Non-Foster Reactances for Electrically-Small Antennas, High-Impedance Surfaces, and Engineered Materials

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Outline of Presentation

- What Does "Non-Foster" Mean?
- Possible Applications of Non-Foster Reactances
  - Electrically Small Antennas
  - High-Impedance Surfaces
  - Artificial High-Permeability Materials
- Realization of Non-Foster Reactances

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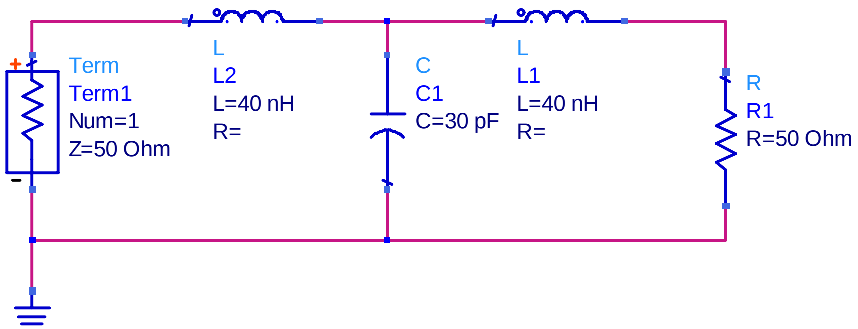
Foster's Reactance Theorem

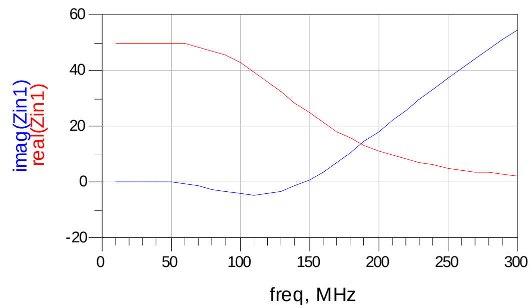
- The theorem is a consequence of conservation of energy.
- The slope of the input reactance (susceptance) of a lossless passive one-port is always positive.
- All zeros and poles of the impedance (admittance) function are simple, and a zero must lie between any two poles, and a pole between any two zeros.

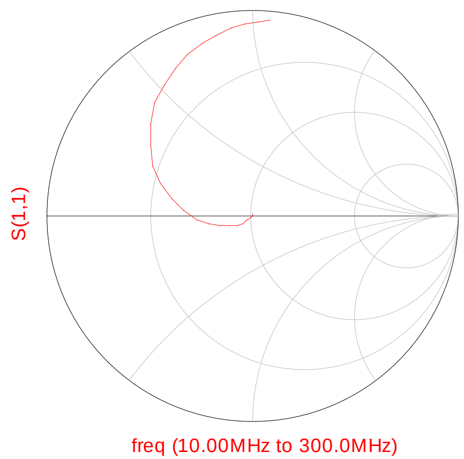
Consequences of Foster's Reactance Theorem

- Impedances (admittances) of passive one-port networks rotate clockwise on the Smith Chart as frequency increases.
- There is no such thing as a negative capacitor or a negative inductor (for passive circuits).

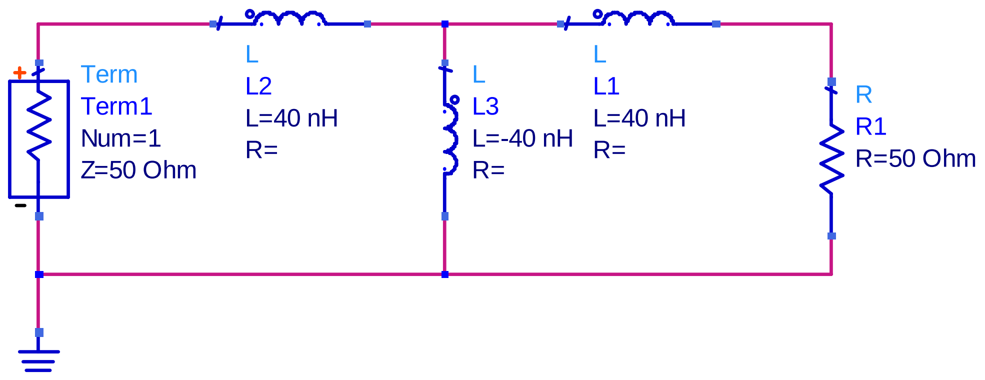
Foster Network

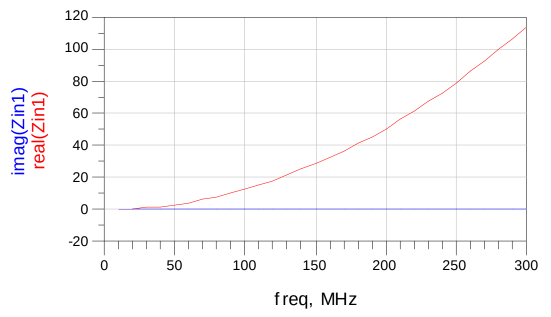


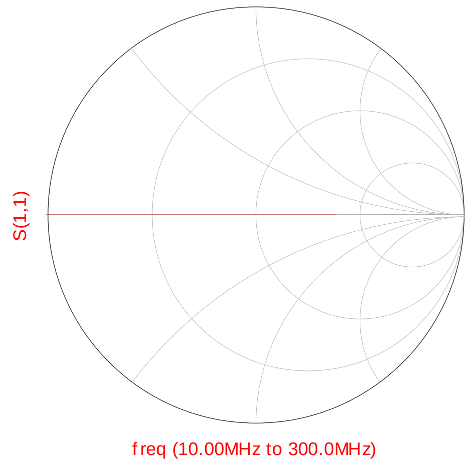




Non-Foster Network







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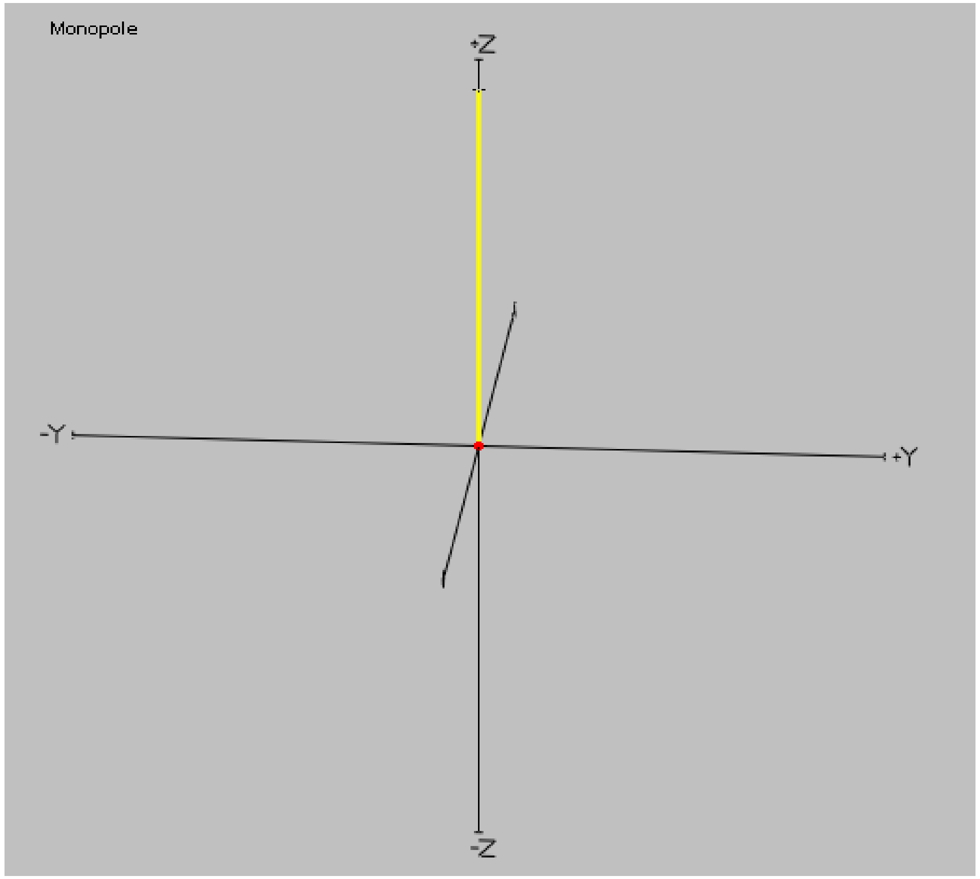
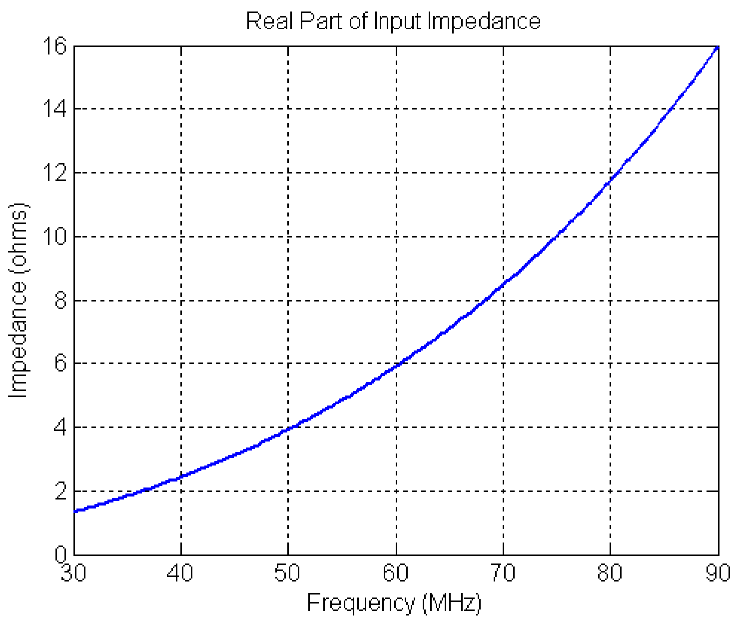
VHF Whip: A Canonical ESA

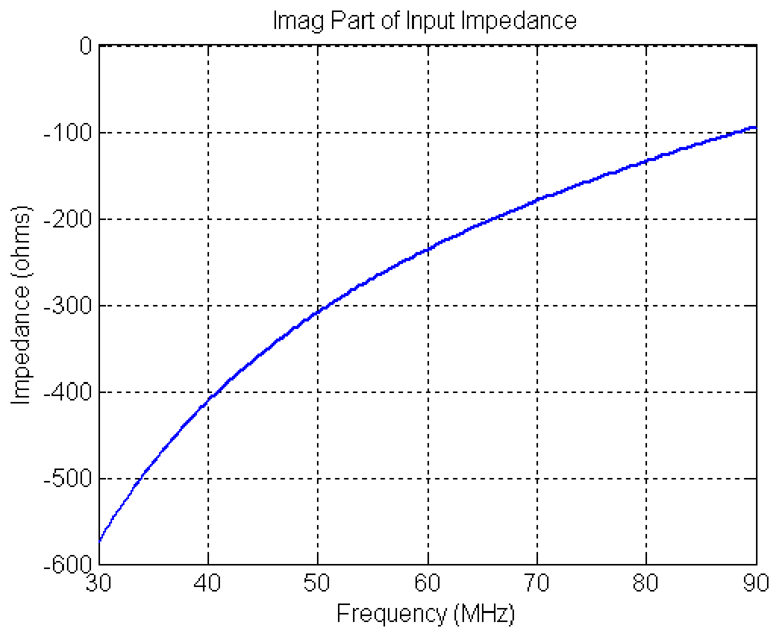


•Geometry of monopole antenna as modeled in **Antenna Model** software. The monopole is a copper cylinder 0.6 meters in length and 0.010 meters in diameter, mounted on an infinite perfect ground plane.

•Frequency range is 30 to 90 MHz.

Input Impedance of VHF Whip From Simulation

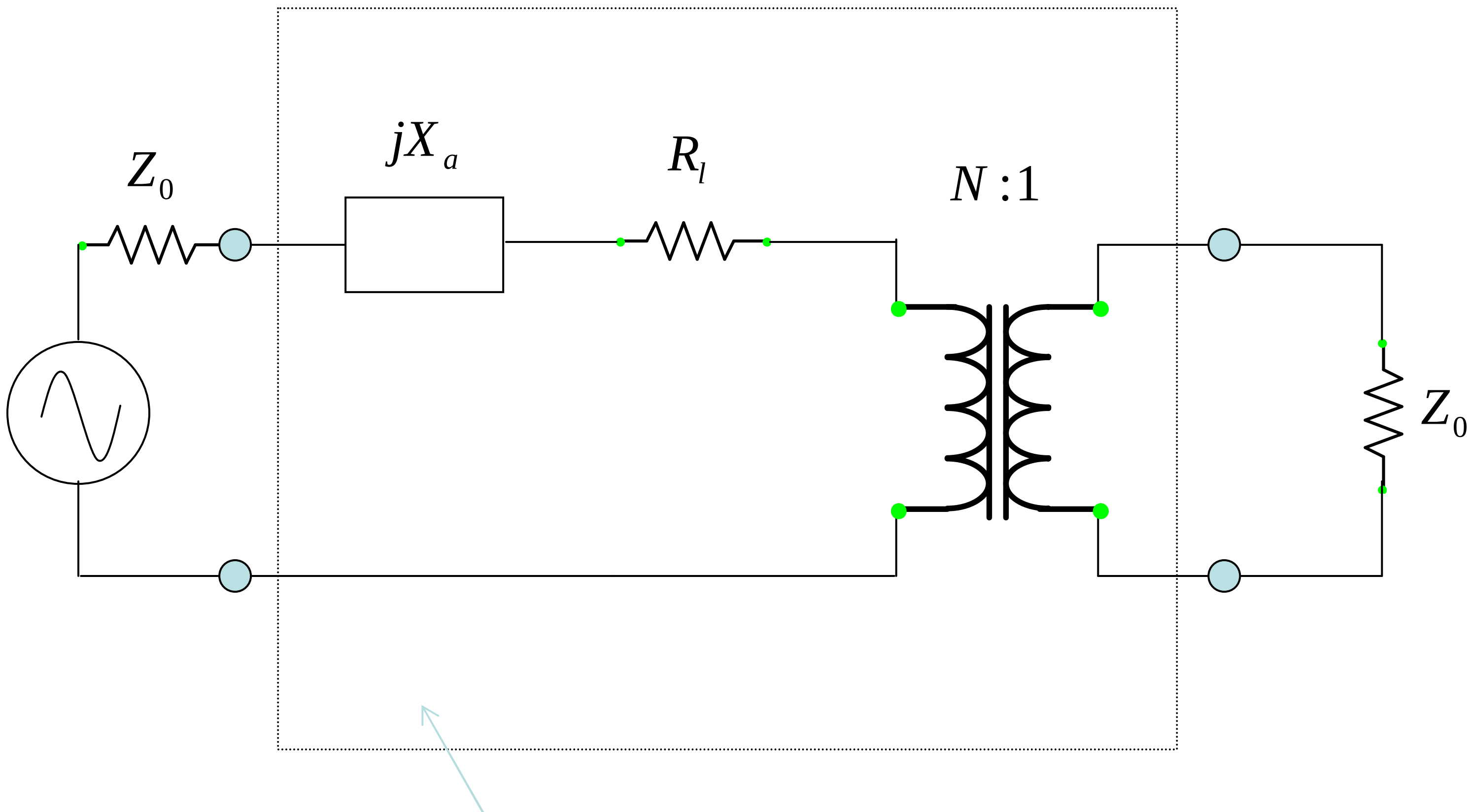




Two Tools to Help With Analysis

- Exact *two-port* representation of antenna in frequency domain in terms of s-parameters.
- Approximate lumped equivalent circuit model of antenna over frequency range of interest.

Two-Port Representation of Antenna



The quantities in this box are re-evaluated at every frequency for which we have data.

Two-Port Representation of Antenna

$$Z_a = R_a + jX_a = R_r + R_l + jX_a$$

$$R_r = e_{cd} R_a = \text{radiation resistance}$$

$$R_l = (1 - e_{cd}) R_a = \text{dissipative loss resistance}$$

$$X_a = \text{antenna reactance}$$

$$N = \sqrt{\frac{R_r}{Z_0}}$$

Two-Port Representation of Antenna

- Antenna impedance and radiation efficiency are used to produce a Touchstone *.s2p file for use in circuit simulation – the exact two-port representation of the antenna at each frequency for which we have data.
- Allows concepts like transducer power gain and stability measures to be applied to antennas. The latter being particularly important for considering the use of non-Foster reactances in antenna matching networks.

Approximate Equivalent Circuit of the Antenna

- To model the antenna, we assume that the real part of the antenna impedance varies as the square of frequency, and the imaginary part behaves as a series LC.

$$\overline{Z}_a = R_0\left(\frac{\omega}{\omega_0}\right)^2 + j\left(\omega L_a - \frac{1}{\omega C_a}\right)$$

Impedance produced by equivalent circuit

Approximate Equivalent Circuit of the Antenna

- Evaluation of the model parameters (R_0, L_a and C_a):

$$R_0 = \Re\left\{Z_a\left(\omega_0\right)\right\}$$

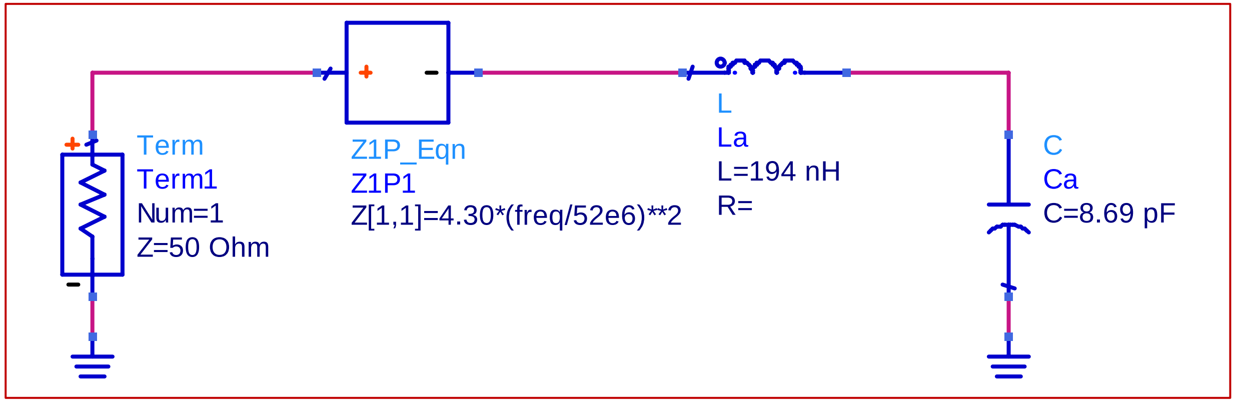
$$\begin{bmatrix} \omega_1 & \dfrac{-1}{\omega_1} \\ \omega_2 & \dfrac{-1}{\omega_2} \end{bmatrix} \begin{Bmatrix} L_a \\ \dfrac{1}{C_a} \end{Bmatrix} = \begin{Bmatrix} \Im\left\{Z_a\left(\omega_1\right)\right\} \\ \Im\left\{Z_a\left(\omega_2\right)\right\} \end{Bmatrix}$$

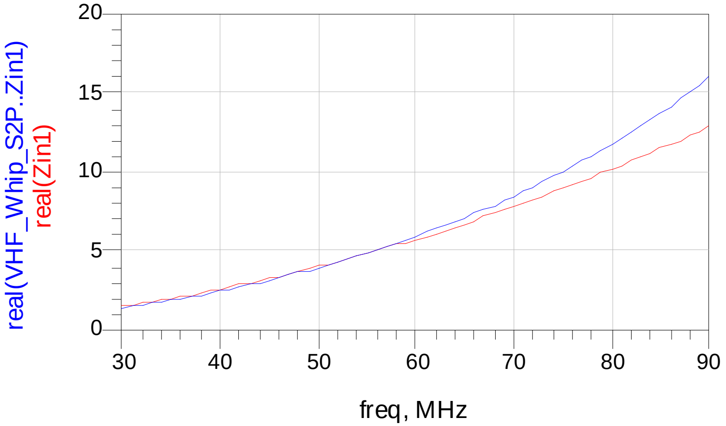
Approximate Equivalent Circuit of the Antenna

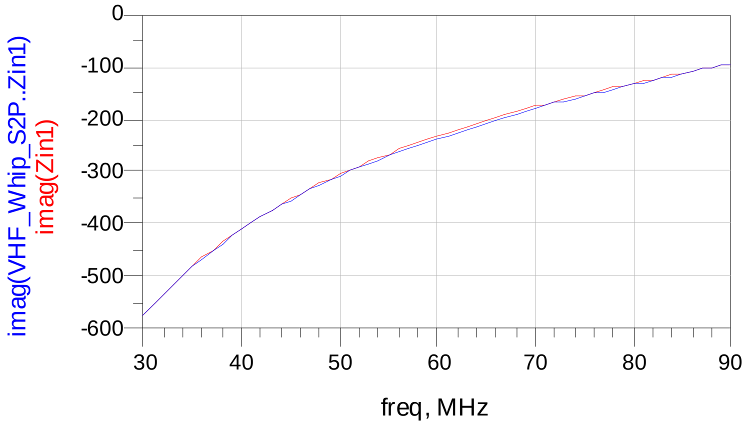
$$R_0 = 4.30\,\Omega$$

$$L_a = 194\,\text{nH}$$

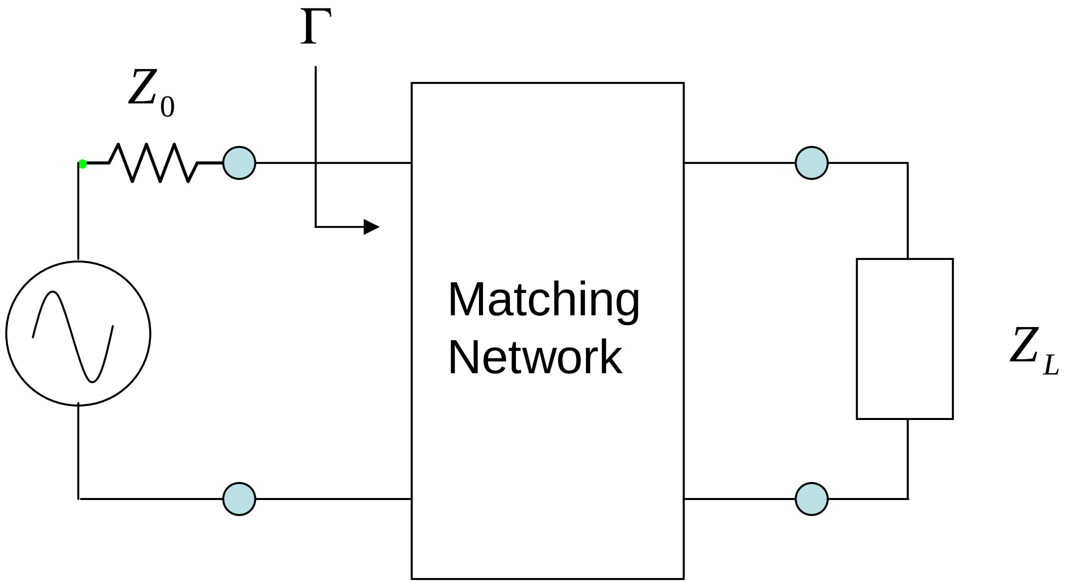
$$C_a = 8.69\,\text{pF}$$







Matching Network Concept



Points to Consider

- A real passive matching network can only approach and never exceed the performance predicted by the Bode-Fano criterion.
- The matchable bandwidth is limited by the *Q* of the load.
- The matchable bandwidth can only be increased by de-Qing the load – that is by intentional introduction of dissipative losses into the matching network – and concomitant reduction in radiation efficiency.

Bode-Fano Criterion

$$\frac{\Delta f}{f_0} \leq \frac{\pi}{Q \cdot \ln\left(\frac{1}{\Gamma_m}\right)}$$

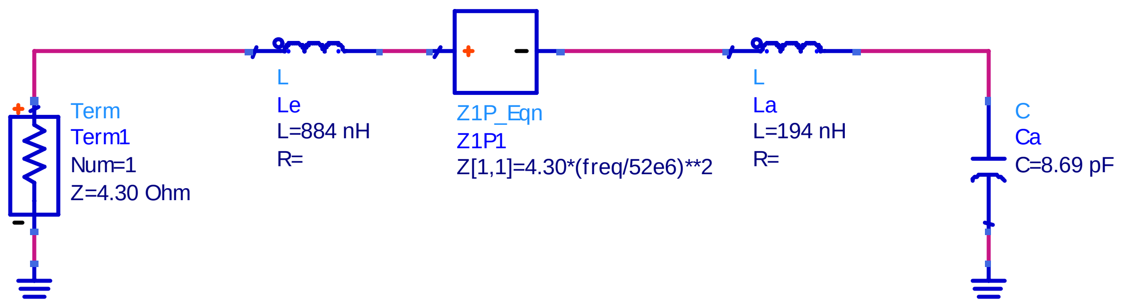
Maximum allowable reflection coefficient

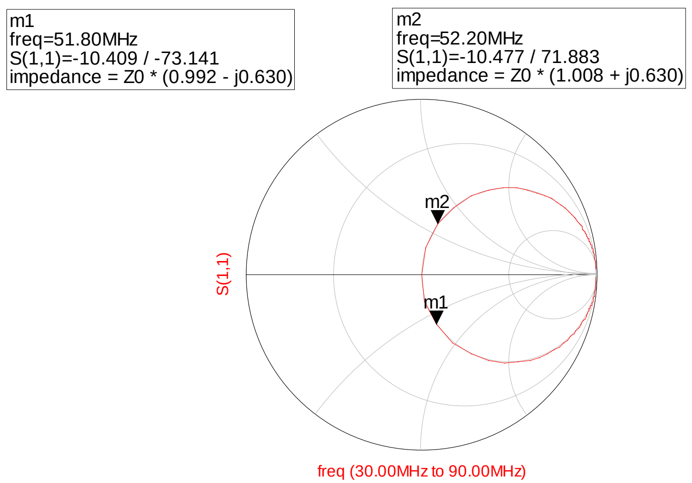
Q of the load

Maximum value of fractional bandwidth that can be achieved with any passive, lossless matching network.

$$Q = 81.9, \Gamma_m = \frac{1}{3} \Rightarrow \frac{\Delta f}{f_0} \leq 0.035$$

Single-Tuned Mid-band Match





$$\frac{\Delta f}{f_0} \approx \frac{52.2 - 51.8}{52} = 0.008$$

Analytical: $$\frac{\Delta f}{f_0} = \frac{1}{\sqrt{2}Q} = 0.009$$

Wheeler-Lopez Double-Tuned Matching

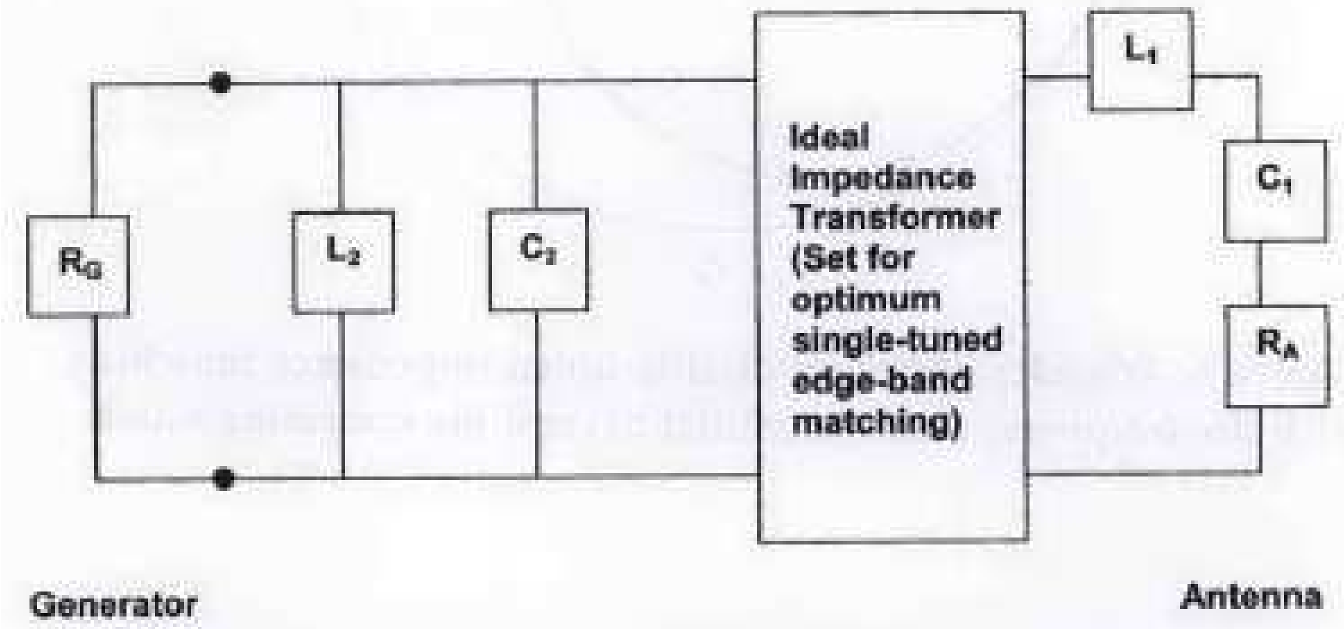


Figure 3. A double-tuned antenna impedance-matching circuit.

A.R. Lopez, “Wheeler and Fano Impedance Matching”, ***IEEE Antennas and Propagation Magazine,*** **Vol. 49, No. 4, August 2007**

Wheeler-Lopez Double-Tuned Matching

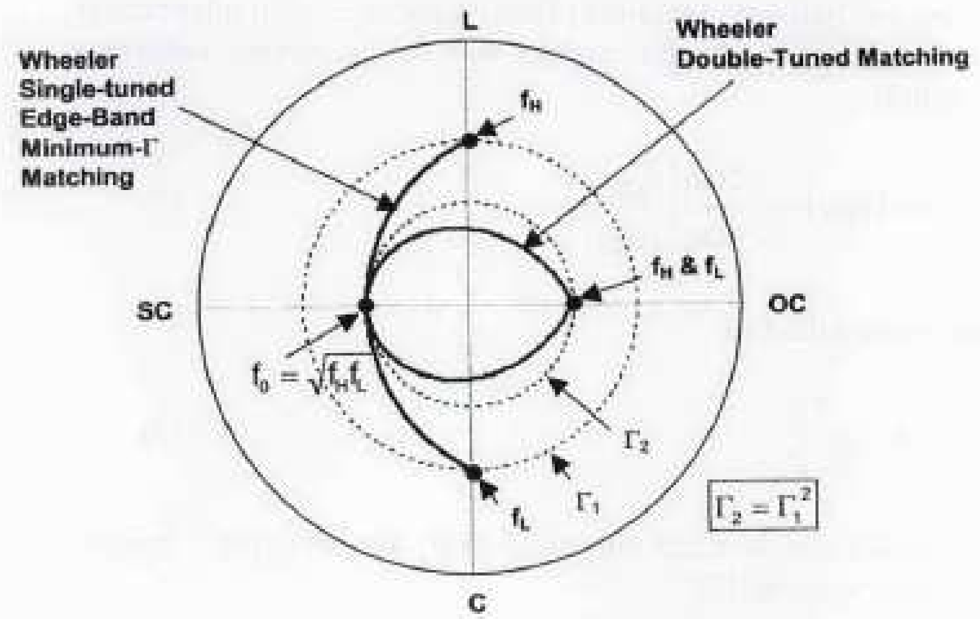
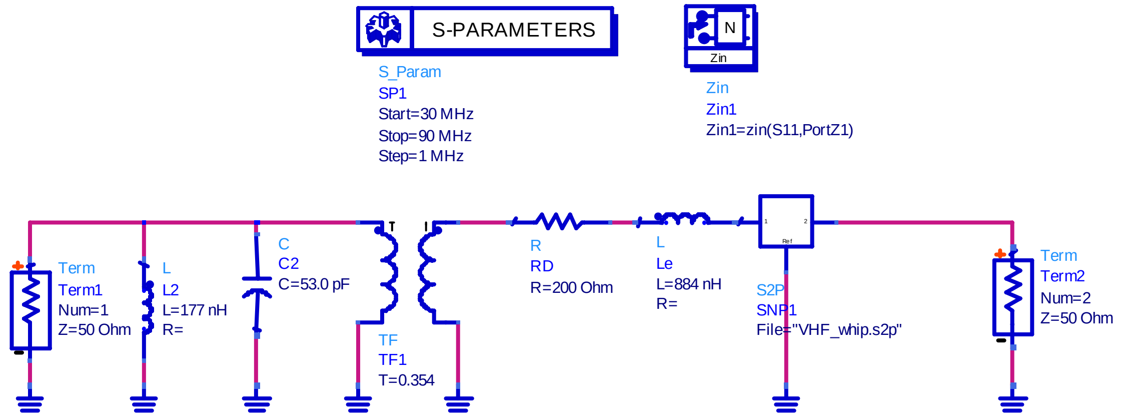
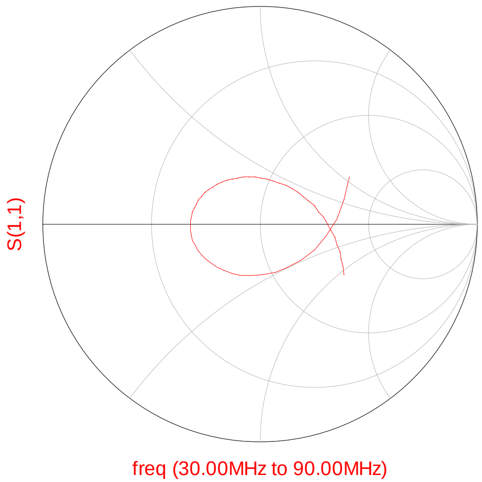


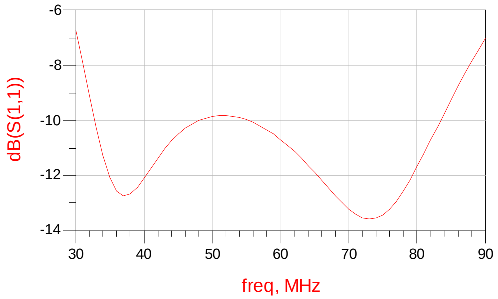
Figure 5. Wheeler optimum double-tuned impedance matching.

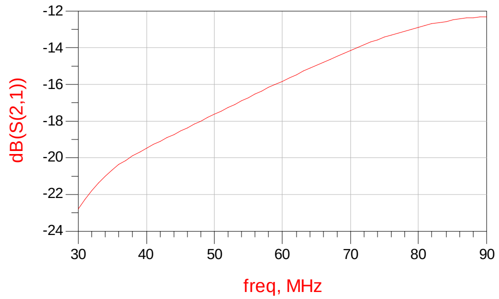
A.R. Lopez, “Wheeler and Fano Impedance Matching”, ***IEEE Antennas and Propagation Magazine,*** **Vol. 49, No. 4, August 2007**

Wheeler-Lopez Double-Tuned Matching with Antenna De-Qing



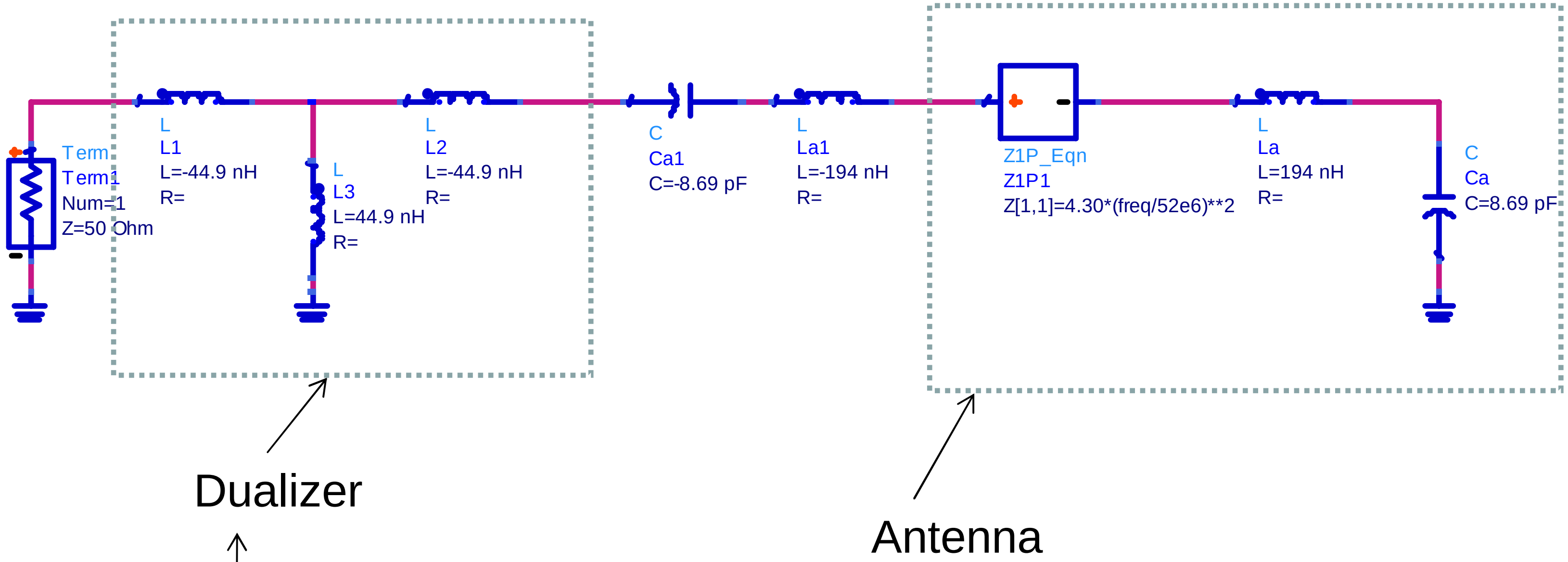






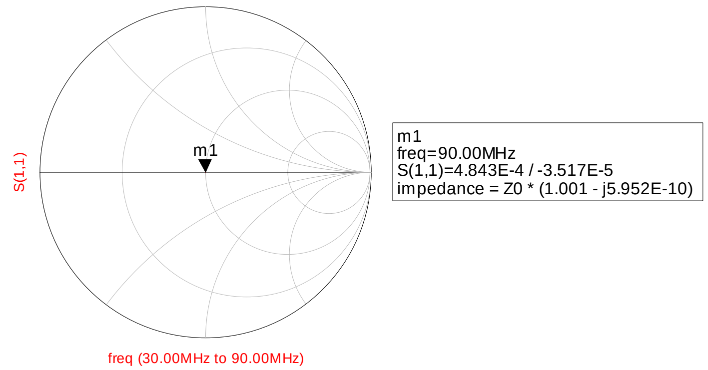
Decent match, poor efficiency

Matching Network with Non-Foster Reactances

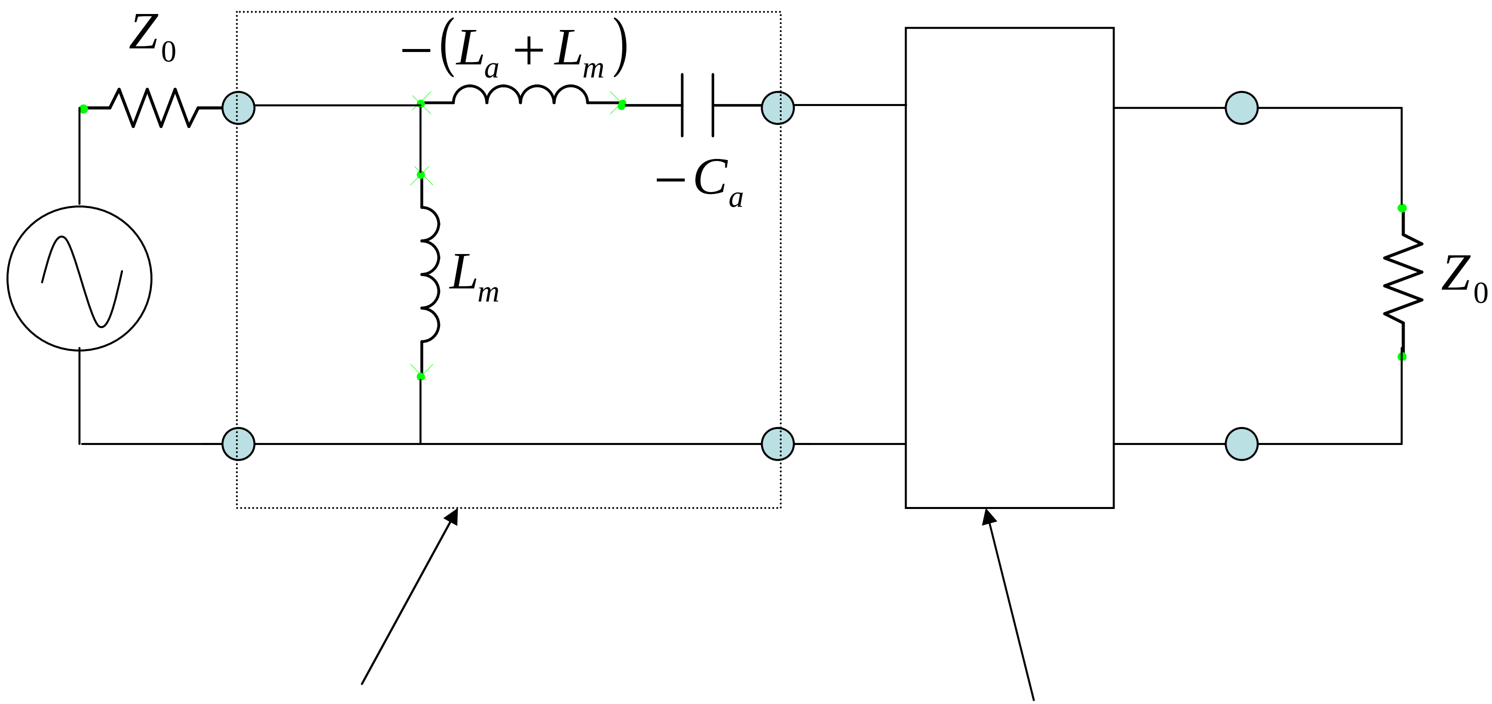


Cancels frequency squared dependence of radiation resistance.

Van Der Pol, Proc, IRE, Feb. 1930



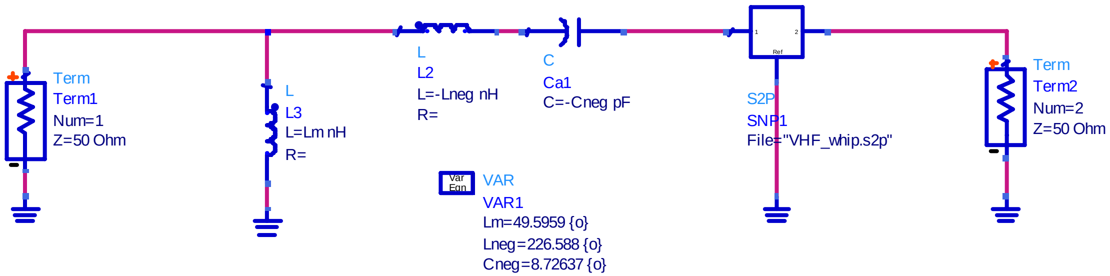
Antenna with More Practical Matching Network using Non-Foster Reactances.

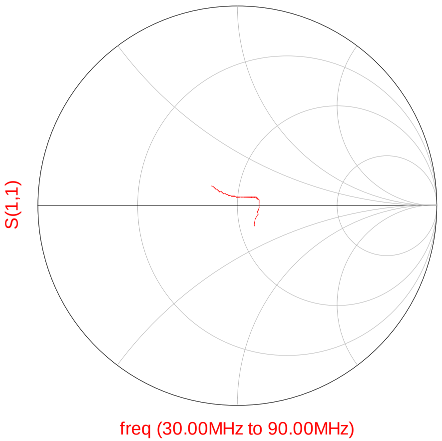


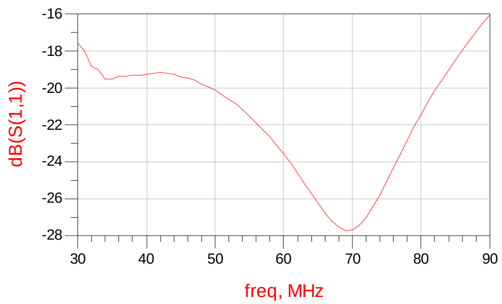
Active matching network

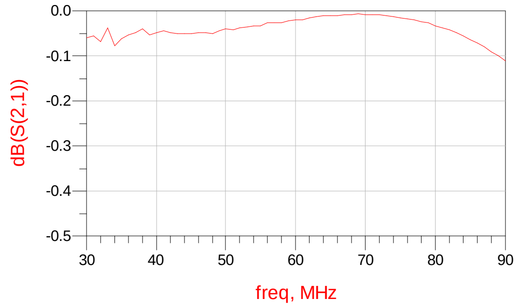
Two-port model of antenna

Optimized Non-Foster Matching Network









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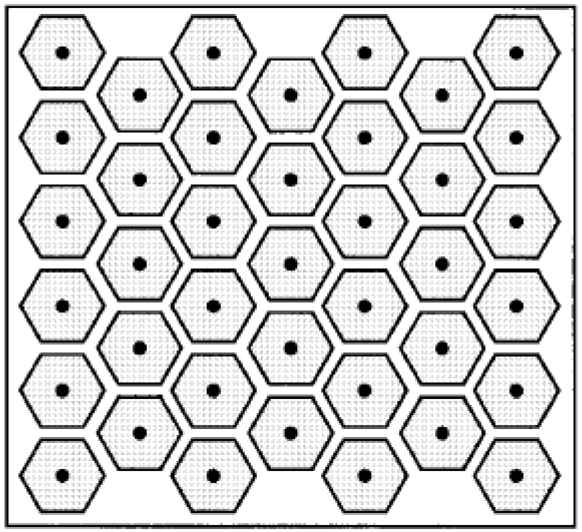
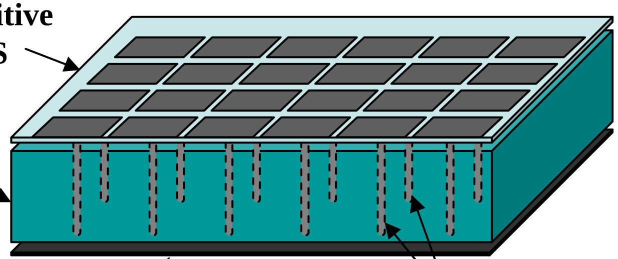
High-Impedance Ground Plane

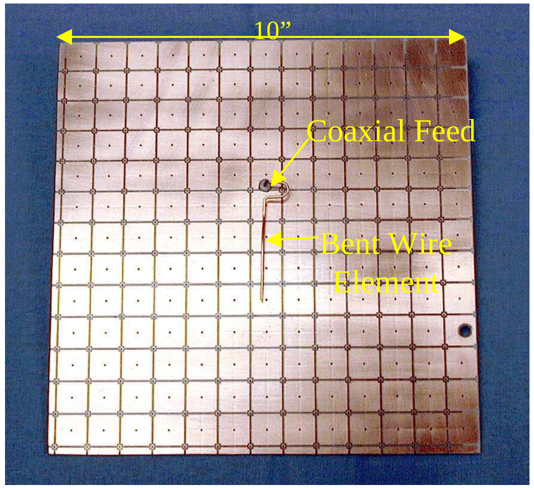
(a)



(b)

Sievenpiper, et. al, IEEE Trans. MTT, Nov. 1999

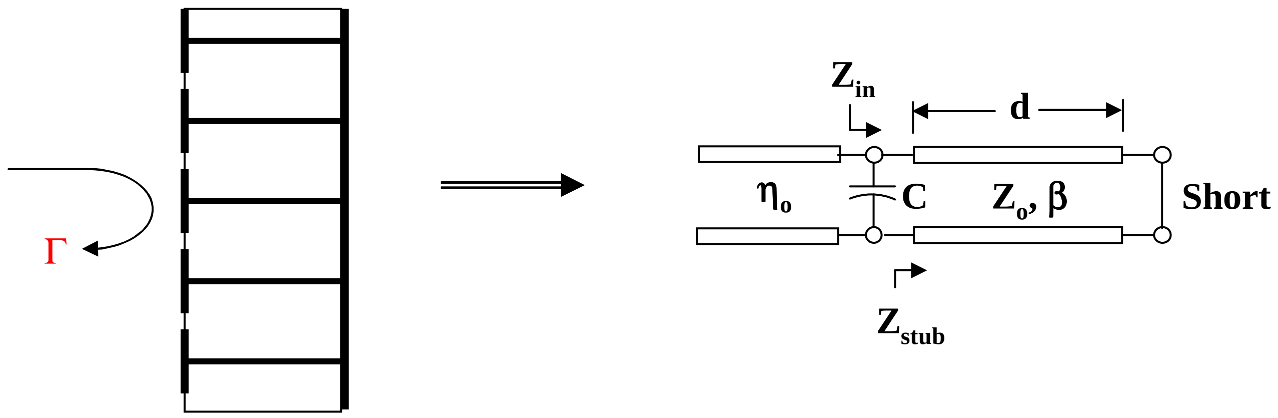




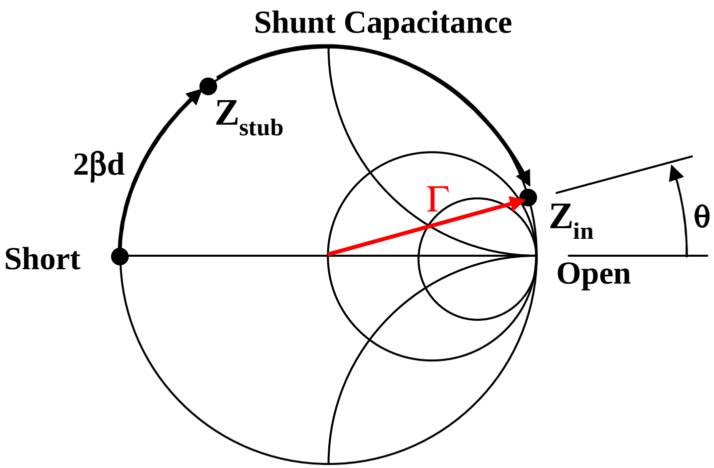
EM Properties of the Sievenpiper High-Impedance Ground Plane

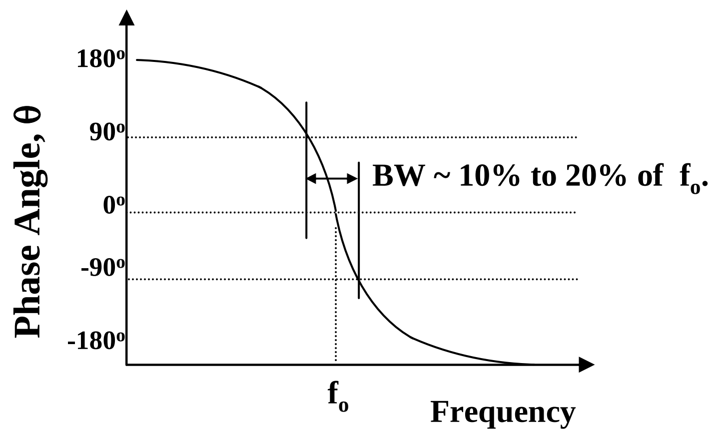
- Surface impedance is (ideally) an open-circuit (emulating a PMC rather than a PEC like a conventional ground plane).
- Propagation of TM and TE surface waves is not supported (thus can be called an electromagnetic bandgap structure).

Model for Surface Impedance of Sievenpiper HIS

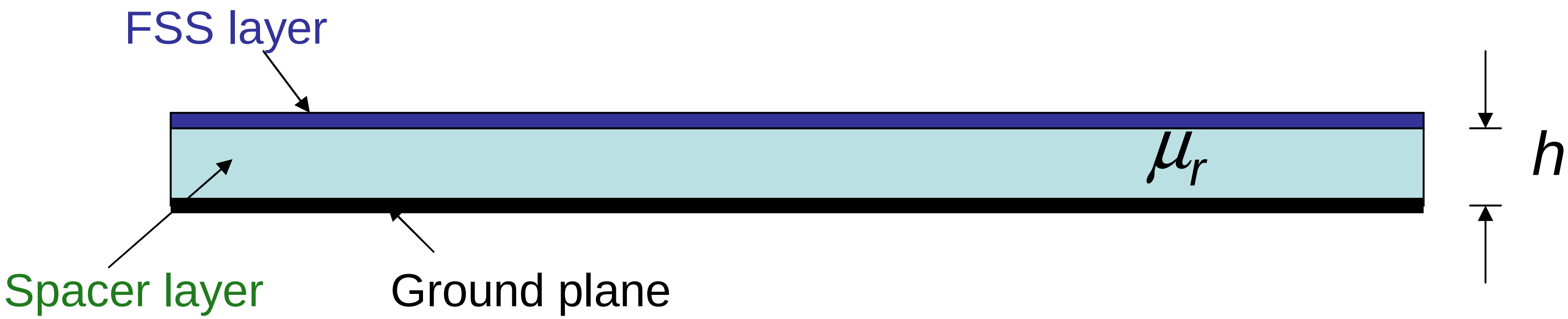


For plane waves at normal incidence, the substrate may be understood as an electrically short length of shorted transmission line in parallel with a shunt capacitance at the reference plane of the outer surface.





Reflection Phase Bandwidth of Sievenpiper HIS

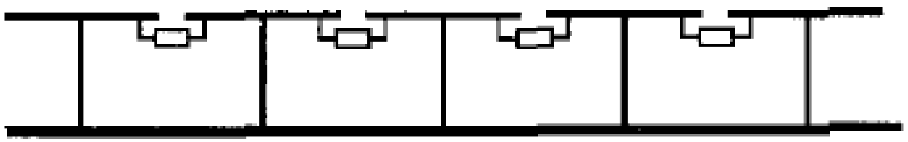


$$\frac{\Delta\omega}{\omega_0} = 2\pi\mu_r \frac{h}{\lambda_0}$$

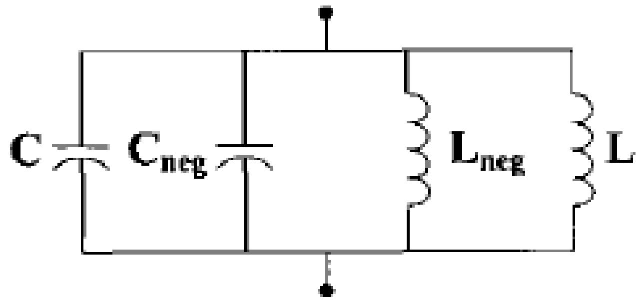
Electrically-Thin Broadband High-Impedance Surface

- In principle, one could realize an electrically-thin broadband HIS by using a high-permeability spacer layer.
- A high-permeability meta-material can be realized using artificial magnetic molecules (AMMs) implement with negative inductance circuits.
- Unfortunately, AMM performance is very sensitive to component tolerances.
- But, there is a better way …

Electrically-Thin Broadband High-Impedance Surface



(a)

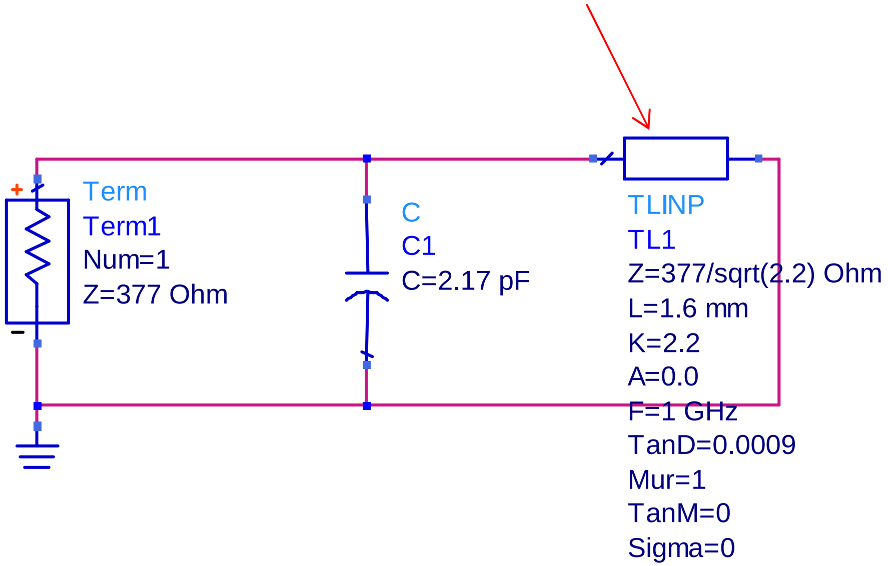


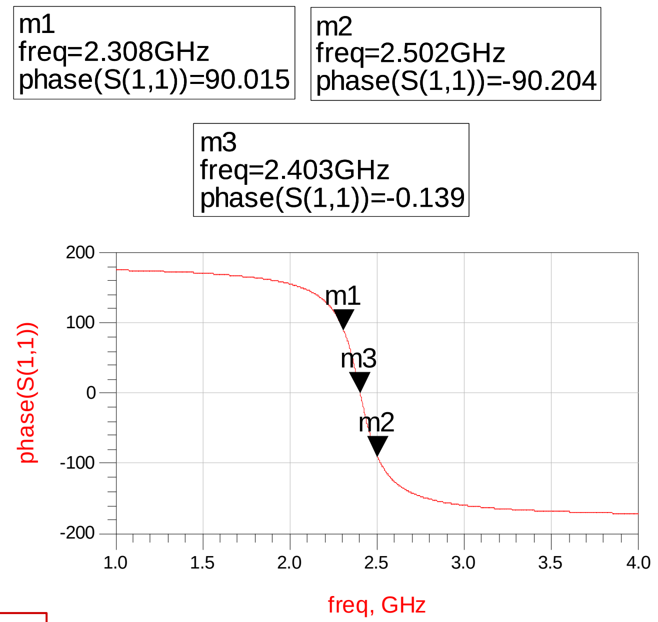
(b)

Kern, Werner, Wilhelm, APS 2003

Electrically-Thin Conventional HIS

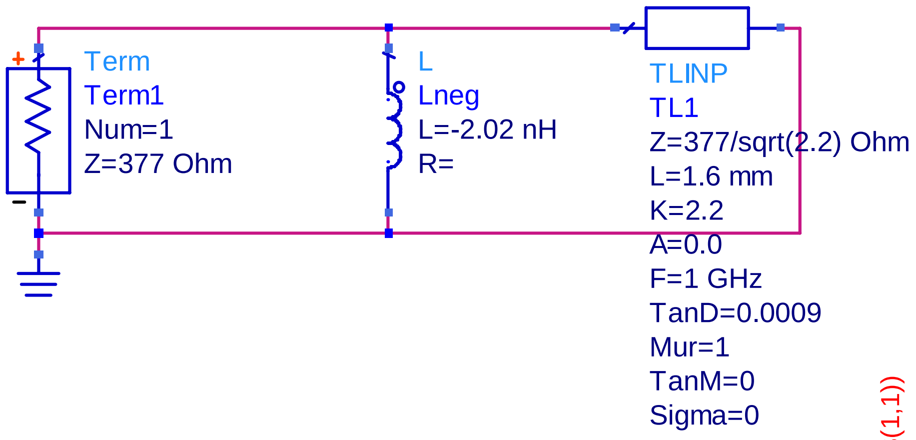
0.062 in Rogers
Duroid 5880

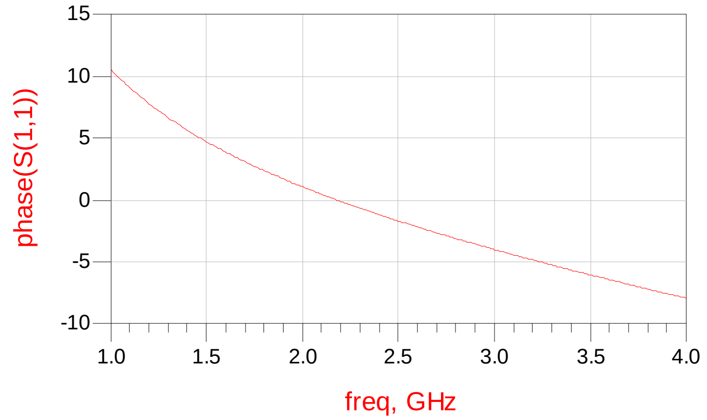




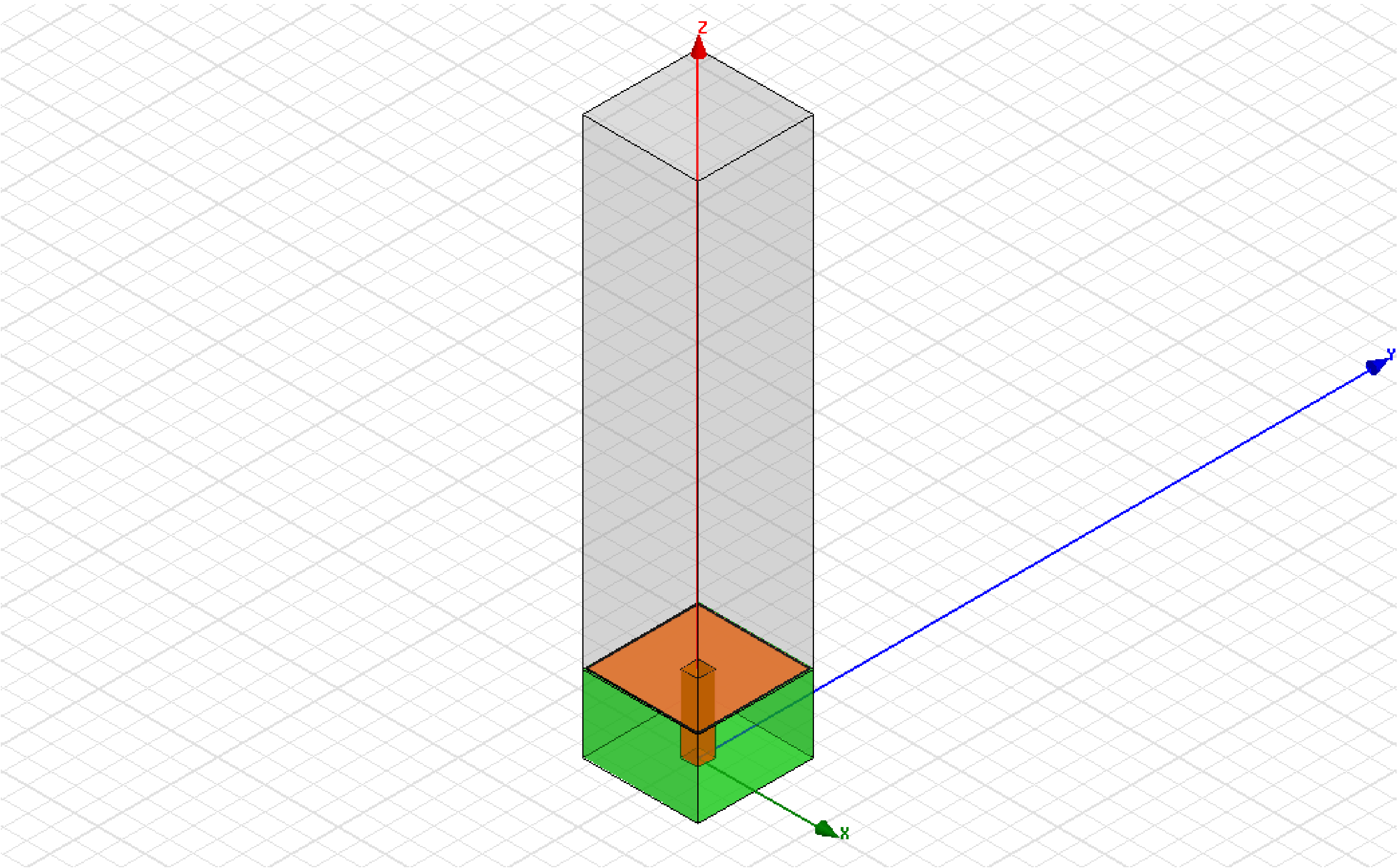
$$\frac{\Delta f}{f_0} = 8\%$$

Electrically-Thin HIS with Negative Inductance

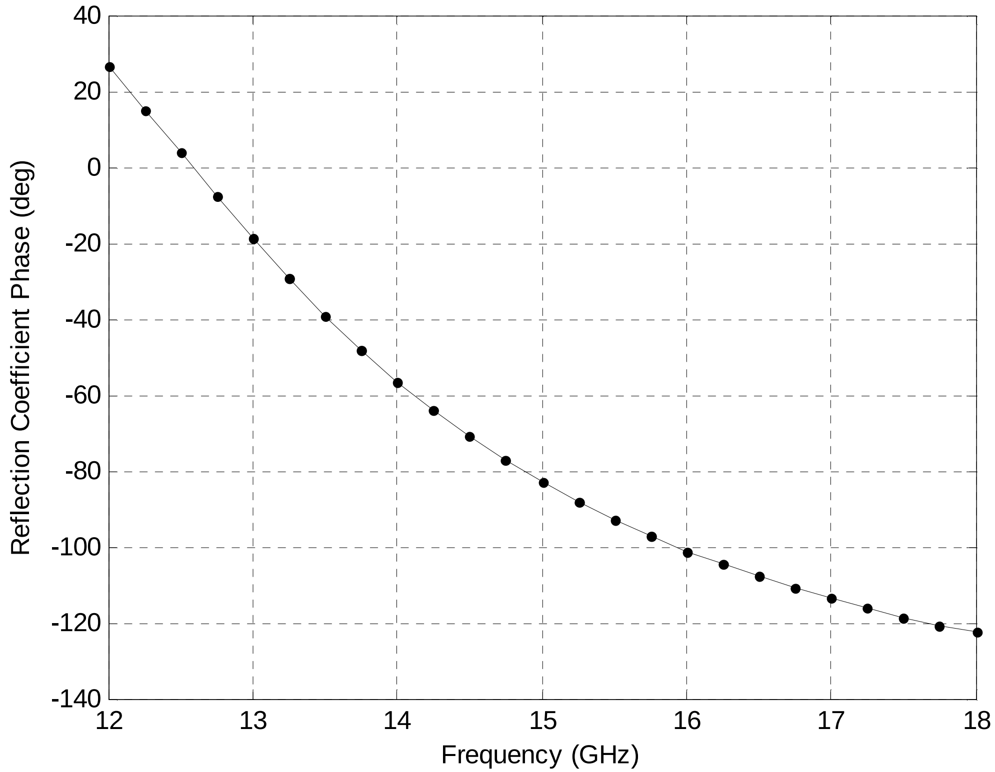




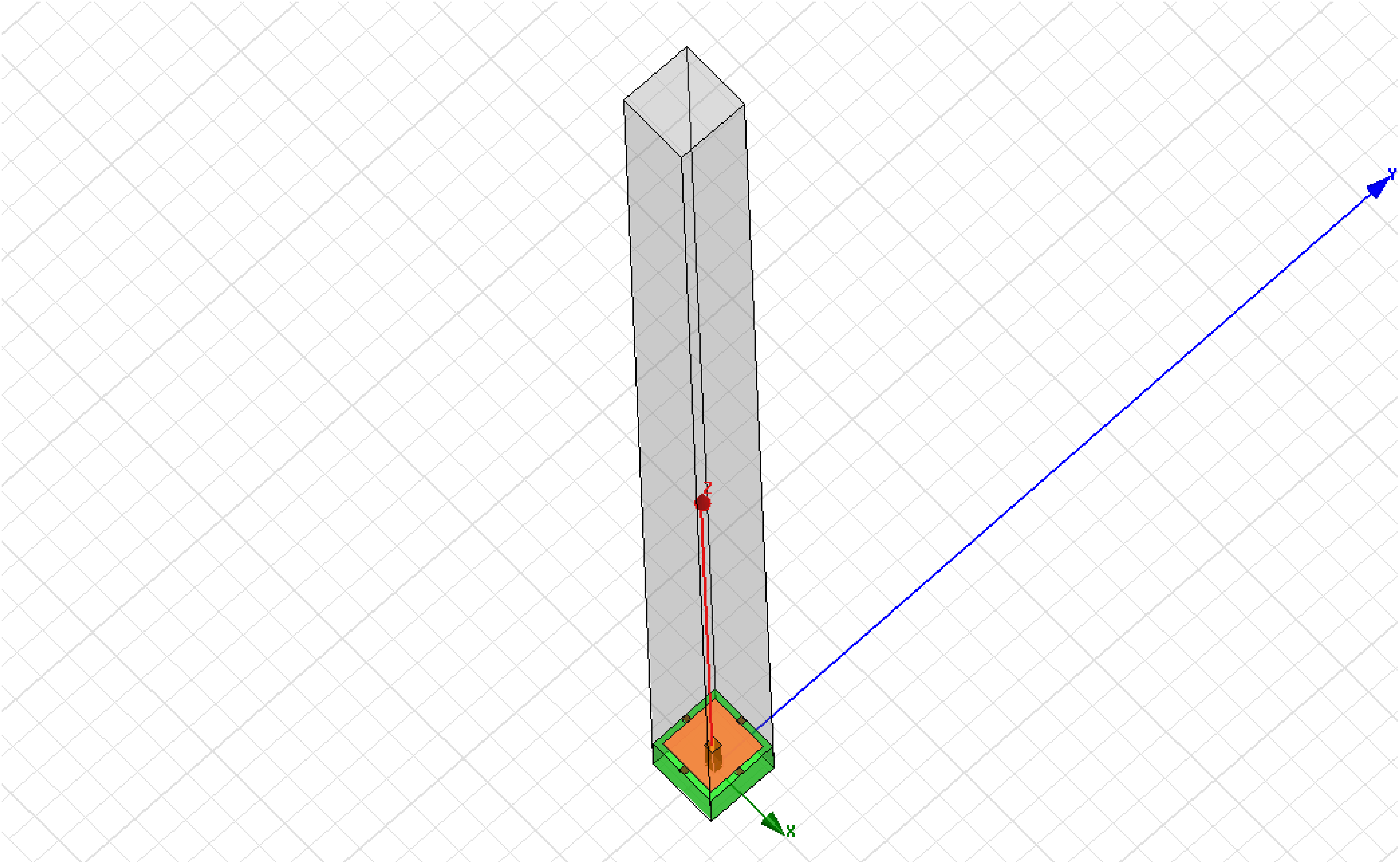
Unit Cell of Sievenpiper HIGP



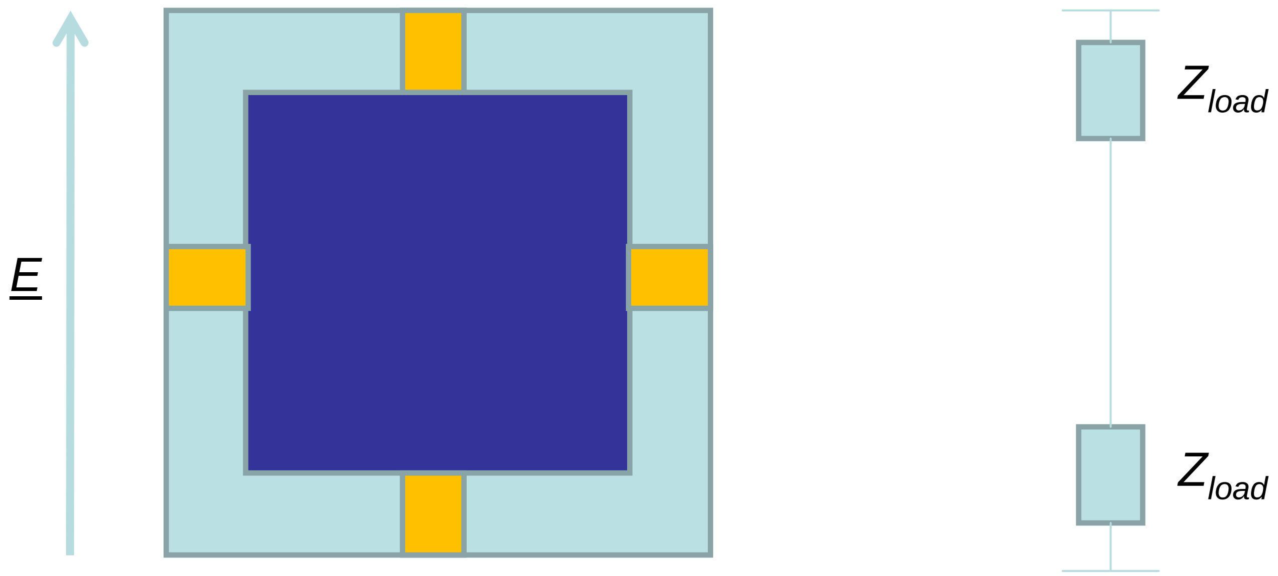
Reflection Phase Response of Sievenpiper HIGP



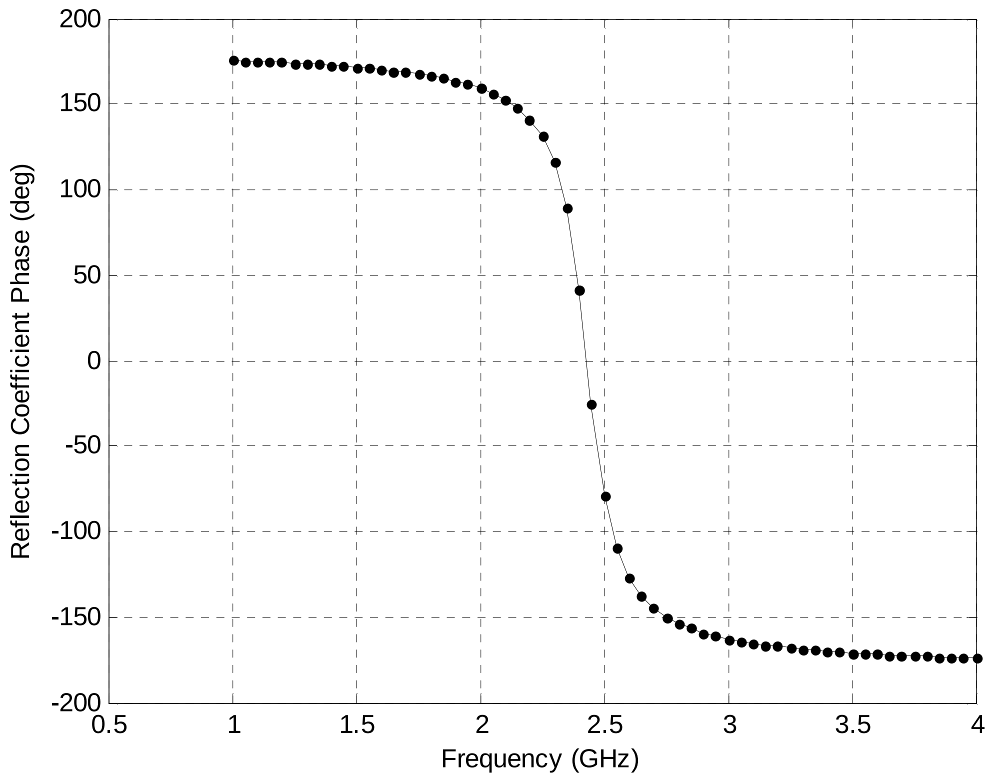
Unit Cell of Sievenpiper HIGP with Reactive Loading



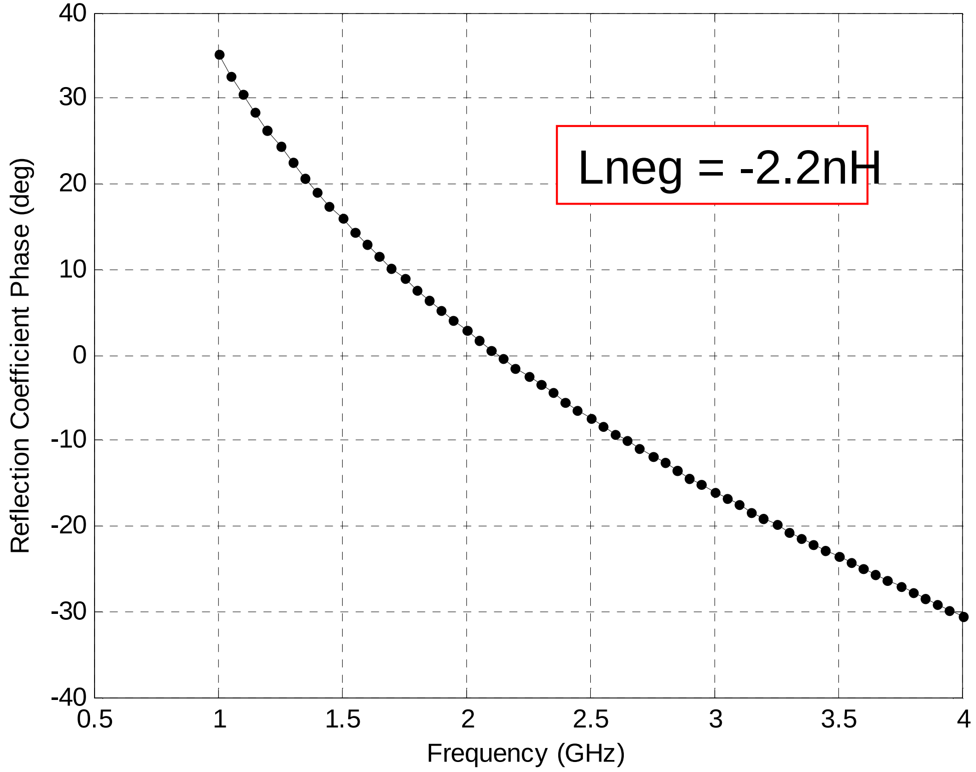
Equivalent Circuit of Loaded HIGP for Normally Incident Plane Wave



Reflection Phase of Capacitively Loaded HIGP



Reflection Phase of Negative-Inductor Loaded HIGP



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What is an Artificial Material?

- An artificial material is a large-scale emulation of an actual material, obtained by embedding a large number of electrically small inclusions ("artificial molecules") within a host medium.
- Like natural molecules, the electrically small inclusions exhibit electric and/or magnetic dipole moments.
- As a result of these dipole moments, the macroscopic electromagnetic constitutive parameters (ε_r and μ_r) are altered with respect to the host medium.

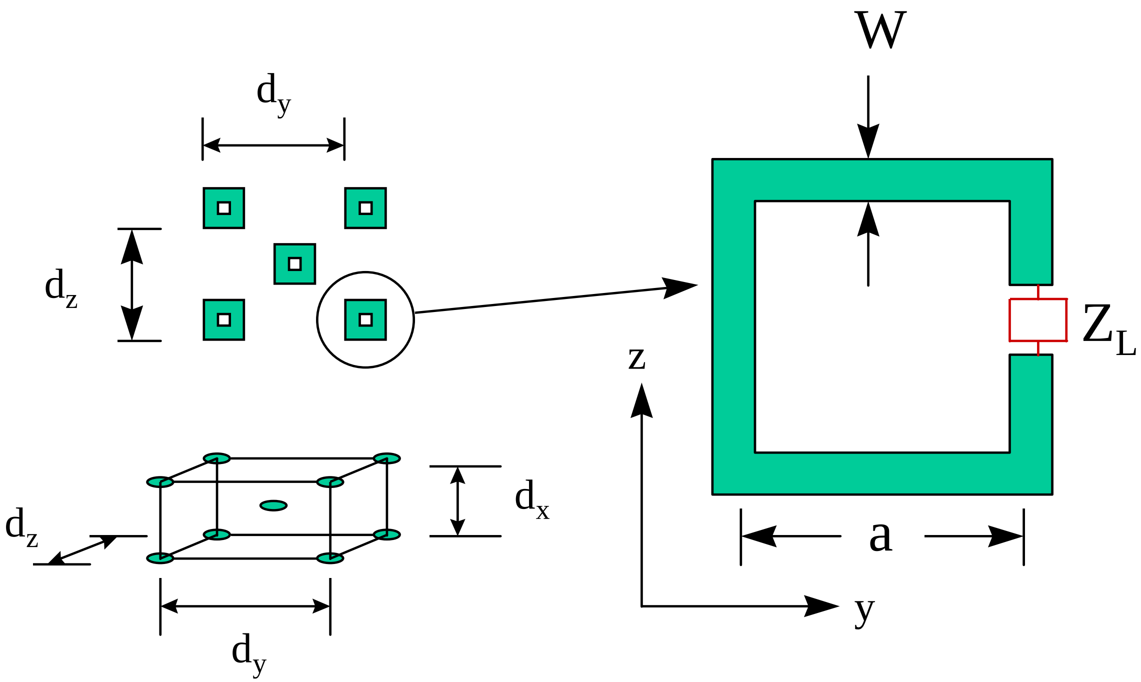
$$\underline{D} = \overline{\overline{\varepsilon}} \bullet \varepsilon_0 \underline{E}$$

$$\underline{B} = \overline{\overline{\mu}} \bullet \mu_0 \underline{H}$$

Why Create an Artificial Magnetic Material?

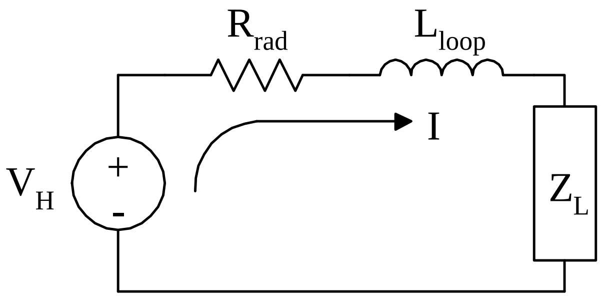
- “Naturally” occurring magnetic materials (ferrites) are heavy, fragile and expensive, and they also exhibit relatively high magnetic losses and dielectric constant.
- Available ferrite materials provide a limited selection of relative permeabilities.
- The permeability tensor of the ferrite is controlled by applying a static magnetic field – permanent magnets and/or electromagnets are required.

Artificial Magnetic Metamaterial



- A 3-dimensional lattice of artificial molecules.
- Electrically small loop with a load impedance

Simple Circuit Model for Artificial Magnetic Molecule (AMM)



Relative permeability

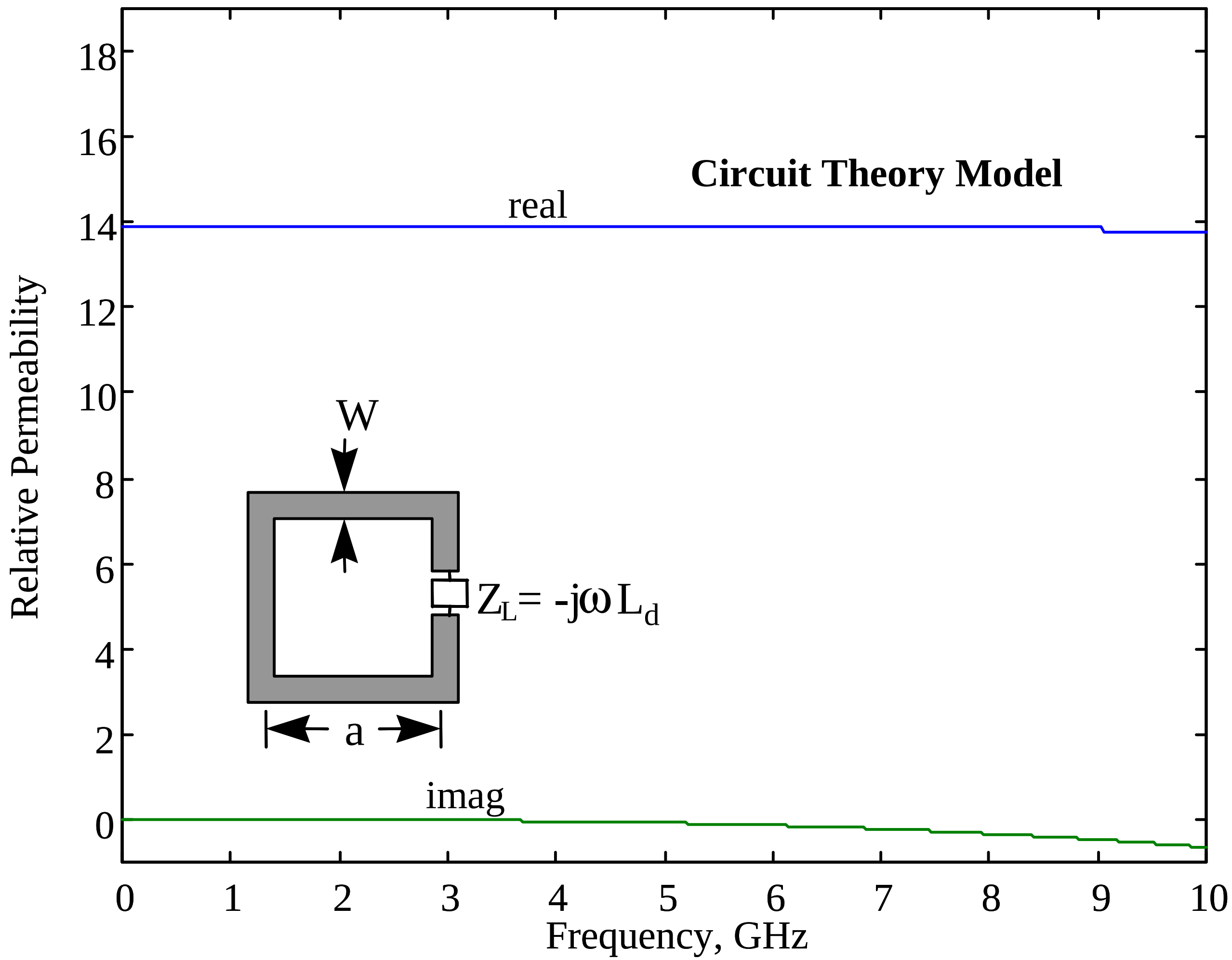
Number of AMMs per unit volume

$$\mu_{xx} = 1 + N\alpha$$

$$\alpha = \frac{m}{H} = \frac{-j\omega\mu_0 a^4}{R_{loss} + j\omega L_{loop} + Z_L}$$

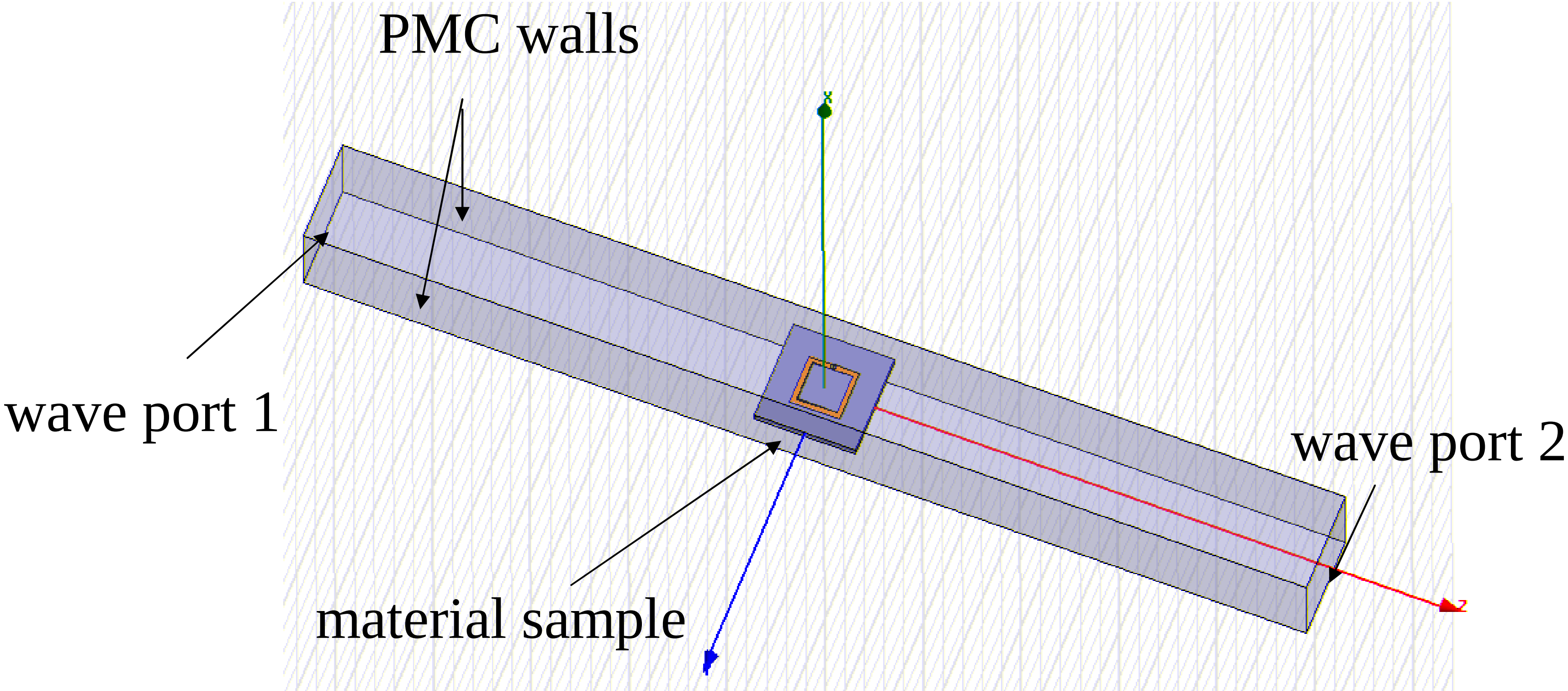
Magnetic polarizability of each AMM

Broadband, High Permeability Requires Negative Inductance



How to Extract Material Properties

(TEM waveguide containing material sample)



How to Extract Material Properties

- HFSS

  -Two port S parameters calculation of TEM waveguide containing material sample.

- MATLAB

  -Shifting of the reference planes.

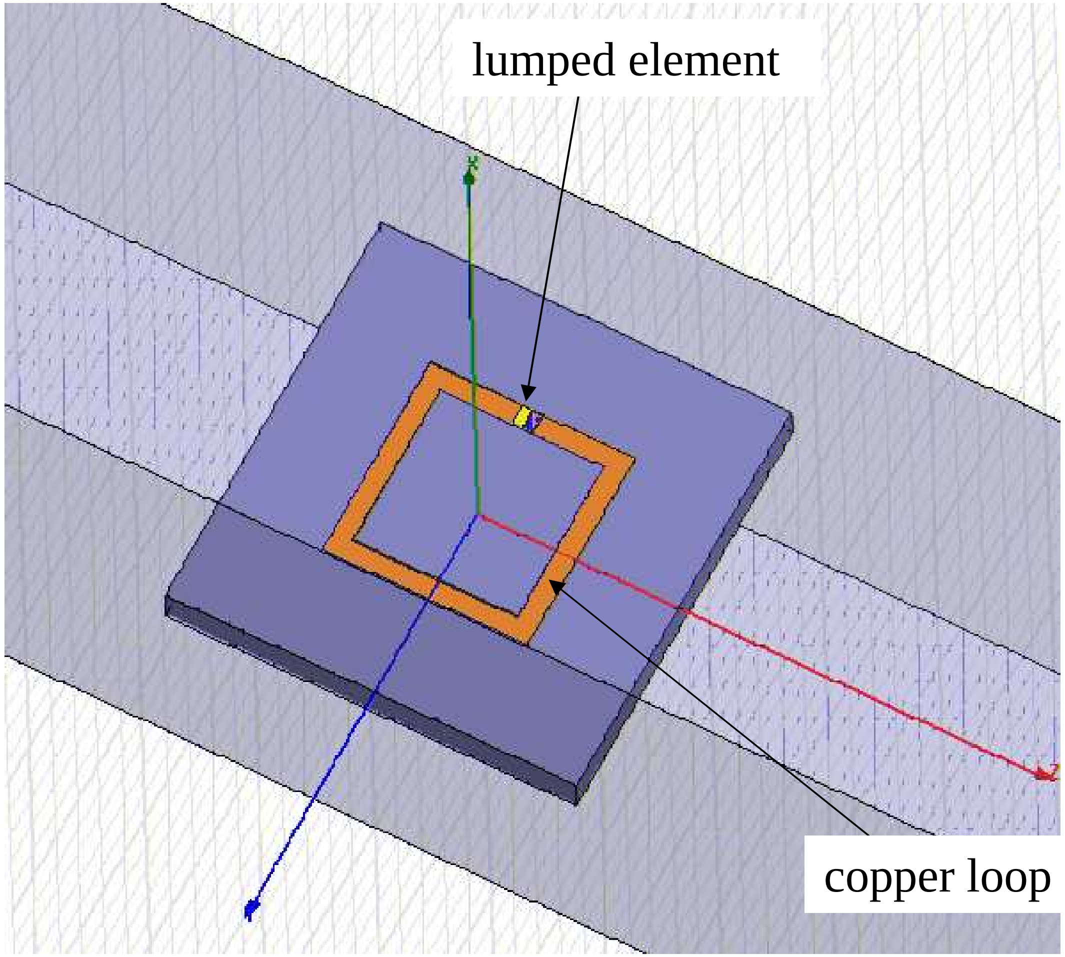
  -Conversion of S-parameters to ABCD parameters.

  -Calculation of propagation constant and characteristic impedance of equivalent transmission line.

  -Evaluation of the material properties.

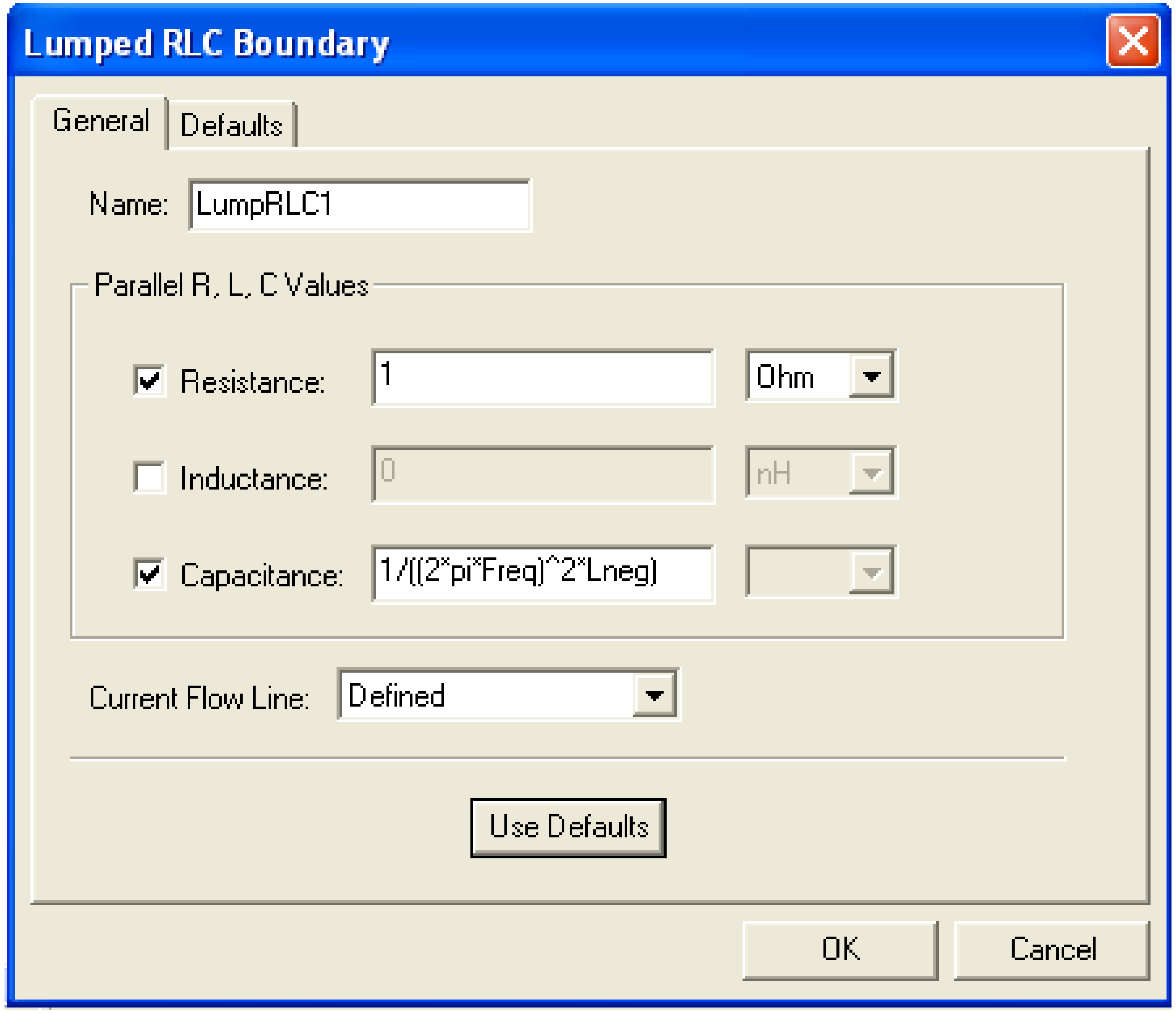
How to Extract Material Properties

(Loop Configuration)

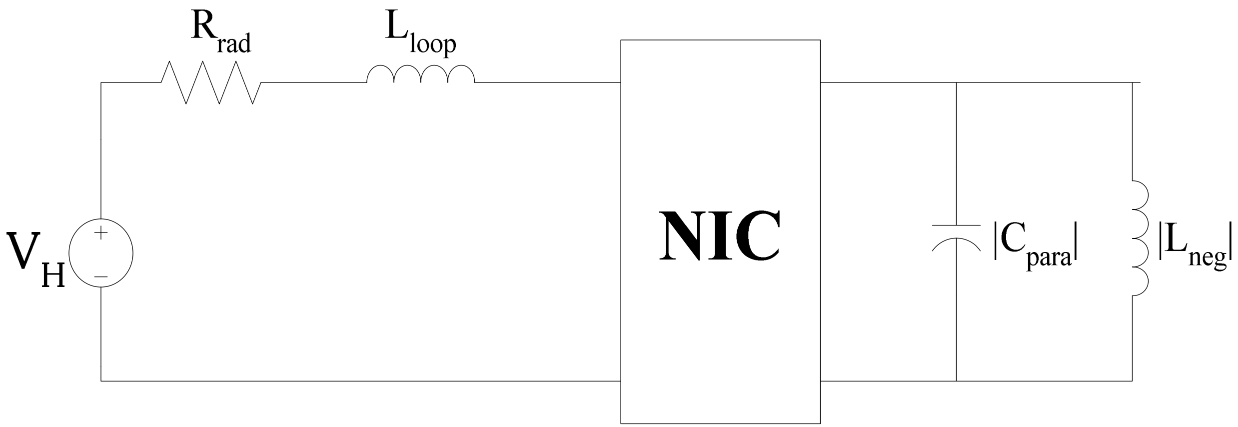


Negative Inductance is Modeled as a Frequency-Dependent Capacitance

$$C_{equiv} = \frac{1}{(2\pi f)^2 \left| L_{neg} \right|}$$

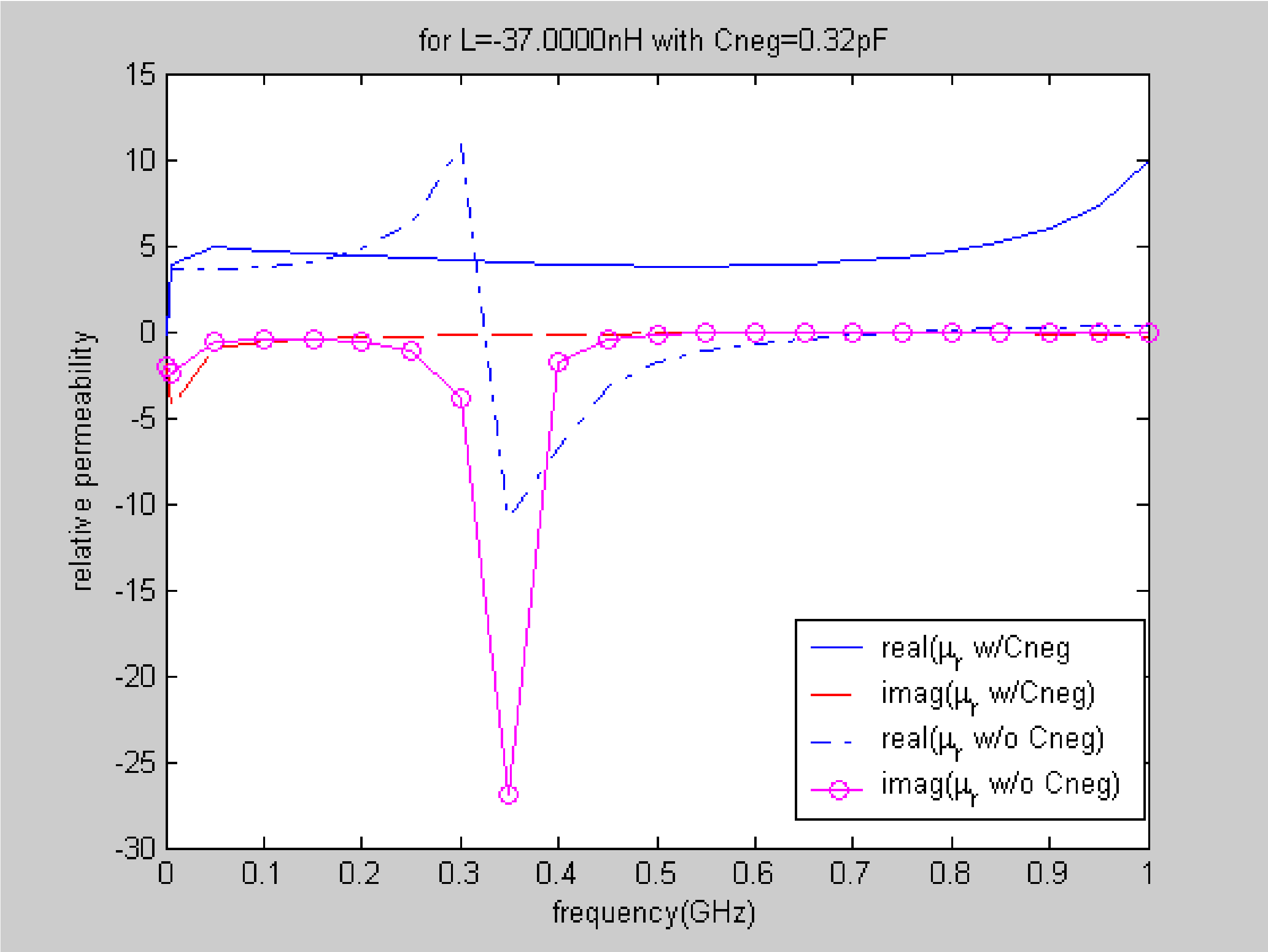


Cancellation of Parasitic Capacitance Using NIC



To remove the resonance, the parasitic capacitance of the loop should be compensated by a negative capacitance.

Remedy for Snoek-Like Phenomenon: Add Negative Capacitance in Shunt with Negative Inductance



Outline of Presentation

- What Does “Non-Foster” Mean?
- Possible Applications of Non-Foster Reactances
  - Electrically Small Antennas
  - High-Impedance Surfaces
  - Artificial High-Permeability Materials
- **Realization of Non-Foster Reactances**

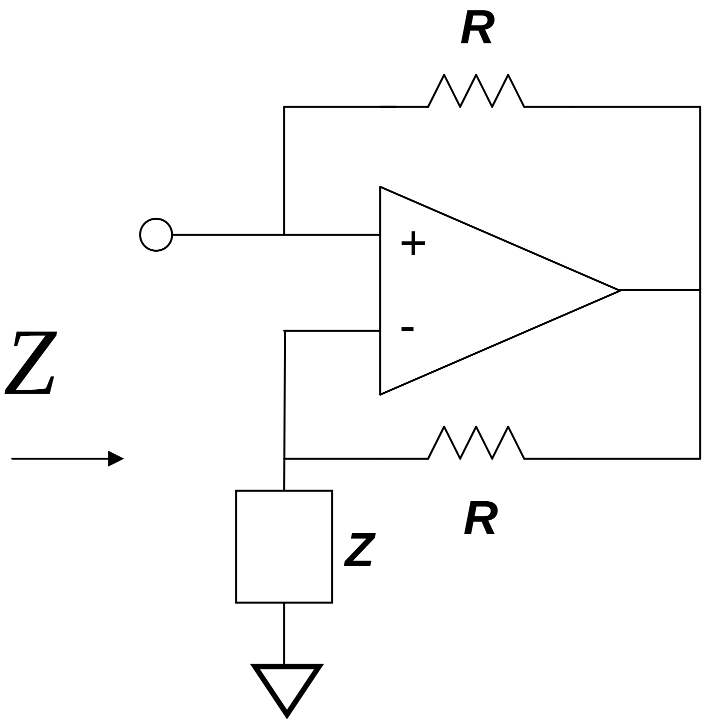
Negative Impedance Converter (NIC)

- An ideal NIC is a two-port network such that when a load impedance is attached to the output terminal, the input impedance is the (possibly scaled) negative value of the load impedance.

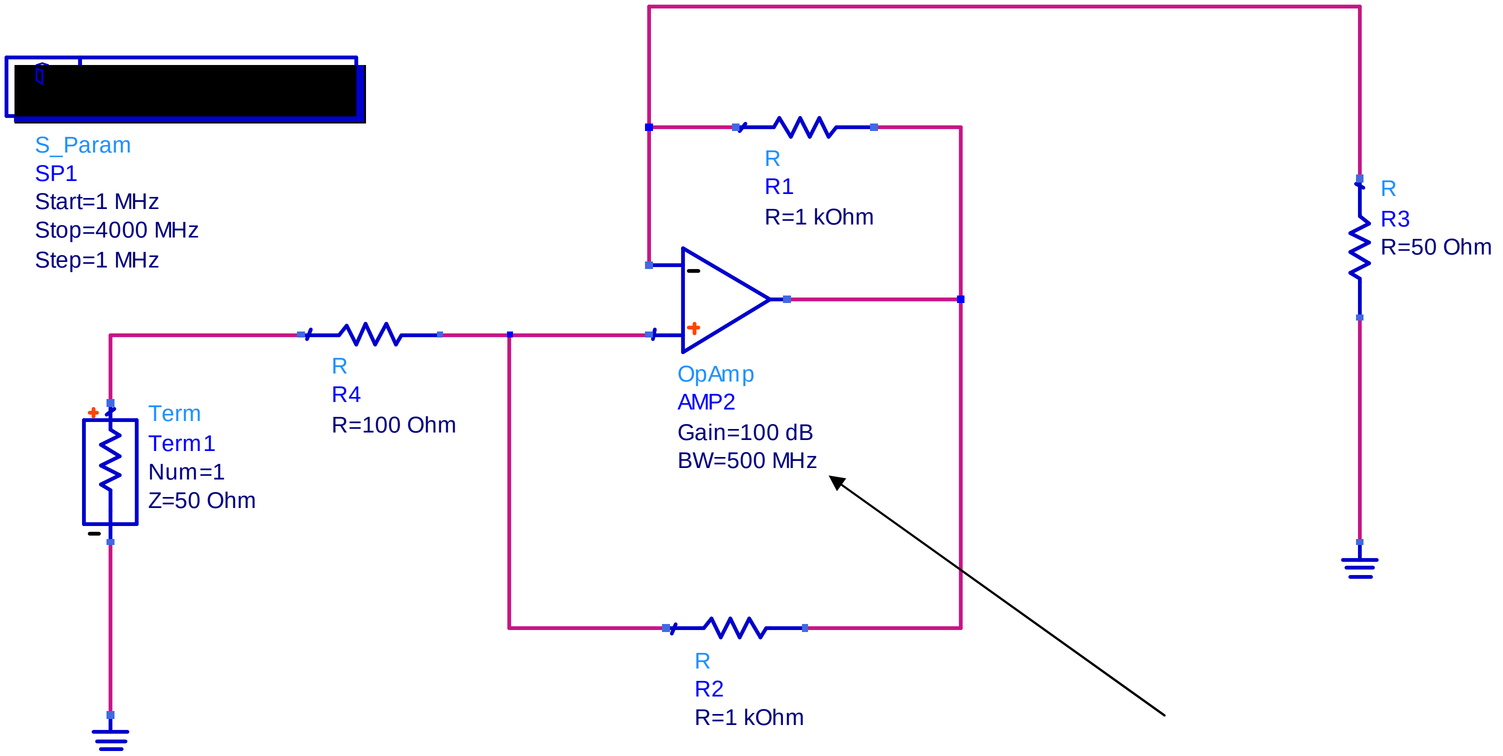
$Z_{in}=-kZ_L$ (k>0)

Canonical NIC

$$Z_{in} = -Z$$



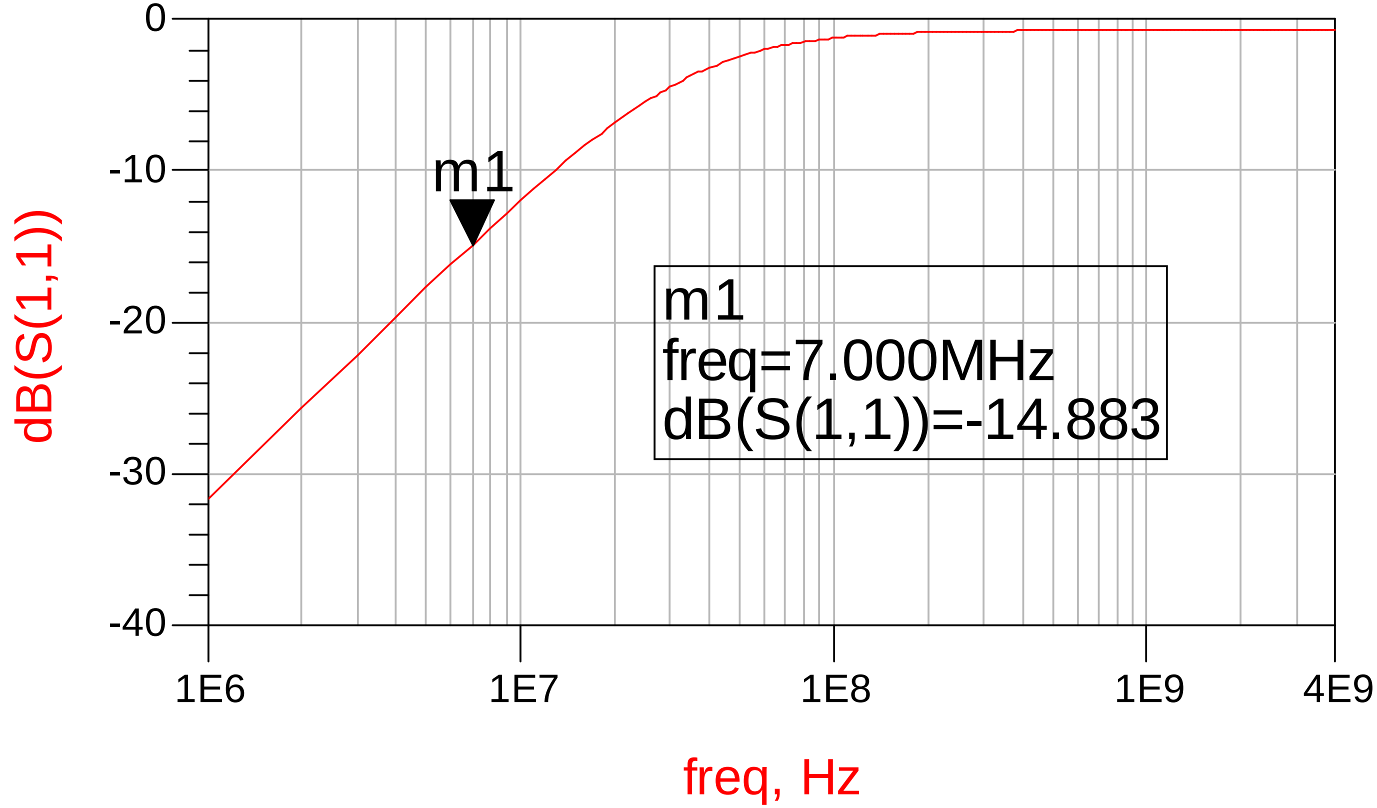
Simple Op-Amp Test Circuit



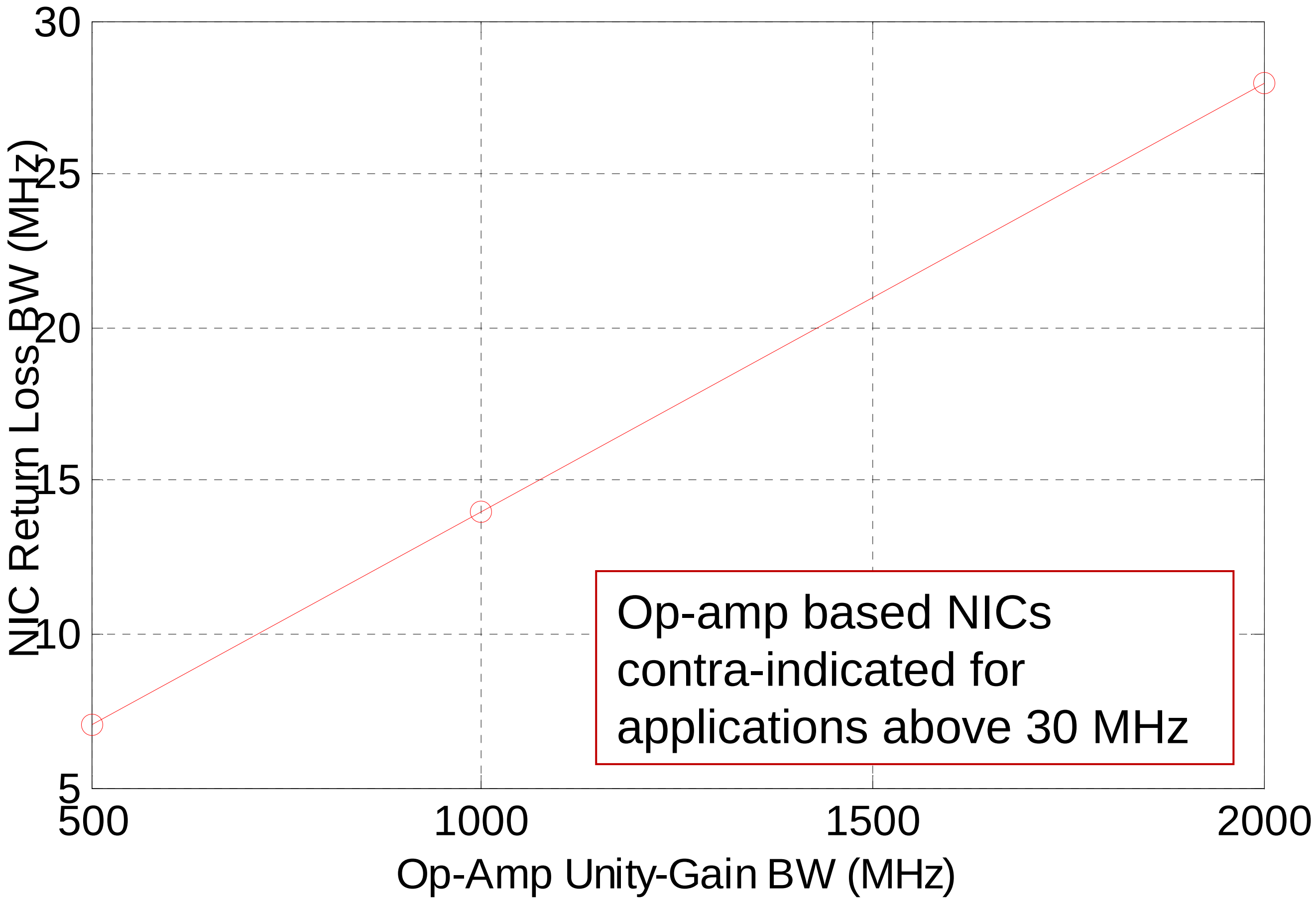
FOM: RL > 15 dB

Can specify DC gain and unity gain BW.

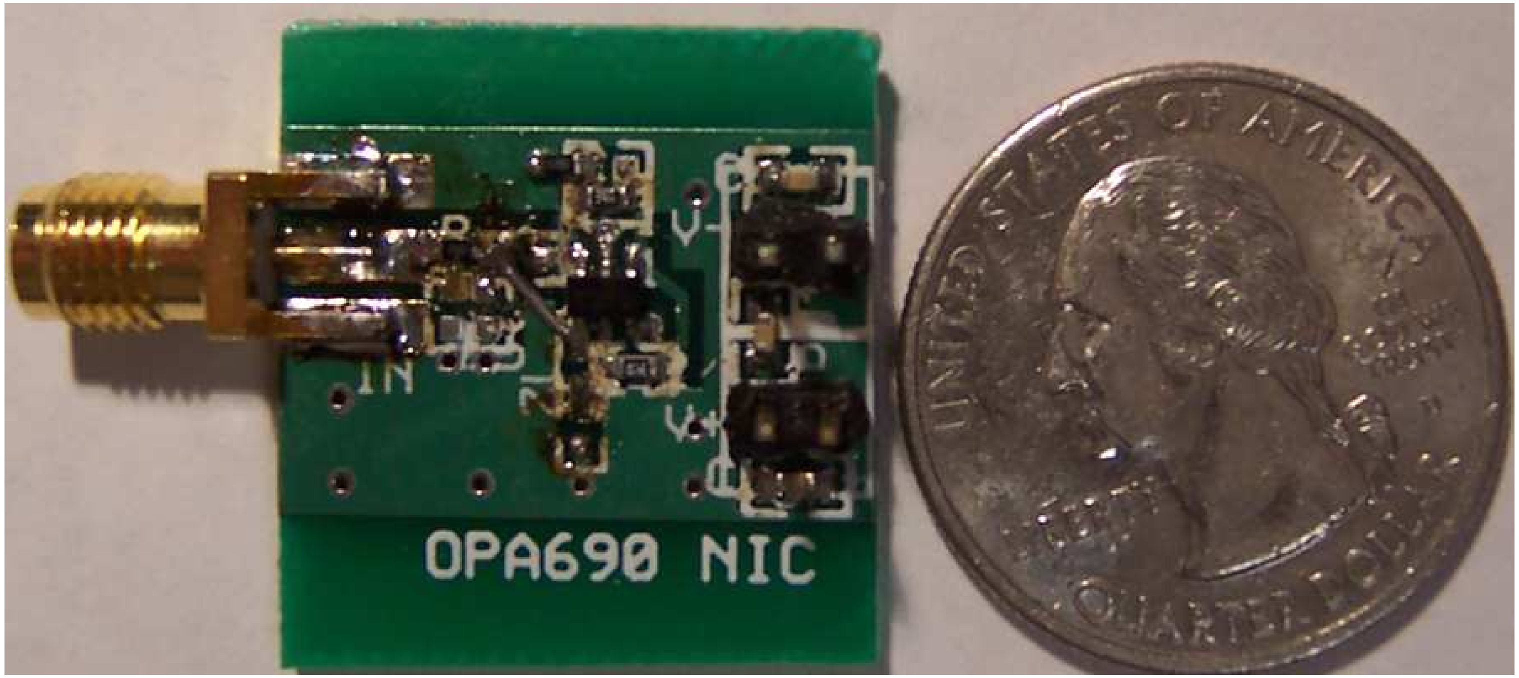
Unity-gain BW = 500 MHz



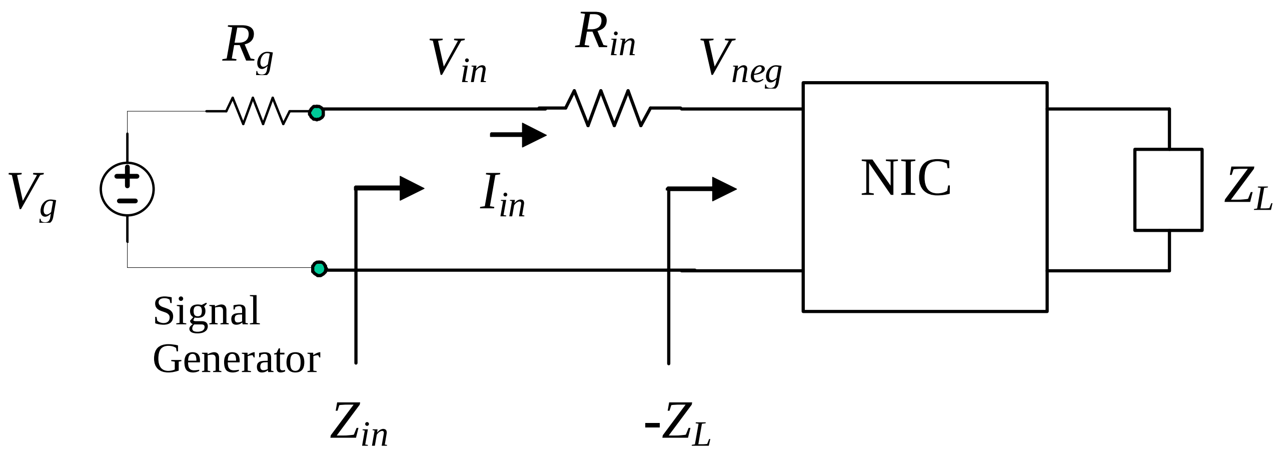
NIC Return Loss BW vs. Op-Amp Unity Gain BW



Fabricated OPA690 NIC Evaluation Board



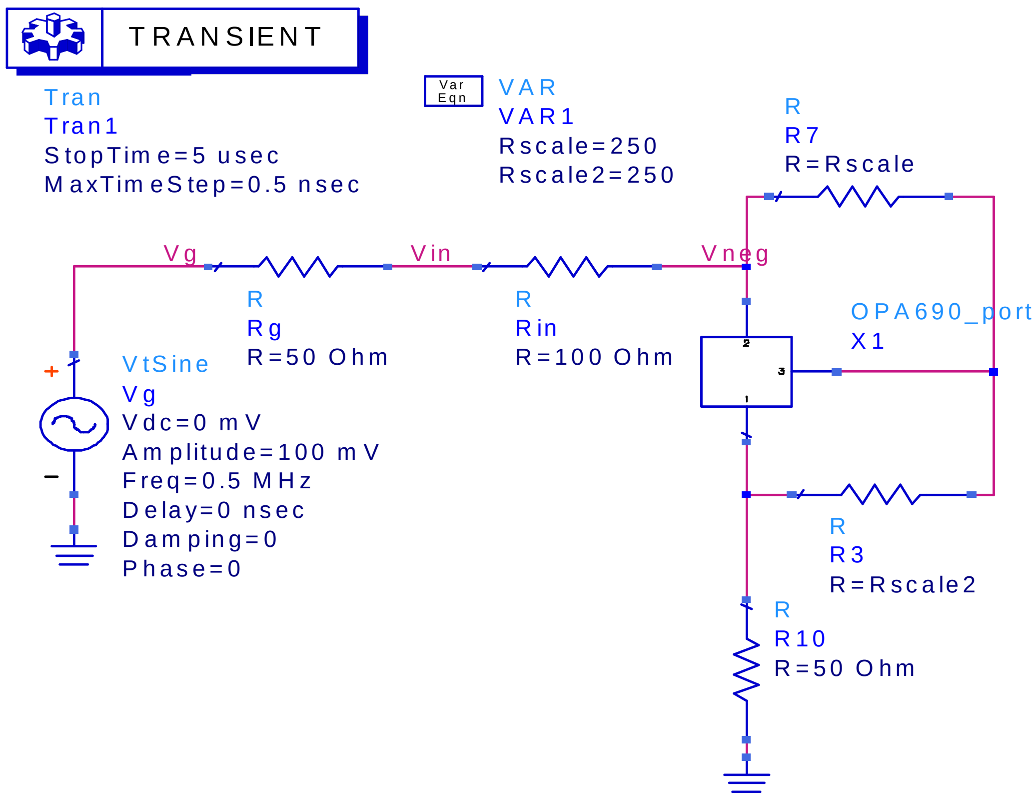
Circuit for evaluating the performance of a grounded negative impedance



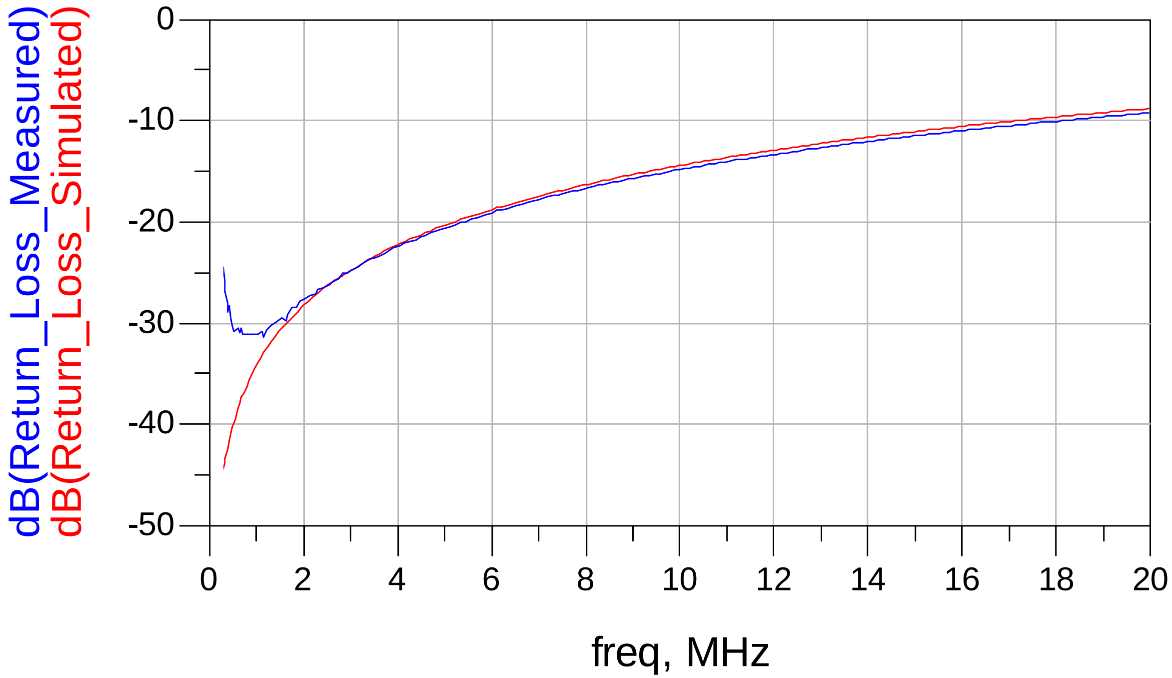
Stability requires that

$$R_{in} > |Z_L|$$

Schematic captured from Agilent **ADS** of the circuit for evaluating the performance of the OPA690 NIC

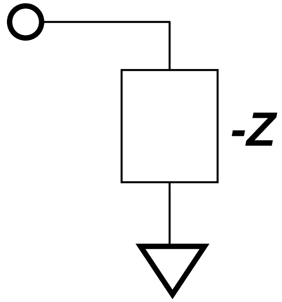


Simulated and measured return loss for the OPA690 NIC evaluation circuit

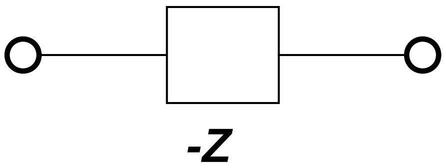


Ground Negative Impedance Versus Floating Negative Impedance

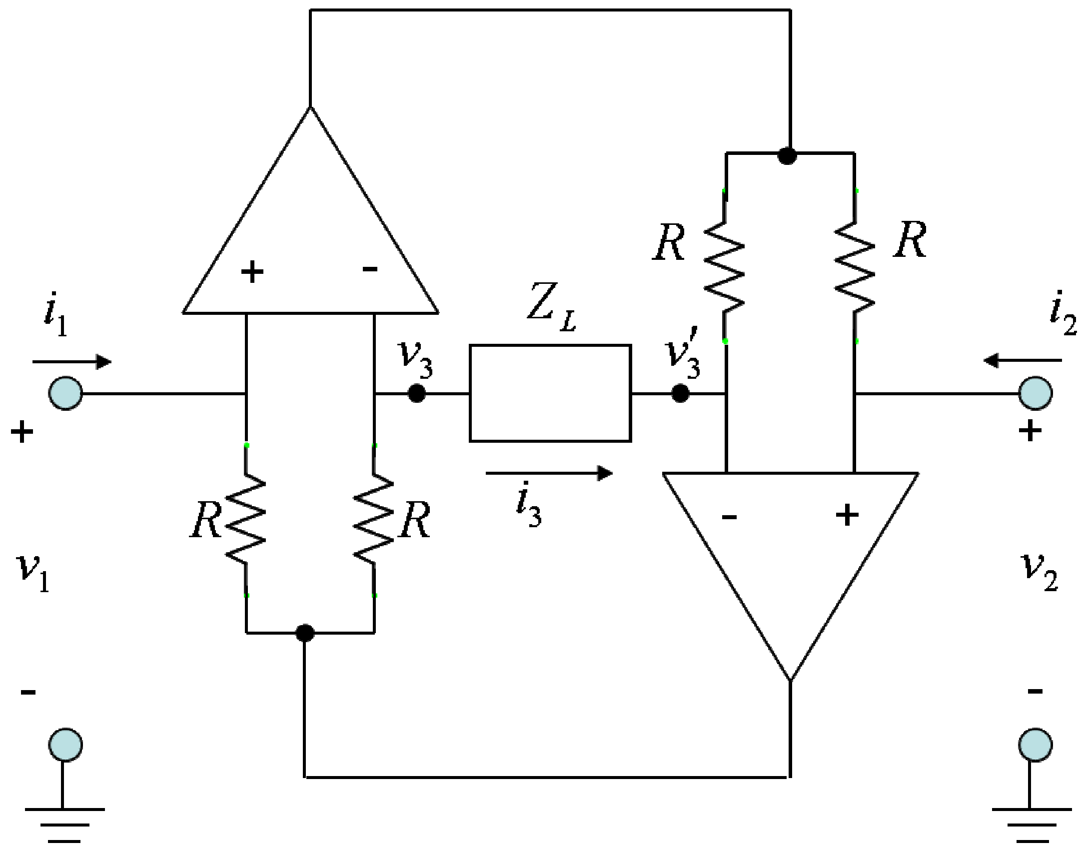
- Canonical NIC and most other NIC circuits in the literature produce ***grounded* negative impedance**



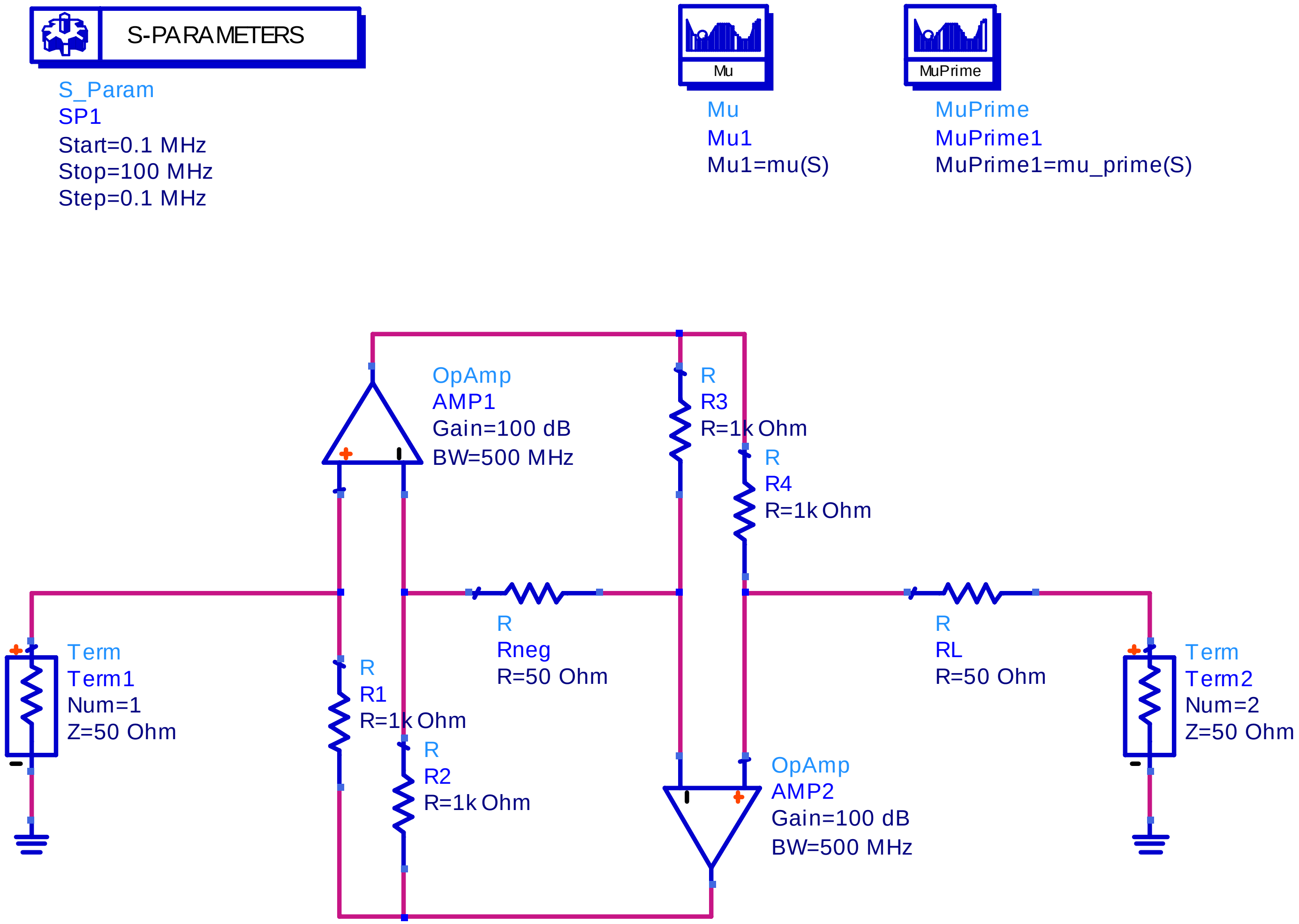
- But for the applications we are considering here, we need ***floating* negative impedance**



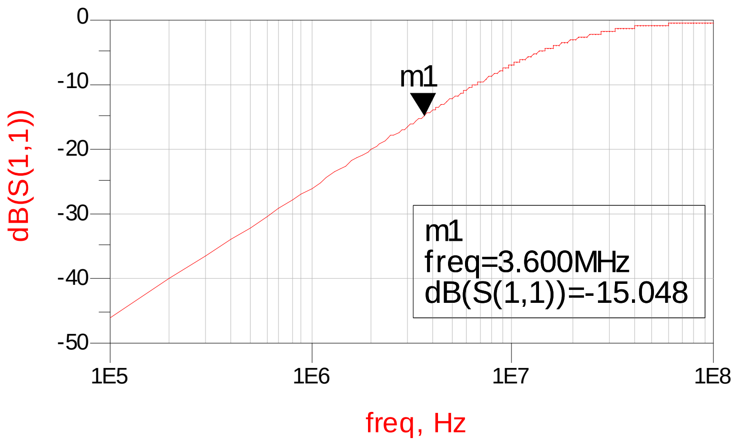
Floating NIC Realized Using Two Op-Amps

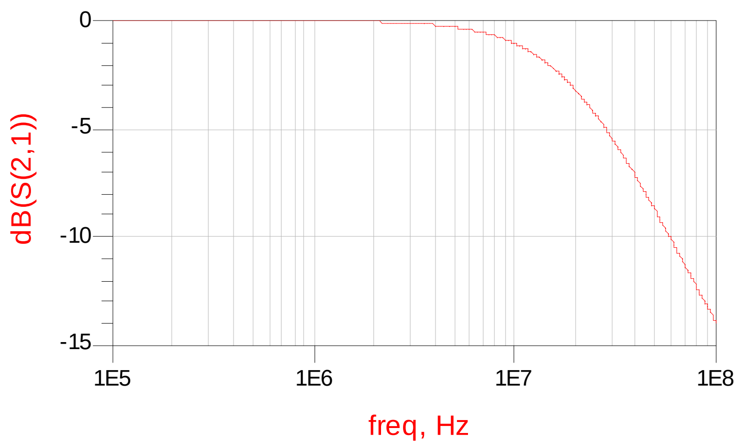


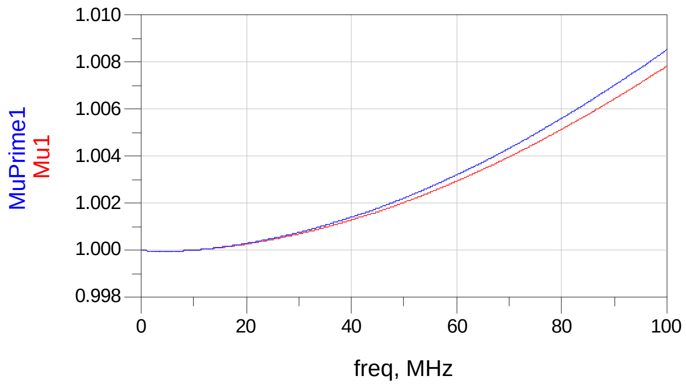
Op-Amp FNIC Test Circuit



Unity-gain BW = 500 MHz



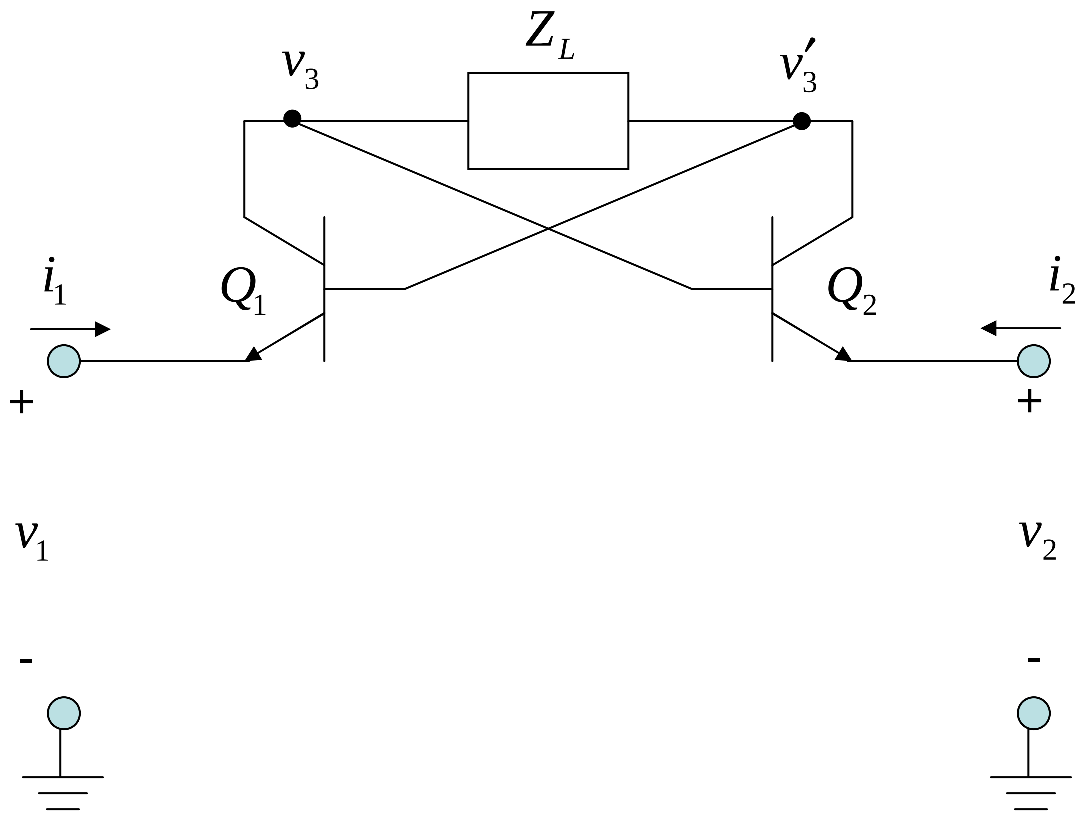




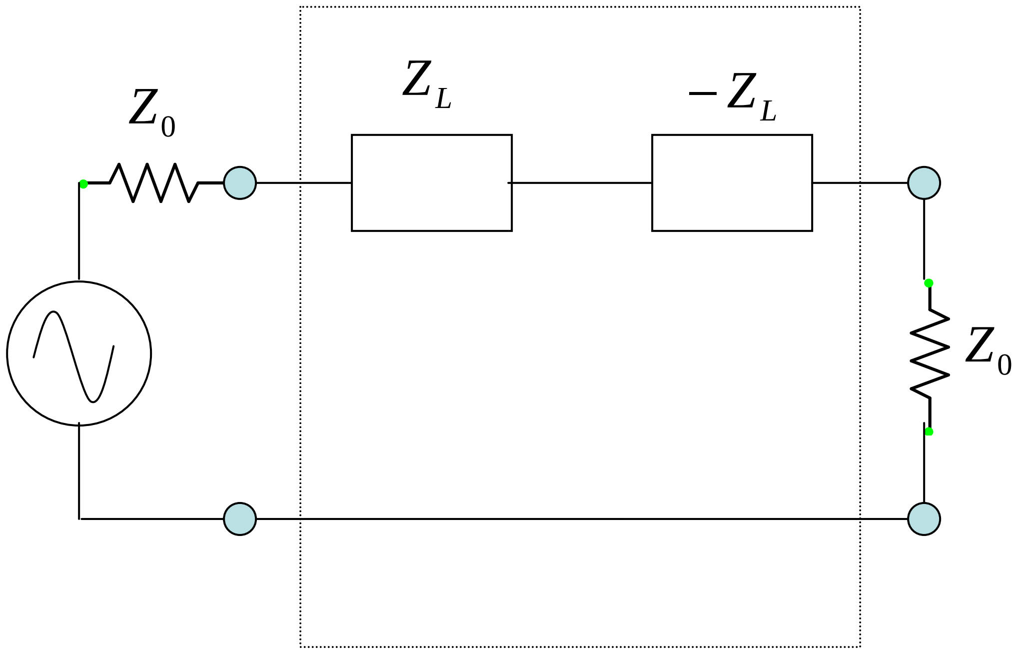
NIC Return Loss BW vs. Op-Amp Unity Gain BW

Op Amp BW	15 dB RL NIC BW
500 MHz	3.6 MHz
1000 MHz	7.2 MHz
2000 MHz	14.5 MHz

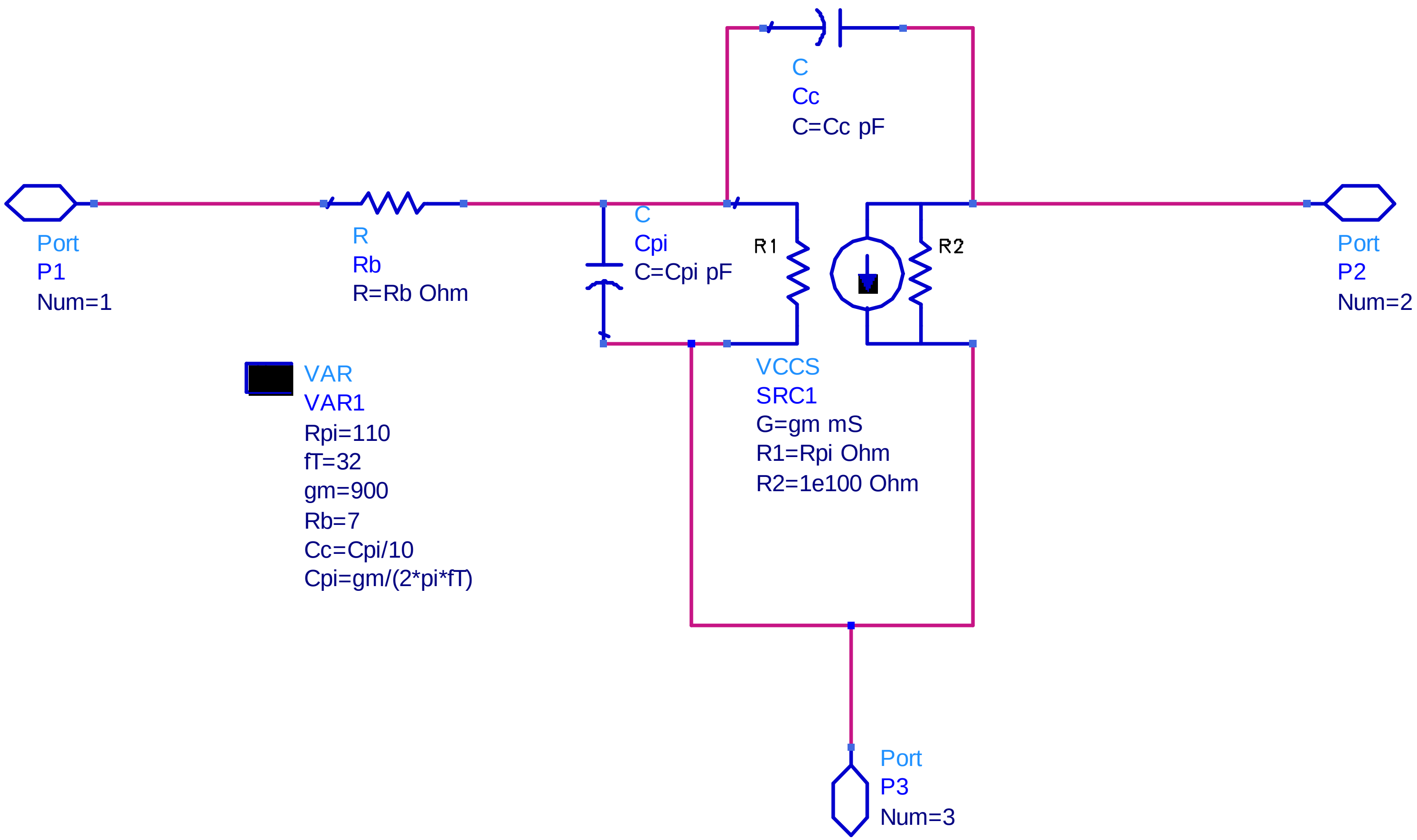
Floating NIC Circuit Using Two Transistors



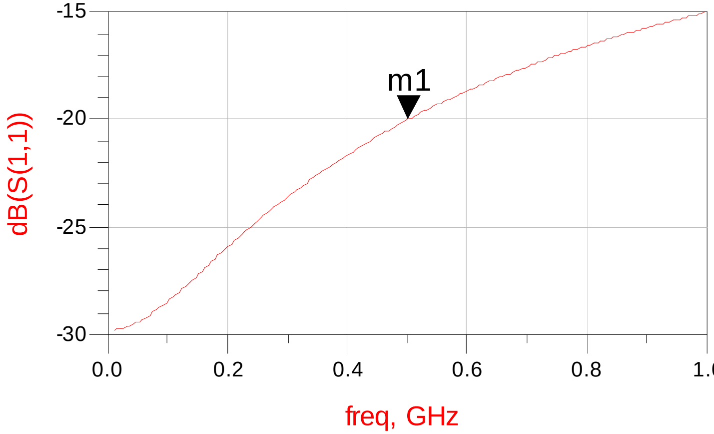
NIC “All-Pass” Test Circuit

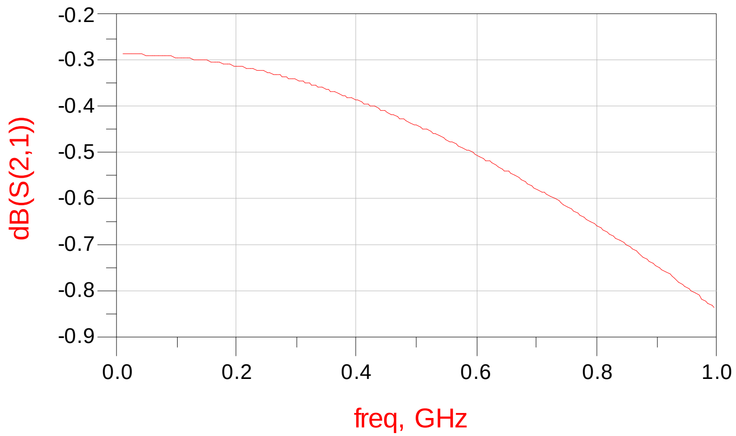


High-Frequency BJT Device Model

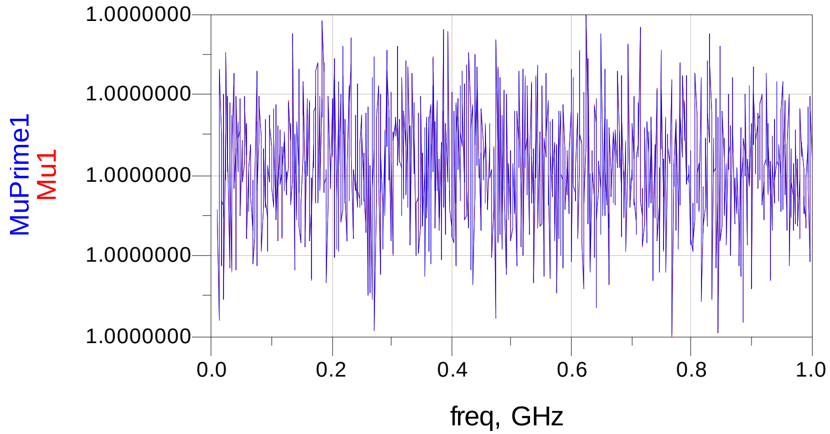


Test Circuit Results (f_T = 32 GHz)

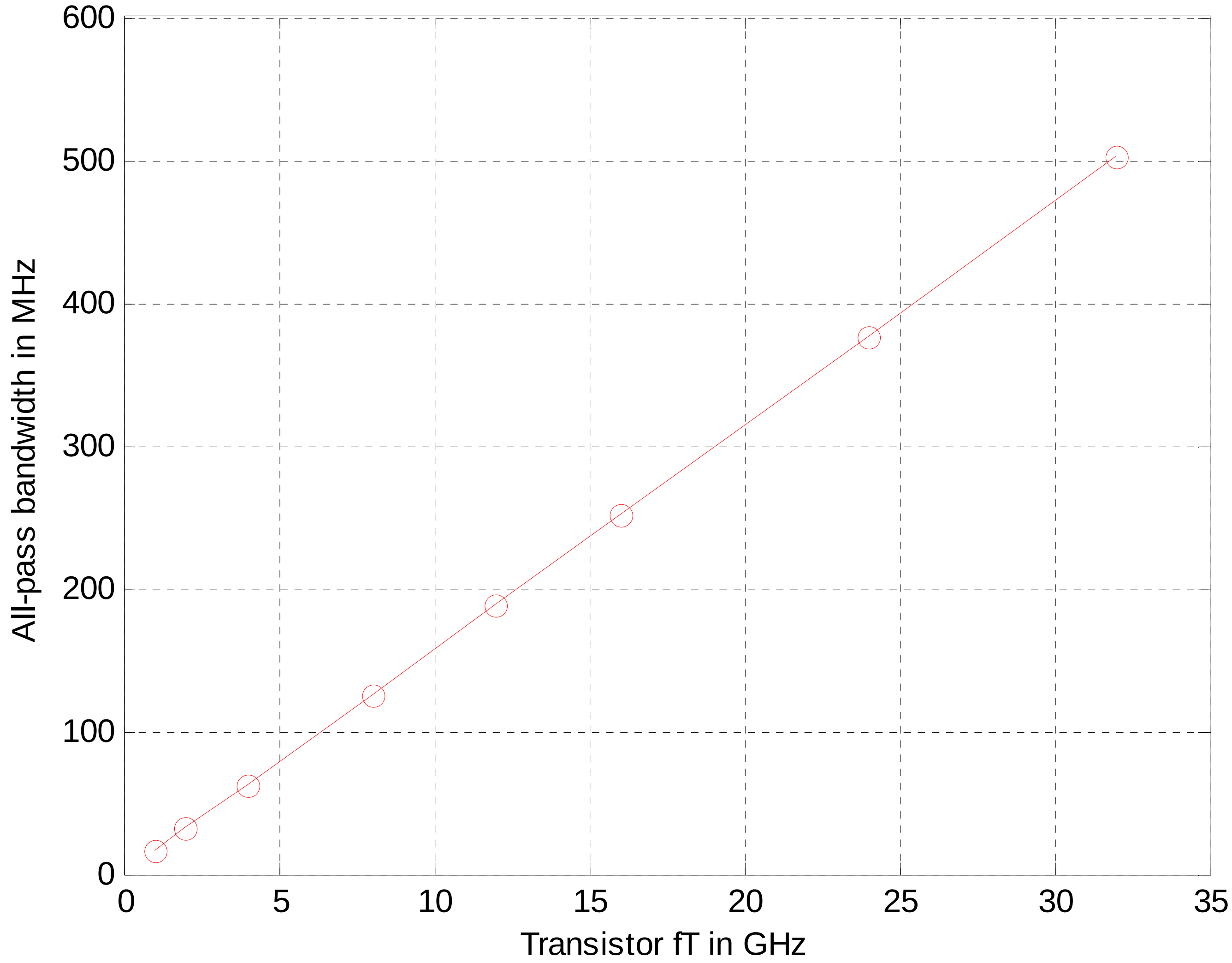




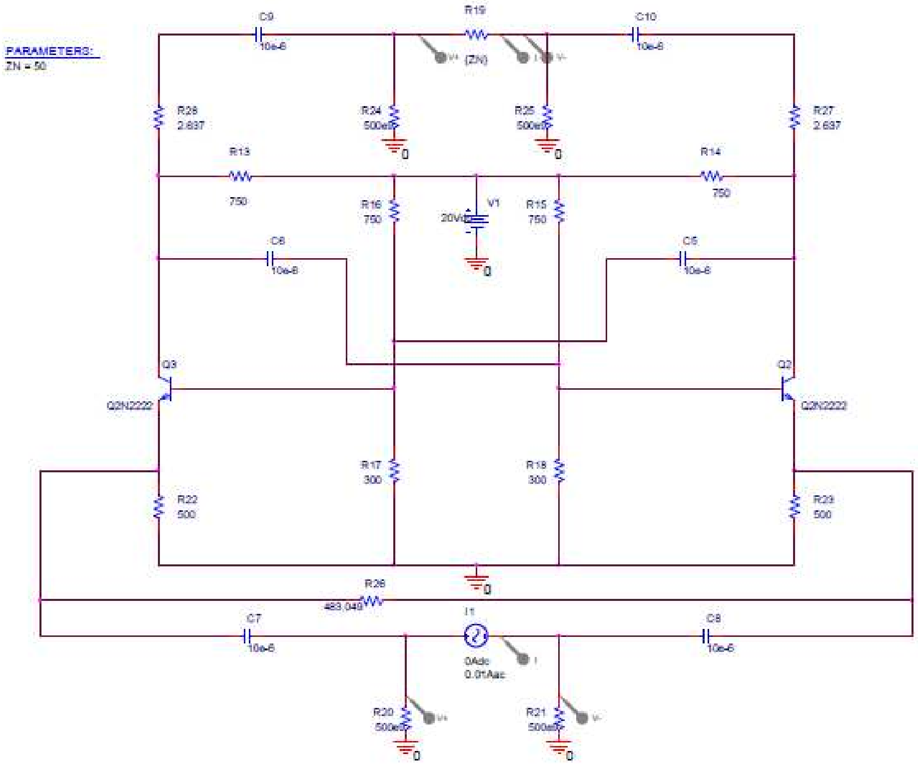
m1
freq=502.0MHz
dB(S(1,1))=-19.995

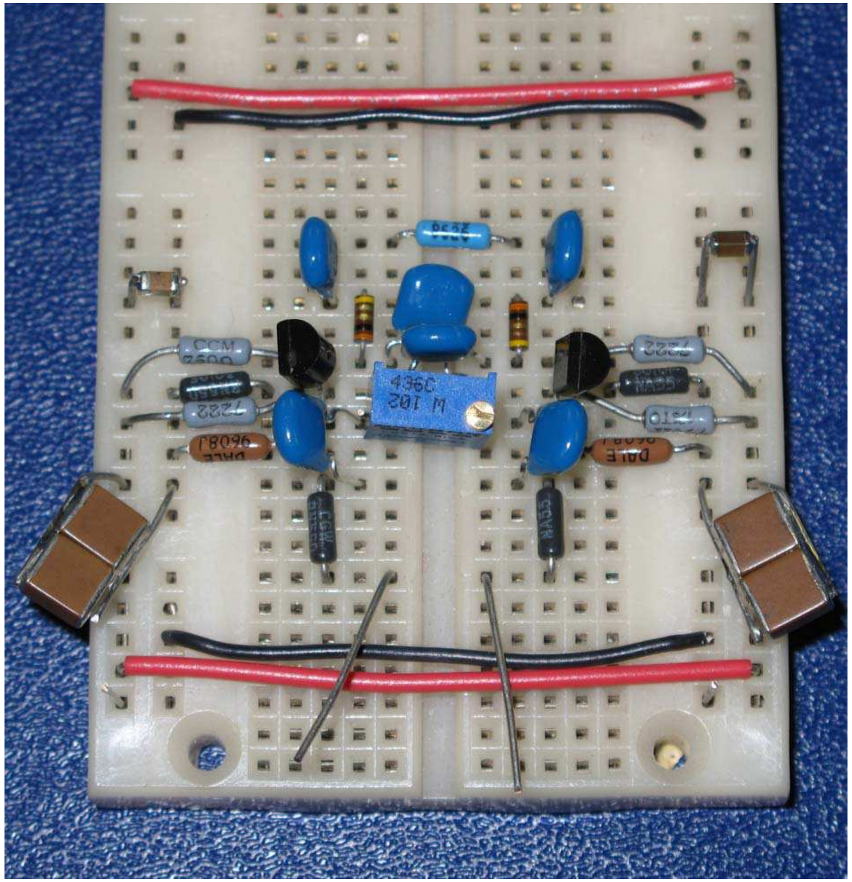


All-Pass -20 dB RL BW v. fT

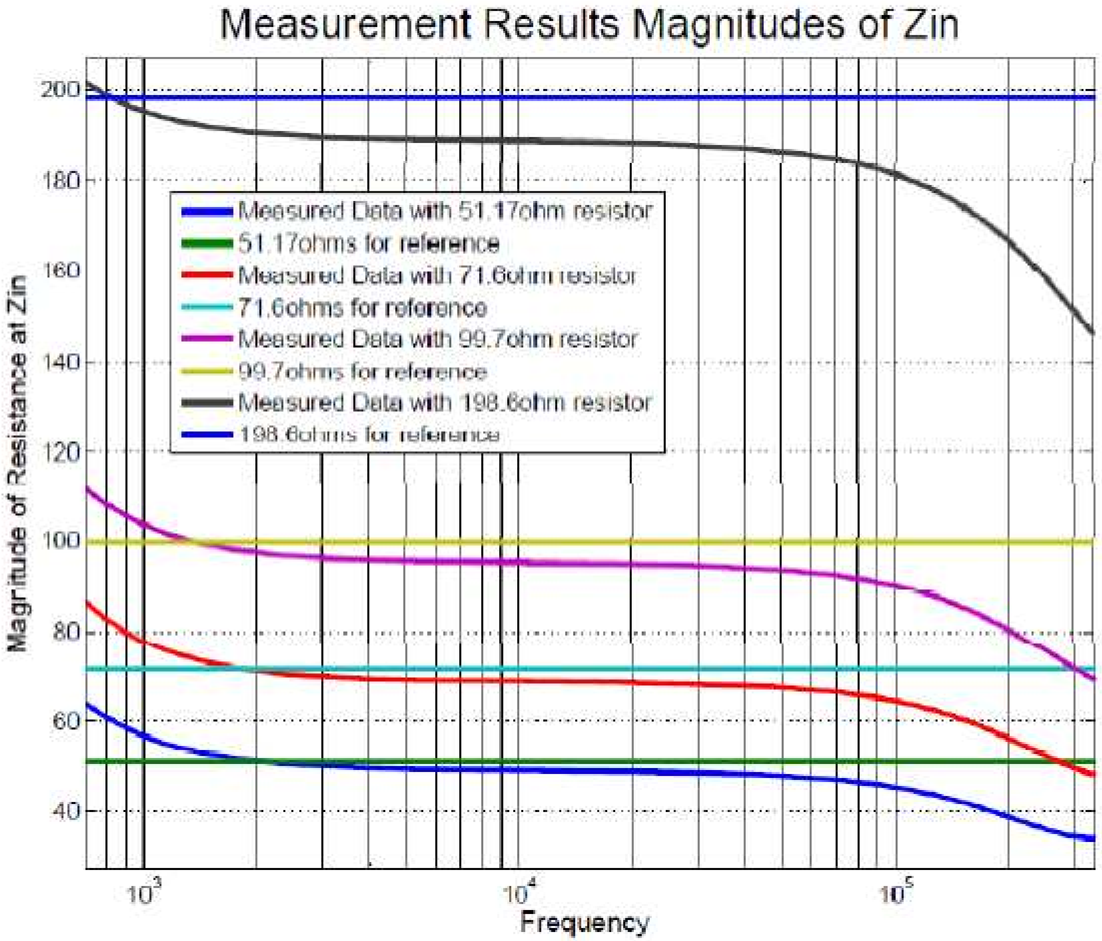


Fabricated Two Transistor Floating NIC Using 2N2222 Devices





Measured Results for Two Transistor FNIC

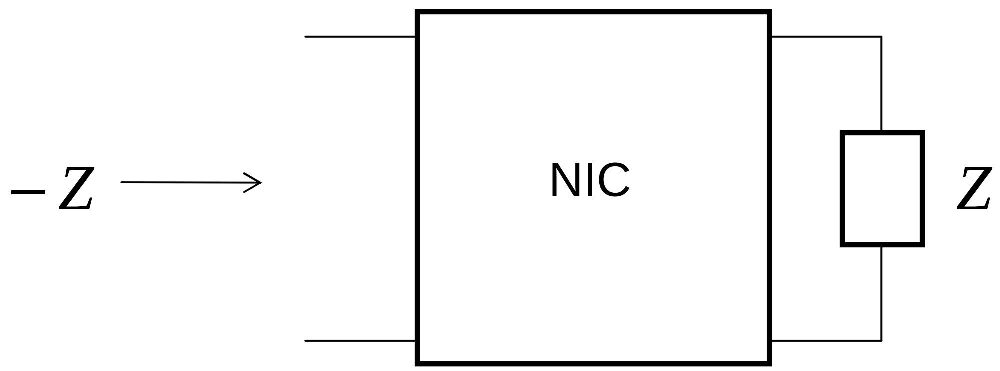


Summary of NIC Developments

- We’ve had some successes in fabricating NICs that work up to about 50 MHz.
- We have had many more failures.
- The main issue concerns stability – small and large signal stability.
- We are making progress, albeit very slowly …
- Someday, someone will make a reliable FNIC that works into the 100s of MHz range.

How Best to Use a NIC to Make a Non-Foster Reactance?

- Direct negation:



How Best to Use a NIC to Make a Non-Foster Reactance?

- Using a certain transformation:

Verman, Proc. IRE, Apr. 1931

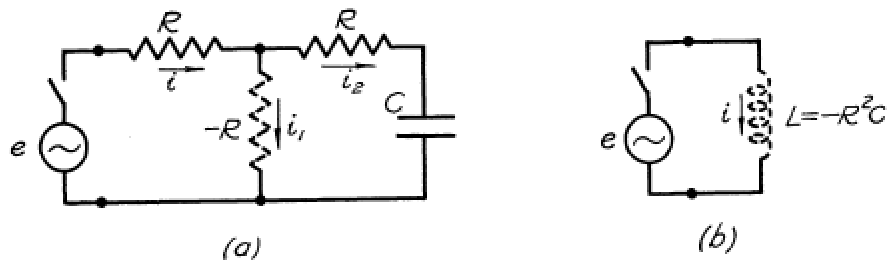


Fig. 1

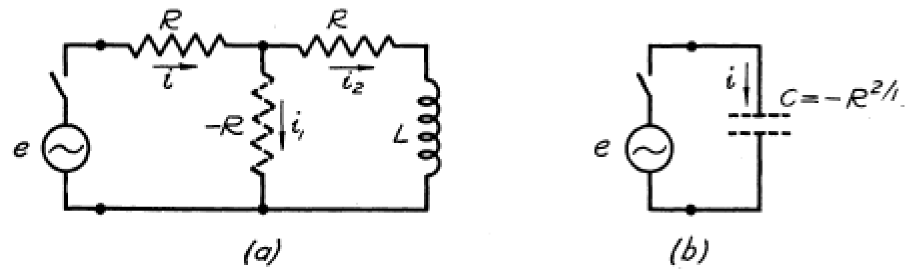
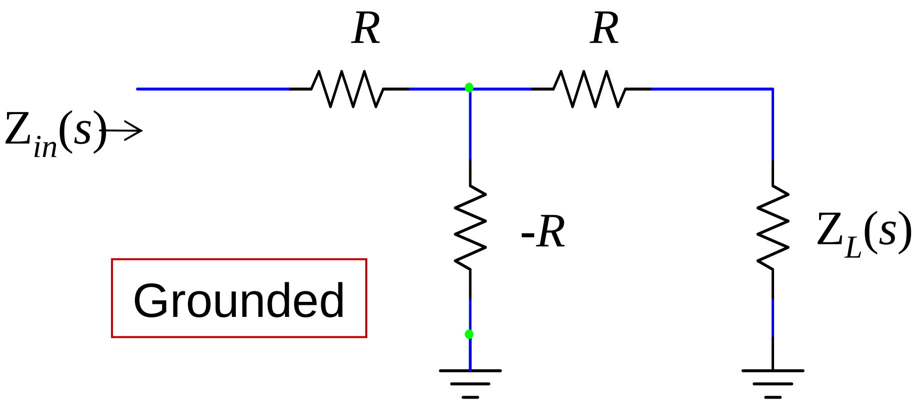
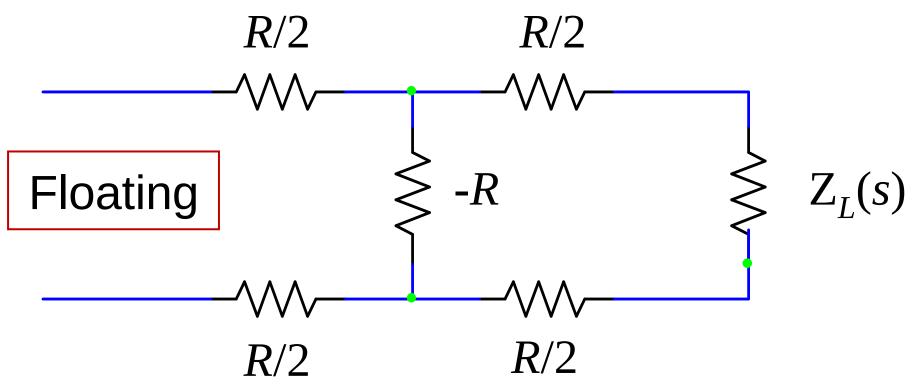


Fig. 2

Negative Impedance Transformation





- Can develop an NIC that needs to work for only one value of real impedance
- Also suggests the possibility of using negative resistance diodes (Tunnel, Gunn, etc.) for NIC realization

$$Z_{in}(s) = \frac{\left(R + Z_L(s)\right)\left(-R\right)}{Z_L(s)} + R = \frac{-R^2}{Z_L(s)}$$

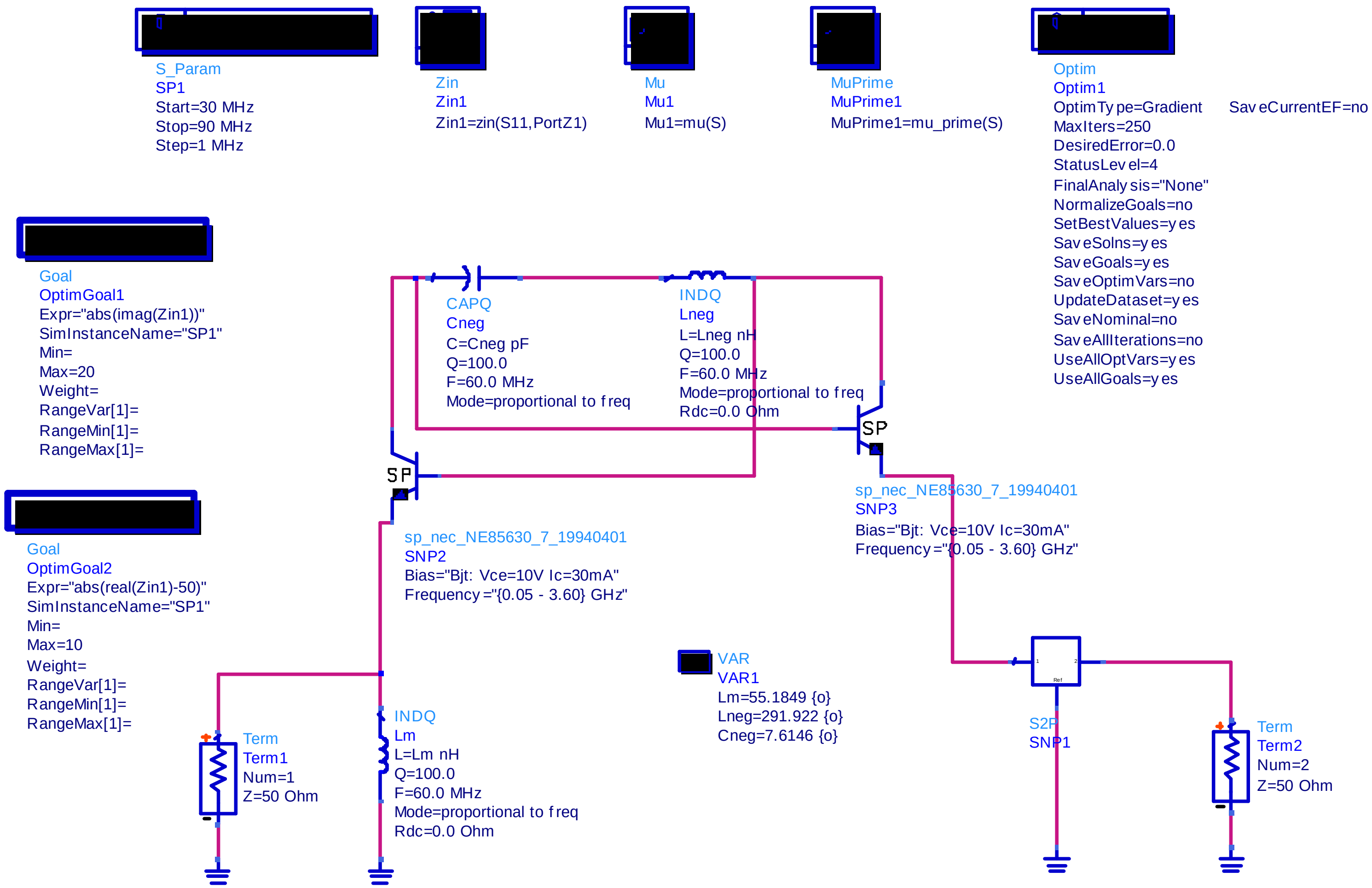
Negative Impedance Transformation

$Z_L(s)$	$Z_{in}(s)$
sL	$\dfrac{-1}{sC_{neg}}$
$\dfrac{1}{sC}$	$-sL_{neg}$
$sL+\dfrac{1}{sC}$	$\dfrac{1}{-sC_{neg}-\dfrac{1}{sL_{neg}}}$
$\dfrac{1}{sC+\dfrac{1}{sL}}$	$-sL_{neg}-\dfrac{1}{sC_{neg}}$

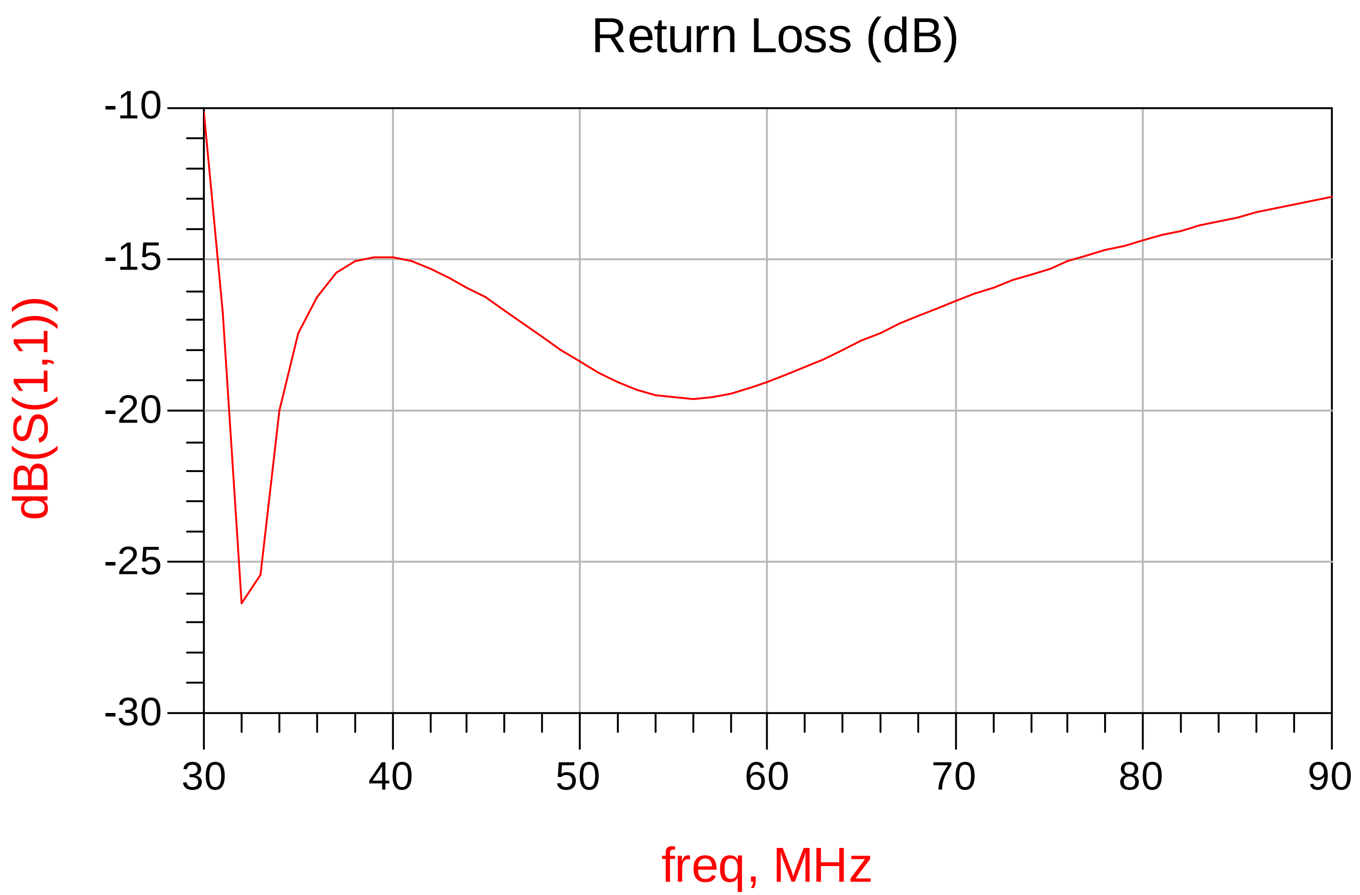
$$L_{neg} = R^2 C$$

$$C_{neg} = L / R^2$$

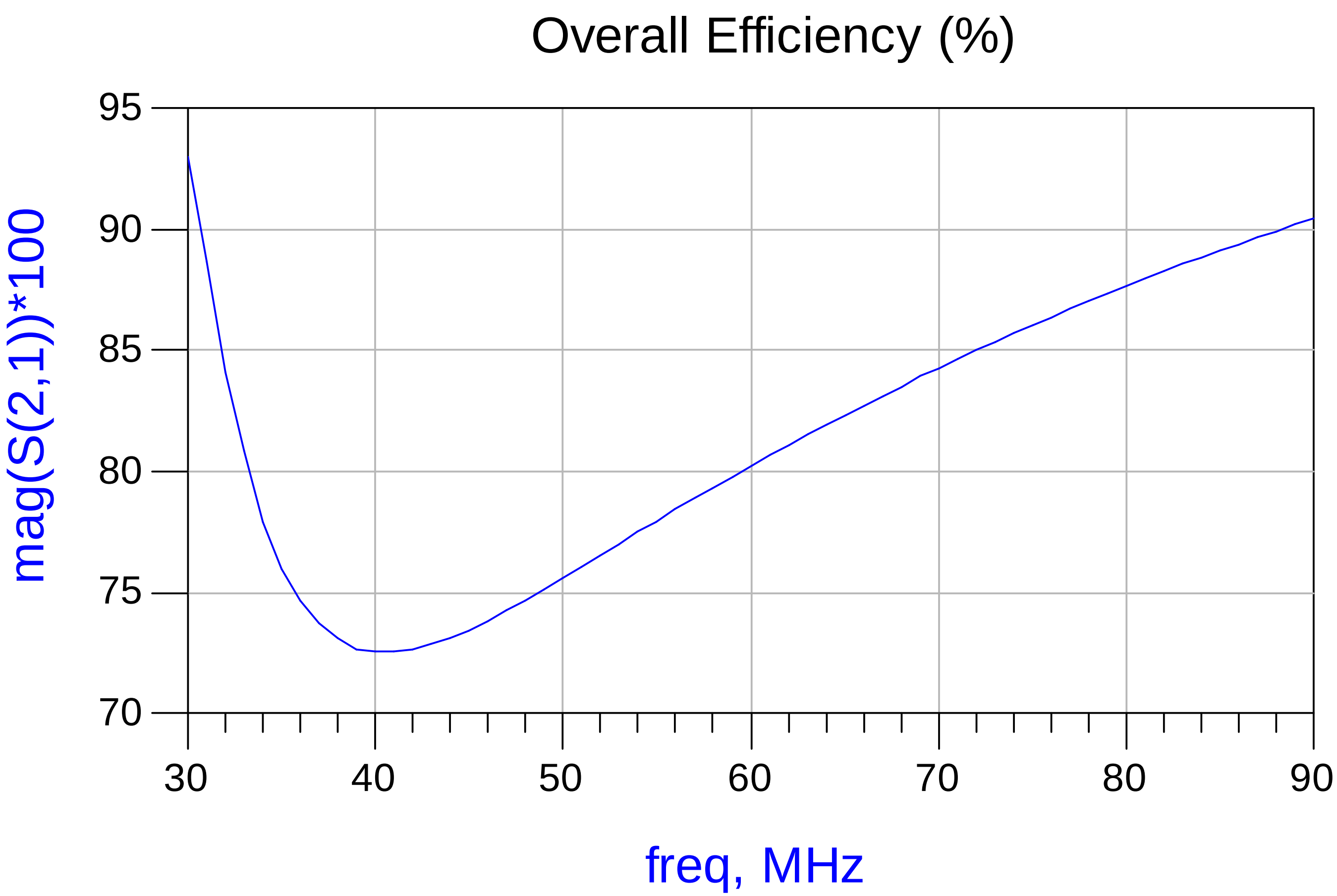
Schematic captured from Agilent ADS of VHF monopole with active matching network



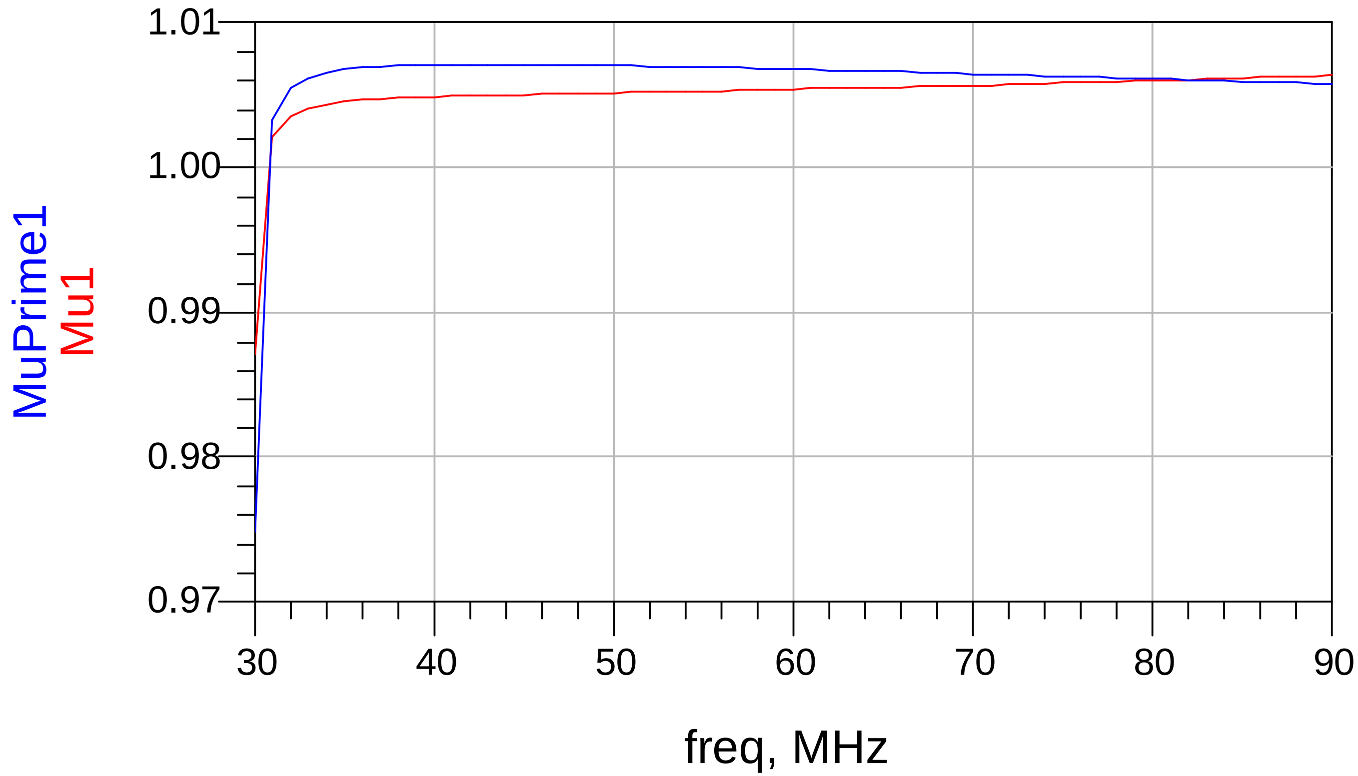
Simulated return loss at input of optimized active matching network and antenna



Overall efficiency (in percent) of optimized active matching network and antenna



Small-signal geometrically-derived stability factor for the optimized active matching network and antenna



Outline of Presentation

- What Does "Non-Foster" Mean?
- Possible Applications of Non-Foster Reactances
  - Electrically Small Antennas
  - High-Impedance Surfaces
  - Artificial High-Permeability Materials
- Realization of Non-Foster Reactances

Summary

- The use of non-Foster reactances could improve the performance of ESAs and HIGPs dramatically.
- Some hard-won successes have been achieved in the development of the requisite NICs.
- But an interdisciplinary team with expertise in circuits as well as field theory and sufficient funding is needed to realize reliable high frequency non-Foster reactances and to integrate them into electromagnetic devices.