Simulation and Modeling of Large Microwave and Millimeter-Wave Systems, Part 1

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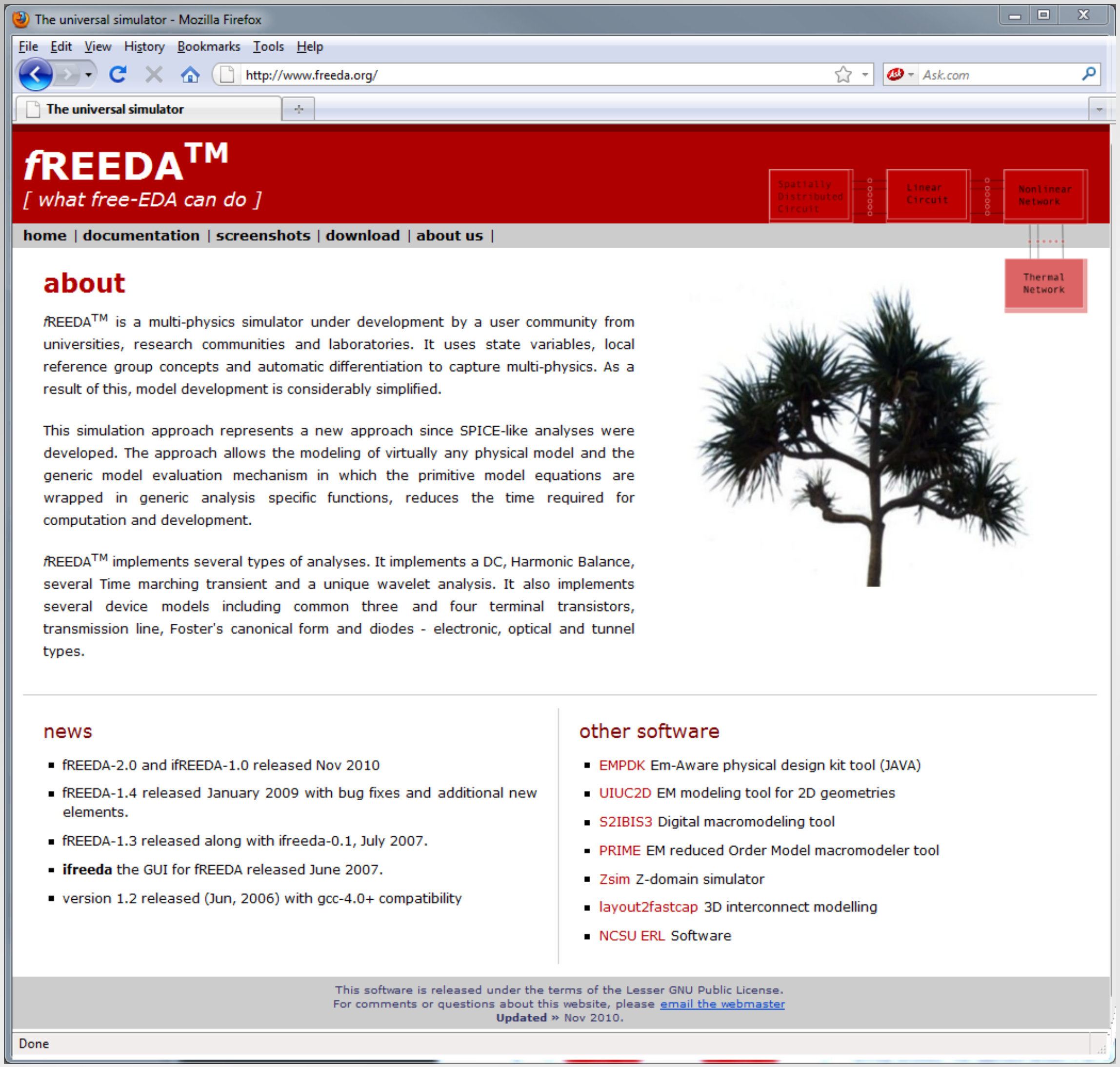
with
Nikhil Kriplani, Carlos Christofferson
and Shivam Priyadarshi

http://www.freeda.org

Outline

- ***Multi-Physics Simulator (fREEDA^{TM})***
  - *Minimizes Energy Error (not KCL)*
  - *Time-domain EM interface Frequency-domain EM (network parameter interface)*
  - *Thermal, Noise*
  - *Photonics, Mechanical*
  - *Molecular Electronics*
  - *Code reuse: Uses Trilinos Numerical Libraries from Los Alamos*
- ***Simple device modeling***
- ***Transient Simulation***
- ***Uncompromised commitment to accuracy***
- ***Circuit/Field Interaction***

fREEDA



Open Source / Open Licensing

BSD License (Open to companies to do what they want), well almost there.

Essential Concepts for Multi-Physics Modeling

- Integration of multi physics problem into the circuit modeling domain
- Object Oriented Approach
- Global Modeling
  - EM Interconnect Modeling
  - Digital Macromodeling
  - Opto Electronic Modeling
  - Quantum Modeling
  - Molecular Modeling
  - Materials Modeling
  - Bio / Chemical Modeling
- Interfaces

Universal Error Concept (Energy Norm)

Universal error concept:
AT A TERMINAL
Σ FLUX = 0
All Potentials are the SAME

	Flow $i(t)$	Effort $v(t)$	LOCAL REFERENCE NODE
ELECTRICAL	I	V	LOCAL GROUND
THERMAL	HEAT CURRENT	TEMPERATURE	ABSOLUTE ZERO
MECHANICAL	FORCE	POSITION	INERTIAL REFERENCE FRAME

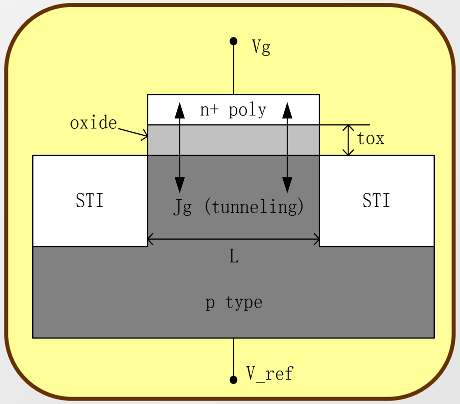
For each state variable *x* there must be a flow and an effort contribution.

Many Unique Models

- *EM Interface (TD and FD)*
- *Electro-Thermal*
- *Dynamic Range*
- *Time Delay*
- *Large Signal Noise*
- *Electro-Optic*
- *Molecular Diode*

MOSCAP

World's first implementation



E.G. The tunnel process cannot be expressed as a current-charge-voltage expression as Spice requires. Instead use state variables to implement tunneling correctly.

Circuit Theory

Background Reading

Computer-Aided Design of RF and Microwave Circuits and Systems

Michael B. Steer, *Fellow, IEEE*, John W. Bandler, *Fellow, IEEE*, and Christopher M. Snowden, *Fellow, IEEE*

IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 50, NO. 3, MARCH 2002

Global Modeling of Spatially Distributed Microwave and Millimeter-Wave Systems

Michael B. Steer, *Fellow, IEEE*, James F. Harvey, *Member, IEEE*, James W. Mink, *Fellow, IEEE*, Mostafa N. Abdulla, *Student Member, IEEE*, Carlos E. Christoffersen, *Student Member, IEEE*, Hector M. Gutierrez, *Member, IEEE*, Patrick L. Heron, *Member, IEEE*, Chris W. Hicks, *Student Member, IEEE*, Ahmed I. Khalil, *Student Member, IEEE*, Usman A. Mughal, *Student Member, IEEE*, Satoshi B. Nakazawa, *Student Member, IEEE*, Todd W. Nuteson, *Member, IEEE*, Jaee Patwardhan, Steven G. Skaggs, *Member IEEE*, Mark A. Summers, *Member, IEEE*, Shunmin Wang, and Alexander B. Yakovlev, *Member, IEEE*

IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 47, NO. 6, JUNE 1999

Background Reading

J. Kunisch and I. Wolff, "The compression approach: A new technique for the analysis of distributed circuits containing nonlinear elements," in *IEEE MTT-S Int. Microwave Symp. Workshop WSK*, Albuquerque, NM, 1992, pp. 16–31.

——, "Steady-state analysis of nonlinear forced and autonomous microwave circuits using the compression approach," *Int. J. Microwave Millimeter-Wave Computer-Aided Eng.*, vol. 5, no. 4, pp. 241–225, 1995.

Circuit Theory for Spatially Distributed Microwave Circuits

Ahmed I. Khalil and Michael B. Steer

IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 46, NO. 10, OCTOBER 1998

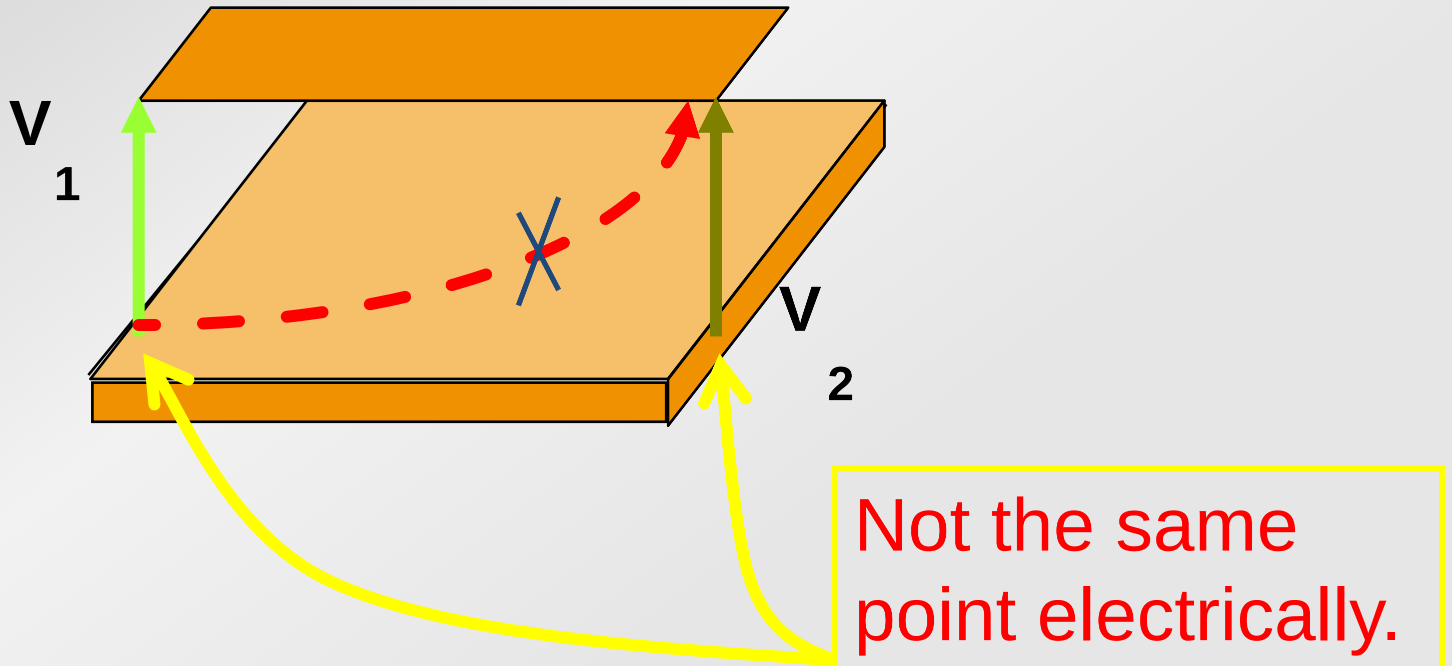
Causal Reduced-Order Modeling of Distributed Structures in a Transient Circuit Simulator

Ramya Mohan, *Student Member, IEEE*, Myoung Joon Choi, Stephen E. Mick, Frank P. Hart, Karthik Chandrasekar, Andreas C. Cangellaris, *Fellow, IEEE*, Paul D. Franzon, *Senior Member, IEEE*, and Michael B. Steer, *Fellow, IEEE*

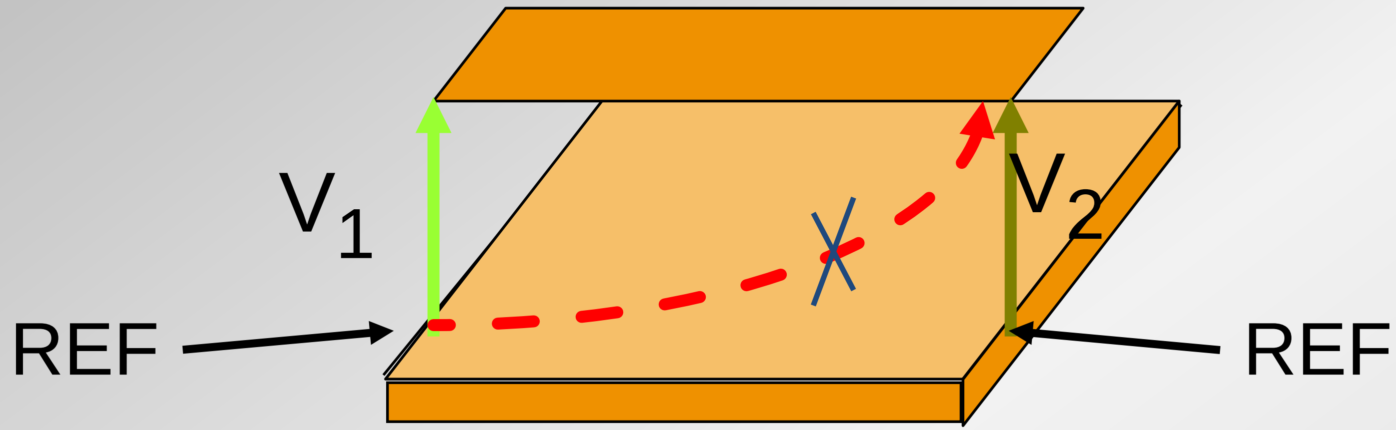
Microstrip Model

- **In a Field Simulator Voltages Are Determined By Integrating The Electric Field Along a Path**
- **In Microstrip Problems the Field is Integrated Over The Paths Shown to Obtain V**
- **The Path of Integration Matters**

The Dashed Path Yields a Different Value of V_2



Microstrip Model



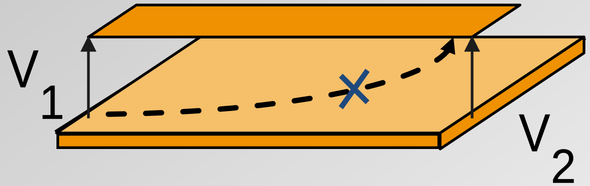
Network Model:

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

But a (SPICE) Circuit does not have two reference terminals.

Global Reference Node

Conventional Microwave Circuits
(e.g. Microstrip)



- *Perfect Ground Plane Assumed*
- *(No Retardation Effects)*
- *In A Field Simulator Voltages Are Determined By Integrating The Electric Field Along a Path*
- *In Microstrip Problems the Field is Integrated Over The Paths Shown to Obtain* V_1 and V_2
- *The Path of Integration Matters*
- *The Dashed Path Yields a Totally Different Value*
- *of* V_2

Current Microwave Simulators (Linear, Harmonic Balance, Transient) are Based on Nodal Voltage Descriptions

To Use Nodal Voltages There Must Be a Common Reference Node

Field Simulators Currently Require A Common Reference Ground

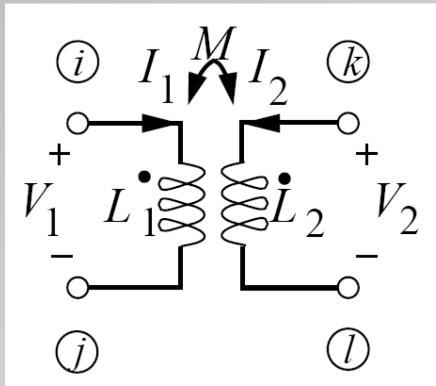
Local reference node concept

- **This avoids non-physical connections and therefore is fundamental for the analysis of spatially distributed circuits as well as for simultaneous thermal-electrical simulations.**

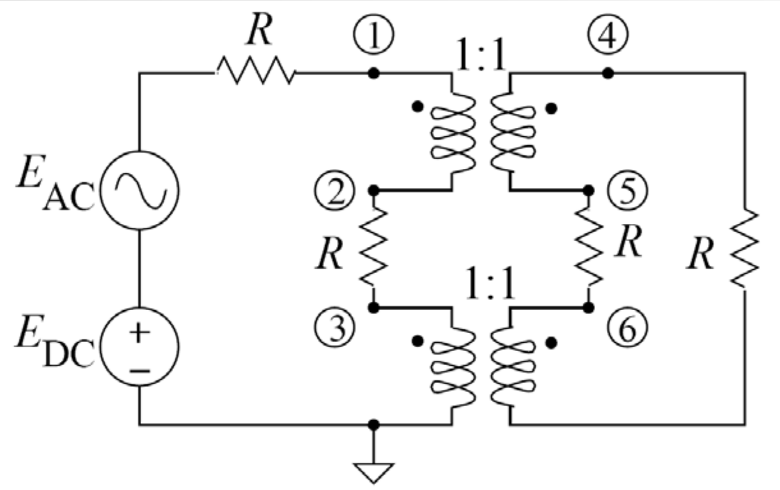
LOCAL REFERENCE TERMINAL

Our common view of a port is that it has two terminals

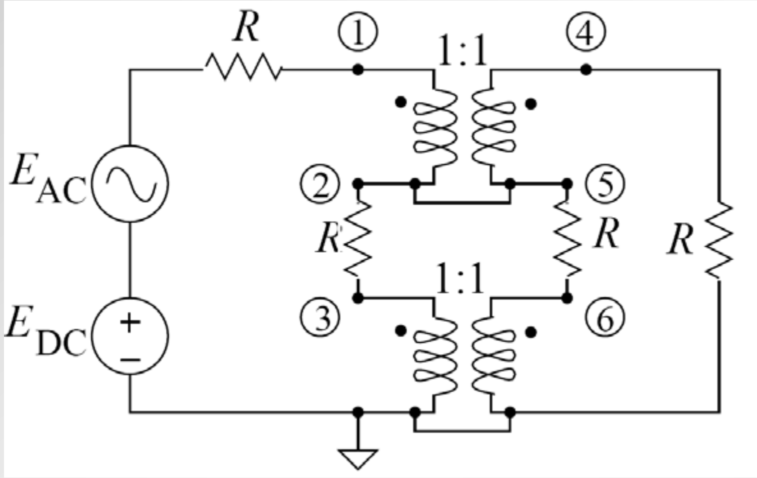
How to extend this beyond two terminal ports?



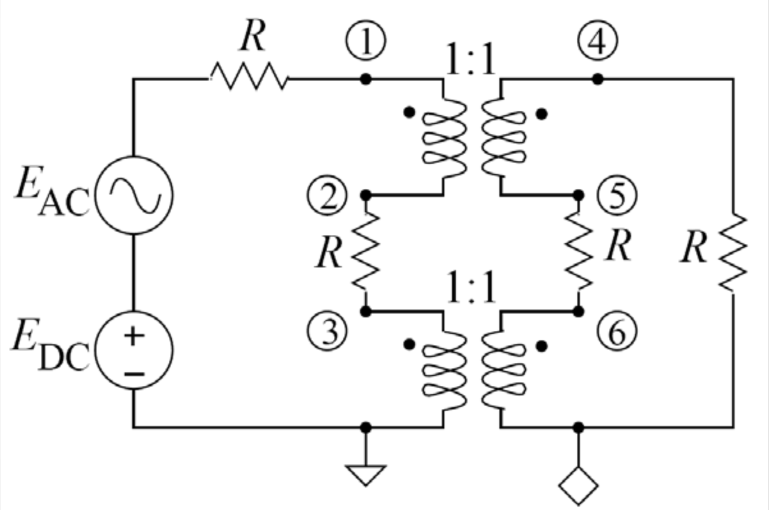
Circuit



Circuit

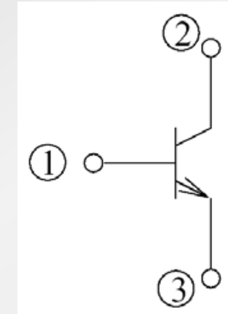


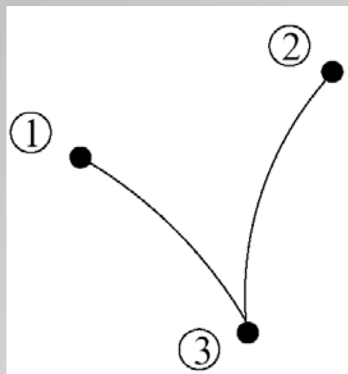
Non- fREEDA



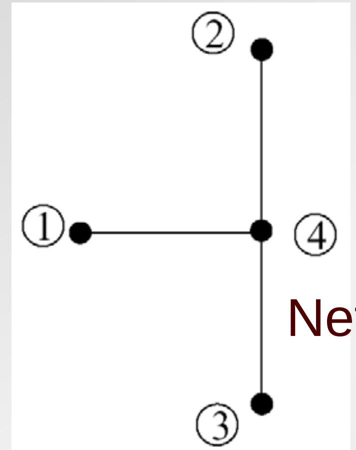
fREEDA

Circuit vs. Network Graph

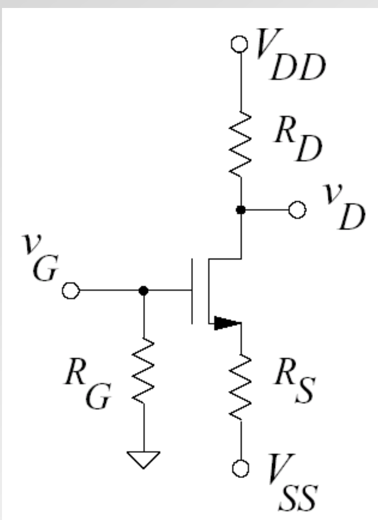




Circuit Graph

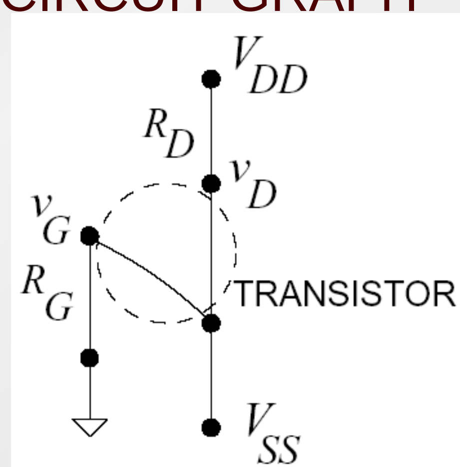


Network Graph

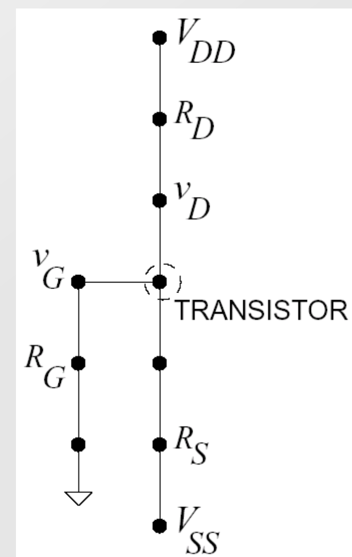


Must use two circuit graphs to represent a general circuit

CIRCUIT GRAPH



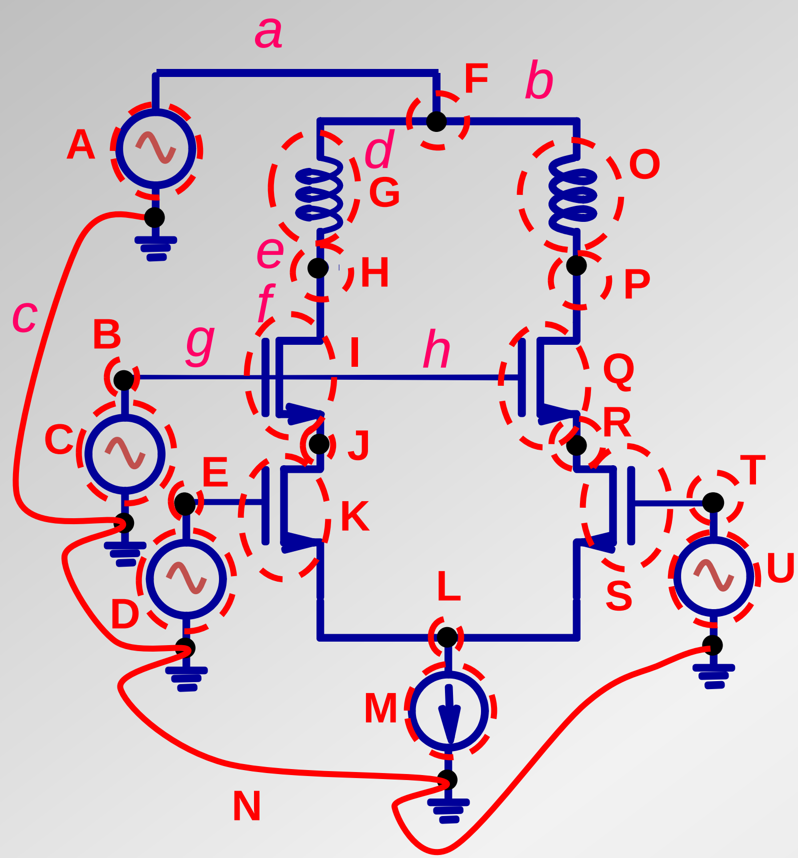
Concept of Spice

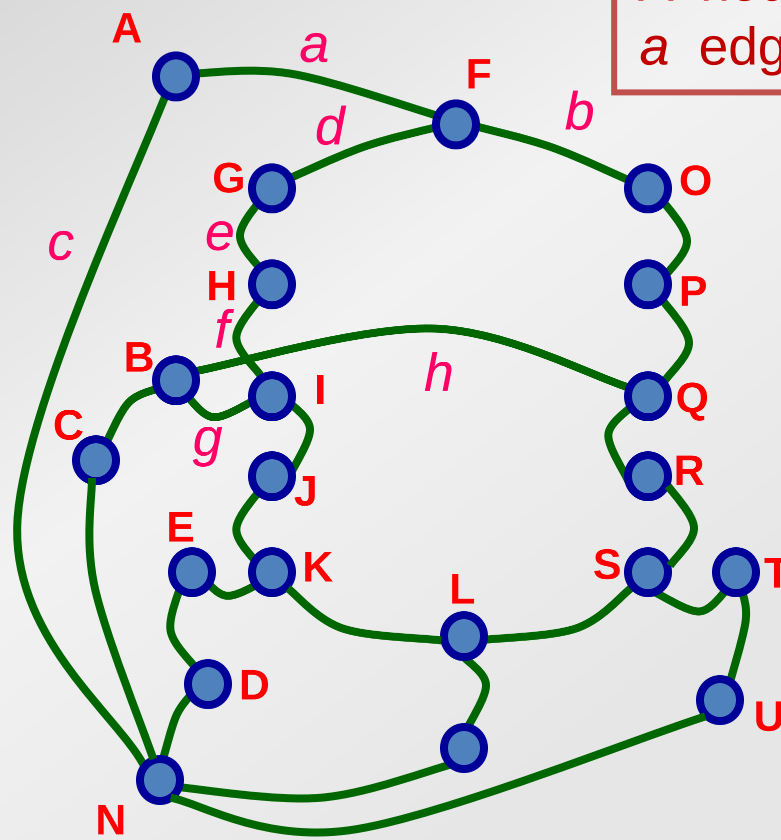


NETWORK GRAPH
Concept of fREEDA

Network Graph

A node
a edge

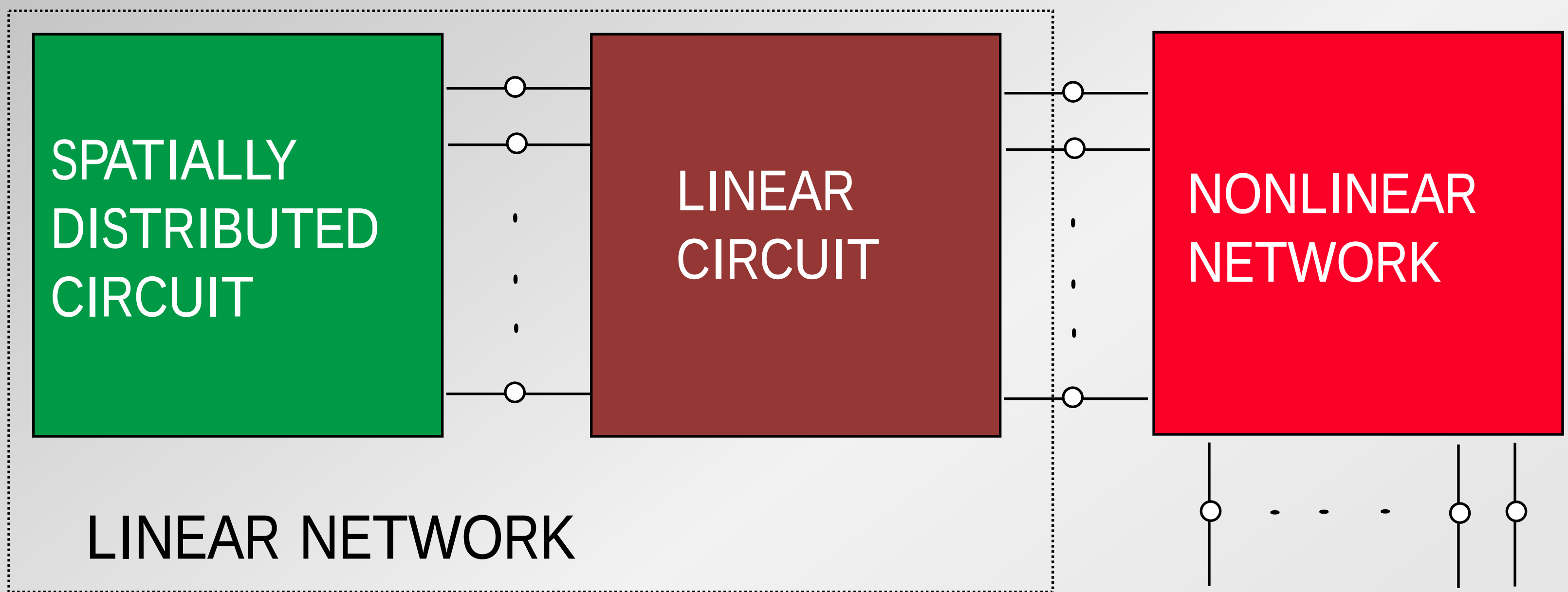


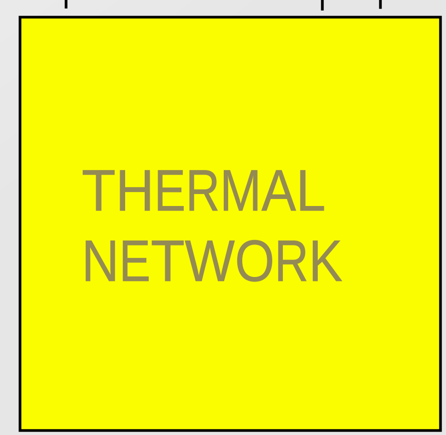


NETWORK GRAPH

Information is stored in fREEDA as a Network Graph but the difference between a terminal and an element is retained.

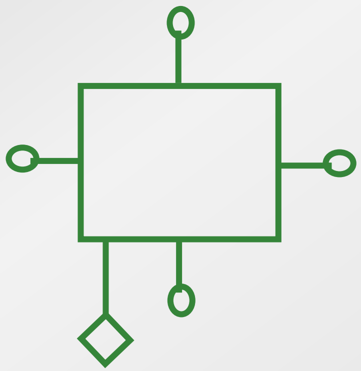
Modeling Concept





- Nonlinear Analysis Must be Point of Integration
  Use SPICE-like & HARMONIC BALANCE analyses
- Use Existing Domain Specific Analyses
  E.G. Thermal, Field
- Behavioral Modeling Is the Key to Using Results of One Simulator In Another

Modeling Scope



Can handle

$$y(t) = F\left[\begin{array}{l} x_1(t),\ldots,x_n(t),\dfrac{dx_1(t)}{dt},\ldots,\dfrac{dx_n(t)}{dt}, \\ \dfrac{d^2x_1(t)}{dt^2},\ldots,\dfrac{d^2x_n(t)}{dt^2},\dfrac{d^3x_1(t)}{dt^3},\ldots,\dfrac{d^3x_n(t)}{dt^3}, \\ x_1(t-\tau_1),\ldots,x_n(t-\tau_1) \end{array}\right]$$

Where *y*(t) is either an *i*(*t*) or a *v*(*t*).

Also in any type of analysis we want *dy/dx* The exact derivatives (w.r.t. time or frequency etc.) we want depend on the type of analysis we are doing (transient, wavelet, harmonic balance). The derivatives needed are calculated using ADOL-C under control of the analysis routines. This is why the same model can be used in any type of analysis.

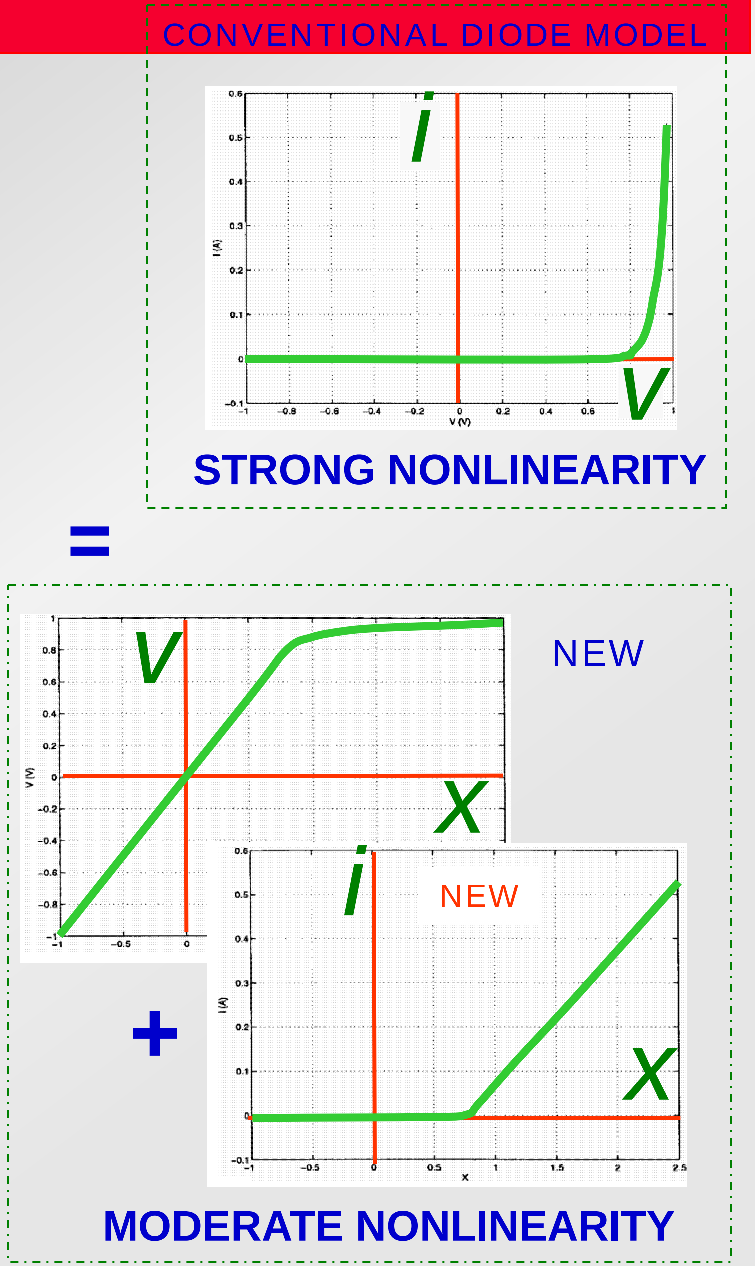
ADOL-C is one of the many support libraries.

fREEDA

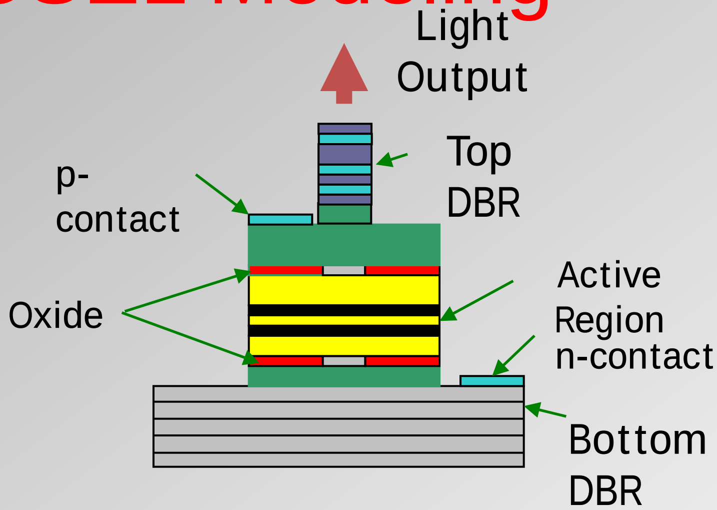
Unique Feature:

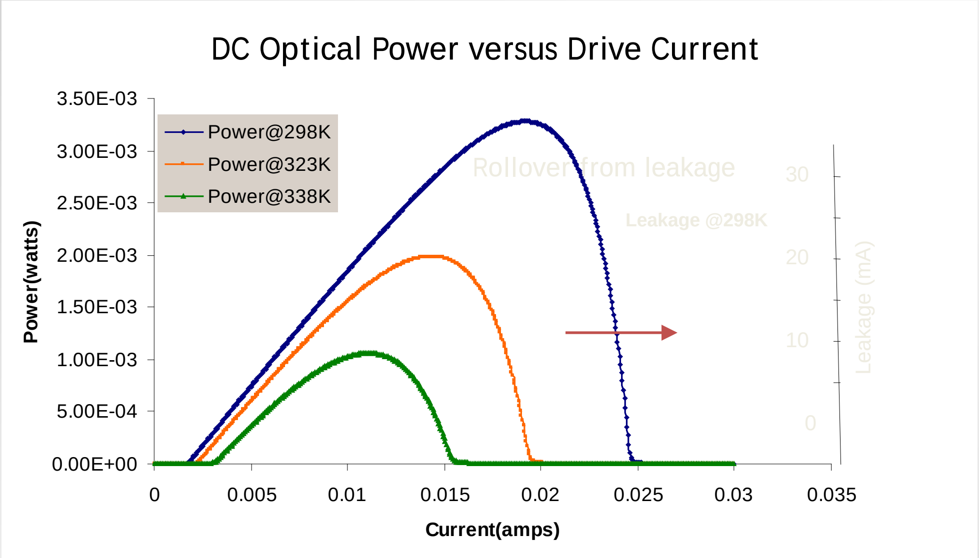
Nonlinear devices models based on state variables:

- This provides great flexibility for the design of new models. All of the analyses are state-variable-based, including a time marching analysis (different integration methods available) and a unique wavelet transient analysis.
- The state variables can be chosen to achieve robust numerical characteristics.
- The calculation of derivatives are free of truncation errors at a small multiple of the run time required to evaluate the original function with little additional memory required. (ADOLC)



VCSEL Modeling





Single Mode Rate Equations

Carrier density

$dN(t)/dt = \eta_i(I(t)-I_L(T))/\tau - N(t)/\tau_{nr} - G(T)(N(t)-N_0(T))S(t)/(1+\varepsilon S(t))$

Photon density

$dS(t)/dt = -S(t)/\tau_p + \beta N(t)/\tau_r + G(T)(N(t)-N_0(T))S(t)/(1+\varepsilon S(t))$

Temperature

$dT(t)/dt = -T(t)/\tau_{th} + (T_0+(I(t)V(t)-P_0(t))R_{th})/\tau_{th}$

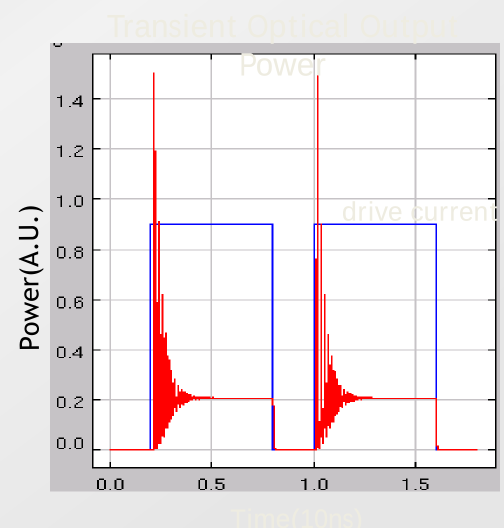
Temperature dependence of Gain and Transparency

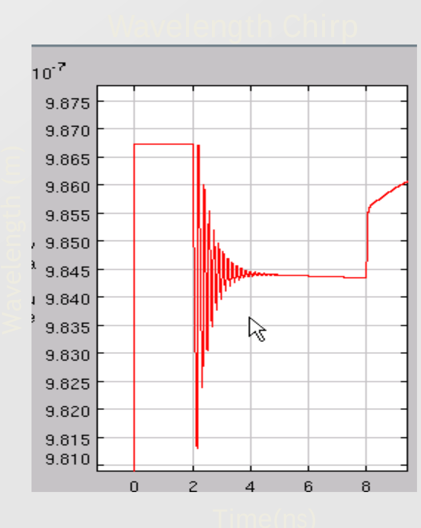
$G(T) = G_0(a_{g0} + a_{g1}T + a_{g2}T^2) / (b_{g0} + b_{g1}T + b_{g2}T^2)$

$N_0(T) = N_{t0}(c_{n0}+c_{n1}T+c_{n2}T^2)$

Leakage Current

$I_L = I_{L0}\exp[(-a_0+ a_1N_0 + a_2N_0T- a_3/N_0)/T]$

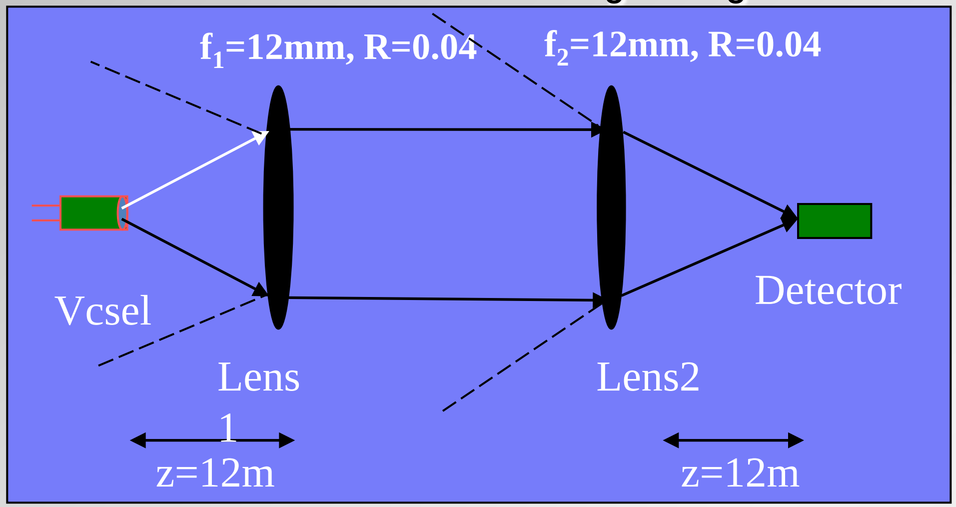




Electro-Optics

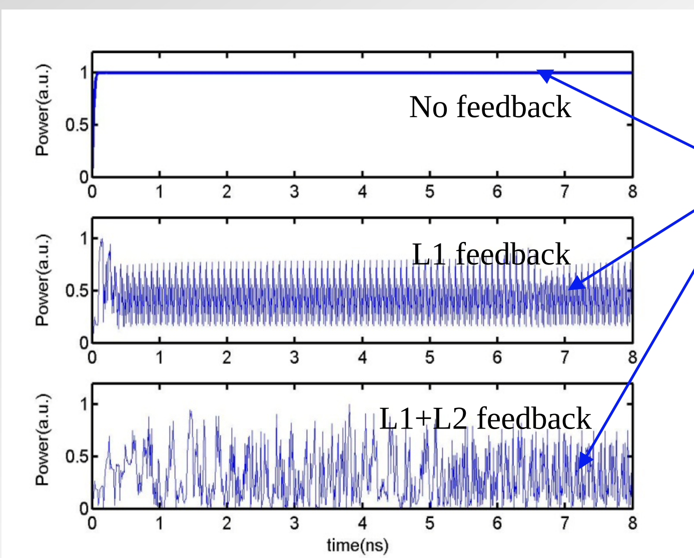
Feedback Results:

- Power and Wavelength degradation due to two components



With:
Mark Niefeld
Ravi Pant
Univ. of Arizona

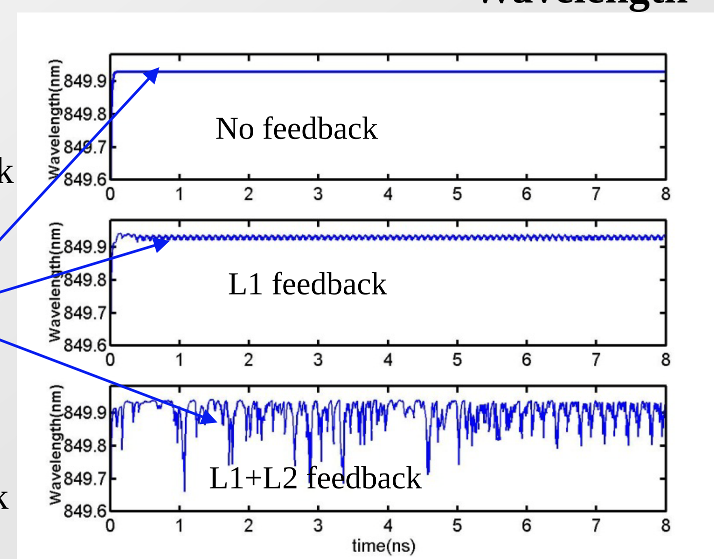
Optical Power



Output power degradation due to single and double lens feedback

Output wavelength degradation due to single and double lens feedback

Wavelength

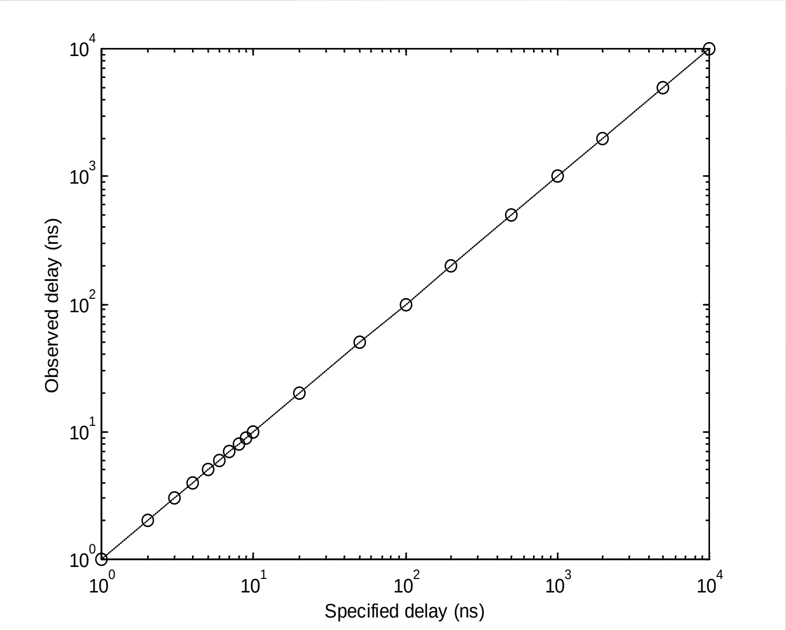


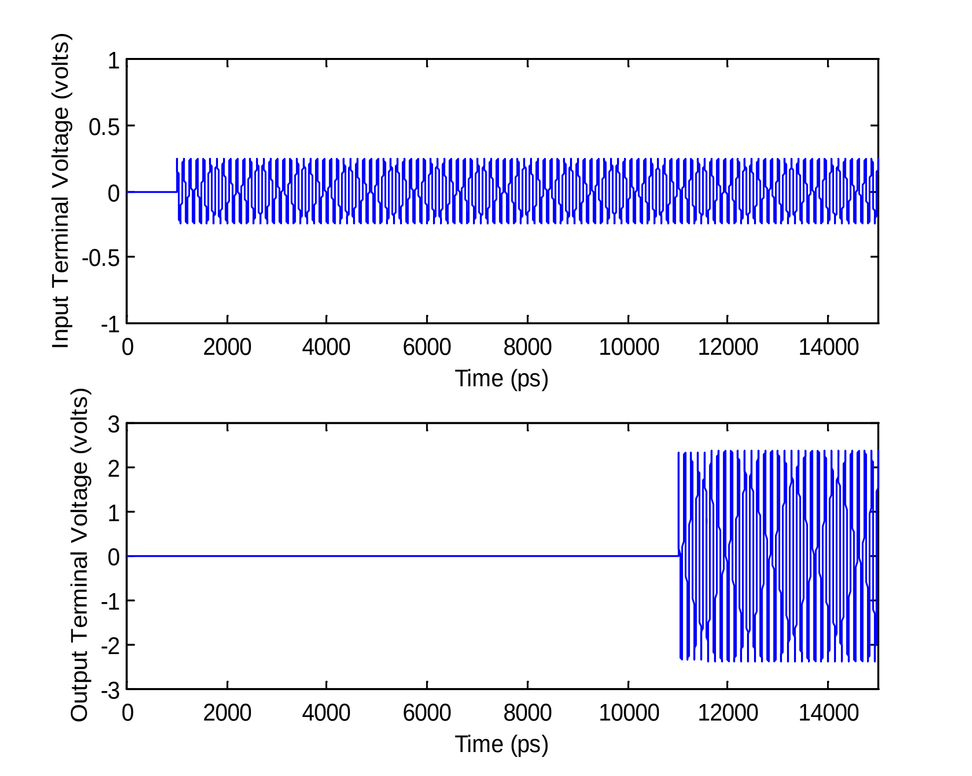
Time Delays

Spice handles only short (< 4 time step) time delays.

*f*REEDA has no limit

TWTA used to validated fREEDA's ability to handle models with long time delays. Also implemented in many transistor models.

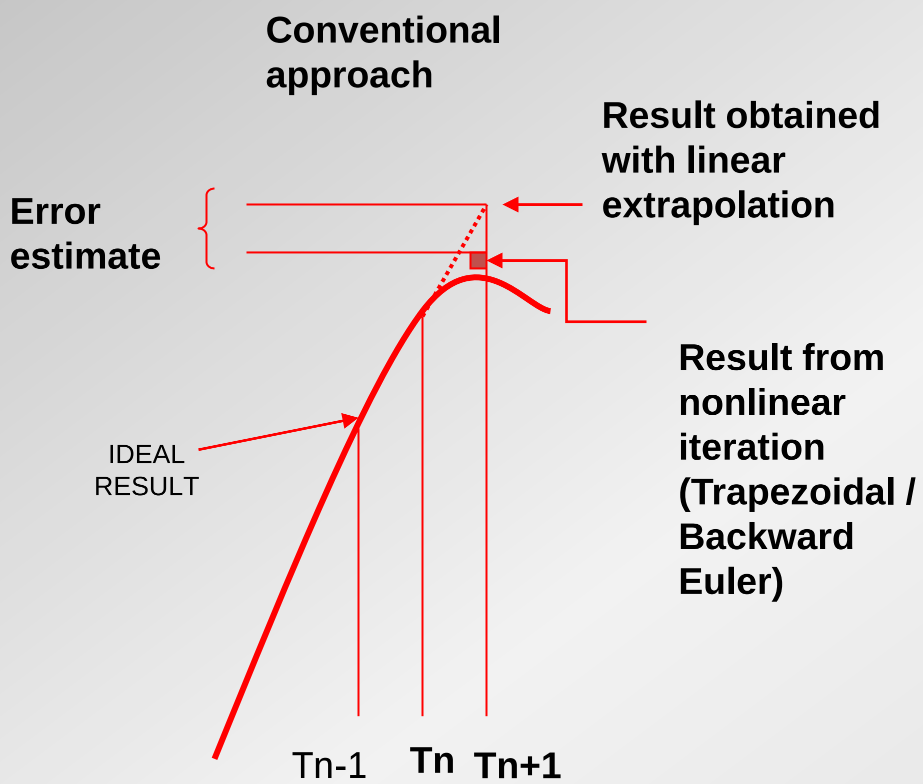




Transient Simulation

Conventional Time Stepping Algorithm

Choice of Time Step to keep error below a set tolerance.

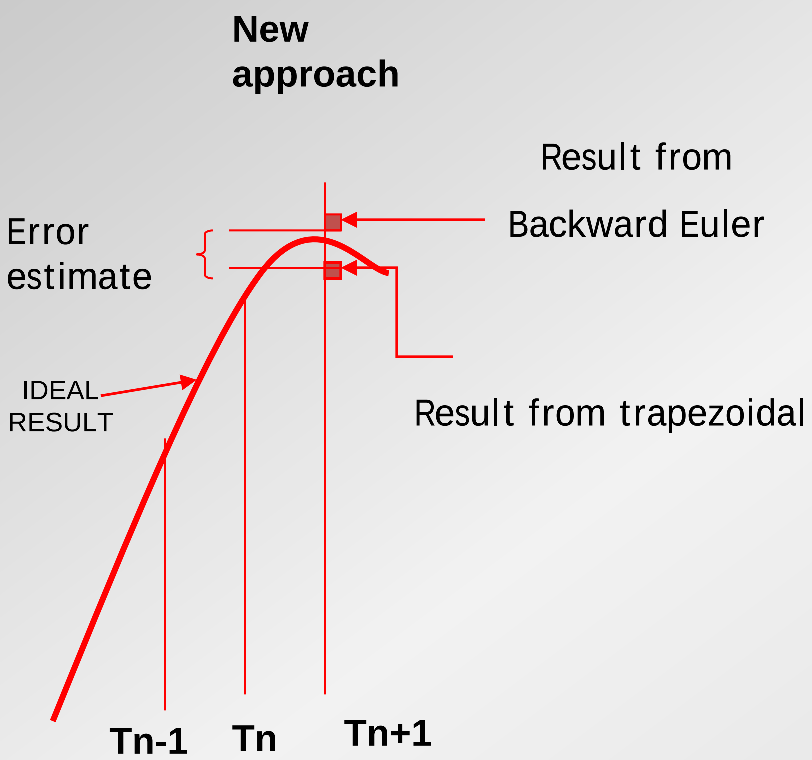


Poor estimate of error leads to inappropriate choice of time step

The difference between the nonlinear iteration and the straight line extrapolation is taken as an estimate of error.
If the error is too large the time step is reduced by a factor of 2.
If the error is very low the time step is increased by A factor of 2.

This results in excessively short time steps around curves and limits dynamic range.

fREEDA Time Stepping Algorithm

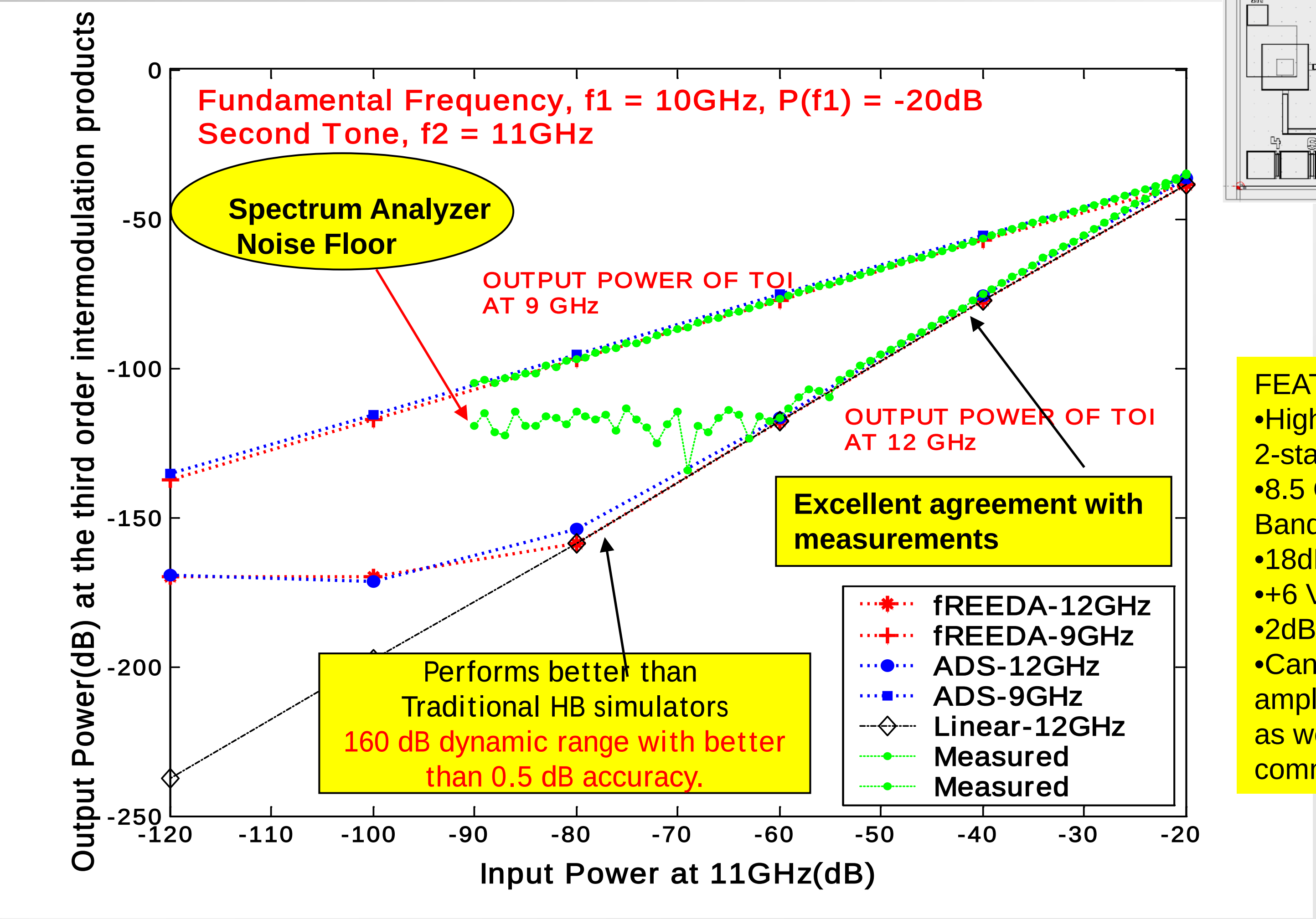


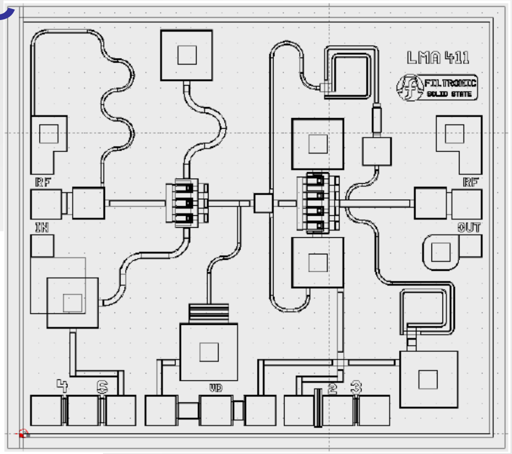
Better estimate of error leads to a better choice of time step

The difference between the Backward Euler and trapezoidal estimates is an incredibly good estimate of error. If the error is too large the time step is reduced by a factor of 2. If the error is very low the time step is increased by A factor of 2.

The half way point is taken as the answer.

Two-Tone Test of Dynamic Range (X-Band Amplifier)





LMA411

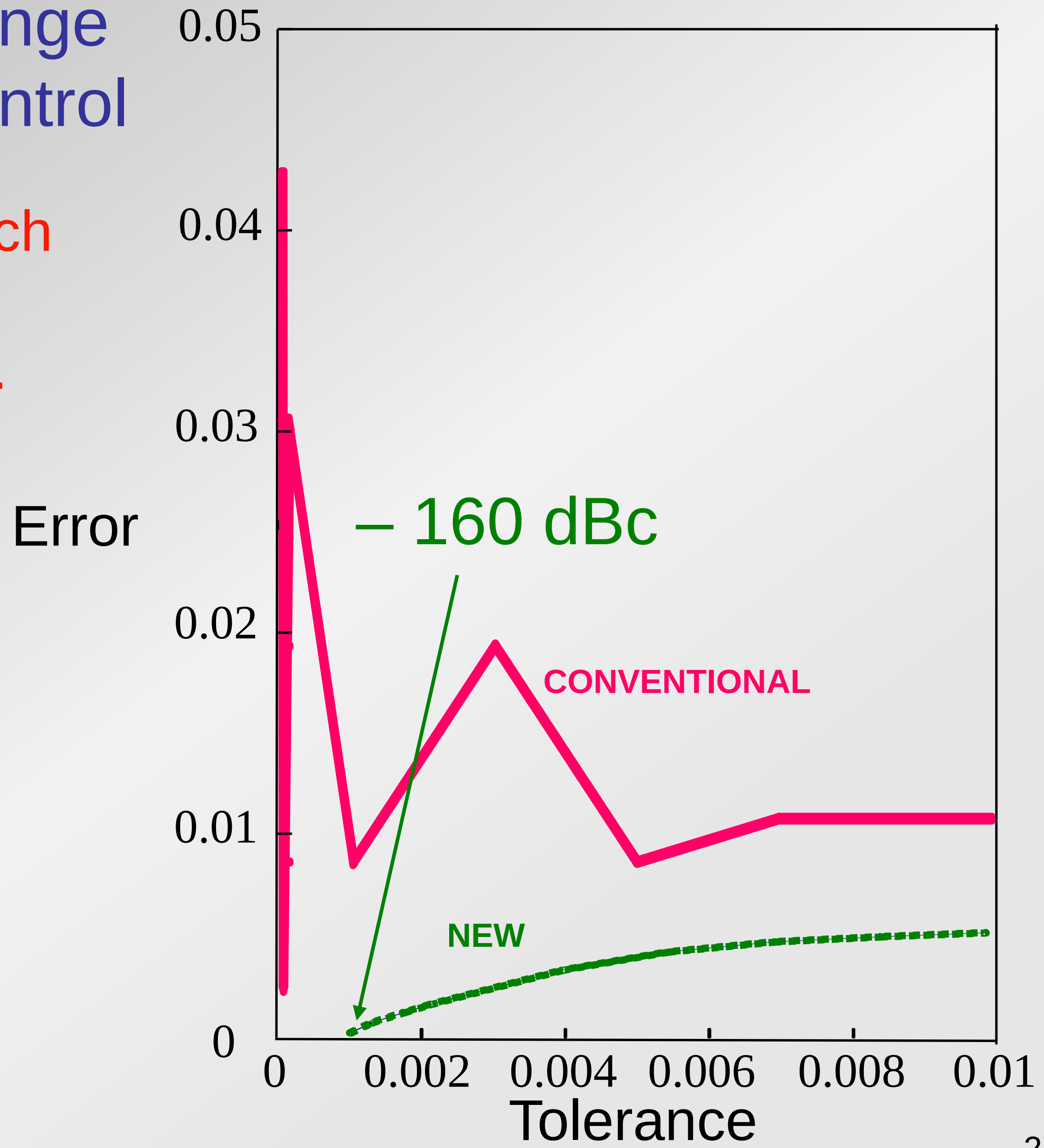
FEATURES:

- High Dynamic Range PHEMT 2-stage Low Noise Amplifier.
- 8.5 GHz to 14 GHz Frequency Band.
- 18dB Gain.
- +6 V Supply Voltage.
- 2dB Noise Figure.
- Can be used as pre-driver amplifier for phased array radar as well as commercial communications applications.

High Dynamic Range Through Error Control

The new approach is a better estimate of error.

Better time point selection.



fREEDA, Transient Simulation and Frequency-Domain Modeling

Three Milestones for Interfacing EM and Circuits

- ***D. Winkelstein, M. B. Steer, and R. Pomerleau, "Simulation of arbitrary transmission line networks with nonlinear terminations," IEEE Trans. on Circuits and Systems, April 1991, pp.418-422. See also, IEEE Trans. on Circuits and Systems, Vol. 38, Oct. 1991.***
    - ***Impulse response and convolution***
    - ***Time and frequency bounded***

- ***C. S. Saunders, J. Hu, C. E. Christoffersen, and M. B. Steer, "Inverse singular value method for enforcing passivity in reduced-order models of distributed structures for transient and steady-state simulation," IEEE Trans. Microwave Theory and Techniques, April 2011, pp. 837–847.***
    - **S parameters to Foster Model**
    - ***Passivity, causality***

- ***C. S. Saunders and M. B. Steer, "Passivity enforcement for admittance models of distributed networks using an inverse eigenvalue method," IEEE Transactions on Microwave Theory and Techniques, In Press.***
    - **y parameters to Foster Model**
    - ***Passivity, causality***
    - **What is needed for circuit simualtpors which are y parameter based**

- **ALL CONVERTERS NEED SOME HUERITIC KNOWLEDGE**
    - **Did the user provide sufficient data**
        - **If not how to extrapolate**
    - **What is the basic response (what to emphasize)**
        - **Low pass, Bandpass**

Approaches to Mixing EM Solvers

Frequency-Domain EM Solvers

Produce a set of S parameters (or equivalent)

Key-Problem is developing a causal/passive/accurate interface for transient simulation

The solution is the Foster Form with Appropriate Fitting Technique

Joining TD EM/ Circuits / FD EM

Approach 1

Use fREEDA with FDTD interface and Foster Cannonical Form Interface

Approach 2

Build Foster Model into FDTD

Workflow

EM Model In Frequency Domain Y(f)

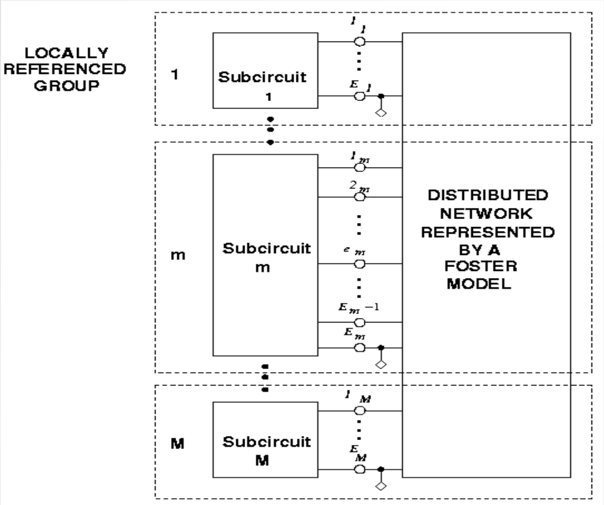
↓

Develop Foster N-Port

↓

Time-Domain Circuit Simulation fREEDA

R. Mohan, J. C. Myoung, S. E. Mick, F. P. Hart, K. Chandrasekar, A. C. Cangellaris, P. D. Franzon and M. B. Steer, "Causal reduced-order modeling of distributed structures in a transient circuit simulator," *IEEE Trans. Microwave Theory and Tech*, Vol. 52, No. 9, Sept. 2004, pp. 2207 – 2214.



$$H(s) = H_0 + H_1 s + \sum_{k=1}^{m}\left(\frac{r_k}{s-p_k}\right) + \sum_{k=1}^{m}\left(\frac{a_k}{s-b_k} + \frac{\bar{a}_k}{s-\bar{b}_k}\right)$$

Passivity Enforcement for Admittance Models of Distributed Networks Using an Inverse Eigenvalue Method

In Review

Christopher S. Saunders, *Student Member, IEEE,* and Michael B. Steer, *Fellow, IEEE*

Either implement a Foster's model directly or synthesize an R, L, C, K subcircuit.

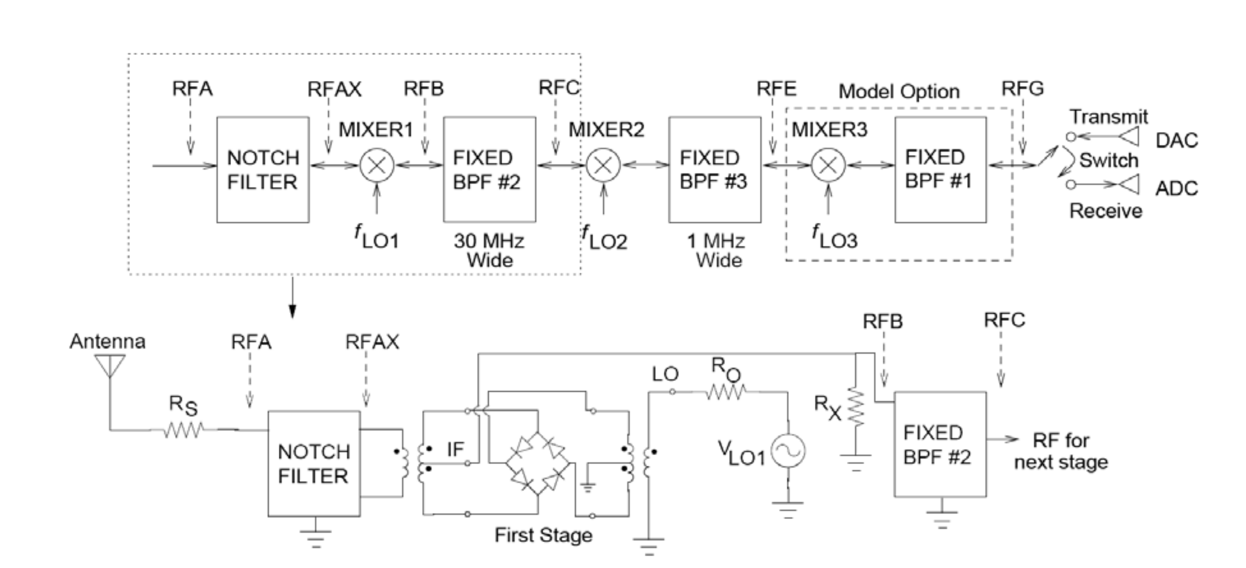
This is the most robust and accurate technique out there. Robustness is not perfect, heuristics required in extraction.

Main issue is in developing model that is

1) Causal
2) Passive
3) Accurate

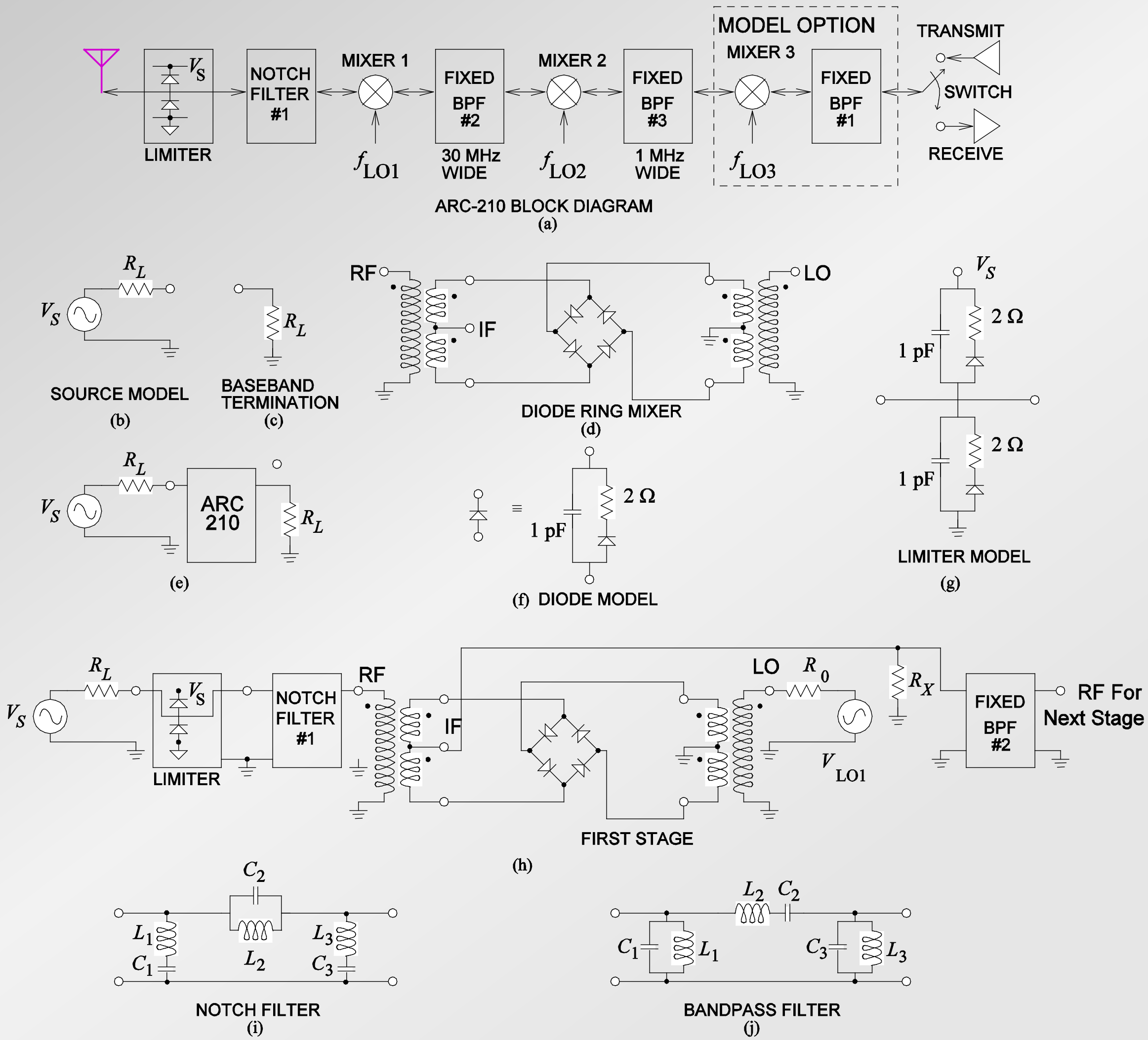
Use to incorporate FD-EM

- in transient circuit simulator
- In xFDTD (not in current scope) but can join xFDTD through fREEDA to EFD-EM solver

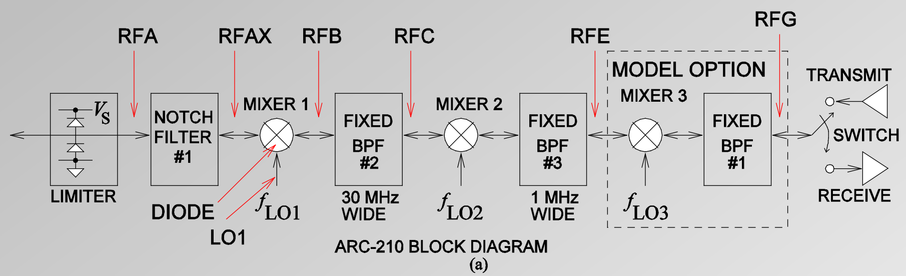


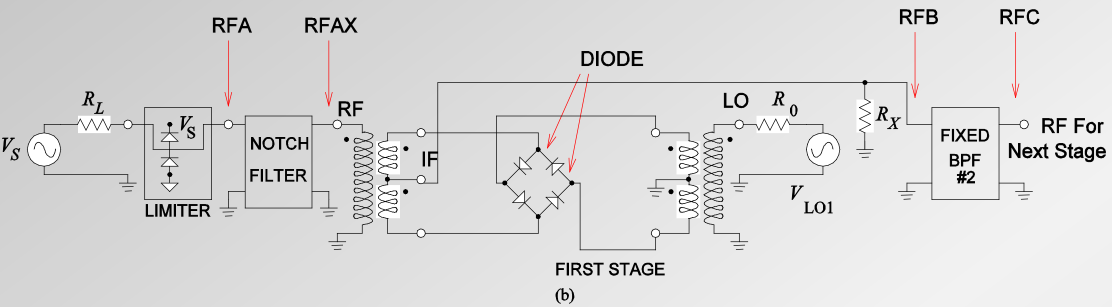
SINGARS ⟷ EM ⟷ SINGARS

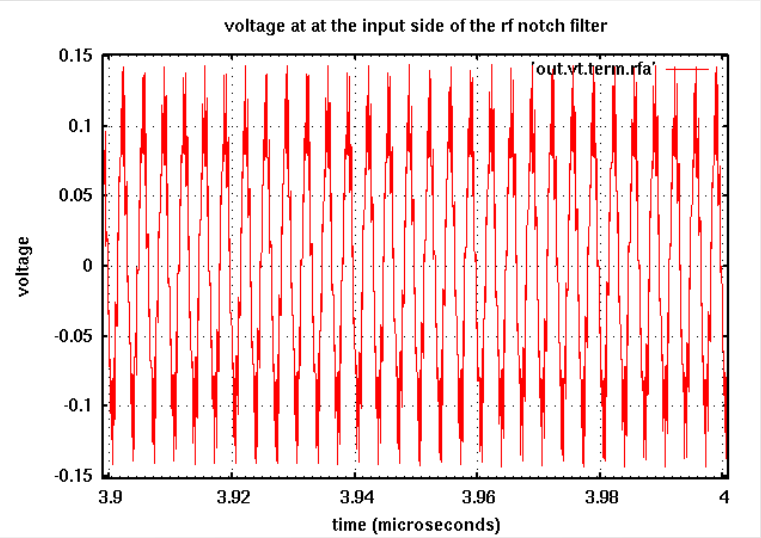
SINCGARS

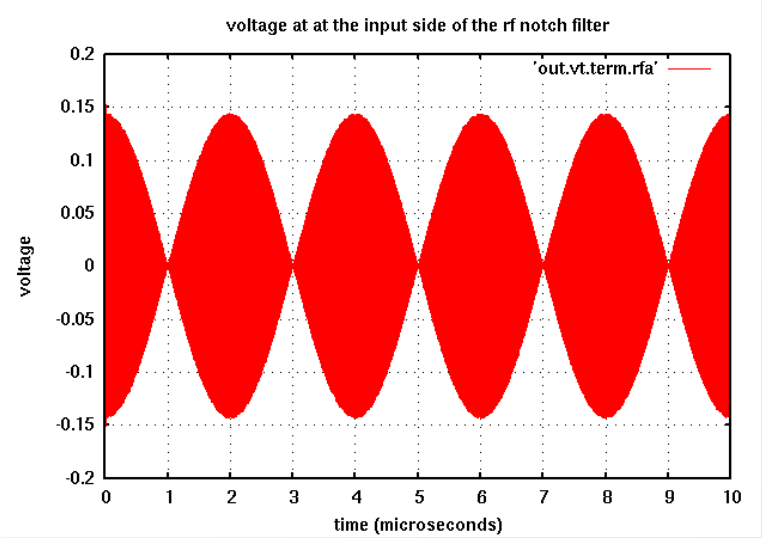

MODEL OPTION
TRANSMIT
MIXER 1
MIXER 2
MIXER 3
NOTCH FILTER #1
FIXED BPF #2
FIXED BPF #3
FIXED BPF #1
SWITCH
RECEIVE
LIMITER
f_{LO1}
30 MHz WIDE
f_{LO2}
1 MHz WIDE
f_{LO3}
ARC-210 BLOCK DIAGRAM
(a)
SOURCE MODEL
(b)
BASEBAND TERMINATION
(c)
RF
LO
IF
DIODE RING MIXER
(d)
2 Ω
1 pF
LIMITER MODEL
(g)
ARC 210
(e)
(f) DIODE MODEL
RF For Next Stage
FIRST STAGE
(h)
NOTCH FILTER
(i)
BANDPASS FILTER
(j)

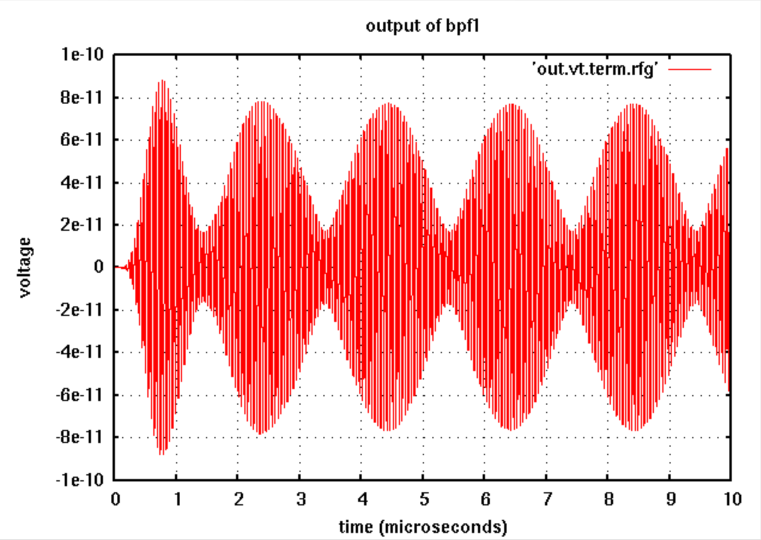
Output Waveforms











Summary

- ***Most robust circuit simulator technology***
- ***Interfaces with TD and FD EM solvers.***
- ***Will be supported commercially.***
- ***fREEDA papers at***

  http://people.engr.ncsu.edu/mbs/Publications/mbs_publications.html