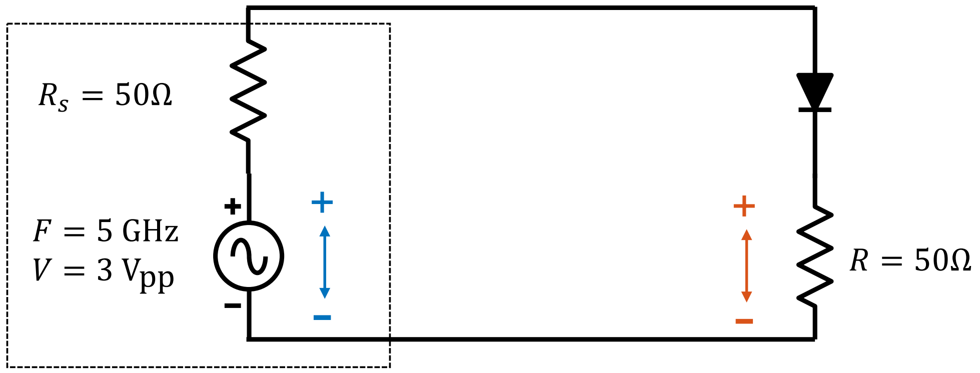
Simulation of a Nonlinear Frequency Multiplier using the FDTD Technique

Joshua M. Kast and Atef Z. Elsherbeni

jkast@mines.edu aelsherb@mines.edu



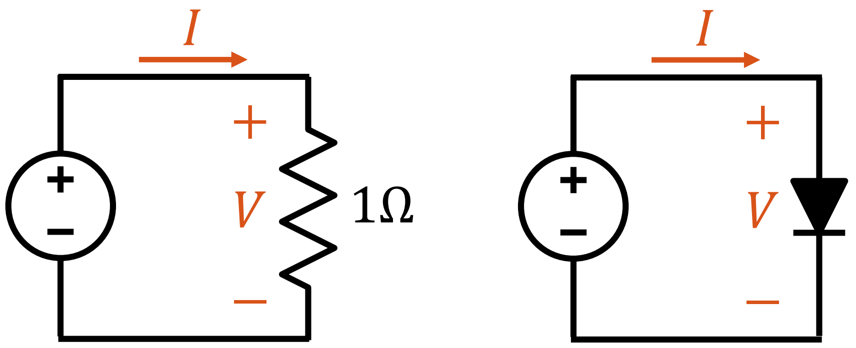
ELECTRICAL ENGINEERING
COLORADO SCHOOL OF MINES

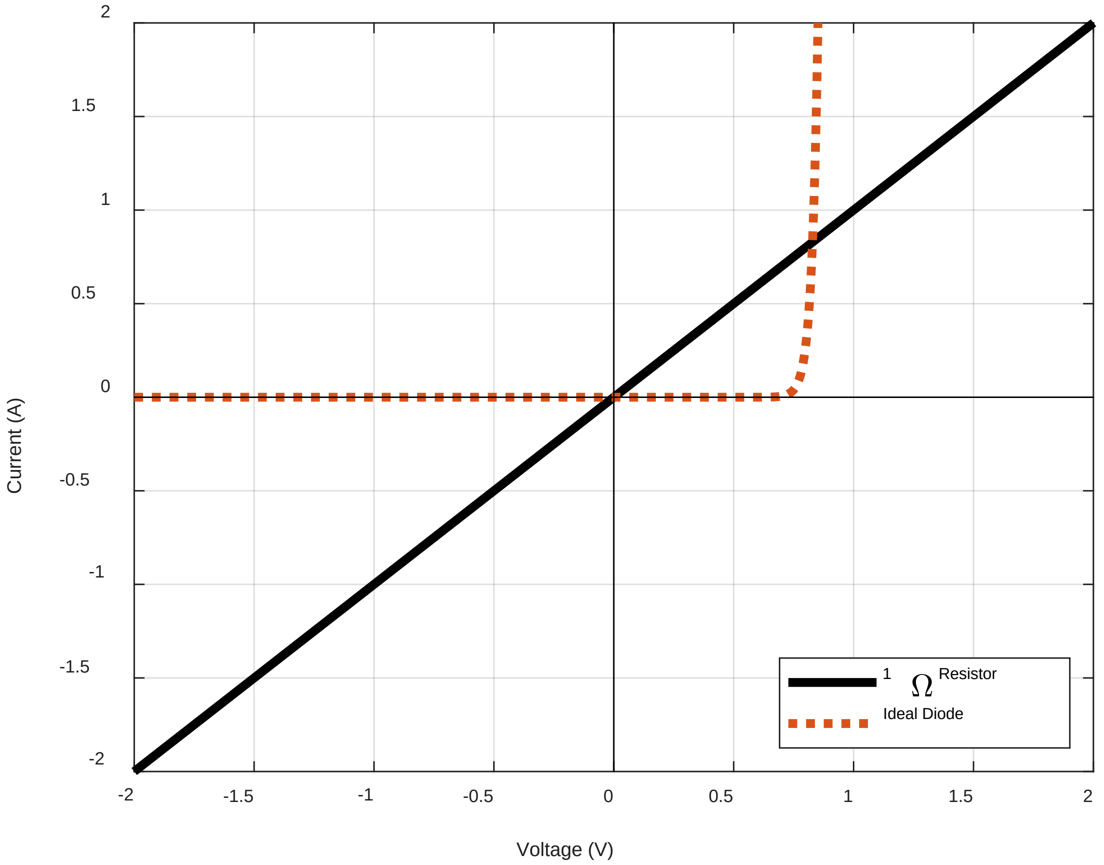
Antenna, RFID, and Computational EM Group

Introduction

- Common RF devices, such as mixers and detectors, employ nonlinear components to function.
- Increasingly, nonlinear effects are employed to improve energy efficiency and thermal properties of modern amplifiers.
- Simulation is challenging with nonlinear devices – frequency-domain approaches break down.
- Goal: use nonlinear lumped-element devices integrated in FDTD grid to demonstrate nonlinear effects relevant to RF communications.

Introduction - Nonlinearity





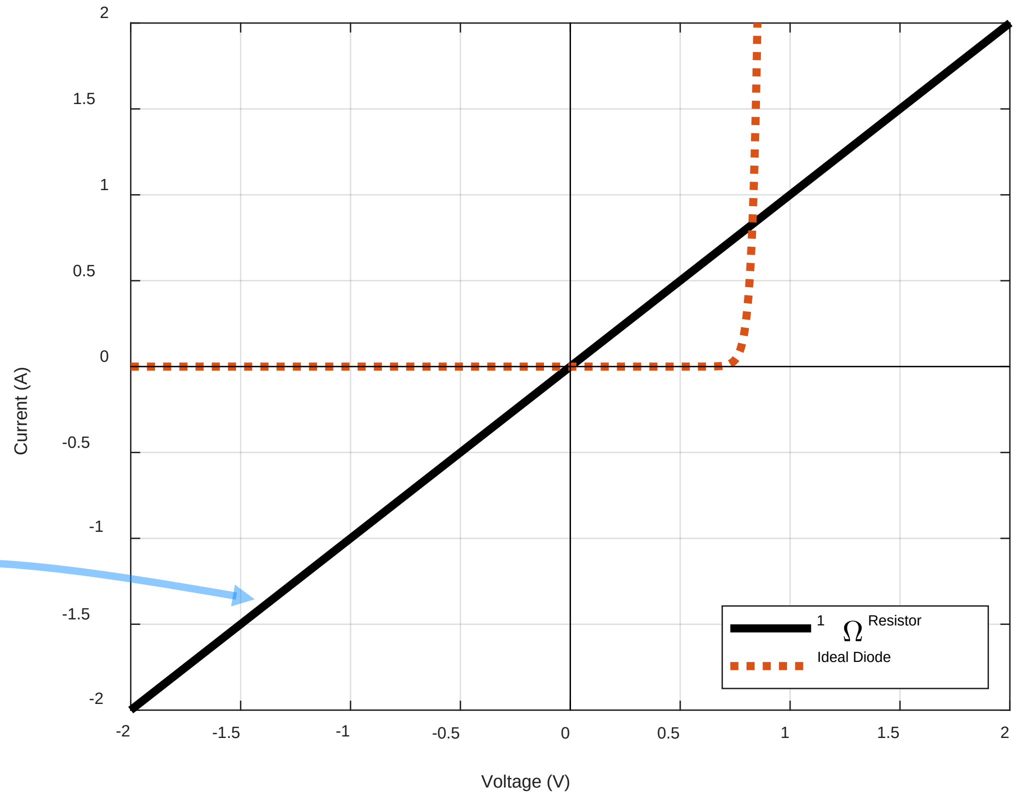
- Linear devices include resistors, inductors, capacitors.
- Nonlinear behavior occurs in diodes, transistors, and ferrites.

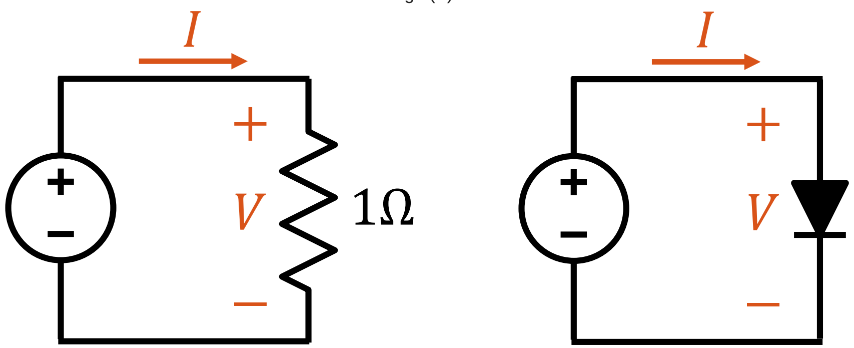
Introduction - Nonlinearity

- Linear devices include resistors, inductors, capacitors.
- Nonlinear behavior occurs in diodes, transistors, and ferrites.
- Example: resistor and diode
  - I/V characteristic for resistor is defined by Ohm's law:

$$I = \frac{V}{R}$$

Linear Equation





Introduction - Nonlinearity

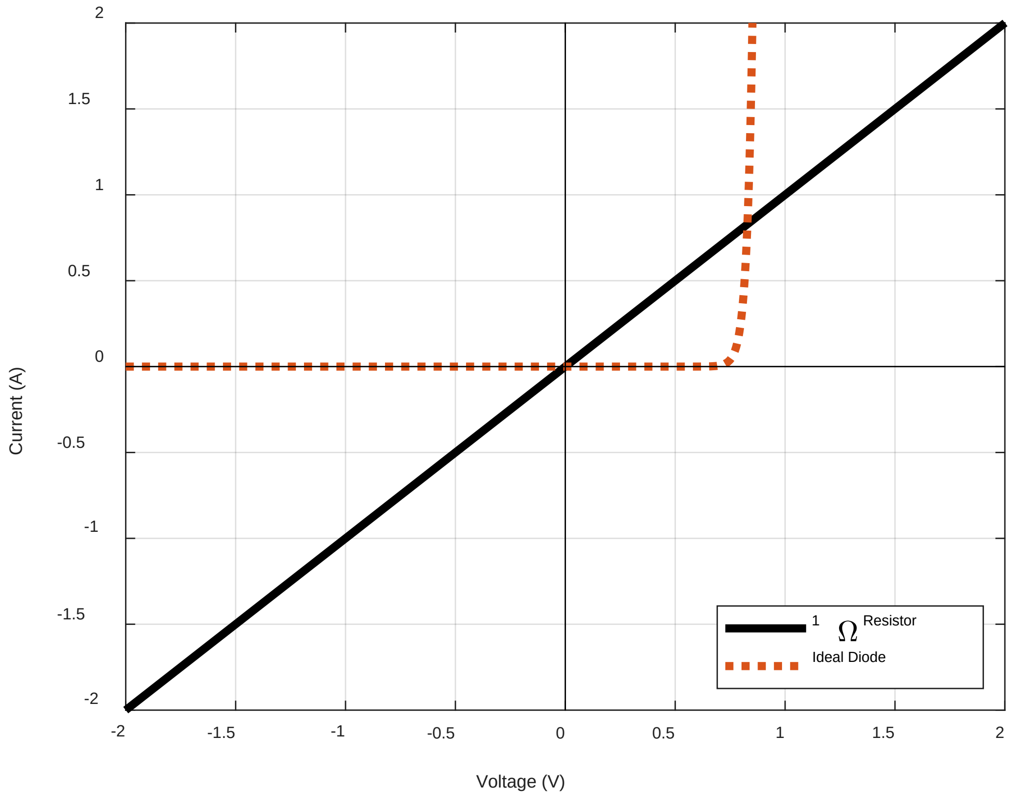
- Linear devices include resistors, inductors, capacitors.
- Nonlinear behavior occurs in diodes, transistors, and ferrites.
- Example: resistor and diode
  - I/V characteristic for resistor is defined by Ohm's law:

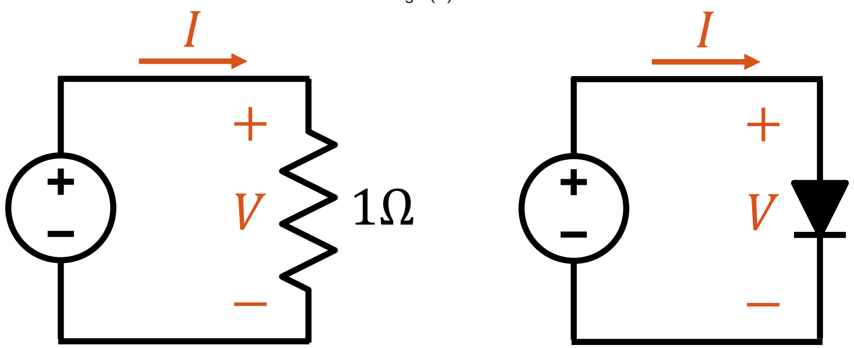
$$I = \frac{V}{R}$$

  - I/V characteristic for diode is defined by an exponential function:

$$I_D = I_S \left[e^{\frac{V_D}{\eta V_T}} - 1 \right]$$

Exponential Equation





ELECTRICAL ENGINEERING
COLORADO SCHOOL OF MINES

Introduction - Nonlinearity

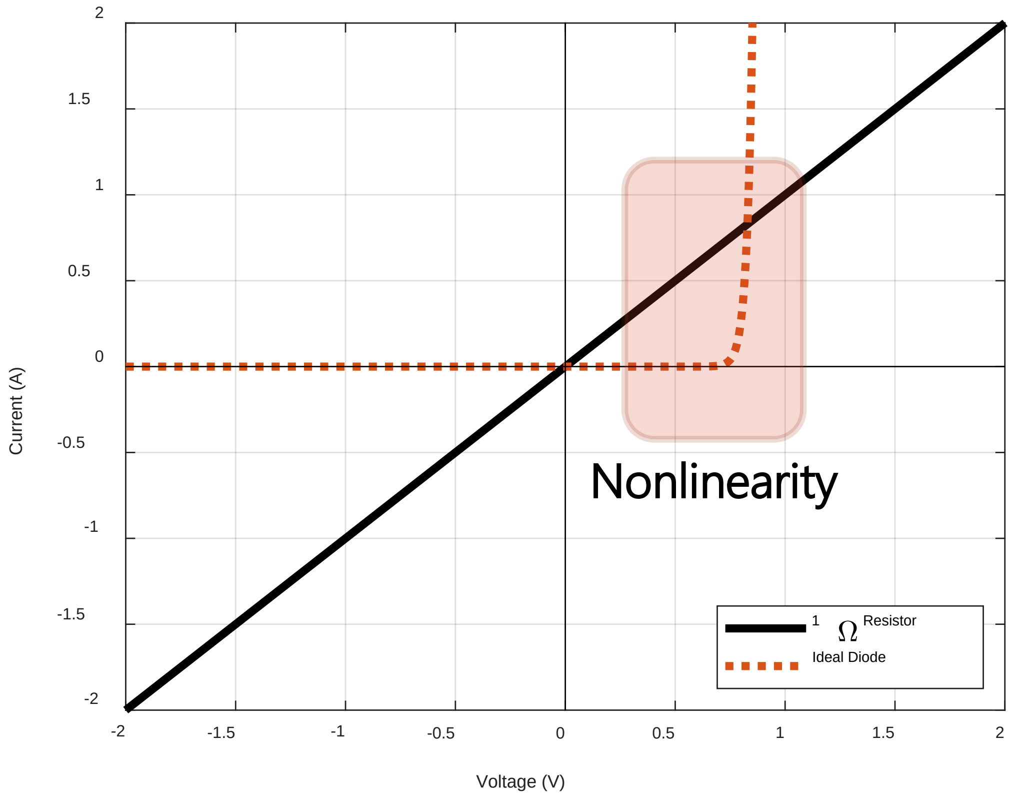
- Linear devices include resistors, inductors, capacitors.
- Nonlinear behavior occurs in diodes, transistors, and ferrites.
- Example: resistor and diode
  - I/V characteristic for resistor is defined by Ohm's law:

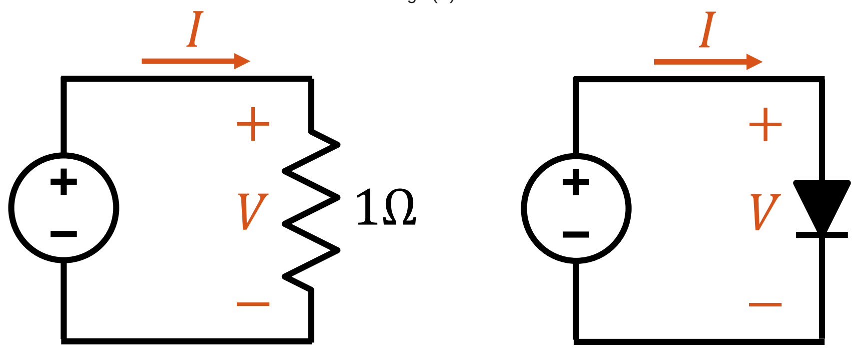
$$I = \frac{V}{R}$$

  - I/V characteristic for diode is defined by an exponential function:

$$I_D = I_S \left[e^{\frac{V_D}{\eta V_T}} - 1 \right]$$

Exponential Equation

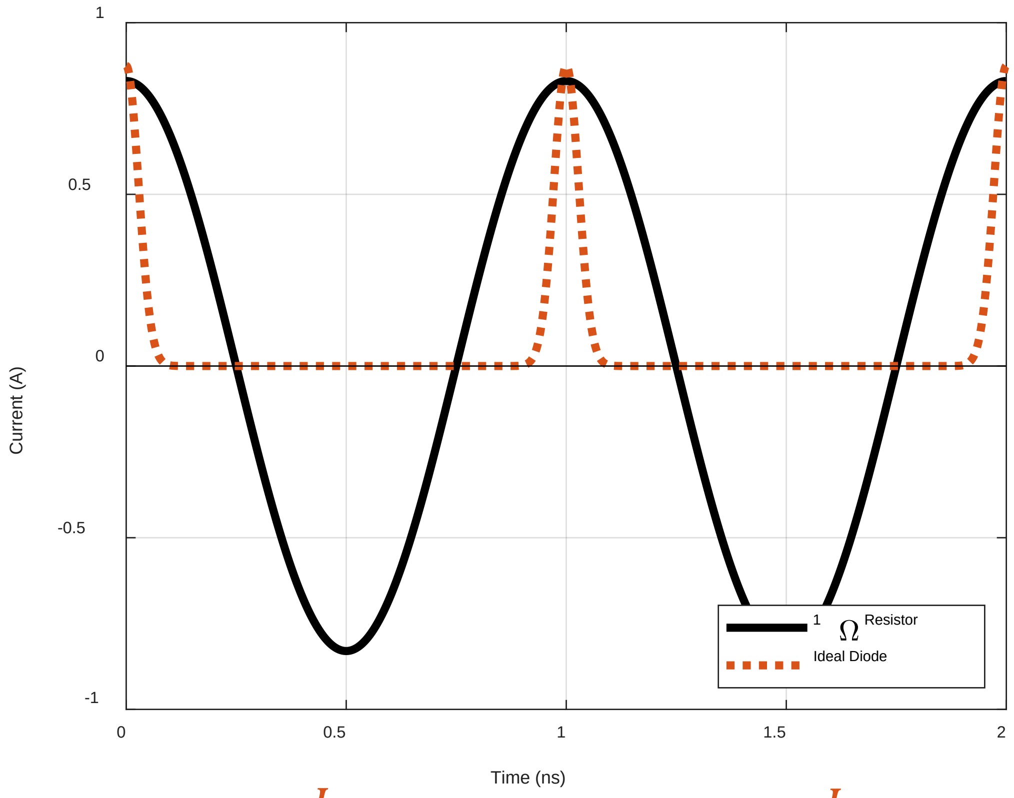


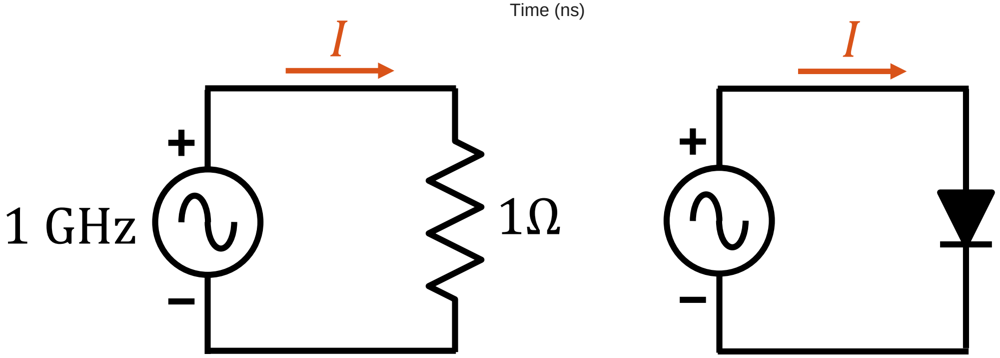


- Example: Excite a diode with a sinusoidal voltage source, measure current.

$$V_D(t) = a\cos(\omega t) \qquad \text{Substitute} \rightarrow \qquad I_D = I_S\left[e^{\frac{V_D}{\eta V_T}} - 1\right]$$

$$I_D(t) = I_S\left[e^{\frac{a\cos(\omega t)}{\eta V_T}} - 1\right]$$





Nonlinearity in The Frequency Domain

- Example: Excite a diode with a sinusoidal voltage source, measure current.

$V_D(t) = a\cos(\omega t)$ Substitute → $I_D = I_S\left[e^{\frac{V_D}{\eta V_T}} - 1\right]$

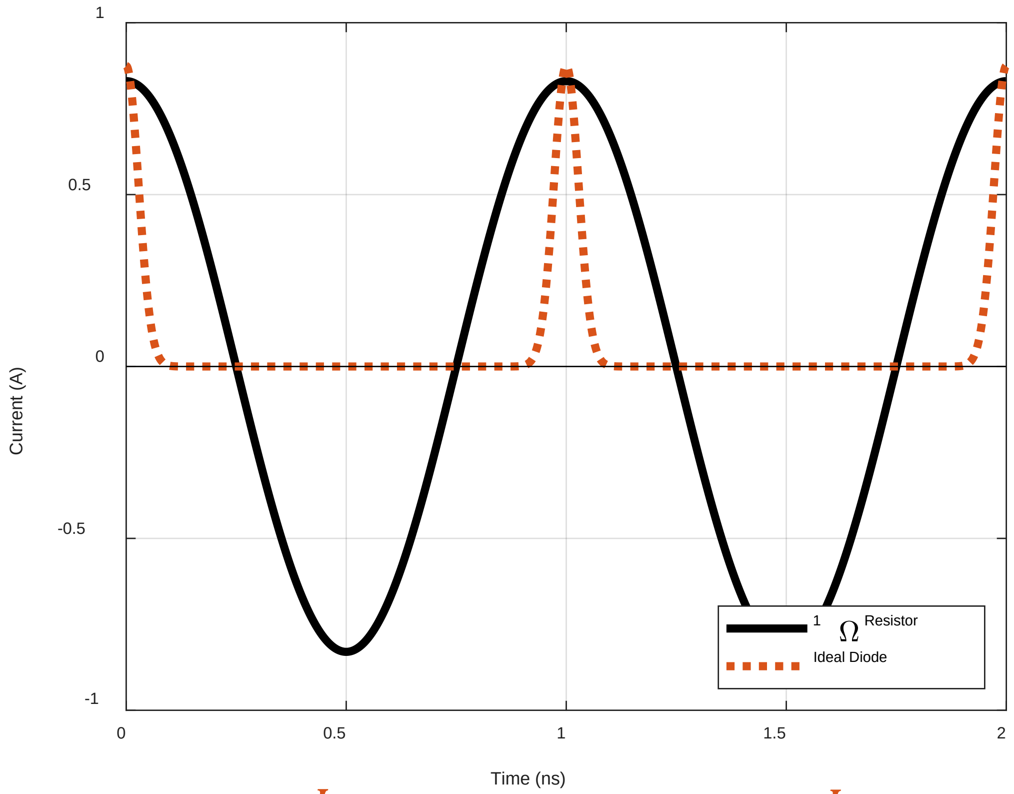
$$I_D(t) = I_S\left[e^{\frac{a\cos(\omega t)}{\eta V_T}} - 1\right]$$

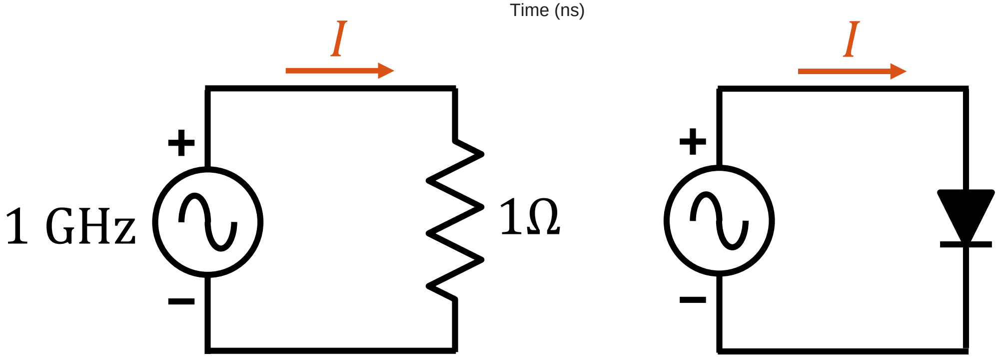
Replace exponential by Maclaurin series:

$$I_D(t) = I_S \sum_{n=1}^{\infty} \frac{\left(\frac{a\cos(\omega t)}{\eta V_T}\right)^n}{n!}$$

Take first three terms:

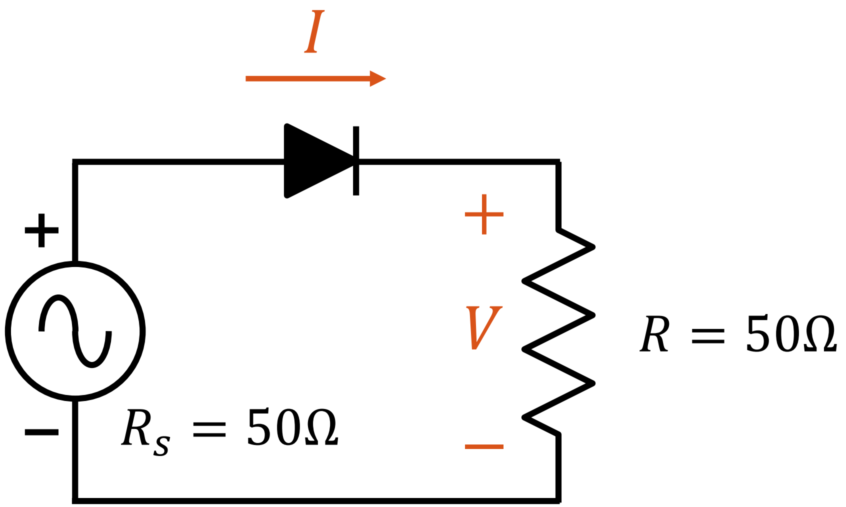
$$I_D(t) \approx I_s\left(\frac{a\cos(\omega t)}{\eta V_T} + \frac{a^2(\cos(2\omega t) + 1)}{4\eta^2 V_T^2} + \frac{a^3(\cos(3\omega t) - 3\cos(\omega t))}{24\eta^3 V_T^3}\right)$$

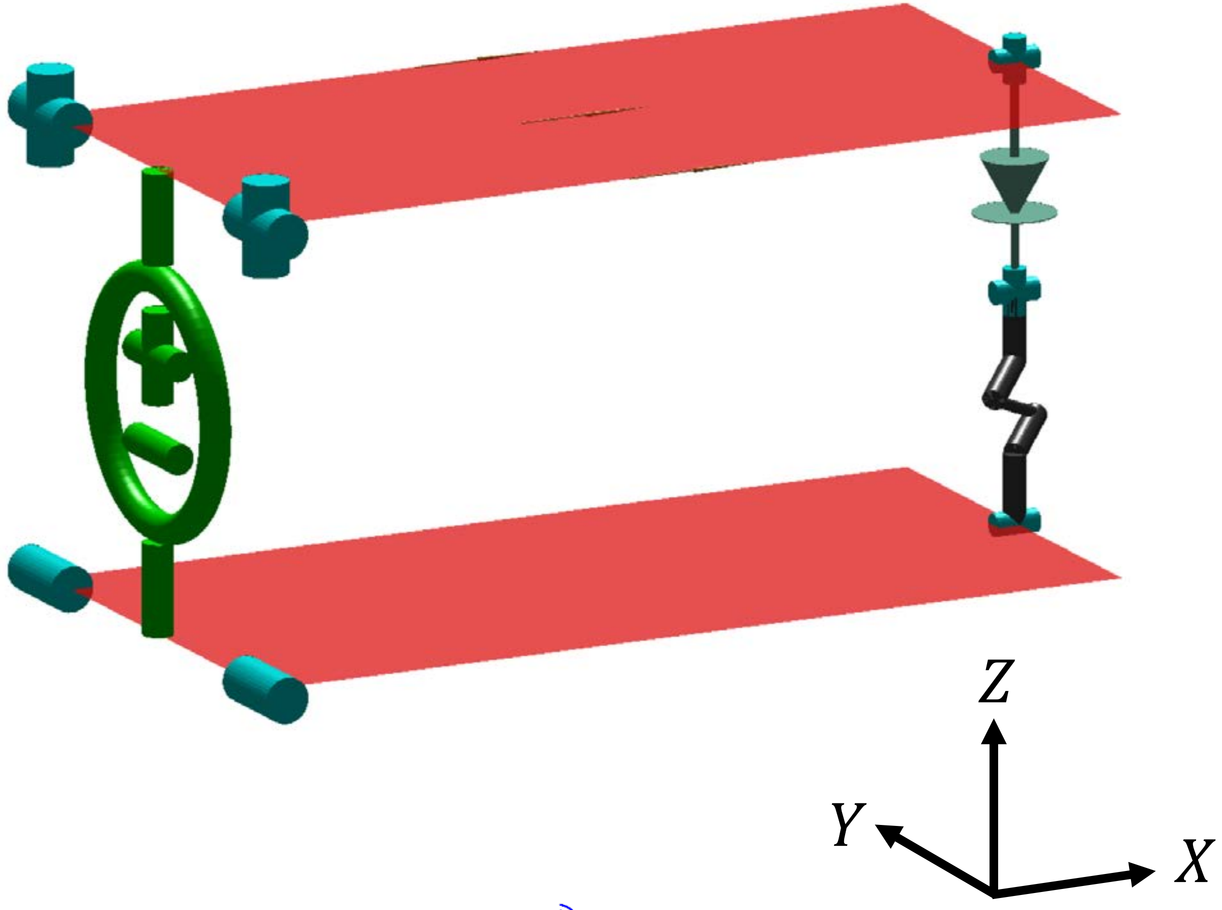




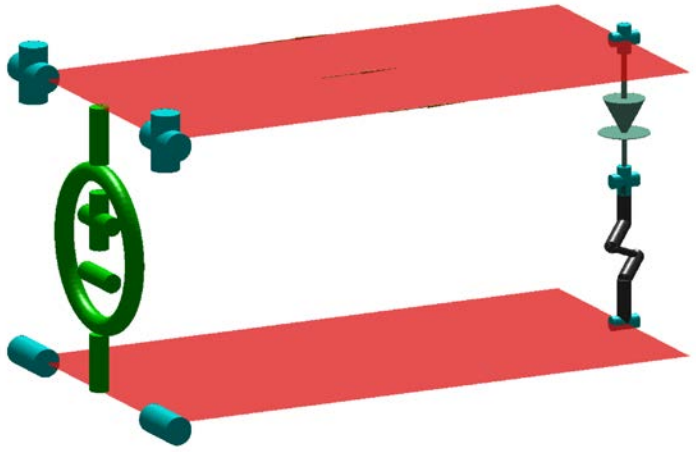
Diode With Series Resistor

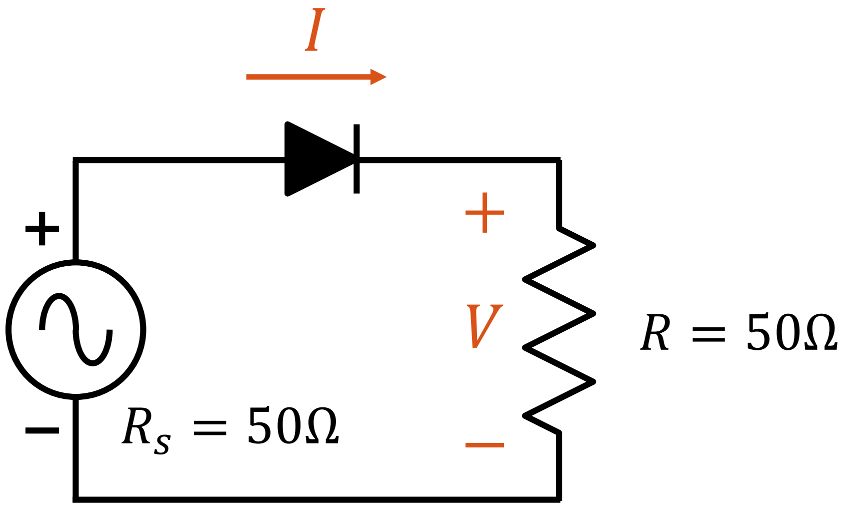
- FDTD Domain: 40 x 38 x 43 (65360) cells
  - CPML Boundaries – 10 cells with 8 cell air-buffer
  - Cell size - $dx = dy = dz = 0.05\ \mathrm{mm}$
- Excitation: 10 V_{pp}, 5 GHz sinusoidal

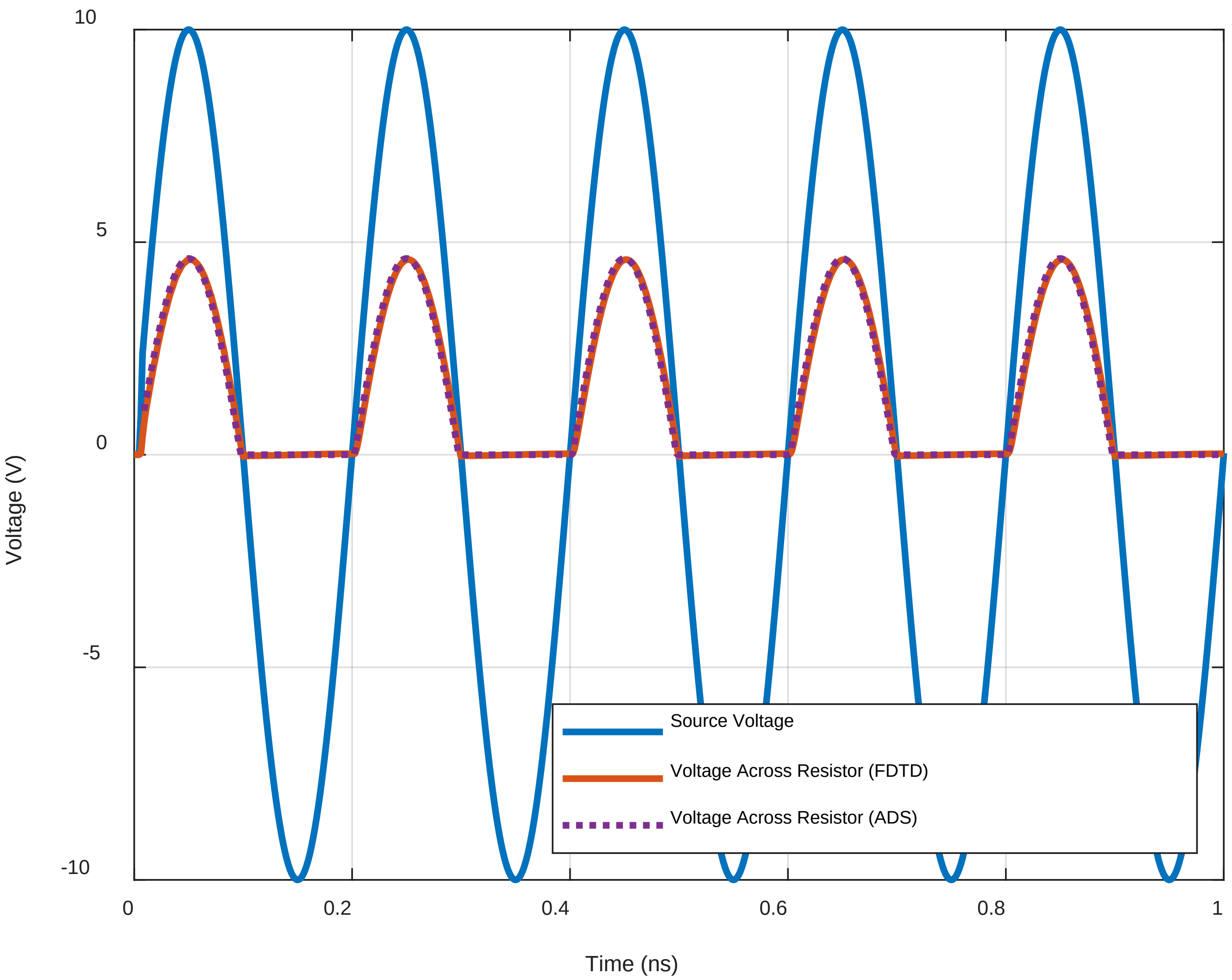




Diode With Series Resistor: Time-Domain Results

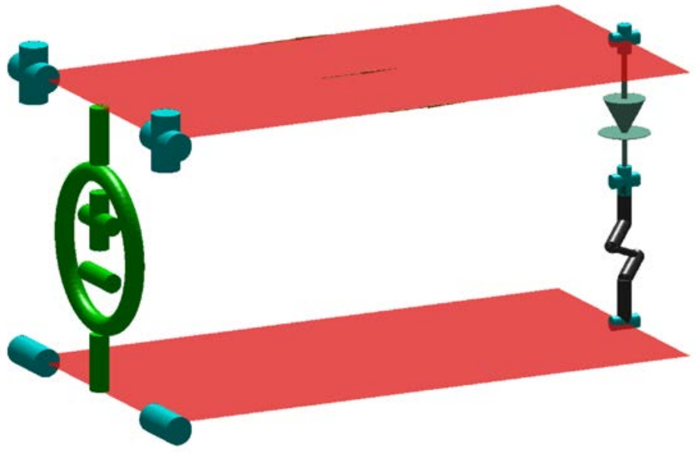


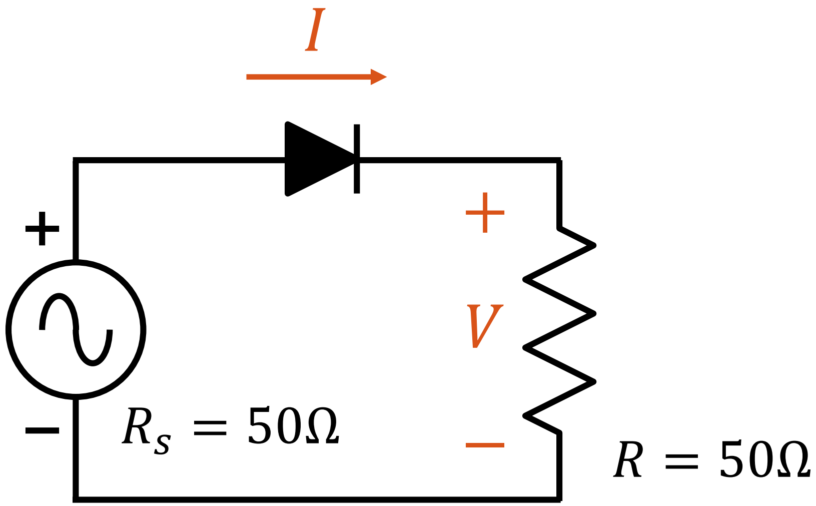


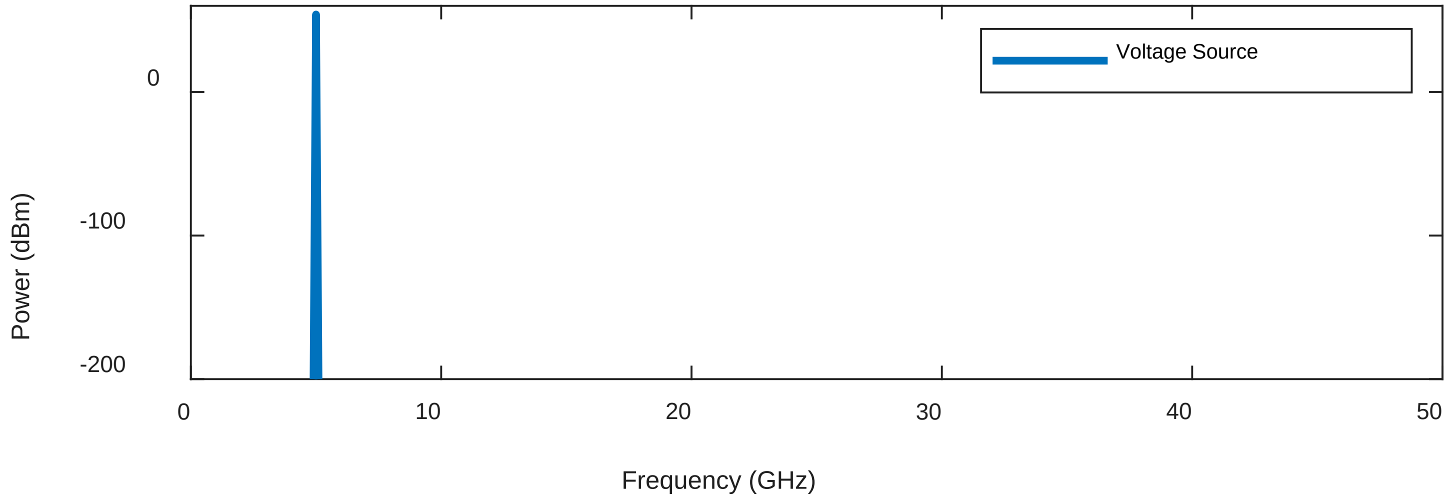


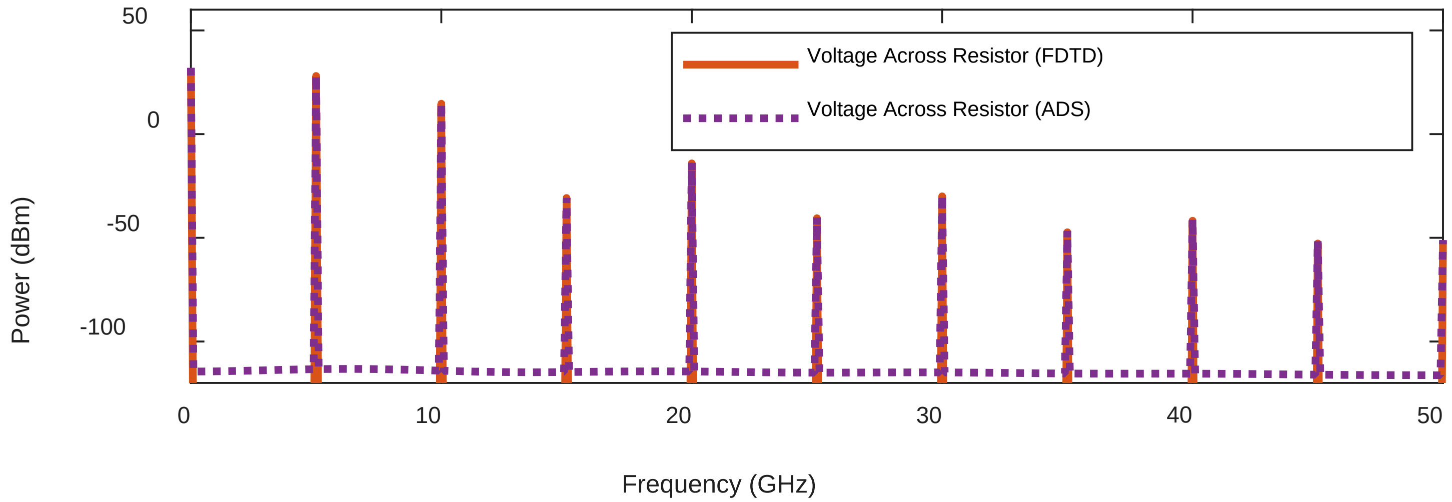
ELECTRICAL ENGINEERING
COLORADO SCHOOL OF MINES

Diode With Series Resistor: Frequency Domain Results







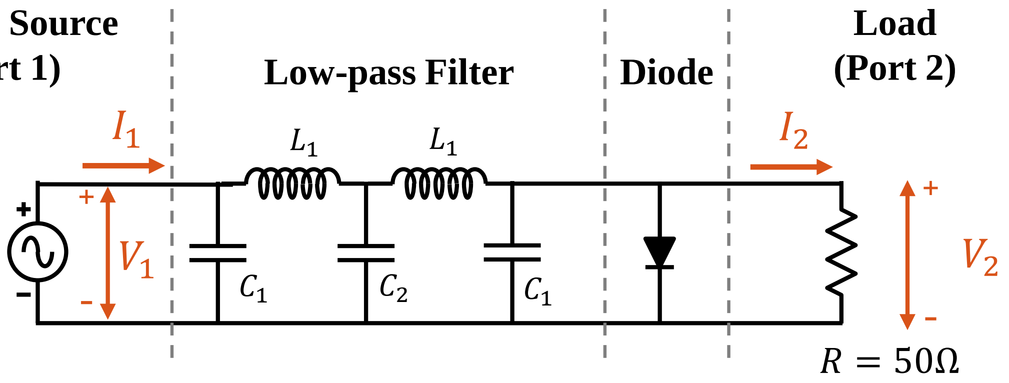


ELECTRICAL ENGINEERING
COLORADO SCHOOL OF MINES

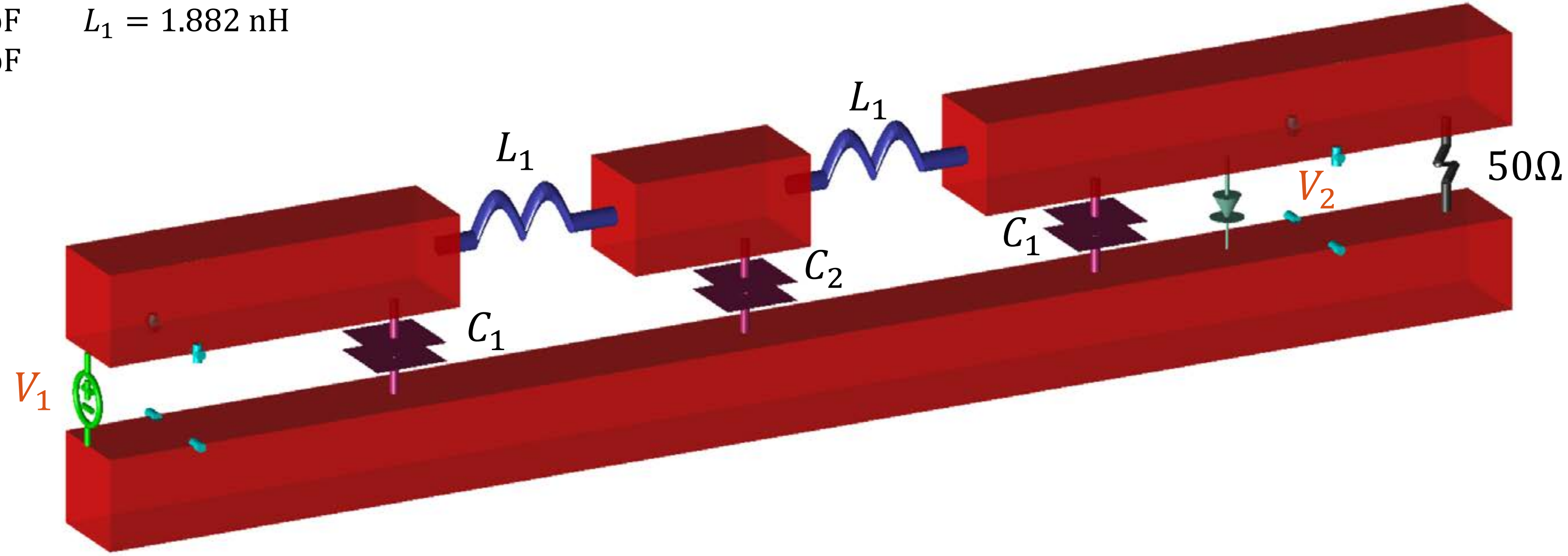
ARC

Diode with Low Pass Filter

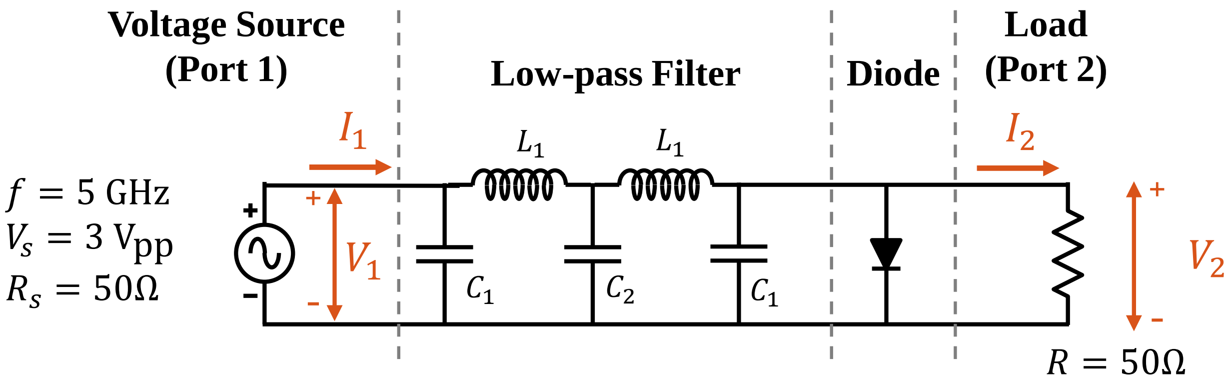
$f = 5$ GHz
$V_s = 3$ Vpp
$R_s = 50\Omega$



$C_1 = 1.044$ pF $\quad L_1 = 1.882$ nH
$C_2 = 1.555$ pF

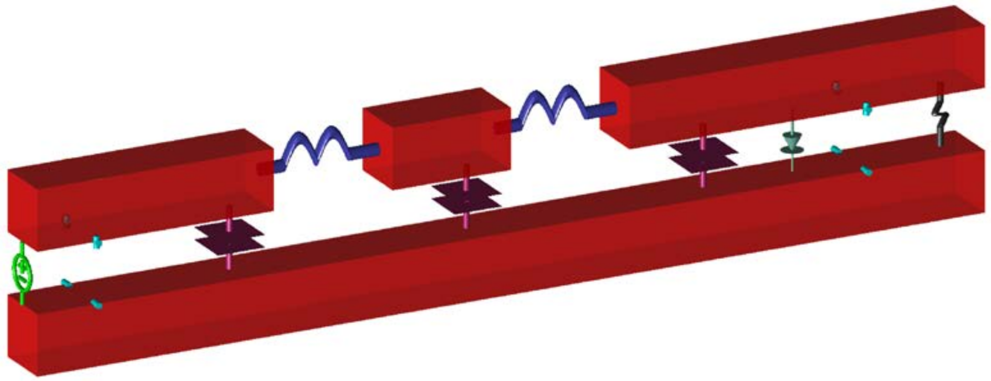


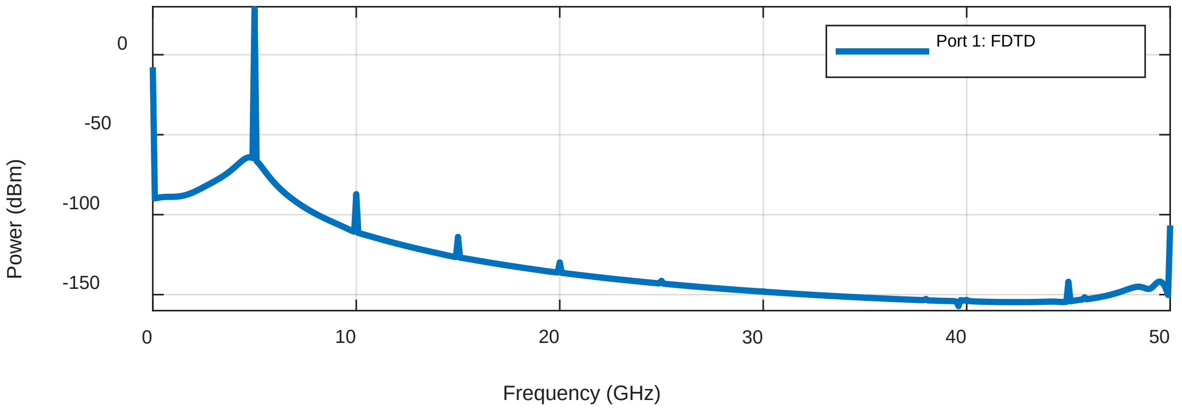
Diode with Low Pass Filter

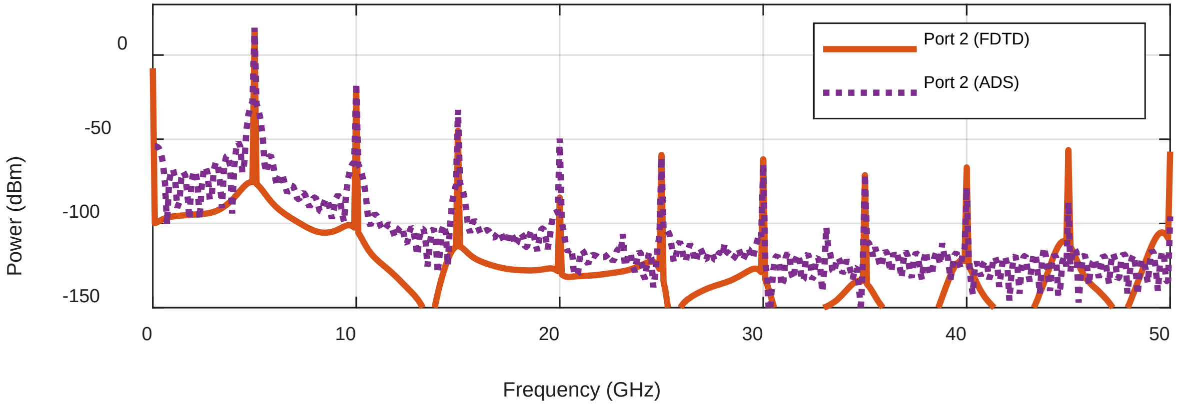


$C_1 = 1.044$ pF $\quad L_1 = 1.882$ nH

$C_2 = 1.555$ pF

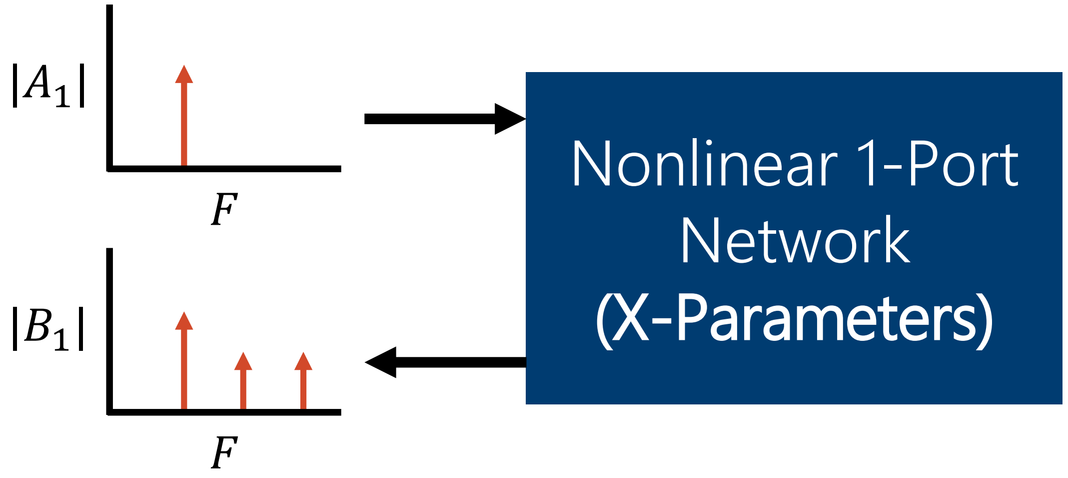






Conclusions and Future Work

- FDTD provides useful simulations of nonlinear components integrated in microwave circuits.
- Future work: analyze the results using the nonlinear X-parameters



References

[1] W. Shockley, “The theory of p-n junctions in semiconductors and p-n junction transistors,” Bell Syst. Tech. J., vol. 28, no. 3, pp. 435–489, Jul. 1949.

[2] W. M. Haynes, Ed., CRC Handbook of Chemistry and Physics, 92nd Edition, 92 edition. Boca Raton, Fla.: CRC Press, 2011.

[3] A. Z. Elsherbeni and V. Demir, The finite-difference time-domain method for electromagnetics with Matlab simulations. Raleigh: The Institution of Engineering and Technology, 2016.

[4] Keysight, Santa Rosa, CA, USA. 2019. Advanced Design System 2019 [Online]. Available: http://www.keysight.comen/pc-1297113/advanced-design-system-ads?&cc=US&lc=eng

[5] S. A. Maas, Nonlinear Microwave Circuits. Artech House, 1988.

[6] K. ElMahgoub and A. Z. Elsherbeni, “FDTD Implementations of Integrated Dependent Sources in Full- Wave Electromagnetic Simulations,” vol. 29, no. 12, p. 10, 2014