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Materials and Components With a Negative Frequency Derivative of Reactance

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Outline

- Practical and performance limitations of metamaterials
- Limitations on small antenna performance
- Foster’s theoreom, and “non-Foster” circuits
- Applications of non-Foster circuits
  - Matching circuits for small antennas
  - Broadband parasitic arrays
  - Superluminal propagation
  - Broadband leaky wave antennas
  - Electrically thin cloaking surfaces
- History and theory of negative impedance converters
- Measured negative inductors and negative capacitors
- Summary and future directions

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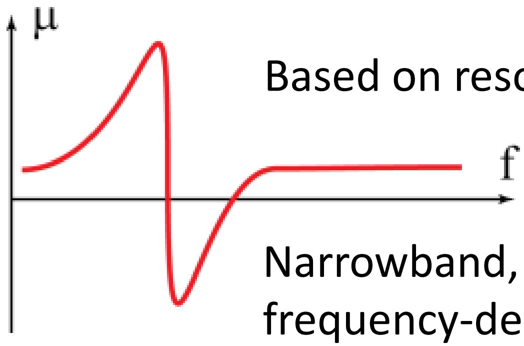
Practical and Performance Limitations on Metamaterials and Their Applications

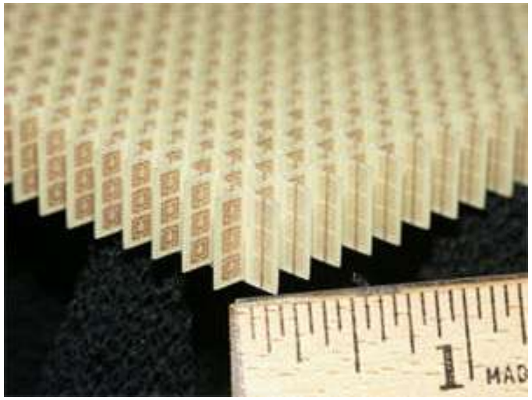
Typical Negative Effective Permeability



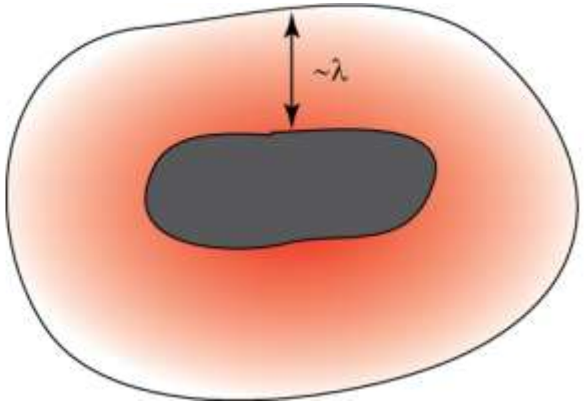
Based on resonance

Narrowband, highly frequency-dependent

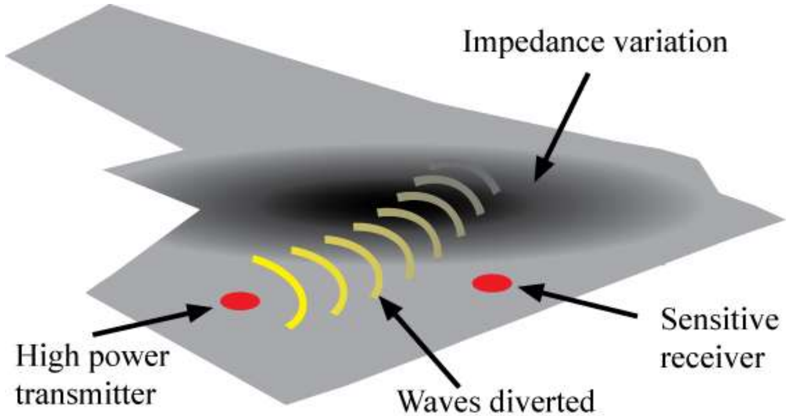
Complex 3D Structures Are Difficult to Build



Thick Volumetric Cloaking Structure



Alternative: Thin Coating for Surface Wave Cloaking



- **Negative index metamaterails are typically narrowband and lossy**
- **3D metamaterials are difficult to build, and are impractical for many applications**

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Active vs. Passive Circuits, Antennas, Metamaterials, and Other Structures

	Passive	Active
Electronics	• Includes just L, R, C	• Includes transistors, diodes, feedback, logic circuits, etc.
Metamaterials **Antennas** **etc.**	• Rely on LC resonance to create effective medium • Limited bandwidth • Prohibitively lossy • Can't surpass fundamental limits of passive structures (e.g. Wheeler/Chu limit)	• Can include all types of active circuits listed above for a wide range of potential effects • Can achieve broad bandwidth using active circuits to tailor group delay or tune the material response • Can include distributed amplification to overcome loss • Posses new kinds of behavior (e.g. superluminal propagation, nonlinear absorption) not possible with passive structures

- **Adding active electronics can enable many of the goals for metamaterials**
- **Can also enable new behavior that is impossible with passive structures**

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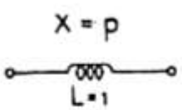
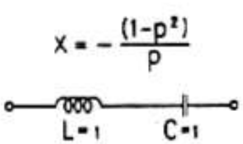
Foster's Reactance Theorem and Active "Non-Foster" Circuits

For any passive, lossless network: dX/df>0

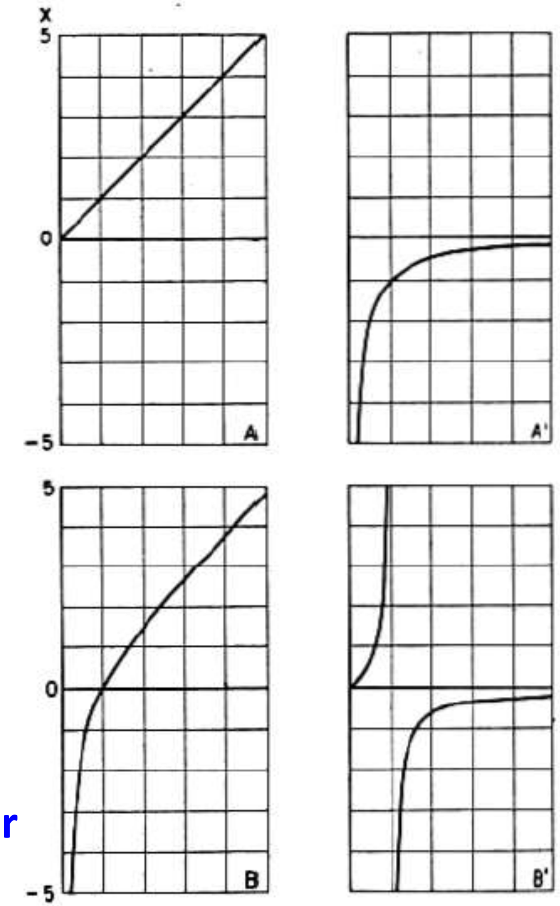
R.M. Foster, "A Reactance Theorem," *Bell Syst. Tech. J.*, vol. 3, no. 2, pp. 259-267, April 1924

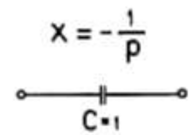


Inductor

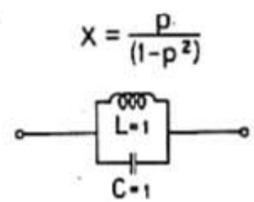


Match Point for Small Antenna

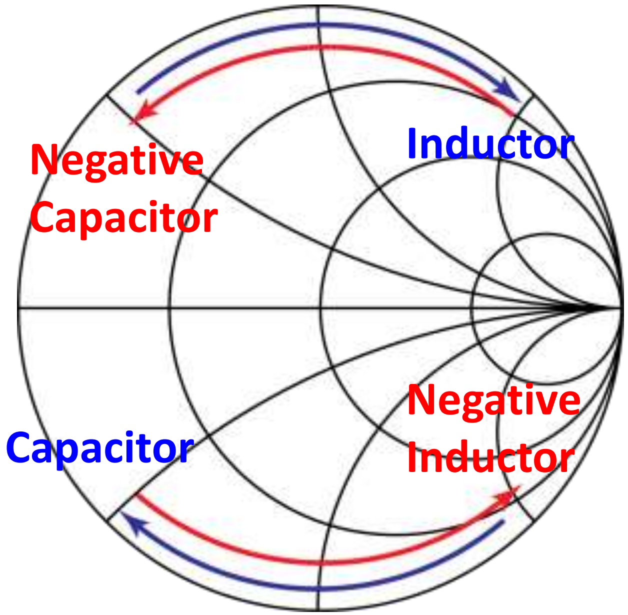




Capacitor



Split Ring Resonator Without Loss



Non-Foster elements traverse Smith chart counterclockwise

- **Broadband negative capacitors and inductors can only be built with active circuits**

Wheeler/Chu Limit on Antenna Q and Bandwidth vs. Electrical Size

Wheeler/Chu limit for Small Antennas

Single mode

$$Q = \frac{1}{ka} + \frac{1}{(ka)^3}$$

Dual mode (e.g. CP)

$$Q = \frac{1}{ka} + \frac{1}{2(ka)^3}$$

Bandwidth vs. Q relationship

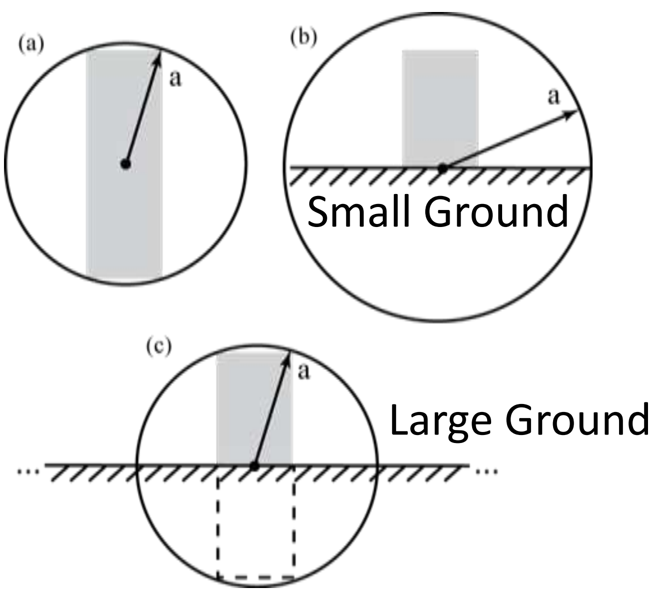
Matched (s=VSWR)

$$B \approx \frac{1}{Q}\left(\frac{s-1}{\sqrt{s}}\right)$$

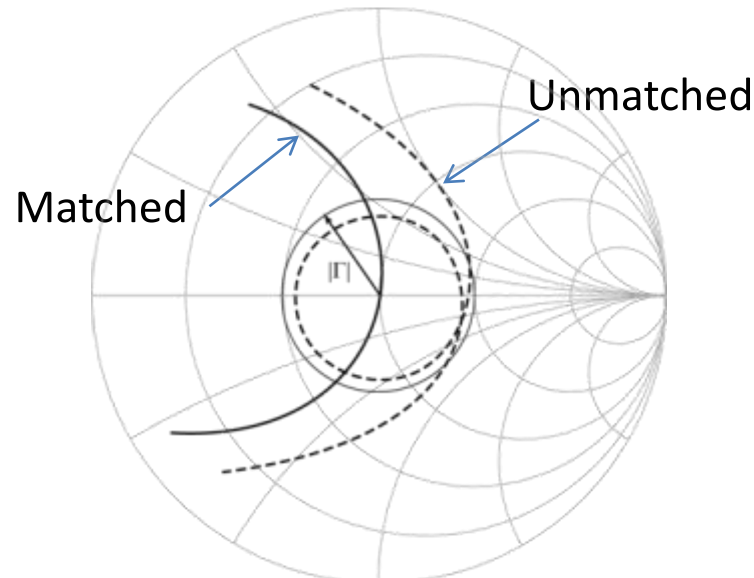
Bode/Fano Limit

$$B = \frac{1}{Q}\frac{\pi}{\ln(1/|\Gamma|)}$$

Antenna Volume Calculation



Matched vs. Unmatched Small Antennas



- **Small antenna cannot exceed bandwidth determined by its electrical size, ka**

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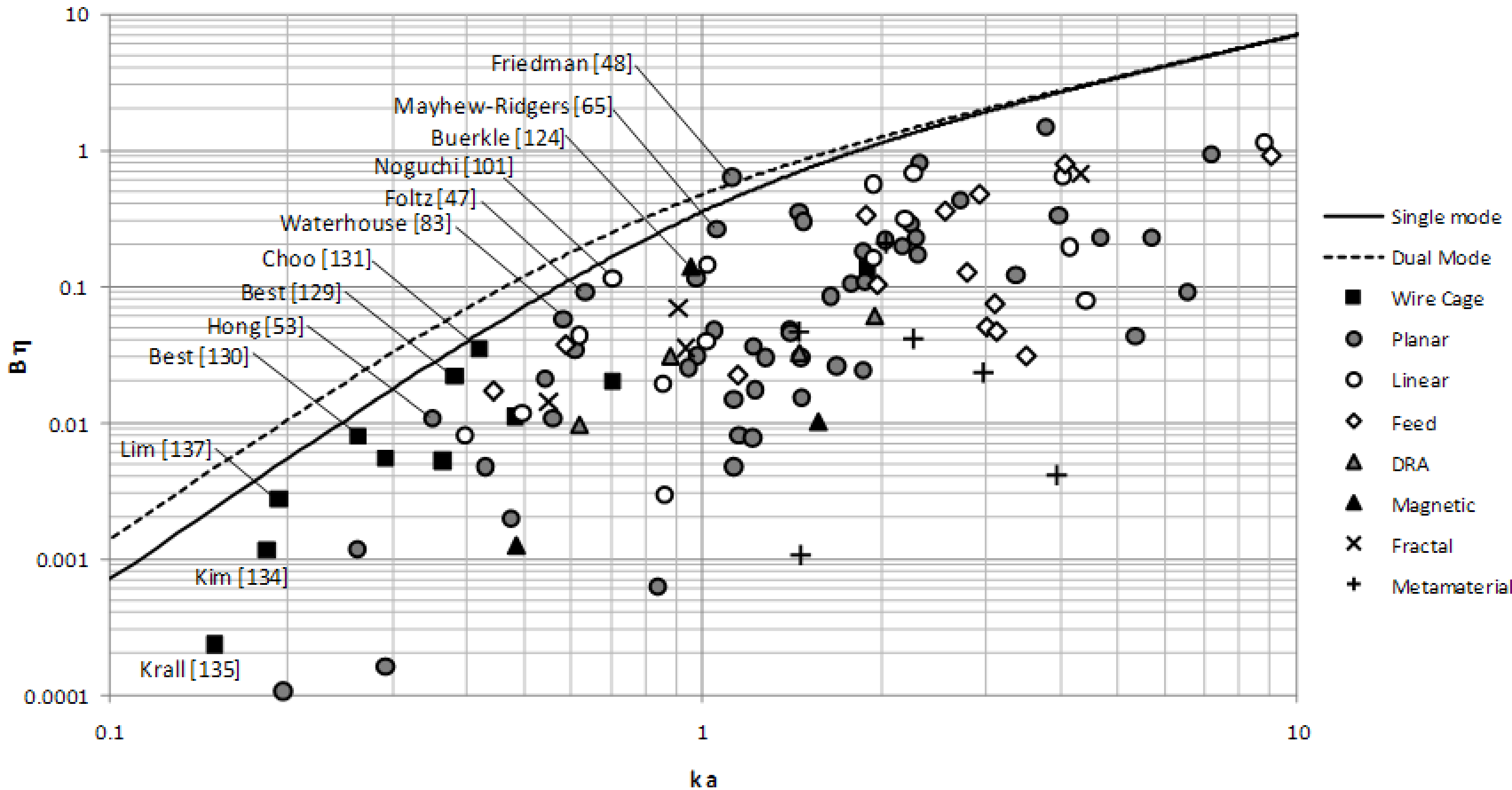
Measured Performance of All Measured Data on Small Antennas in IEEE T-AP



- Wheeler/Chu limit for small antennas is verified by decades of measured data
- Friedman's (similar to Goubau's) is unmatched antenna – see Bode/Fano limit.

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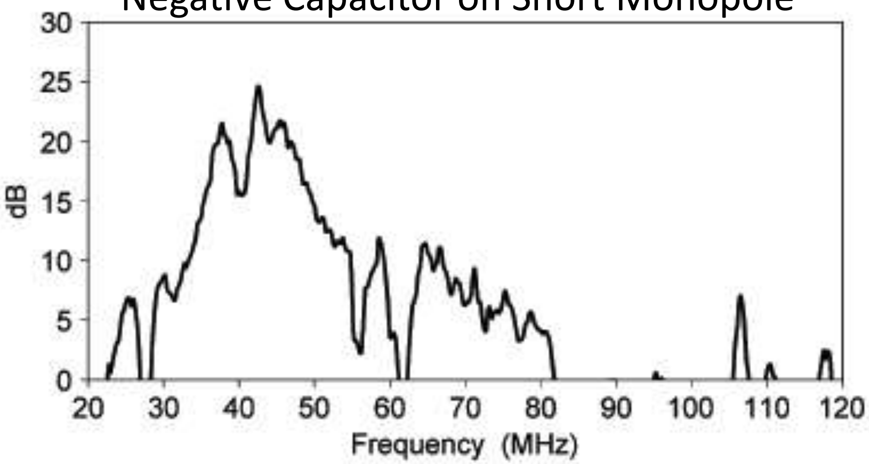
Measured Broadband Non-Foster Matching of Electrically Small Antennas

Two examples of matching a small monopole antenna with a negative capacitor: (Not enough just to show good match, must show improved performance!)

S. Sussman-Fort, R. Rudish, 2009

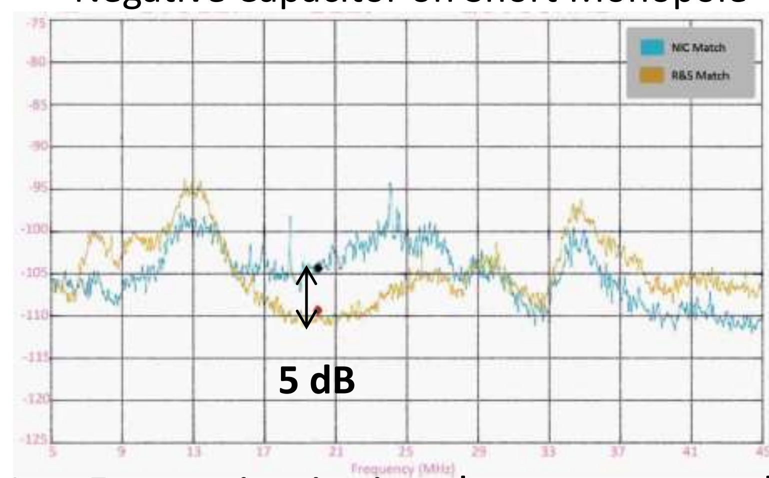
Signal/Noise Ratio Improvement
Negative Capacitor on Short Monopole



Non-Foster circuit gives higher signal/noise ratio for small monopole antenna over 20-80 MHz compared to unmatched or lossy match.

S. Stearns, 2011

Noise Floor Improvement
Negative Capacitor on Short Monopole

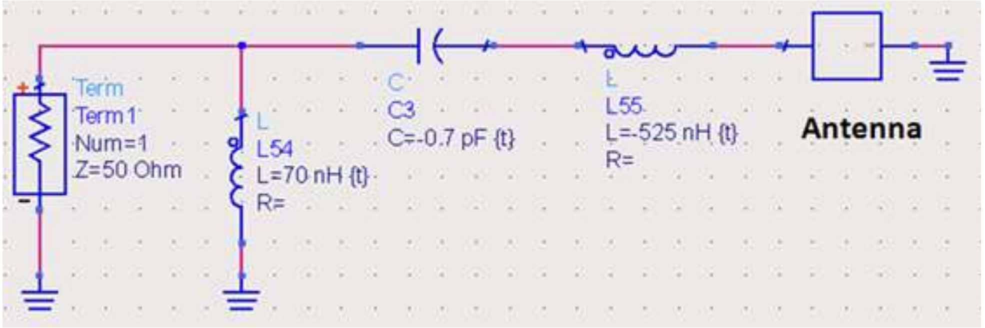


Non-Foster circuit gives lower measured noise floor for a small monopole antenna compared to a preamplifier, over 15-28 MHz

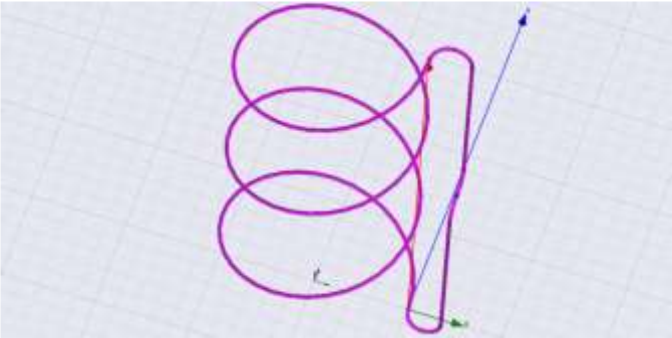
- **Non-Foster matching can allow small antennas that exceed Wheeler/Chu limit**
- **Measurements show broadband improvement in SNR or noise floor**

Broadband Non-Foster Matching of an Electrically Small Loop Antenna

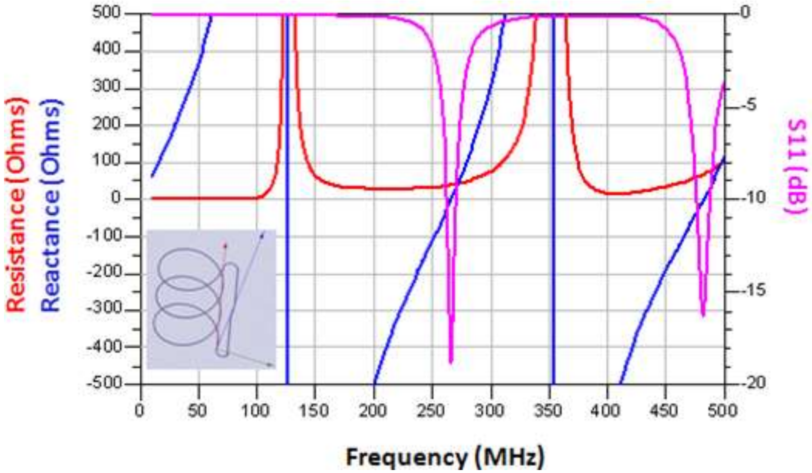
Non-Foster Matching Network for Small Loop Antenna



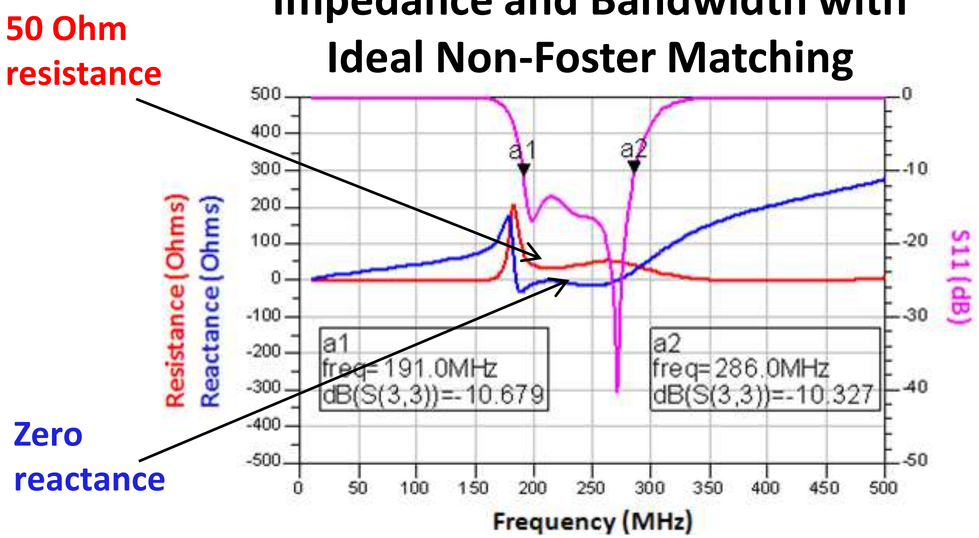
3 turn, 5 cm radius, 7 cm pitch



Impedance and Bandwidth of Electrically Small Loop Antenna



Impedance and Bandwidth with Ideal Non-Foster Matching



- **The bandwidth is increased to 2.9 times the passive Wheeler/Chu limit**

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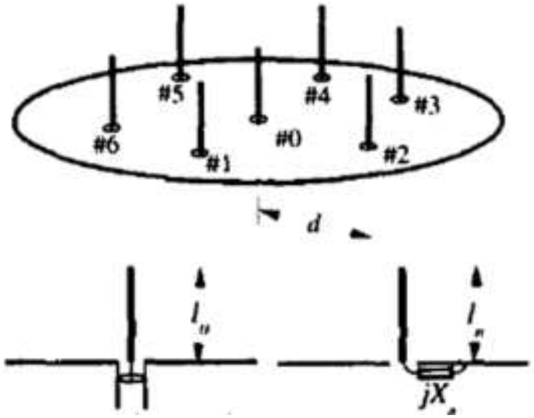
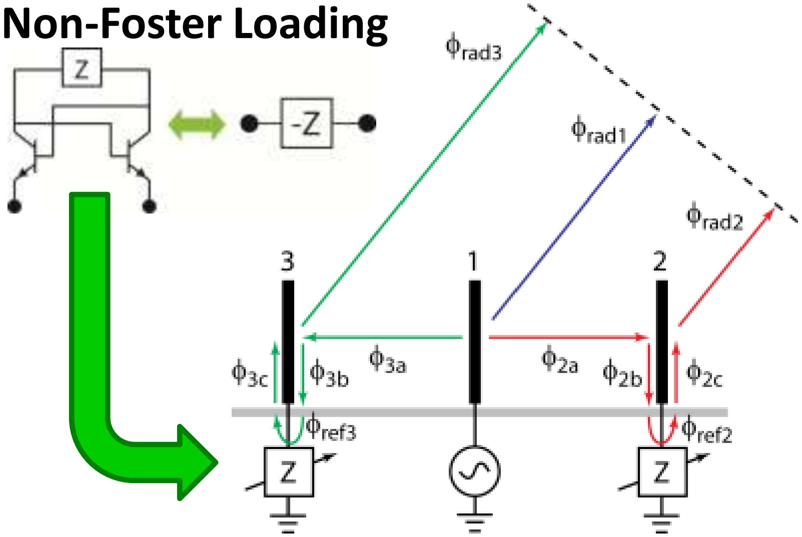
Non-Foster Loading for Broadband Parasitic Antenna Arrays

Yagi-Uda Antenna

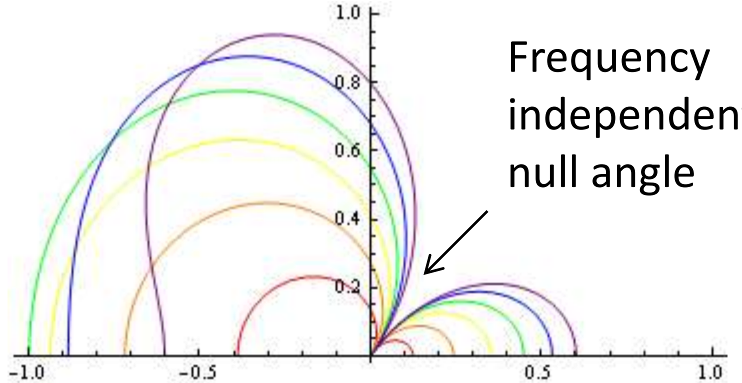
EAPAR (Electronically Steerable Passive Array Radiator) Antenna



Non-Foster Loading



Parasitic element with Negative Inductor



Frequency independent null angle

- **Non-Foster circuits can cancel phase shift due to delay between elements**

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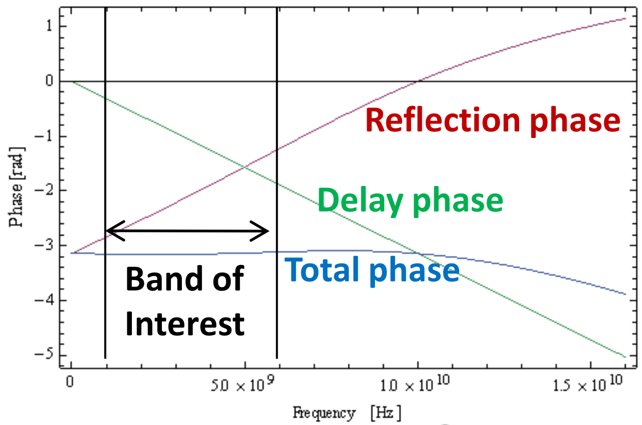
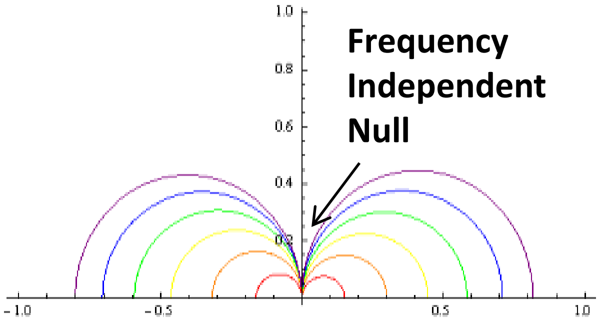
Two-Element Array with Tunable -L-C Circuit Loading the Parasitic Element

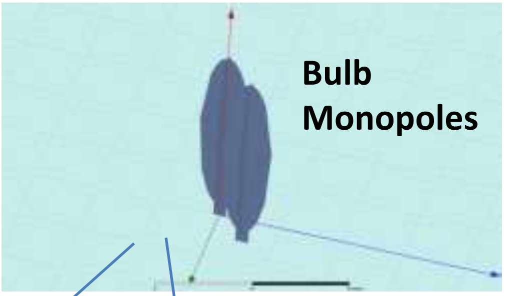
Want Total Phase Linear with Freq.



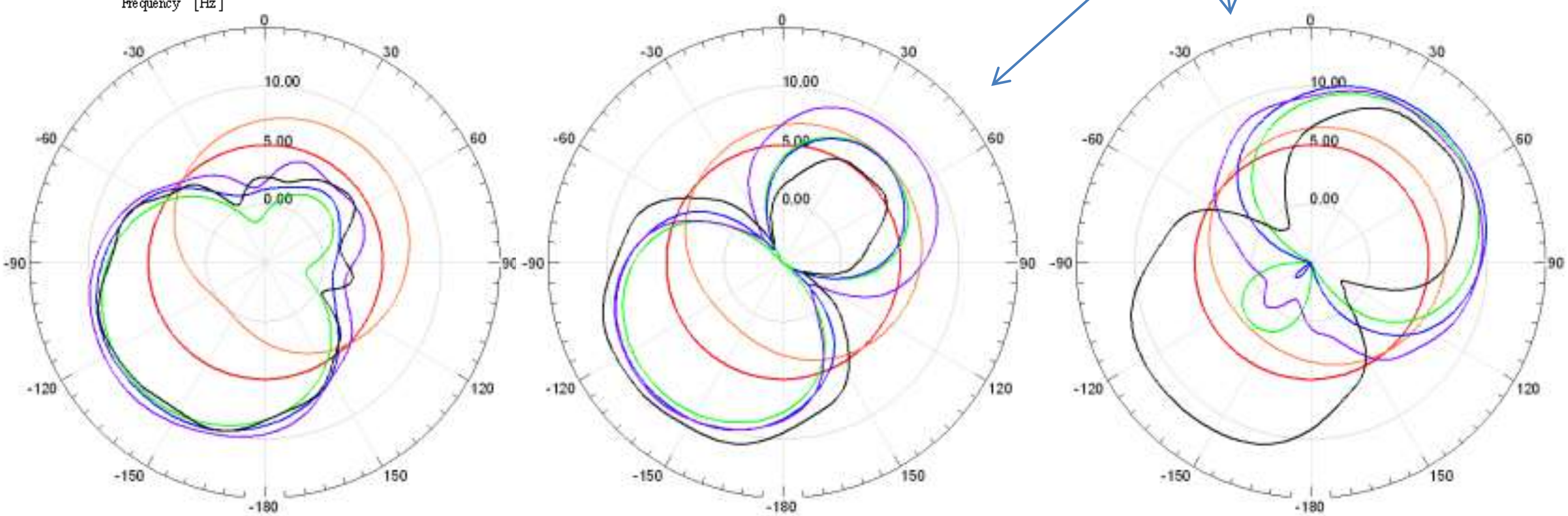
Calculated Pattern for Ideal Antenna Elements



EM Simulation for Real Antenna Elements



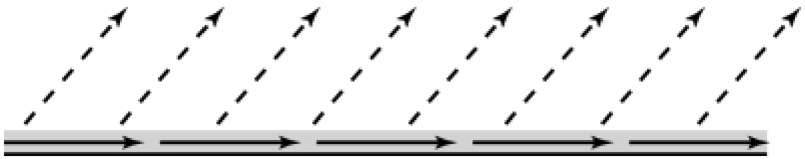
1 GHz
2 GHz
3 GHz
4 GHz
5 GHz
6 GHz



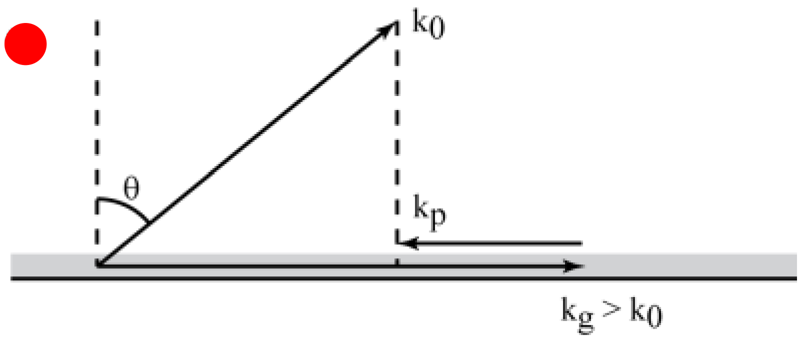
- **Broadband steerable pattern, bandwidth limited by antenna element**

Leaky Wave Antennas, Phase Matching, and Superluminal Leaky Waves

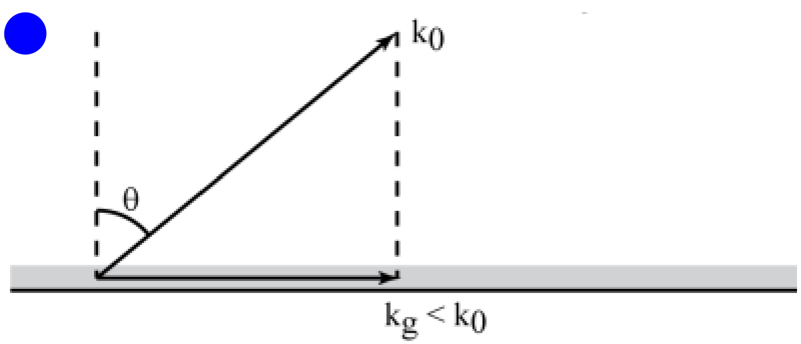
Leaky Wave Antenna



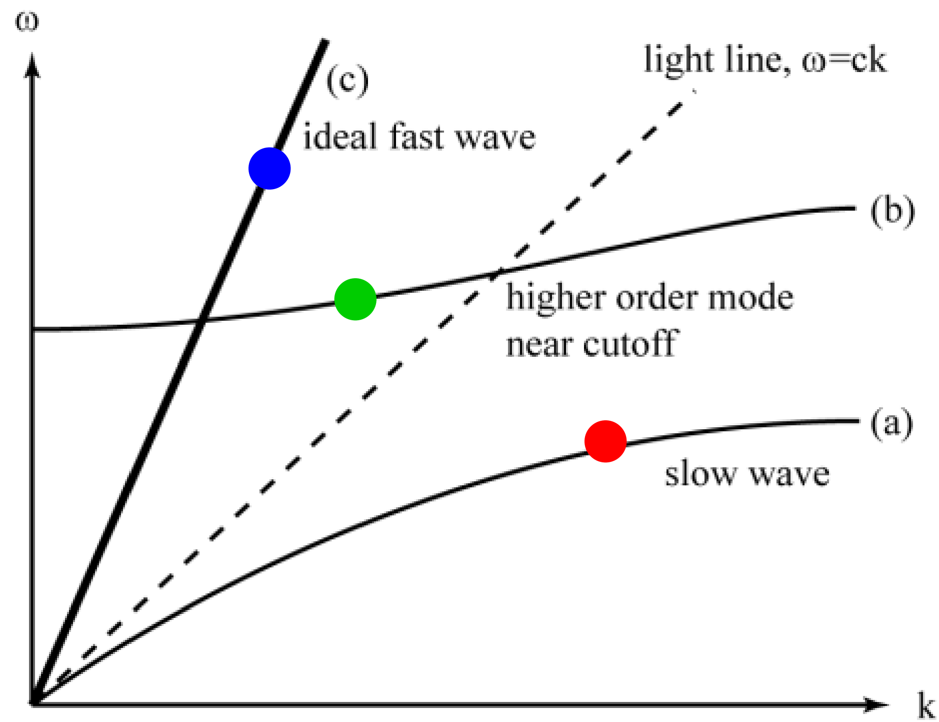
Phase Matching for Slow Waves



Phase Matching for Fast Waves



Various Possible Dispersion Curves



- Mode near cutoff can support fast wave, but is highly dispersive

- **Fast wave enables squint-free (frequency independent) leaky wave antennas**

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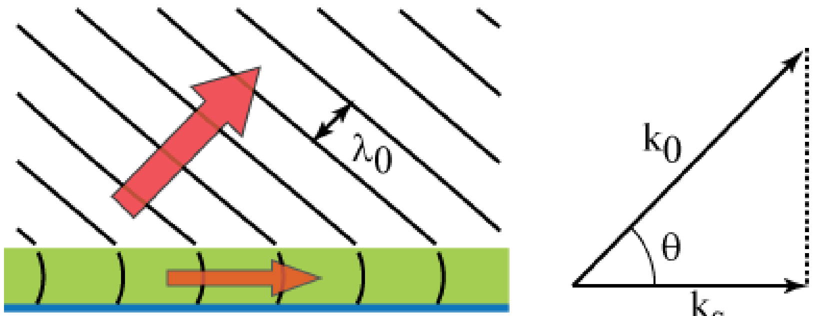
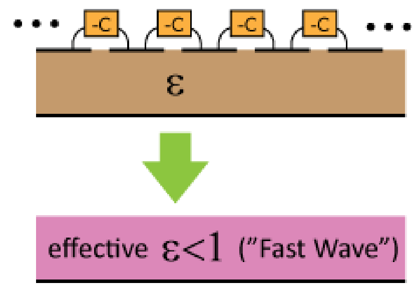
Non-Foster Loaded Waveguides for Superluminal Propagation

Phase Matching in Leaky Wave Antennas

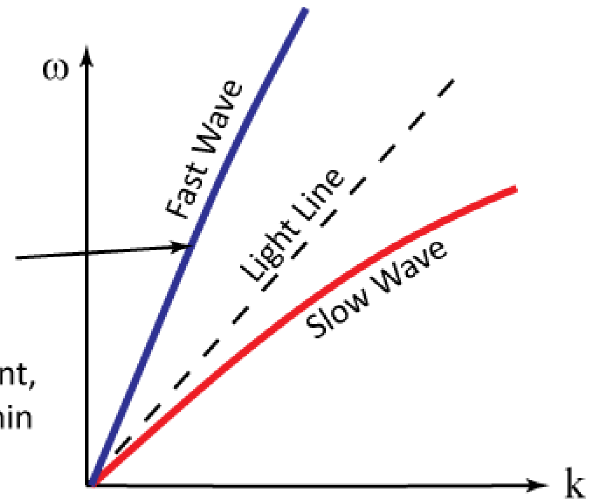


Dielectric layer with 0<ε<1

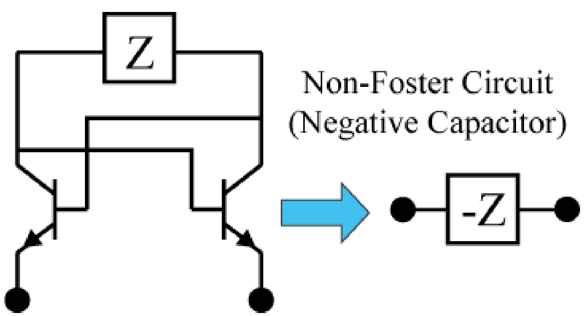
Fast Wave (Superluminal) Propagation



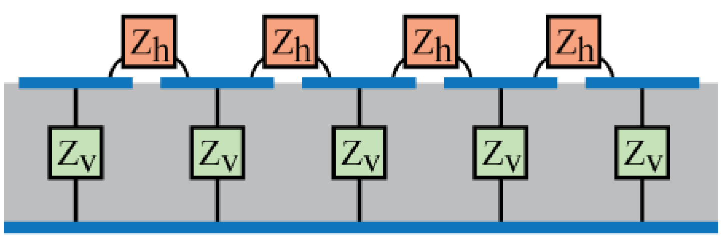
Broadband leaky wave antenna with no beam squint, or broadband electrically thin cloaking structure



Implementation with Non-Foster Circuits

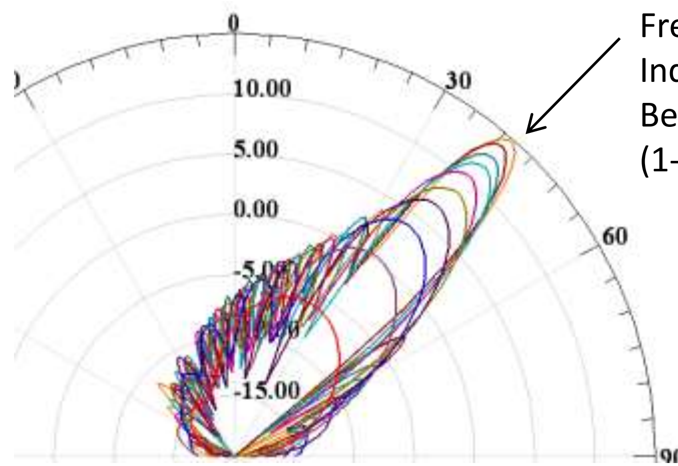


Non-Foster Circuit (Negative Capacitor)



Fast-Wave Guiding Structure

Simluation of Leaky Waves on ε=0.3 Slab



Frequency Independent Beam Angle (1-10 GHz)

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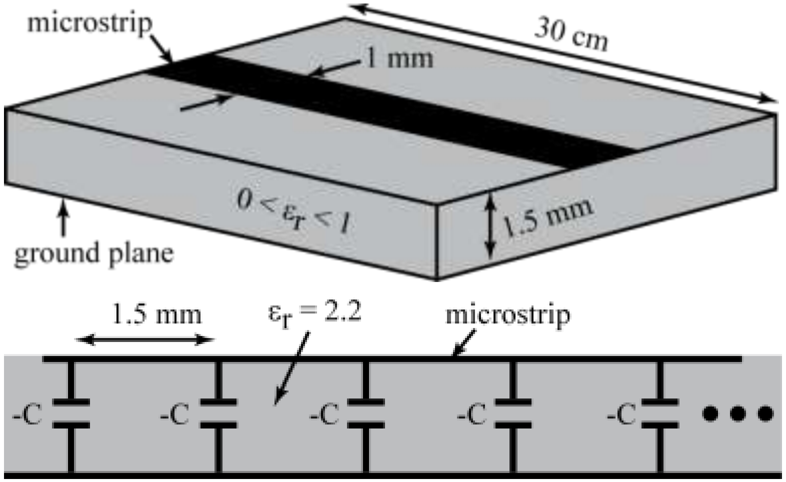
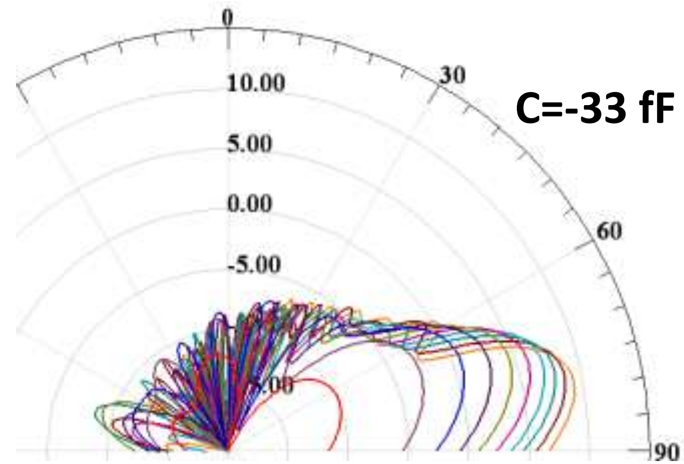
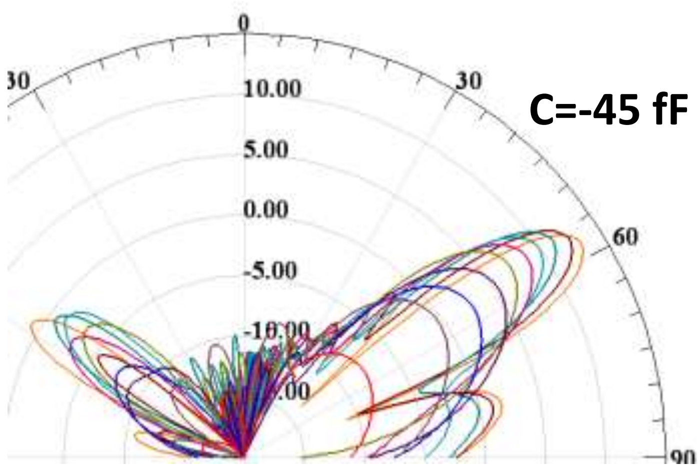
Broadband Steerable Antenna Has Constant Pattern over 1-10 GHz

Physical Structure, Period = 1.5 mm

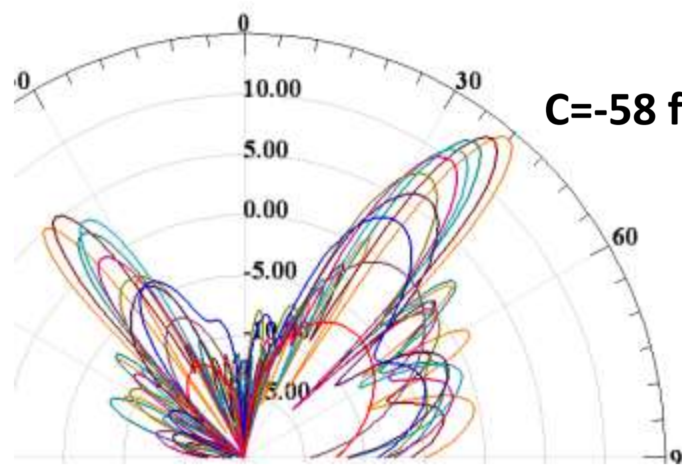




C=-33 fF



C=-45 fF



C=-58 fF

- **Steerable leaky wave radiation has constand angle over 10:1 bandwidth**

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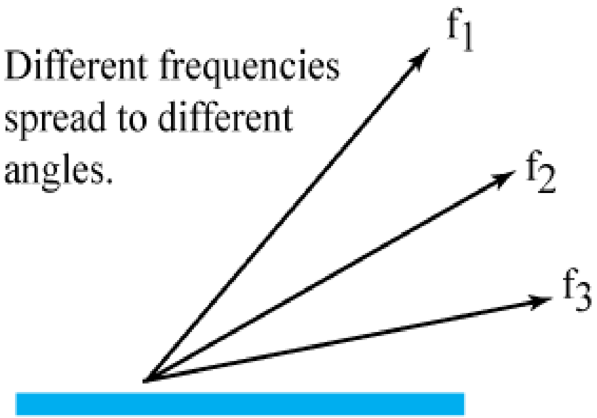
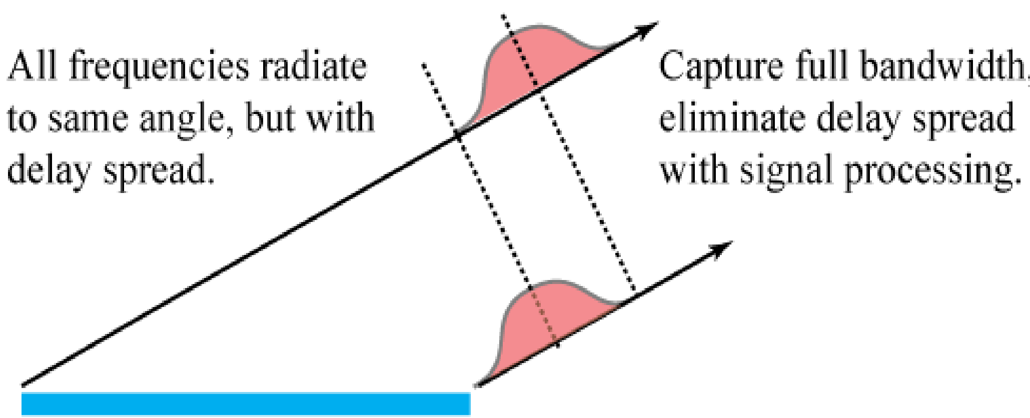
Effects of Causality in Superluminal Waveguides and Antennas

- Causality results in signal delay spread of across the surface
- Pulses (or symbols) shorter than a minimum time width will be distorted, resulting in bandwidth limitation
- All frequency components still radiate to the same angle
- May be possible to compensate for delay spread with OFDM



Conventional Phased Array Antenna



Non-Foster Loaded Leaky Wave Antenna

- **Superluminal waveguide does not violate causality**
- **Causality-induced bandwidth limitation depends on antenna geometry**

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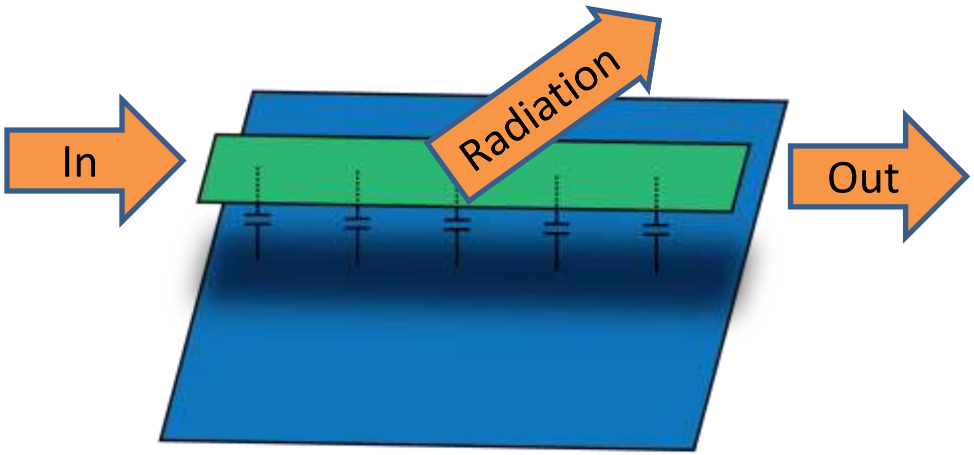
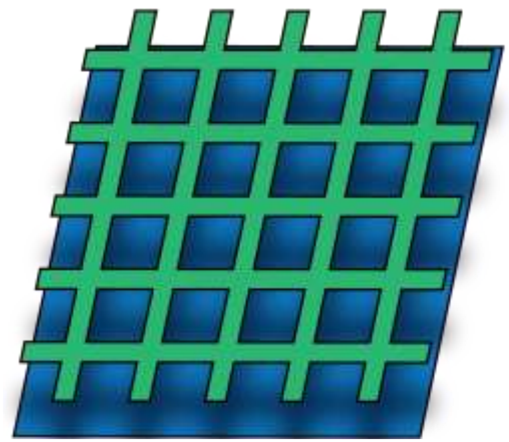
Next Steps and Future Directions for Superluminal Waveguides and Surfaces

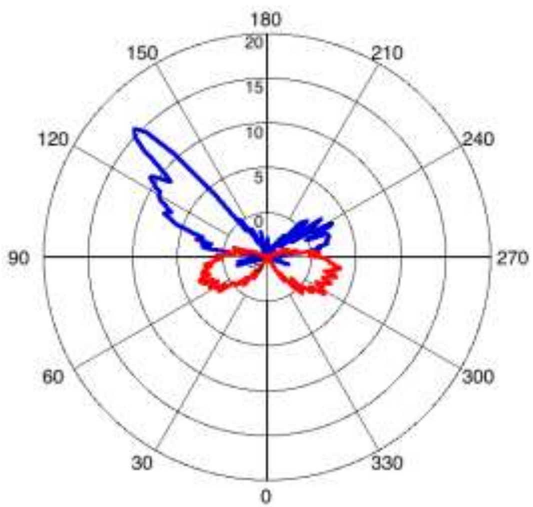
Measure Phase Velocity & Beam Angle



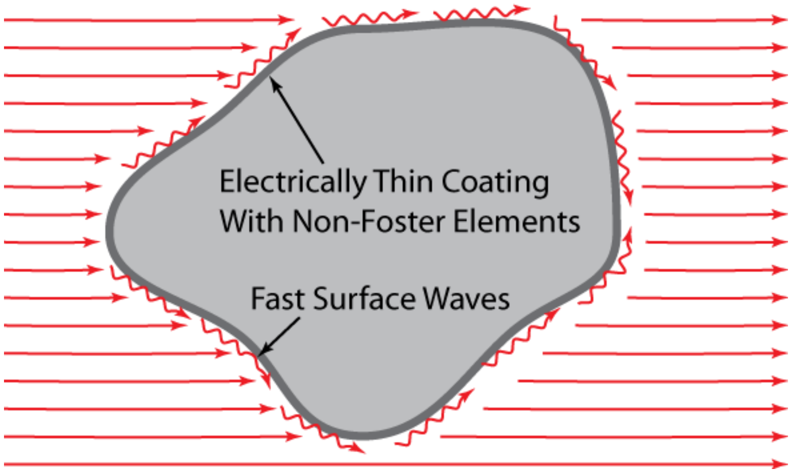
Extend to 2D Surface



Prior Work – Wave Wraps Around Cylinder



Non-Foster Based Thin, Broadband Cloak



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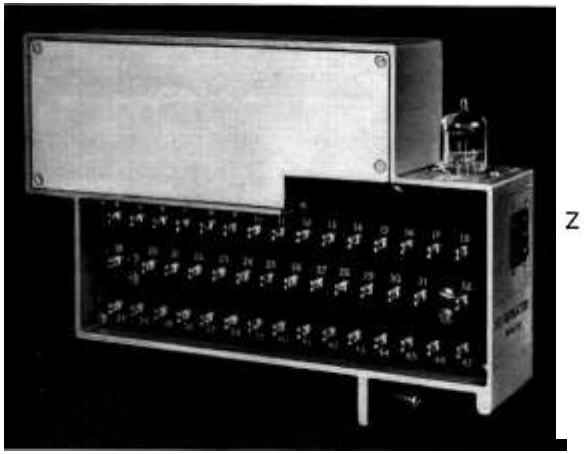
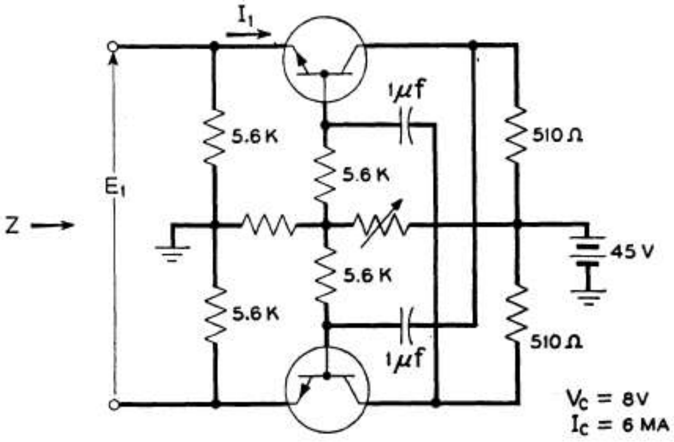
History, and Understanding How Negative Impedance Converter Circuits Work

Bell Telephone E2 Repeater



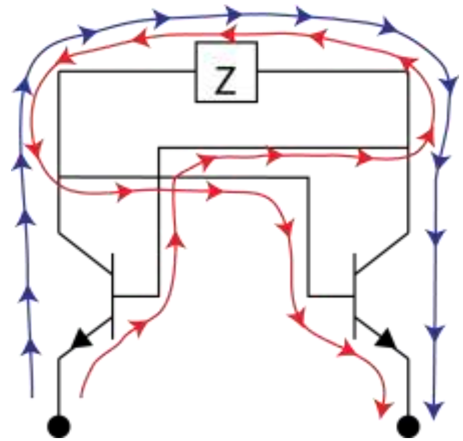
- Negative impedance converter produces negative resistance
- Bidirectional amplifier in telephone lines
- Implemented in vacuum tubes, 1950's

Linvill Transistor-Based NIC



- Transistor version of similar circuit to E2 (1953)
- OCS at emitter terminals
- SCS at collectors/bases
- At least 10 NIC/NII circuits published so far, but all are same basic concept

Simple Circuit Example



- Voltage follows red path (V_{BE})
- Current follows blue path (I_{CE})
- π phase shift in V/I
- Impedance seen across emitter terminals is -Z

- **Negative impedance converters have been designed and used for decades**
- **Issues are stability & high frequency operation (UHF in discretes, GHz in ASICs)**

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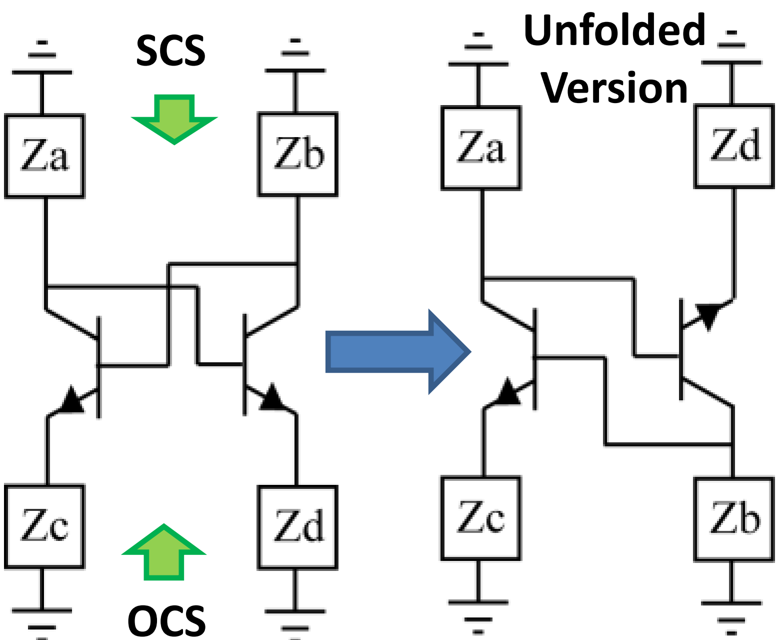
Universal NIC/NII Board for building any OCS/SCS, Fixed/Tunable, -L/-C Circuit

- Initial deisgns did not match measurements at all
  - Had to include all parasitics, circuit board, component resonances
- Each new design required new board to be simulated
  - Came up with universal design that can work for all non-Foster circuits



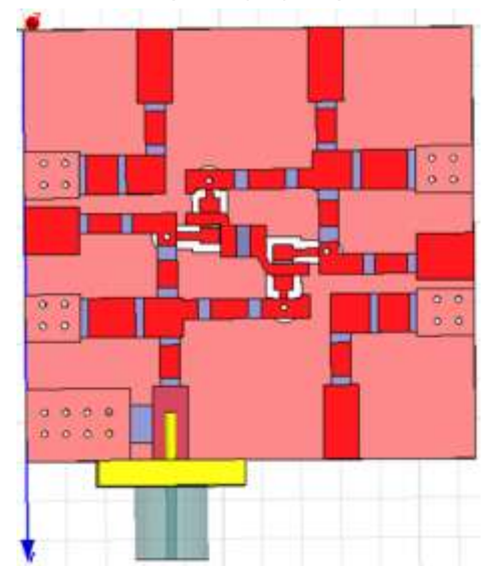
$$Z(port\_a) = -\frac{Zc \cdot Zd}{Zb}$$

$$Z(port\_b) = -\frac{Zc \cdot Zd}{Za}$$

$$Z(port\_c) = -\frac{Za \cdot Zb}{Zd}$$

$$Z(port\_d) = -\frac{Za \cdot Zb}{Zc}$$

Circuit Board Layout for EM Simulation



- **Requires full EM simulation of board, and all component parasitics**

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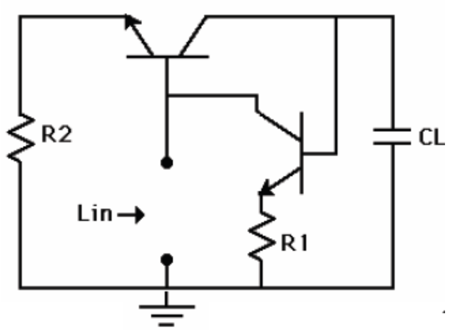
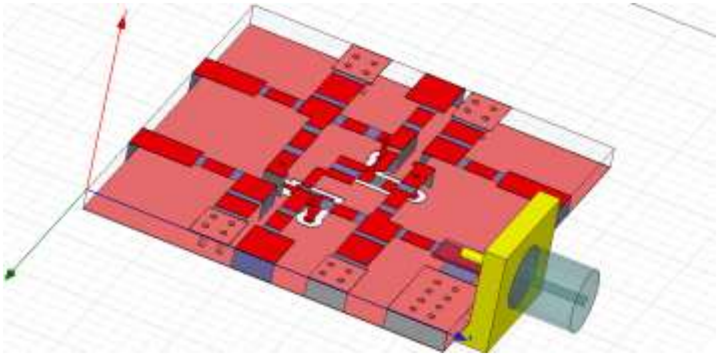
Successful Measurement of Negative Inductor Circuit in UHF Range

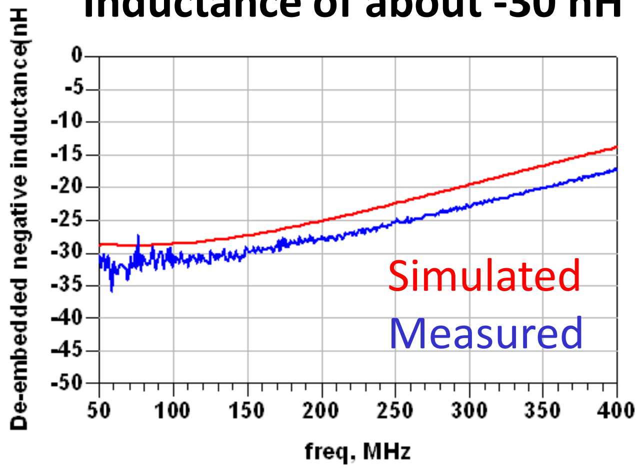
-L Circuit Schematic



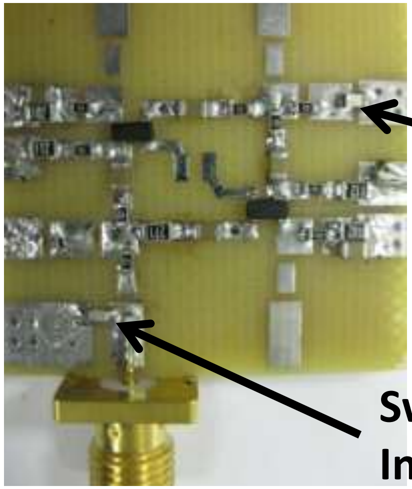
Simulated Board Layout



Inductance of about -30 nH



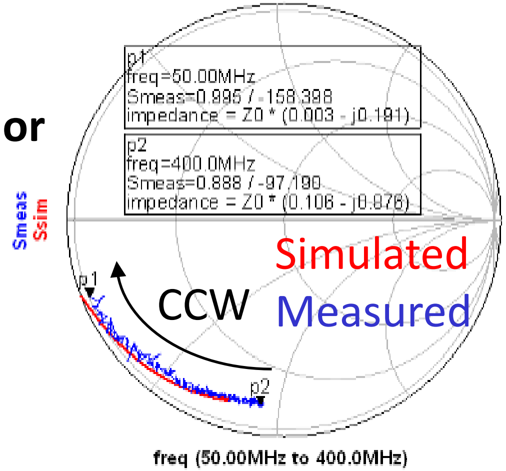
Fabricated –L circuit



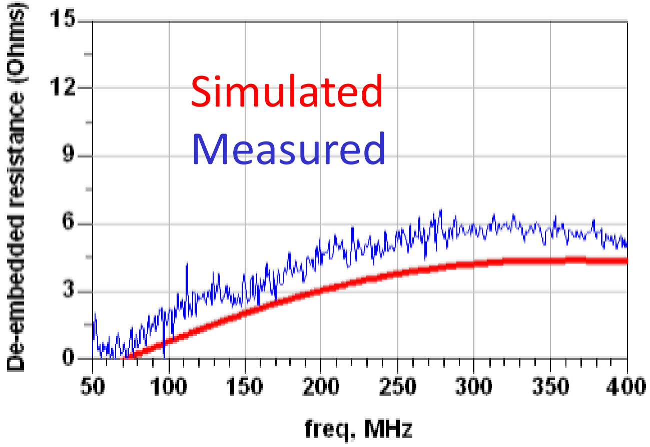
Inverted capacitor or varactor

Swamping Inductor

-L on Smith Chart



Resistance of about 4 Ohms

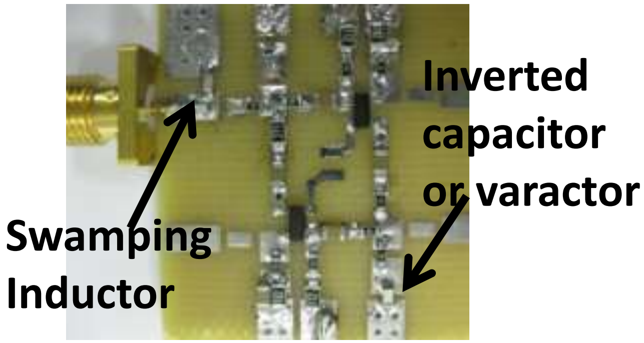


- **Non-Foster circuits can be implemented in UHF range with discrete components**

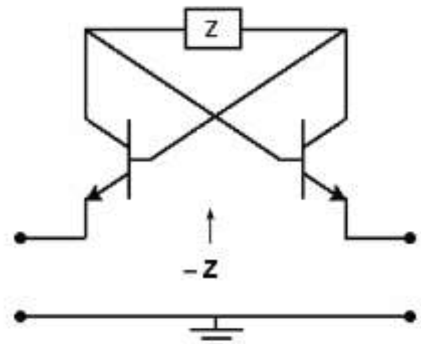
Dan Sievenpiper - UCSD, 858-822-6678,dsievenpiper@eng.ucsd.edu

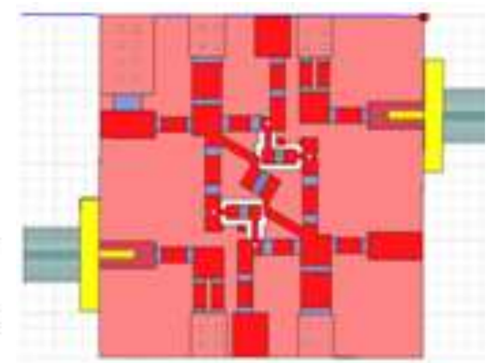
Tunable Negative Inductor, and Floating Negative Inductor

Measured Tunable Negative Inductor

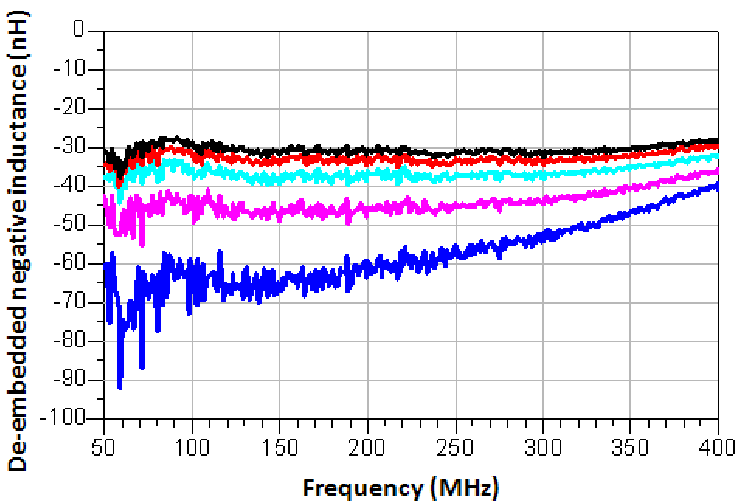


Floating NIC Schematic and Circuit Board

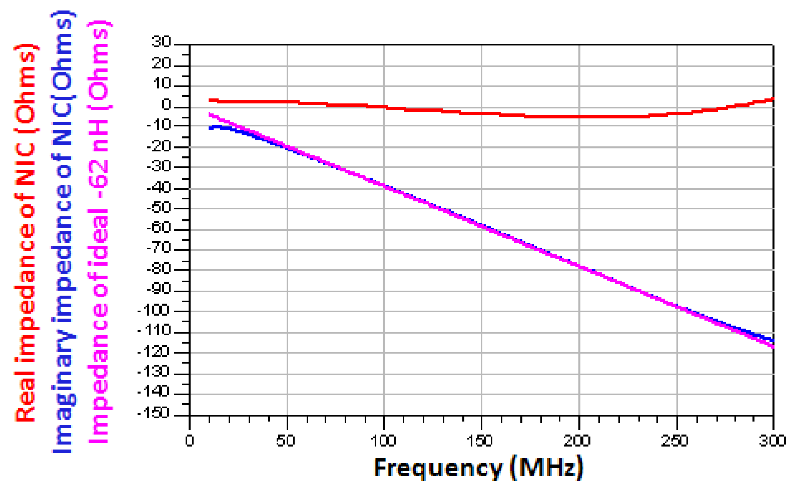




-65 nH to -30 nH for 5 V to 25 V tuning



Simulated Floating -62 nH Inductor



- **Can also make tunable negative inductor using varactor, or floating version**

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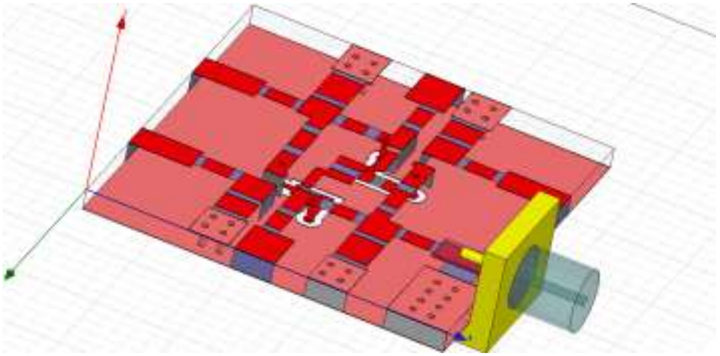
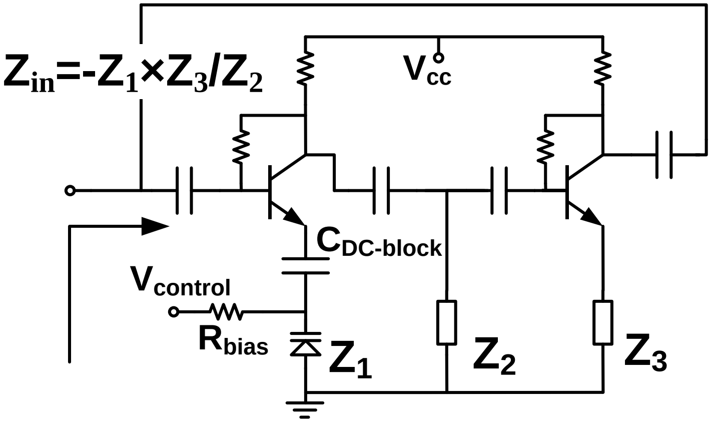
Measured Tunable Negative Capacitor

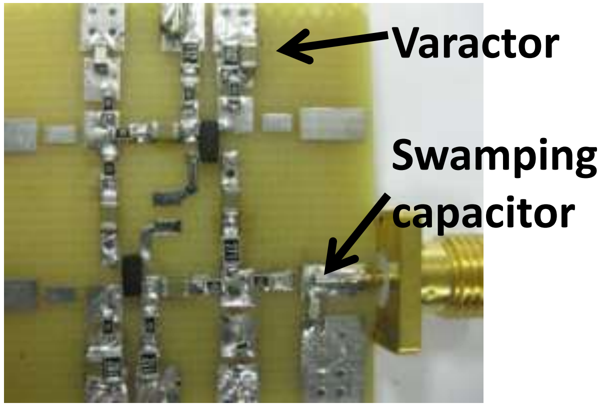
Circuit Board EM Simulation



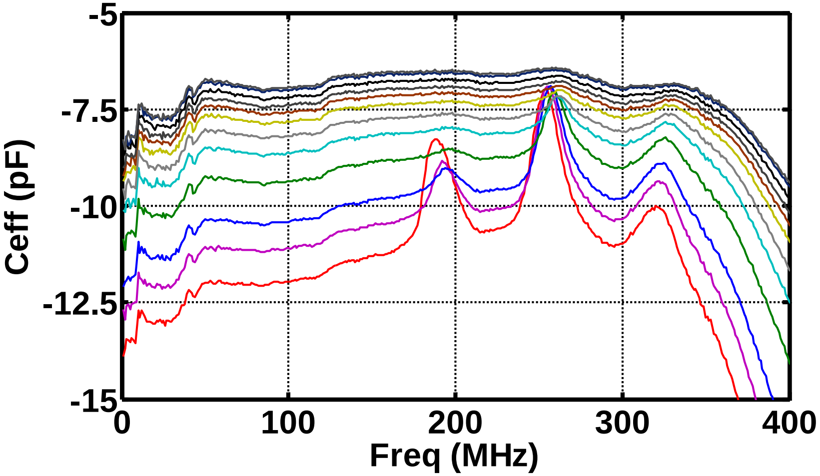
Tunable Negative Capacitor Schematic



Fabricated Circuit



Measured Tunable Negative Capacitor



- Measured -7 to -12 pF for 5v to 30v tuning voltage

Summary and Future Directions

- If we only rearrange metals and dielectrics, we will not exceed the performance of today's materials, antennas, etc.
- Integrating active electronics into electromagnetic structures can allow new behavior that is impossible with passive structures (superluminal propagation, exceed Wheeler/Chu, etc.)
- Non-Foster circuits have been successfully built and measured
- Next step: Integration of active circuits with EM structures