Broadband Fabry-Pérot Antenna with non-Foster Metasurface - How to Test the Basic Idea ?

Silvio Hrabar[1], Tomislav Debogovic[2]

[1]Faculty of Electrical Engineering and Computing, University of Zagreb, Croatia

[2]Ecole Polytechnique Fédérale Lausanne (EPFL), Lausanne, Switzerland

Prof. Julien Perruisseau-Carrier and University of Zagreb EM Group

- Collaboration between EPFL and UNIZG has been lasting almost 25 years through European COST activities
- 2003-2009 informal ‘ad-hoc’ collaboration with Julien on various topics
- 2009 Tomislav Debogovic (a student at UNIZG) goes to CTTC, Barcelona, Spain and Julien becomes his co-superviser
- 2010 Julien visits ICECOM 2010 in Dubrovnik, Croatia
- 2011. Julien moves back to EPFL, Tomislav defends his Ph.D thesis on reconfigurable PRS antennas
- 2011 Start of collaboration on non-Foster-based antennas

Outline

- **Pros and cons of Fabry-Perot antenna**

➢ Is it possible to obtain both high-gain and broadband operation ?

- **Recent idea: Fabri-Perot antenna with Non-Foster Active Metsurface**

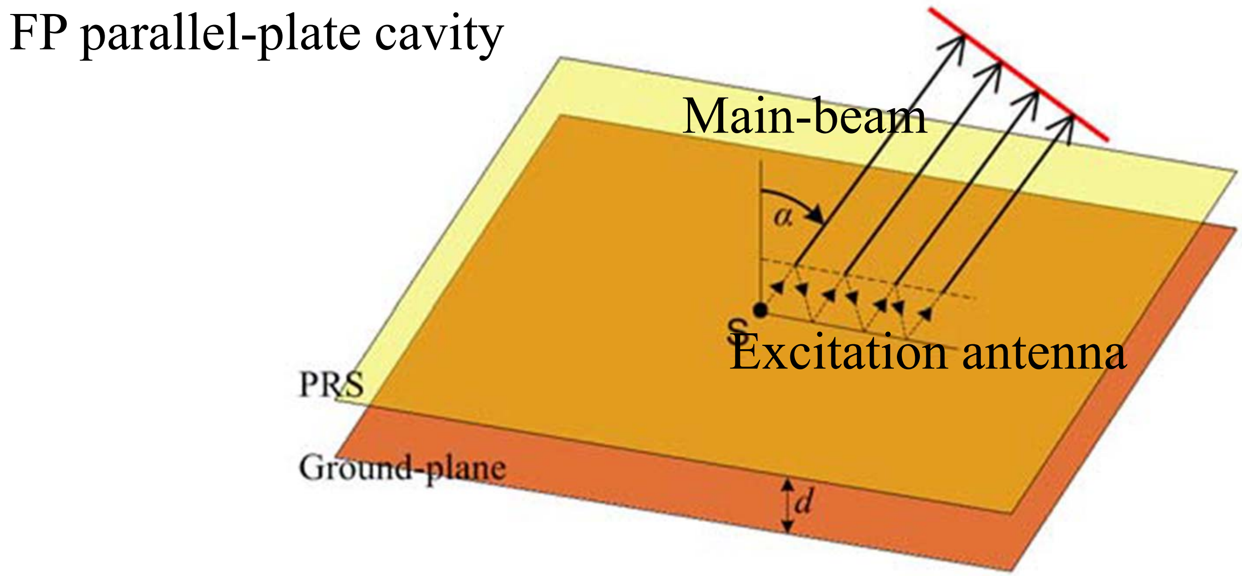
- **Stability issue**

➢ Is non-Foster approach a bright future of antenna technology or just hopeless academic juggling?)

- **From basic idea towards practical realization**

- **Conclusions**

Classical Fabry-Perot (FP) antenna – a basic idea



Phenomenon of constructive interference

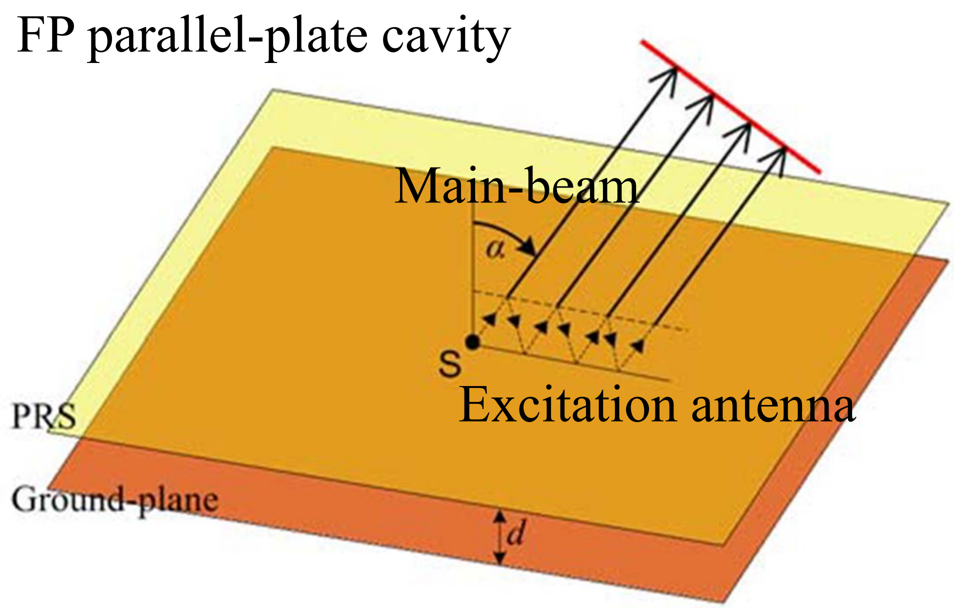
$$D_e(\alpha) = \frac{1 - R^2}{1 + R^2 - 2R\cos\left(\psi - \pi - \frac{4\pi d}{\lambda}\cos(\alpha)\right)}$$

PRS contribution $\Gamma = R e^{j\psi}$

ground plane contribution

FP cavity contribution

Classical FP antenna – maximal directivity



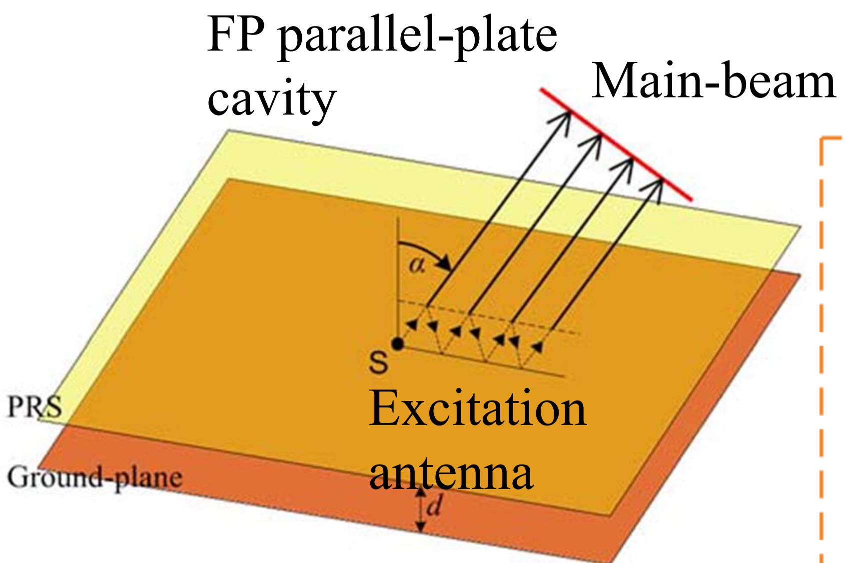
For maximal directivity one choses

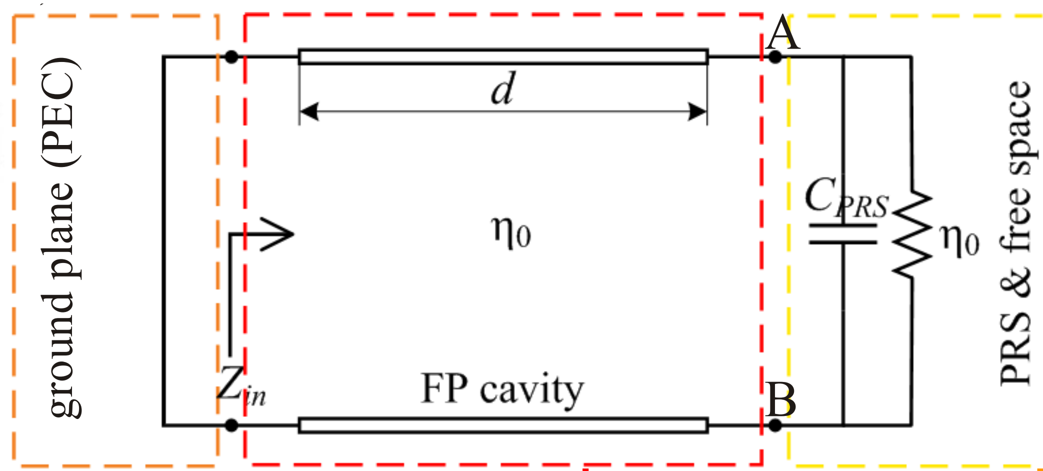
$$\psi - \pi - \frac{4\pi d}{\lambda} = 2N\pi$$

$$D_{e0} = (1 + R) / (1 - R)$$

D_{e0} is typically in the order of 20 dB.

FP antenna –
How to compensate for the frequency dependence?





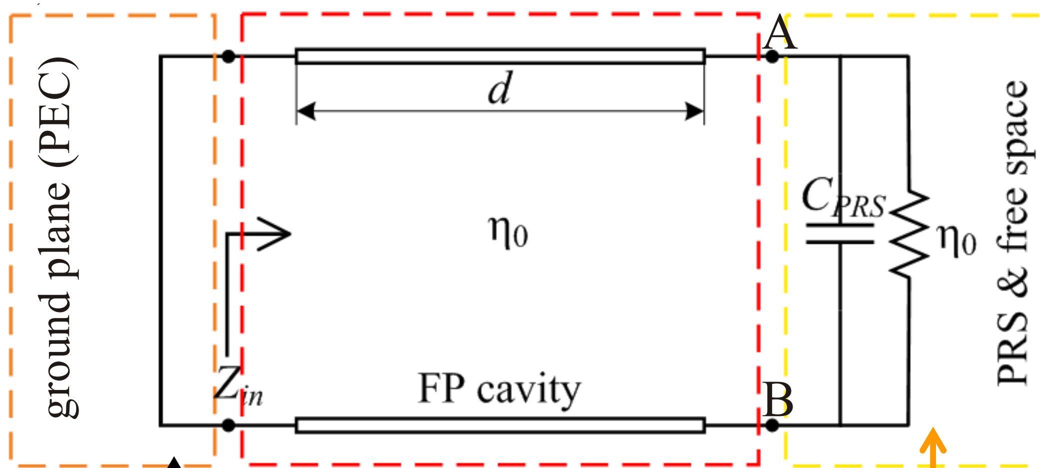
$$D_e(\alpha) = \frac{1 - R^2}{1 + R^2 - 2R\cos\left(\psi - \pi - \frac{4\pi d}{\lambda}\cos(\alpha)\right)}$$

FP cavity contribution decreases with the frequency

Typical −1 dB directivity bandwidth of 2%

PRS contribution decreases with the frequency

FP antenna –
How to compensate the frequency dependence?



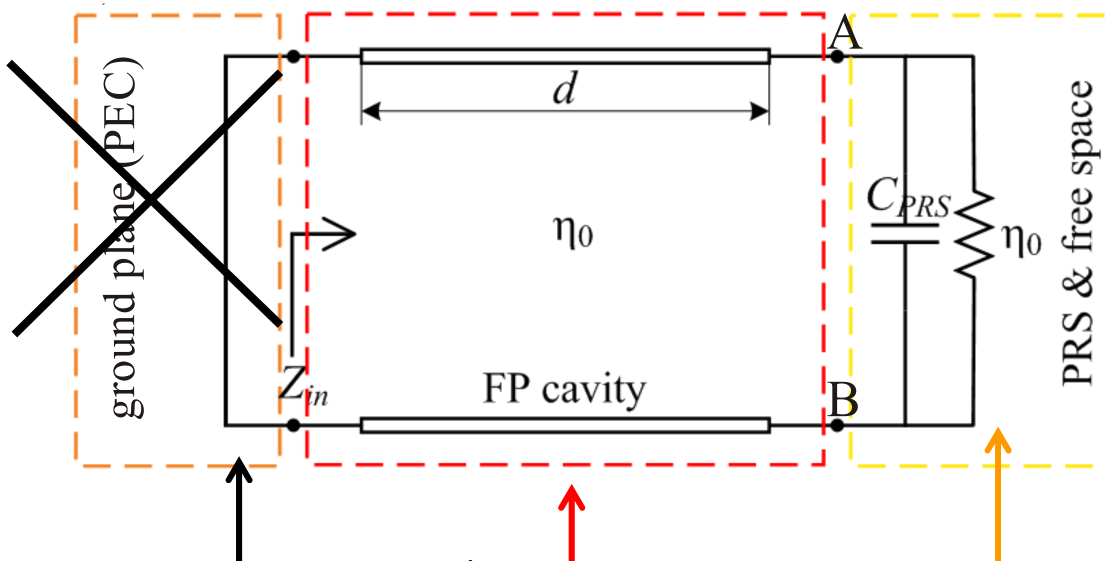
$\Gamma_{GP} = 1e^{j\pi}$

βd decreases with the frequency

$\Gamma_{PRS} = Re^{j\psi}$

ψ decreases with the frequency

FP antenna –
How to compensate the frequency dependence?



$\Gamma_{GP} = 1e^{j\pi}$

βd decreases with the frequency

$\Gamma_{PRS} = Re^{j\psi}$

ψ decreases with the frequency

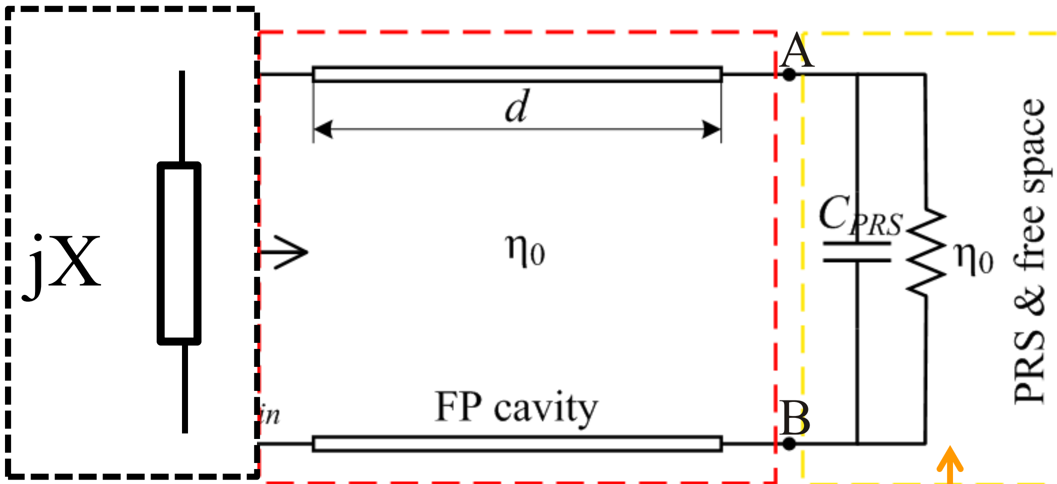
FP antenna –
How to compensate the frequency dependence?

jX – artificial reactive surface

$\Gamma_X = 1e^{j\chi}$

$$\frac{\partial \chi}{\partial \omega} > 0 \Rightarrow \frac{\partial X}{\partial \omega} < 0$$

Non-Foster behavior is required !



βd decreases with the frequency

$\Gamma_{PRS} = Re^{j\psi}$

ψ decreases with the frequency

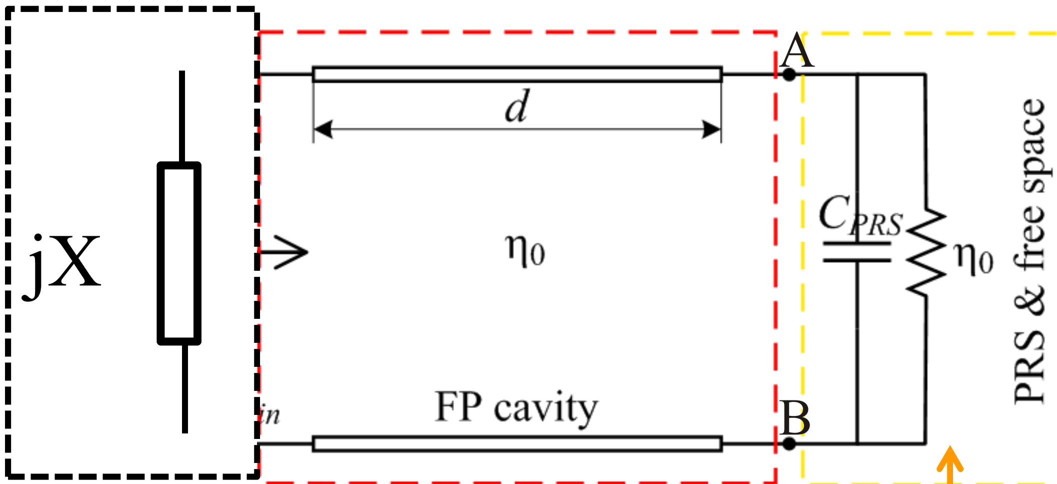
Novel FP antenna with non-Foster metasurface

jX – artificial reactive surface

$\Gamma_X = 1e^{j\chi}$

$$\frac{\partial \chi}{\partial \omega} < 0 \Rightarrow \frac{\partial X}{\partial \omega} < 0$$

Non-Foster behavior is required !

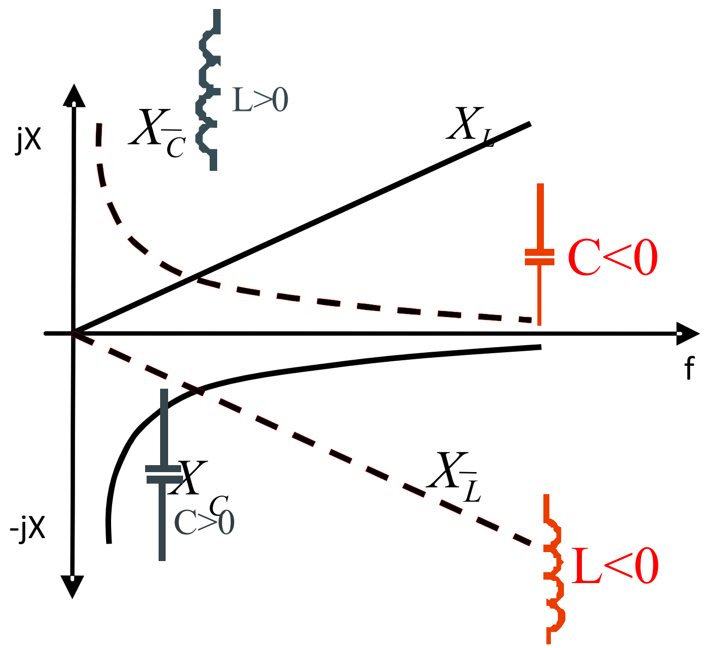


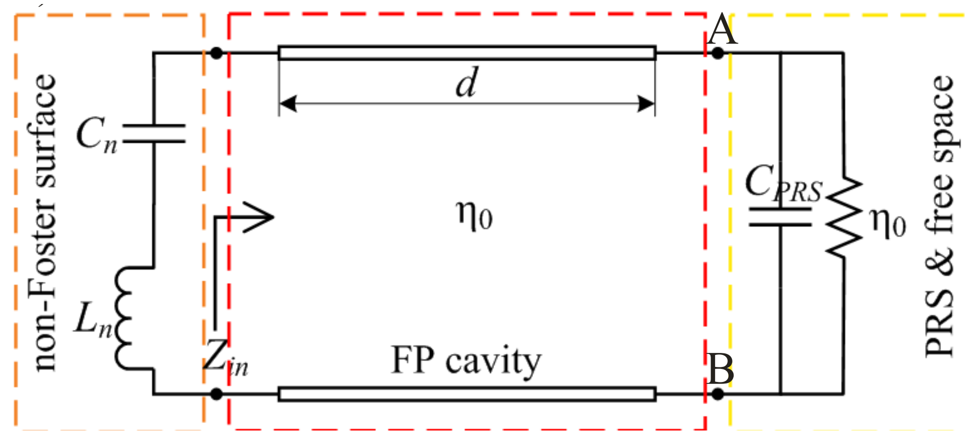
βd decreases with the frequency

$\Gamma_{PRS} = Re^{j\psi}$

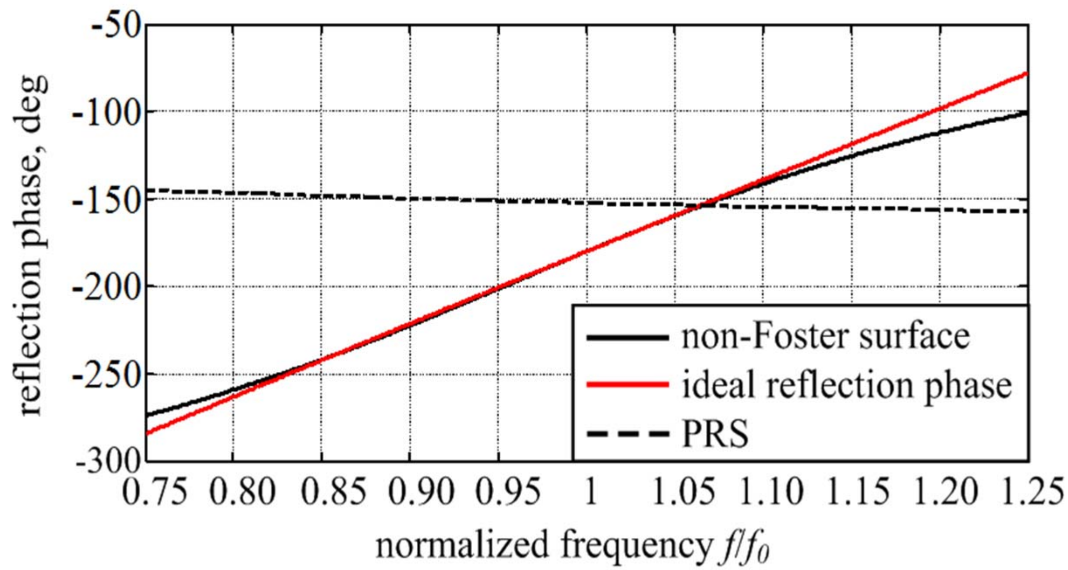
ψ decreases with the frequency

What are Non-Foster (negative) reactive elements needed for broadband FP antenna ?

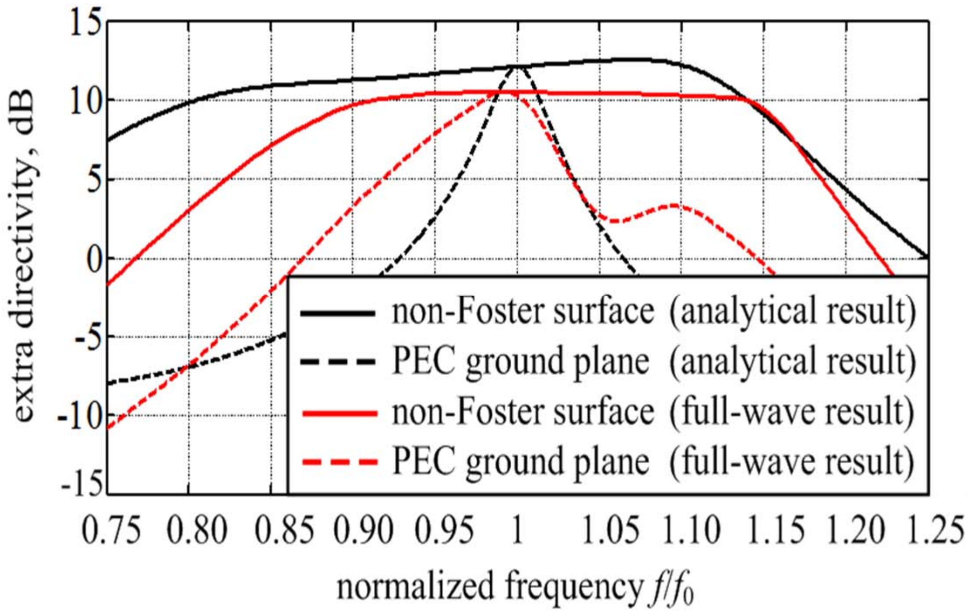


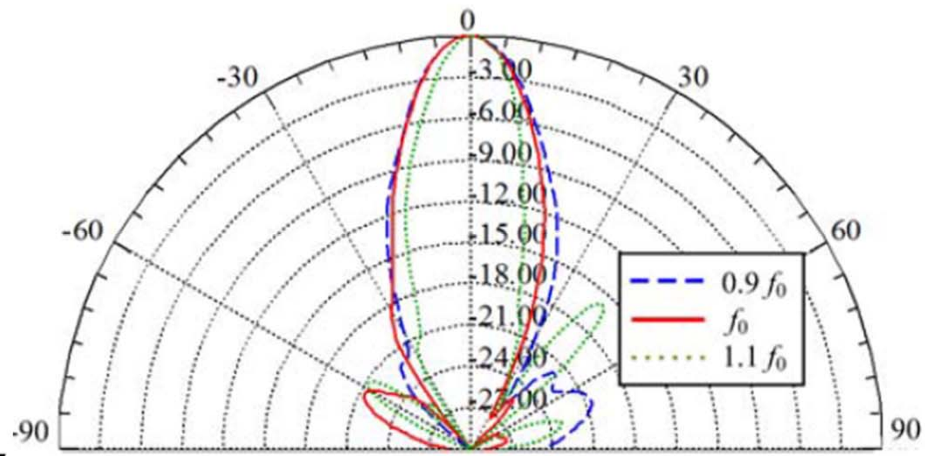


Non-Foster surface type	Series LC tank circuit
Design frequency, Hz	f_0
PRS impedance @ f_0 , Ω	$(-j100 \parallel \eta_0)$
Normalized inductance, H·Hz	$-110 / f_0$
Normalized capacitance, F·Hz	$-230e\text{-}6 / f_0$
PRS distance	$0.54\,\lambda_0$



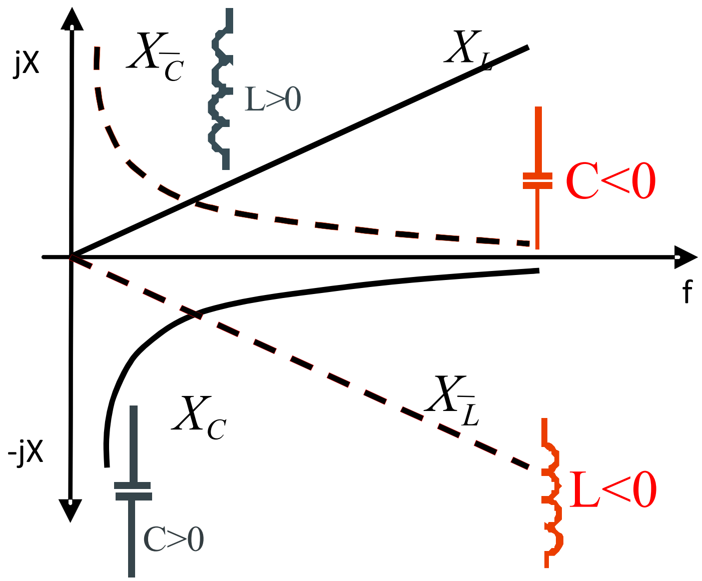
What would be the properties of a FP antenna with non-Foster metasurface?

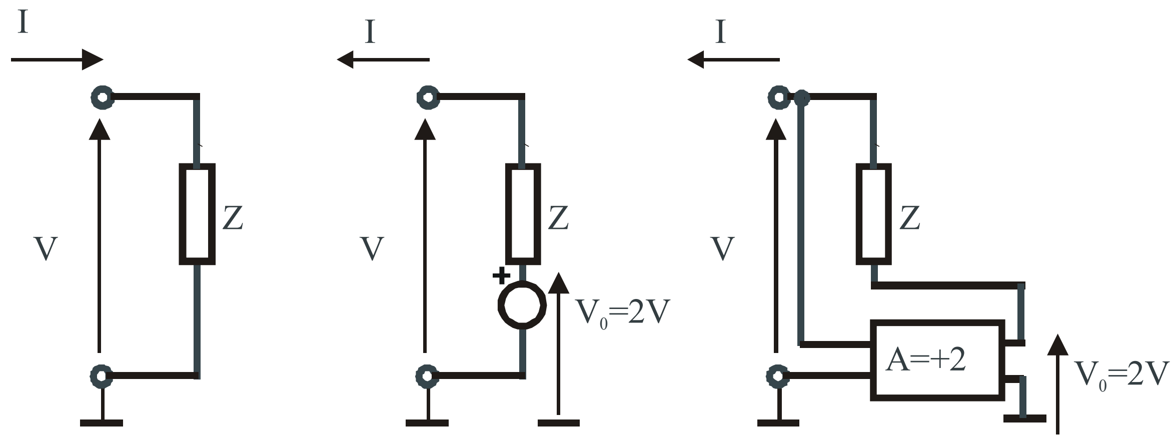




Nearly tenfold improvement of the −1 dB directivity bandwidth (from 1.75% to 17.4%)

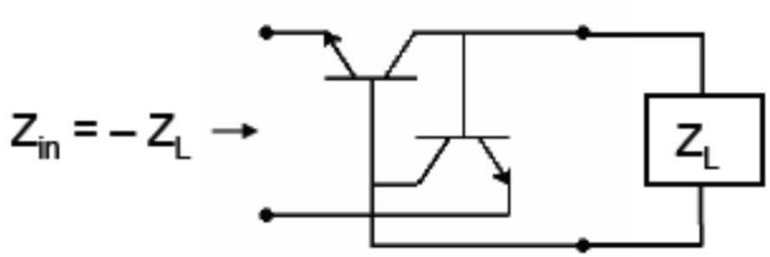
How to construct on-Foster reactive elements (negative C and negative L)



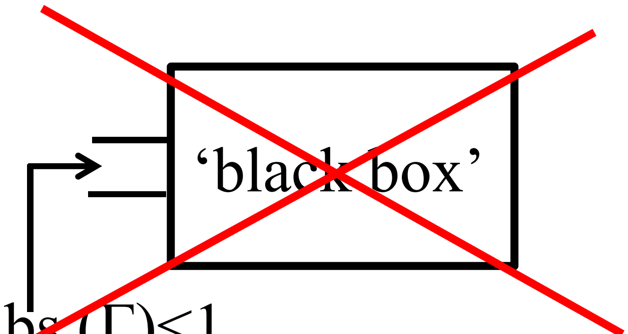


$$Z_{in} = \frac{V_{in}}{I_{in}} = \frac{-V_l}{I_l} = -Z_l$$

Floating negative impedance
(Linvill, 1953)

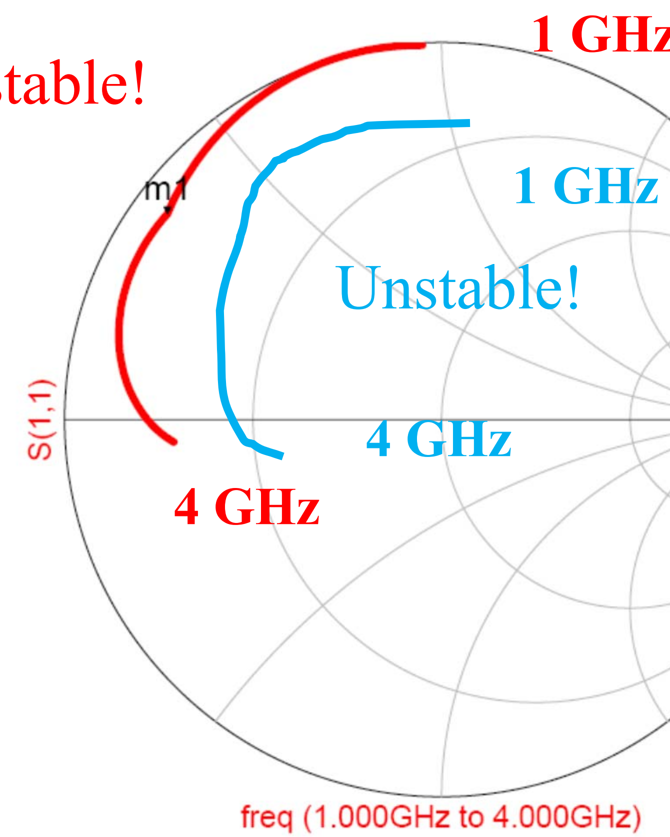


What about stability issue?



abs (Γ)<1,
OK_

WRONG !!!

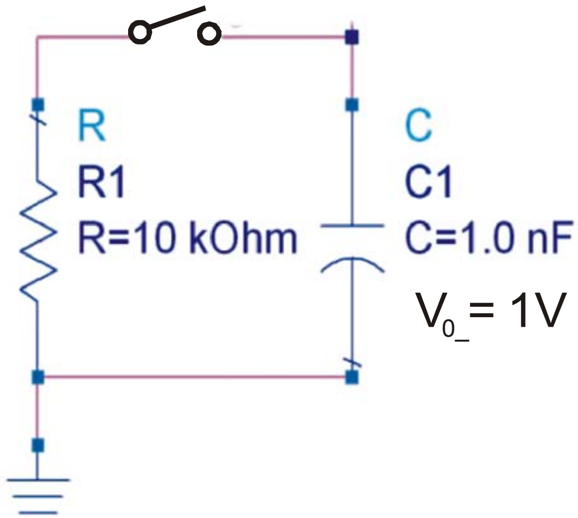


Use of ordinary stability factors (Rolett, Stern …) can give completely wrong predictions!

Ugarte-Munoz, E.; Hrabar, S. ; Segovia-Vargas, D. ; Kiricenko, A. **Stability of Non-Foster Reactive Elements for Use in Active Metamaterials and Antennas , IEEE TAP, July 2012**

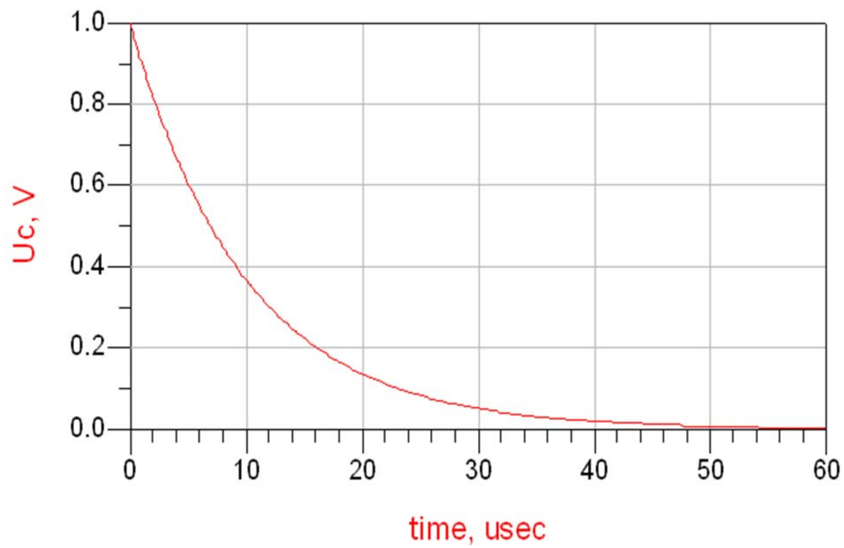
Stearns, S.D, **Circuit stability theory for non-Foster circuit, IMS, June 2013**

What about stability issue?

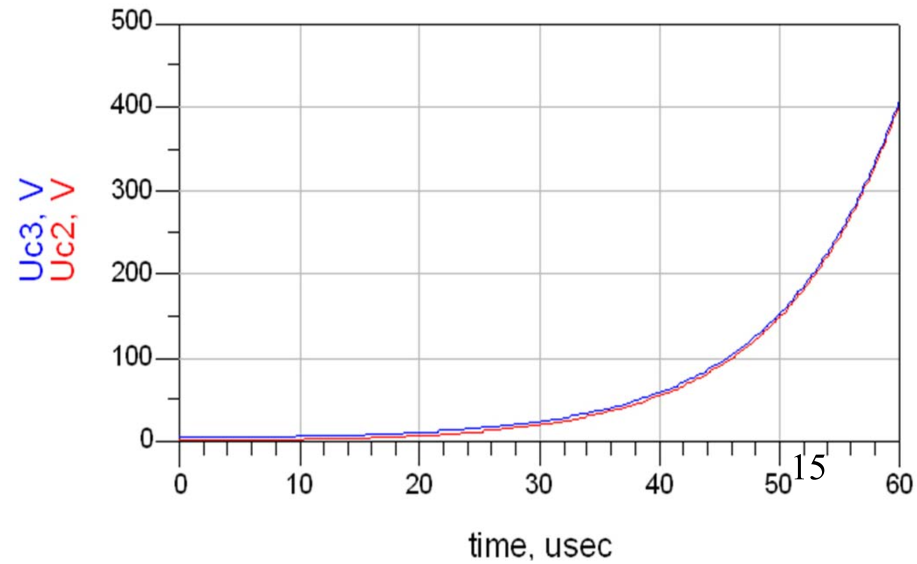


$$u(t) + CR\frac{du(t)}{dt} = 0$$

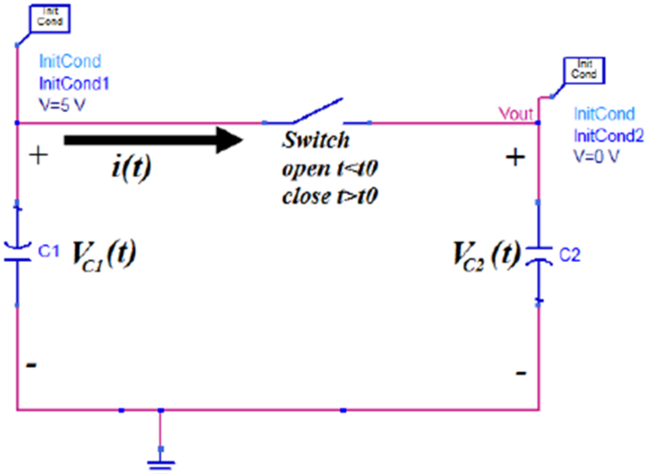
$C > 0$ $\quad u(t) = u(0)e^{-\frac{t}{(RC)}}$



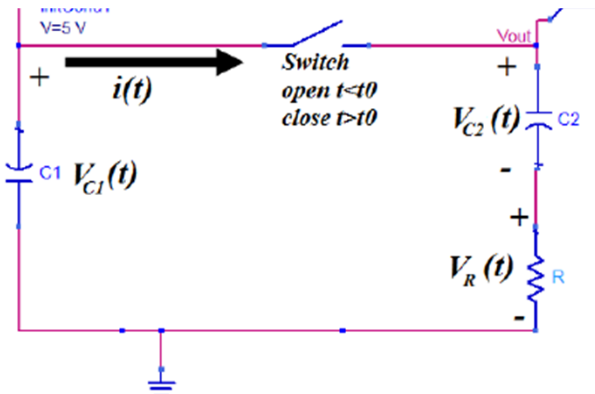
$C < 0$ $\quad u(t) = u(0)e^{-\frac{t}{RC}} = u(0)e^{+\frac{t}{R|C|}}$



Simple approach: keep overall C positive!



sign of C_1	sign of C_2	Stability
+	+	**Stable**
+	-	**Stable**
+	-	**Unstable (if |C_2|>C_1)**



R	$C_{eq}=C_1C_2/(C_1+C_2)$	**Stability**
+	+	Stable (if C_2>0, C_2<0 and |C_2|>C_1)
+	-	Unstable (if |C_2|<C_1)
-	-	Stable
-	+	Unstable

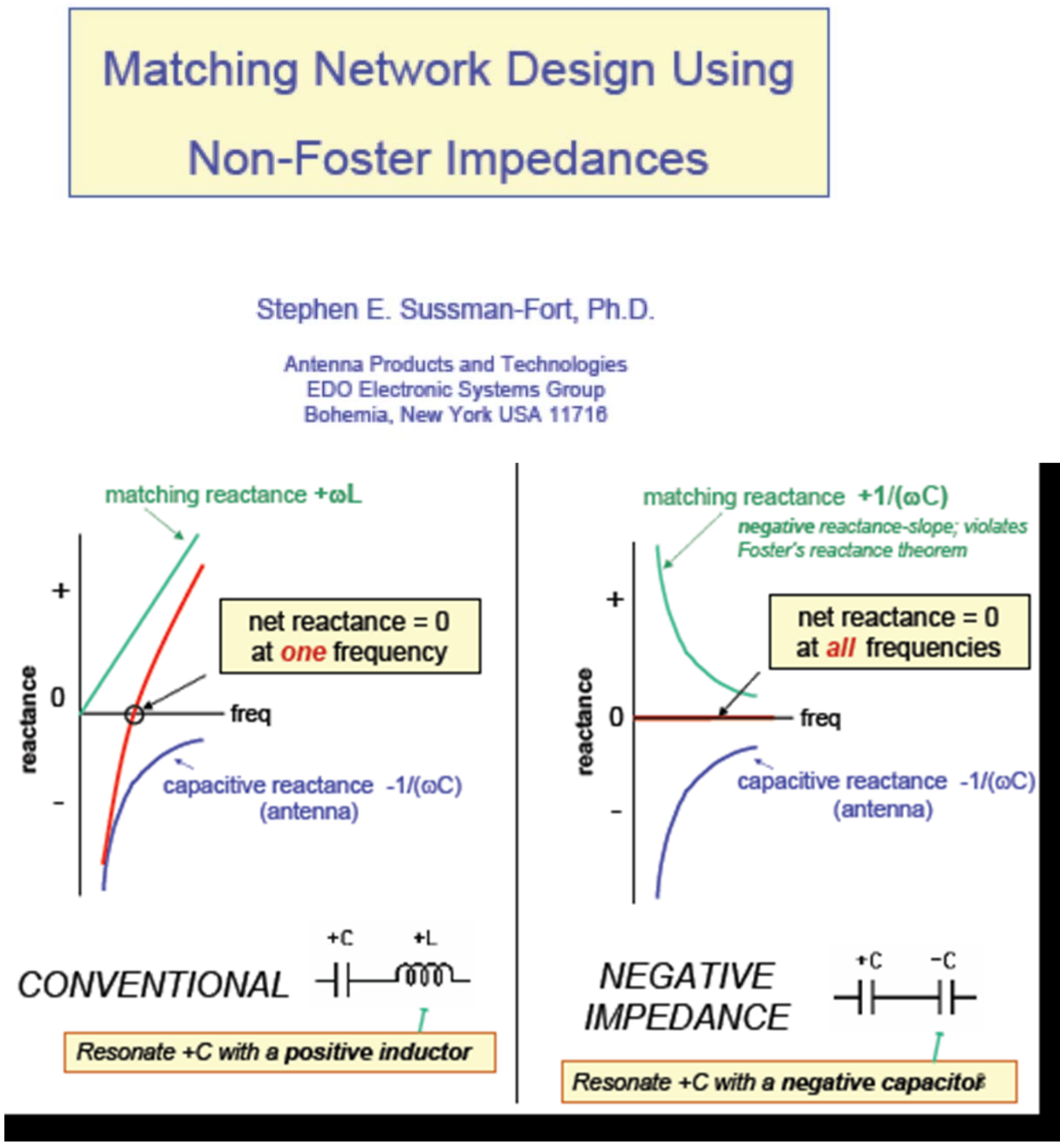
Arbitrarily small but **positive** C (the ENZ behavior) – the stable case.

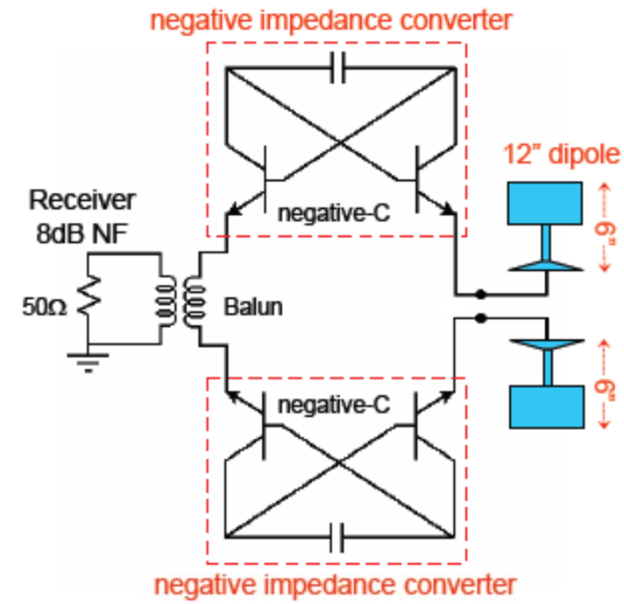
Ugarte-Munoz, E.; Hrabar, S. ; Segovia-Vargas, D. ; Kiricenko, A. **Stability of Non-Foster Reactive Elements for Use in Active Metamaterials and Antennas , IEEE TAP, July 2012**

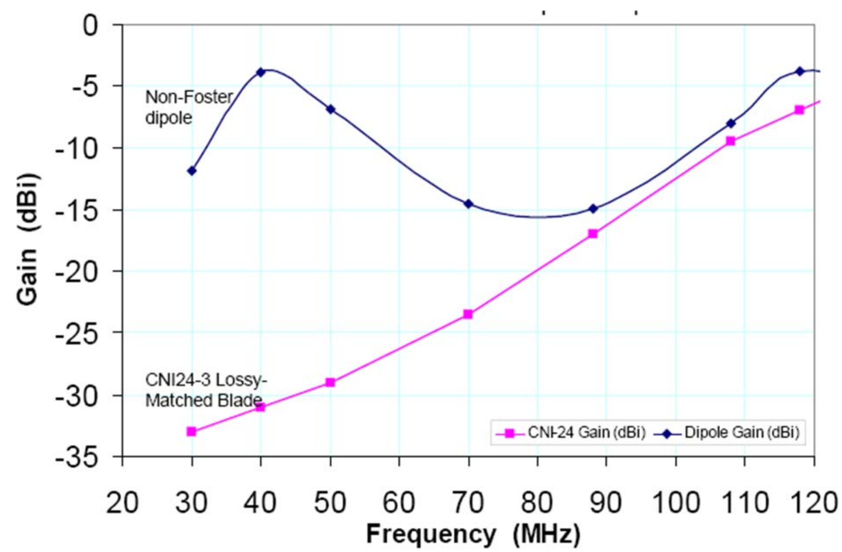
Stearns, S.D, **Circuit stability theory for non-Foster circuit, IMS, June 2013**

Application of Non-Foster elements

- **Matching of small antennas**

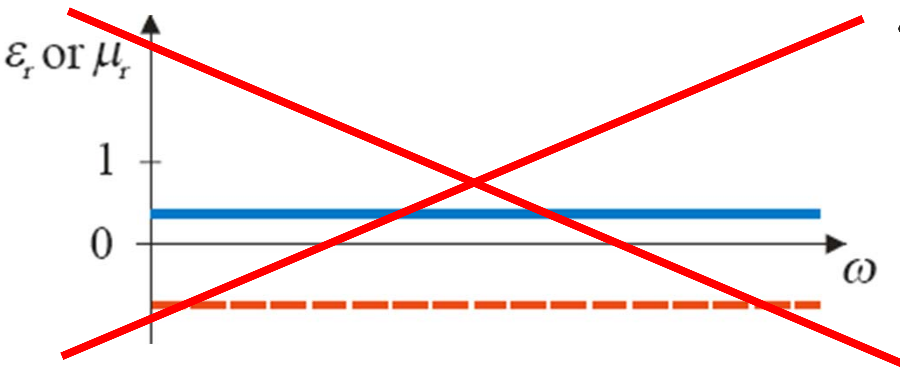


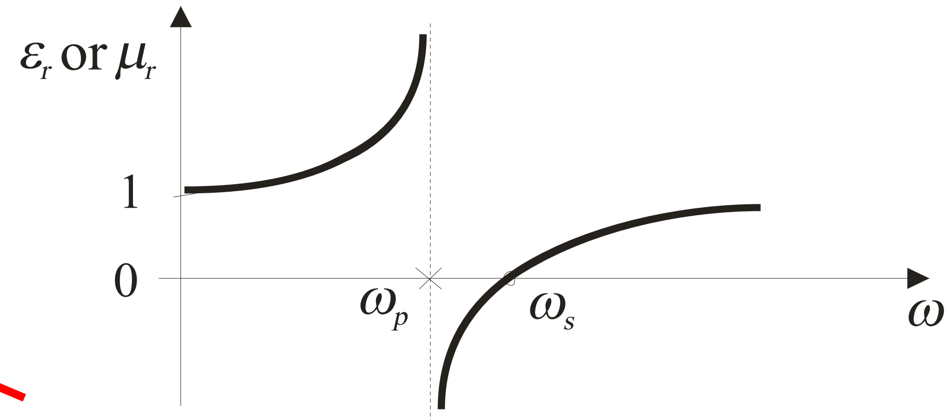




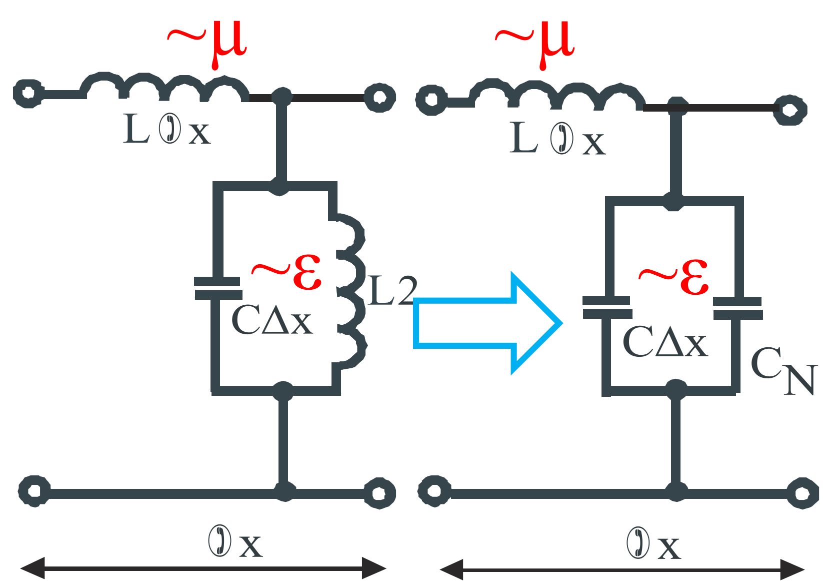
Application of Non-Foster elements

- **Broadband active metamaterials**





Broadband ENZ MTM
(Hrabar et al, APS 2008)



$$C = C_1 + C_2$$

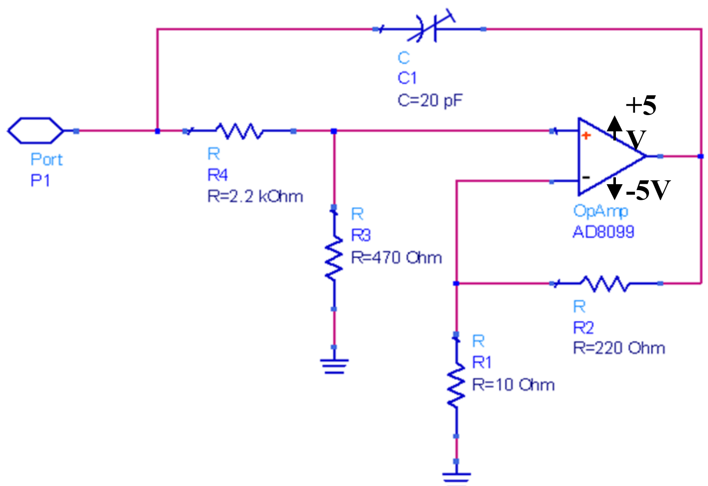
$$\varepsilon_e = \varepsilon_0 + \varepsilon_- = \varepsilon_0 - \left|\varepsilon_-\right| \quad \Rightarrow \quad 0 < \varepsilon < 1$$

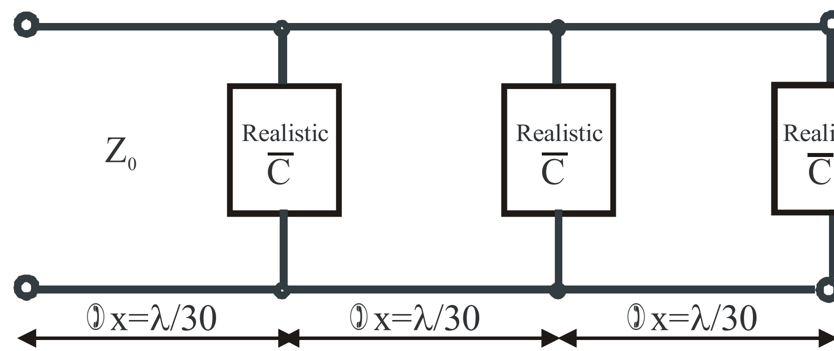
The first introduction of non-Foster transmission line

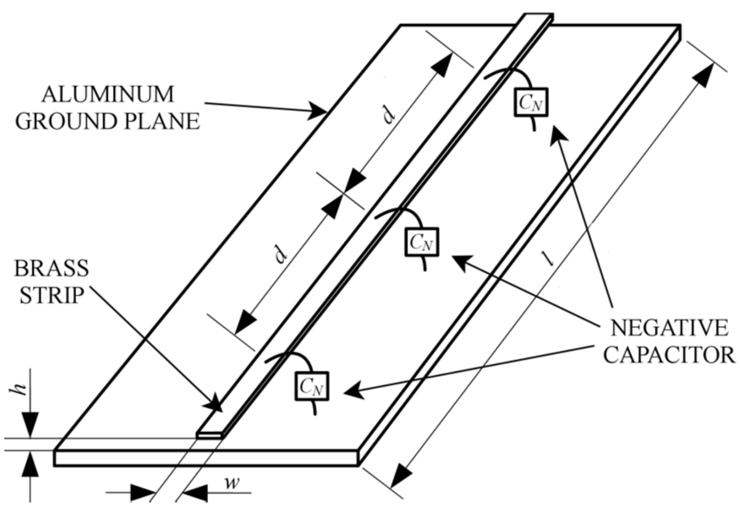
APPLIED PHYSICS LETTERS **99**, 254103 (2011)

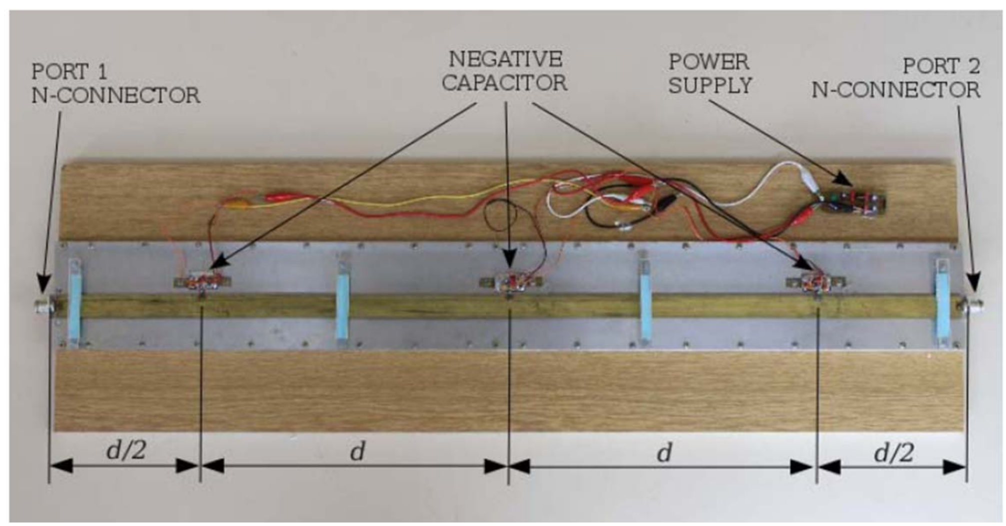
Negative capacitor paves the way to ultra-broadband metamaterials

Silvio Hrabar,[a)] Igor Krois, Ivan Bonic, and Aleksandar Kiricenko
Faculty of Electrical Engineering and Computing, University of Zagreb, Unska 3, Zagreb, HR 10 000, Croatia

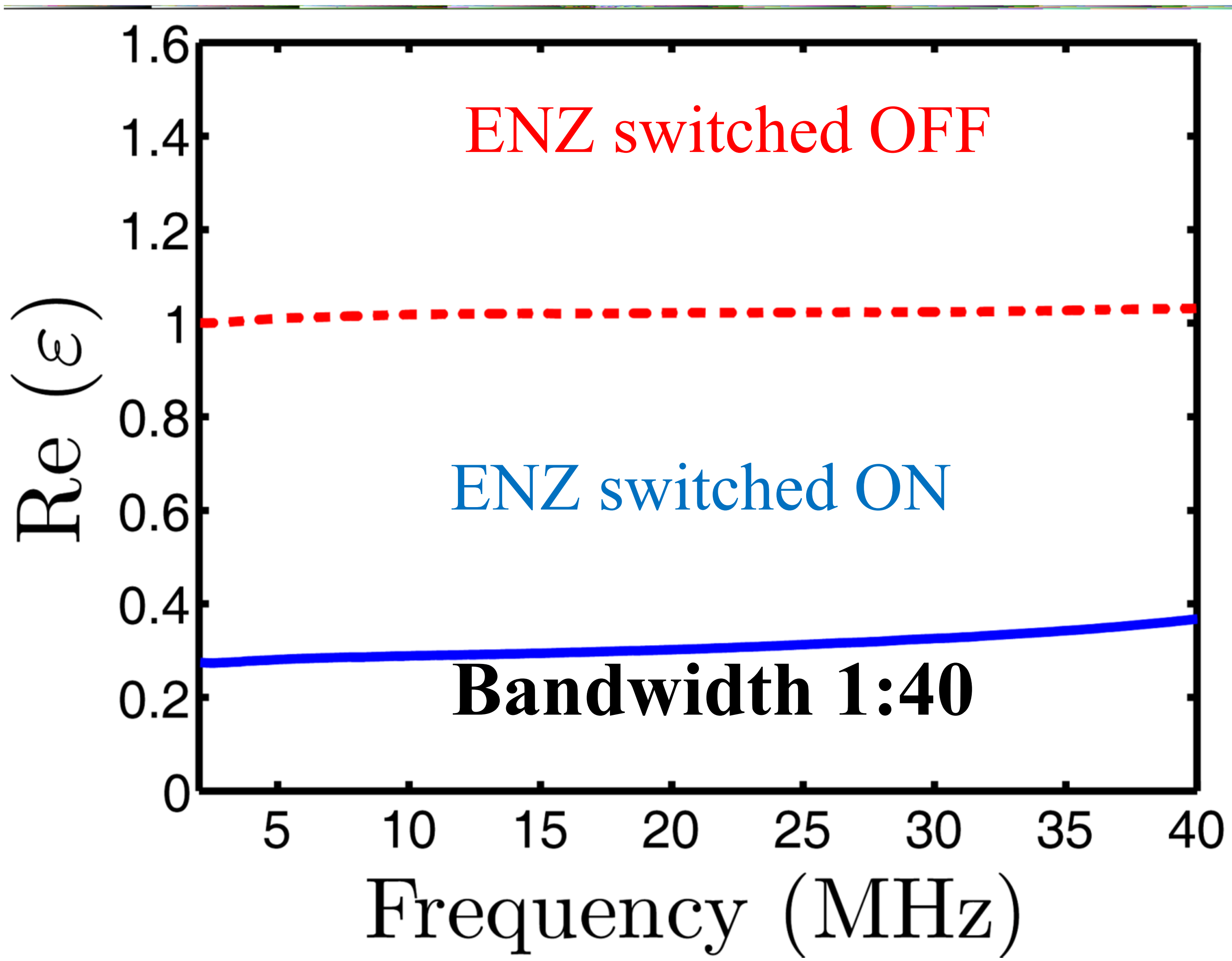








Measurement of effective permittivity of ENZ Active TL with Three Unit Cells



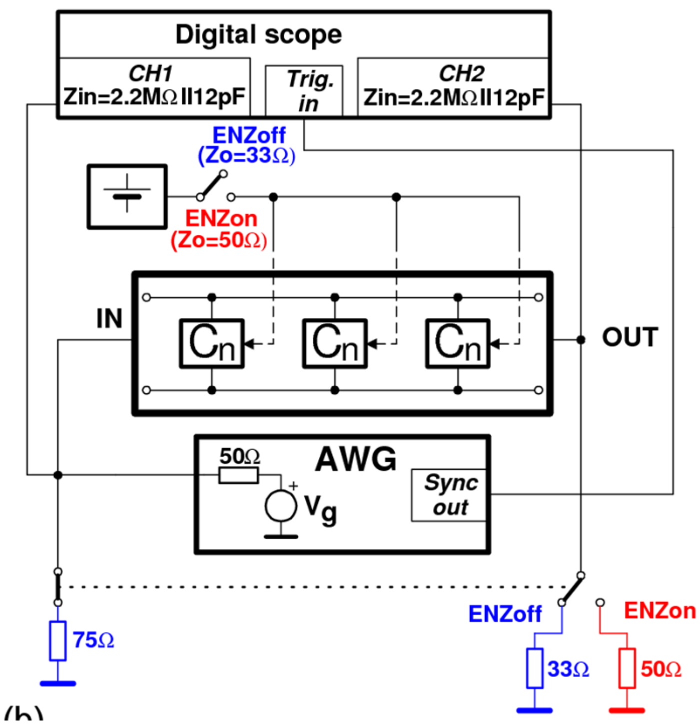
Best passive MTM: 20%!

The newest prototype (1-700 MHz) Bandwidth 1:700 !!!

APPLIED PHYSICS LETTERS **102**, 054108 (2013)

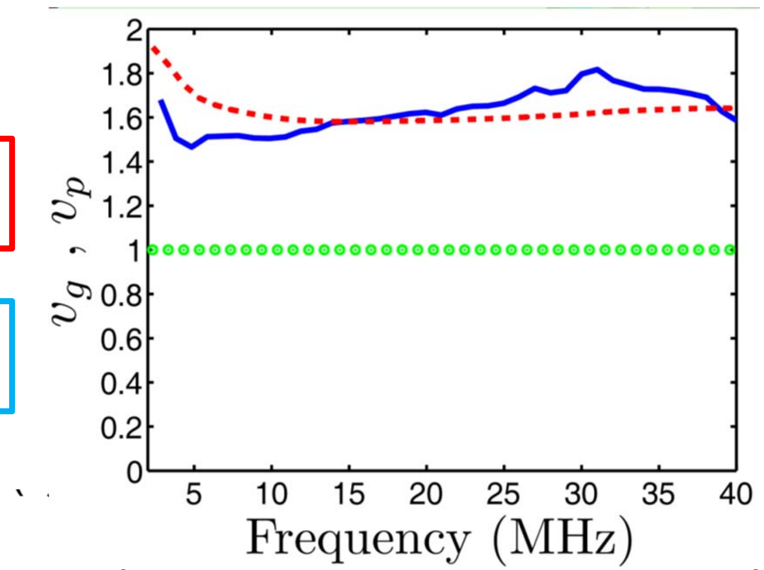
Ultra-broadband simultaneous superluminal phase and group velocities in non-Foster epsilon-near-zero metamaterial

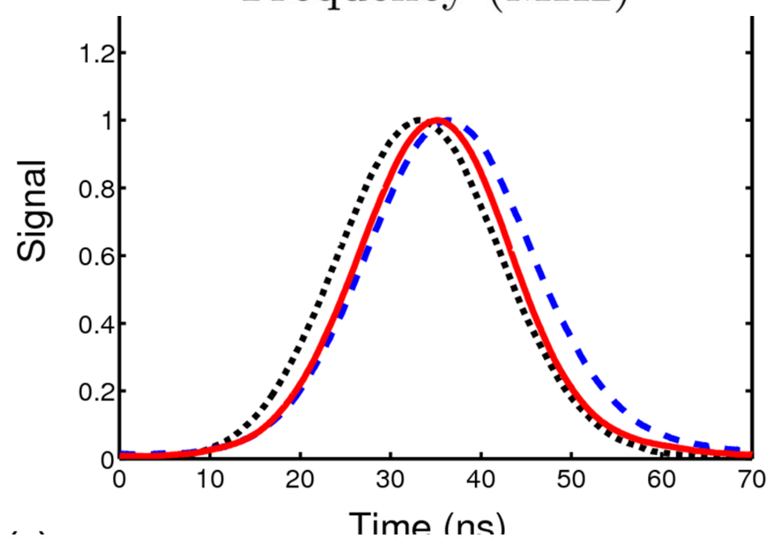
Silvio Hrabar,[a)] Igor Krois, Ivan Bonic, and Aleksandar Kiricenko
Faculty of Electrical Engineering and Computing, University of Zagreb, Unska 3, Zagreb, HR 10 000, Croatia



$v_p > c$

$v_g > c$

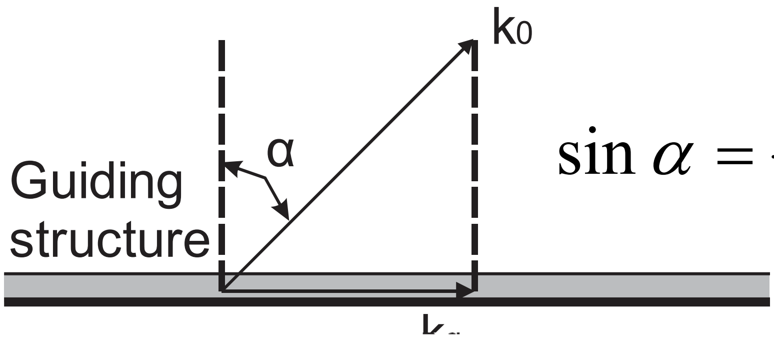




input signal: dashed-black, output signal with ENZ off: dashed-blue, output signal with ENZ on: solid-red

Application of Non-Foster elements

- **Squint-free leaky wave antenna**



$$\sin\alpha = \frac{k_g}{k_0}$$

Classical leaky-wave antena

- fast waves structure ($k_0 > k_g$)

Beam squinting with frequency!

IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS, VOL. 10, 2011

Superluminal Waveguides Based on Non-Foster Circuits for Broadband Leaky-Wave Antennas

Daniel F. Sievenpiper, *Fellow, IEEE*

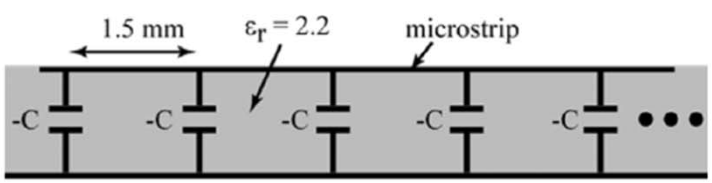


Fig. 5. Superluminal medium constructed with negative capacitors attached between a microstrip line and the ground plane. The geometry is identical to that in Fig. 3. The capacitors are implemented as lumped *RLC* boundaries.

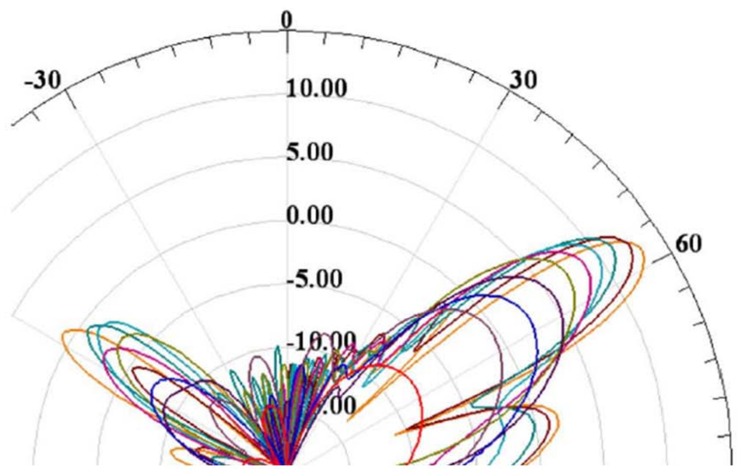
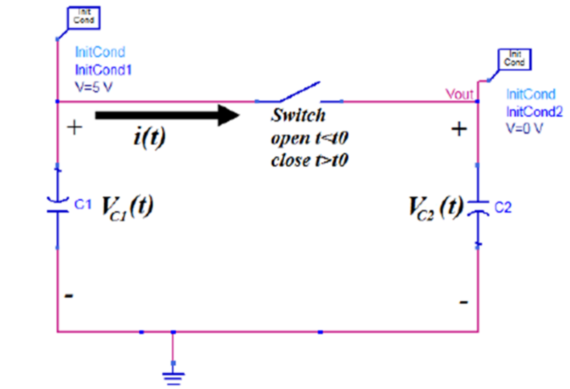


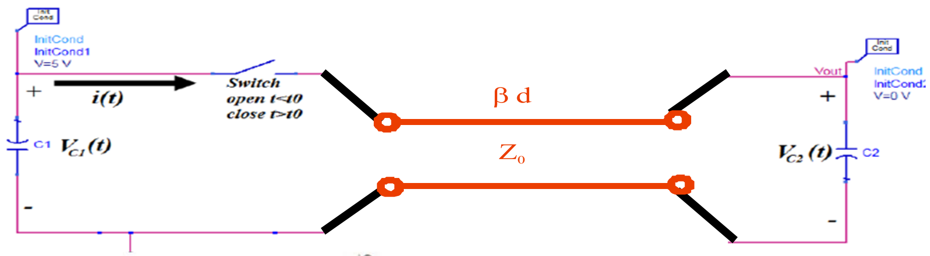
Fig. 6. Radiation patterns (gain in dBi) for the structure shown in Fig. 5 with capacitance values of (a) −33, (b) −45, and (c) −58 fF. The 10 patterns are for 1–10 GHz, and higher gain patterns are for higher frequencies.

Theoreticall proposal!

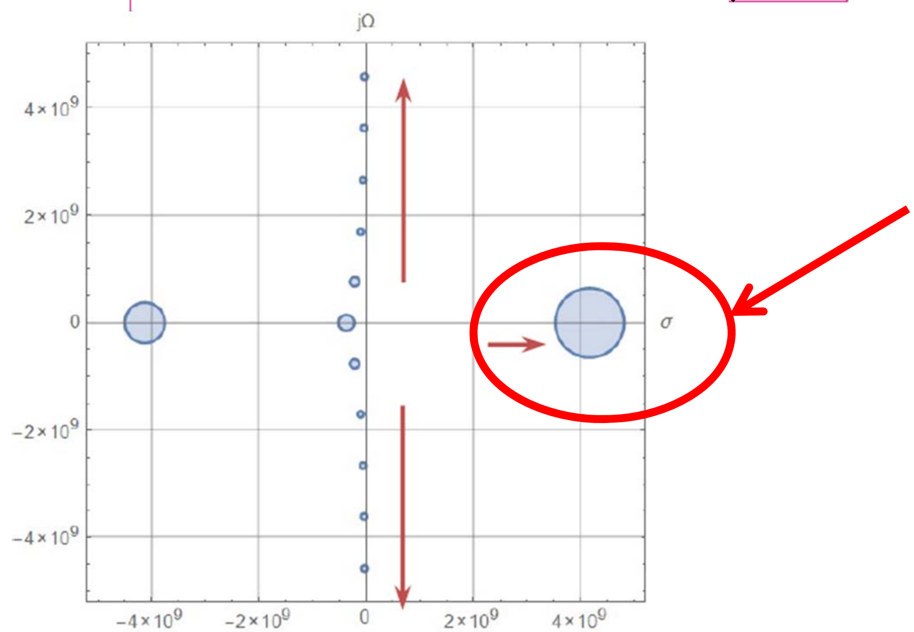
What would happen if a negative capacitor were ideal ?



Stable If $C_1<0$ and abs $(C_1) > C_2$

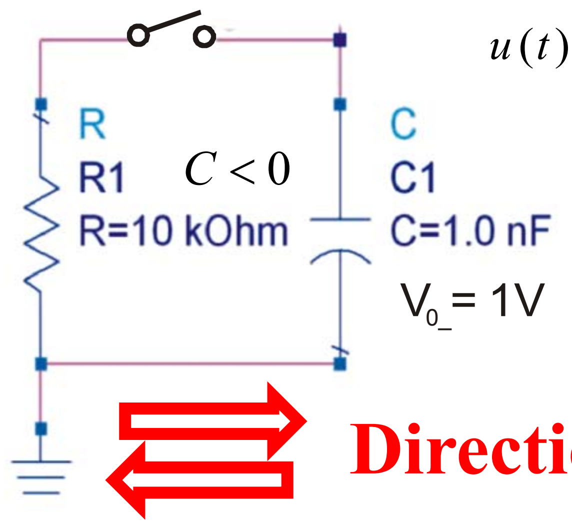


If $C_1<0$, always unstable (except d=0) !???



Inherent unstable pole lies on real axis (DC pole)!

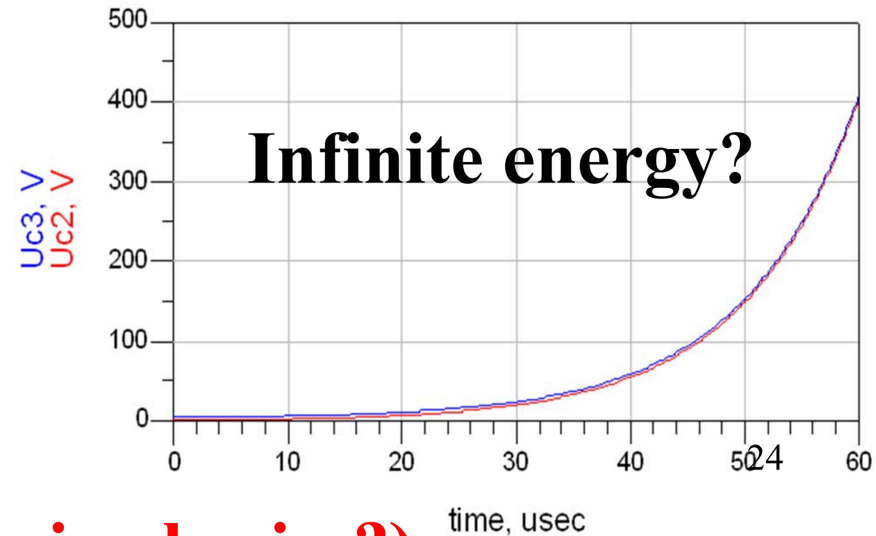
Fortunately, a negative capacitor cannot be ideal !



$$u(t) + CR\frac{du(t)}{dt} = 0$$

$$u(t) = u(0)e^{-\frac{t}{RC}}$$

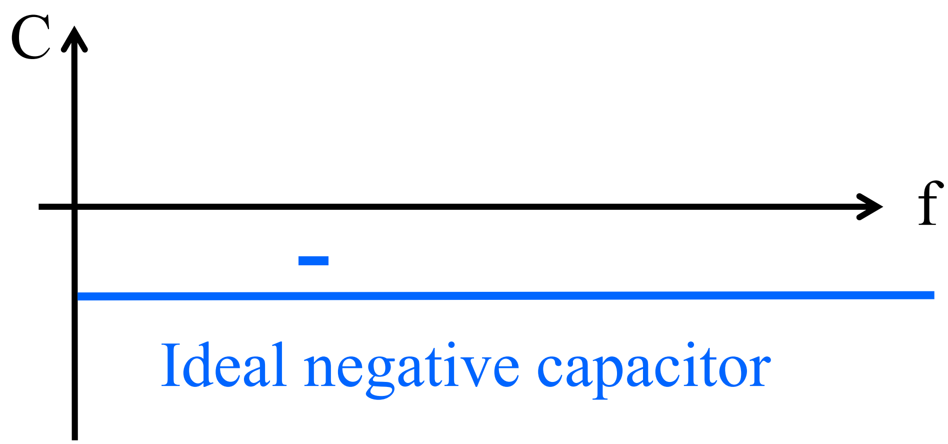
$$= u(0)e^{+\frac{t}{R|C|}}$$

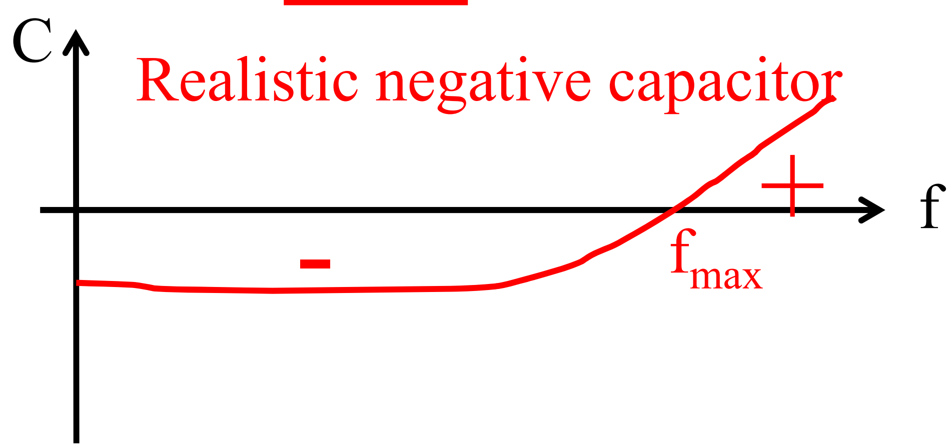


Direction of energy flow (i.e. basic physics?)

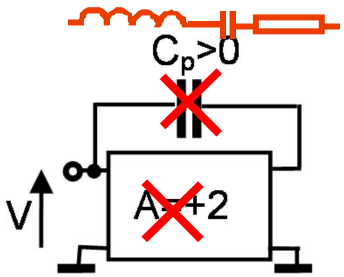
If ε_r<1 and entirely dispersive, the energy would travel superluminally !?

$$v = \frac{c}{\sqrt{\varepsilon\mu}},$$



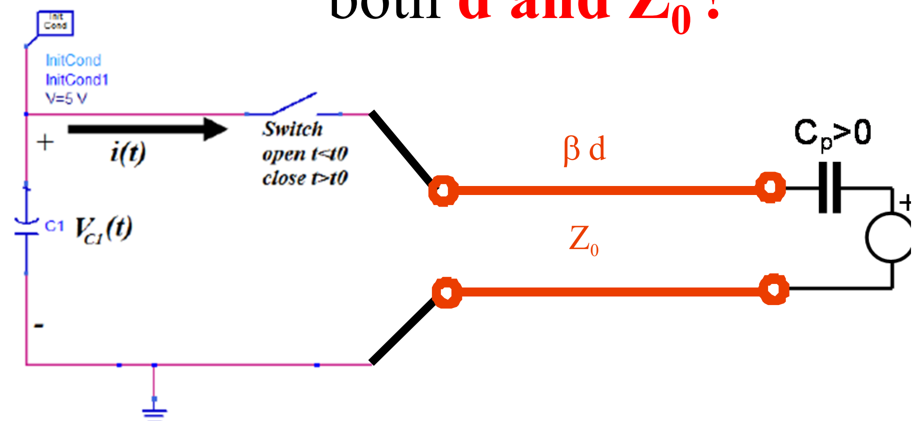


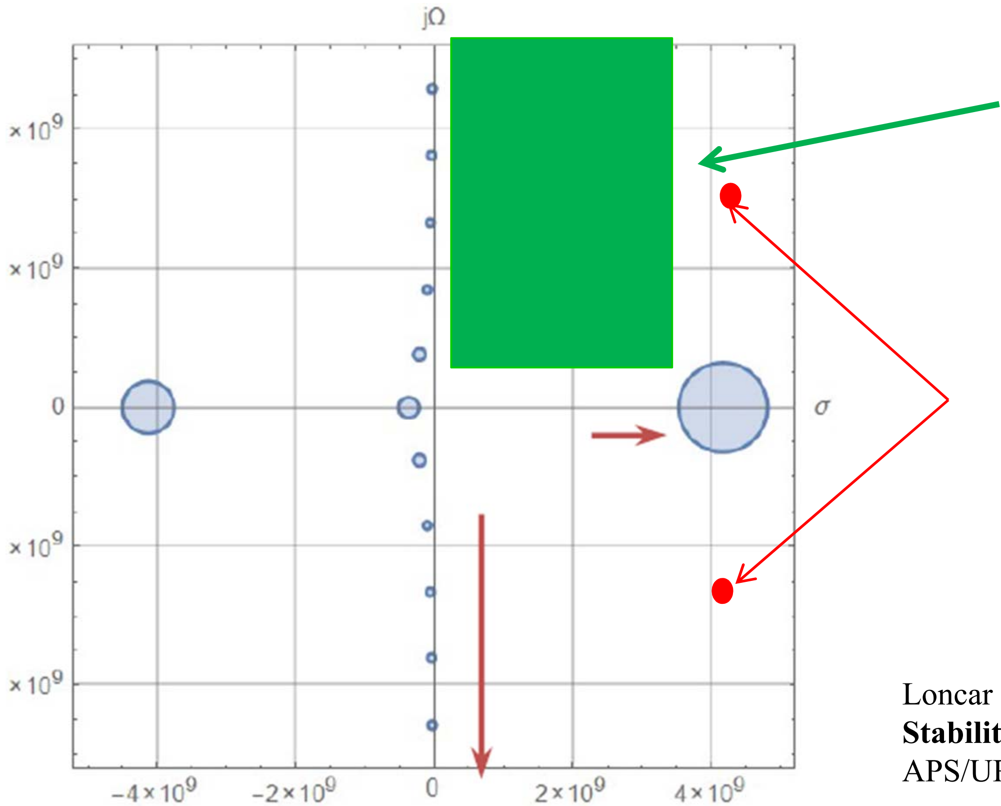
Tailoring non-ideal behavior in order to assure stable operation



$$A(s) = \frac{A_0}{1+s\tau}, \omega_p = \frac{1}{\tau}$$

Stability depends on both **d and Z_0 !**



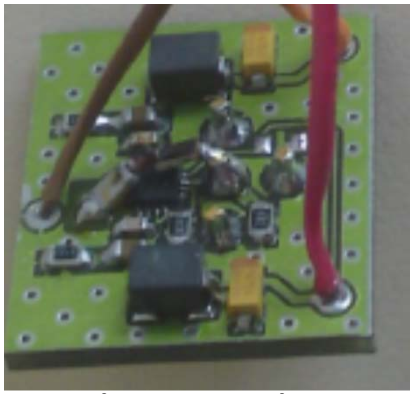


DC pole can be 'removed' by restricting operating region!

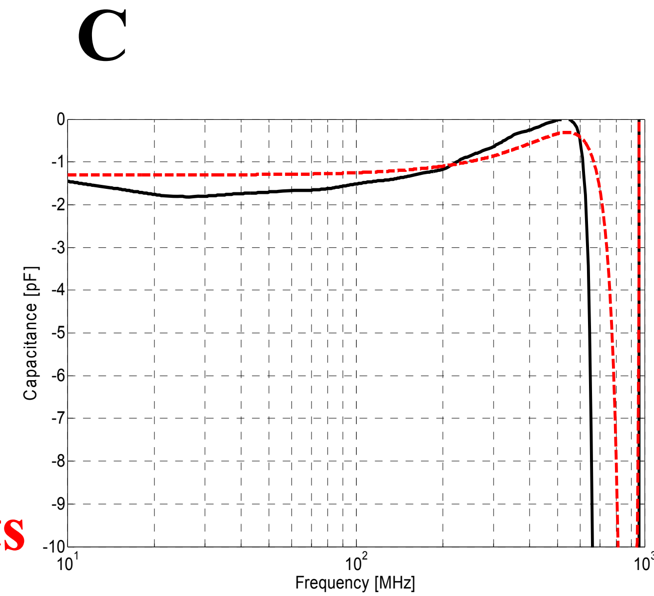
Complex poles can be 'removed' by appropriate selection of line length and properties of the amplifier!

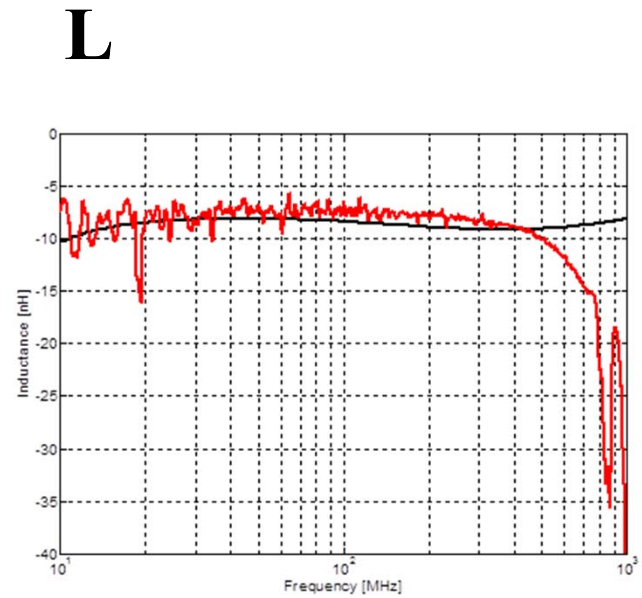
Loncar J, Muha D.. Hrabar, S. ; **Influence of Transmission Line on Stability of Networks Containing Ideal Negative Capacitors,** APS/URSI 2015

Tunable negative capacitor and negative inductor (100 kHz - 700 MHZ, 9 octaves!), Hrabar, Krois, Muha, EOARD 2013)



- simulation
- measurements

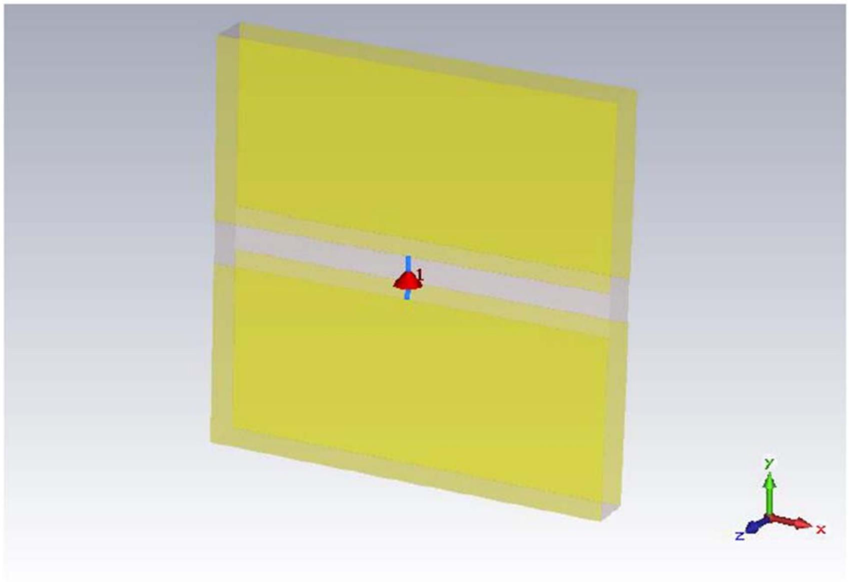


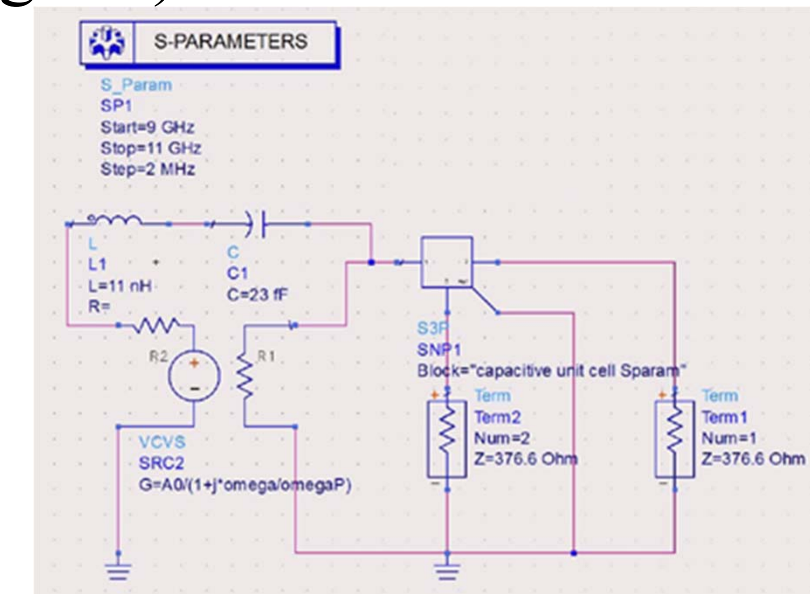


Extracted equivalent parameters of experimental 2D unit cell

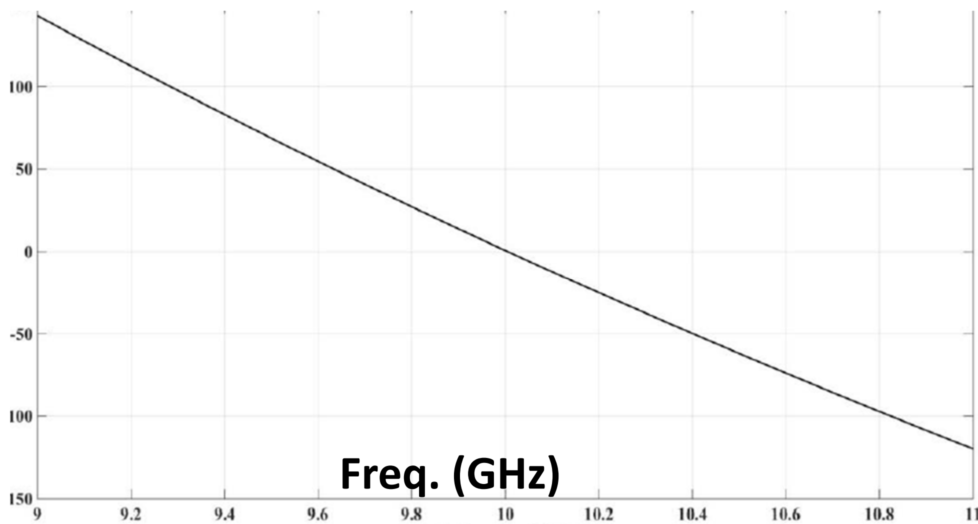
ENZ cell: relative permittivity of **0.2 – 0.8** (dispersion ± 15%, operating bandwidth **100 kHz-700 MHz**).
MNZ cell: relative permittivity of **0.3 – 0.5** (dispersion ± 20%, operating bandwidth **100 kHz-700 MHz**)

Construction of an entire non-Foster FP metasurface (in progress)

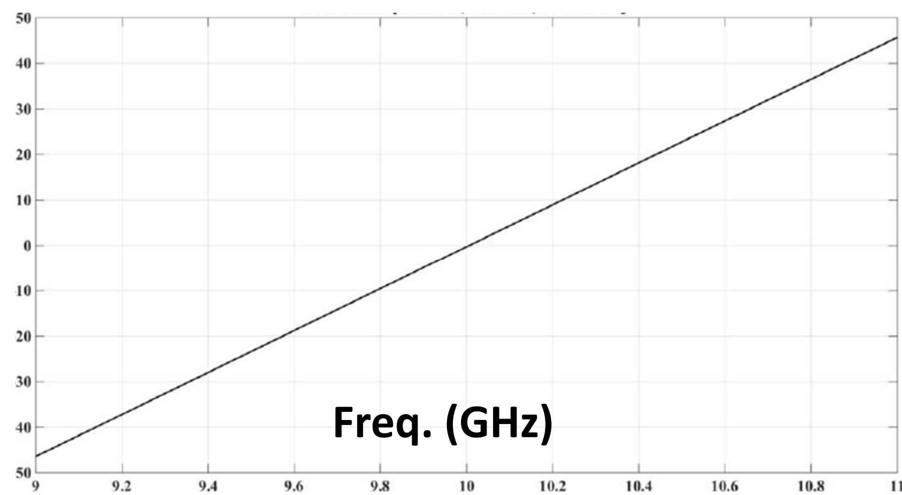




Im(surface reactance) (ohm)



Re(surface reactance)) (ohm)



Conclusions

- An idea of a broadband FP antenna with active non-Foster metasurface has been presented

- Analytical and numerical results have revealed ten-fold BW improvement in comparison to ordinary FP antenna

- It was shown analytically, numerically and experimentally that is feasible to build a stable negative RLC circuit needed for a non-foster FP antenna

- Both discrete and integrated versions of active non-Foster elements needed for a non-foster FP antenna have been constructed and successfully tested

- Design and prototyping of the whole antenna is in progress