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

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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-supervisor
- 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

FP parallel-plate cavity

Phenomenon of constructive interference

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

PRS contribution

\[ \Gamma = R e^{i\psi} \]

ground plane contribution

FP cavity contribution
Classical FP antenna – maximal directivity

For maximal directivity one choose

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

\[ D_{e0} = \frac{(1 + R)}{(1 - R)} \]

\( D_{e0} \) is typically in the order of 20 dB.
FP antenna –
How to compensate for the frequency dependence?

Excitation antenna

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?

- $\beta d$ decreases with the frequency
- $\psi$ decreases with the frequency

$\Gamma_{GP} = 1e^{j\pi}$
$\Gamma_{PRS} = Re^{j\psi}$
FP antenna –
How to compensate the frequency dependence?

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

$\beta d$ decreases with the frequency

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

$\psi$ decreases with the frequency
FP antenna –
How to compensate the frequency dependence?

\[ jX \text{ – artificial reactive surface} \]
\[ \Gamma_X = 1e^{j\chi} \]
\[ \frac{\partial \chi}{\partial \omega} > 0 \Rightarrow \frac{\partial X}{\partial \omega} < 0 \]

Non-Foster behavior is required!

\[ jX \]
\[ \beta d \text{ decreases with the frequency} \]
\[ \psi \text{ decreases with the frequency} \]
Novel FP antenna with non-Foster metasurface

\[ jX - \text{artificial reactive surface} \]

\[ \Gamma_X = 1e^{j\chi} \]

\[ \frac{\partial \chi}{\partial \omega} < 0 \Rightarrow \frac{\partial X}{\partial \omega} < 0 \]

Non-Foster behavior is required!

\[ \beta d \text{ decreases with the frequency} \]

\[ \psi \text{ decreases with the frequency} \]
What are Non-Foster (negative) reactive elements needed for broadband FP antenna?

![Diagram showing reactance and circuit components]

<table>
<thead>
<tr>
<th>Non-Foster surface type</th>
<th>Series LC tank circuit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design frequency, Hz</td>
<td>$f_0$</td>
</tr>
<tr>
<td>PRS impedance @ $f_0$, Ω</td>
<td>$(-j100 \</td>
</tr>
<tr>
<td>Normalized inductance, H·Hz</td>
<td>$-110 / f_0$</td>
</tr>
<tr>
<td>Normalized capacitance, F·Hz</td>
<td>$-230e-6 / f_0$</td>
</tr>
<tr>
<td>PRS distance</td>
<td>$0.54 \lambda_0$</td>
</tr>
</tbody>
</table>

![Graph showing reflection phase vs. normalized frequency]
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)

\[ V = I \times Z \]

\[ V_0 = 2V \]

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

Floating negative impedance (Linvill, 1953)
What about stability issue?

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

WRONG !!!

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


Stearns, S.D, Circuit stability theory for non-Foster circuit, IMS, June 2013
What about stability issue?

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

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

\[ C < 0 \quad u(t) = u(0)e^{-\frac{t}{RC}} = u(0)e^{+\frac{t}{RC}} \]
Simple approach: keep overall $C$ positive!

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

<table>
<thead>
<tr>
<th>$C_1$</th>
<th>$C_2$</th>
<th>Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>+</td>
<td>Stable</td>
</tr>
<tr>
<td>+</td>
<td>-</td>
<td>Stable</td>
</tr>
<tr>
<td>+</td>
<td>-</td>
<td>Unstable (if $</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$R$</th>
<th>$C_{eq} = C_1C_2/(C_1+C_2)$</th>
<th>Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>+</td>
<td>Stable (if $C_2 &gt; 0$, $C_2 &lt; 0$ and $</td>
</tr>
<tr>
<td>+</td>
<td>-</td>
<td>Unstable (if $</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>Stable</td>
</tr>
<tr>
<td>-</td>
<td>+</td>
<td>Unstable</td>
</tr>
</tbody>
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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)

\[ C = C_1 + C_2 \]

\[ \varepsilon_e = \varepsilon_0 + \varepsilon_- = \varepsilon_0 - |\varepsilon_-| \implies 0 < \varepsilon < 1 \]
The first introduction of non-Foster transmission line

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Negative capacitor paves the way to ultra-broadband metamaterials

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

![Diagram of the circuit and components related to non-Foster transmission line.](image-url)
Measurement of effective permittivity of ENZ
Active TL with Three Unit Cells

ENZ switched OFF

ENZ switched ON

Bandwidth 1:40

Best passive MTM: 20%!

The newest prototype (1-700 MHz) Bandwidth 1:700!!!
Ultra-broadband simultaneous superluminal phase and group velocities in non-Foster epsilon-near-zero metamaterial

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

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

Classical leaky-wave antenna - fast waves structure ($k_0 > k_g$)

Beam squinting with frequency!

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.
What would happen if a negative capacitor were ideal?

Stable If $C_1 < 0$ and $\text{abs}(C_1) > C_2$

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

Inherent unstable pole lies on real axis (DC pole)!
If $\varepsilon_r < 1$ and entirely dispersive, the energy would travel superluminally!?

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

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

If $\varepsilon_r < 1$ and entirely dispersive, the energy would travel superluminally!?

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

Fortunately, a negative capacitor cannot be ideal!
Tailoring non-ideal behavior in order to assure stable operation

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!

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)

Freq. (GHz)
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 it 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