ease of fabrication
+ Large bandwidth
+ Good thermal properties
– Weak beam-wave coupling



Simulate Before You Fabricate

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Large time/monetary costs of fabrication

→ Avoid trial-and-error productions

→ Characterize device at the PC level

→ Optimize performance beforehand

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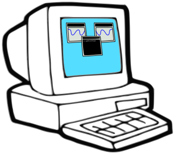

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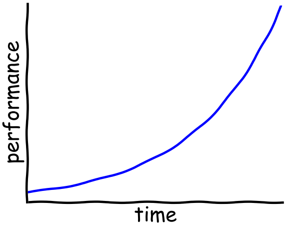

Generalized vs. Specialized Software

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Generalized Tool

+ **Predict performance of any new/exotic device**
+ Exploration of new concepts
+ Analysis of phenomena
– Limited suitability for design

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Specialized Tool

+ **Computational efficiency**
+ Enables optimization in a feasible time frame
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Equivalent Circuit Description

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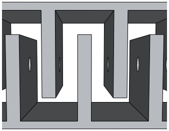

- Electromagnetic waves propagate along delay line
- Dispersive properties are mapped to lumped-element circuit[1]
- Voltage and current amplitudes define waves

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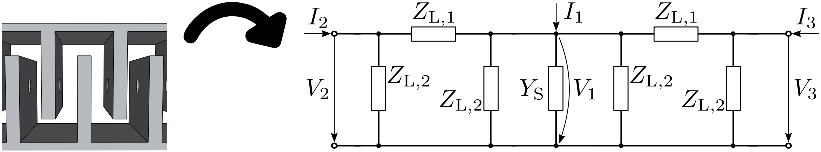

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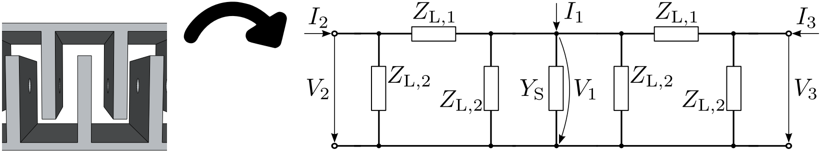

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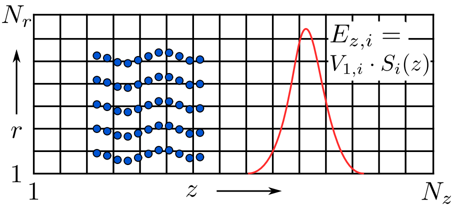
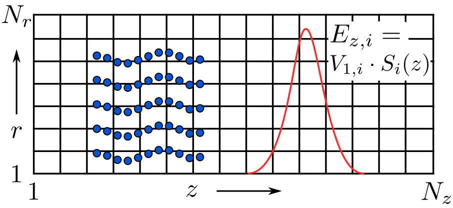
Particle-in-Cell Approach



- Discrete macro-particles propagate inside a discretized domain
- Solution of Lorenz force equation $\ddot{x} = -q/m_q \cdot E$
- Field shape function defines link between fields and amplitudes

Particle-in-Cell Approach



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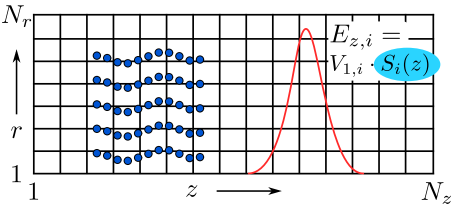

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Significance of Axial Electric Field

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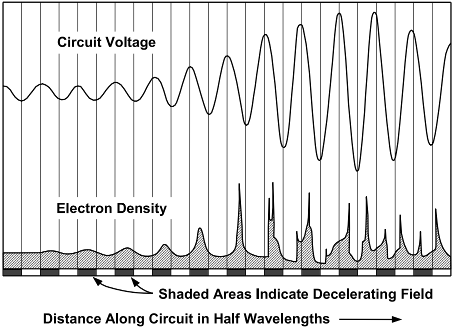

Figure: Illustration of field strength and charge density[2].

- Electric field induces beam modulation and counteracts de-bunching forces

→ Influence on maximum achievable efficiency

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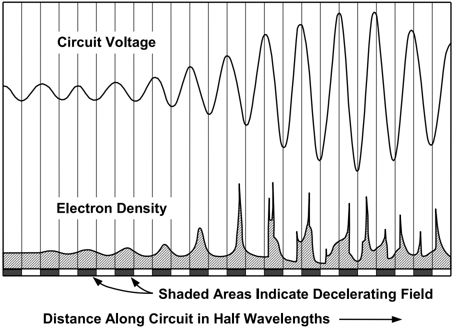

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About Spatial Harmonics

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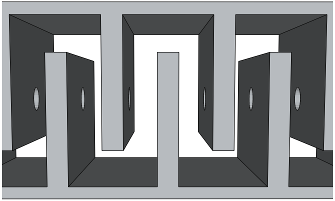

Figure: FW delay line.

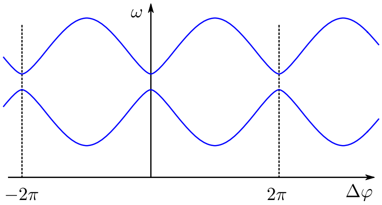

Figure: Dispersion diagram.

- Periodic structure supports propagating modes
- EM fields are superposition of spatial harmonics
- All harmonics have same group but different phase velocity
- Amplitude of synchronous harmonic defines beam-wave coupling

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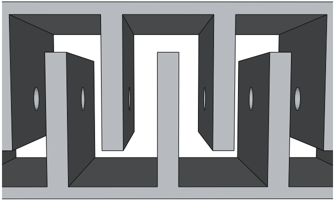

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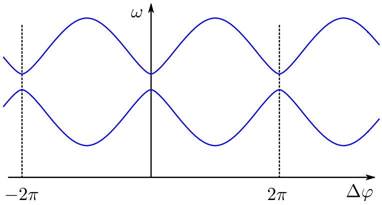

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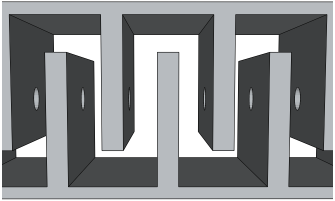

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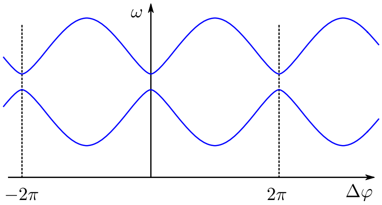

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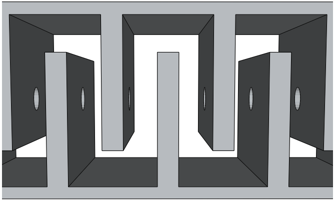

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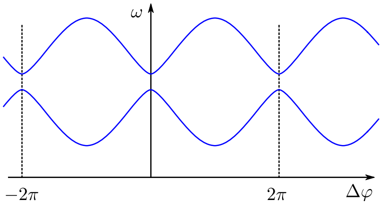

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Cold Impedance Parameters

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- Coupling impedance $R_{\mathrm{c},n}$ defined by Pierce[3]
  - Strength of nth space-harmonic amplitude independent of transported power
- Kino impedance R_{Kino} defined by Curnow[4]
  - Measure of total field strength (all spatial harmonics) independent of transported power

$\rightarrow$ Related by shape of axial electric field

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Hyperbolic Field Shape Model

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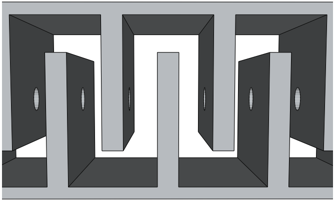
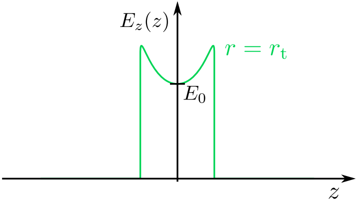
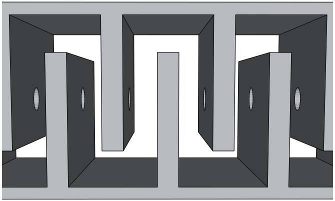


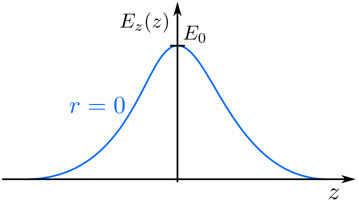


- At beam tunnel radius axial field is zero on the metal and has hyperbolic features in the gap[5]
- Unknown curve parameter of hyperbolic shape
- Sudden change of field distribution at gap corner

[5] H. G. Kosmahl and G. M. Branch, Jr., "Generalized Representation of Electric Fields in Interaction Gaps of Klystrons and Traveling-Wave Tubes", *IEEE Trans. Electron Devices*, vol. 20, no. 7, pp. 621-629, 1973.

Field Shape From Laplace Equation





- Axial field at beam center has features similar to a Gaussian
- Evanescent fields in beam tunnel (waveguide below cut-off)
- Extract from solution of Laplace equation

Comparison of Shape Models

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Hyperbolic cosine

+ Analytical expression
– Fixed far from beam axis
– More information necessary

Laplace equation

+ Depends only on geometry
+ Computationally inexpensive
+ Shape outside axis included

→ **Harmonic amplitudes are not controlled in either model!**

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Synthesis of Shape Function

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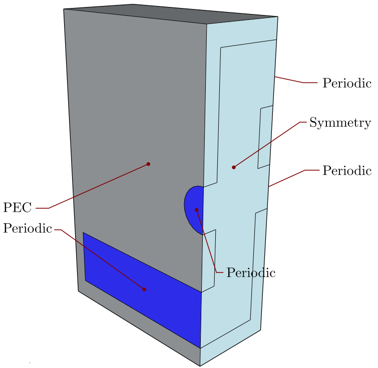

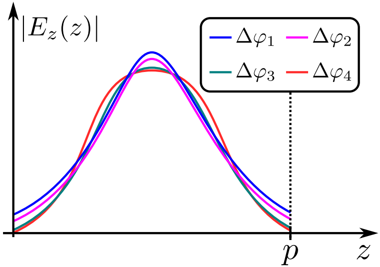

- Periodic unit cell with corresponding boundary conditions
- Eigenfrequencies and -modes for each phase advance $\Delta\varphi$
- Extract complex axial electric field $E_z(z, \beta)$

Derivation of the Shape[6]

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Periodic field in unit cell

$$E_z(z,\beta) = V_\beta \cdot \sum_{m=-\infty}^{\infty} S(z - mp) \cdot e^{-jm\beta p}$$

... some time and ink later ...

[6]Similar approach to N. M. Ryskin and V. N. Titov, "Nonstationary Simulation of Electron Beam Interaction with Coupled Resonant Microwave Oscillators", *Proc. IEEE Int. Conf. Plasma Science (ICOPS)*, 2007, 725.

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Local field shape

$$S(z) = \frac{p}{2\pi} \int_0^{2\pi/p} \frac{E_z(z, \beta)}{V_\beta} \mathrm{d}\beta$$

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Derivation of the Shape (cont.)

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Synthesis formula

$$S(z) = \frac{1}{\pi} \int_0^{\infty} \beta p \sqrt{\frac{R_{\mathrm{c},\beta}}{R_{\mathrm{Kino},\beta}}} \cdot \cos(\beta z) \mathrm{d}\beta$$

+ Shape is related to geometry
+ Correct representation of harmonic amplitudes
– Integration needs to be truncated
– Eigenmode simulation required

Derivation of the Shape (cont.)

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Radial Extrapolation of Field Shape

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Radial wavenumber

$$\gamma^2 = \beta^2 - k^2$$

- Local cylindrical symmetry

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Axial/Radial shape functions

$$S_z(z,r) = \frac{1}{\pi}\int_0^\infty I_0(\gamma r)\cdot \beta p \sqrt{\frac{R_{c,\beta}}{R_{\mathrm{Kino},\beta}}}\cdot \cos(\beta z)\mathrm{d}\beta$$

$$S_r(z,r) = \frac{1}{\pi}\int_0^\infty \left(\frac{\beta}{\gamma}\right)\cdot I_1(\gamma r)\cdot \beta p \sqrt{\frac{R_{c,\beta}}{R_{\mathrm{Kino},\beta}}}\cdot \cos(\beta z)\mathrm{d}\beta$$

Outline

Example Geometry

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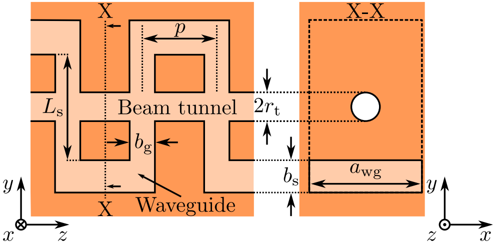
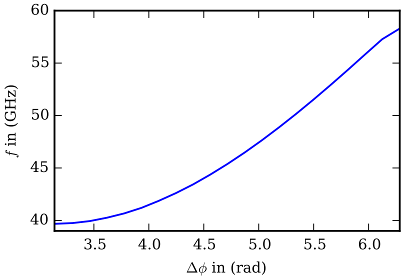


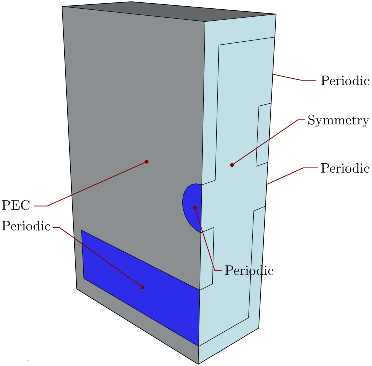
Geometry parameters in (mm).

p	r_t	L_s	a_{wg}	b_s	b_g
1.1	0.35	2.0	3.8	0.55	0.55

- Conventional FW delay line
- Homogeneous cross section
- Relatively small beam tunnel

Eigenmode Simulation Results





- Simulation results of Ansys EM
- Passband from approx. 40 GHz to 58 GHz
- Coupling impedance between 1 Ω and 10 Ω

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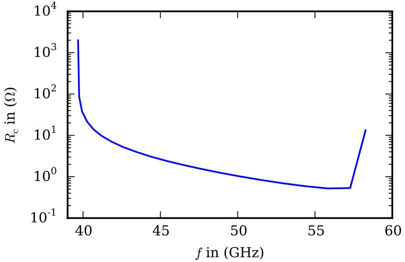

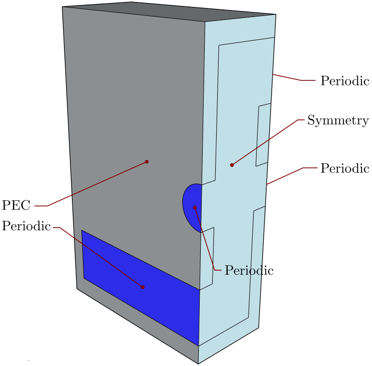

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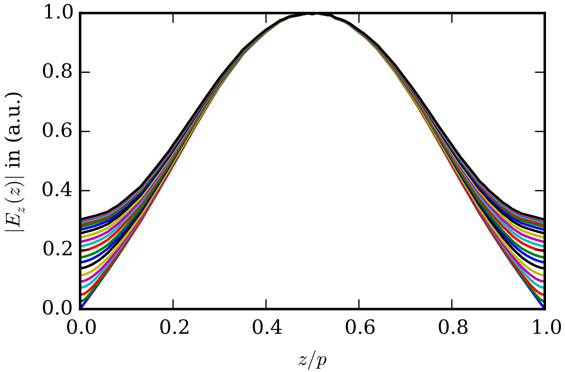
Axial Electric Field



- Axial field varies with frequency, or rather, phase advance
- Actual shape is significantly different

Extracted Field Shape and Spectrum

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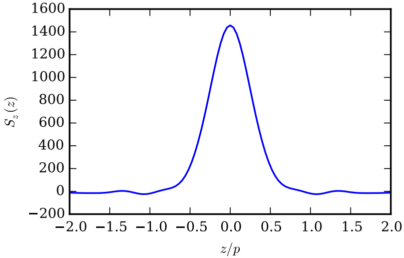
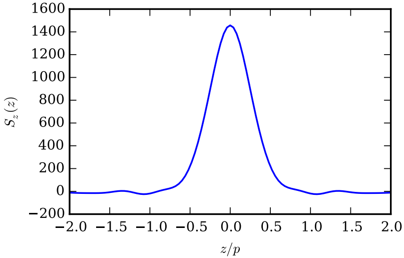
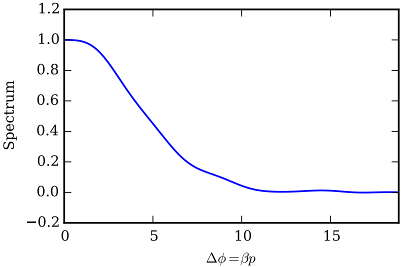


- Strongly localized field shape
- Small contribution to adjacent cells ($z = \pm p$)
- Spectrum largest for $\Delta\phi \leq 2\pi$

Extracted Field Shape and Spectrum

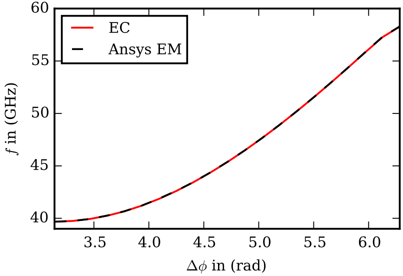
TUHH





- Strongly localized field shape
- Small contribution to adjacent cells ($z = \pm p$)
- Spectrum largest for $\Delta\phi \leq 2\pi$

Comparison of Results



- Equivalent circuit fits dispersion nicely
- With $S_z(z)$ the coupling impedance is well represented
- Error below 10 % across band suitable for beam-wave interaction computation[7]

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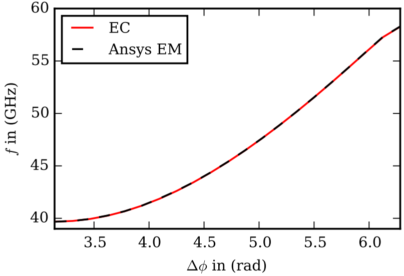

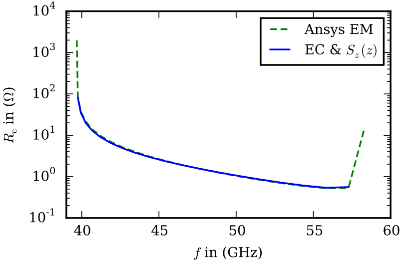

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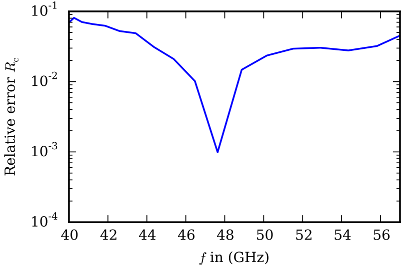

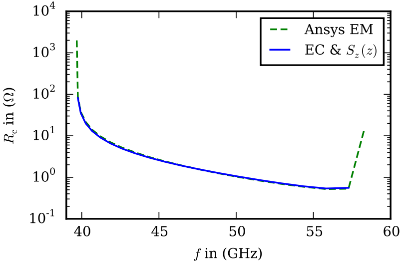

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Outline

Conclusion

- Representation of electric field for equivalent-circuit based beam-wave interaction algorithms
- Correct amplitudes of space harmonics
- Pre-processing steps required

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- Implementation in beam-wave interaction algorithm
- Applicability to other delay line topologies

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Thank you for your attention!

Acknowledgments

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DLR

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