IN MEMORIAM
JULIEN PERRUISSEAU-CARRIER
1979 - 2014

Sean Victor Hum

22 July 2015

Lausanne, SWITZERLAND, 23 April 2014

Julien Perruisseau-Carrier

- Born in Lausanne, Switzerland on October 30, 1979
  - Swiss and French nationality
- Avid sportsman (tennis, skiing, swimming)
- Passionate guitar player
- Member of the Social Democratic Party in Switzerland

Julien Perruisseau-Carrier: Chronology

1999 – 2003	M.Sc. in Electrical Engineering, *EPFL, Switzerland*
2003	Junior scientist, *University of Birmingham, UK*
2004 – 2007	Ph.D. in Electrical Engineering, *EPFL, Switzerland* Topic: *Microwave Periodic Structures Based on MicroElectroMechanical Systems (MEMS) and Micromachining Techniques*
2007 – 2011	Research associate (PDF), *CTTC, Barcelona, Spain*
2011 – 2014	Professor (Swiss National Science Foundation), *EPFL, Switzerland*

Adaptive MicroNano Wave Systems Lab at EPFL: From Microwaves to THz

Dynamic reconfiguration

- Update device functionality in real time
- Sense and adapt to environment

Joint antenna-coding techniques

- Higher data-rate and lower-power
- MIMO
- Disruptive techniques for reduced complexity mobile terminals

Artificial EM materials

- Tailor extraordinary effective EM properties

Use of micro/nano-technology:

Graphene, MEMS, Electroactive polymers…

- EM performance, higher freq., integration, low power
- Novel sensing applications (graphene)

Adaptive MicroNano Wave Systems Lab at EPFL

- Associated with two EPFL laboratories:
  - Laboratory of Electromagnetics and Acoustics (LEMA, Prof. Mosig)
  - Nanoelectronic Devices Group (Nanolab, Prof. Ionescu)
- Included 3 PostDocs and 5 PhD students

FNSNF
SWISS NATIONAL SCIENCE FOUNDATION
esa
SEVENTH FRAMEWORK PROGRAMME
ThalesAlenia Space
cost
HASLERSTIFTUNG

Julien's PhD students and subjects (2012/13 – 2015/16)

- **Reduced-complexity Antennas / RF Front-ends for MIMO Systems** by Mohsen Yousefbeiki.
- **Graphene RF-NEMS** by Pankaj Sharma.
- **Adaptive millimeter-wave and THz devices based on electro-active polymers**, by Pietro Romano.
- **Theory, design, and measurement of near-optimal graphene reconfigurable and non-reciprocal devices**, by Michele Tamagnone.
- **New Frontiers in Reflectarray Systems**, by Hamed Hasani.

Julien's PDFs

- **J. Sebastian Gomez-Diaz**, now at U. of Austin (Prof. Alu)
- **Eduardo Carrasco Yepez**, now with IT'IS Zurich, Switzerland
- **Daniel Rodrigo**, now with Prof. Haltug at EPFL, Switzerland

Julien's Achievements

- Nearly 200 contributions, 80 journal papers (2007-2015)
  - *IEEE Transactions, Journal of Applied Physics*, *Optics Express*, and *Nature Photonics*
- 1555 citations (Google Scholar)
- h-index of 21 (Google Scholar)
- Senior Member of the IEEE
- Received URSI Young Scientist Award twice
- Recipient, Uslenghi Letters Prize Paper Award, 2015 (with M. Tamagnone)

Julien's Involvement and Service

- Associate Editor of the *IEEE Transactions on Antennas and Propagation*, 2012-2014
- Member of the MTT-25 Technical Committee on RF Nanotechnology (2013)
- Switzerland's National Delegate in Commission B on "Fields and Waves" of the International Union of Radio Science (URSI)
- European Coordination Action COST IC1102 "Versatile, Integrated, and Signal-Aware Technologies for Antennas" (VISTA)
- Actively involved with EuCAP, EurAAP, IEEE AP-S

Julien's Collaborations

- CTTC, Spain (X. Artiga and others)
- IBM Thomas J. Watson Research Center, USA (T. Low)
- DESI Center Free-Electron Laser Science, Germany. (A. Fallahi)
- UPC Barcelona Spain (J. Romeu)
- UPM, Madrid, Spain (J.A. Encinar)
- U. of Cartagena, Spain (J. S. Gomez-Diaz, A. Alvarez-Melcon)
- METU Ankara (O. Aydin Civi, C. Guclu)
- University of Geneva, Switzerland (A. Kuzmenko)
- U. of Zagreb, Croatia (S. Hrabar, J. Bartolic)
- Aalborg University (O. N. Alrabadi)
- Athens IT, Greece (A. Kalis)
- EPFL Switzerland (many Labs and Groups)
- ECE, U. of Toronto, Canada (S. V. Hum)

My Connection to Julien

- Met in 2007 at the IEEE Electromagnetic Theory Symposium, Ottawa, Canada
- Short course with Julien, J. A. Encinar, and K. van Caekenberghe at EuCAP 2011 on “Electronically Scanned Reflectarrays”
- Short course with Julien and J. A. Encinar at IEEE APS 2012 on “Reflectarray Antennas: Design, Reconfigurability And Potential Applications”

Lausanne, SWITZLERLAND, 2014

My Connection to Julien

- Published invited review paper in 2014, “Reconfigurable reflectarrays and array lenses for dynamic antenna beam control: A review,” *IEEE Trans. Antennas Propag.*
- Lecturer with Julien (posthumous), J. A. Encinar, others in 2014 European School of Antennas on “Arrays and Reflectarrays”
- Fellow Associate Editor, IEEE Transactions on Antennas and Propagation


Rome, ITALY, 2011


The Hague, NETHERLANDS, 2014

Advances in Reconfigurable Antennas and Space-Fed Arrays: Contributions by Julien Perruisseau-Carrier

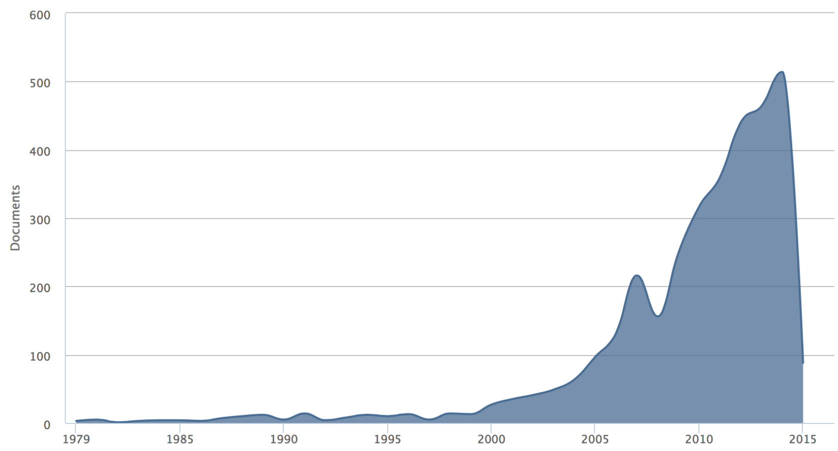
Sean Victor Hum

University of Toronto

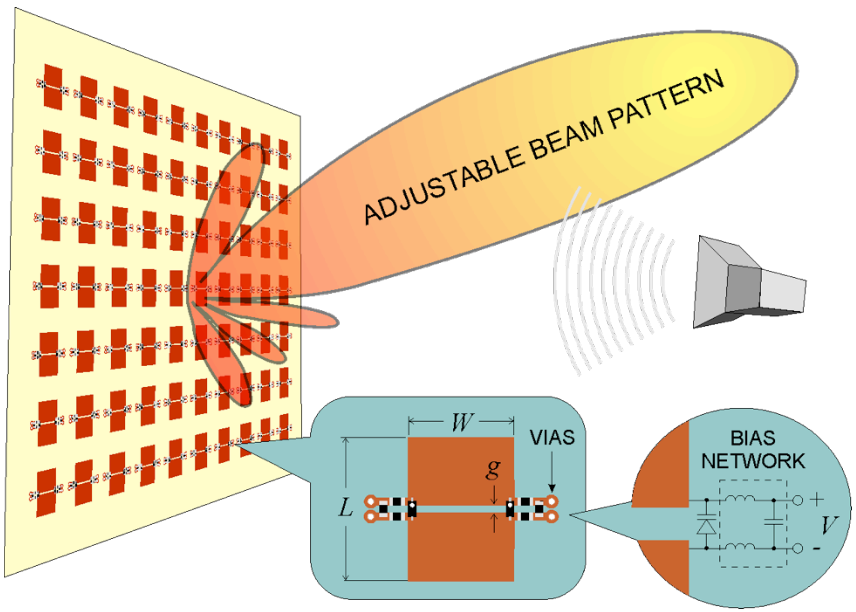
Reconfigurability in Electromagnetics

- The idea of reconfigurable EM devices fascinated Julien throughout his career
- He applied reconfigurable concepts to space-fed arrays (reflectarrays, transmitarrays), as well as antennas

GLOBAL PUBLICATIONS ON RECONFIGURABLE ANTENNAS (SOURCE: SCOPUS)



Reconfigurable Surfaces: Reflectarrays



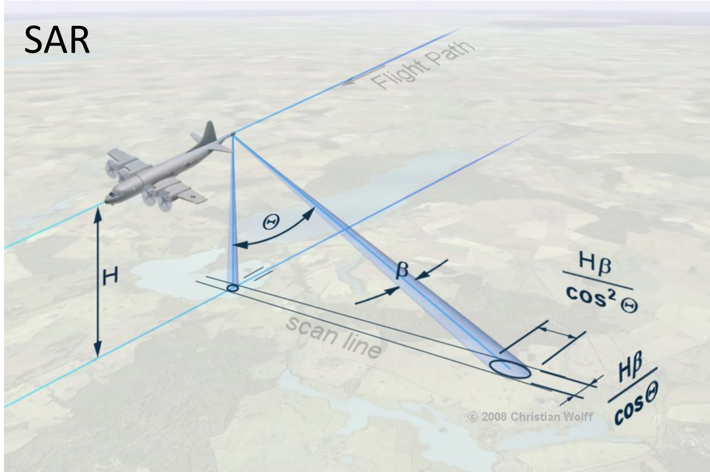
EXAMPLE OF SEMICONDUCTOR-BASED RECONFIGURABLE REFLECTARRAY

S. V. Hum, M. Okoniewski, and R. J. Davies, IEEE Trans. Antennas Propag., vol. 55, no. 8, pp. 2200–2210, Aug. 2007.

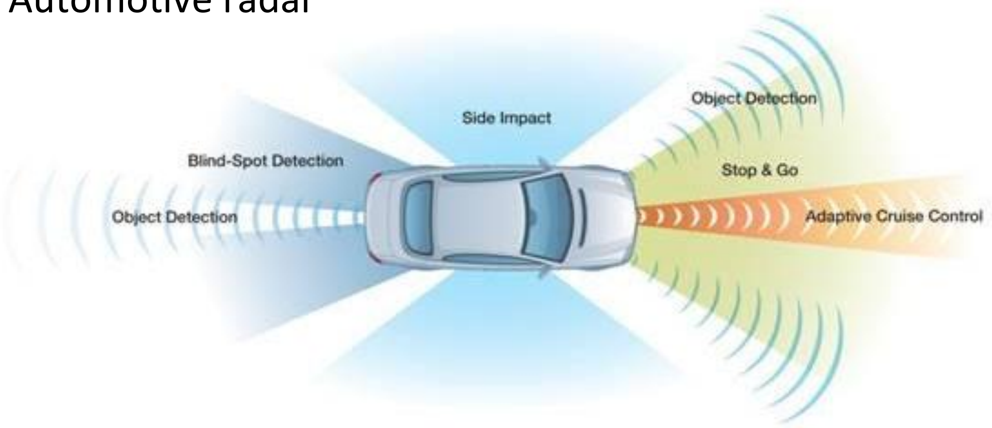
- Reconfigurable reflectarrays allow for real-time adaptive beam steering / synthesis
- Provide gain of a reflector antenna with the flexibility of an array
- Feed losses and layout problems eliminated through the use of a spatial feed

Applications of Adaptive Apertures

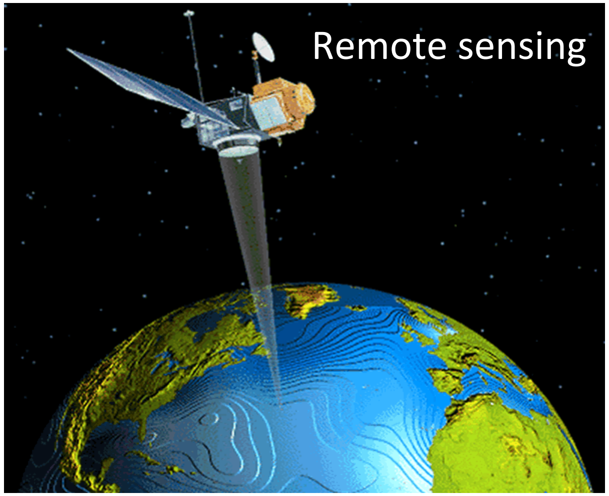
SAR



Automotive radar



Remote sensing

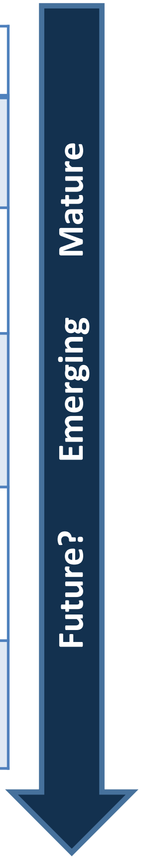


Adaptive satellite antennas for mobile applications

Image credits: radartutorial.eu, Freescale, Westjet

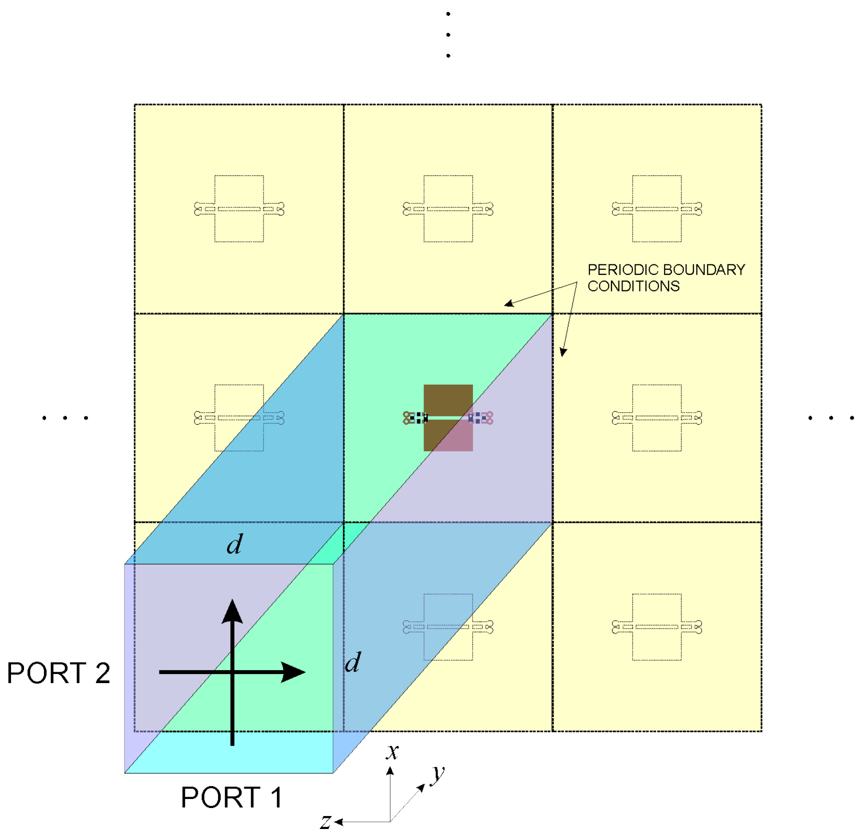
Technologies for Microwave Reconfiguration

	Pros	Cons
Ferrite devices	• Reliability • Power handling	• Bulky • Magnetic control
Semiconductors	• Reliability • Availability	• Non-linearities • Losses • Power consumption
MEMS	• Very low loss • High Freq. • 'Zero' power consumpt. • Very linear • Integration	• Reliability, availability • Switching speed • Precision
Liquid Crystals	• Suitable to very high freq. (upper mm-wave) • Cheap?	• Loss at microwave frequencies • Switching speed • Sensitivity (temp., initial state, etc.)
NEMS (CNT, graphene)	• Integr. with nanoelectronics • Switching speed	• Very few capabilities demonstrated yet!

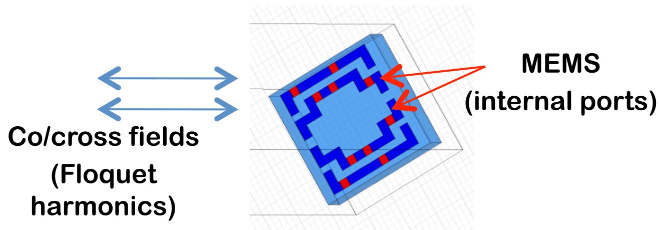


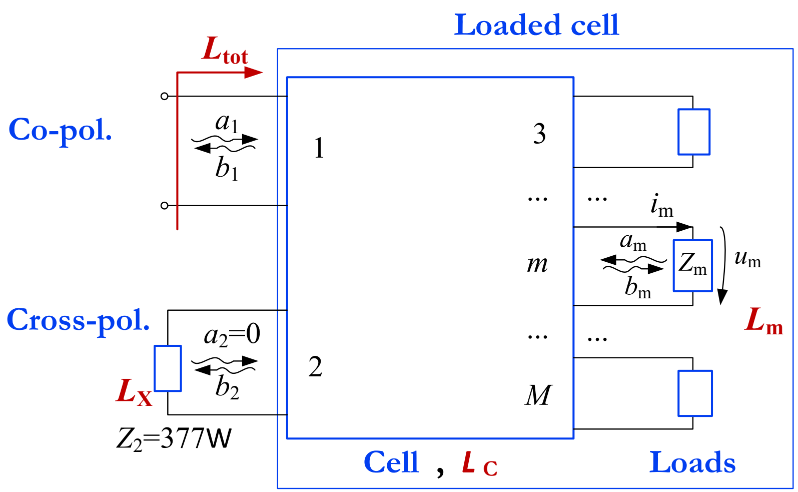
Major Theoretical Contributions: Efficient Modeling of Lumped Elements

- Similar to standard reflectarray cells, scattering response determined by placing cell in periodic (Floquet) waveguide (infinite array analysis)
- Broadside characterization using PEC / PMC boundary conditions
- TE / TM / TEM reflection coefficient Γ measured
  - Magnitude (reflection loss)
  - Phase
  - Polarization



Major Theoretical Contributions: Efficient Modeling of Lumped Elements





J. Perruisseau-Carrier *et al*, "Contributions to the modeling and design of reconfigurable reflecting cells embedding discrete control elements," *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 6, pp. 1621–1628, 2010.

$$\begin{bmatrix} \mathbf{b}_{12} \\ \mathbf{b}_{3M} \end{bmatrix} = \begin{bmatrix} \mathbf{S}_A & \mathbf{S}_B \\ \mathbf{S}_C & \mathbf{S}_D \end{bmatrix} \begin{bmatrix} \mathbf{a}_{12} \\ \mathbf{a}_{3M} \end{bmatrix}$$

$$\mathbf{\Gamma} = \mathrm{diag}(\Gamma_3, \Gamma_4, \ldots, \Gamma_M)$$

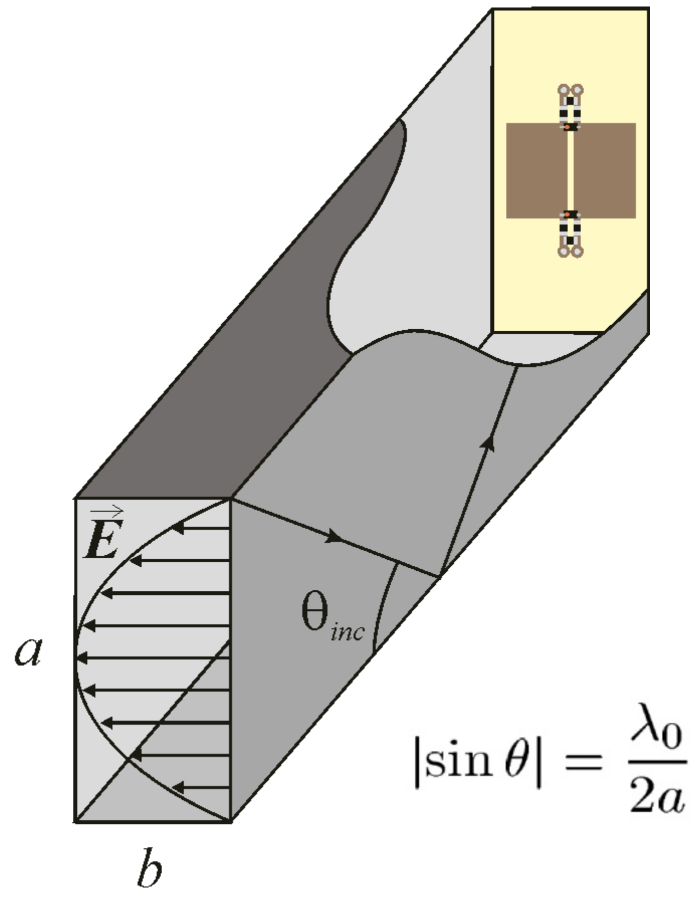
$$\mathbf{a}_{3M} = \mathbf{\Gamma}\mathbf{b}_{3M}$$

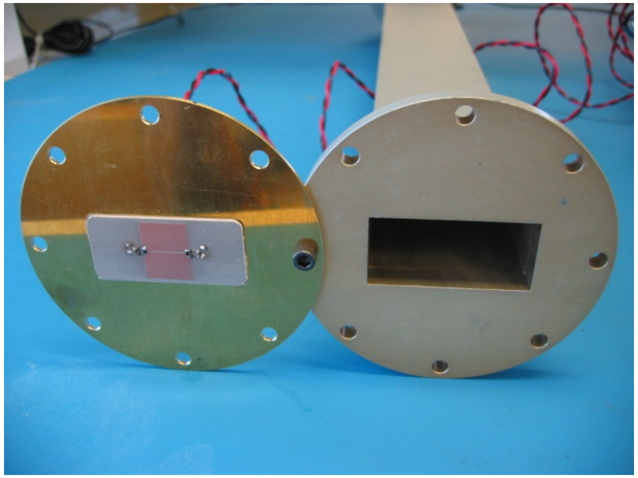
Solving:

$$\mathbf{b}_{12} = \underbrace{[\mathbf{S}_A + \mathbf{S}_B\mathbf{\Gamma}(\mathbf{I} - \mathbf{S}_D\mathbf{\Gamma})^{-1}\mathbf{S}_C]}_{\mathbf{S}_L}\mathbf{a}_{12}$$

$\mathbf{S}_L$ is the desired two-port GSM linking the incident and reflected Floquet Harmonics

Major Theoretical Contributions: RWG Simulators of Reflectarray Unit Cells





- Waveguides provides a practical way for measuring reflectarray cells
- Simulates non-broadside incidence in infinite array scenario

P. Hannan and M. Balfour, “Simulation of a phased-array antenna in waveguide,” *IEEE Trans. Antennas Propag.*, vol. AP-13, no. 3, pp. 342–353, Mar. 1965.

Major Theoretical Contributions: RWG Simulators of Reflectarray Unit Cells

- Waveguide simulators limited in only characterizing cells that are double symmetric
- Further, geometry constrains testable frequency range

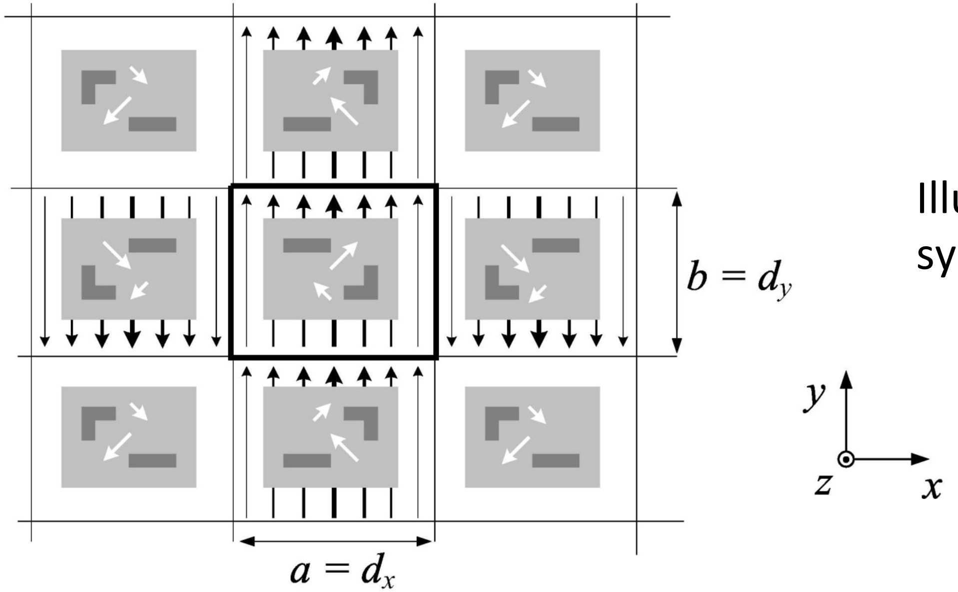


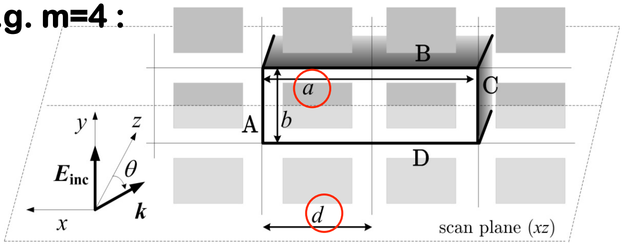
Illustration of non-symmetric case

Major Theoretical Contributions: RWG Simulators of Reflectarray Unit Cells

- Number of elements placed in the RWG is not necessarily one. Image theory -> any number m of half-elements, so for the lattice spacing d:

$$a = \left(\frac{m}{2}\right) d \qquad m \in \mathbb{N}^*$$

e.g. m=4 :

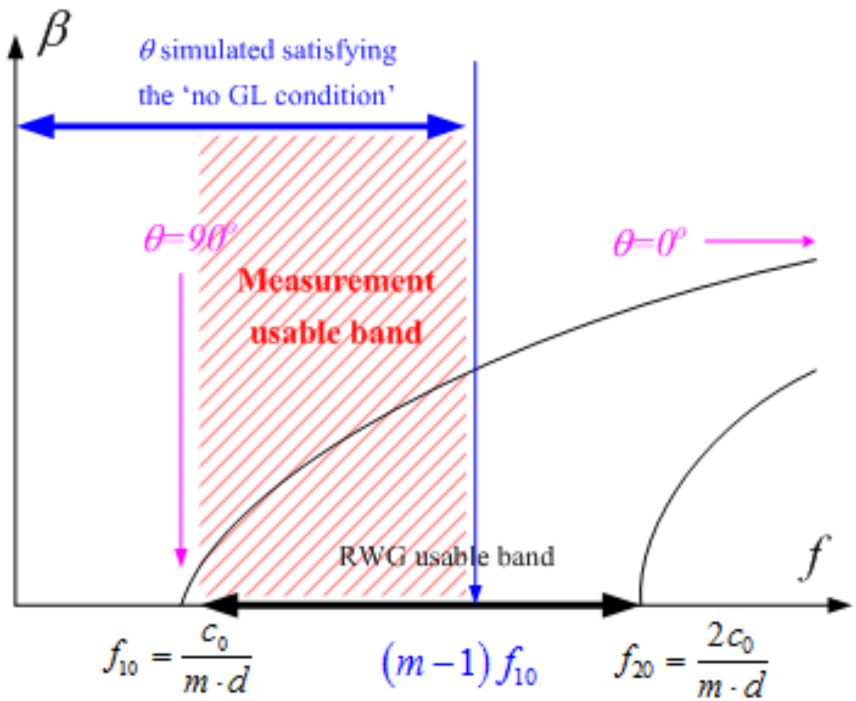


- An array scanning full space without grating lobes must have:

$$d < \lambda_0/2$$

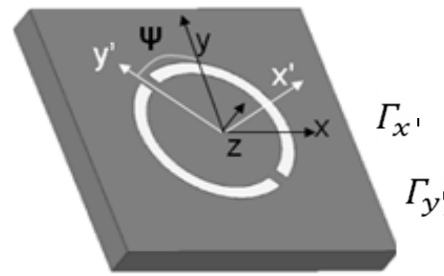
- The second mode of the RWG with a > 2b is propagated from f_{20} with:

$$f_{10} = 0.5 f_{20} = \frac{c_0}{2a}$$



Major Theoretical Contributions: Polarization Management in RAs

- General principle: sequential rotation

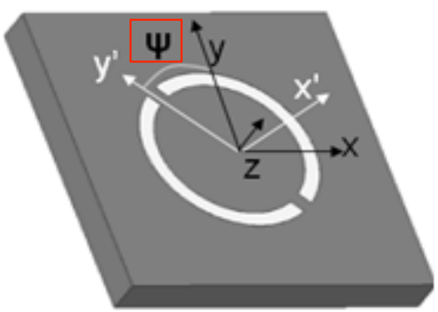


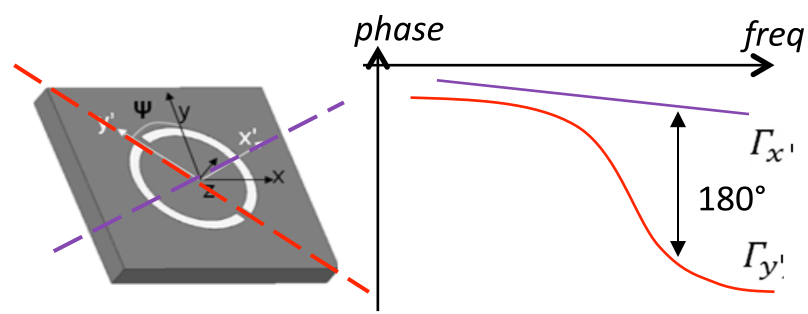
$$\overrightarrow{E^i} = (\hat{a}_x + j\,\hat{a}_y)E^i\,e^{jz}$$

$$\overrightarrow{E^r} = \underbrace{0.5E^i(\Gamma_{x'} - \Gamma_{y'})(\hat{a}_x - j\,\hat{a}_y)e^{j2\psi}e^{-jz}}_{\text{co-pol.}} + \underbrace{0.5E^i(\Gamma_{x'} + \Gamma_{y'})(\hat{a}_x + j\,\hat{a}_y)\,e^{-jz}}_{\text{cross-pol.}}$$

→ Control the co-polarized phase by the rotation of the element

→ Cancel the cross-polarized term by optimization of the cell





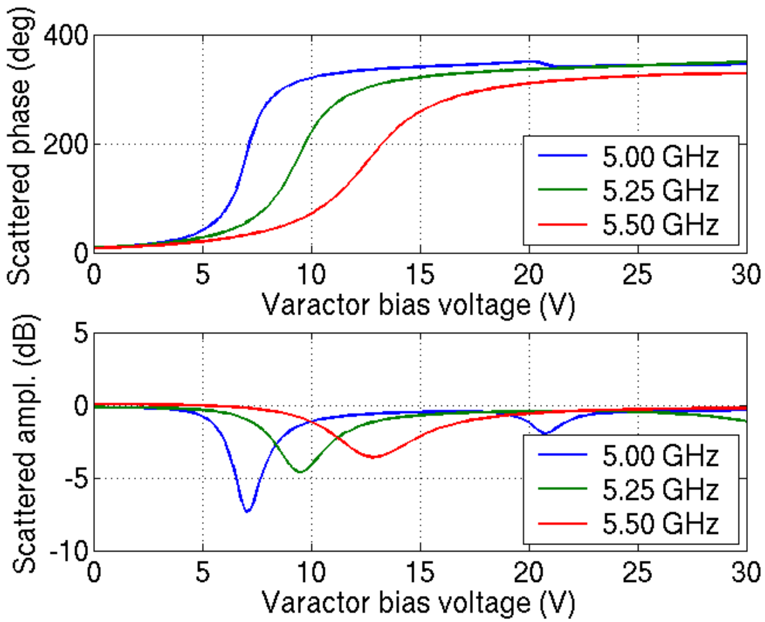
Guclu et al. "Proof of Concept of a Dual-band CP RF MEMS Beam-Switching Reflectarray" *IEEE Trans. Ant. Propag.*, 2012.

Major Experimental Contributions in Reflectarrays

- Reconfigurable reflectarrays: MEMS, semiconductors, switches
- Graphene as a next-generation material for realizing reflectarray unit cells
- Novel technologies (e.g. dielectric elastomer actuators) applied to antennas

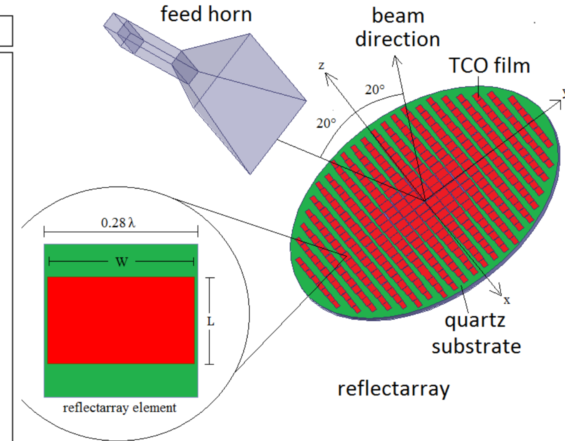
Perspectives on Future Reconfigurable Reflectarray / Surface Challenges

- Further cost reductions required
- Mitigation of losses
- Increased capabilities mm-wave frequencies
- New materials / platforms
- Multi-band / wideband capabilities required



New Platforms: Transparent Reflectarrays

Parameter	Reflectarray Design
No. of elements	392
Design frequency (f_0)	26 GHz
Substrate permittivity (ε_r)	3.8
Substrate height (h)	1 mm
Patch length (L)	1.2 mm to 3.2 mm
Patch width (W)	3.1 mm
ITO thickness (t)	1 μm
Element spacing/ periodicity (P)	3.23 mm (0.28λ)
Offset Angle	20°
Beam Angle	20°
Focal Distance	8.0 cm
Reflectarray diameter (D)	76.2 mm (3 in)
Reflectarray area	40.8 cm^2
Theoretical Aperture Gain (G_{ap})	25.8 dBi

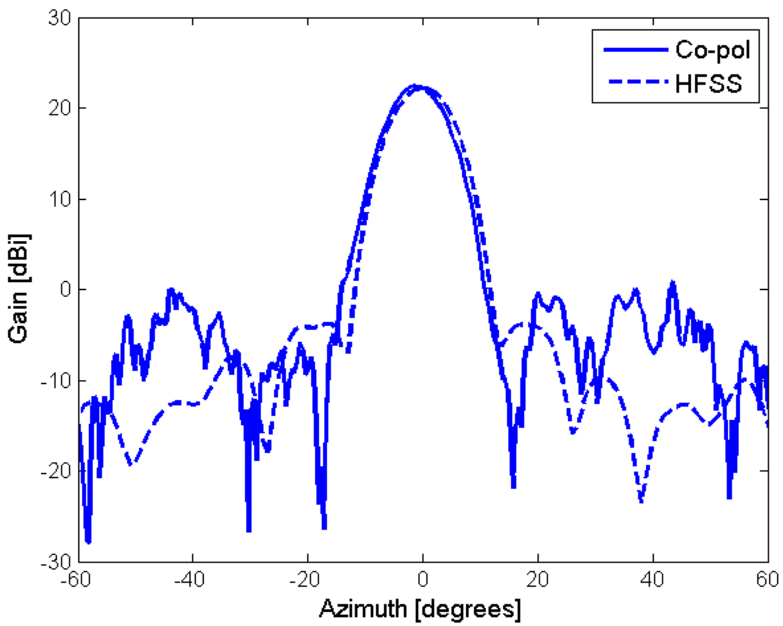


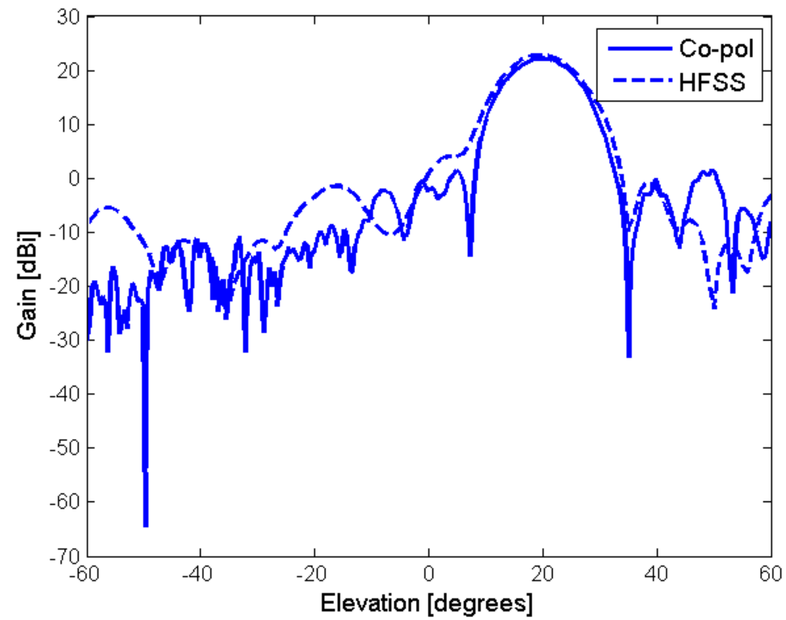
Through careful cell design, ohmic losses in transparent oxides can be managed

C. Kocia and S. V. Hum, “Optically transparent reflectarray for satellite applications,” in 2014 Eur. Conf. Ant. Propag. (EuCAP 2014), Apr. 2014.

P. Dreyer, M. Morales-Masis, S. Nicolay, C. Ballif, and J. Perruisseau-Carrier, “Copper and transparent-conductor reflectarray elements on thin-film solar cell panels,” IEEE Transactions on Antennas and Propagation, vol. 62, no. 7, pp. 3813–3818, July 2014.

New Platforms: Transparent Reflectarrays

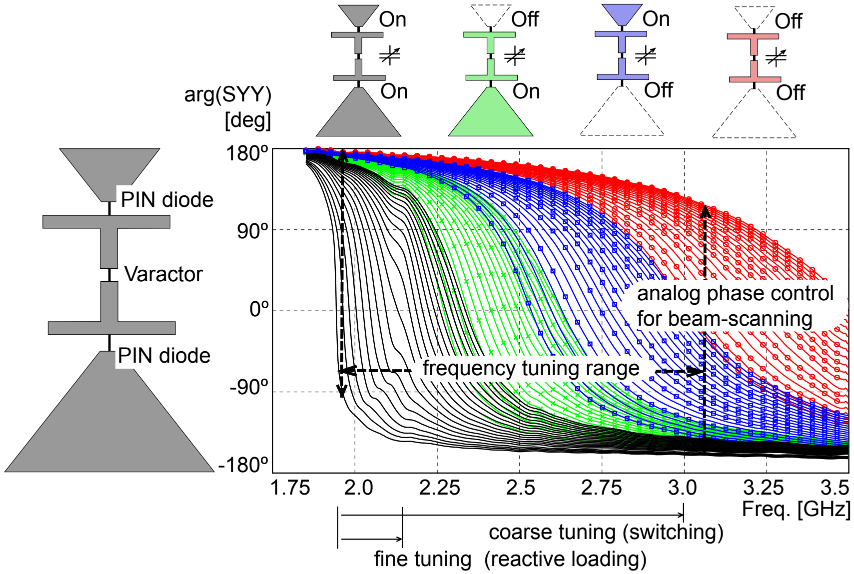




Conductor loss	1.4 dB
Spillover loss	0.3 dB
Taper loss	0.5 dB
Blockage loss	0.1 dB
Phase loss	0.6 dB
Theoretical Expected Gain	22.9 dBi

C. Kocia and S. V. Hum, "Design of optically transparent reflectarrays using transparent conducting oxides (submitted)," IEEE Trans. Antennas Propag., 2015.

Multi-band / Wideband Reflectarrays

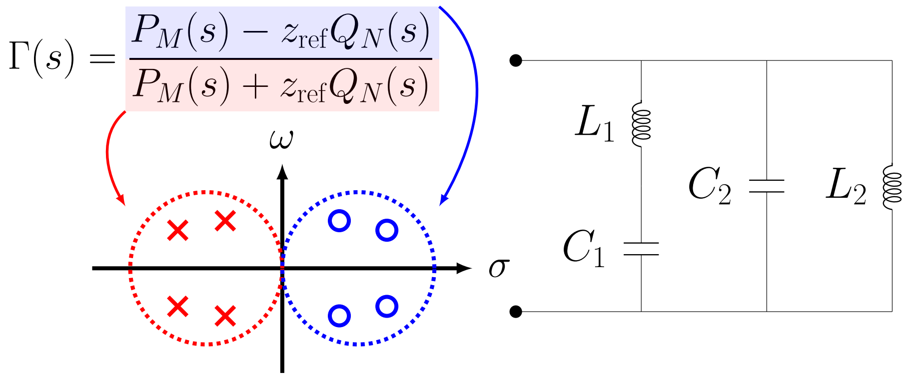


Rodrigo, D.; Jofre, L.; Perruisseau-Carrier, J., "Unit Cell for Frequency-Tunable Beamscanning Reflectarrays," *Antennas and Propagation, IEEE Transactions on* , vol.61, no.12, pp. 5992,5999, Dec. 2013

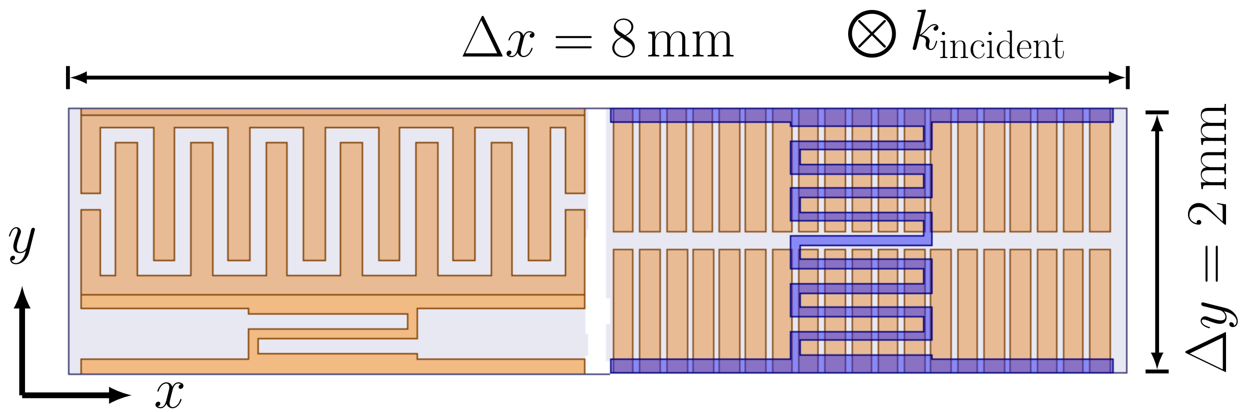
- Idea: use switches to configure centre frequency of unit cell
- An analog phase range above 270° is achieved over a 50% frequency range, from 1.88 GHz to 3.07 GHz, with flat losses of 0.8 dB
- For an analog phase range of 180° the cell achieves a 1:2 frequency reconfiguration range

Wideband Reflecting Metasurfaces

- Idea: design metasurface scatterers to mimic Bessel filters (flat group delay)
- Scatterers realize inductive / capacitive filter elements needed

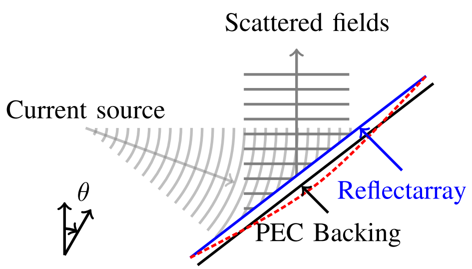


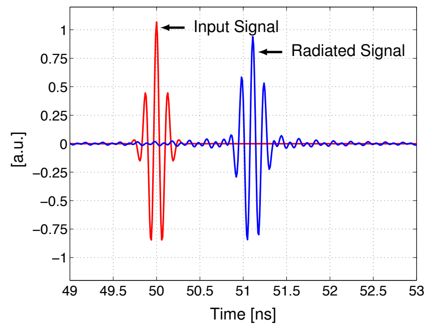
Example: 2nd order filter

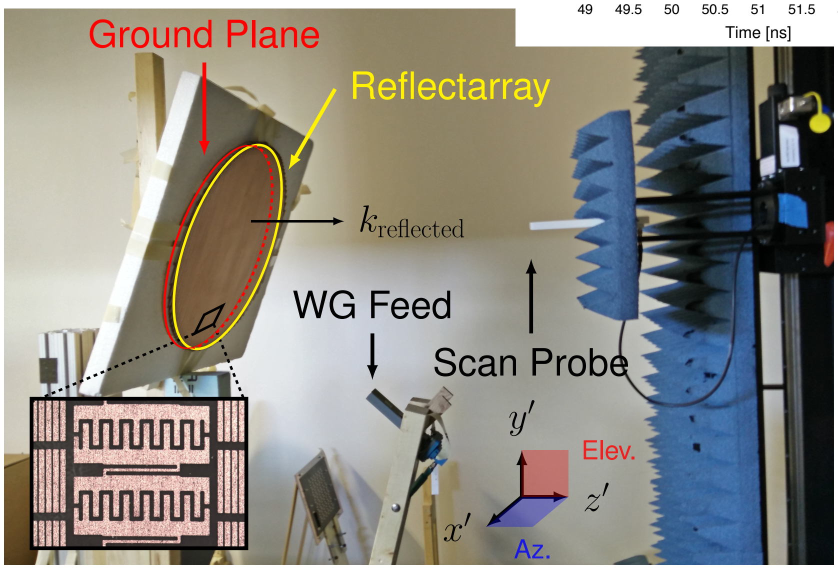


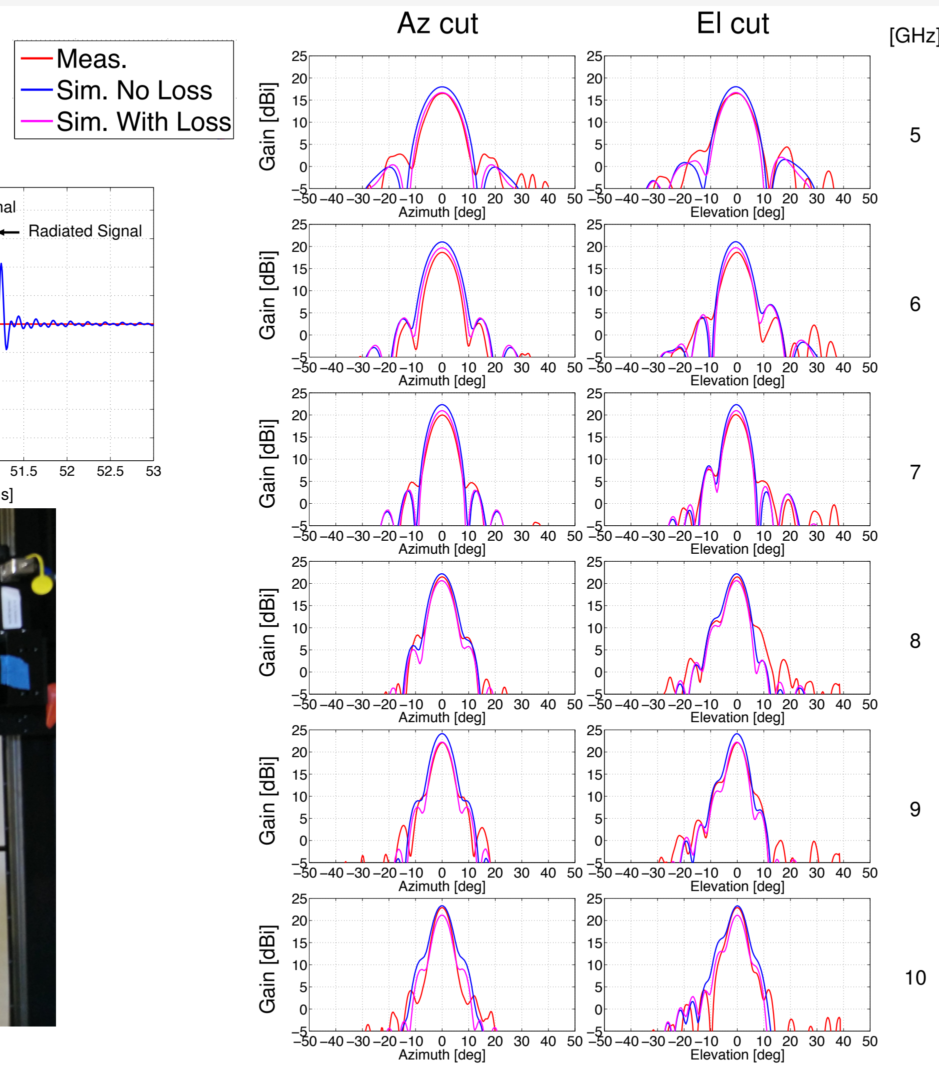
T. Liang and S. V. Hum, *Proc. 2015 IEEE AP-S Symposium*

Wideband Reflecting Metasurfaces









Conclusions

- Julien was a prolific researcher, compassionate teacher, and honest friend that was taken from us far too soon
- His legacy will be felt for years through his contributions in reflectarrays, reconfigurable antennas, and electromagnetic surfaces
- Julien helped to pioneer a field that continues to expand and find new applications each year

THANK YOU, JULIEN

We never said farewell, nor even looked
Our last upon each other, for no sign
Was made when we the linkèd chain unhooked
And broke the level line.

And here we dwell together, side by side,
Our places fixed for life upon the chart.

Two islands that the roaring seas divide
Are not more far apart.

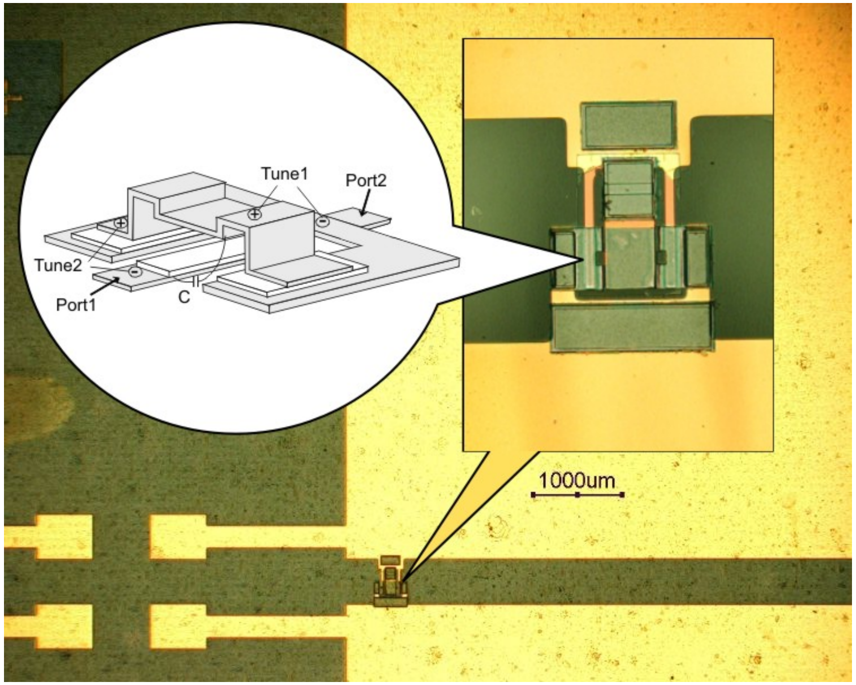
Robert Louis Stevenson

Enabling Technologies for Reflectarrays and Array Lenses

Type	Technology	Maturity / reliability	Integration	D/A control	Complexity (cost)	Loss (µwave / THz)	Bias power	Linearity	Switching time
Lumped components	PIN diodes	+	-	D	+	-/-	-	0	+
	Varactor diodes	+	-	A	+	-/-	+	-	+
	RF MEMS	-	+	D*	+	+/0	+	+	0
Hybrid	Ferro-electric thin film	0	+	A	0	0/-	+	0	+
Tunable materials	Liquid crystal	0	0	A	0	-/+	0	0	-
	Graphene	-	+	A	0	-/+	+	-	+
	Photo-conductive	0	-	A	0	-/-	-	-	+
Mechanical	Microfluidic	0	-	A	0	0/+	+	0	-
	Micromotors	-	0	A	-	+	0	+	-

Enabling Technologies for Reflectarrays and Array Lenses

- Many research groups (including Julien's) explore technologies in two areas
- Lumped tuning:
  - Semiconductors
  - MEMS
- Distributed tuning:
  - Liquid crystals
  - Graphene (unique to Julien)



S. V. Hum, G. McFeetors, and M. Okoniewski, "Integrated MEMS reflectarray elements," in *Proc. EuCAP 2006*. ESA SP-626, Nov. 2006.

Learning More

IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 62, NO. 1, JANUARY 2014 183

Reconfigurable Reflectarrays and Array Lenses for Dynamic Antenna Beam Control: A Review

Sean Victor Hum, *Senior Member, IEEE*, and Julien Perruisseau-Carrier, *Senior Member, IEEE*

Invited Paper

***Abstract*—Advances in reflectarrays and array lenses with electronic beam-forming capabilities are enabling a host of new possibilities for these high-performance, low-cost antenna architectures. This paper reviews enabling technologies and topologies of reconfigurable reflectarray and array lens designs, and surveys a range of experimental implementations and achievements that have been made in this area in recent years. The paper describes the fundamental design approaches employed in realizing reconfigurable designs, and explores advanced capabilities of these nascent architectures, such as multi-band operation, polarization manipulation, frequency agility, and amplification. Finally, the paper concludes by discussing future challenges and possibilities for these antennas.**

***Index Terms*—Antenna arrays, array lenses, beam steering, lens antennas, micro-electro-mechanical systems (MEMS), microstrip arrays, reconfigurable antennas, reflectarrays, reflector antennas, semiconductor diodes, transmitarrays, varactors.**

very high implementation cost. Phased arrays also diminish in efficiency at millimeter-wave frequencies due to the use of transmission-line feeding networks which become increasingly lossy at high frequencies.

Reflectarrays and array lenses are interesting hybrids between aperture antennas and antenna arrays. They have been studied extensively in the past 20 years due to their attractive qualities, namely their low-profile nature, ease of manufacturing, low weight, good efficiency, and overall promise as high-gain antenna alternatives. Recently, researchers have become interested in electronically tunable versions of reflectarrays and array lenses to realize reconfigurable beam-forming. By making the scatterers in the aperture electronically tunable through the introduction of discrete elements such as varactor diodes, PIN diode switches, ferro-electric devices, and MEMS

Electromagnetic Surfaces and Reconfigurability

- EM surfaces have evolved from macroscopic level (arrays) to microscopic level (metasurfaces), yielding a host of functions
- **Reconfigurability** of these surfaces enables new possibilities, ranging from beam-steering to frequency agility