Stability of Tunnel Diode based Negative Impedance Circuit

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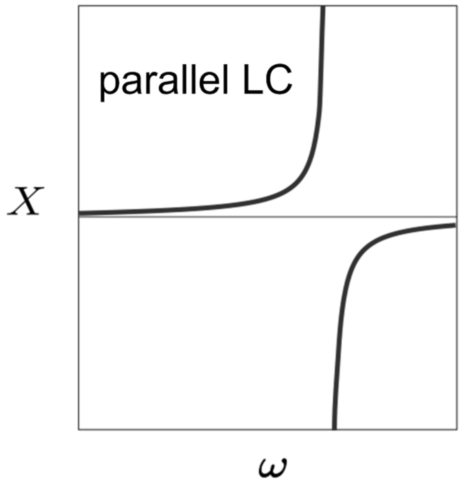
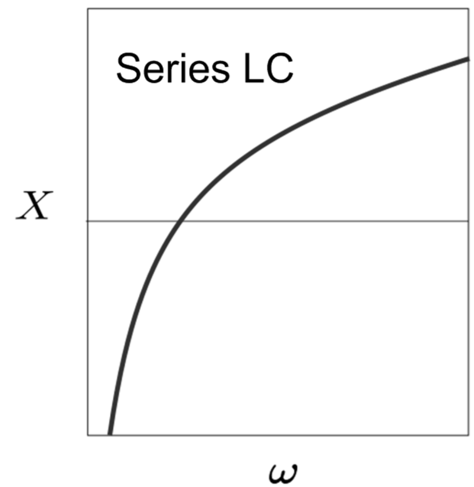
Outline

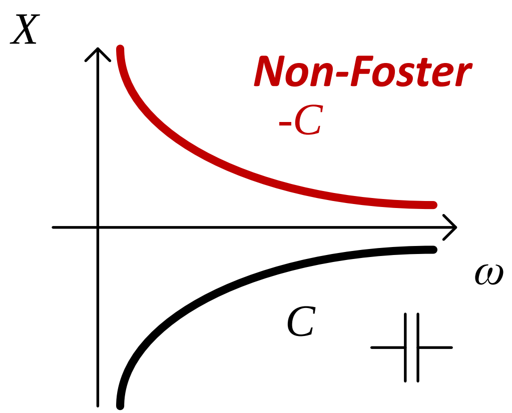
- Introduction
- Circuit configurations
- Stability analysis methods
- NDF and stable region
- Performance evaluation
- Summary

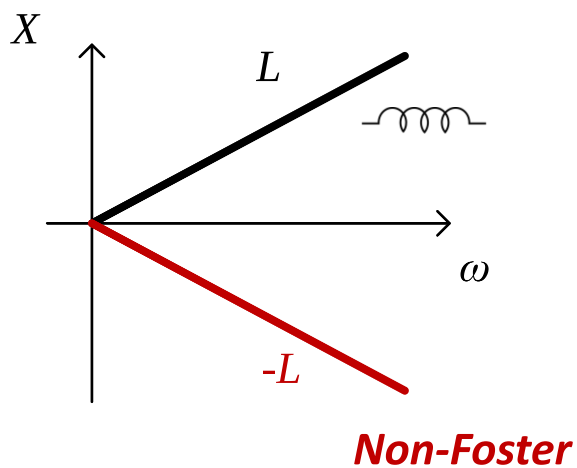
Negative C and Negative L

***Foster's reactance theorem*:**



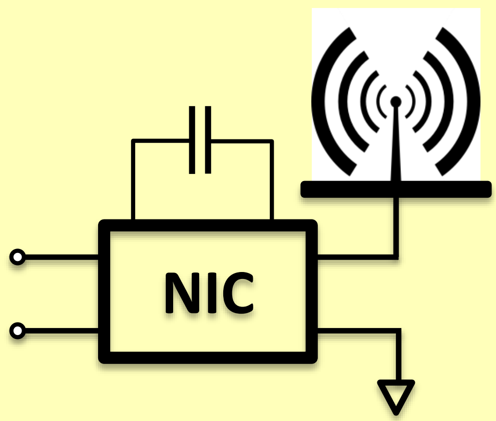






NIC for broadband matching purpose

- ***Non-Foster antennas***



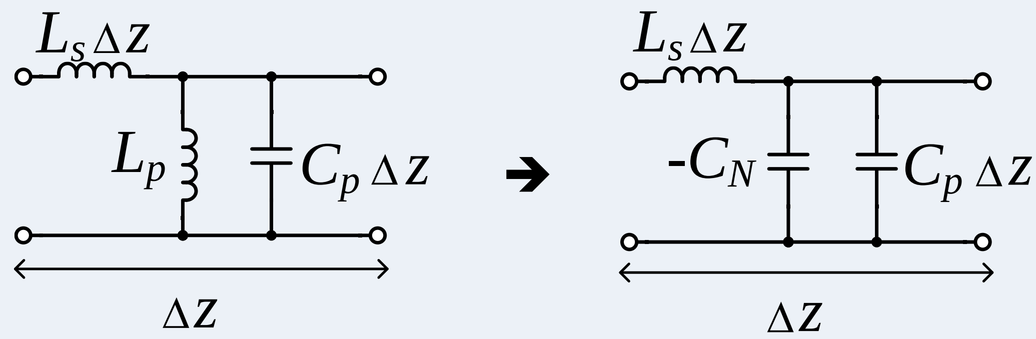
Surpass Chu limit:

$$Q \approx \frac{1}{(ka)^3}, \text{for } ka << 1$$

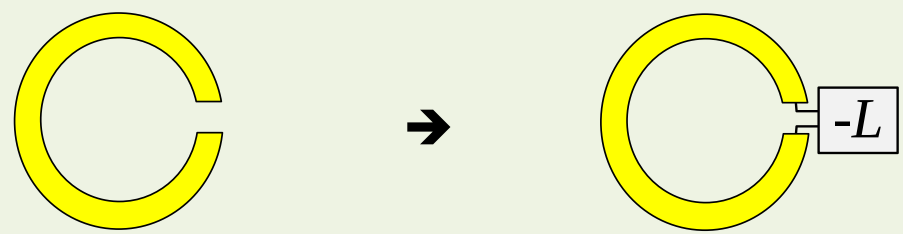
Bode-Fano limit:

Return loss ⇔ bandwidth

- ***dispersionless metamaterial***



$$\varepsilon_r(\omega) = \frac{1}{\varepsilon_0}\left(C_p - \frac{1}{\omega^2 L_p \Delta z}\right) \rightarrow \varepsilon_r(\omega) = \frac{1}{\varepsilon_0}\left(C_p - \frac{C_N}{\Delta z}\right)$$

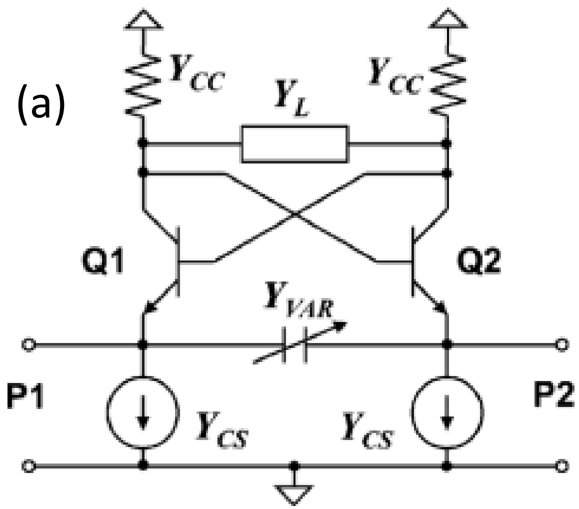


$$\mu_{\text{eff}} = 1 - \frac{F}{1 - 1/(\omega^2 LC) + \mathrm{i}(R/\omega L)},$$

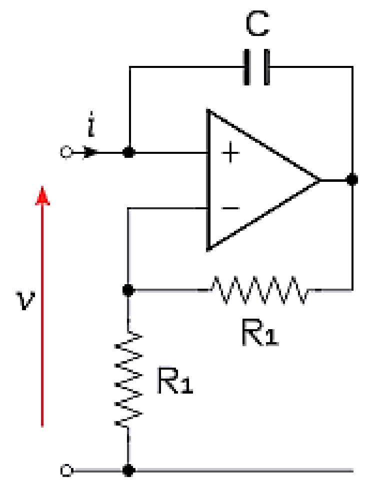
$$\rightarrow \mu_{\text{eff}} = 1 - \frac{F}{1 - L_N/L + \mathrm{i}(R/\omega L)} \overset{R\rightarrow 0}{\approx} 1 - \frac{F}{1 - L_N/L}$$

Types of NIC

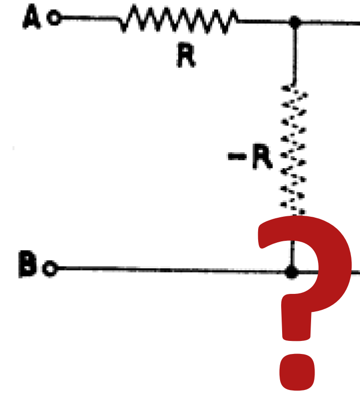
(a)



(b)



(c)



Transistor based [1]

- Mainstream
- Linvill, 1953
- Parasitic resistance

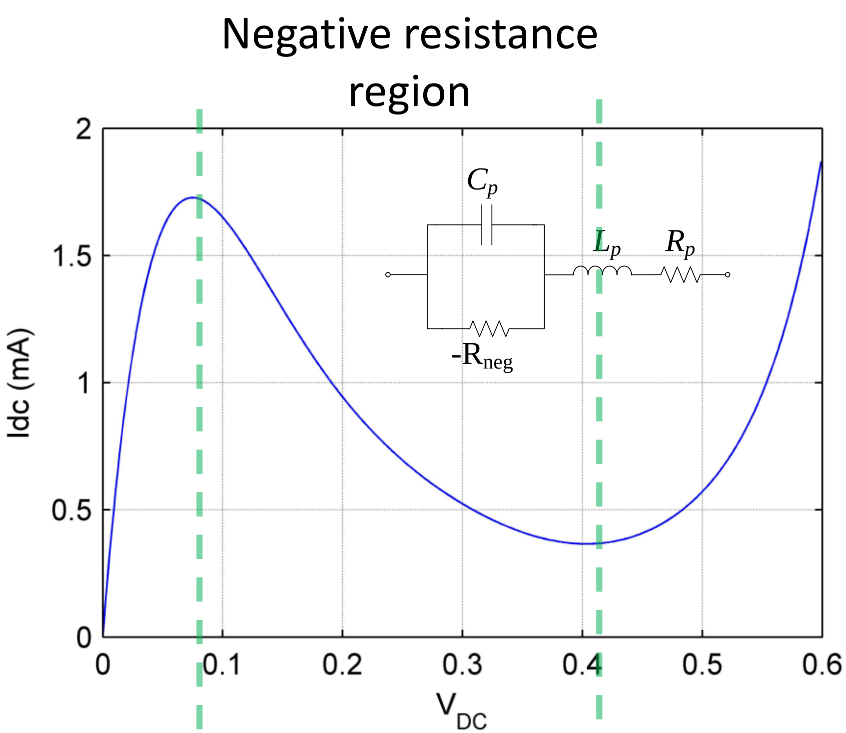
Op-amp based

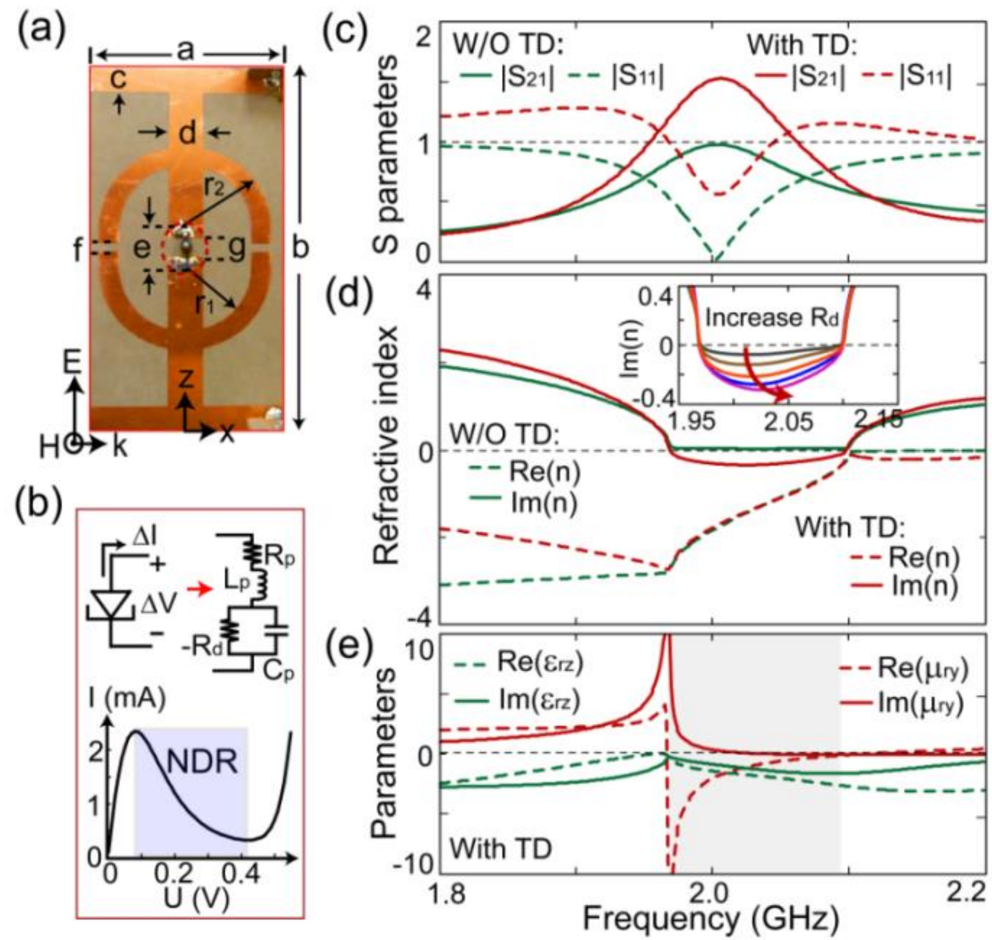
- Relatively robust
- Low operation frequency
- Large parasitic negative resistance [2]

Neg. resist. based

- Origin:
  - A. C. Bartlett, 1927
  - Van der Pol, 1930
  - Verman, 1931
- Simple
- Not well studied

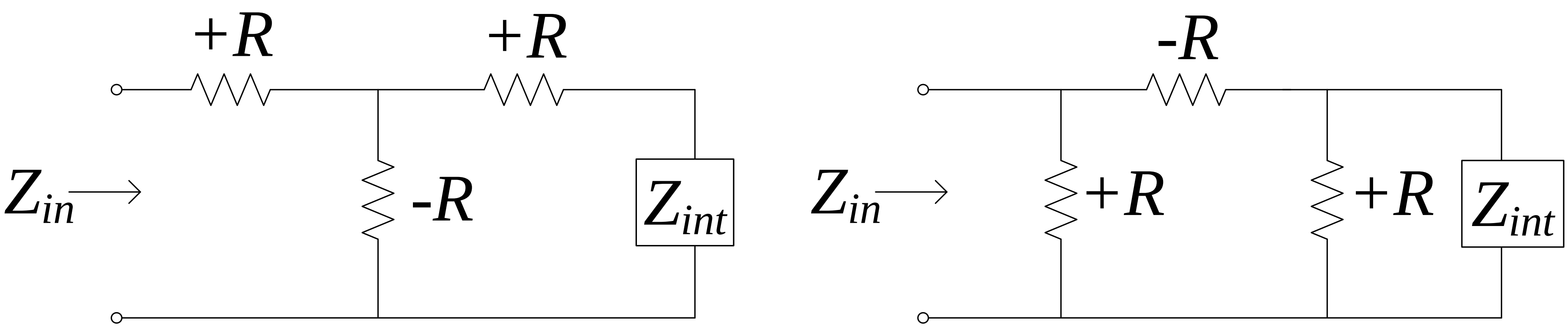
Tunnel diode and negative resistance





1. Compensating loss → Telephony line repeaters, active MTM
2. Nonlinearity → Oscillators, mixer, multiplier
3. *Broadband matching → Negative impedance converter*

Negative-resistance based NIC

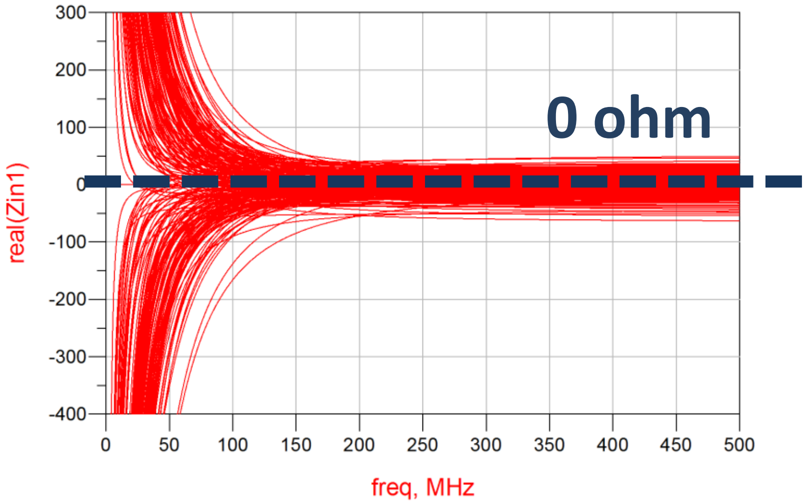


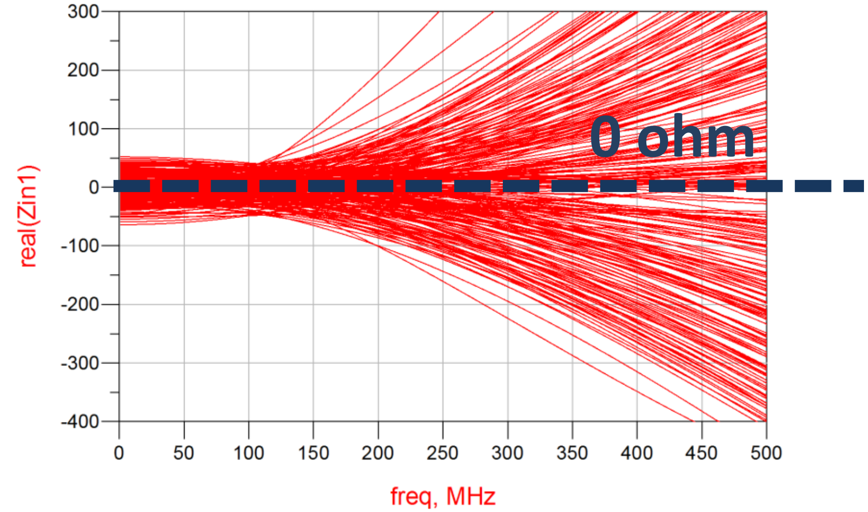
$$Z_{in} = \frac{-R^2}{Z_{\text{int}}}$$

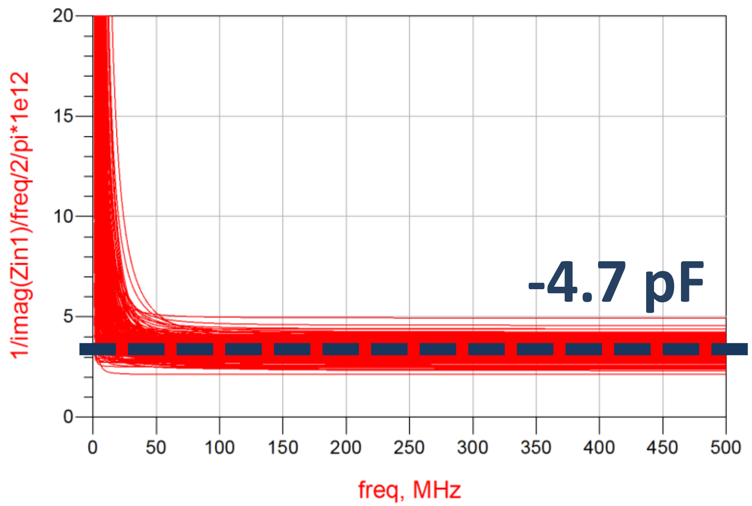
$$Z_{in} = \frac{-R^2}{j\omega L} = \frac{1}{j\omega(-L/R^2)}$$

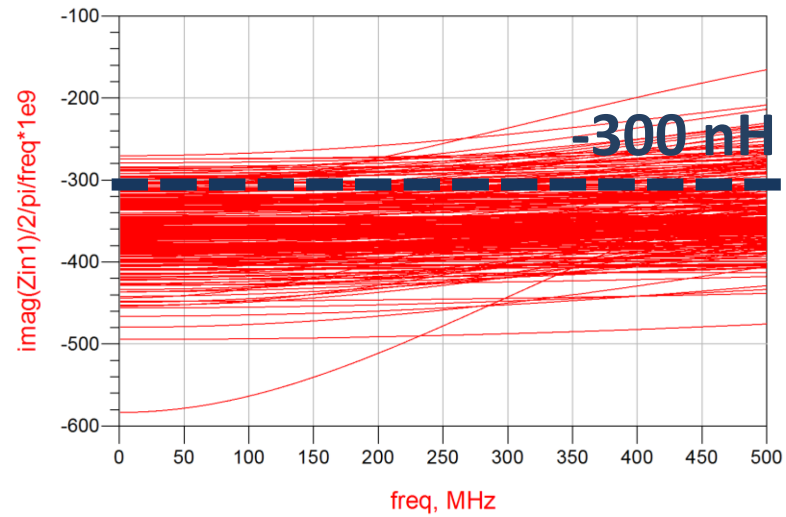
Sensitivity analysis of Z_{in}

- Inductor: +/- 10% deviation
- Resistor and capacitor: +/- 5% deviation

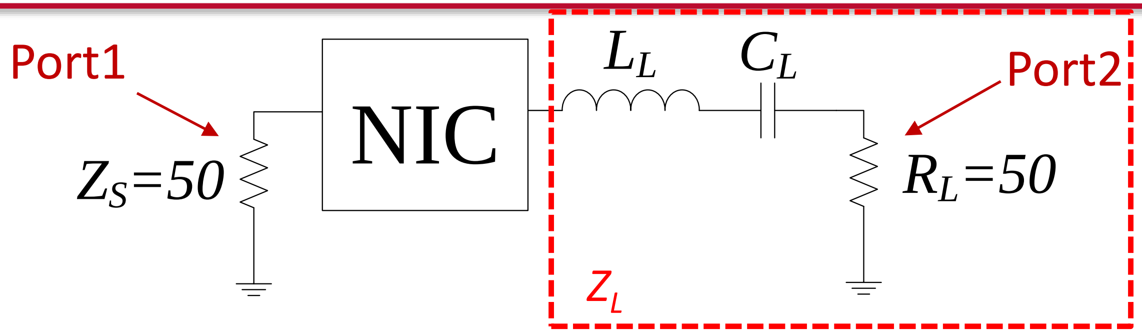




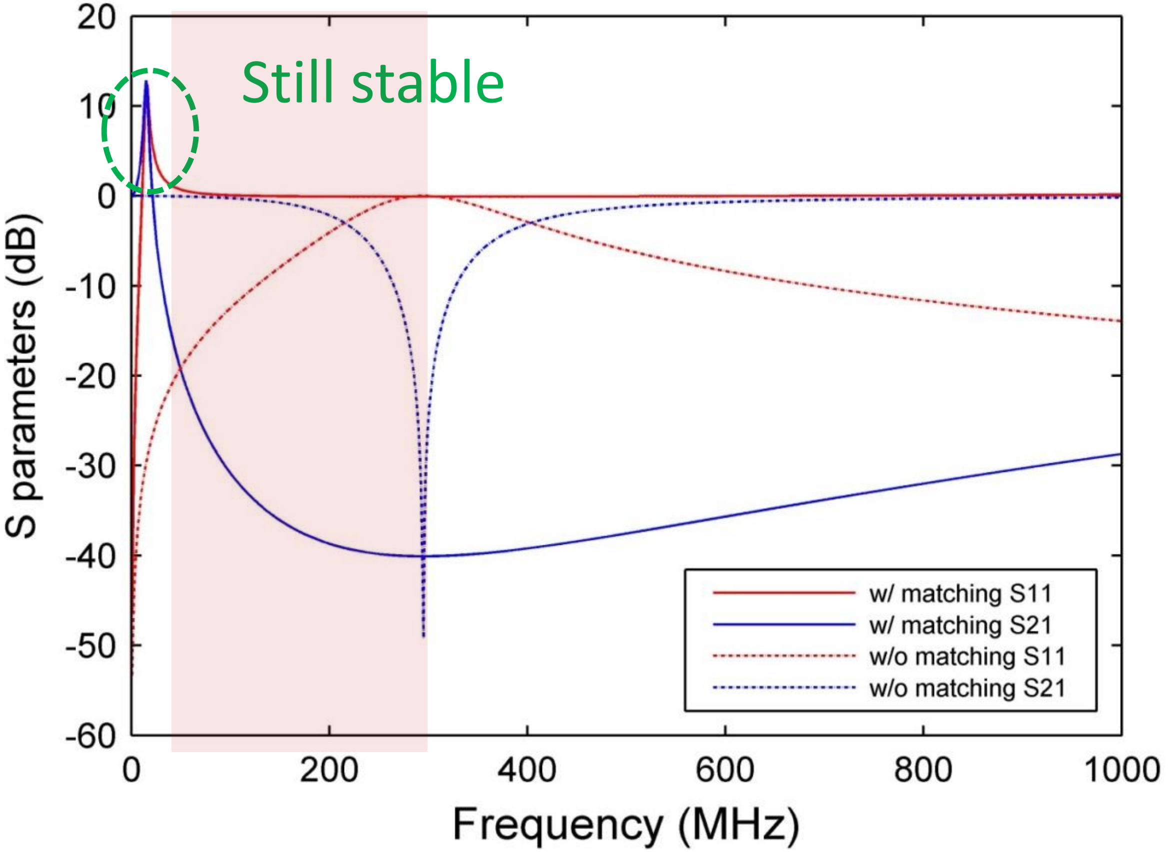




Benefits and difficulties



A constant resistance as an assumption



Benefits:

- Broadband matching
- Efficiency improvement

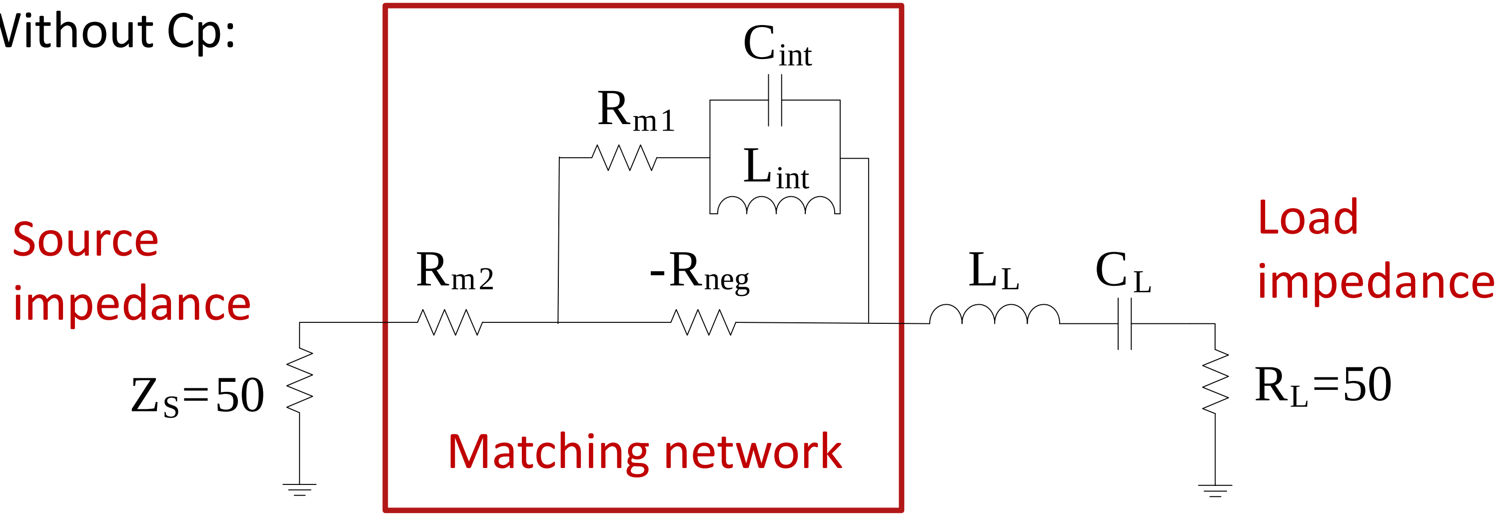
Difficulties:

- Stability
- Parasitic effect

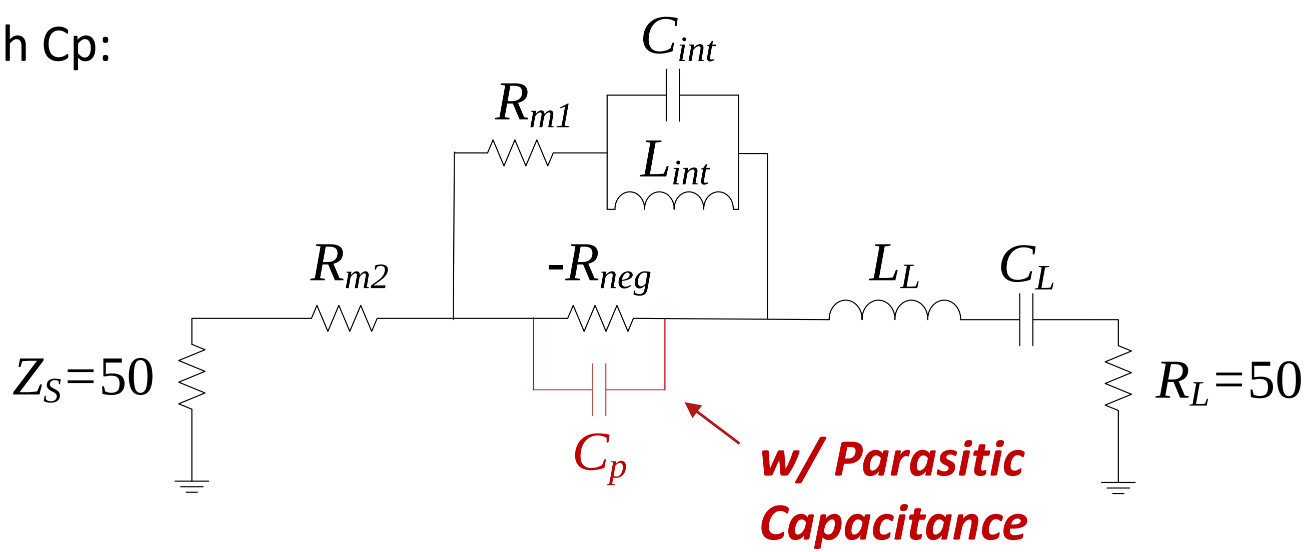
Circuit parameters: $R_{m1}=R_{m2}=R_m=301$, $R_{neg}=-300$, $L_L=83.4nH$, $C_L=3.4pF$

Verman's circuit

1. Without Cp:

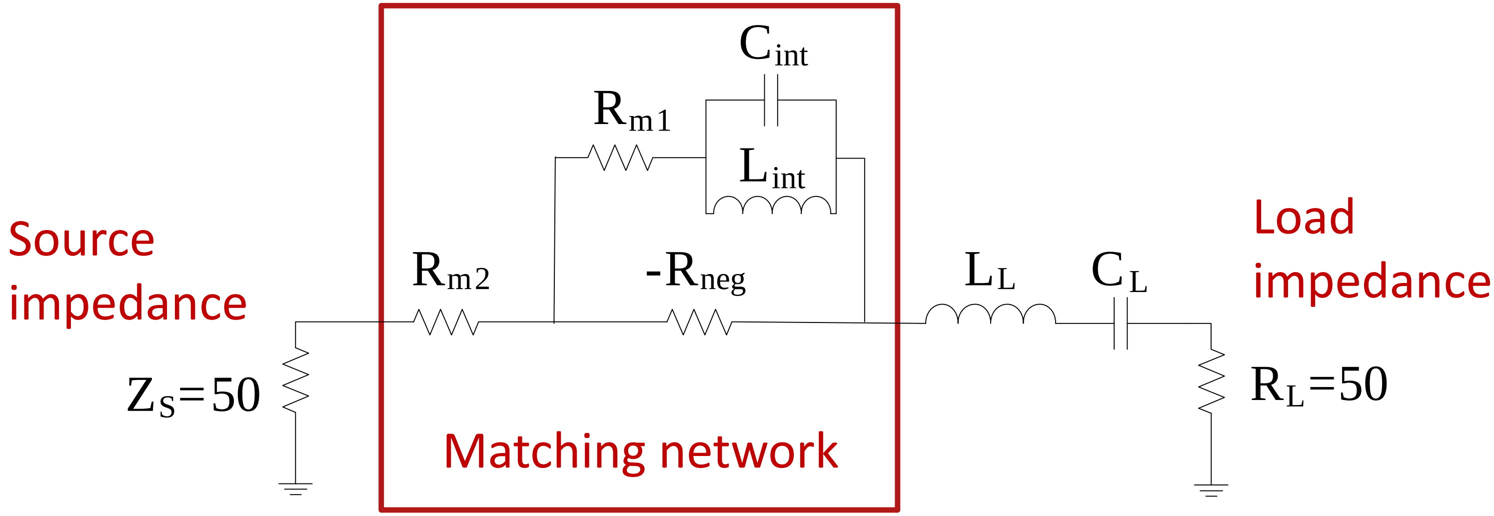


2. With Cp:



Parametric study w/o Cp

Verman's circuit without parasitic capacitance [4]



Parameter	Value	Parameter	Value
Rm1	Rm	-Rneg	-300
Rm2	Rm	C_L	3.4pF
Cint	L_L/Rm^2	L_L	84nH
Lint	C_L/Rm^2		

Different ways to analyze stability

Time domain (Transient simulation)

- Inefficient for parametric study
- not being able to predict degrees of stability
- inaccurate if time interval is not long enough

Frequency domain:

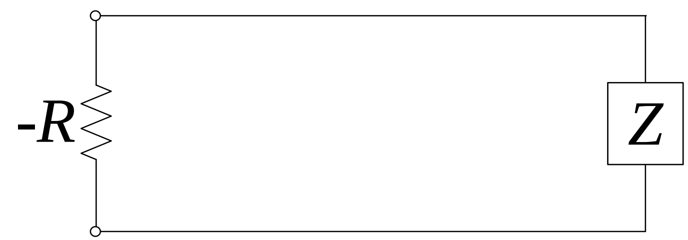
- Return difference, Normalized Determinant Factor (NDF) method
- loop gain
- impedance/admittance method (single-negative-resistor case)

NDF analysis and parasitic effect in stability

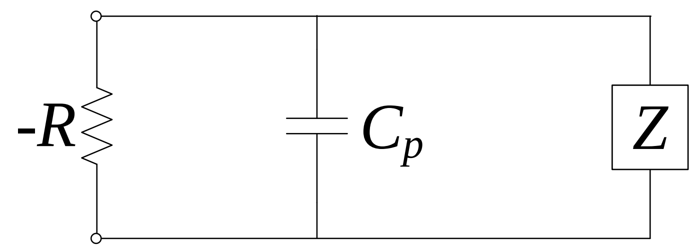
NDF procedure:

1. Separate out negative resistors
2. Perform a mesh or nodal analysis of the network and get matrix H
3. Calculate the determinant of the matrix as Z
4. Deactivate the negative resistors in mesh analysis is by setting R_N=0 (or inf. in nodal analysis) and calculate the determinant as Z_0.
5. NDF=Z/Z_0
6. NDF has no RHP zeros.

$$Z = \frac{N}{D} = \frac{a_0 + a_1 s + a_2 s^2 + \cdots}{b_0 + b_1 s + b_2 s^2 + \cdots}$$

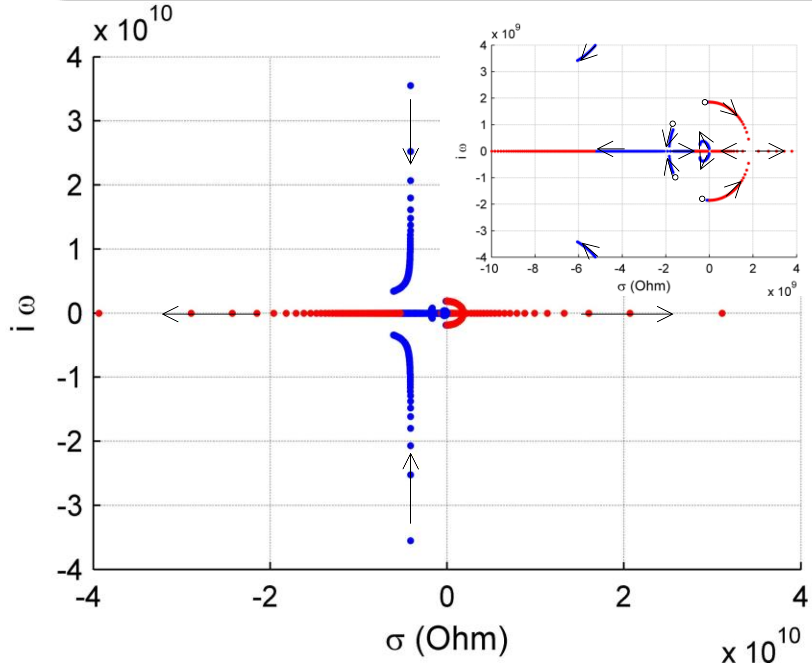


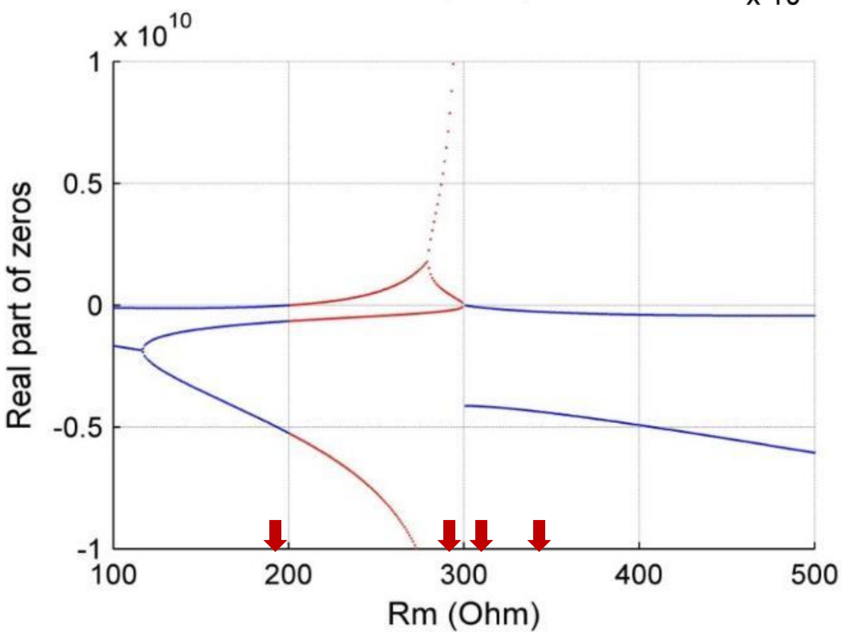
$$N - DR = 0$$

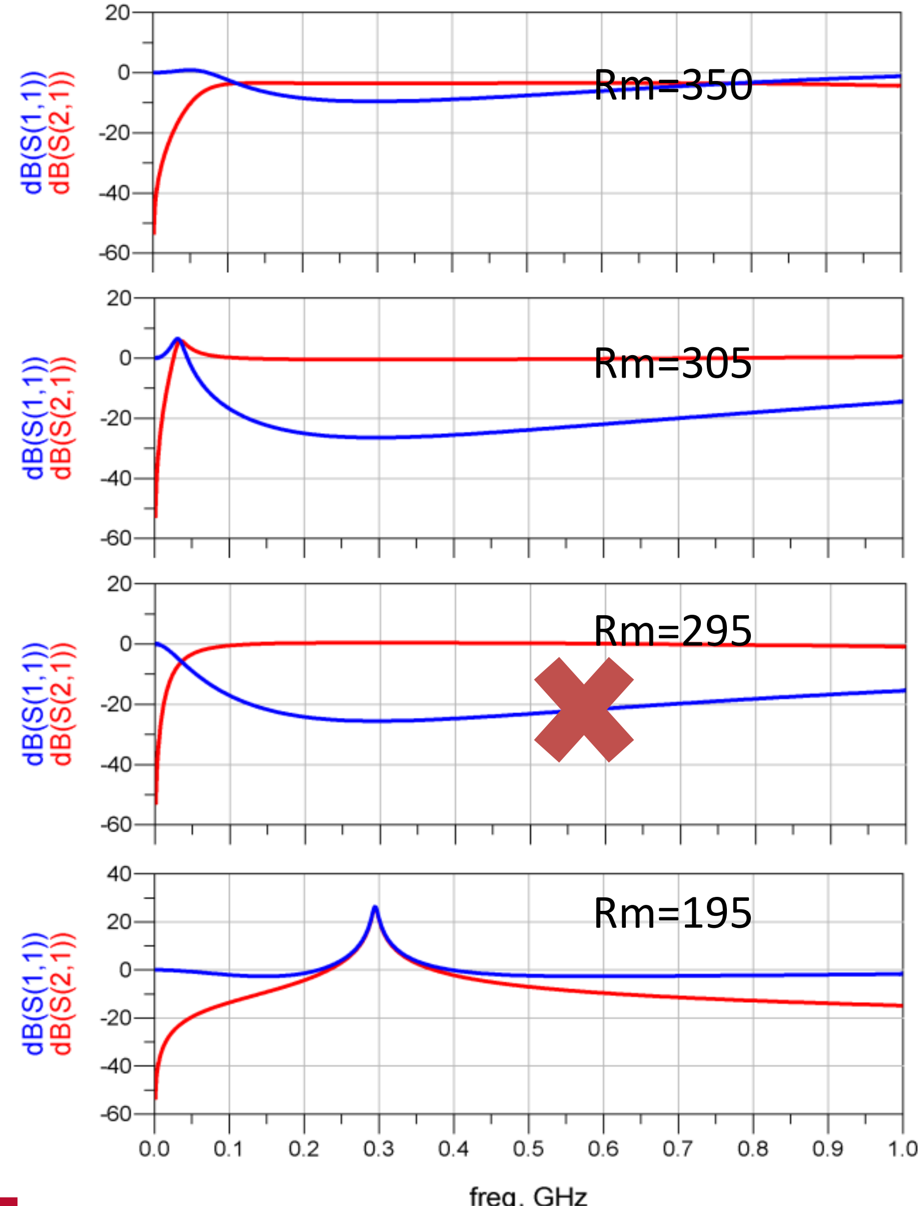


$$(1 - sC_p R)N - DR = 0$$

Root locus by sweeping R_m

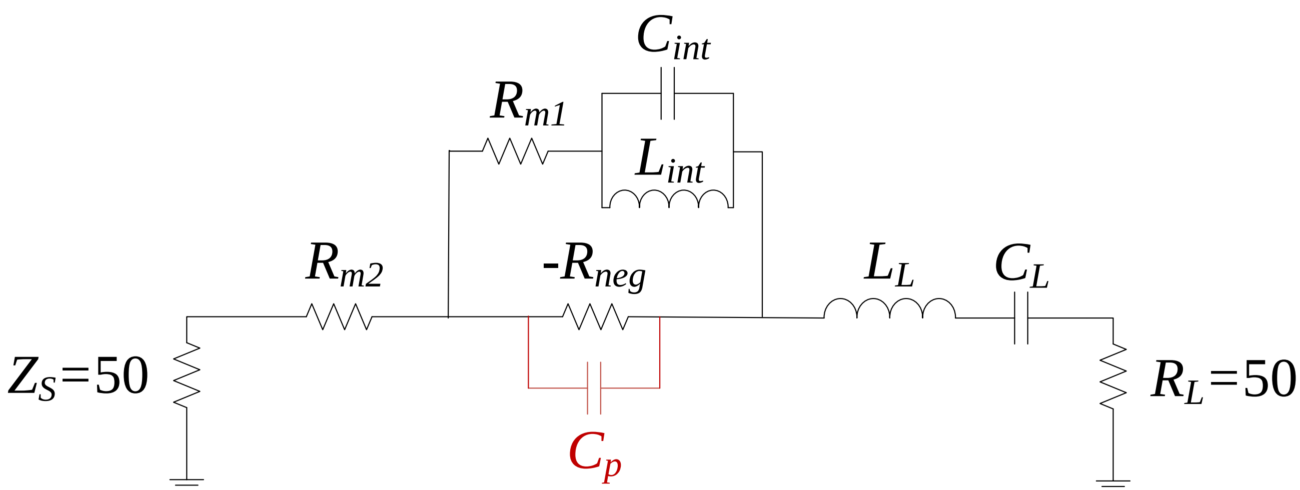






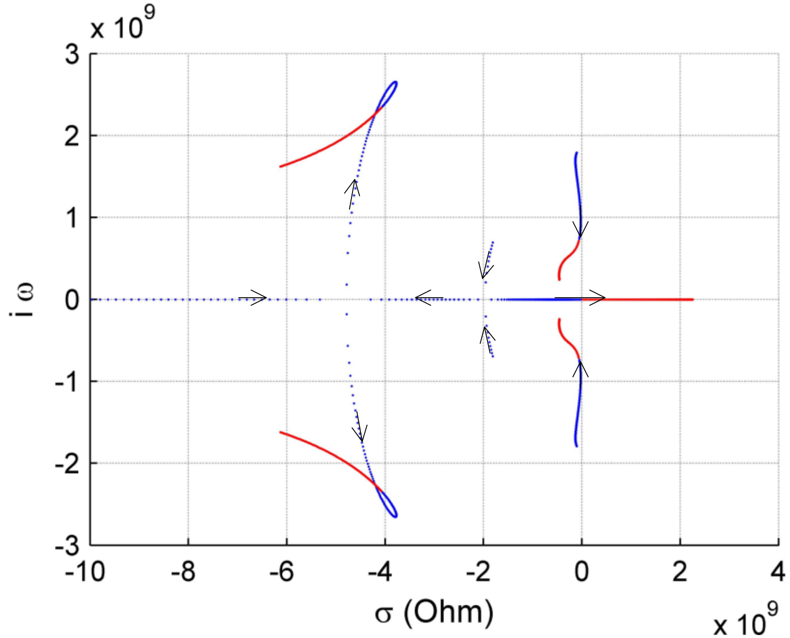
Parametric study w/ Cp

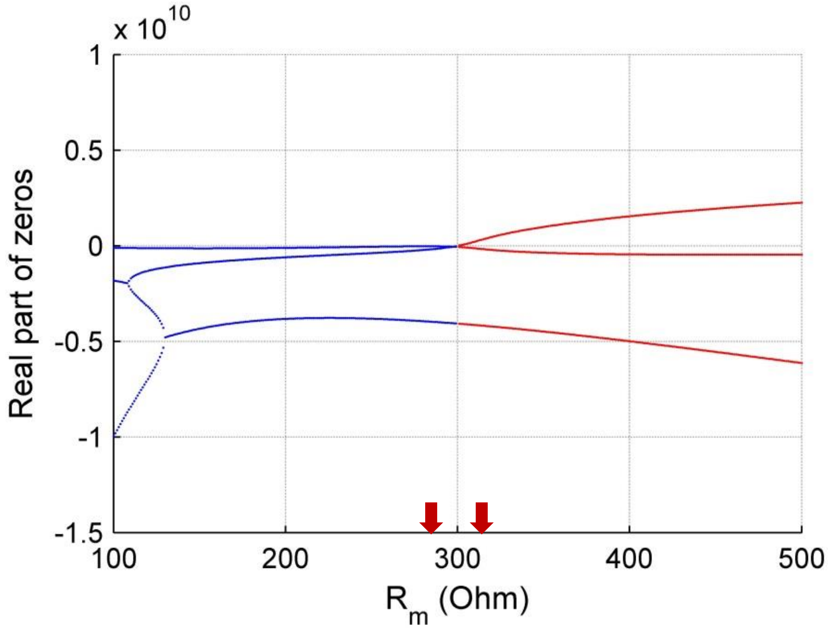
Verman's circuit with parasitic capacitance

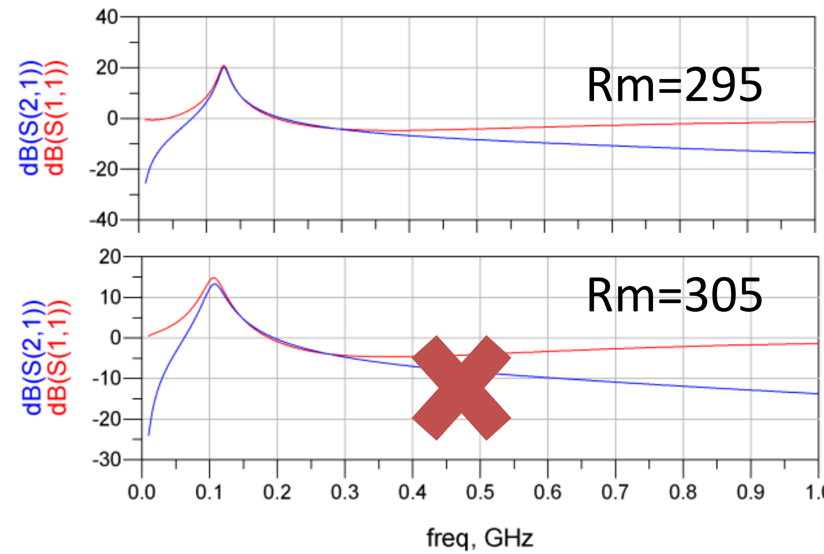


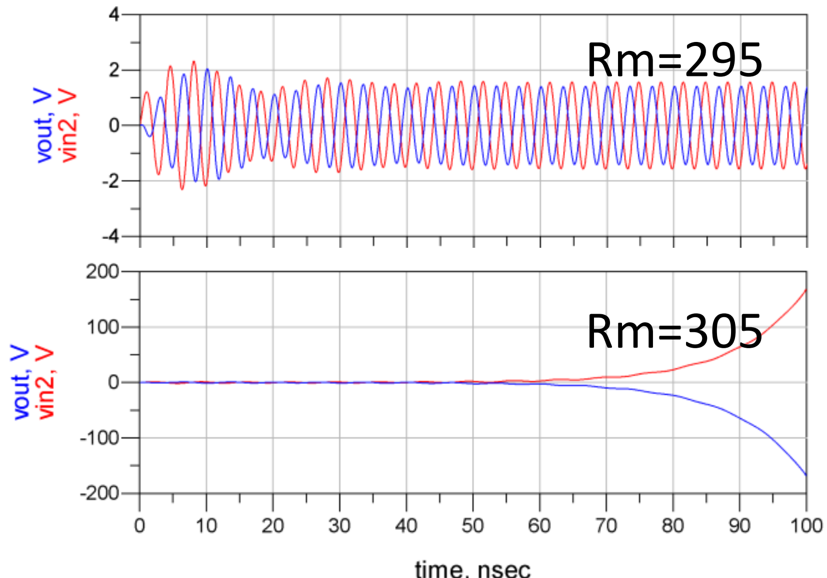
Parameter	Value	Parameter	Value
Rm1	Rm	-Rneg	-300
Rm2	Rm	C_L	3.4pF
Cint	L_L/Rm^2	L_L	84nH
Lint	C_L/Rm^2	C_p	0.65pF

Root locus by sweeping R_m



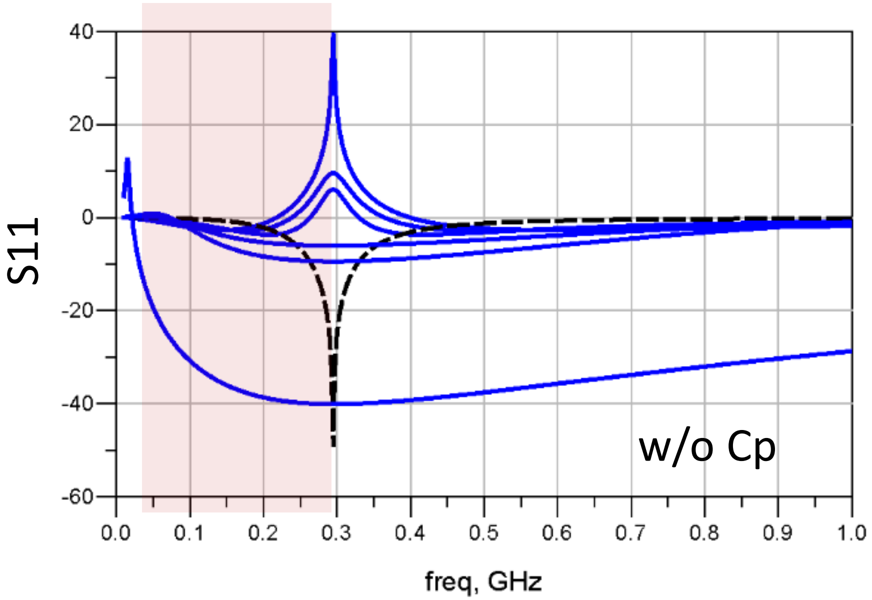


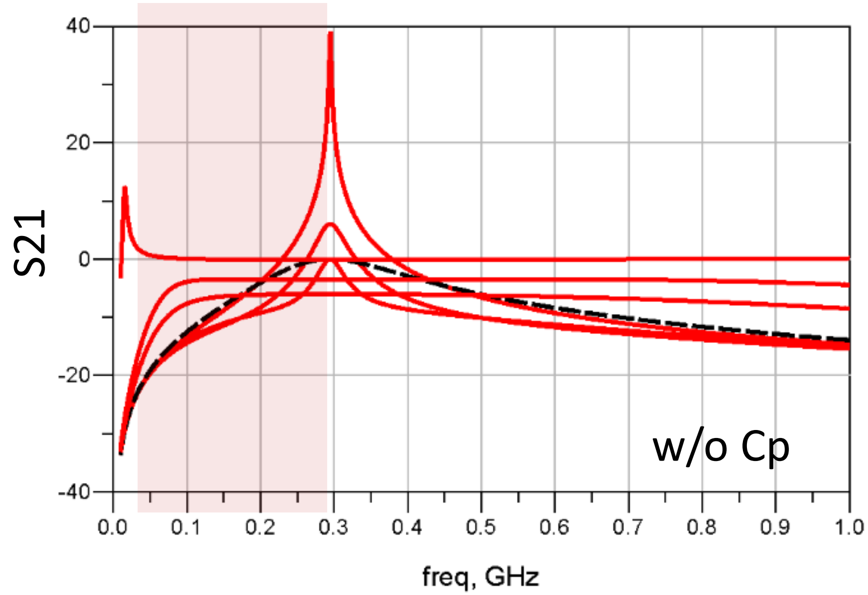




Performance evaluation

- Find stable region using NDF and sweep *Rm* in stable region

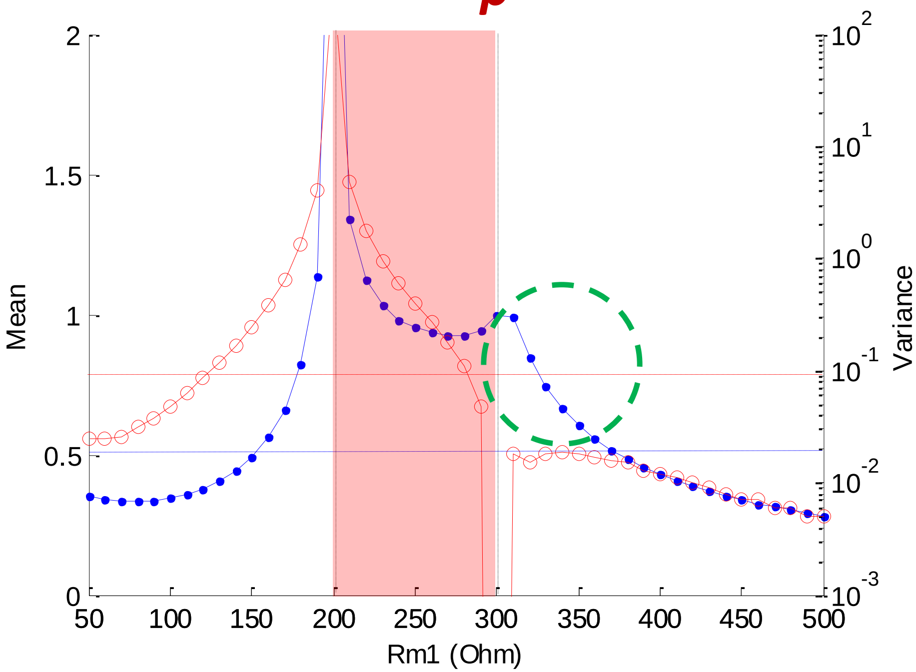




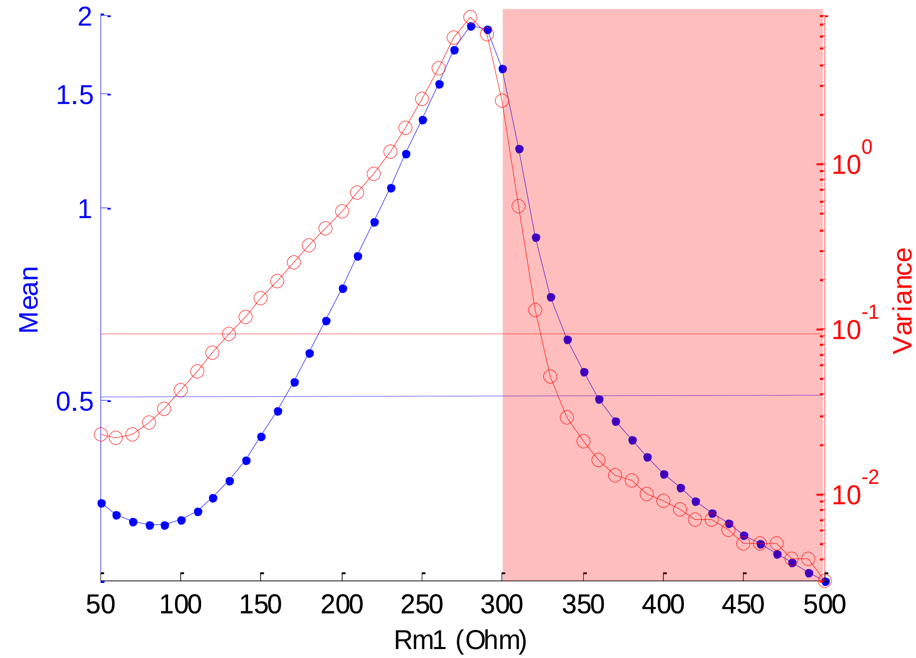
- Given the bandwidth in design spec (30 -300MHz)
- Quantify matching performance:
  - Return loss ➔Min{mean(S_{11})}
  - Efficiency ➔Max{mean(S_{21})}
  - Inband fluctuation of S_{21} ➔ Min{var(S_{21})}

Verman circuit example

w/o C_p

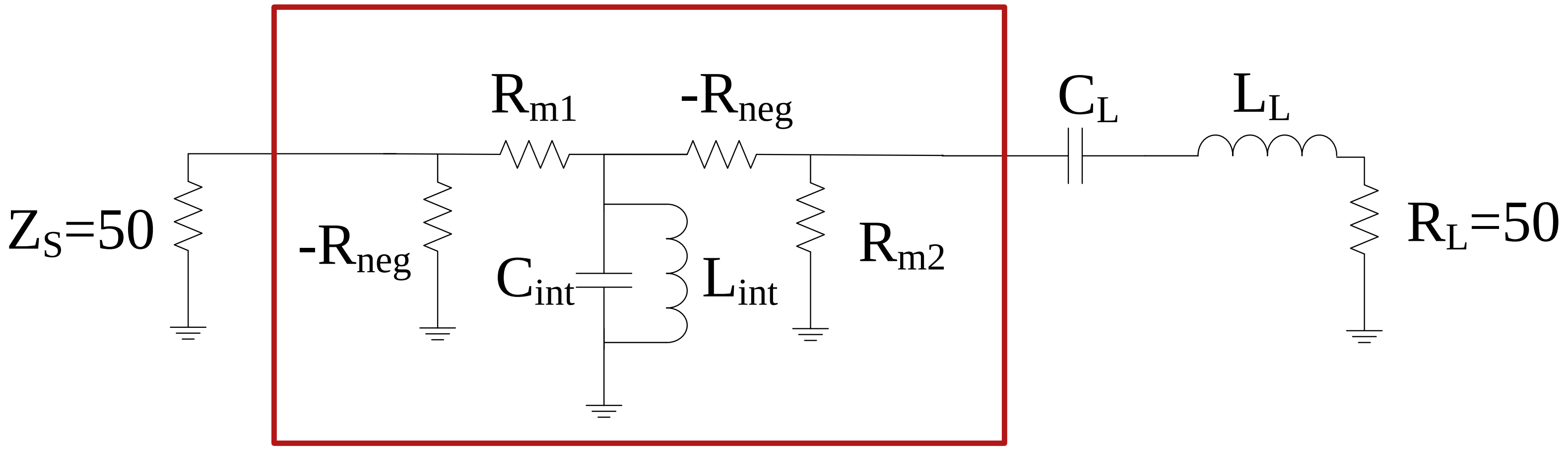


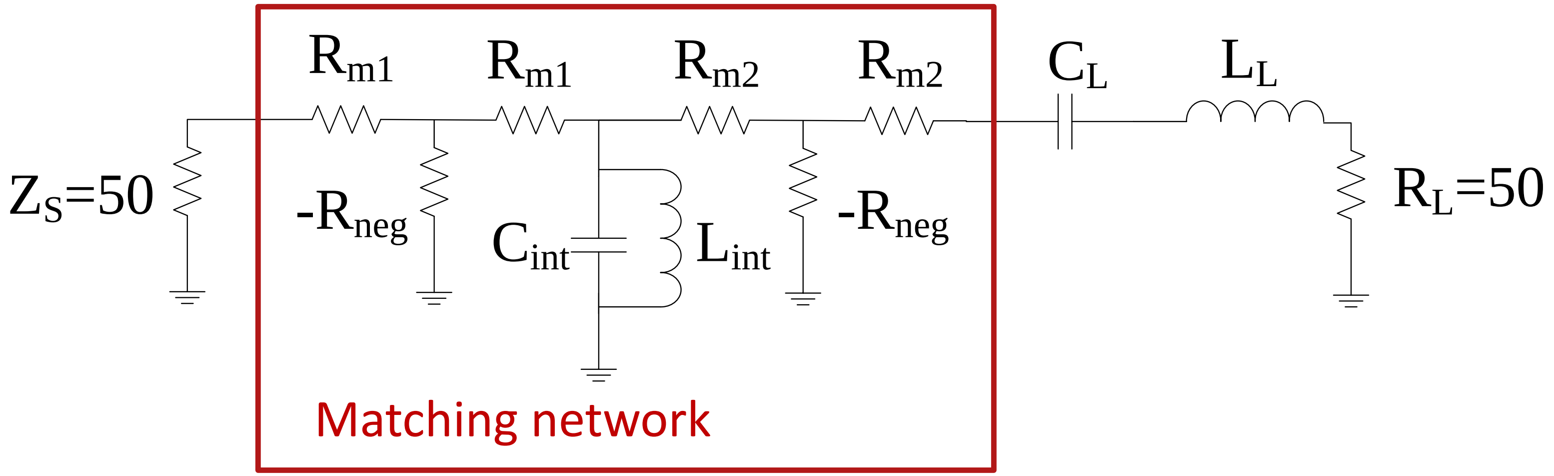
w/ C_p



- Dashed straight lines are without NIC matching case for mean(S_{21})=0.51 and var(S_{21})=0.095

Stearns' circuit





Stearns circuit example

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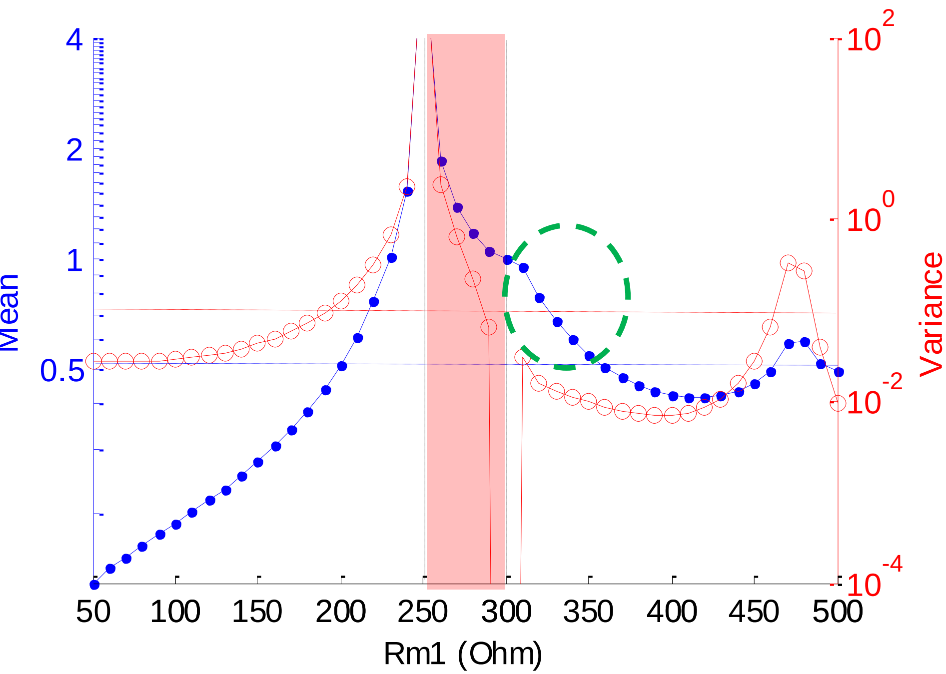
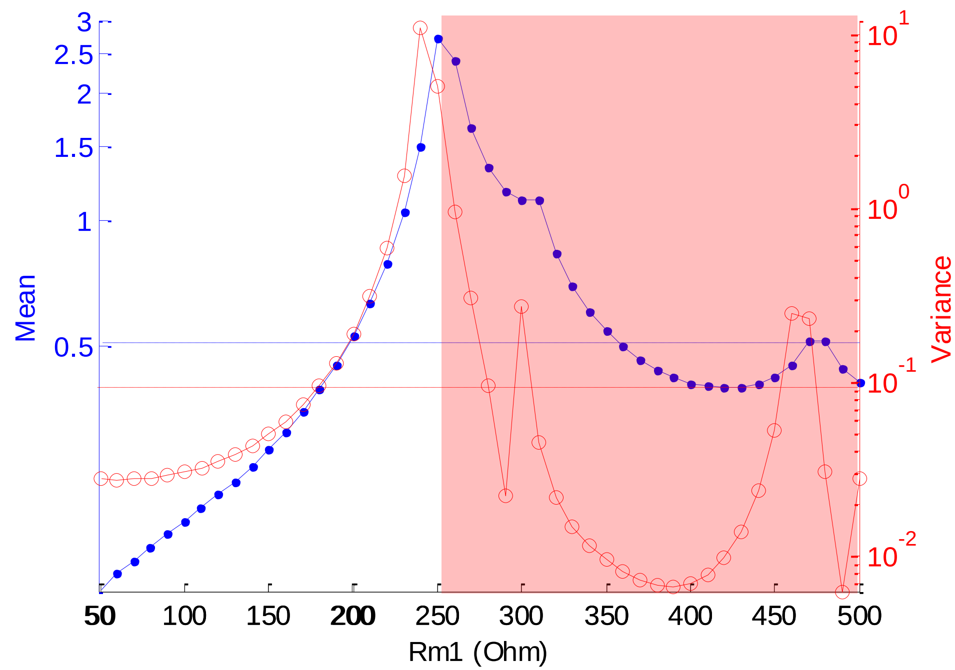


w/ Cp

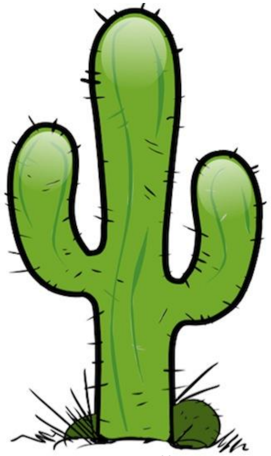


Summary

- Propose an analysis flow for negative resistor based NIC. Stability region can be analyzed using NDF methods and performance can be optimized within stable region.
- For S11>1 problem
  - Use a quadrature coupler/ isolator to avoid power reflected back to the device before matching (e.g. PA).
  - Imaging, sensing applications, or active metamaterial applications may still be available.
- Negative resistance based NIC circuits still remains in theory. Practical implementations require resolving several main problems, including stability, parasitics, biasing networks, loading effect and sensitivity of circuit elements.
- Potential methods to resolve the problem is to use unilateral gain devices instead of bilateral negative resistors.

Thank you for your attention!

Questions?



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