Metamaterial Roadmap

Metamorphose
vision for the future advancements

April 2008

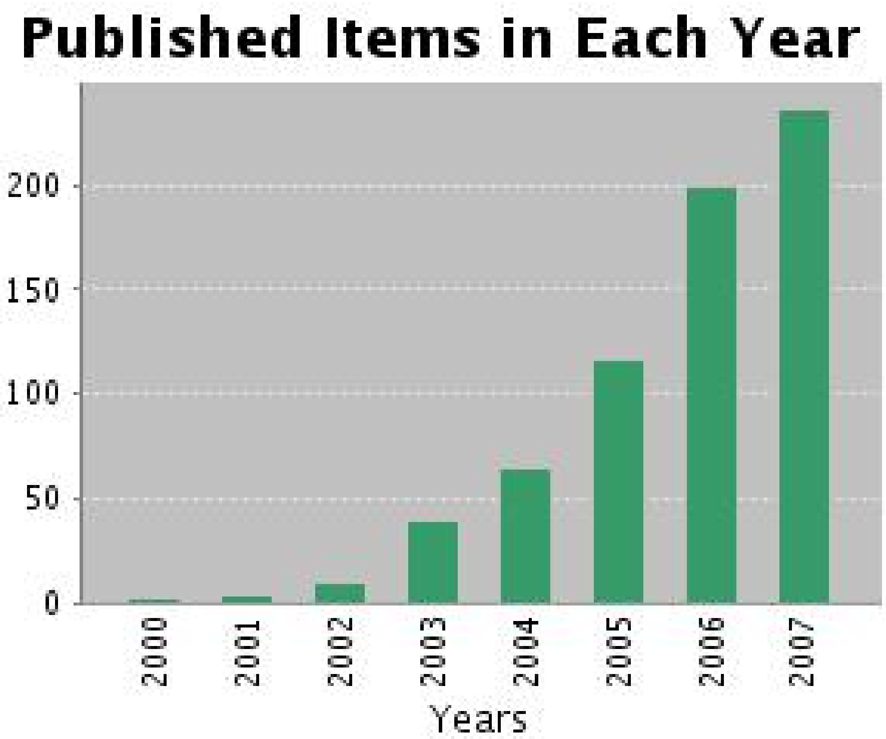
Sergei Tretyakov, Ekmel Özbay, Christophe Crayene, and many other Metamorphose partners

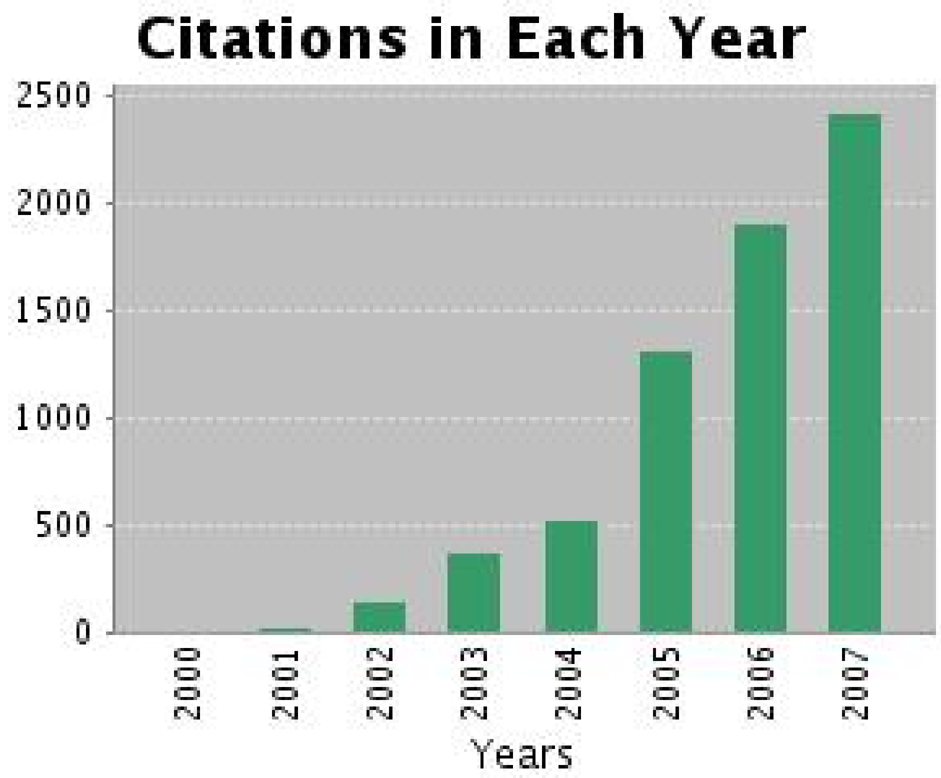
Definition

Metamaterial is an arrangement of artificial structural elements, designed to achieve advantageous and unusual electromagnetic properties.

More precisely, properties that cannot be achieved at the atomic or molecular level are achieved through the electromagnetic interaction between the “particles” formed at levels much higher than the atomic level and whose dimensions are small compared to the wavelength of operation.

Metamaterials Research





Search in SCI for “metamaterials”
Other common names, LHM, BW etc. not included

A Comparison of Metamaterials Research

VIEW RECORDS	Field: Country/Territory	Record Count	% of 671	Bar Chart
	USA	262	39.0462 %	
	PEOPLES R CHINA	109	16.2444 %	
	ENGLAND	52	7.7496 %	
	SPAIN	49	7.3025 %	
	GERMANY	42	6.2593 %	
	CANADA	35	5.2161 %	
	TURKEY	30	4.4709 %	
	RUSSIA	27	4.0238 %	
	GREECE	26	3.8748 %	
	ITALY	22	3.2787 %	
	AUSTRALIA	21	3.1297 %	
	FRANCE	21	3.1297 %	
	JAPAN	20	2.9806 %	
	SINGAPORE	14	2.0864 %	
	FINLAND	13	1.9374 %	

Search in SCI for “metamaterials”
Other common names, LHM, BW etc. not included

METAMORPHOSE

- **A European network of excellence (NoE) dedicated to metamaterials**
- **Coordinator: Prof. Sergei Tretyakov (TKK, Finland)**
- **Strategic Manager: Dr. Vladimir Podlozny (TKK, Finland)**
- **Lifetime: June 2004 - May 2008**
- **www.metamorphose-eu.org**

Participants

1	Helsinki University of Technology	**HUT**	Finland
2	Universite Catholique de Louvain	**UCL**	Belgium
3	Universidad del País Vasco / Euskal Herriko Unibertsitatea	**UPV**	Spain
4	Swiss Federal Institute of Technology, Lausanne	**EPFL**	Switzerland
5	University of Southampton	**UoS**	UK
6	Bilkent University	**Bilkent**	Turkey
7	Universidad Publica de Navarra	**UPNA**	Spain
8	University of Glasgow	**U. Glasgow**	UK
9	Siegen University	**Siegen**	Germany
10	St. Petersburg Electrotechnical University	**ETU**	Russia
11	FORTH, Institute of Electronic Structure and Laser	**FORTH**	Greece
12	Warsaw University	**WU**	Poland
13	University Roma Tre	**Roma Tre**	Italy
14	Loughborough University	**Lough**	UK
15	University of Siena	**UNISI**	Italy
16	Thales Research & Technology	**TRT**	France
17	Universitat Politechnica de Catalunya	**UPC**	Spain
18	Queen's University of Belfast	**QUB**	UK
19	Université Paris-Sud	**UPS/LEGEP**	France
20	Universidad Autonoma de Barcelona	**UAB**	Spain
21	Institute of Electronic Materials Technology	**ITME**	Poland

Life after METAMORPHOSE?

- Lifetime of Metamorphose: June 2004 - May 2008
- New structure: Metamorphose VI
- One of the first virtual institutes envisioned by the EU Commission to follow-up NoE
- www.metamorphose-vi.org
- The Virtual Institute for Artificial Electromagnetic Materials and Metamaterials (”Metamorphose VI”) is a non-for-profit international association whose purposes are the research, the study and the promotion of artificial electromagnetic materials and metamaterials
- A research roadmap is one of the VI instruments

What is a roadmap?

WIKIPEDIA

A roadmap may refer to:

A map of roads (where they might lead nobody knows), and possibly other features, to aid in navigation

A plan, e.g.

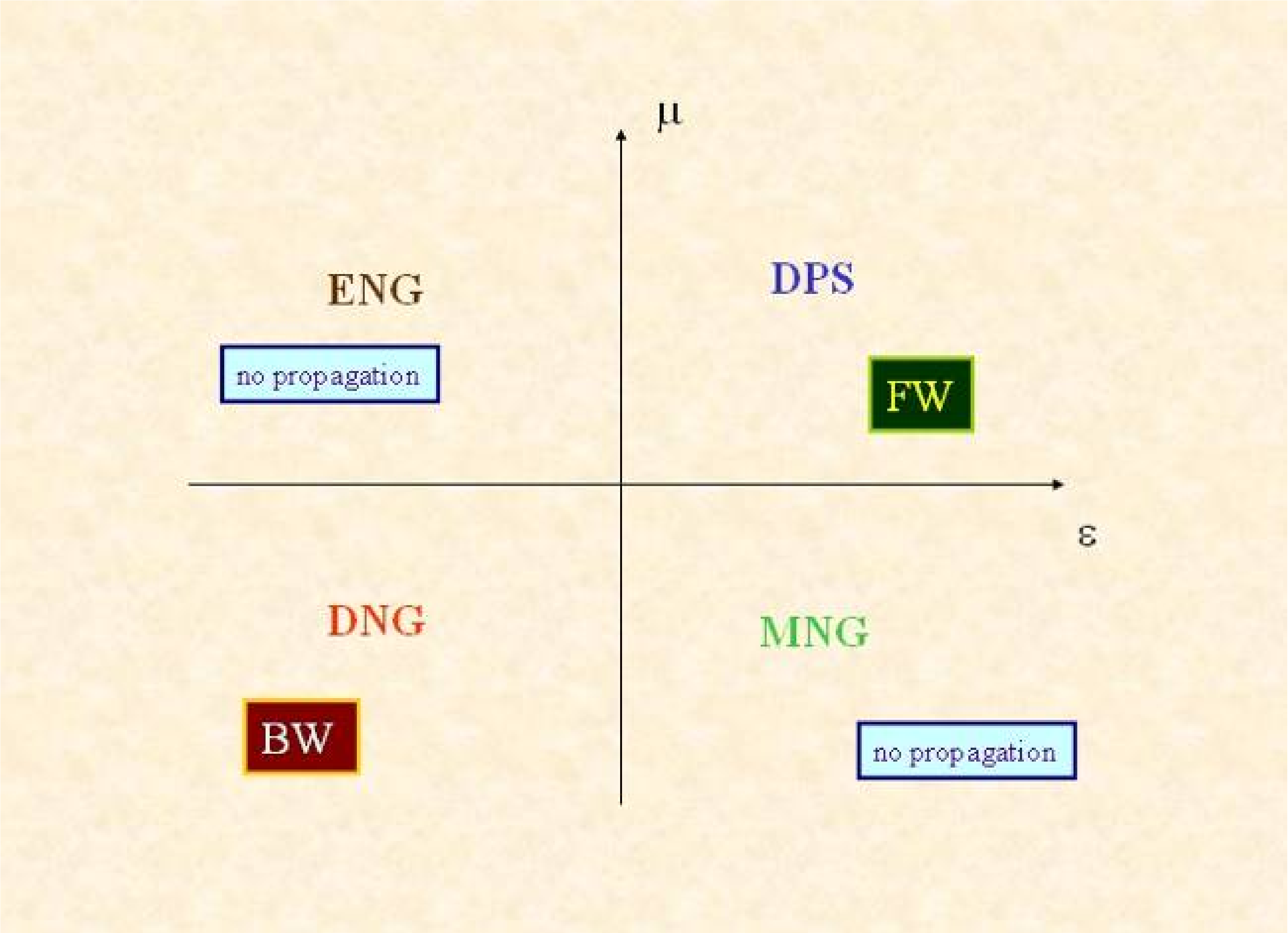
Road map for peace, to resolve the Israeli-Palestinian conflict

Technology roadmap, a management forecasting tool

Goals

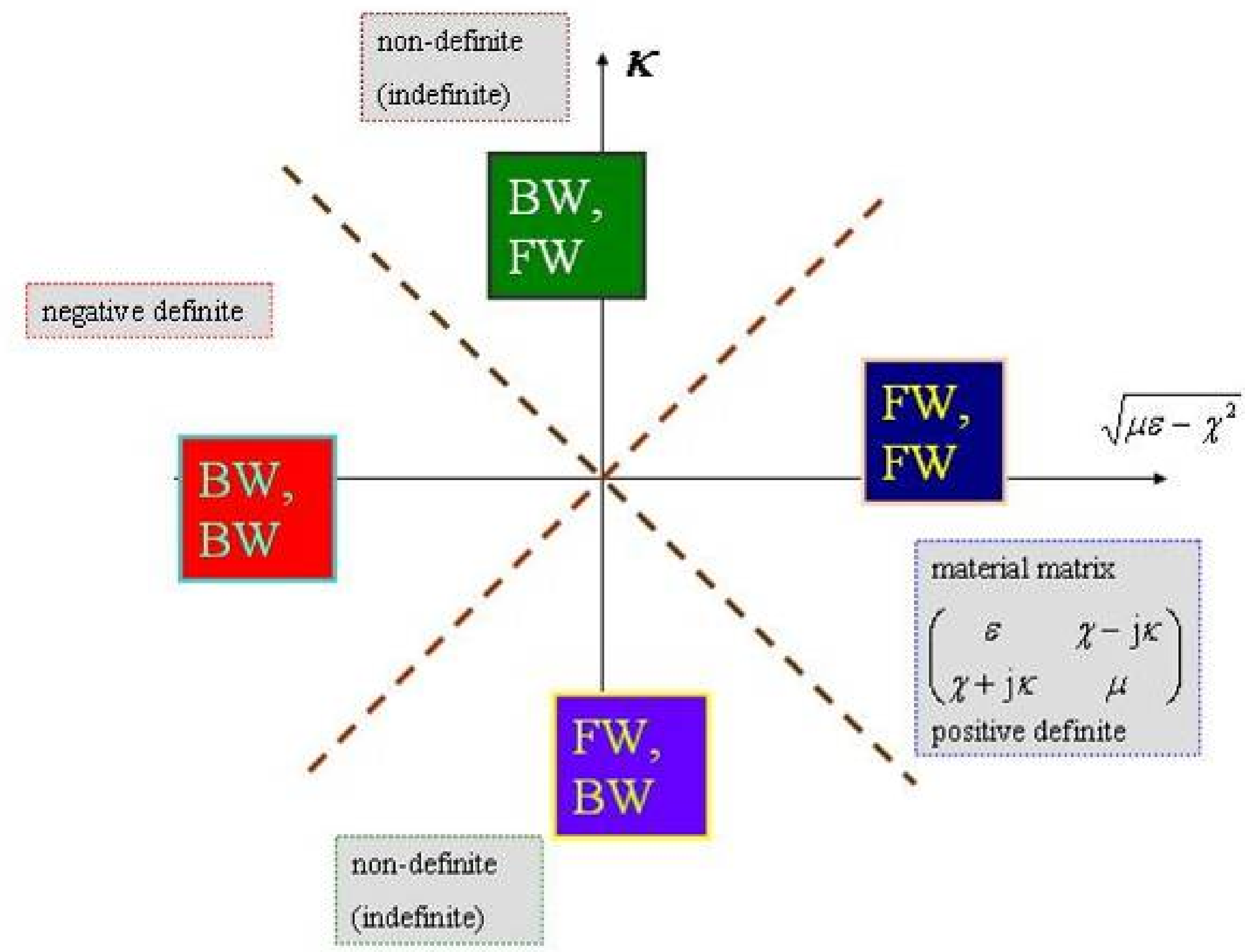
- **Get a clear idea of opportunities and challenges offered by metamaterials**
- **Obtain a structured view of possible research orientations**
- **Organise research at European level**
  - **to avoid overlaps**
  - **to achieve good coverage**
  - **to be fast picking up the fruits of joint efforts**

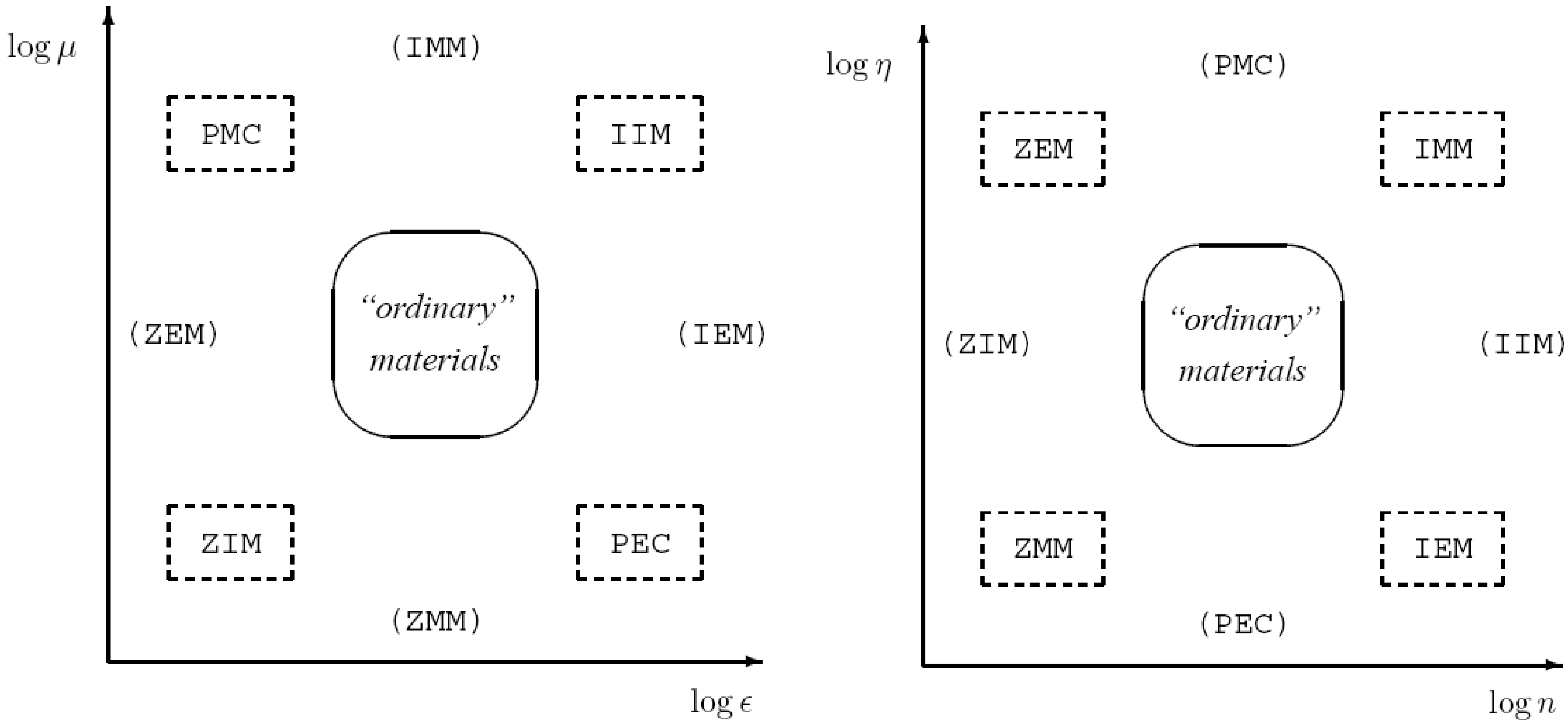
Classification



$$D = \varepsilon E + (\chi - j\kappa)H$$

$$B = (\chi + j\kappa)E + \mu H$$




log μ
(IMM)
PMC
IIM
"ordinary" materials
(ZEM)
(IEM)
ZIM
PEC
(ZMM)
log ϵ
log η
(PMC)
ZEM
IMM
"ordinary" materials
(ZIM)
(IIM)
ZMM
IEM
(PEC)
log n

$\eta\mu$

		ε	μ	n	η
PEC	perfect electric conductor	large	small	undefined	very small
PMC	perfect magnetic conductor	small	large	undefined	very large
ZIM	zero-index material	small	small	very small	undefined
IIM	infinite-index material	large	large	very large	undefined
ZEM	zero-electric material	very small	undefined	small	large
ZMM	zero-magnetic material	undefined	very small	small	small
IEM	infinite-electric material	very large	undefined	large	small
IMM	infinite-magnetic material	undefined	very large	large	large

Three wavelength regimes with different challenges:

1. **Microwaves: based on well-established research in the field of antennas and microwave circuits.**
2. **TeraHertz: new field because of strong instrumental limitations at this stage.**
3. **Optics: also based on strong background, but bigger challenges, related to availability of low-loss nano-structured metamaterials and nano-fabrication techniques.**

Different goals in different frequency ranges

1. Develop new processes and **materials with engineered micro- or nano-scopic structure** for improvement of **microwave and millimetre-wave** devices and creation of new devices with new capabilities, mainly for information technologies. The issues of tunability, including electrical control, and integration in larger systems are at the forefront.

Different goals in different frequency ranges

2. Create new artificial materials, devices and applications for **TeraHertz frequencies**, based on special phenomena, like left-handed materials. The cost of fabrication and testing still being very high in this frequency range, the research roadmap in the field of TeraHertz technologies will **partly rely on conceptual experiments at microwave frequencies**.

Different goals in different frequency ranges

3. At **optical frequencies**, the first objective is to prove the **feasibility** of lensing metamaterials with the help of artificial materials like plasmonic devices, split-ring resonators and new types of materials and engineered (structural) thin sheets. Second, materials with extreme dielectric or magnetic properties are also looked for. A big challenge for material scientists is to find low-loss plasmonic materials.

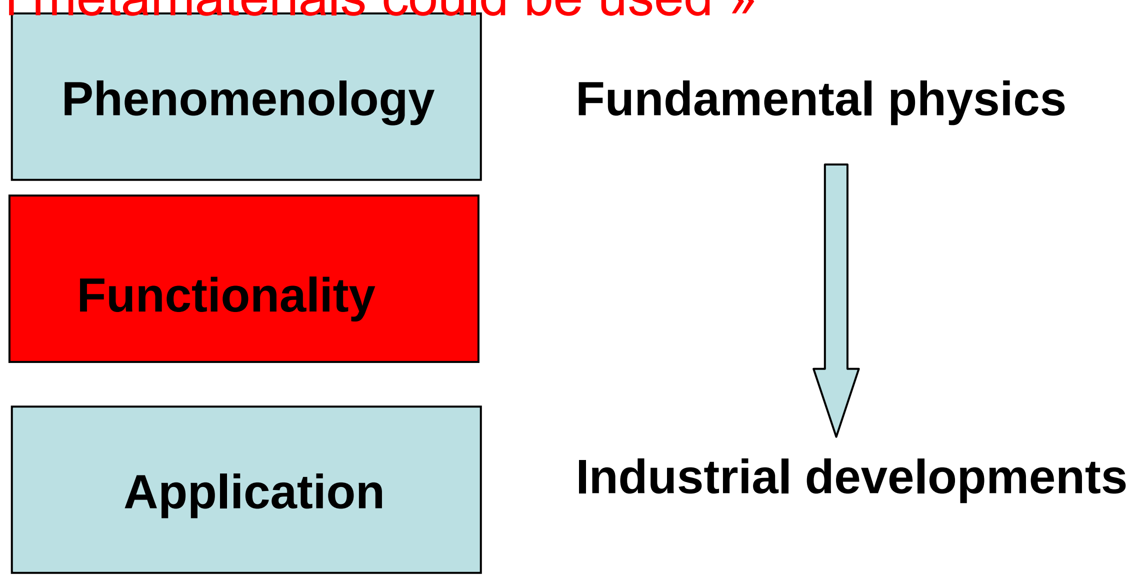
Roadmap formation process

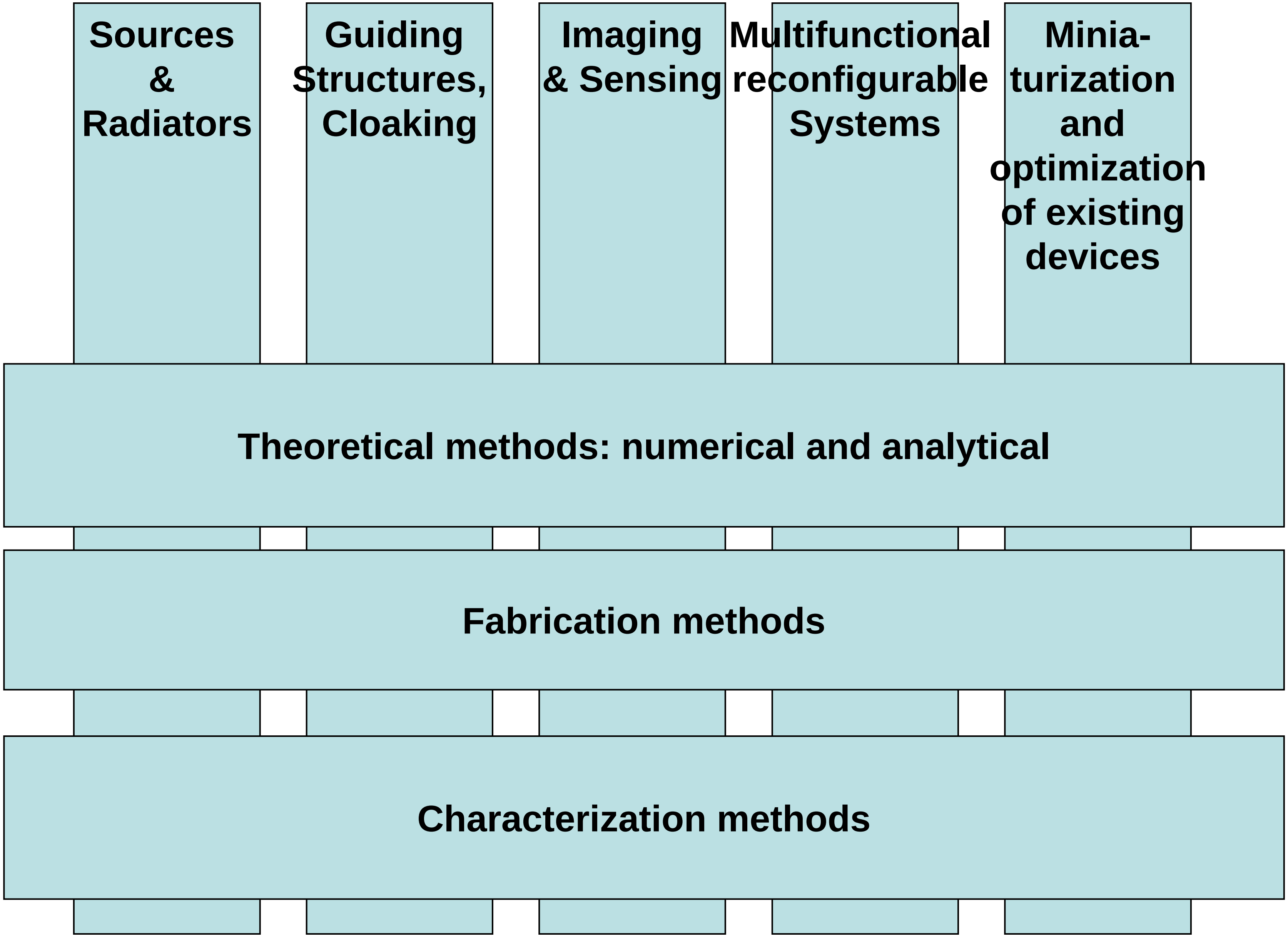
Matematerials are still at a relatively fundamental level:

Some applications are almost commercial (collimators, microwave antennas, phase shifters), while others are still purely at conceptual level (invisibility).

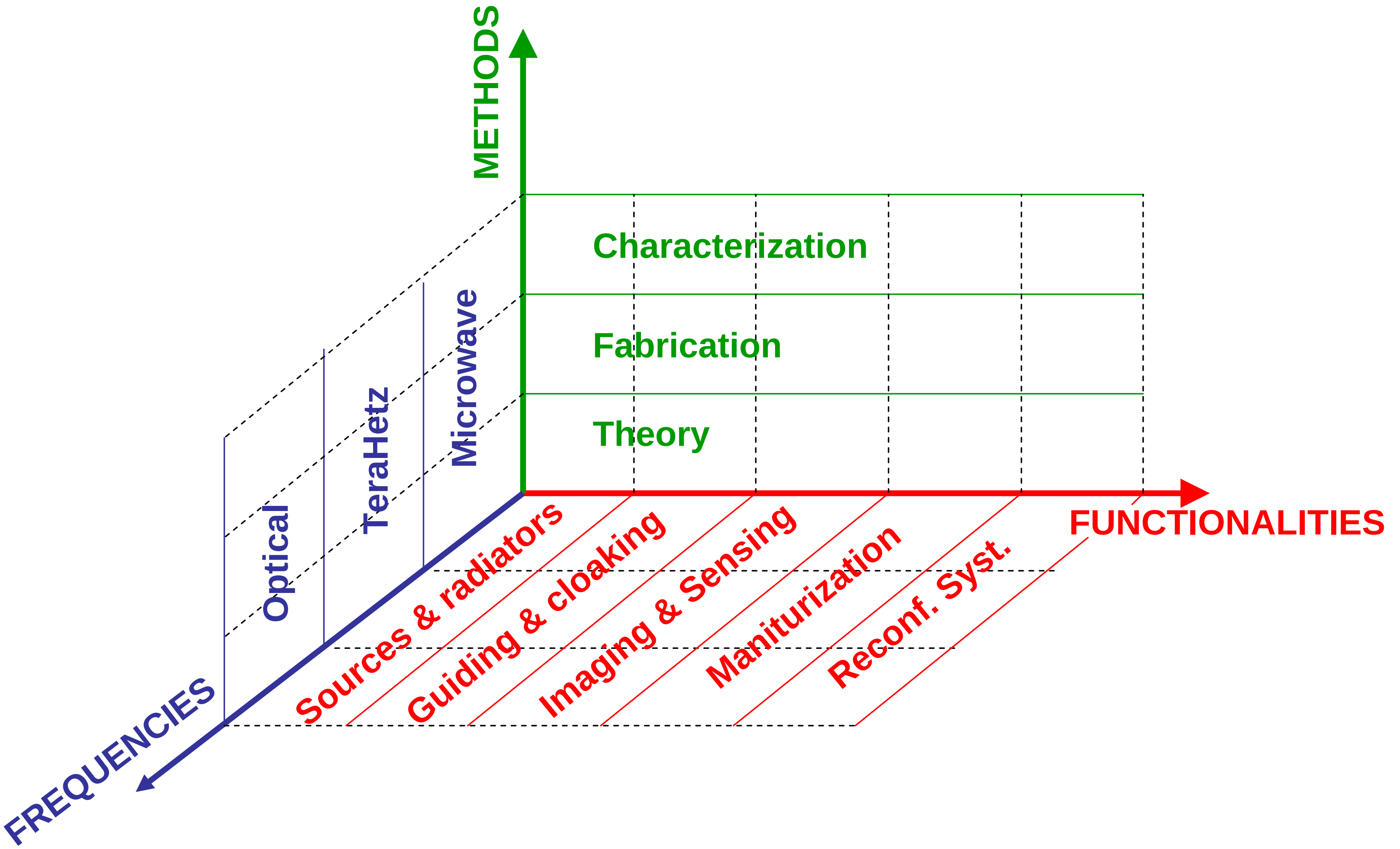
⇒ Work at some intermediate level: functionality

« Properties for which metamaterials could be used »





Sources & Radiators
Guiding Structures, Cloaking
Imaging & Sensing
Multifunctional reconfigurable Systems
Minia-turization and optimization of existing devices
Theoretical methods: numerical and analytical
Fabrication methods
Characterization methods


METHODS
Characterization
Fabrication
Theory
FUNCTIONALITIES
Sources & radiators
Guiding & cloaking
Imaging & Sensing
Maniturization
Reconf. Syst.
FREQUENCIES
Optical
TeraHetz
Microwave

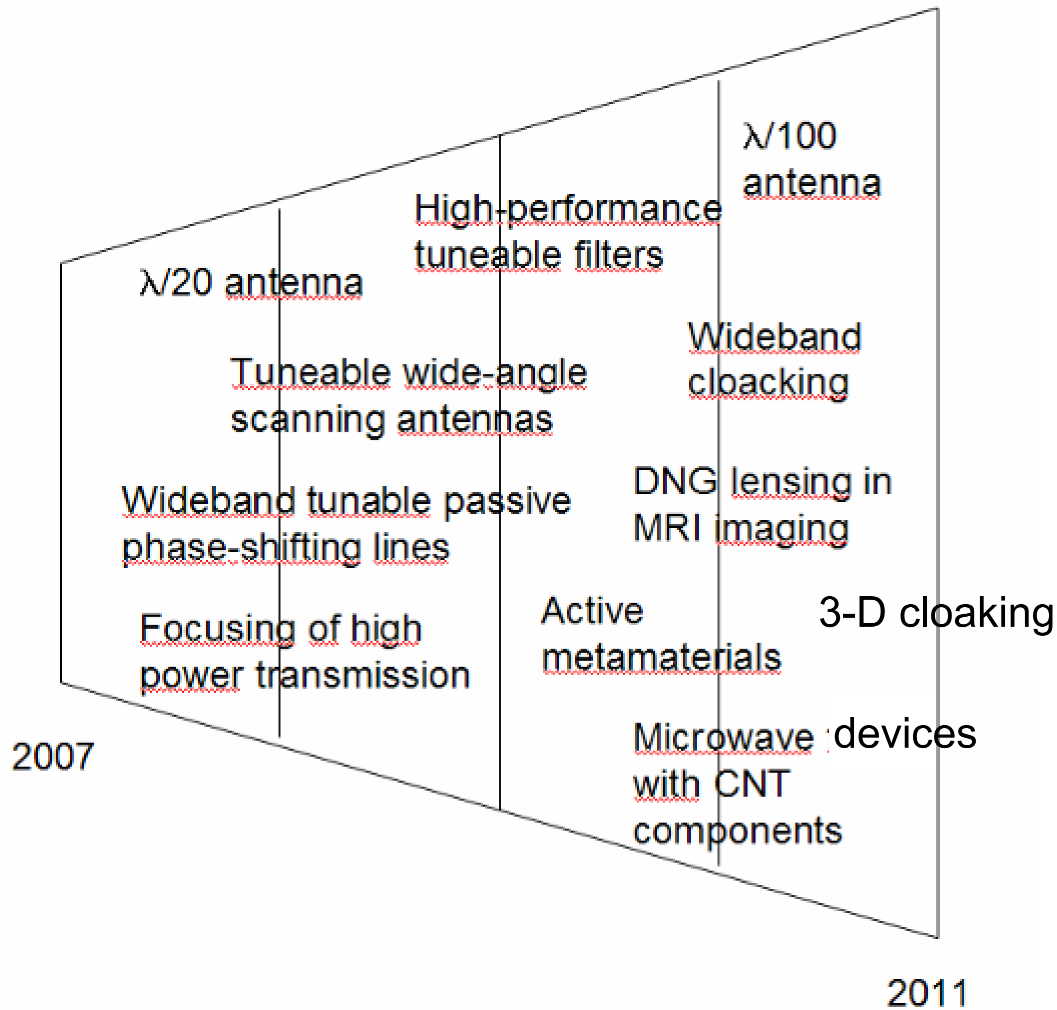
Functionality		**Phenomenology**	**Application (system)**	**Fabrication & measurement**	**Analysis techniques**
Imaging and sensing	Collimation	Low-epsilon materials, low-mu materials, spatial dispersion	MRI imaging, health applications,	Mechanical assembly	ASM, Method of Moments
	lensing	Matching + Refraction index close to -1, using DNG, SNG or chiral material, plasmonic surfaces, strong spatial dispersion	Imaging, detection, focusing of power, health applications	Photo-lithography, FTIR (Infrared and visible domain), 3D microwave imaging, micro and nano-machining	Special treatment of resonant structures in Finite Element Method Eigenmode analysis
	Sensing	Resonance frequency shift	Biosensors	nanolithography	

	Functionality	Phenomenology	Application (system)	Fabrication & measurement	Analysis techniques
	Sources and radiators	Composite magnetic materials, (artificial) low-epsilon materials, reduction of mutual coupling, reduction of overal size with the help of DNG materials	Mobile terminals, compact antennas, large scan angles and highly efficient systems, UMTS, WIMAX, WIFI	Various deposition techniques, optical lithography	Finite Element Methods
	Miniaturisation and optimisation	Backward and forward waves, high-Q resonance	Front-end module of wireless communications	Thin film and screen-printing technique, multilayer ceramic technology, PCB and other planar microelectronic technologies	Method of Moments, Electroma gnetic software

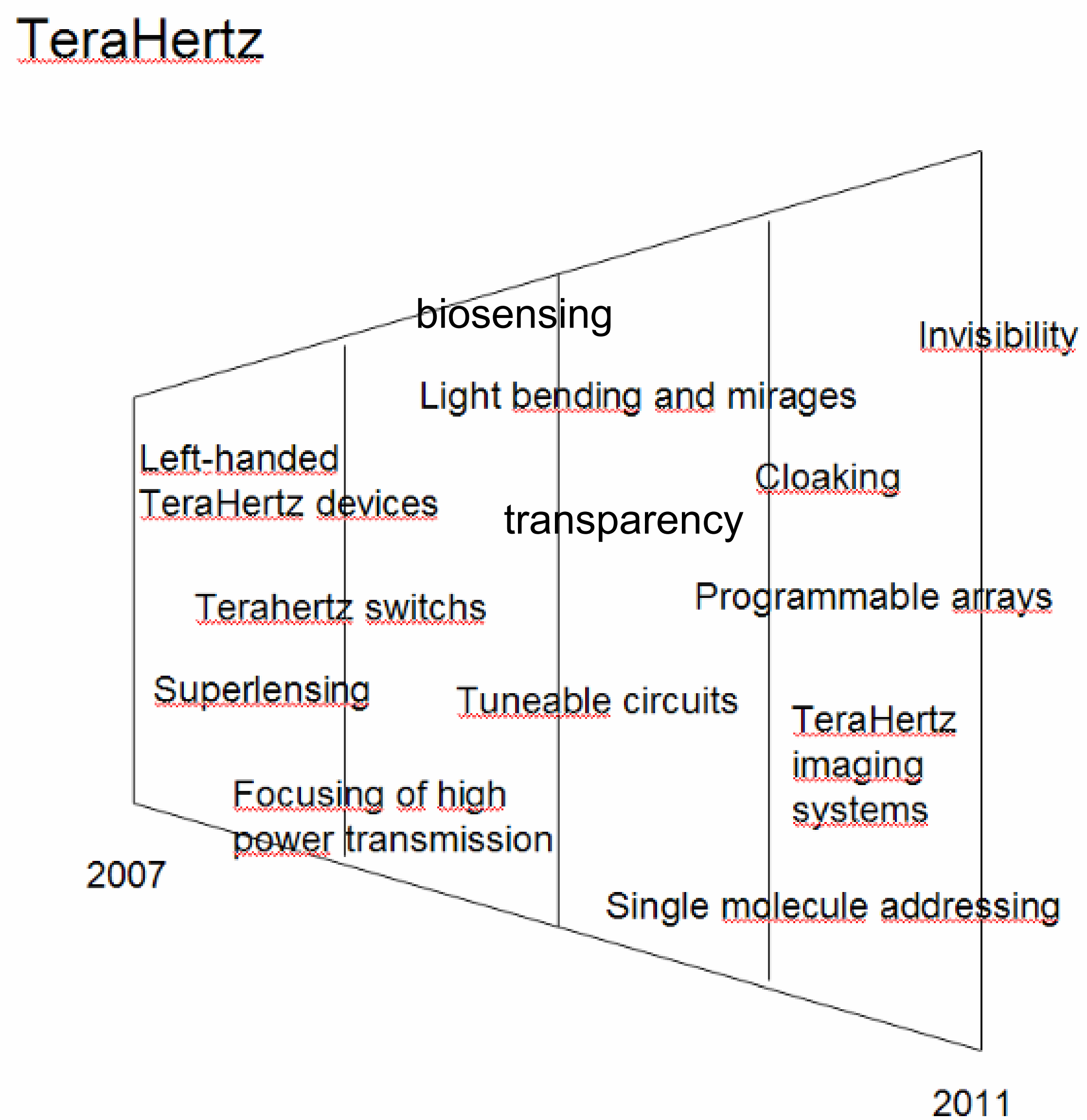
Functionality		**Phenomenology**	**Application (system)**	**Fabrication & measurement**	**Analysis techniques**
Multi-functionnal reconfigu-rable systems	Reconfigurab-ility /tunability	Dielectric response of ferro-electric material or varactors, tunable constitutive elements, ferroelectric varactors, non-linear metamaterials, photonic FSS's. Integration of MEMS switches HBV	Reconfigurable components/front-ends, electromagnetic windows, EM compatibility, tunable filters, parametric amplifiers, frequency multiplexers, mixers, Tunable delay lines, phase shifters, tunable filters	Photo and e-beam lithography, Thin film and screen-printing technique, multilayer ceramic technology, PCB, RF-MEMS, Micro-milling, magnetron and laser sputtering, lithography e-beam lithography, nano-imprint Nano soft lithography, self assembly of nanostructures	Electromagnetic software, and electrical solvers. Time-domain solvers for non-linear materials, Sonnet, Momentum, Harmonic balance simulations for large signal (non-linear)

Expected achievements in 5 coming years:

Microwaves

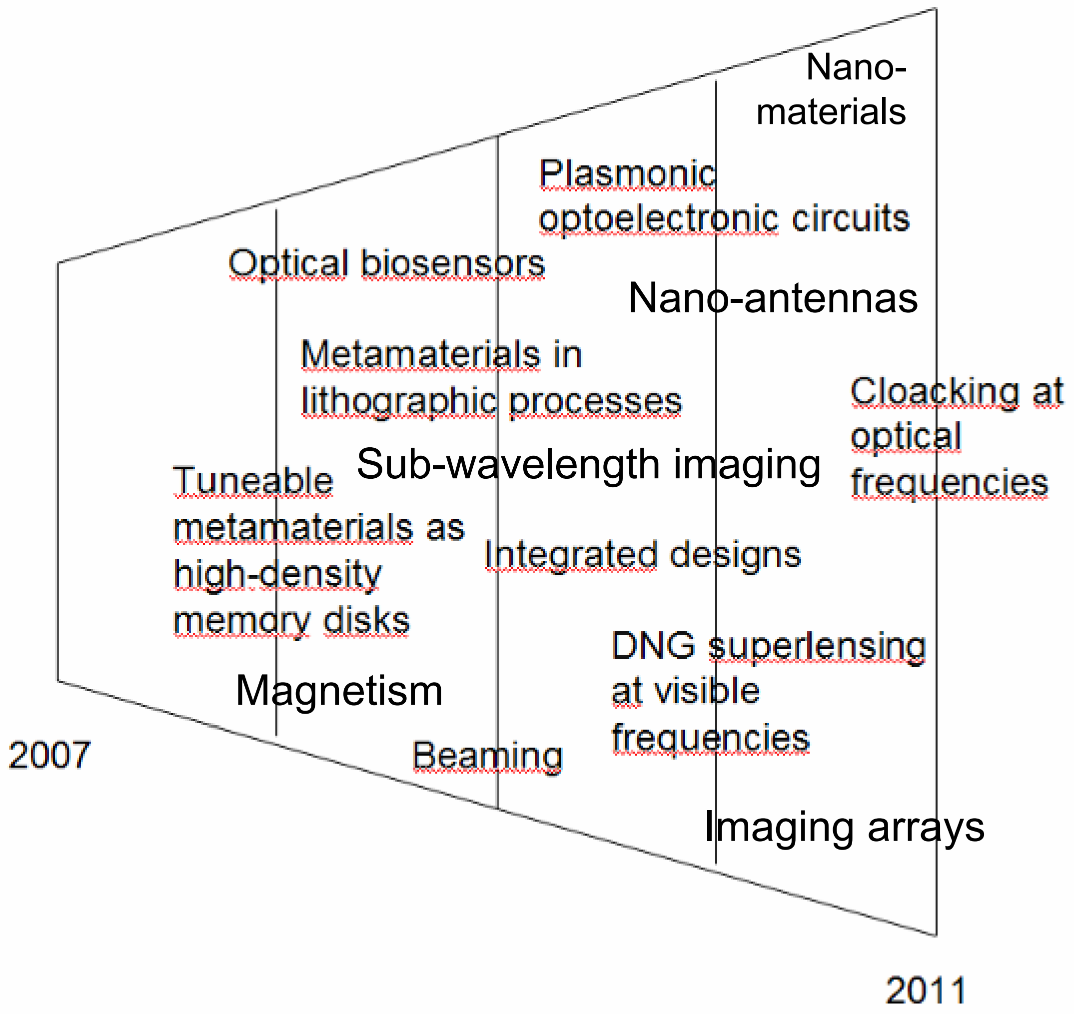


Expected achievements in 5 coming years:



Expected achievements in 5 coming years:

Optical



Conclusions and further prospects

- Research topics (re)organized along 3 axes: functionalities, methods and frequencies
- Long-term expectations projected per frequency
- Contributions and cooperations determined

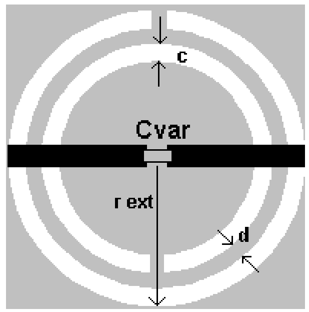
  - avoid overlap
  - get coverage

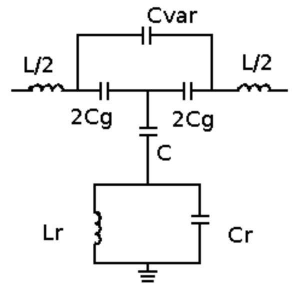
- Cooperation results will be reviewed every year

  - reaping fruits of efforts

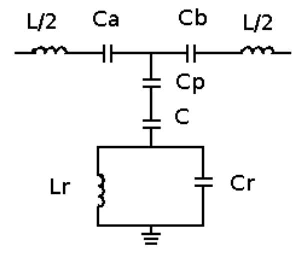
Yearly cycle within the Virtual Institute

New tunable metamaterial transmission lines based on CSRRs and varactors (UAB)

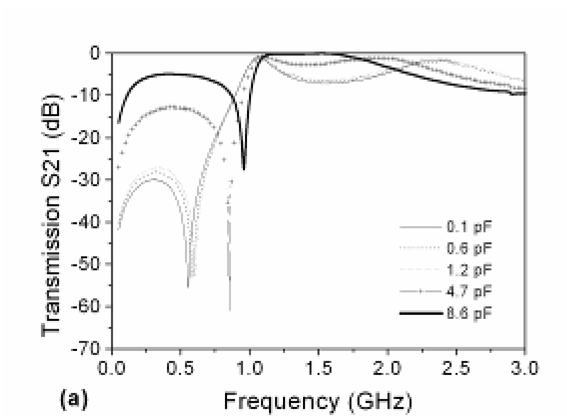


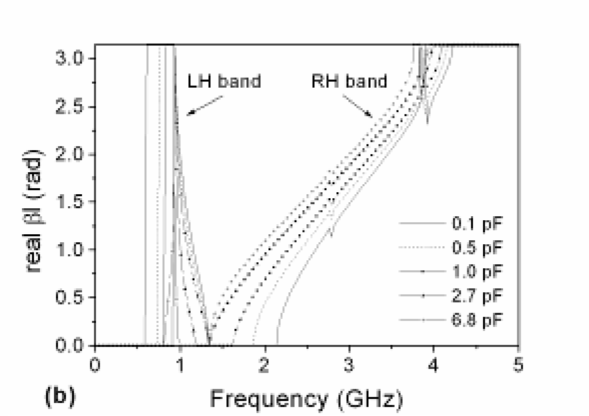


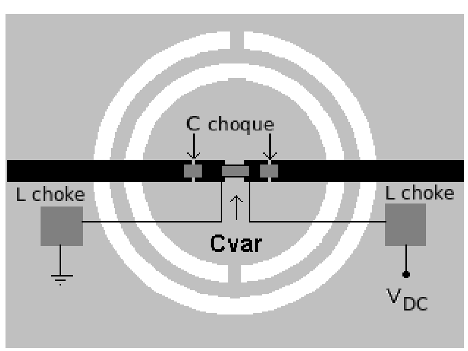
(b)

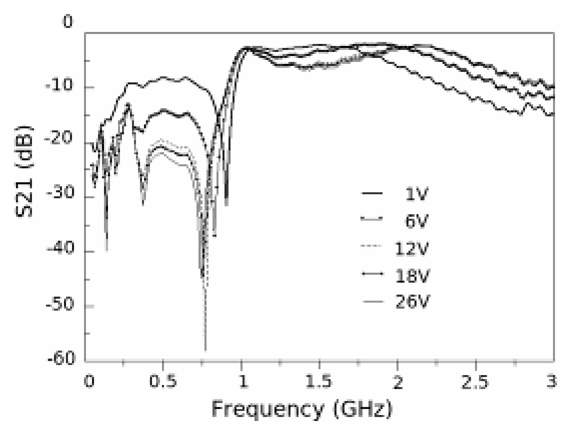


(c)

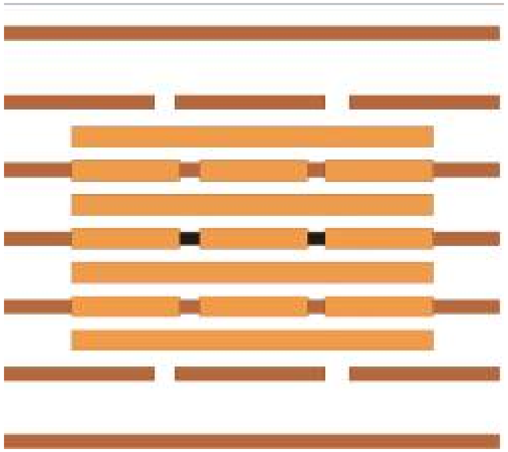


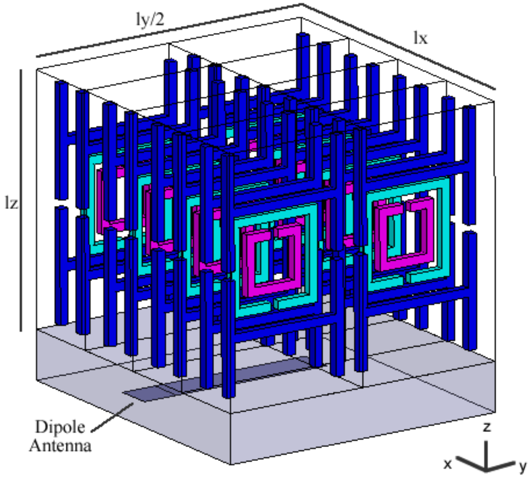




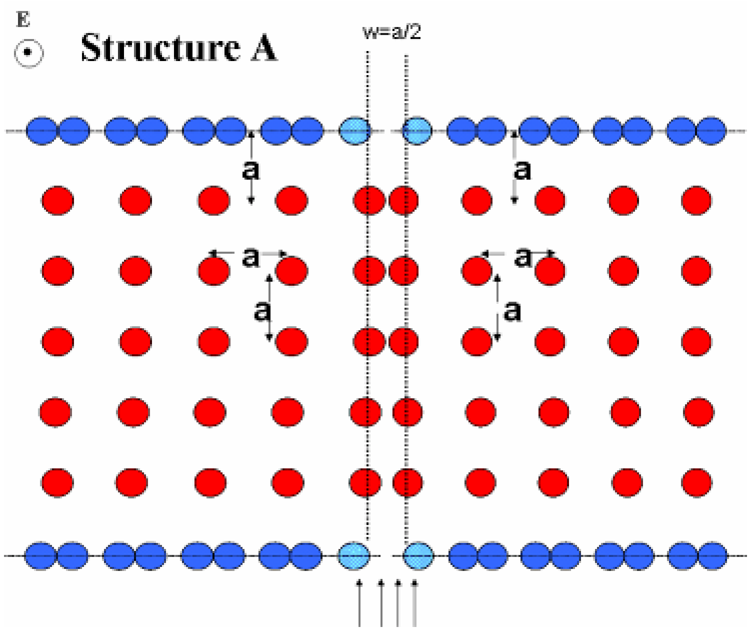


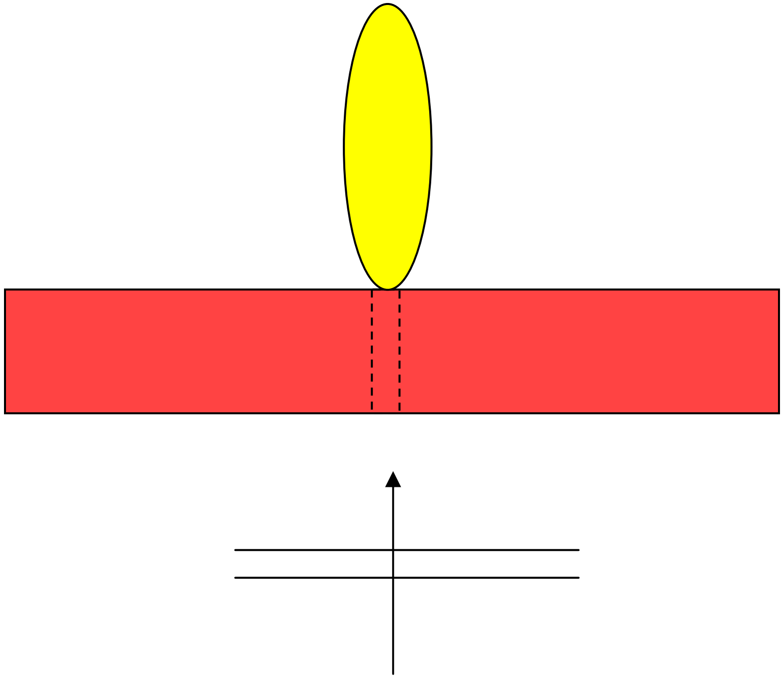
Metasurfaces for enhanced radiation properties (UPNa, LOUGH, TKK)





Forth – UNISI - Bilkent
Efficient beaming at optical frequencies.





Broadband transpolarising surfaces (UPC,UCL)

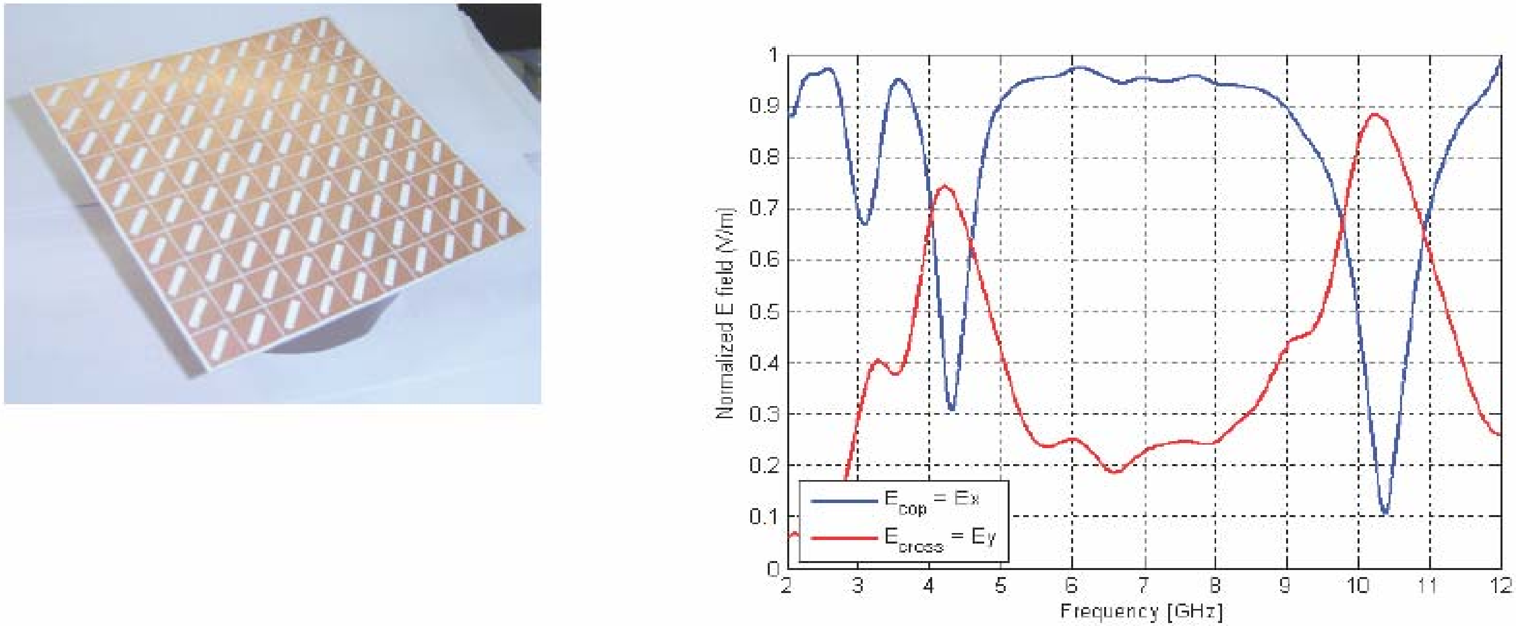
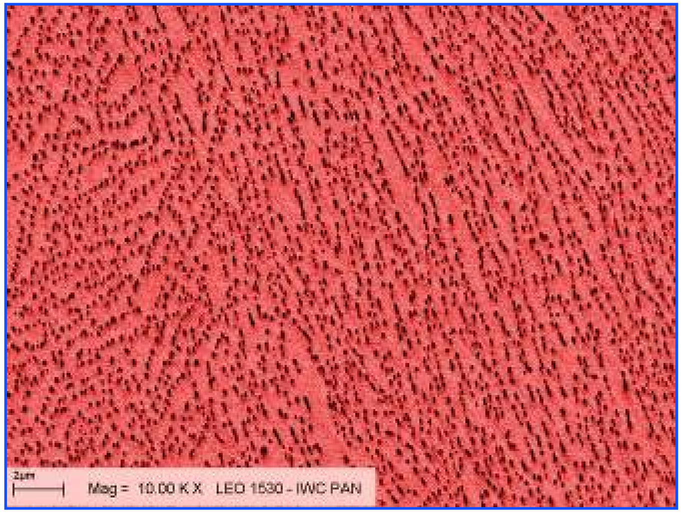


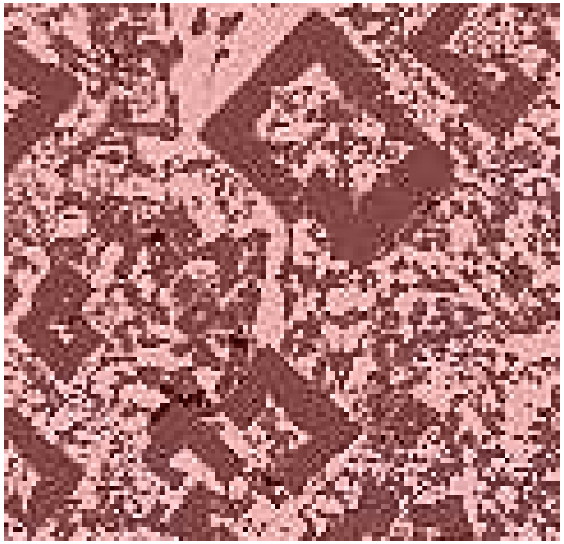
Figure 2: Trans-surface (left) and reflected Ex (Ecop) and Ey (Ecross) measured results.

P.J. Ferrer (UPC19), Carlos López-Martínez, X. Fàbregas, J.M. González-Arbesú (UPC19), J. Romeu (UPC19), A. Aguasca, and C. Craeye (UCL03),“Transpolarizing Surfaces for Polarimetric SAR Systems Calibration”, *IEEE Geoscience and Remote Sensing (IGARSS07)* conference.

P.J. Ferrer (UPC19), J.M. González-Arbesú (UPC19), J. Romeu (UPC19), and C. Craeye (UCL03), “Design and Fabrication of a Cross-Polarising AMC Surface”, *EuCAP07*.

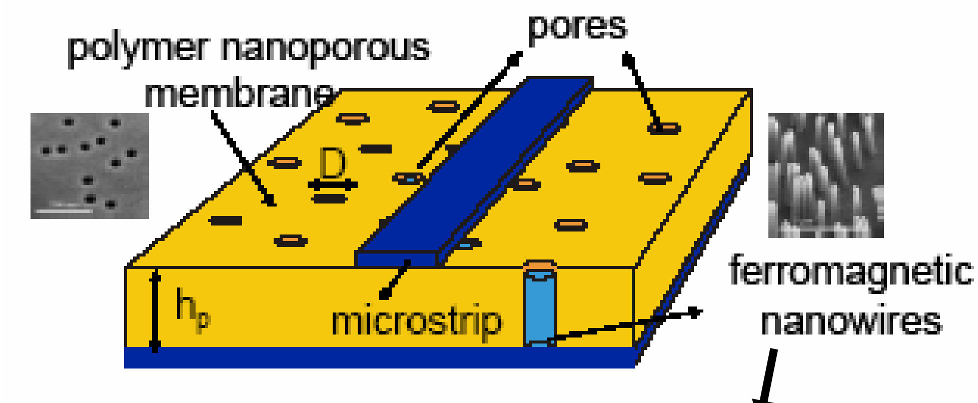
Self-organized metamaterials from eutectics (ITME, Bilkent, Siegen)





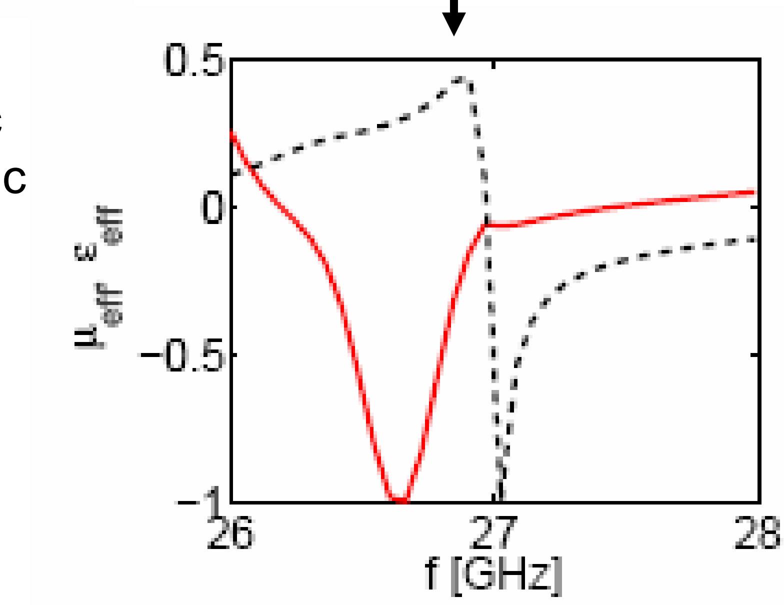
Tunable metamaterial transmission lines based on ferromagnetic nanowires (UCL)

Mu-negative

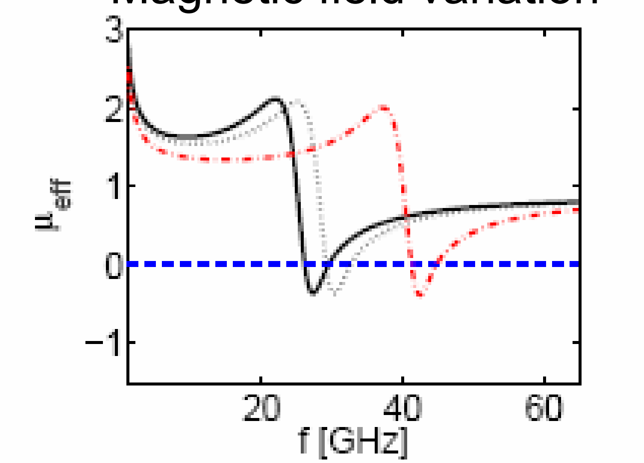


By adding a shunt inductance, a DNG structure is achieved.

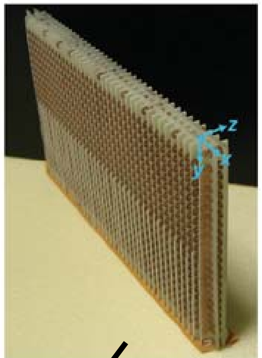
Generate a macroscopic ferromagnetic resonance



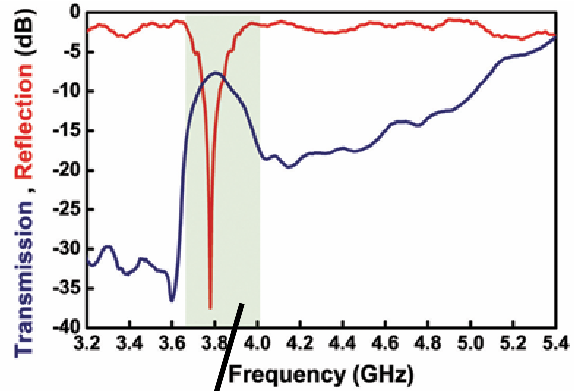
Magnetic field variation



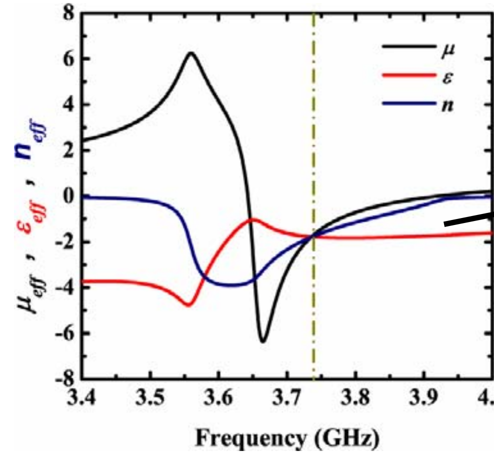
Subwavelength resolution by a negative-index metamaterial superlens



2D metamaterial composed of SRR and wire arrays

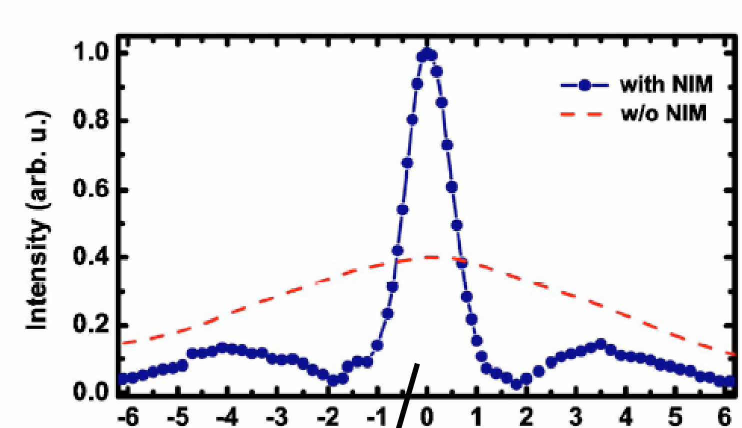


A left-handed transmission band is observed between 3.65 and 4.00 GHz.

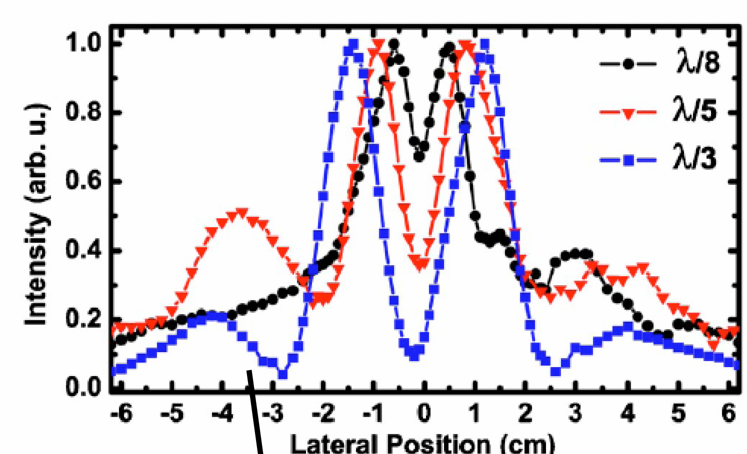


At 3.74 GHz real part of ε and μ are equal, $\varepsilon=\mu=-1.8$.

ε and μ are both negative btw. 3.63 and 3.93 GHz. Refractive index is also negative.



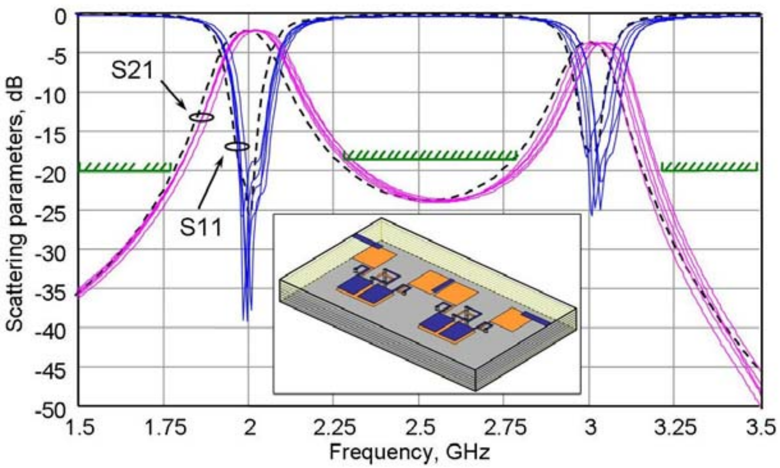
A point source is resolved by a 3-layer NIM superlens with a resolution of 0.13λ. The beam size in free space is on the order of wavelength.

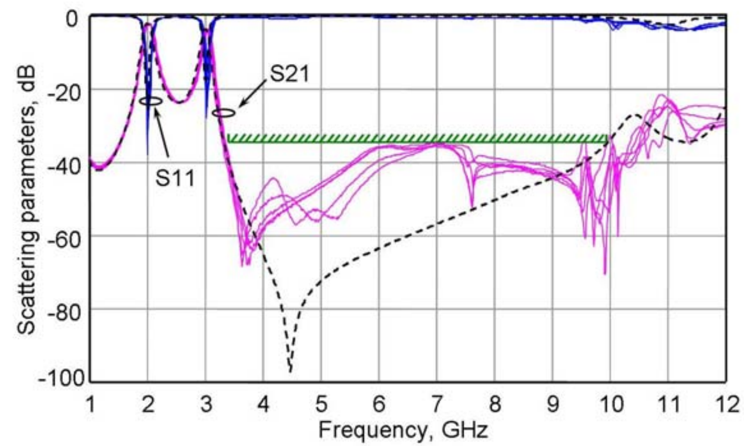


Two subwavelength features separated by distances of λ/8, λ/5 and λ/3 are resolved with the superlens.

Aydin et al., APL **90**, 254102 (2007)

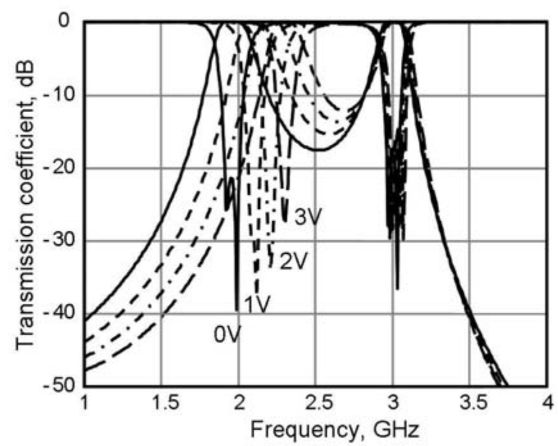
Tunable Dual-Band Microwave Filter Based on a Combination of Left/Right-Handed Transmission Lines



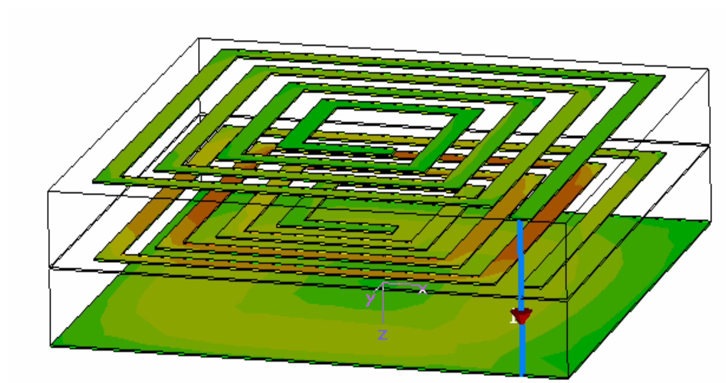


Multilayer LTCC implementations of spurious-free stepped-impedance resonators and dual-band filters based on a combination of right- and left-handed transmission line (RH and LH TL) sections was derived. The measured microwave performance of the devices exhibited high resolution and excellent reproducibility. Based on the analysis of the tunability of the devices based on RH and LH TLs sections, the functionality of these miniature devices is further enhanced. The one-band tunable filter was designed using varactor diodes.

The combination of careful design of combined structures with a reliable three-dimensional low-cost fabrication technology opens a wide potential for commercial applications.

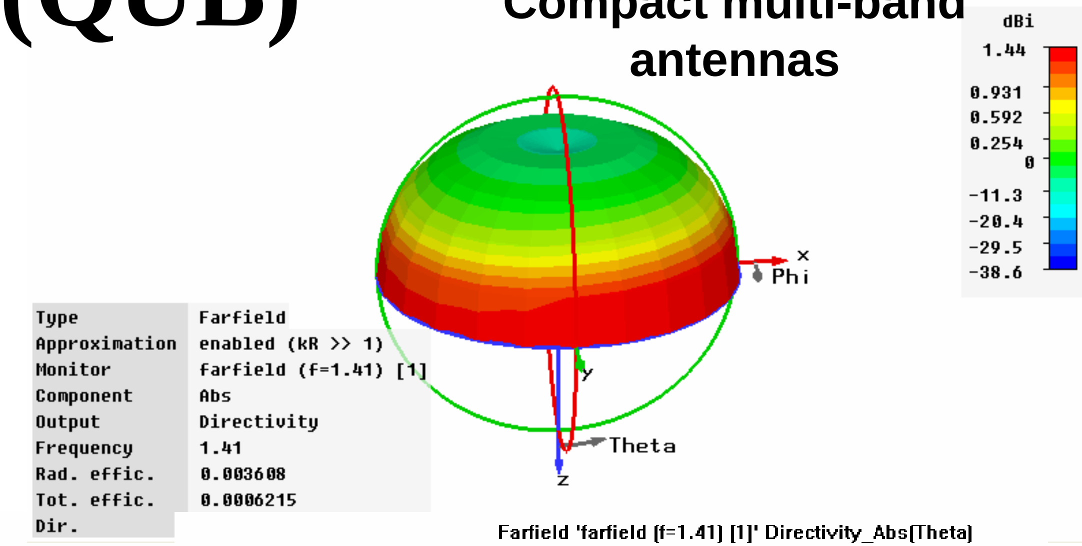


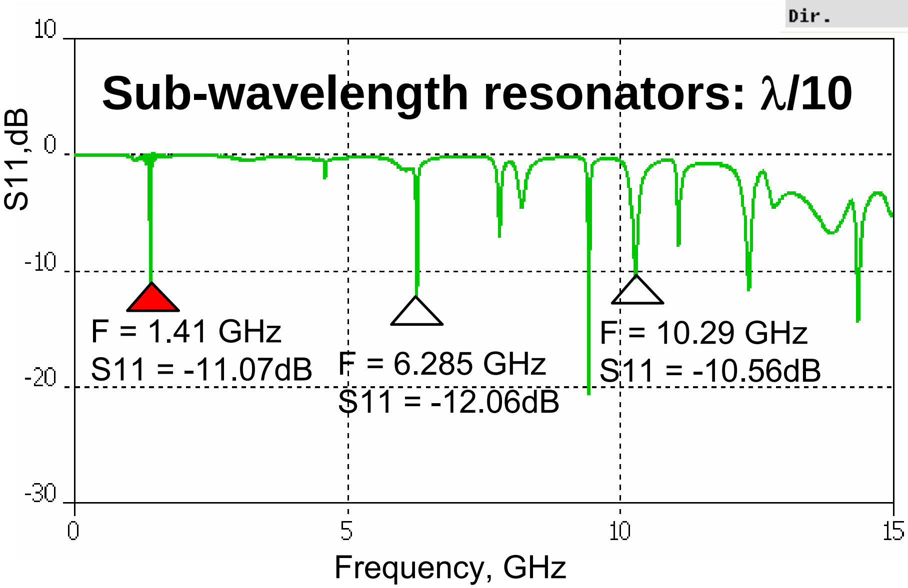
Paired Spiral Resonators & Antennas (QUB)

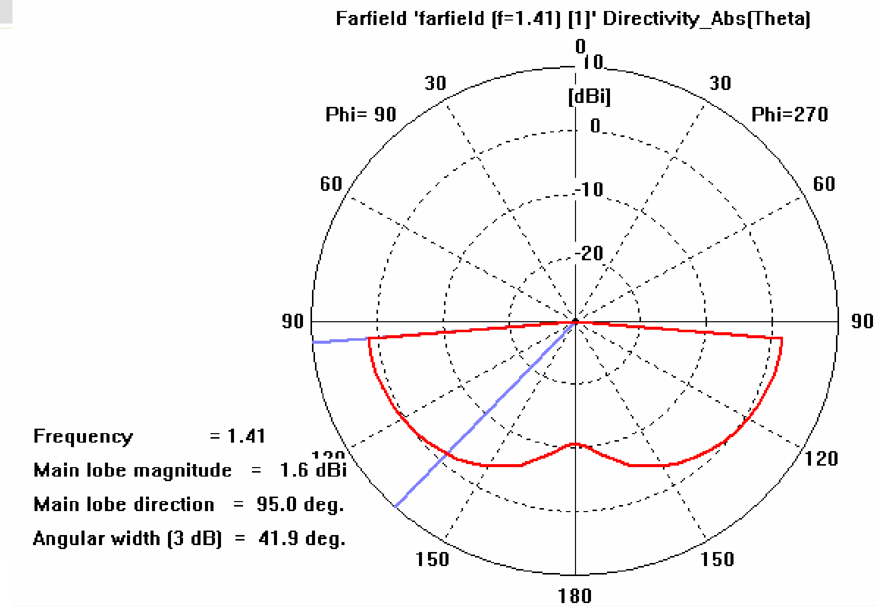


Stacked spirals above ground

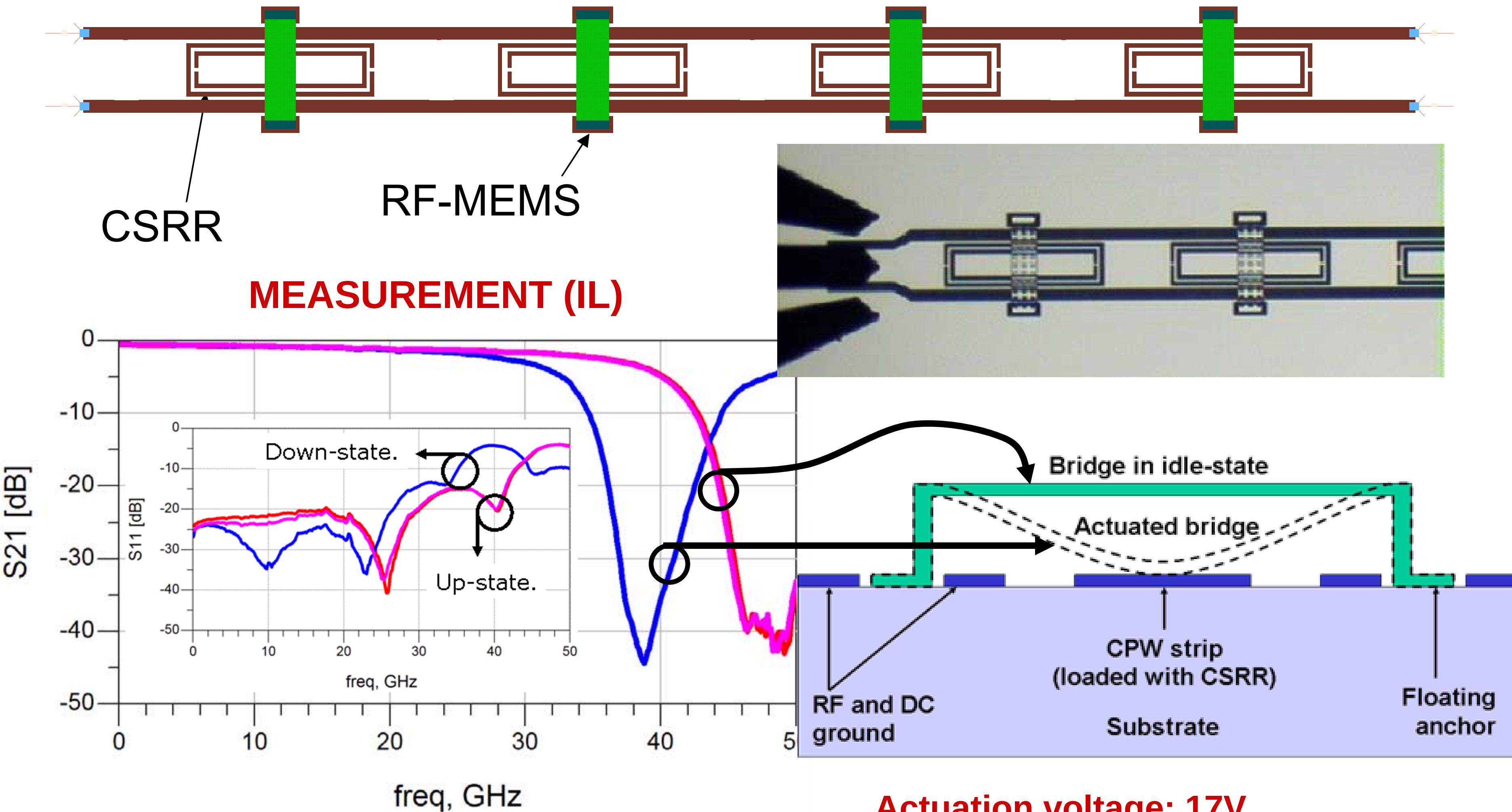
Compact multi-band antennas







Tunable metamaterial-based stop-band filters in RF-MEMS technology



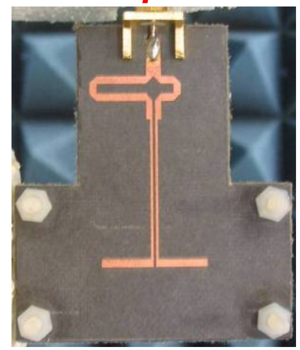
Actuation voltage: 17V

Meta-surfaces illuminated by dipole antennas

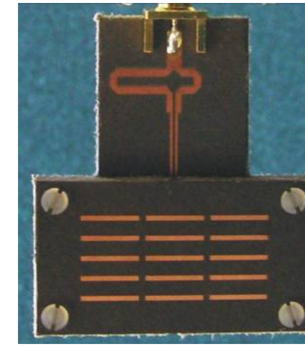
- Dipole antenna tuned to the pass band of the meta-surface
- **Thin profile** = 0.137 λ_0 at f_r =10.48 GHz
- **Good matching** S_{11} = -15 dB;
- **Enhanced directivity** D = 8.2 dBi
- **High aperture efficiency**: η_{ap} = 1.1
- **High radiation efficiency** η_r:

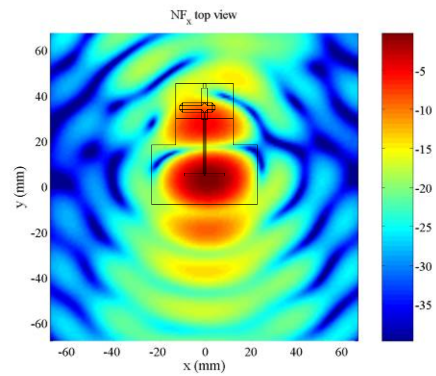
  $\eta_{r\ dipole}$ = 0.98; $\eta_{r\ superstrate}$=0.90
- **Low back radiation**
- **Mutual coupling reduction** in array configuration

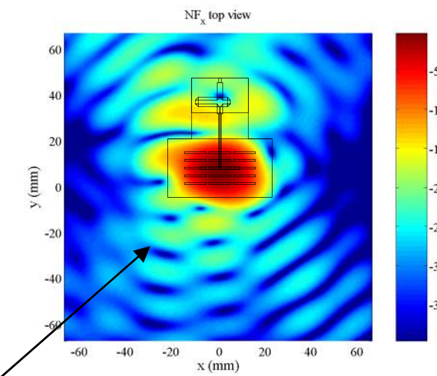
Dipole

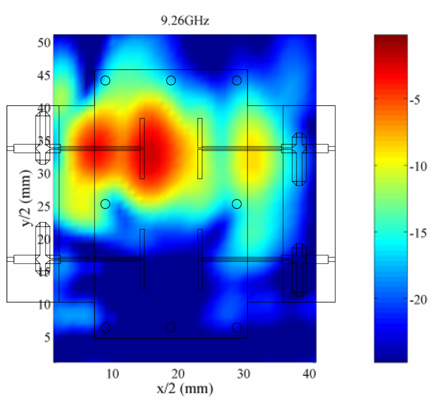


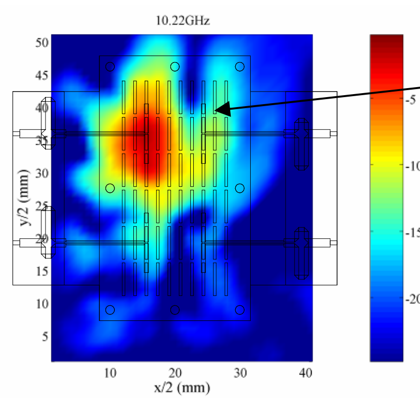
Dipole + meta-surface



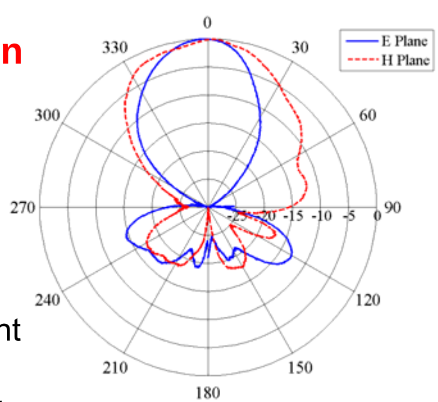








Field confined on the aperture



In collaboration with Bilkent University and Helsinki University of Technology

Decorrelation of two close antennas with a Metamaterial AMC Spacer (UPC, Spain)

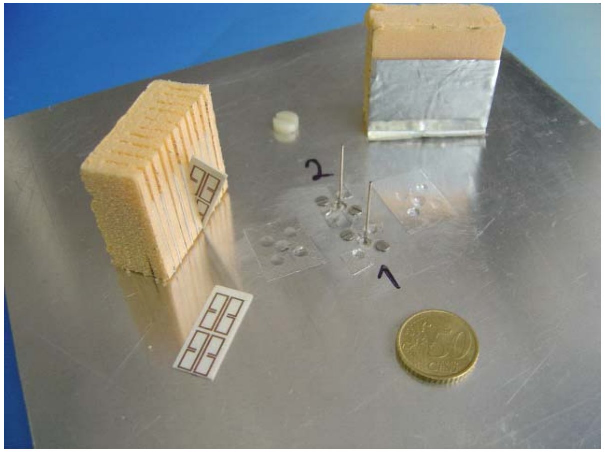
Introduction

• A bidirectional CLL based metamaterial slab provides a PMC response (phase{S11}$|_{f=f0}$ = 0º) on both sides.

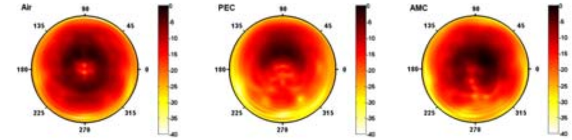
• Applied to close antennas, decoupling (low S21) and decorrelation (high C11 and low C12) has been achieved for a wide bandwidth. Results compared with Air and PEC spacers.

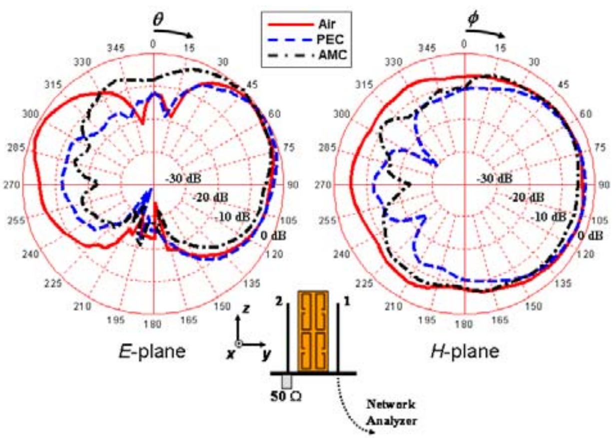
• Radiation with an AMC spacer is concentrated into a half-space, obtaining quasi-orthogonal patterns

• *Application* → Compact antenna systems (routers, handhelds).

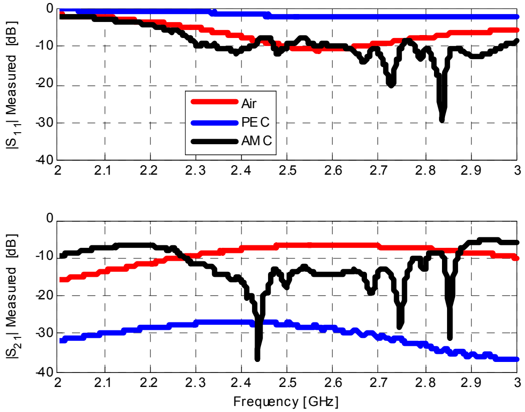


Radiation patterns





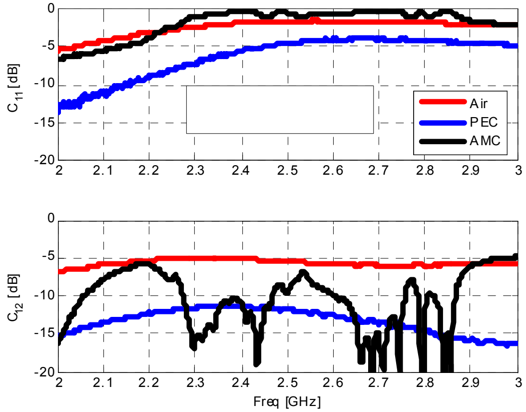
S-parameters



S_{11} < -10 dB
S_{21} < -10 dB

	Air	PEC	AMC
S_{11}	✓	✗	✓
S_{21}	✗	✓	✓

Correlation-parameters



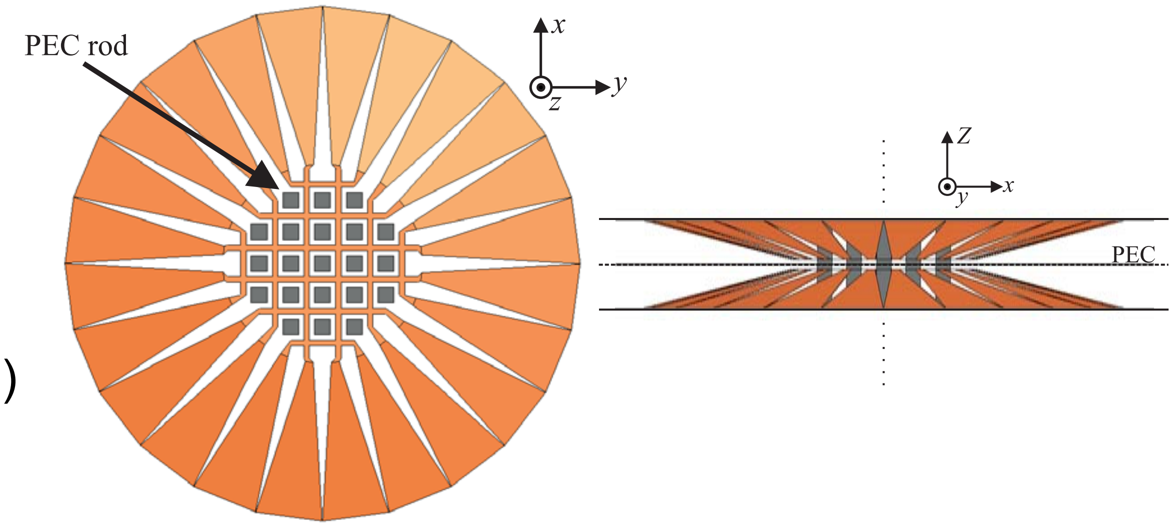
$C_{11} \approx 0$ dB
C_{21} < -10 dB

	Air	PEC	AMC
C_{11}		✗	✓
C_{21}	✗	✓	✓ ✓

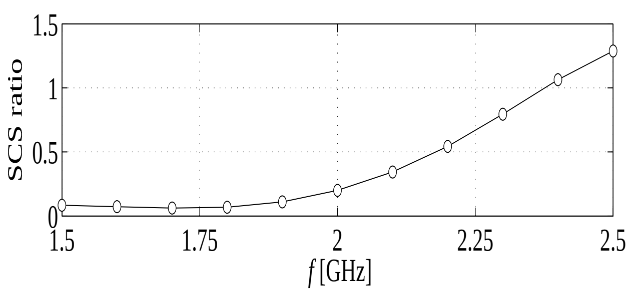
P.J. Ferrer, J.M. González-Arbesú, and J. Romeu, "Decorrelation of two closely spaced antennas with a Metamaterial AMC Surface", *Microw. Opt. Tech. Lett.*, vol. 50, no. 5, pp. 1414-1417, May 2008.

Electromagnetic cloaking based on transmission-line networks (TKK)

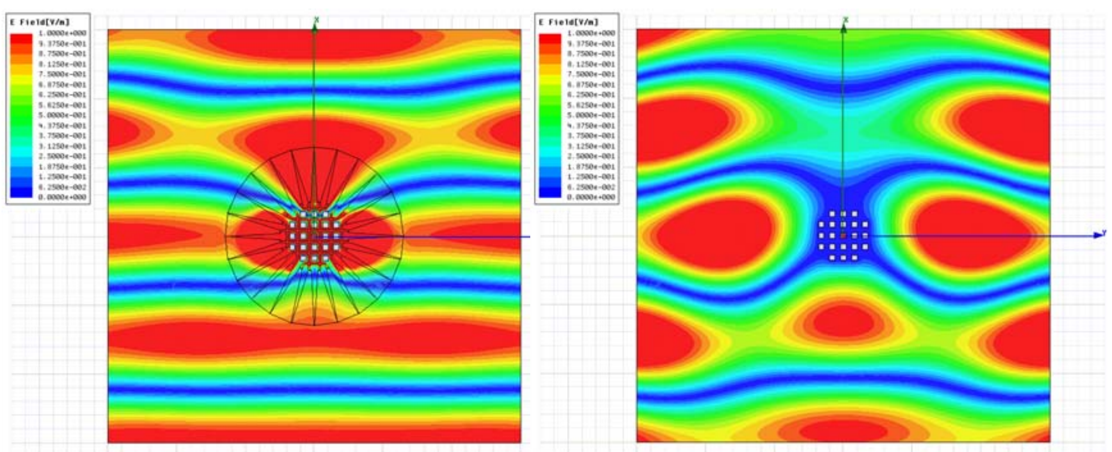
Transmission-line networks designed for the reduction of the total scattering cross section of periodic structures (2D arrays of metal rods here)



Total SCS is shown to be greatly reduced in a large bandwidth

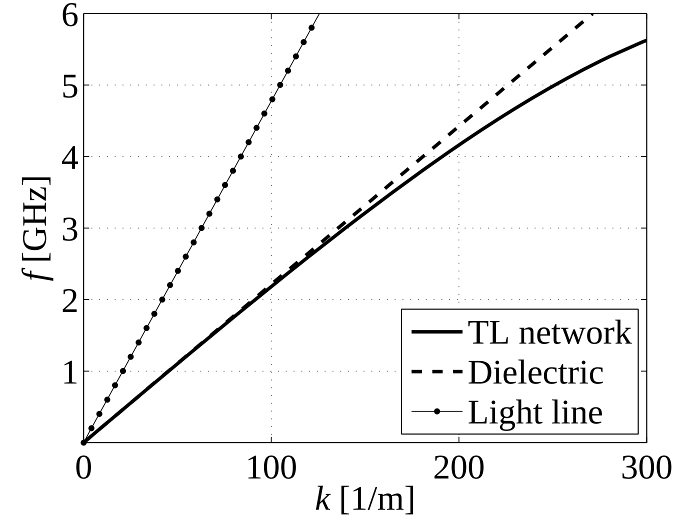


Electric field at 2 GHz:

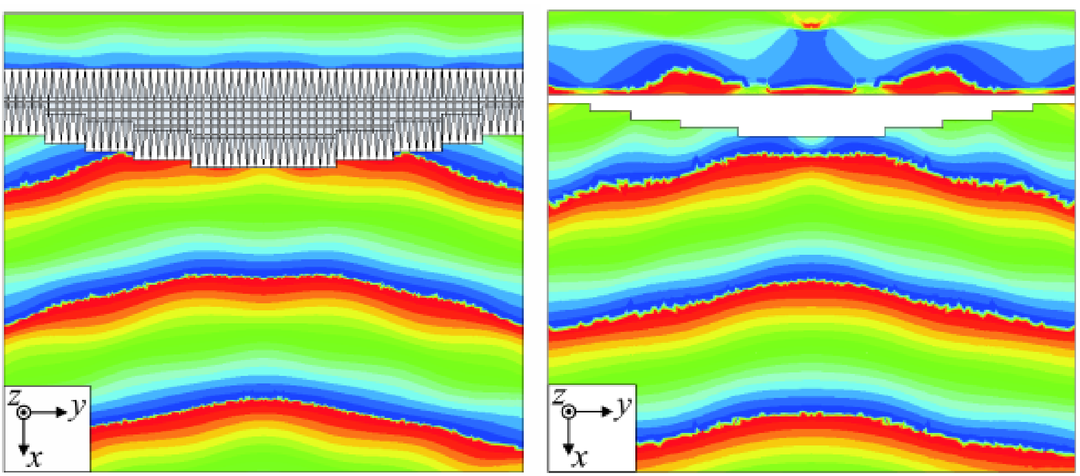


Impedance-matched microwave lenses (TKK)

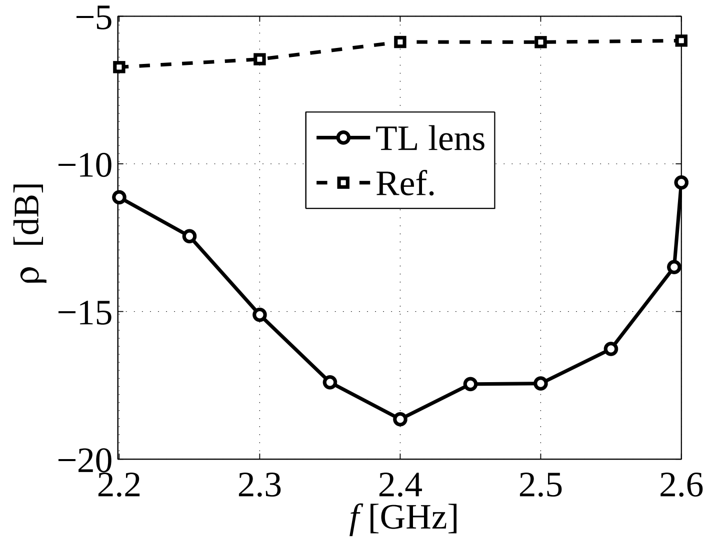
Transmission-line networks are designed to have a certain index of refraction while maintaining impedance-matching with free space in a large bandwidth



Simulated electric field phase with the proposed lens and a reference dielectric lens at 2.4 GHz



Simulated reflectance



SEVENTH FRAMEWORK PROGRAMME

Cooperation

NMP Theme

Call identifier: FP7-NMP-2007-CSA-1

COORDINATING AND SUPPORT ACTION (Coordinating)

Project acronym:

ECONAM

Project full title:

Electromagnetic Characterization of Nanostructured Materials

Work programme topics addressed:

NMP-2007-2.1-3 Characterisation of nanostructured materials

THANK YOU!

Gracias!

GRAZIE!

Dank u!

Dziękuję!

Kiitos!

Danke schön!

TEŞEKKÜR!

Merci!

ευχαριστώ πολύ!

Спасибо!

Tag!