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METAMATERIAL

Möbius Metamaterial Strips: Applications in Sensors, Frequency Source, and RF Energy Harvesting

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Outline

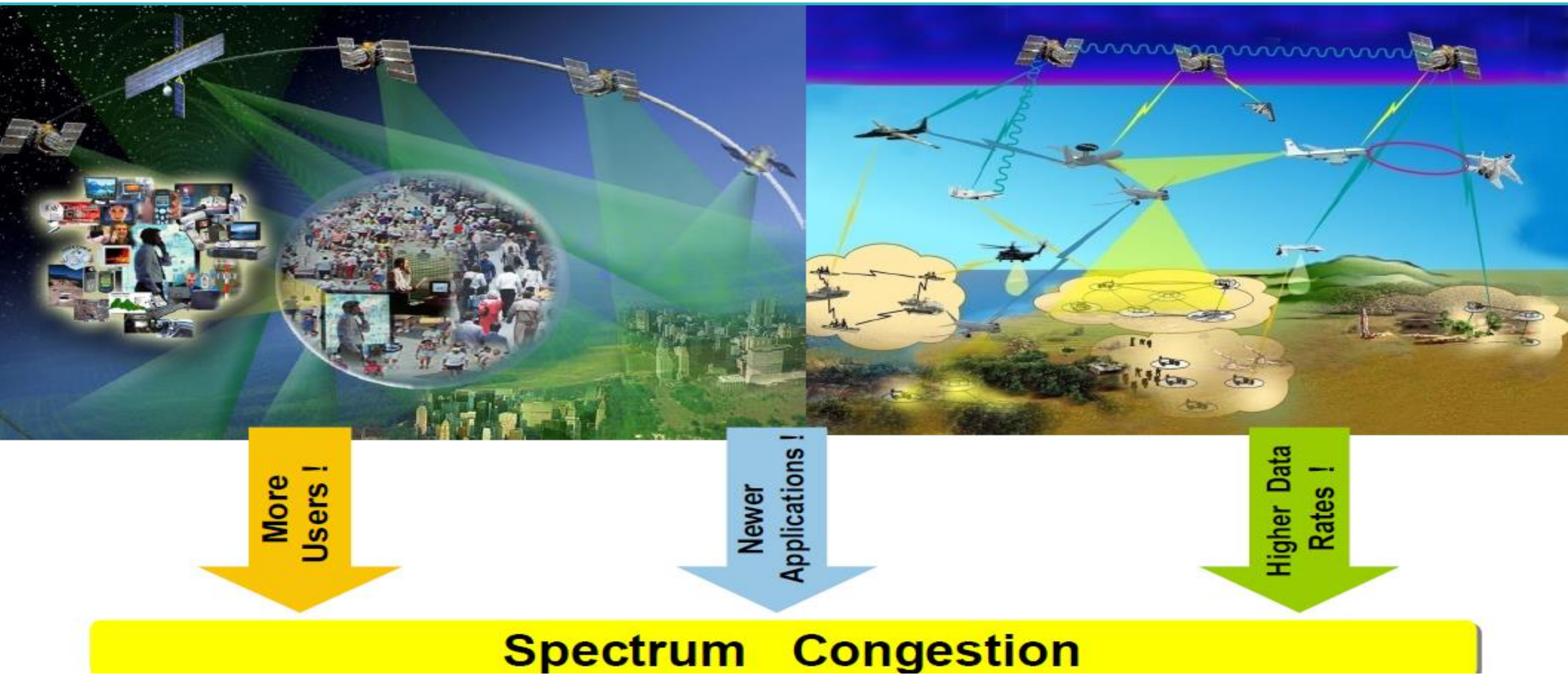
- Motivation
- Möbius Strips Resonator
- Metamaterial Resonator

MMS Möbius Metamaterial Sensors

- Metamaterial Sensors, Sources, RF/MW Components
- Energy Harvesting: Möbius Recycling:

GO GREEN

Motivation !



Problem Statement:

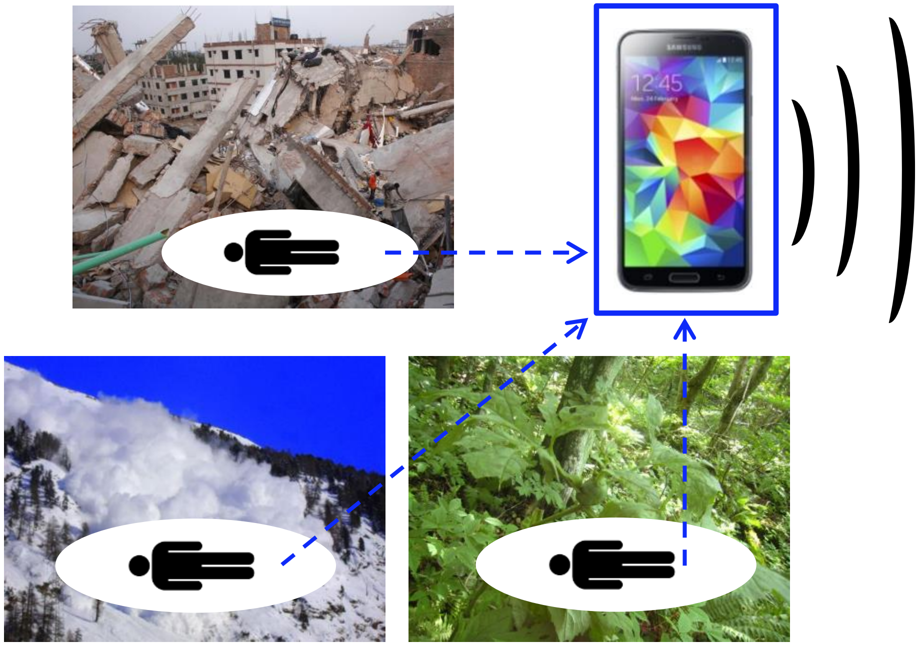
Spectrum Congestion is a concern to both Civilian and Military Sectors !

Requirement:

Low Cost and Low Phase Noise Synthesized Sources !

Energy Harvesting

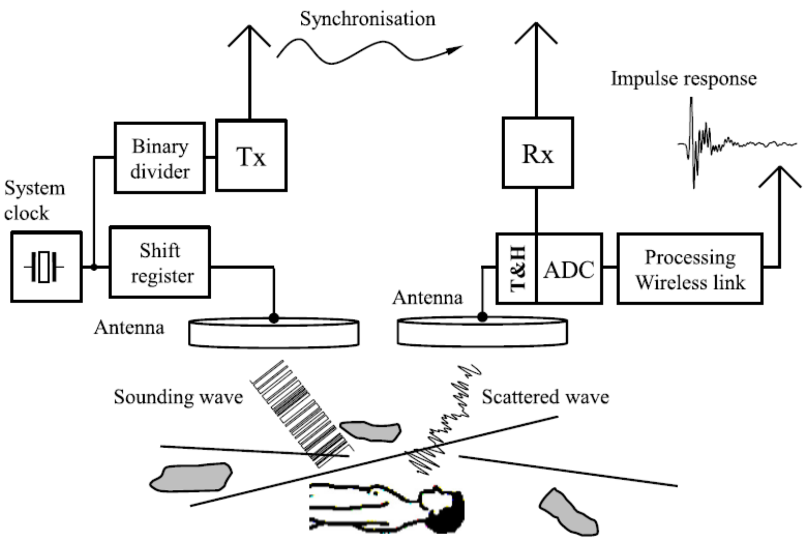
Motivation!



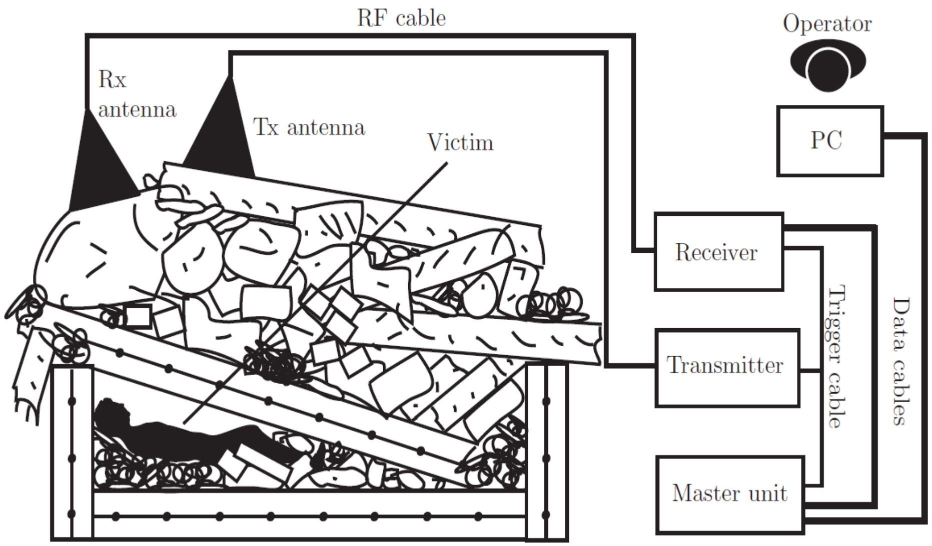
- **Trapped Victims at Emergency Situation**
  - Collapsed building, avalanche, landslide → Need to send information of victims' location to rescue
  - Unexpected situation, unconscious victims →No way to intentional communicate with rescue
- **Tracking location of victims using a portable device**
  - Mobile phone (brought by everyone)
  - Battery might be discharged after long trapped time
- **Small form factor module / Always operating regardless of battery level**

Motivation!

Radar-based trapped-victim detection system



Ultra-wideband (UWB) ground penetrating radar (GPR)
"Remote vital sign detection for rescue, security, and medical care by UWB pseudo-noise radar", Ad Hoc Network, 2014



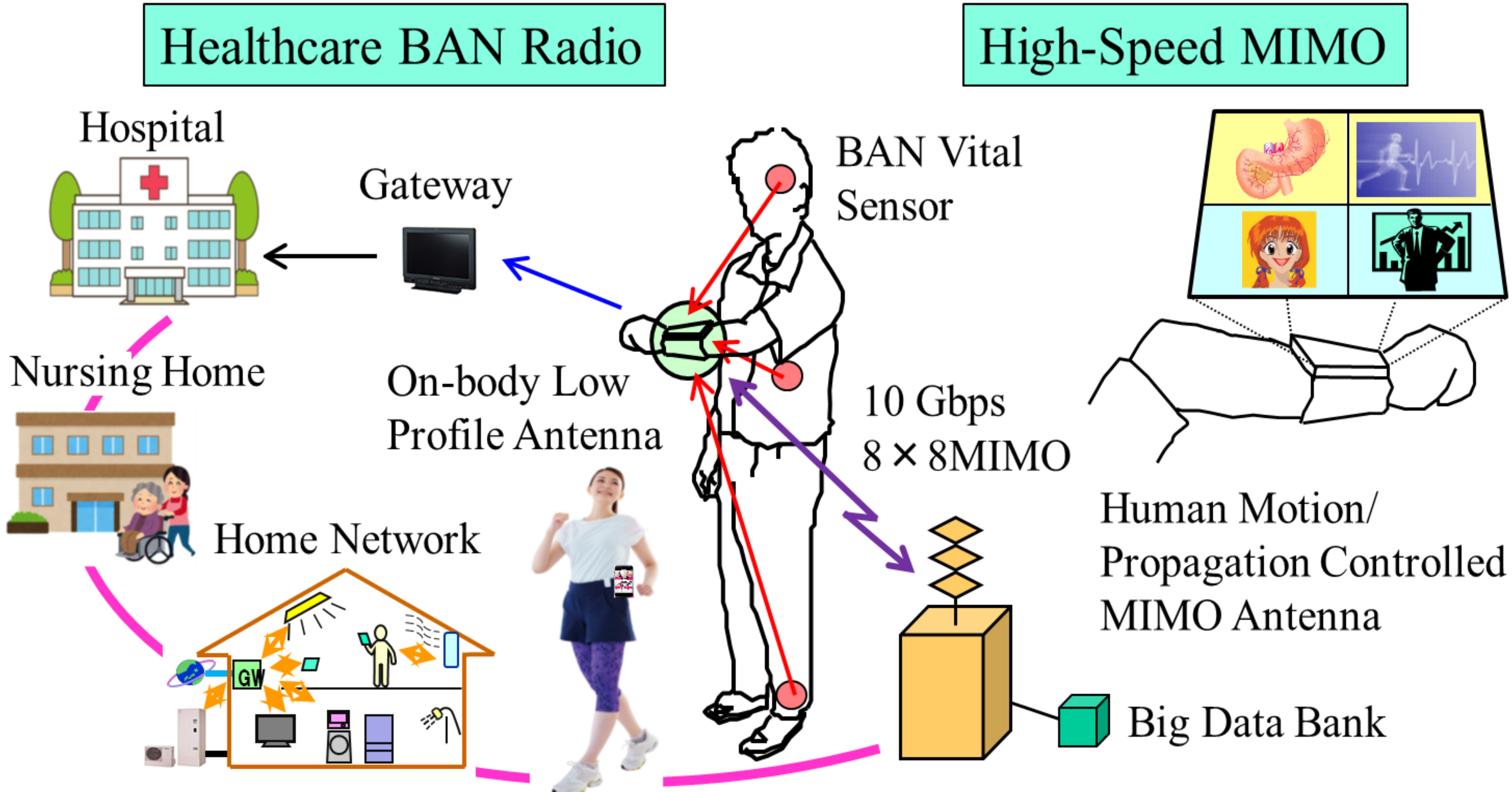
Typical set-up during trapped-victim detection using radar
"Remote vital sign detection for rescue, security, and medical care by UWB pseudo-noise radar", Ad Hoc Network, 2014

- **Motion detection system using UWB radar**
  - Impulse radar, Pseudo-random noise radar, CW UWB radar
- **Extraction of changes in frequency, phase, and arrival time of response from victims**
  - Sensitive to clutter or objects around victims
  - Signal from victims hidden in reflection from clutters and objects
- **Need of insensitive technology to existence of clutters**

Ground penetrating RADAR

Möbius Metamaterial Wearable Sensors

Body Area Network (BAN) has received considerable attention owing to the increasing demand of the applications in health care wireless communication technologies and entertainment systems. Wearable antenna for BAN system is working to realize a new wireless communication network. Our target is to reduce medical cost, to support aged people, and to activate everyday life for everybody.

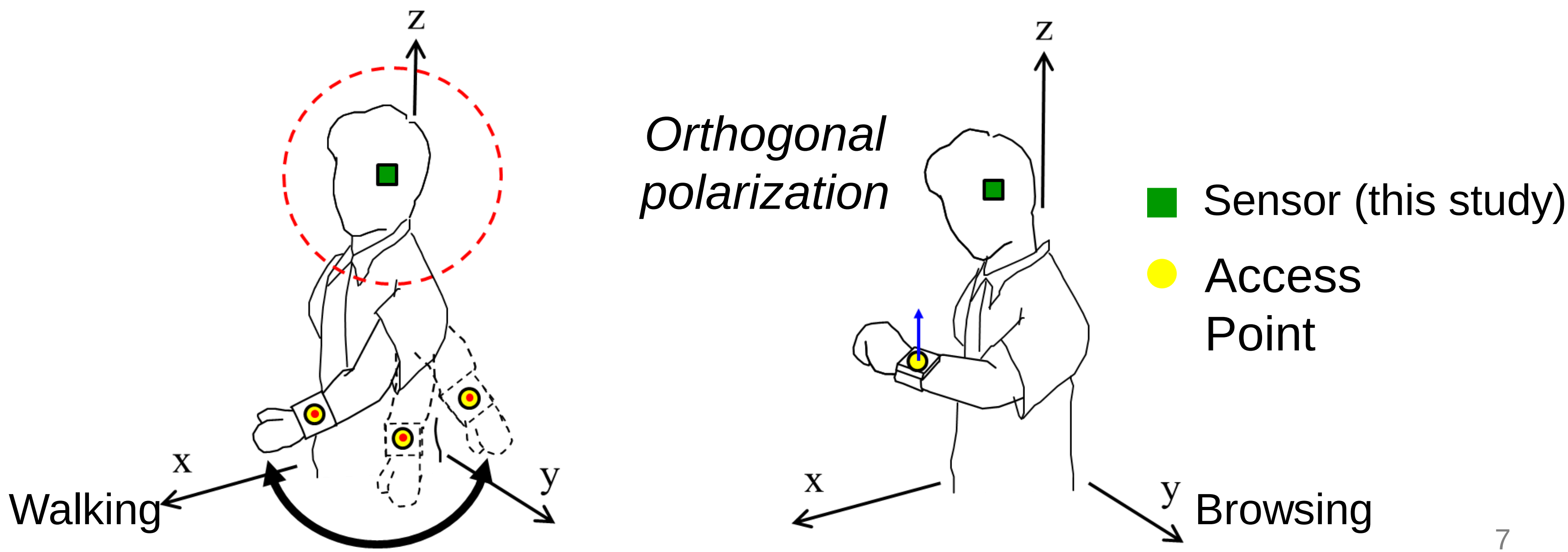


Möbius Metamaterial Wearable Sensors

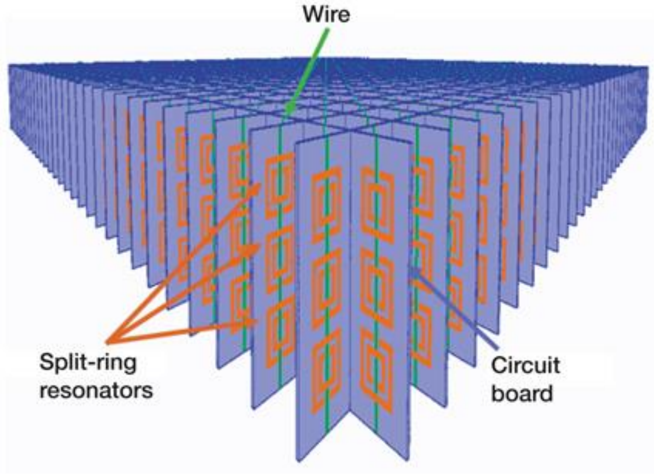
In on-body situation, due to the dynamic effects from human motion, significant signal variations between two on-body antennas will occur. Particularly, when the access point antenna is located on the wrist, a polarization mismatch caused by the arm-swing motion may result in a severe reduction of signal level.

Target of this study:

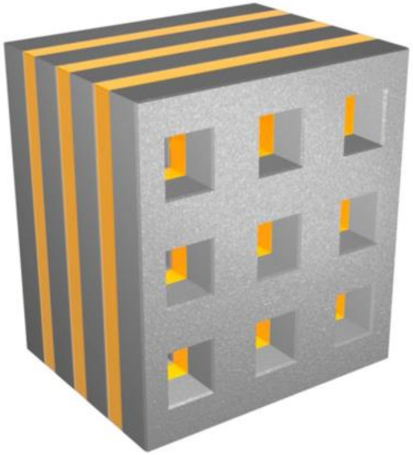
1. Omnidirectional radiation pattern to ensure the identical receiving ability against any angles of incident waves from the access point antenna mounted at the wrist .
2. Both vertically and horizontally-polarized radio wave components with equivalent magnitude are essential due to the polarization rotation caused by the variation of the access point antenna.



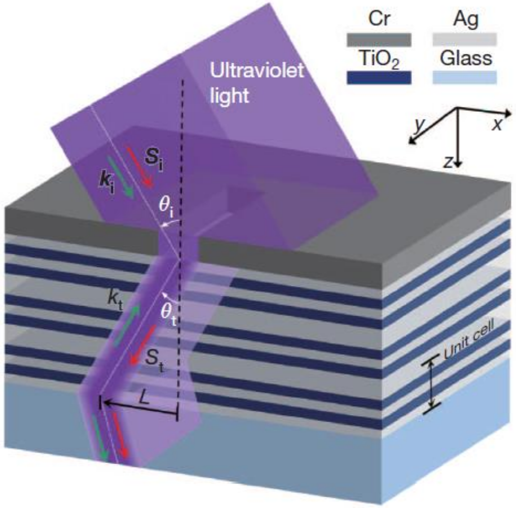
Typical Metamaterial Structure



split-ring resonators and thin wires (SRR/TW)[1]



fishnet [2]



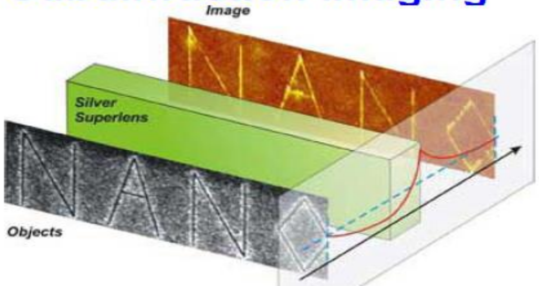
stacked plasmonic waveguide [3]

[1] R. A. Shelby, D. R. Smith, S. C. Nemat-Nasser, S. Schultz, *Applied Physics Letters* 78 (2001).
[2] C. García-Meca, J. Hurtado, J. Martí, A.Martínez, W. Dickson and A. V. Zayats , *Physical Review Letters* 106 (2011).
[3] T. Xu, A. Agrawal, M. Abashin, K. J. Chau and H. J. Leze, *Nature*, 497 (2013).

Metamaterial: State-of-The-Art Applications

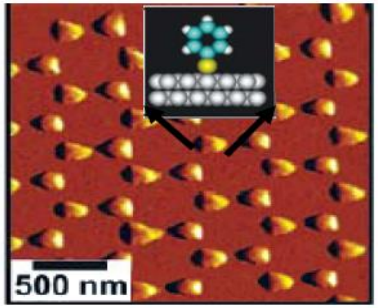
Material Today's top 10 advances in material science over the past 50 years

Subdiffraction imaging



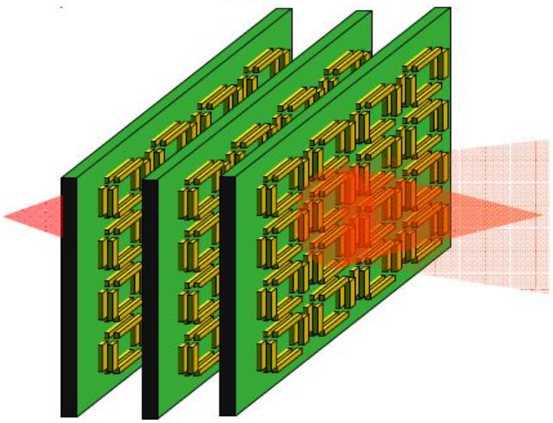
Fang *et al.*, Science, 2005

Sensing

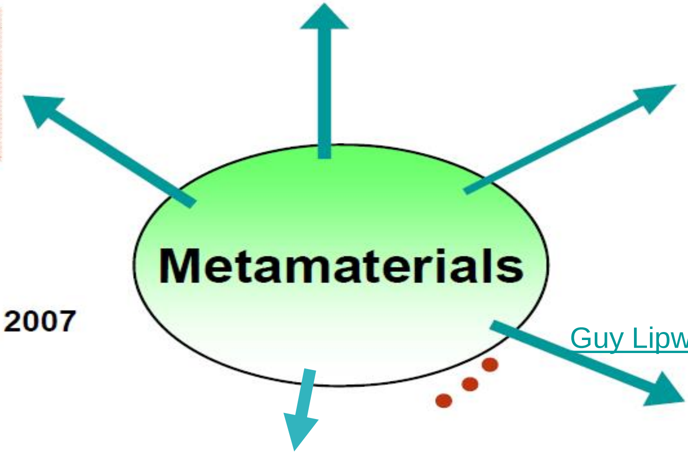


Van Duyne *et al.*, MRS bulletin, 2005

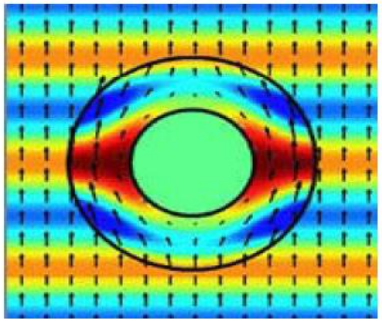
Telecom applications



Logeeswaran *et al.*, Appl. Phys. A, 2007

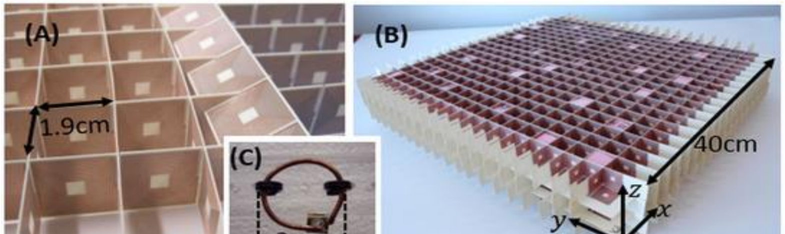


Invisibility cloaks



Chen *et al.*, PRL, 2007

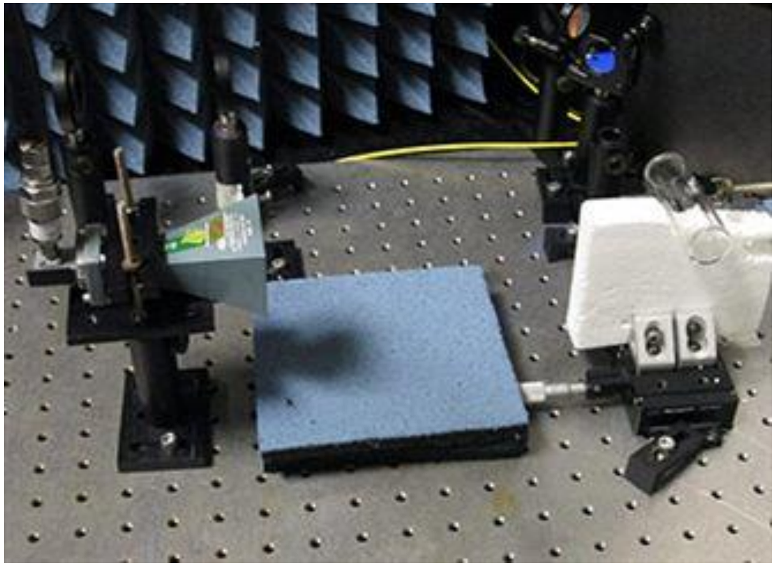
Magnetic metamaterial & superlens assembly



Guy Lipworth, et. al. 2014

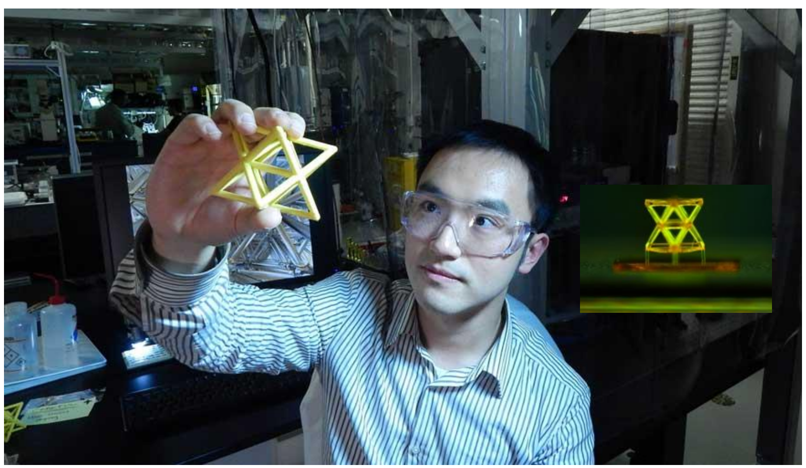
June 2014 report:
Metamaterial business will increase from 200m USD to 10 Billion USD in 10 years

Metamaterial: Status-June 2014 !



Scientists at NIST reported Sub-wavelength images at Radio Frequencies, on June 17, 2014

The NIST and Michigan researchers mapped field strength as a function of position at resolutions as low as one-hundredth of an RF wavelength, far below normal antenna limits. Such data might be used to make colorized 2D images. In theory, the technique should work for wavelengths ranging from 600 to 300,000 micrometers.



3D Printers to Print Objects 400X's Stronger Than Current Standards on June 20, 2014

When it comes to 3D printing, most people visualize the process on a macro scale, a scale which can be observed with the human eye. Critics of 3D printing argue that, in its current state, the technology is best used for prototypes. This is because we are limited by 2 factors: Material availability, and resolution of prints.

A group of researchers from MIT andLawrence Livermore National Laboratory developed micro-architected Metamaterials that print the objects 400X's Stronger Than Current Standards . It allows for extraordinary precision, in not only the 3D printing of an object, but the microstructure of that object as well.

Metamaterial: Current Status-June 2015 !

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SCIENCE

The Waves of the Future May Bend Around Metamaterials

By JOHN MARKOFF MARCH 23, 2015

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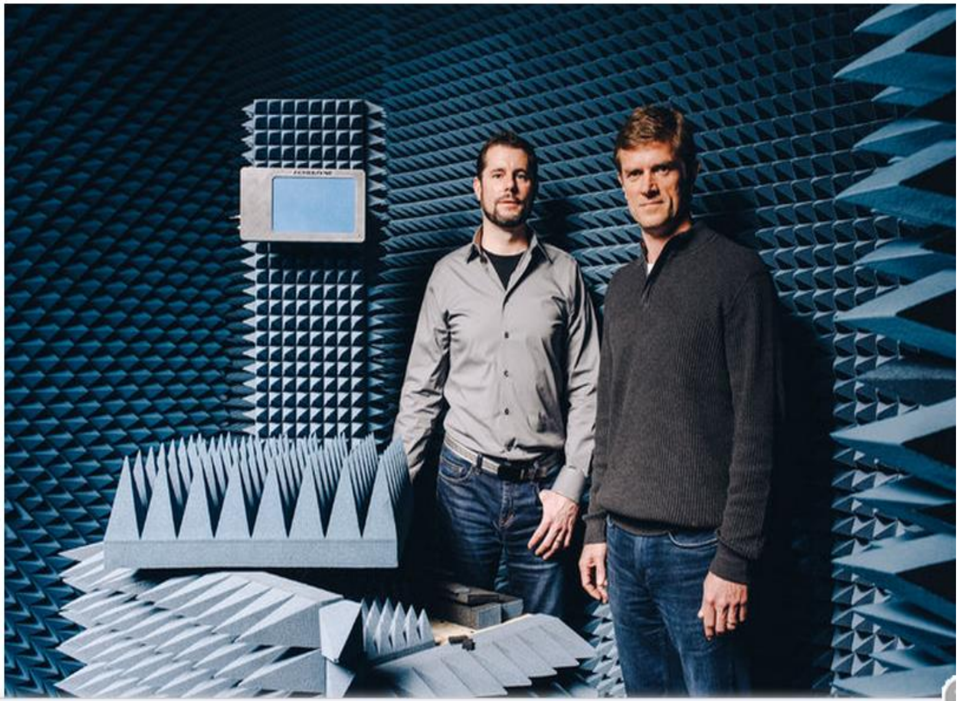
BELLEVUE, Wash. — Plastics. Computers. Metamaterials?

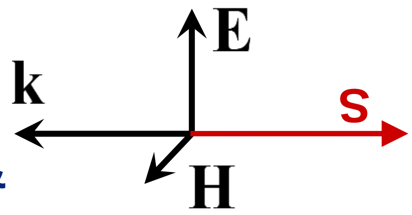


Almost half a century after Dustin Hoffman was taken aside in "The Graduate" and given the famous "one word" line about the future, it may be time to update the script again. And metamaterials appear to have the same potential to transform entire industries. Over the past 15 years or so, scientists have learned how to construct materials that bend light waves, as well as radar, radio, sound and even seismic waves, in ways that do not naturally occur.

First theorized in 1967 by the Russian physicist Victor Veselago and invented in 1999 by a group

Metamaterial-Characteristics

Backwards propagation (opposite phase & energy velocity)

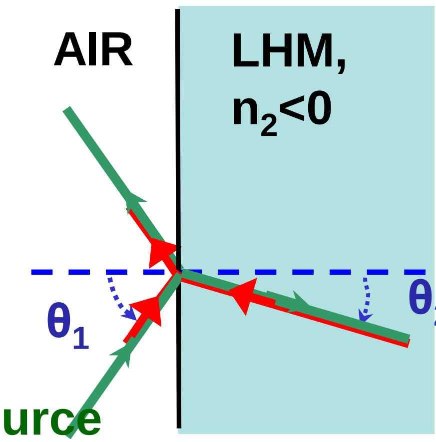


$$\mathbf{k} \times \mathbf{E} = \frac{\omega}{c} \mu \mathbf{H}$$

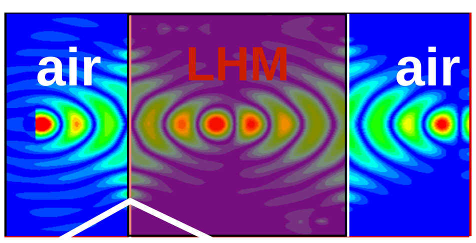
S=E×H

Negative refraction

$$\sin\theta_2 = \frac{n_1}{n_2} \sin\theta_1$$



Flat lenses - "Perfect" lenses (subwavelength resolution)



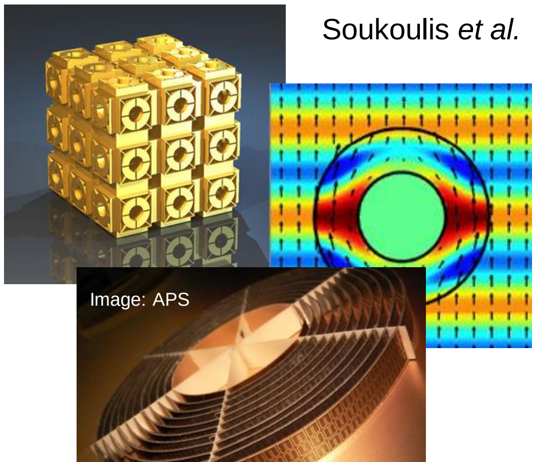
- **Zero-reflection possibility**
- **Opposite Doppler effect**
- **Opposite Cherenkov radiation**
- **……**

•Interesting physical system

•New possibilities for light manipulation → important potential applications

Why are Metasurface Interesting?

3D Metamaterials

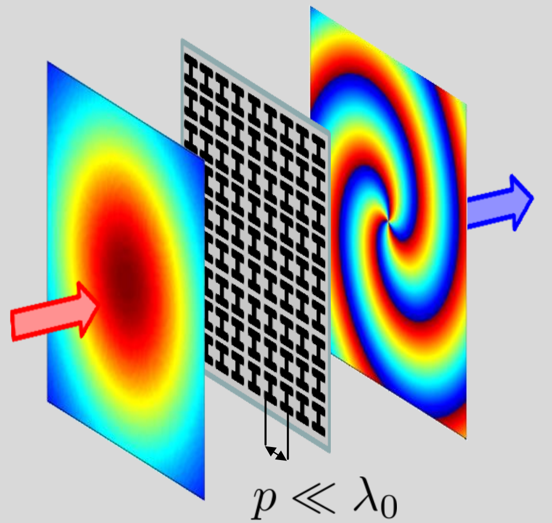


Soukoulis *et al.*

Smith *et al.*

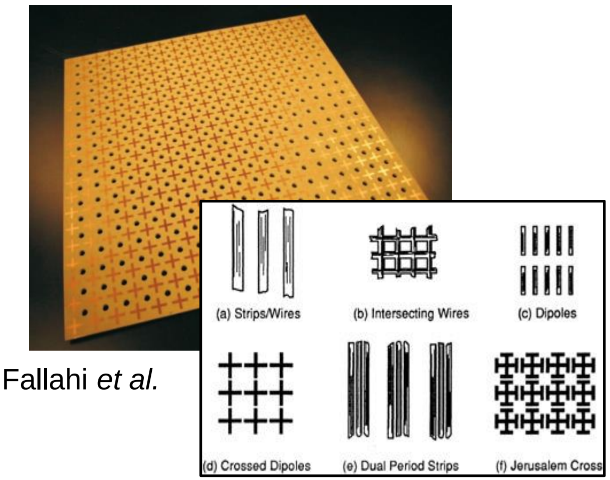
- ☺ Extra Field Control
- ☺ Signal Processing
- ☹ Bulkiness
- ☹ High Loss
- ☹ Fabrication Difficulty

Metasurfaces



- ☺ Extra Field Control
- ☺ Extensive Processing
- ☺ Reduced Dimensionality
  - ☺ Small Profile
  - ☺ Low Loss
  - ☺ Fabrication Easiness

Frequency Selective Surfaces (FSSs)



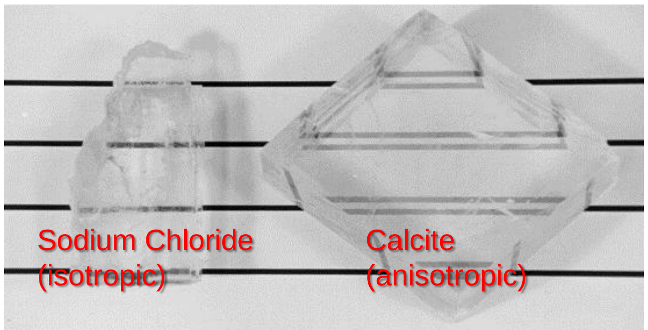
Fallahi *et al.*

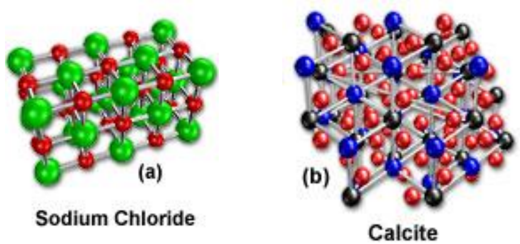
- ☺ Reduced Dimensionality
- ☺ Filtering & Polarization
- ☹ Limited Signal Processing
- ☹ Uniformity Restriction

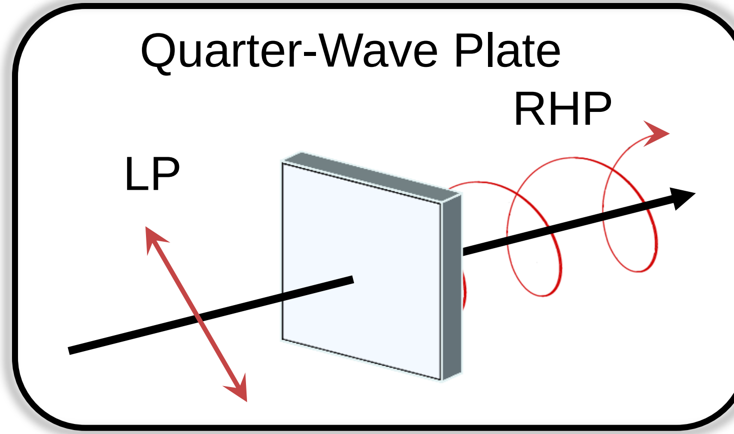
Dimensional Reduction of Metamaterials & Functional Extension of FSSs

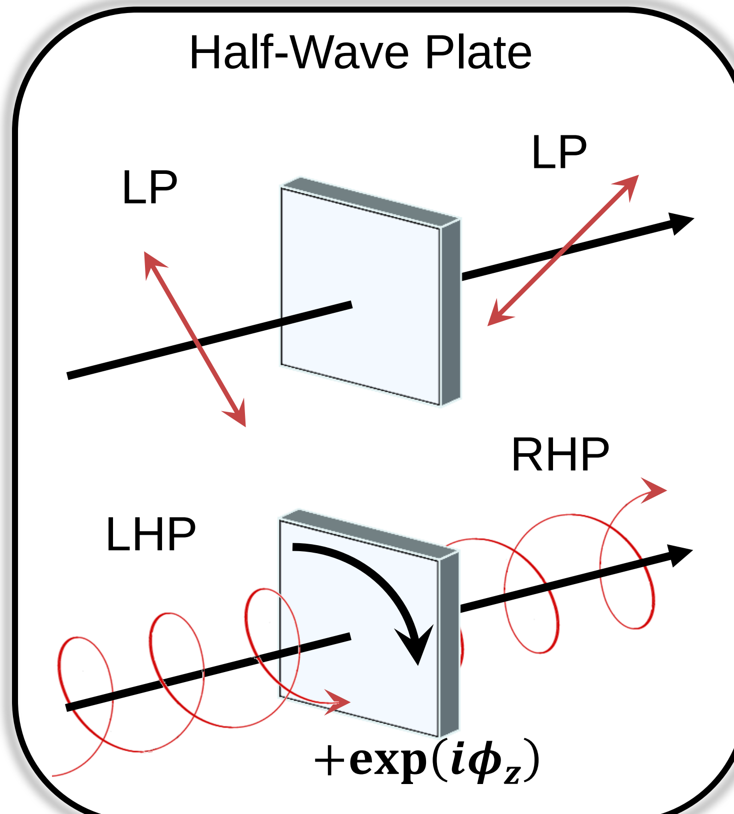
Birefringent Metasurface ?

Birefringence:
Refractive index depends on polarization







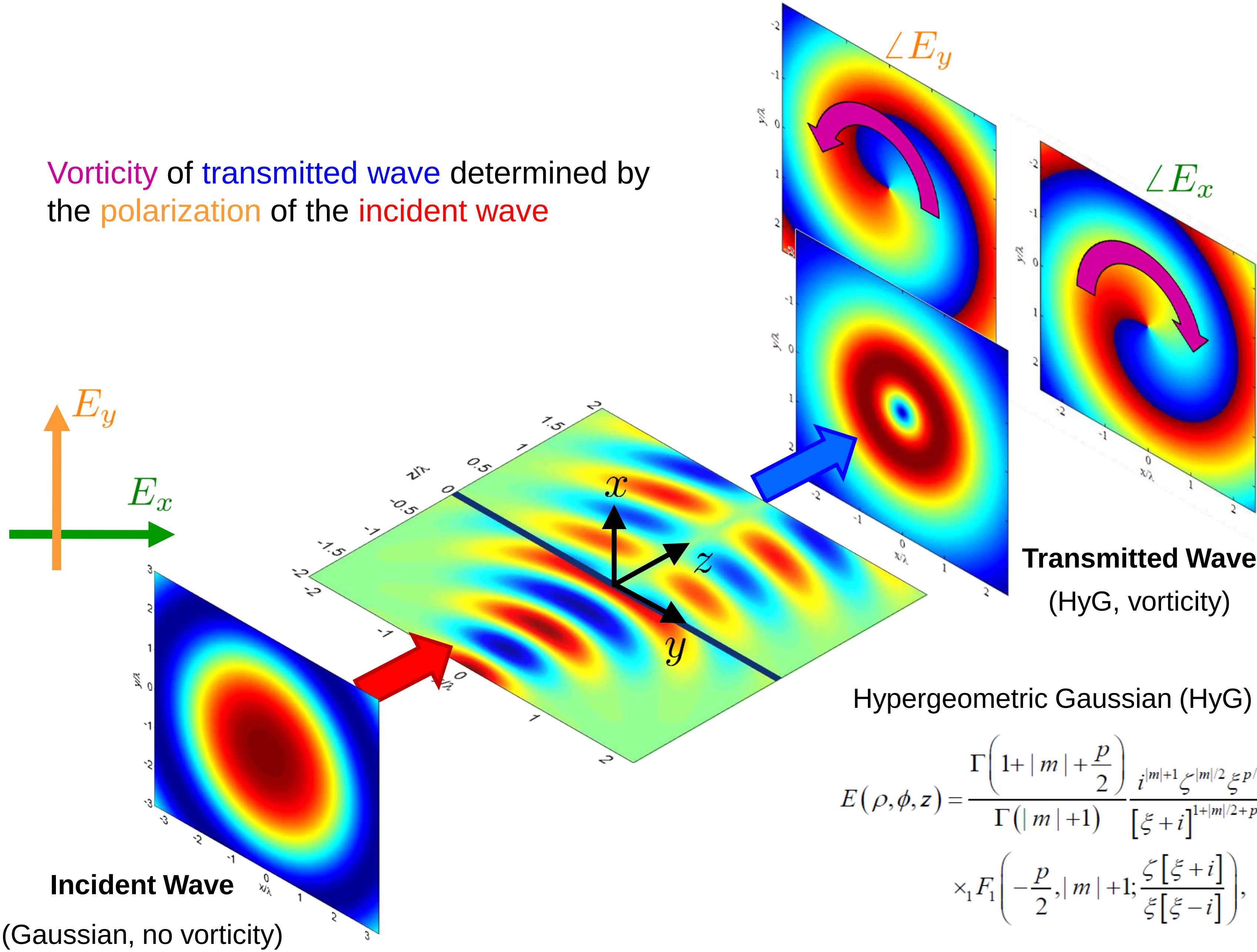


Pancharatnam-Berry Effect

Birefringent metasurface:
Field control depends on polarization
Extra degree of electromagnetic field control

Birefringent Vortex Wave Conversion

Vorticity of transmitted wave determined by the polarization of the incident wave



Hypergeometric Gaussian (HyG) Beam

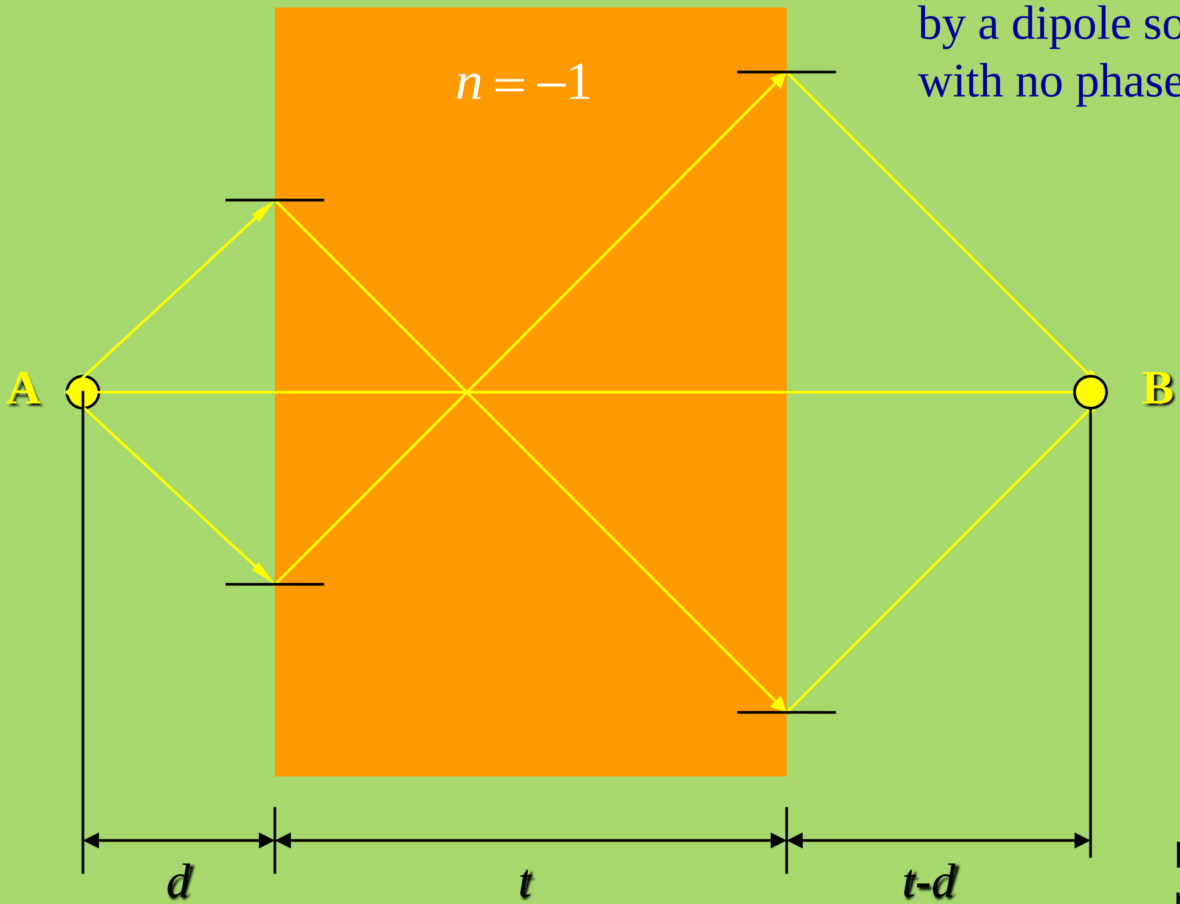
$$E(\rho,\phi,z)=\frac{\Gamma\left(1+|m|+\frac{p}{2}\right)}{\Gamma(|m|+1)}\frac{i^{|m|+1}\zeta^{|m|/2}\xi^{p/2}}{[\xi+i]^{1+|m|/2+p/2}}e^{im\phi-i\zeta}$$

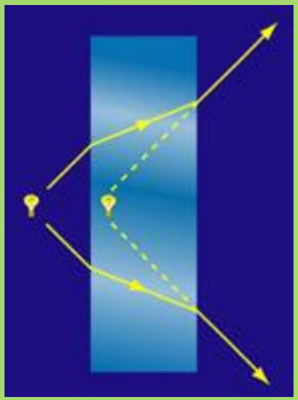
$$\times{}_1F_1\left(-\frac{p}{2},|m|+1;\frac{\zeta[\xi+i]}{\xi[\xi-i]}\right),$$

Metamaterial-Characteristics

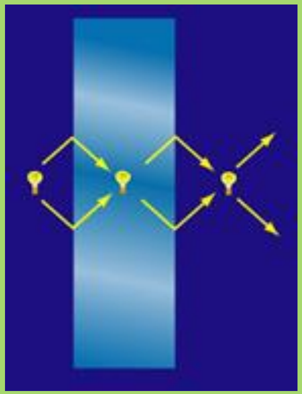
Possibility of the Realization of Perfect Lens

The lens focuses all the "planes waves" radiated by a dipole source (even the evanescent waves), with no phase or amplitude distortion





Light enters n > 0 material → deflection



Light enters n < 0 material → focusing ("Veselago Lens")

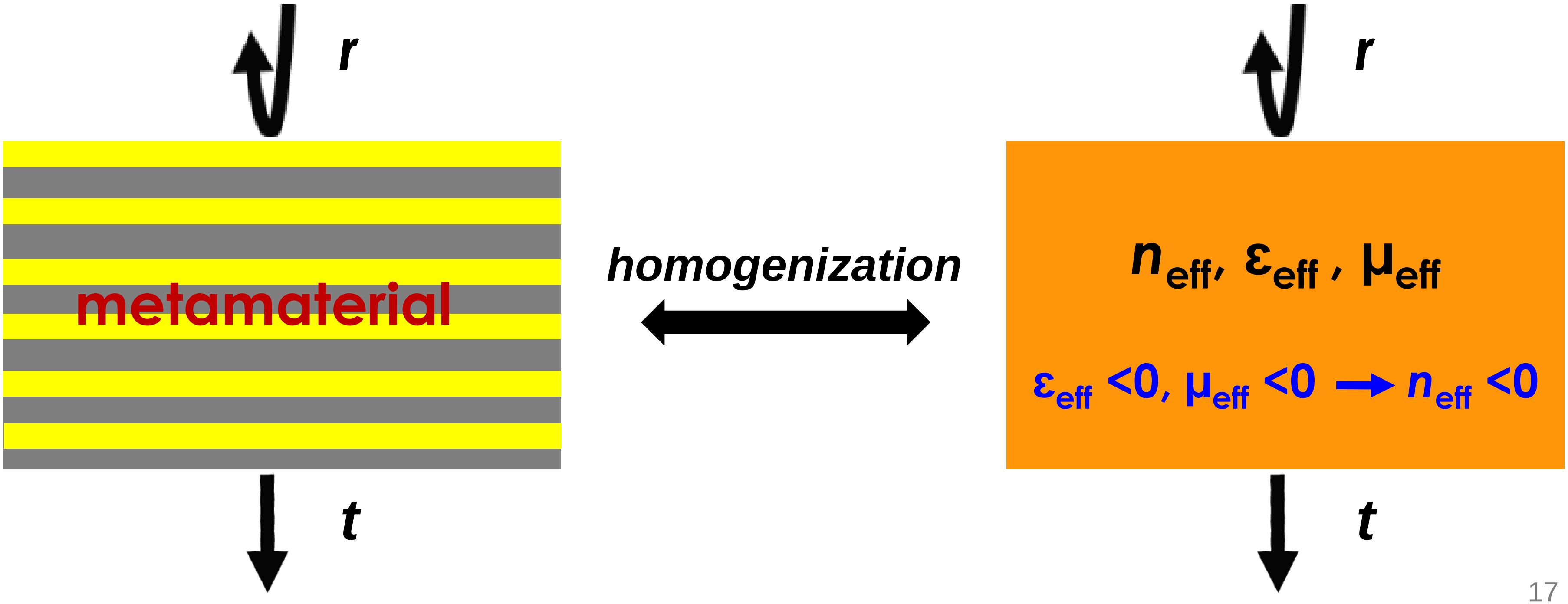
Metamaterial: Concept of Effective Parameters

Effective Parameters:

It is a significant challenge to homogenize Metamaterials, i.e. to determine the effective material parameters.

Crucial Parameters:

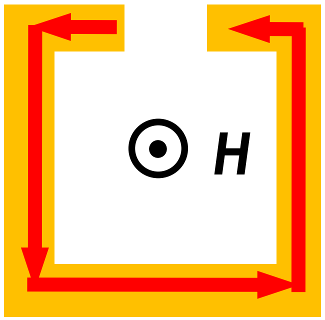
effective refractive index n_{eff} , effective permittivity ε_{eff} and effective permittivity μ_{eff} …



Negative index in the Microwaves Region

Magnetic Response

Split Ring Resonator (SRR)

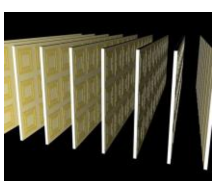


Collection of SRR forms effective magnetic medium.

$$\mu_{eff} = 1 - \frac{F\omega^2}{\omega^2 - \omega_0^2 + i\omega\Gamma}$$

Γ: dissipation factor F: fractional factor

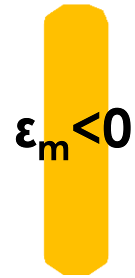
Array of SRR



Pendry, J. B., et al., 47, 2075, IEEE Trans. Microw. Theory Tech. (1999)
Pendry, J. B., et al., 76, 4773 , Phys. Rev. Lett. (1996)

Electric Response

Metallic Wires



Collection of conducting wires forms an effective electrical medium with a controllable plasma frequency.

$$\varepsilon_{eff} = 1 - \frac{\omega_P^2}{\omega^2}$$

ω_P: controllable plasma frequency

Array of Metallic Wires

For long wavelengths an array of metallic wires interacts with electromagnetic waves as a plasma, and thus exhibits a negative permittivity below the plasma frequency:

Negative index in the Microwaves Region

Material Dispersion

DNG metamaterials: can be achieved by frequency resonance of a mixture of metallic and/or dielectric particles in a host medium.

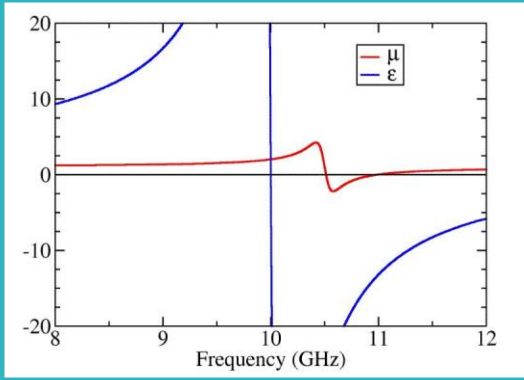
$$\frac{\varepsilon}{\varepsilon_0} = \frac{\omega_{e_p}^2 - \omega_{e_0}^2}{\omega_{e_p}^2 - \omega^2 - i\omega\gamma_e} \qquad \frac{\mu}{\mu_0} = \frac{\omega_{m_p}^2 - \omega_{m_0}^2}{\omega_{m_p}^2 - \omega^2 - i\omega\gamma_m}$$

ω_{e_p} : Electric plasma frequency

ω_{e_0} : Electric resonance frequency

ω_{m_p} : "Magnetic plasma frequency"

ω_{m_0} : Magnetic resonance frequency.



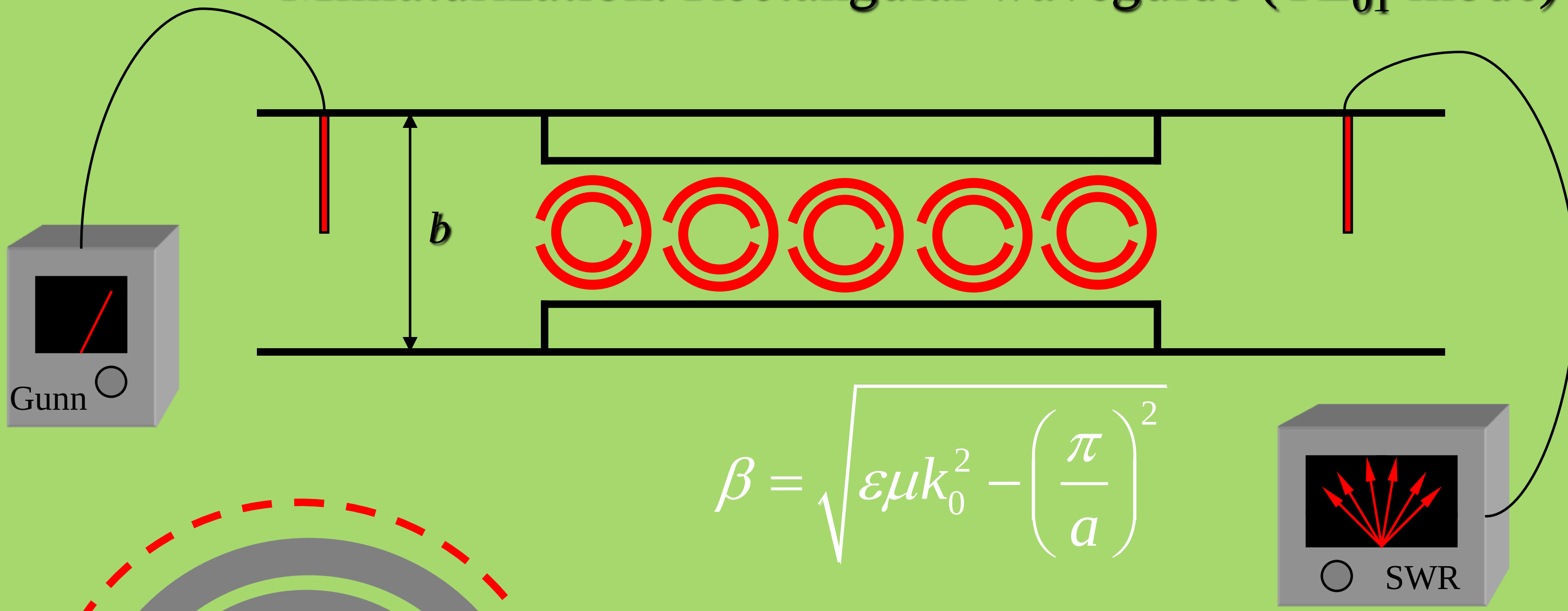
Negative permittivity (effect of wires)

Negative permeability (effect of rings)

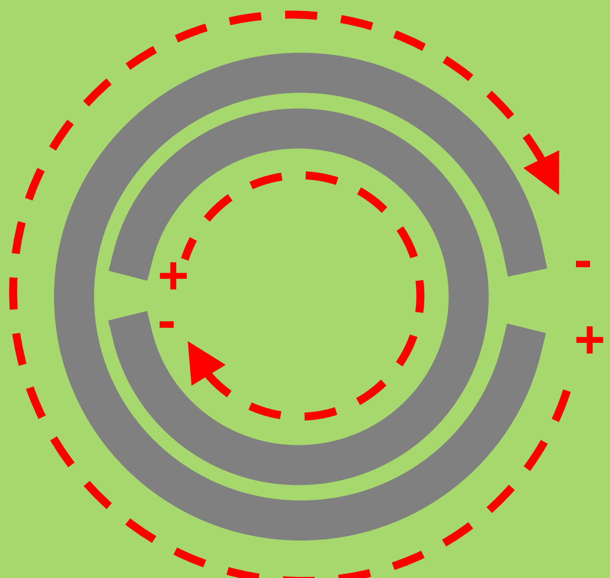
Split-ring resonators (SRRs) based metamaterial, functioning in microwave spectrum. R. A. Shelby *et al.*, Vol. 292, pp. 77 - 79, Science (2001).

Metamaterial For Miniaturization of WG

Miniaturization: Rectangular waveguide (TE_{01} mode)



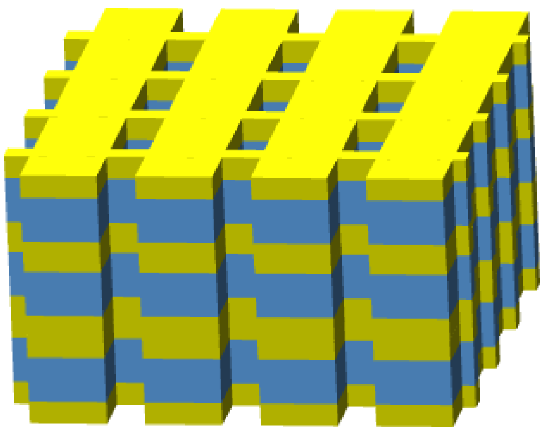
$$\beta = \sqrt{\varepsilon\mu k_0^2 - \left(\frac{\pi}{a}\right)^2}$$



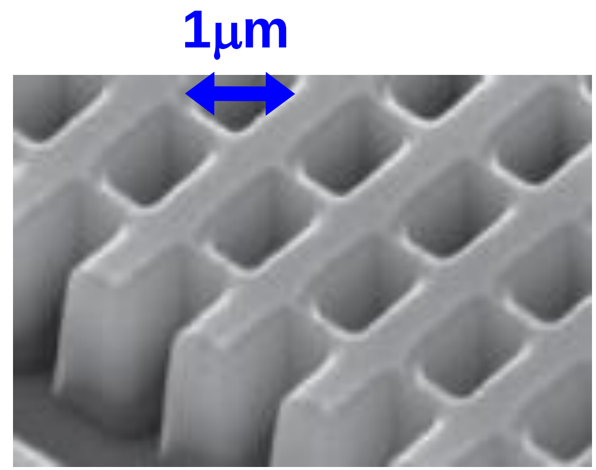
- External magnetic field penetrates through the rings and currents are induced.
- Gap prevents currents from flowing around the ring, which considerably increases the resonance frequency of the structure.
- SRR provides a resonant structure which is much smaller than the resonance wavelength.

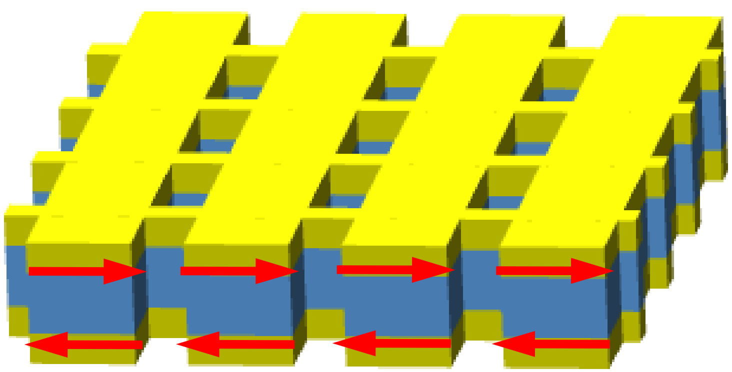
Moving to Optical Spectrum

Conceptual Difficulties: high dissipation of metals, saturation of magnetic resonance…
Fabrication Difficulties: difficulty of scaling-down and stacking-up…



Fishnet Metamaterial



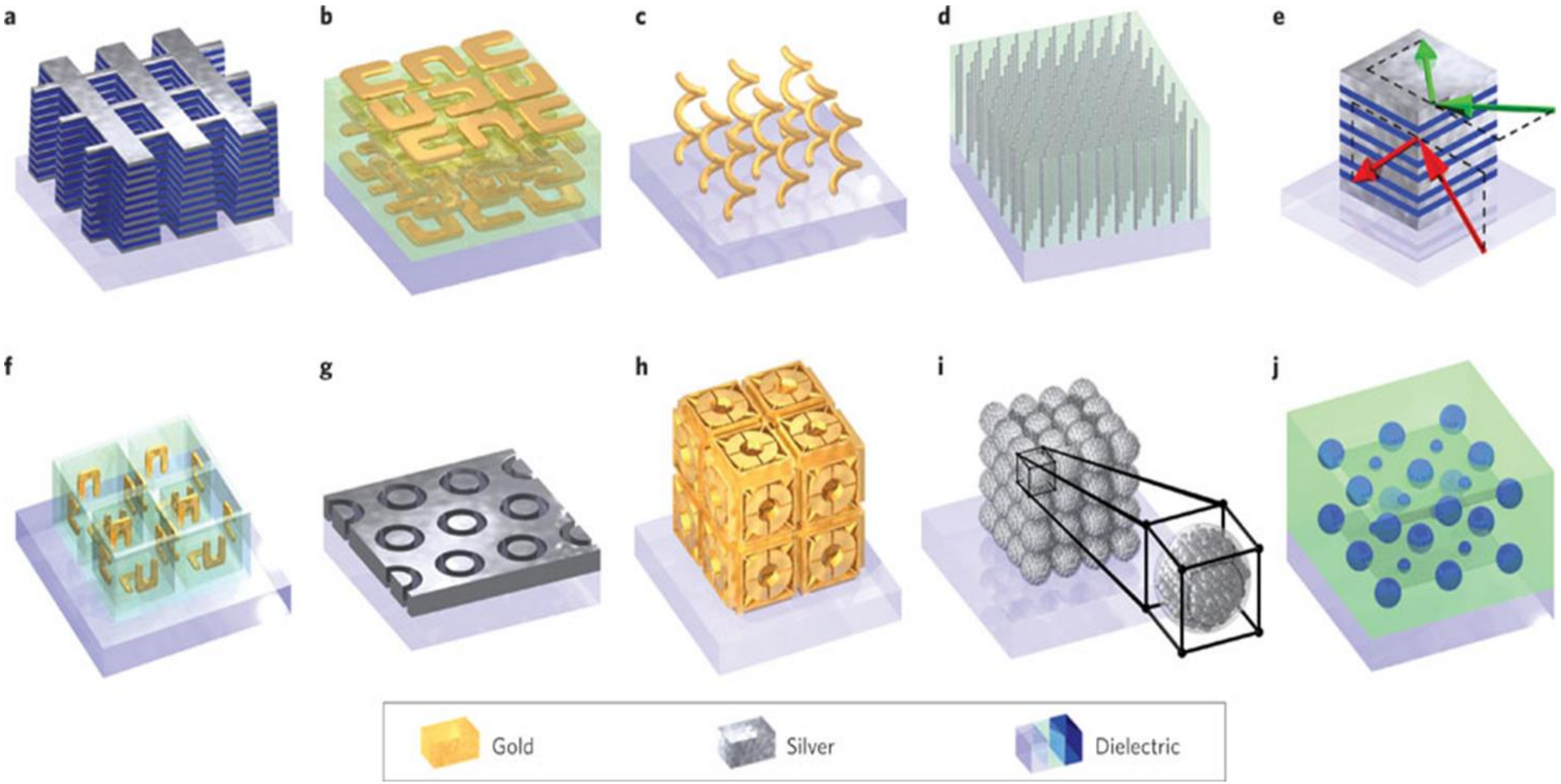


Current Loop

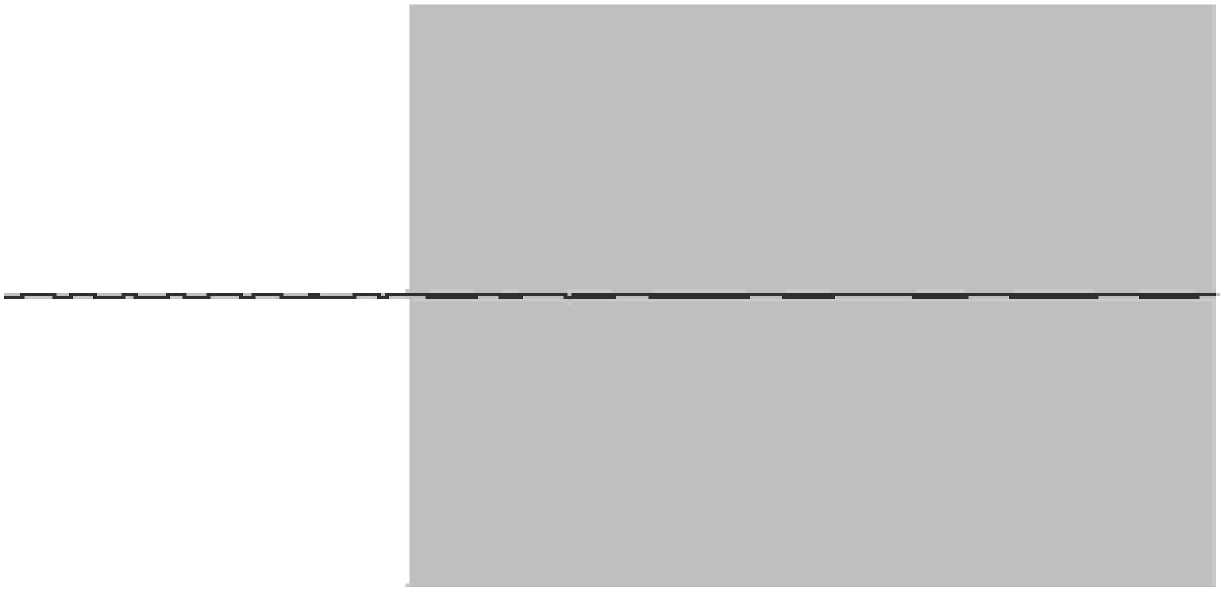
Fishnet metamaterials, functioning in near-infrared spectrum.

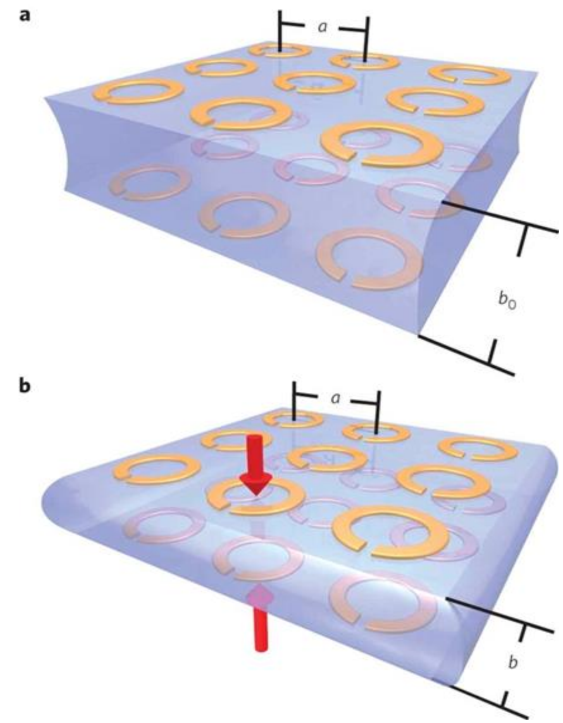
J. Valentine *et al*., 455, 376-379, Nature (2008).

Metamaterial-Fabrication Technologies



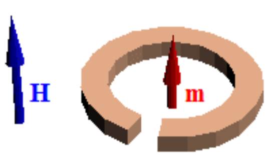
Moving to Oscillator Resonator Applications

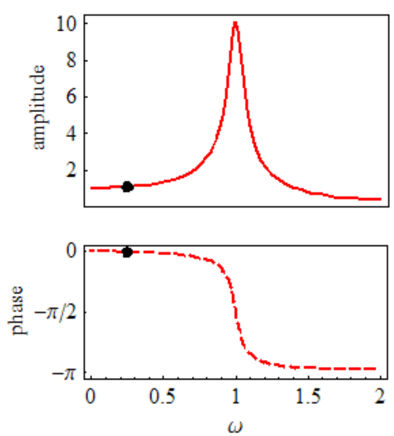


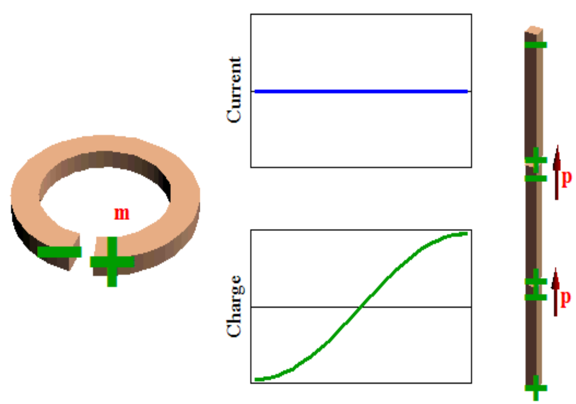


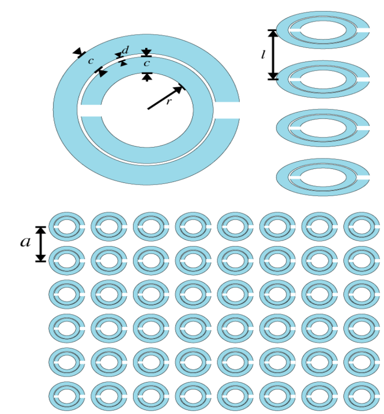
Positive Index Medium

Negative Index Medium
(Evanescent Mode amplification)





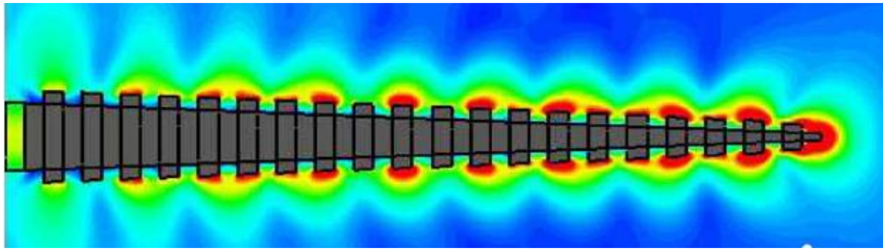




Synergy Role : Metamaterial Möbius Sensors

- Metamaterial Technology
  - Metamaterial : Applications
  - Metamaterial Based Microwave Sensors
  - Metamaterial Resonator Based Oscillators
- Möbius Technology
  - Möbius Strips
  - Möbius Strips Resonator: Applications in Oscillators, Synthesizers
  - Möbius Resonator Based Microwave Sensors
- Metamaterial Möbius Technology
  - High Performance Signal sources
  - RFID Technology

Tapered MMR Rod

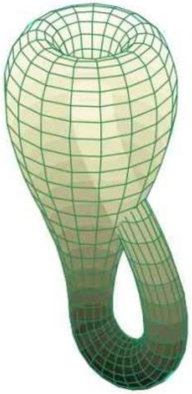


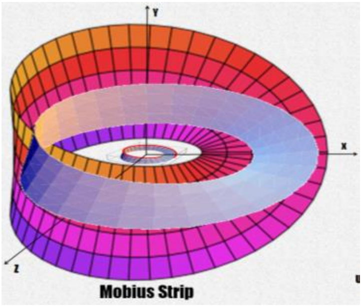
- Ability to localize electromagnetic energy below the diffraction limit
- Focusing, imaging, sensing, detection

Typical Möbius Strip Surface

- A typical Möbius is a surface with only one side and only one boundary component, the mathematical property of being non-orientable.
- The concept of the Möbius strips is based on the fact that a signal coupled to a strip shall not encounter any obstruction when travelling around the loop and the loop shall behave like an infinite transmission line, therefore exhibit large group delay resulting improved Q-factor.
- Challenge: 3-D structure not easily amenable for planar integrated circuit solution

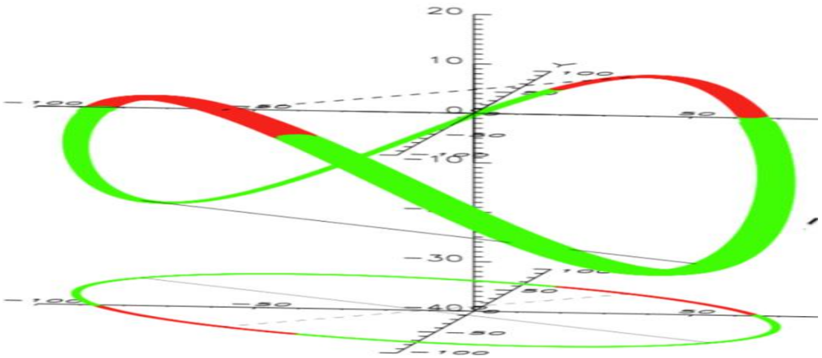
➢ Möbius Resonator Based Oscillator presents several advantages in comparison with conventional planar resonator for a given size :
  - high Q-factor and improved selectivity
  - easy integration in MIC/MMIC technologies
  - small dimensions and weight
  - multi-band characteristics
  - relatively insensitive to EMI and EMC

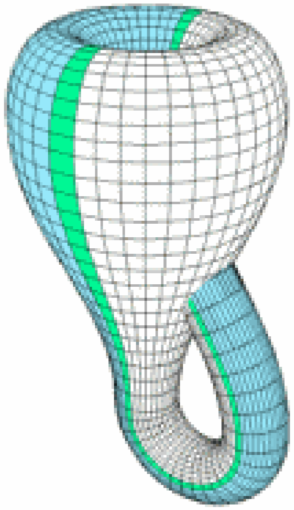


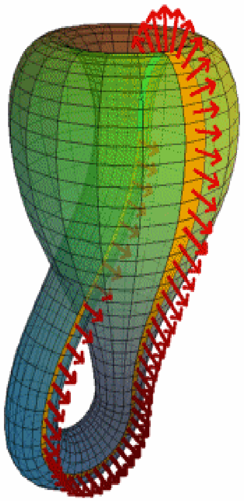


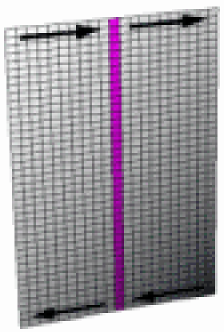
Typical Möbius Strip Surface

A typical Möbius is a surface with only one side and only one boundary component, the mathematical property of being non-orientable. Bisecting Möbius results into dual Möbius Strips with same radius



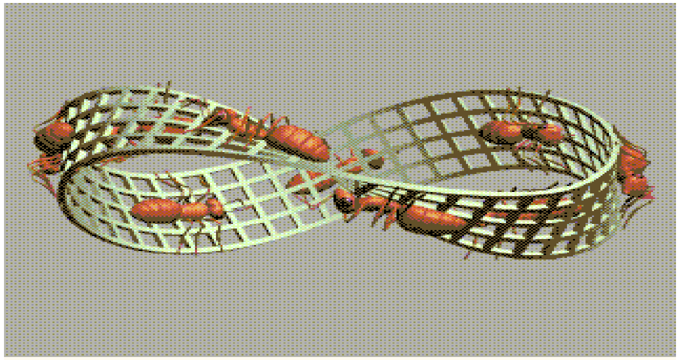


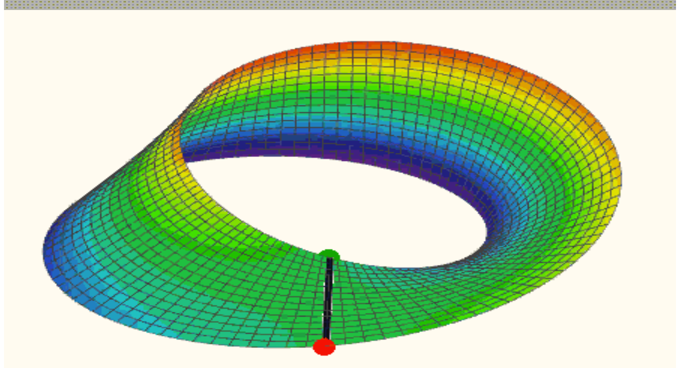


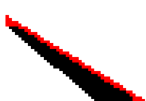


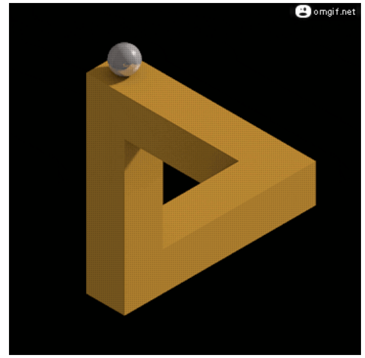
Möbius Strips

Mysterious Möbius Strips

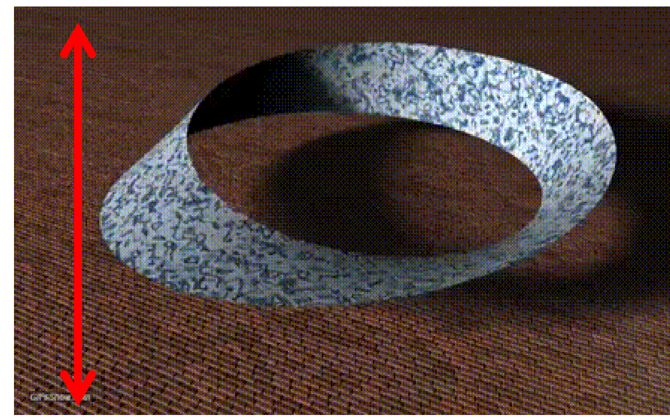








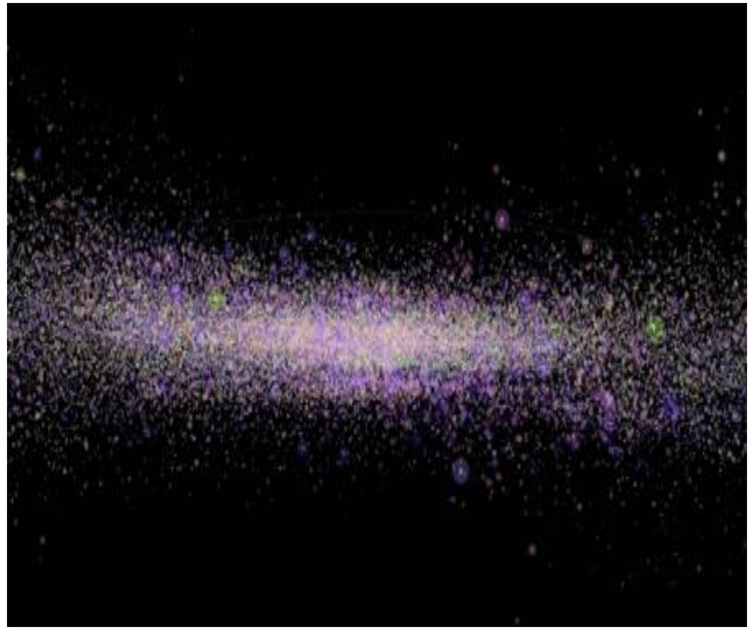
Anti gravity effect

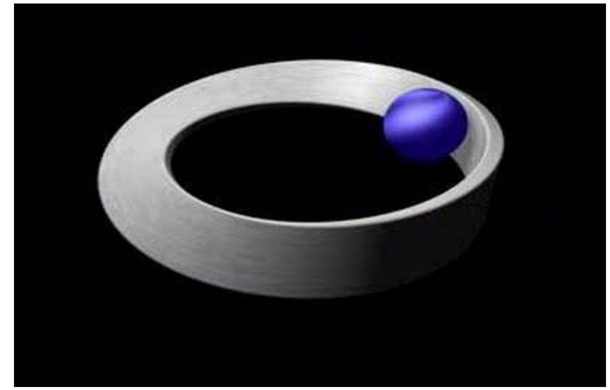


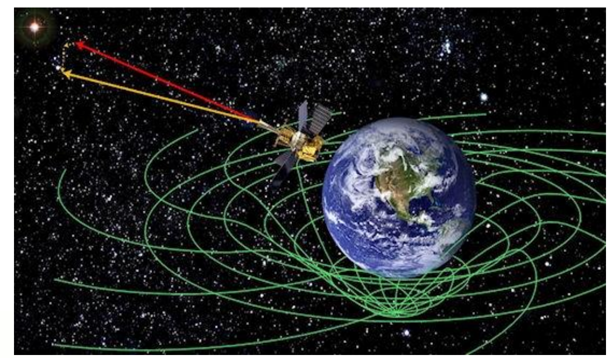
Mobius strip in the galactic center, Courtesy: NASA

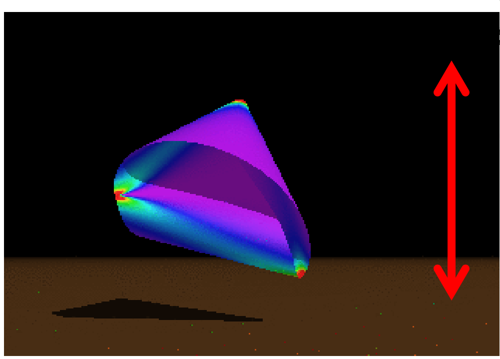
Mysterious Möbius Strips

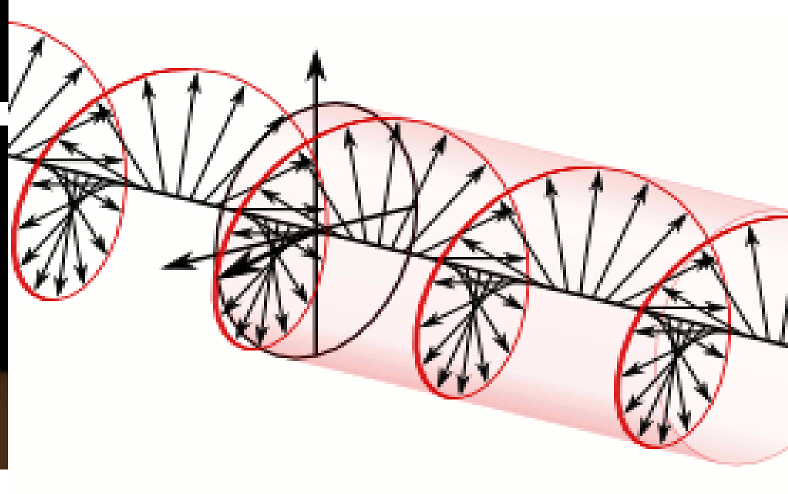
Mobius strip in the galactic center, Courtesy: NASA

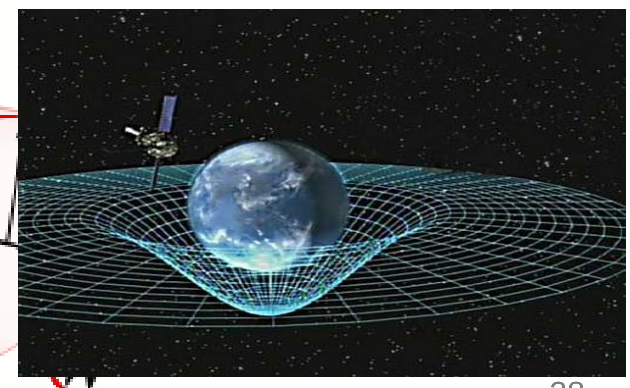






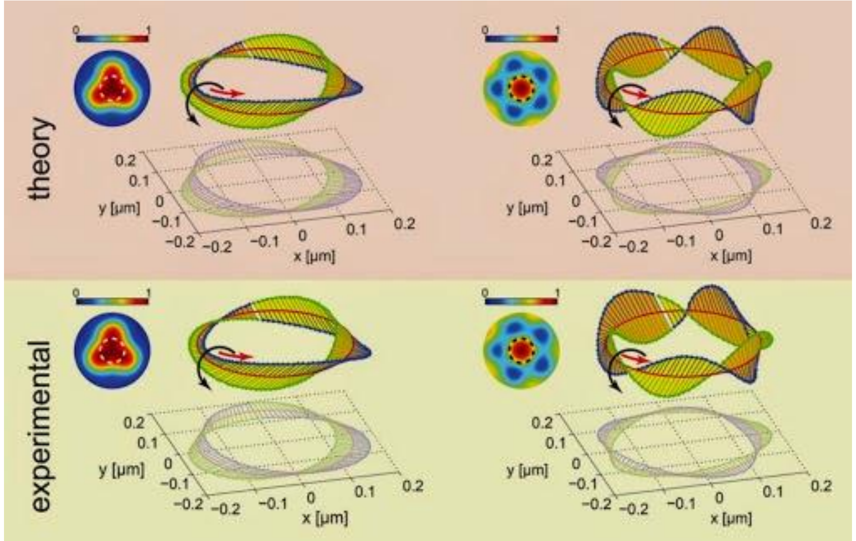


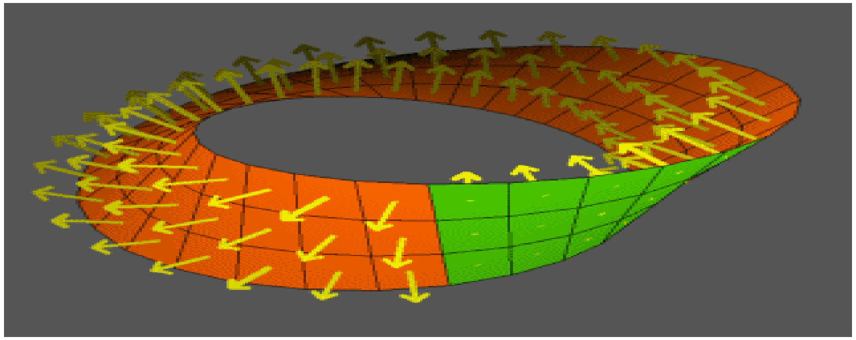


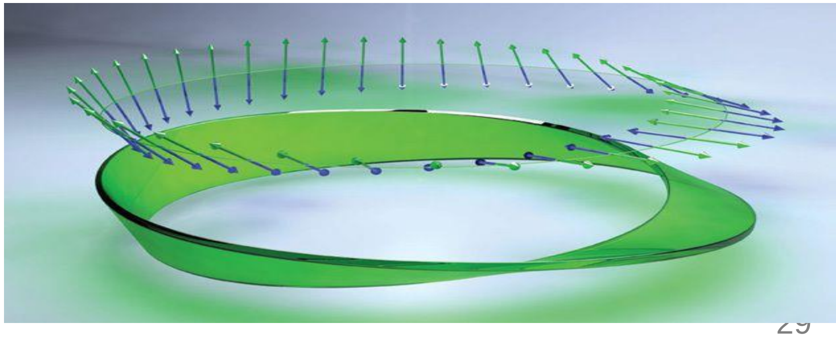


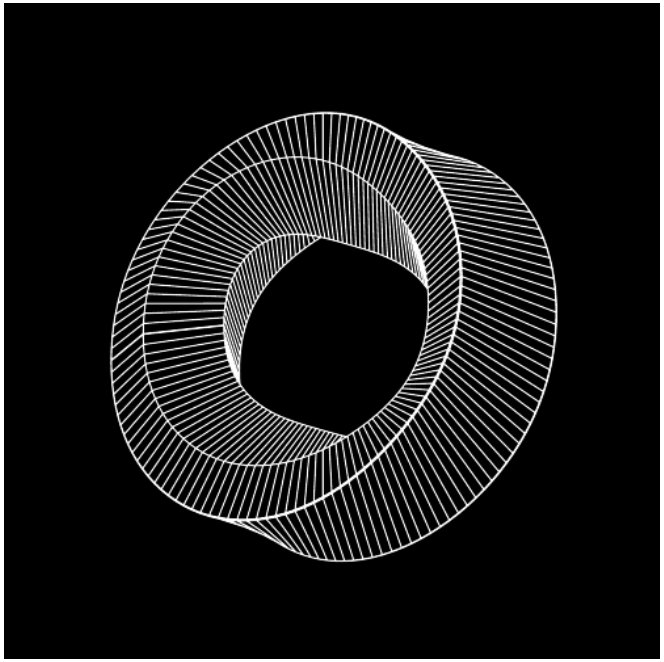
Mysterious Möbius Strips

Figure shows the typical Möbius surface made of polarization states of light beam. The creation of EM wave around Möbius contour is interesting for improving the fundamental understanding of optical polarization and the complex light beam engineering for developing optical micro-and nano-fabrication structure.









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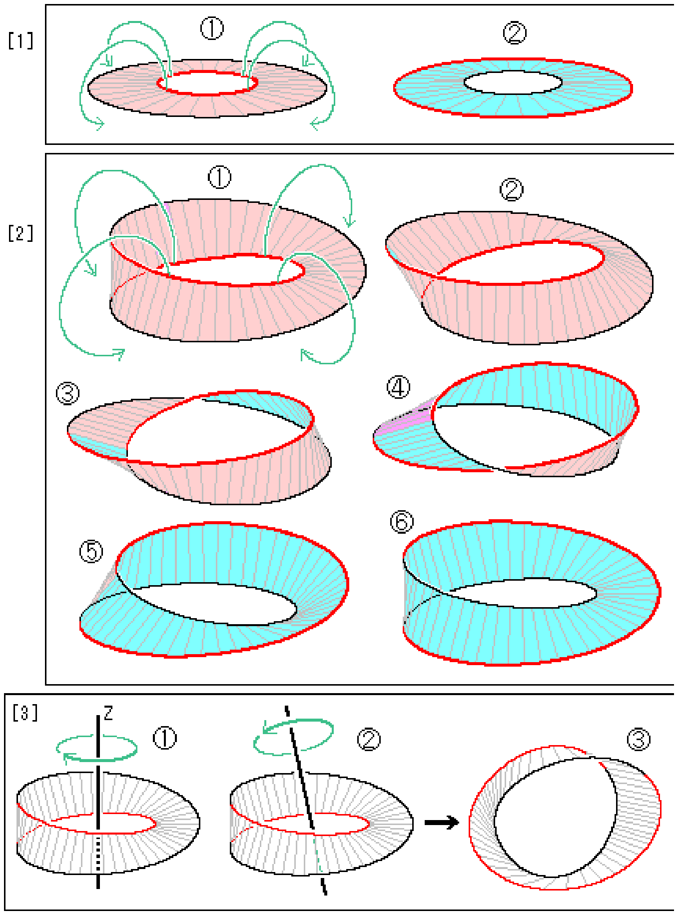
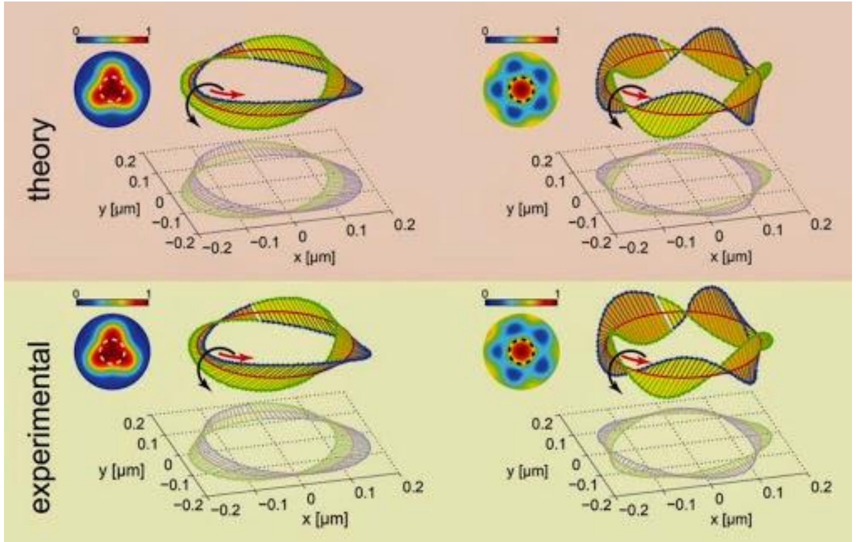
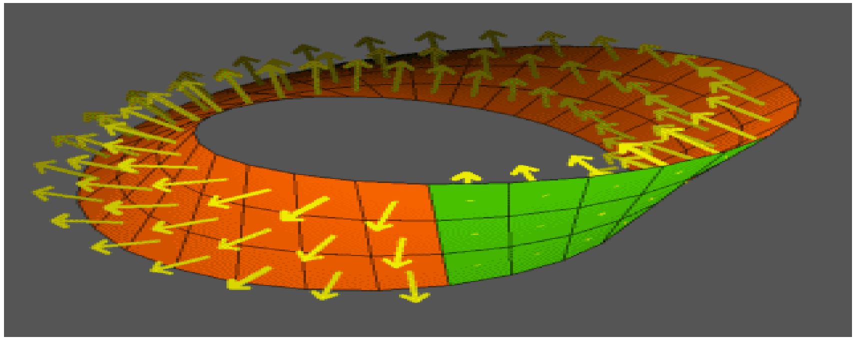
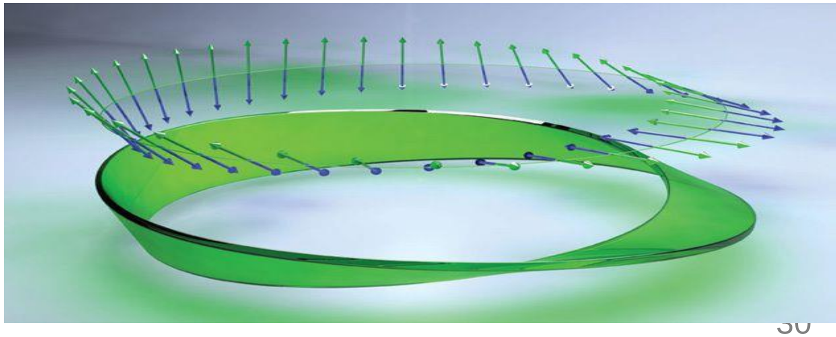
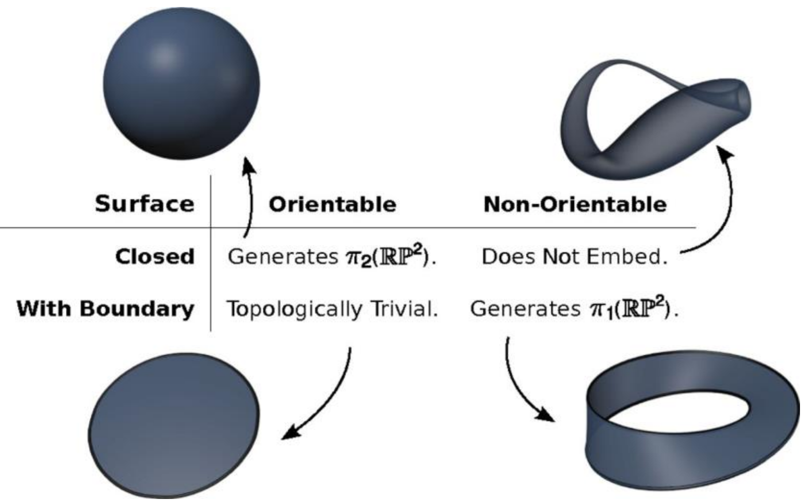




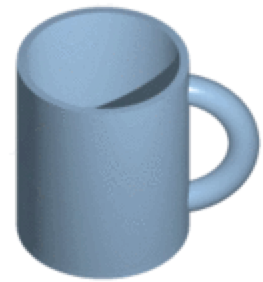




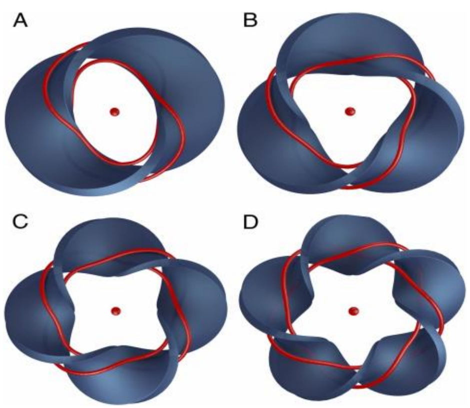
Emerging Technology: Multi-Knots Möbius Strips

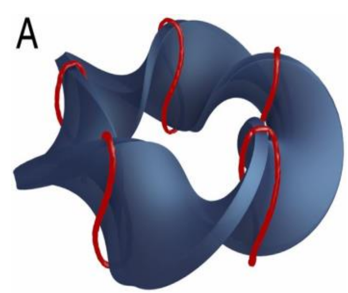


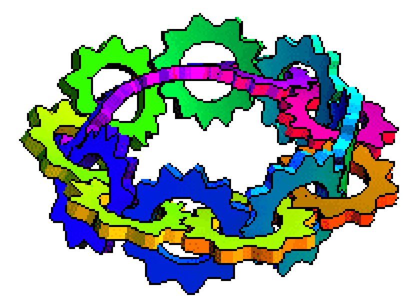
Topological Characterization



Multi-Knots Möbius Strips: Mysterious Knots !







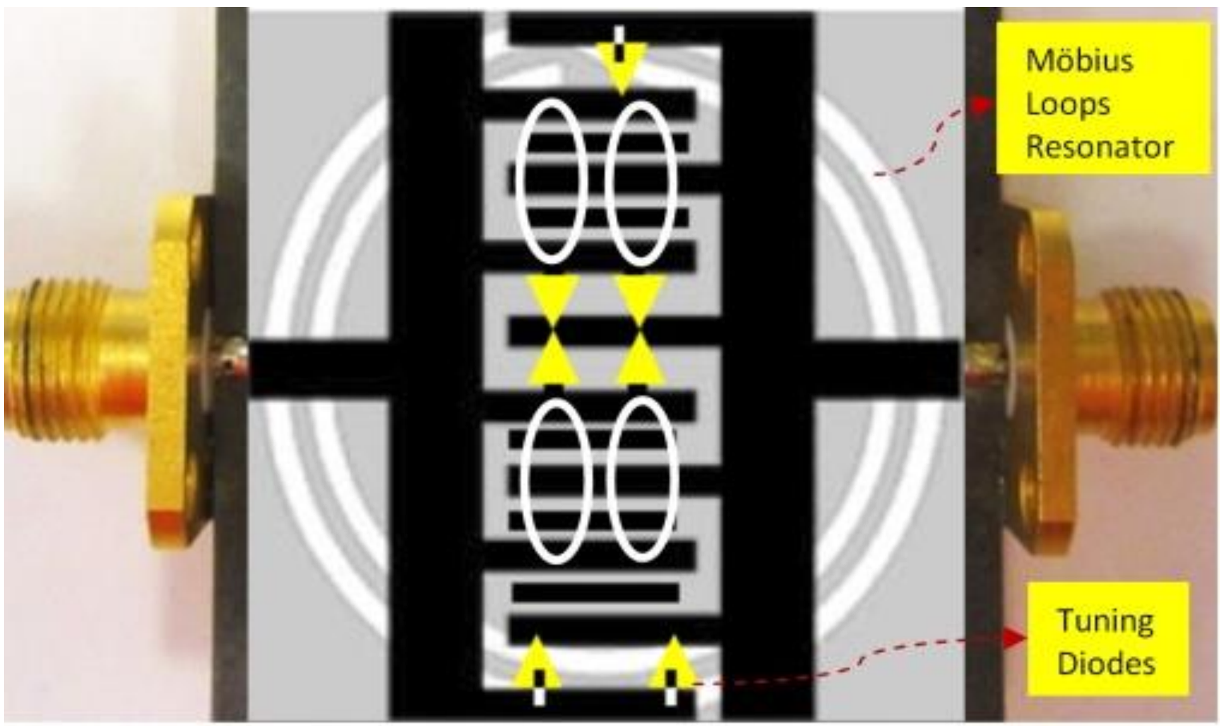
Motivation

- Mobius strip increases the **circumferential length** of the resonator with the same radius of ring resonator.
- Mobius loop enable miniaturization of the physical dimension and maintaining the same resonant frequency.
- Mobius strip resonator shows the **multi-mode resonant** characteristic and ability to store the evanescent-mode energy for improving the group delay, Q-factor, and enabling **self-injection mode & phase-locking**

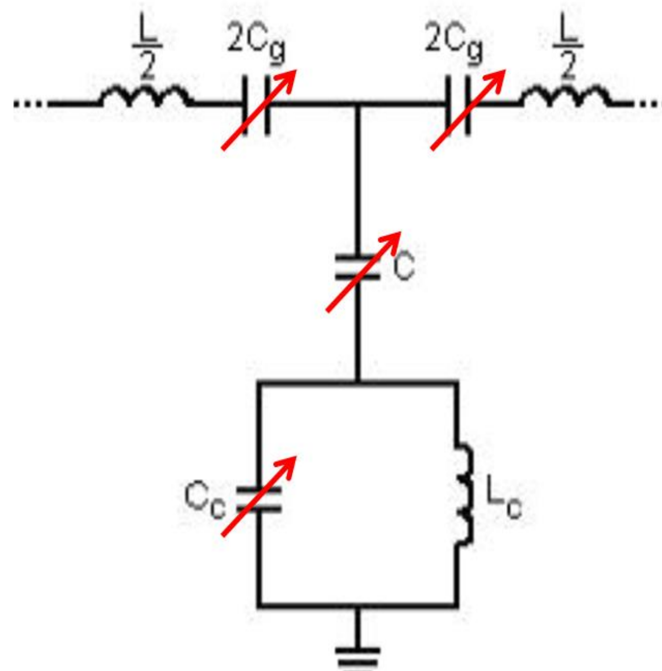
Möbius Strips: Novel Resonator

Möbius ring resonator exhibits a topological half-twist transformation divides into half-integral and integral normal mode indices. The eigenfunctions of the Möbius resonator form an orthogonal basis set; presents an interesting possibility for the design of high Q-factor resonator for the application in tunable oscillators, and filter circuits.

Printed Möbius Metamaterial Resonator



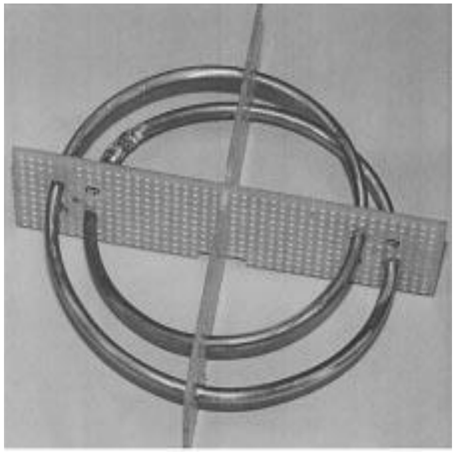
Lumped Model



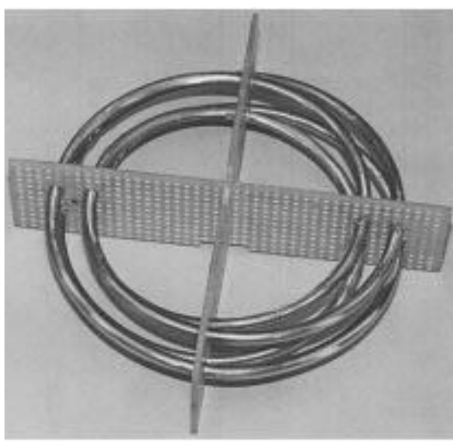
Non-Planar and Planar Möbius Strips Resonator

Non-planar Möbius resonator Filter

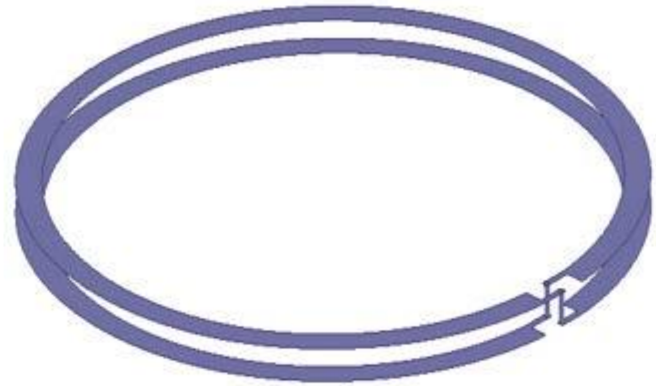
Dual-Mode [1]

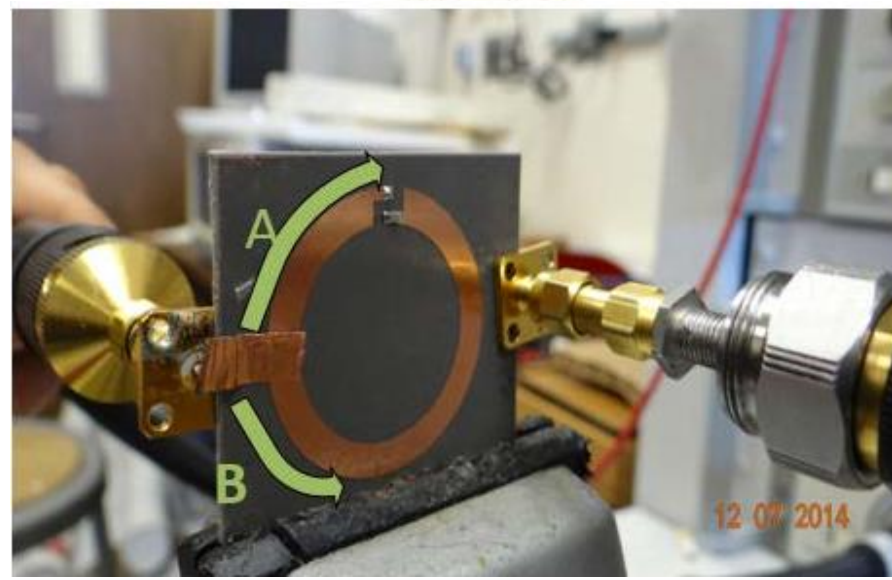


Quad-Mode [2]



Planar Möbius resonator filter [3]

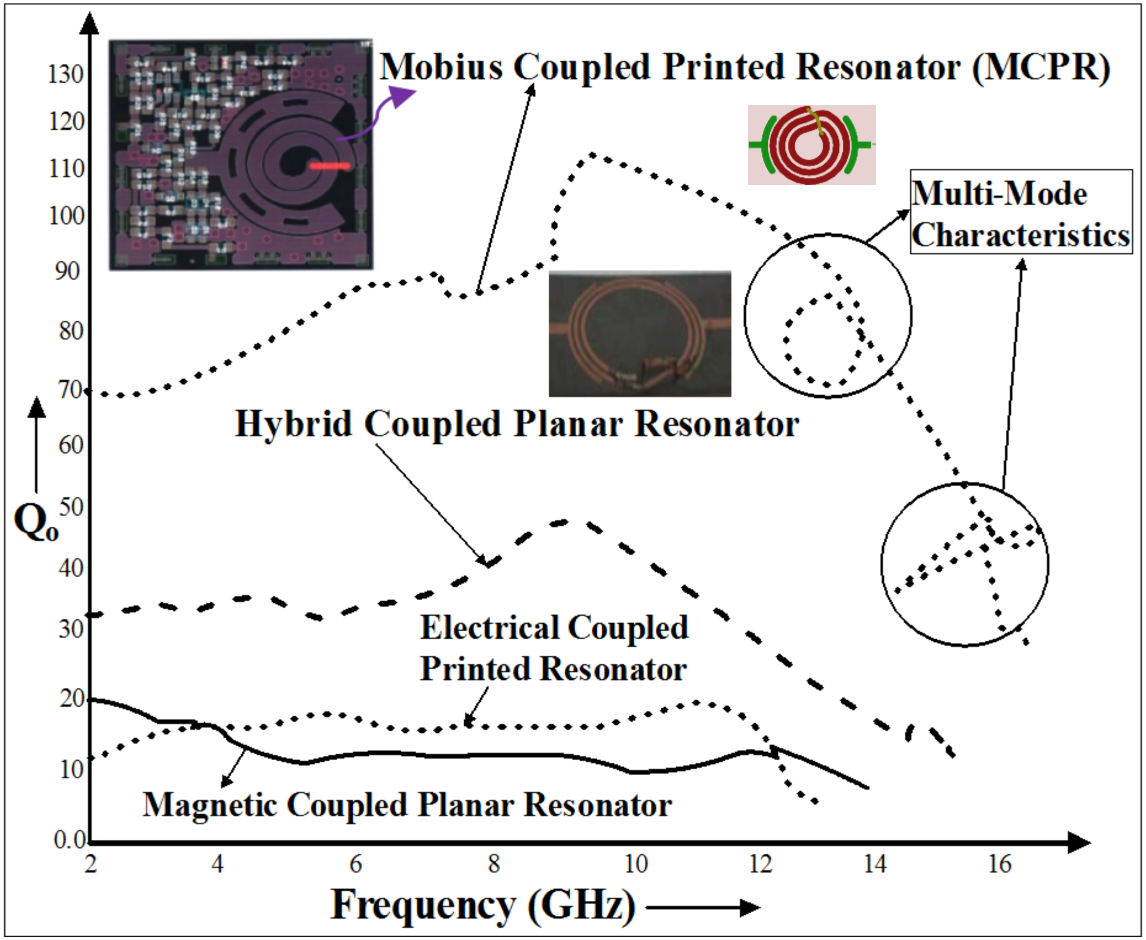




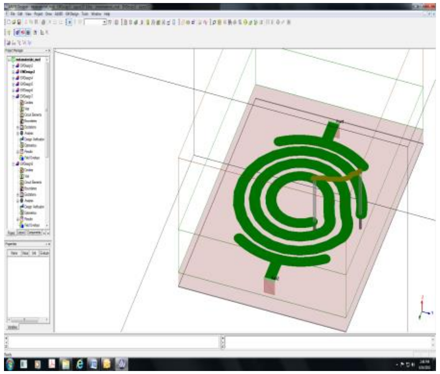
[1] J. M. Pond, “Mobius Dual Mode Resonators and Bandpass Filter”, IEEE. Trans. of MTT Vol. 48, No.12, Dec 2000, pp 2465-2471.
[2] J. M. Pond, et.al. "Band-pass Filters Using Dual-Mode and Quad-Mode Mobius Resonators," IEEE Trans on MTT vol.49, pp.2363-2368, Dec.2001.
[3] K. Dhwaj , H. Lee, L. Jiang, and T. Itoh, “Transmission-Line Equivalent and Microstrip Structure for Planar Mobius Loop Resonator, IMS 2015

Quality Factor: Printed Möbius Resonator

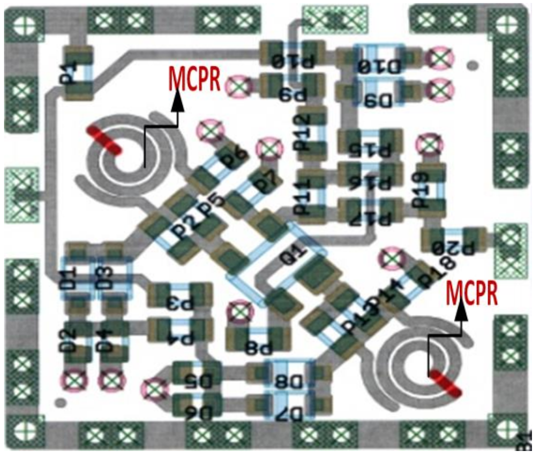
Plot of unloaded Q-factor of printed resonators



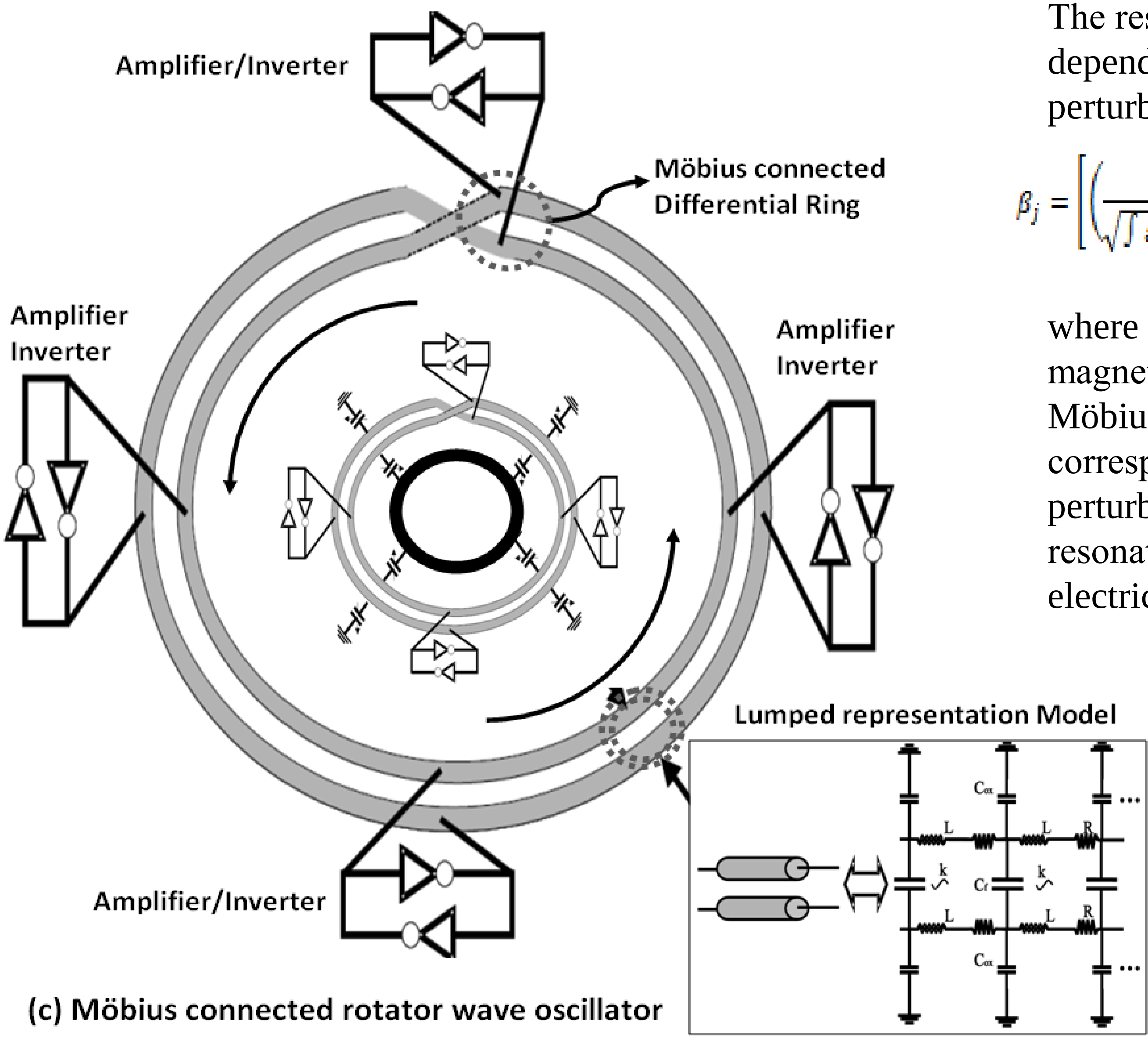
Mobius Resonator



Mobius resonator VCO



Möbius Strips: Rotator Wave Oscillator



(c) Möbius connected rotator wave oscillator

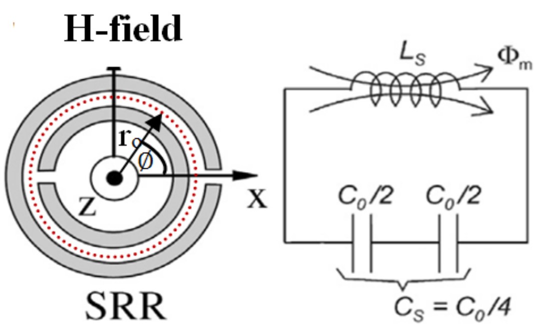
The resonator coupling coefficient 'β_j' depends upon the geometry of the perturbation:

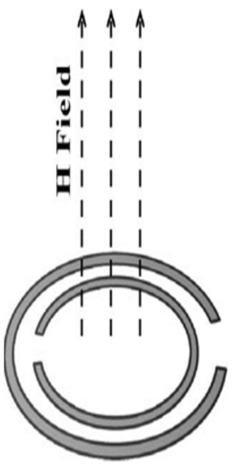
$$\beta_j = \left[\left(\frac{\int \varepsilon E_a . E_b \, dv}{\sqrt{\int \varepsilon E_a^2 dv \int \varepsilon E_{bd}^2 dv}} \right)_e + \left(\frac{\int \mu H_a . H_b \, dv}{\sqrt{\int \mu H_a^2 dv \int \mu H_b^2 dv}} \right)_m \right]$$

where E_a and H_a are the electric and magnetic fields produced by the Möbius strip, and E_b, H_b are the corresponding fields due to perturbation or nearby adjacent resonator, subscript 'e' and 'm' are the electrical and magnetic coupling.

RWO:
Clocking applications

Metamaterial Realization: Split Ring Resonator



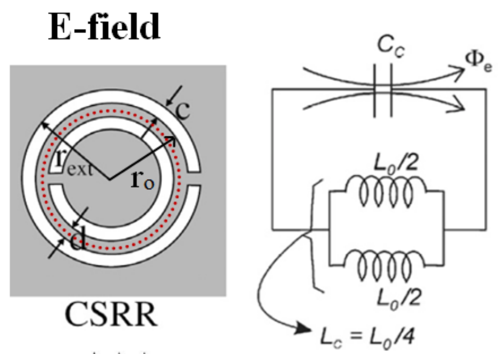


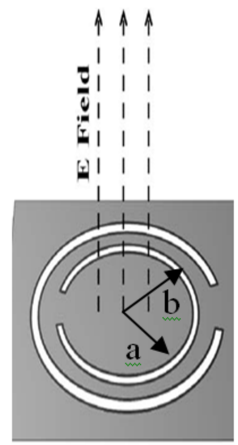
(a) SRR

$$C_o = 4\left(\frac{\epsilon_o}{\mu_o}\right) L_o$$

$$f_o = \frac{1}{2\pi\sqrt{L_S C_S}}$$

$$C_s = \frac{C_o}{4}$$



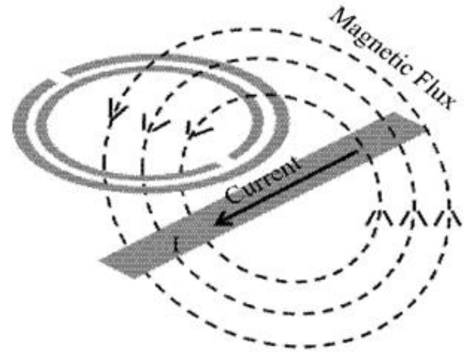


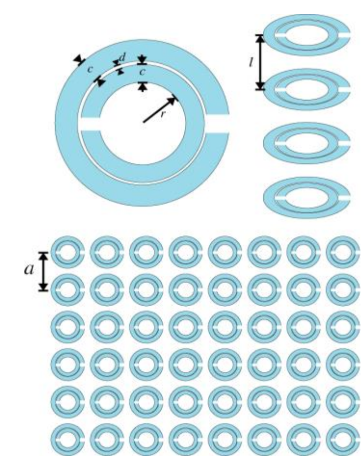
(b) CSRR

$$C_c = 4\left(\frac{\epsilon_o}{\mu_o}\right) L_S$$

$$f_o = \frac{1}{2\pi\sqrt{L_C C_C}}$$

$$L_C = \frac{L_o}{4}$$





$$C_c = \frac{\epsilon_0 \pi^3}{c^2}\int_0^{\infty}\left[\frac{1}{2}+\frac{\varepsilon}{2\epsilon_0}\left(\frac{\epsilon_0+\varepsilon tgh(kh)}{\varepsilon+\epsilon_0 tgh(kh)}\right)\right]\left[\frac{[b\beta(kb)-a\beta)ka)]^2}{k^2}\right]dk \qquad L = \frac{\mu_0 \pi^2}{I^2}\int_0^{\infty}[\tilde{I}(k)]^2 k^2 dk$$

$\tilde{I}(k)$: Fourier–Bessel transform of the current function on the ring

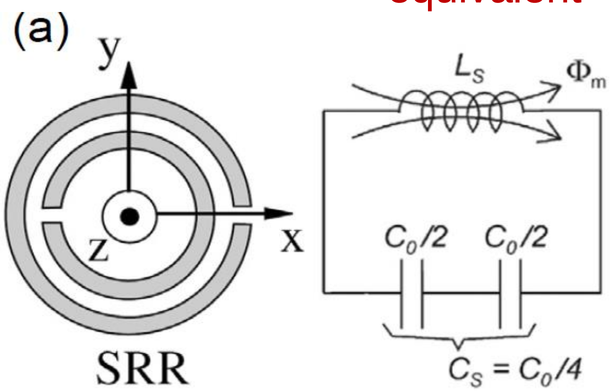
$I(r) = \int_0^{\infty} J_{s,\emptyset}(r')dr'$ $\quad \beta(x) = S_o(x)J_1(x) - S_1(x)J_o(x)$ $\quad J_n\ S_n$: being nth-order Struve and Bessel functions

$J_{s,\emptyset}(r')$ is the azimuthal surface current density on the ring, c is the slot width, r_o is the average radius of the ring of SRR, a and b are the geometrical parameters

Negative μ_r : Array of Split Rings

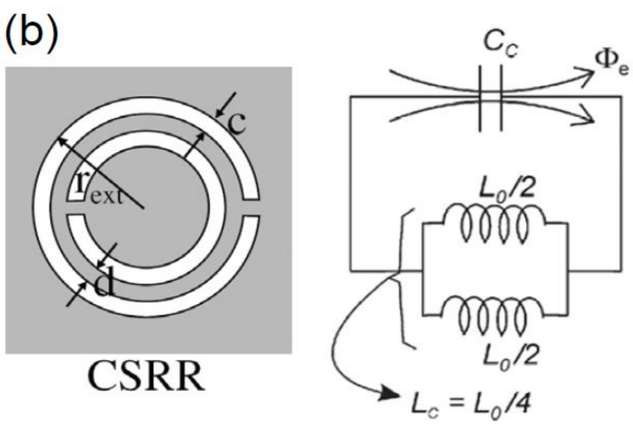
Split Rings

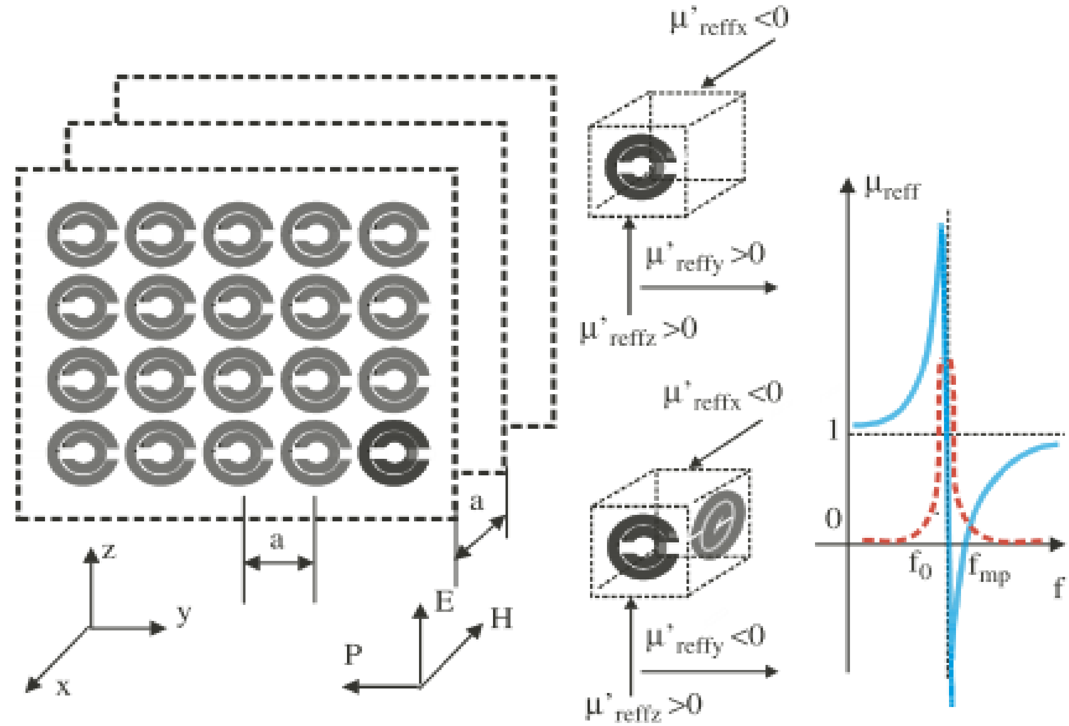
Electrical equivalent



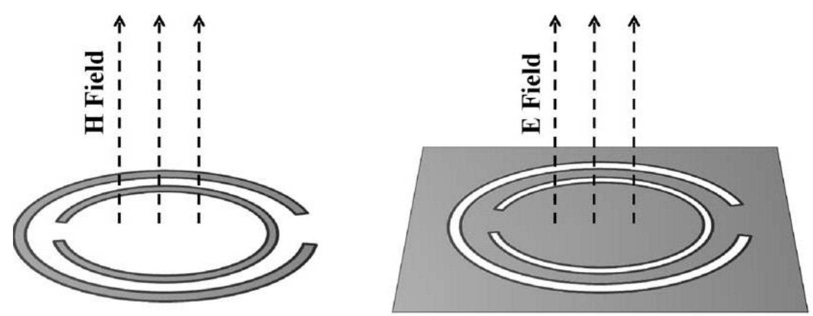
Complementary Split Rings

Electrical equivalent





(a)Array of SRs (b) Unit cell (c) Permeability

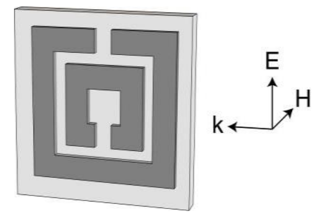


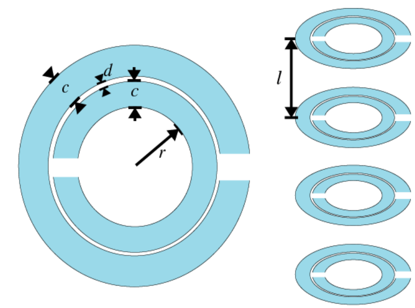
A typical planar SRR and CSRR structure: SRR excitation by H-field, CSRR excitation by E-field

Negative μ_r : Retrieval

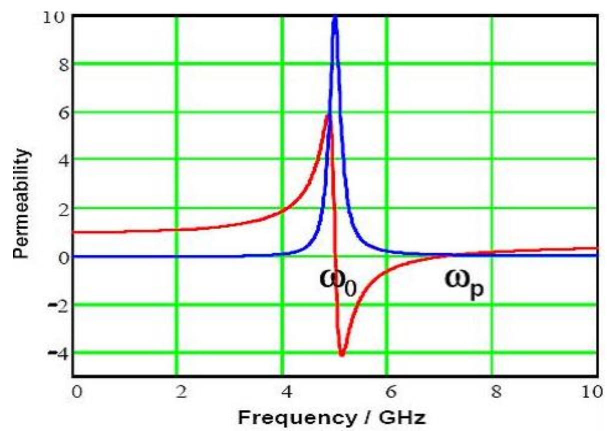
Tunable 'μ': SRR

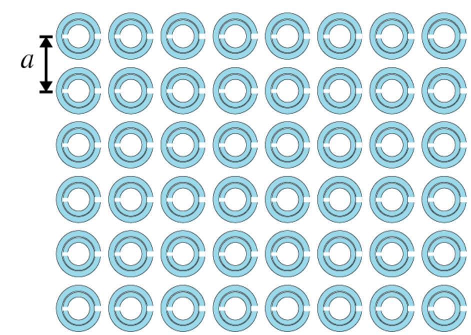
$$\mu_{eff} = 1 - \frac{\dfrac{\pi r^2}{a^2}}{1 + \dfrac{2\sigma i}{\omega r \mu_0} - \dfrac{3}{\pi^2 \mu_0 \omega^2 C r^3}}$$

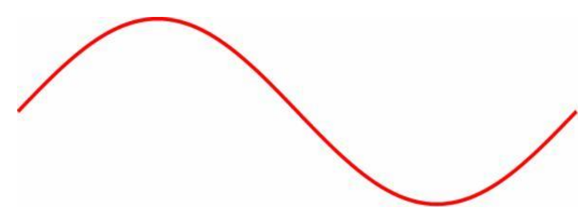


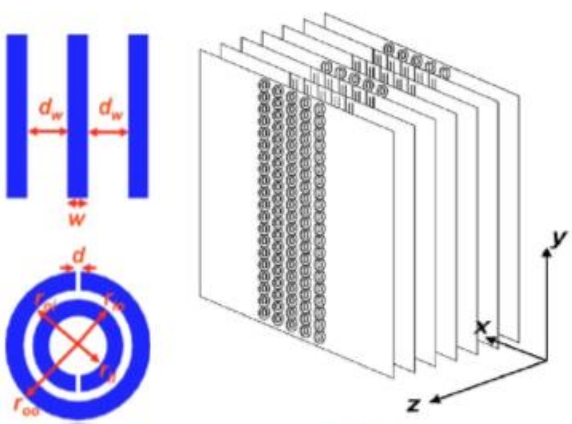


J.B. Pendry *et al*., *IEEE Trans. Microwave Tech*. **2075** (1999).

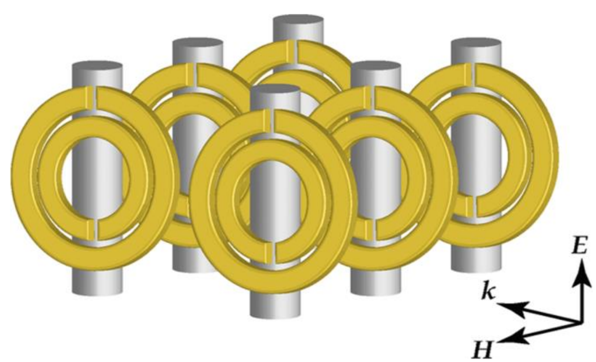




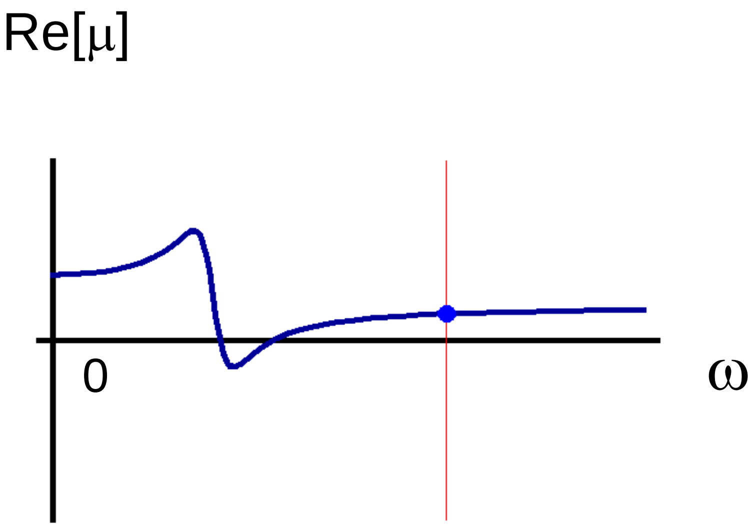




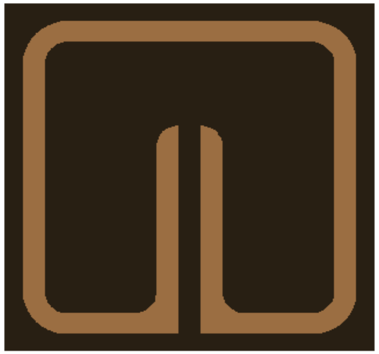
(g) Metamaterial resonator consists of SRR/wires

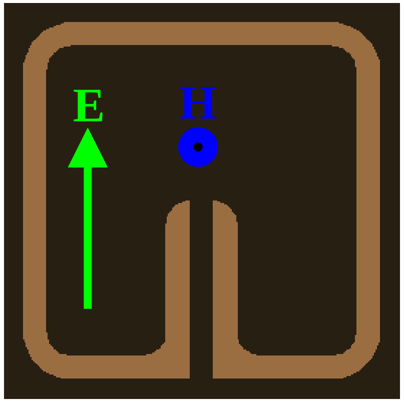


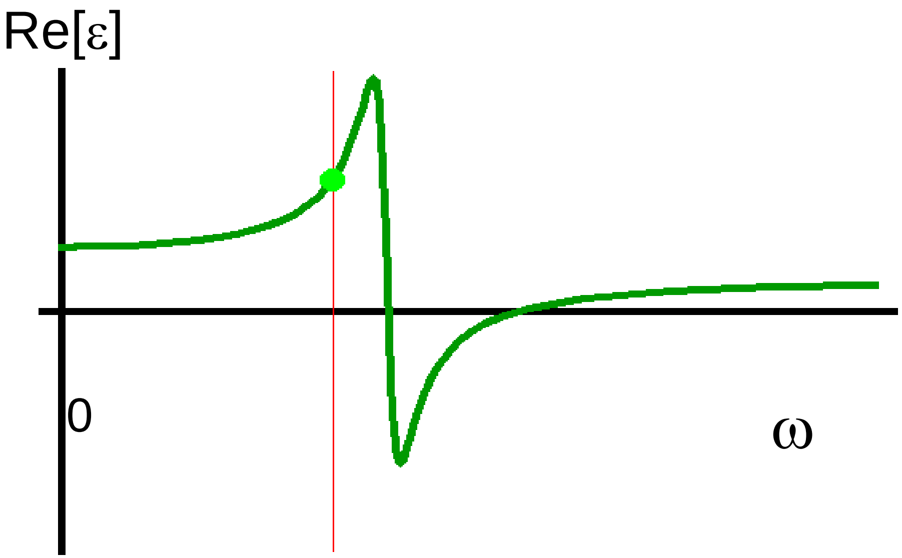
Tunable Index (μ, ε) Resonator

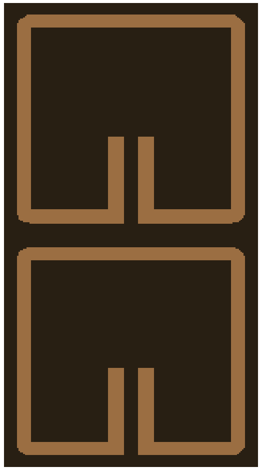


$$\omega_0 = \frac{1}{\sqrt{LC}}$$



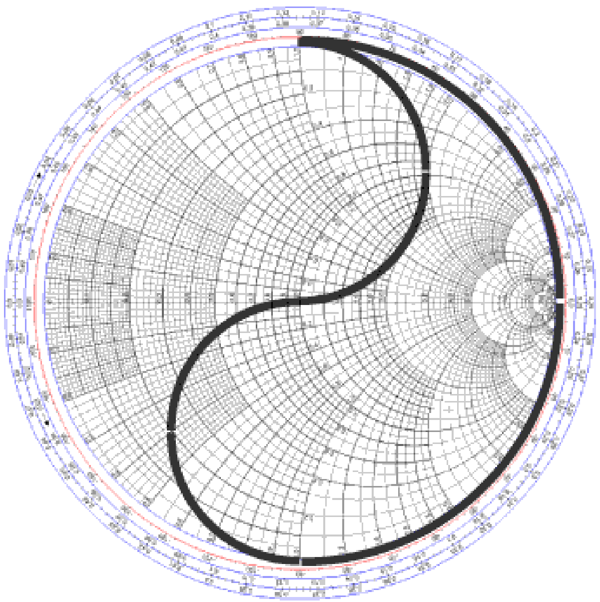


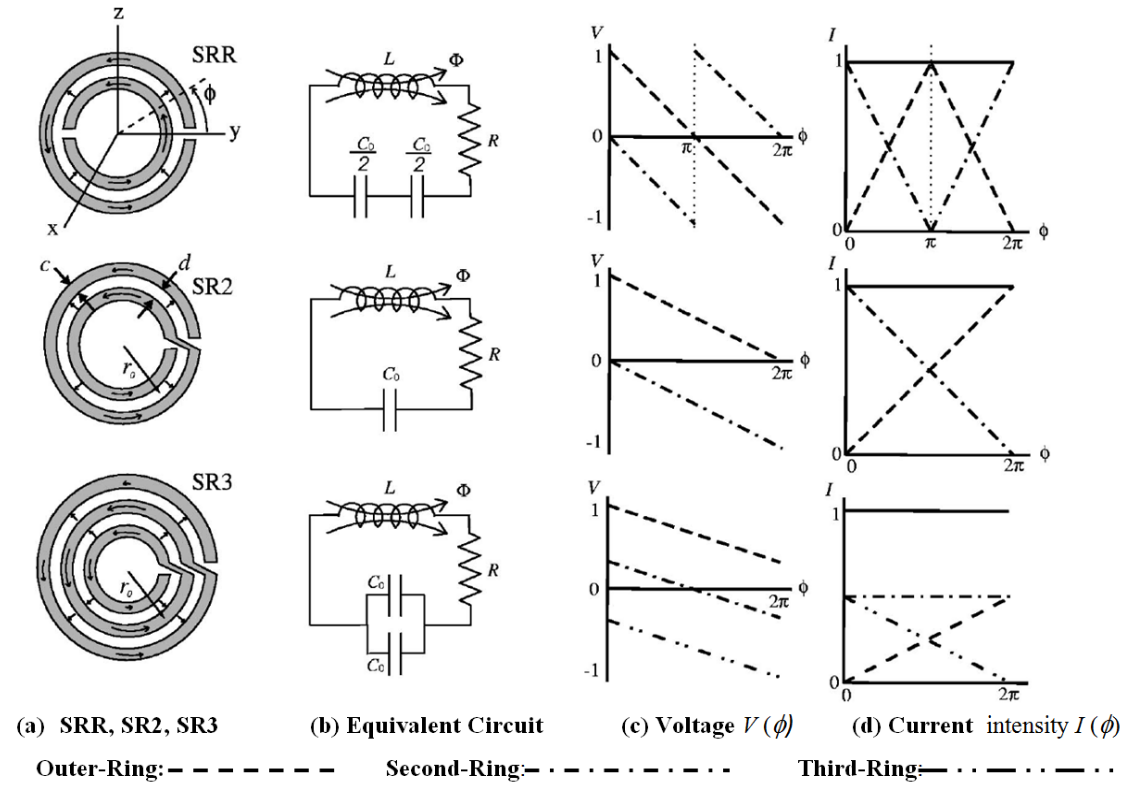




$$\omega_0 = \frac{1}{\sqrt{LC}}$$

Split Ring Resonator: Möbius Twist !





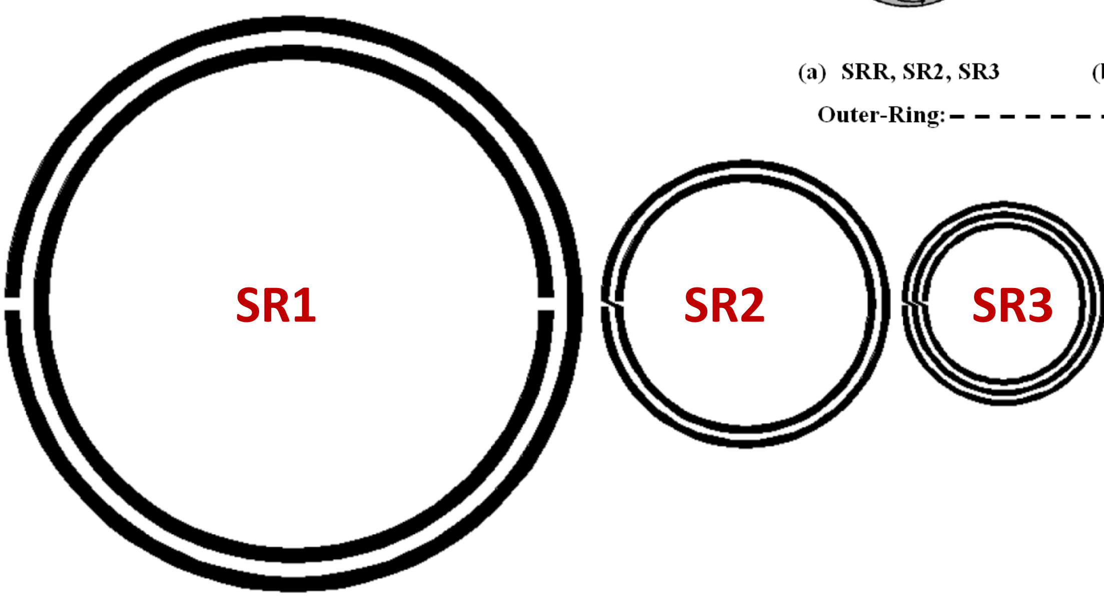


Figure: A typical comparison layout: (a) SR1 (b) SR-2, and (c) SR-3 (same resonance frequency, the reduction factors are about 50% and 65% with respect to the original SRR), SR-2 and SR-3 are promising topology for Möbius-Loop

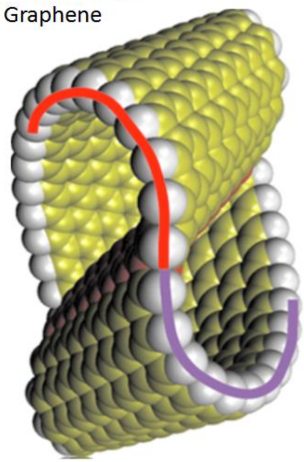
Möbius Twist Metamaterial: Graphene

Graphene

- Single layer of graphite, exhibits mechanical properties like planar paper or plastic with large bulk modulus, easily bent and wrap into carbon nanotubes without deformation

- This unique characteristic qualifies to use Graphene as a promising material to build Möbius metamaterial strips for the applications in developing microwave and optical components for modern communication systems.

Möbius Strips Graphene



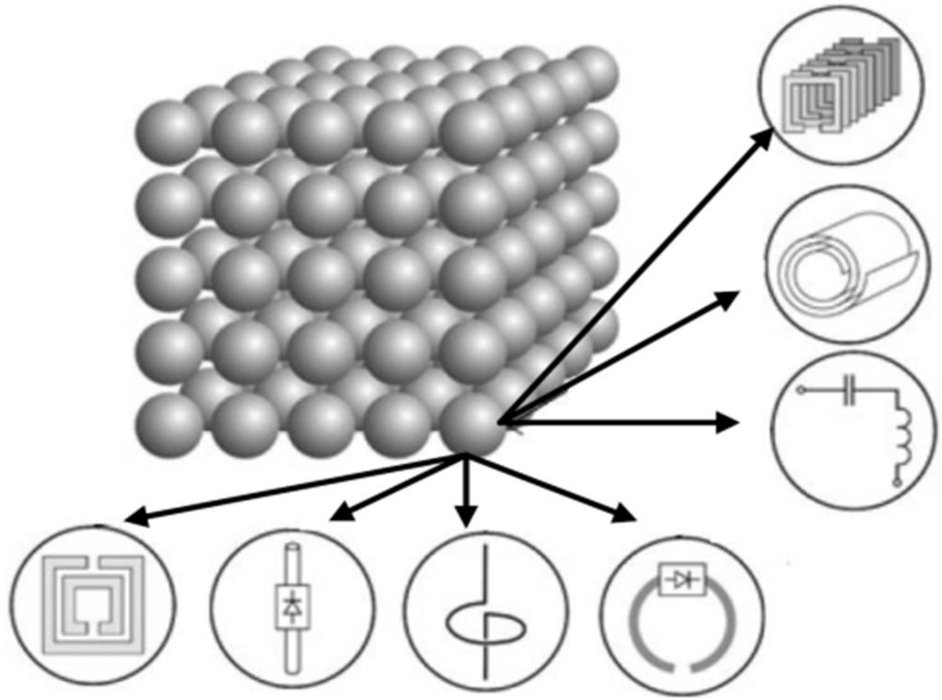
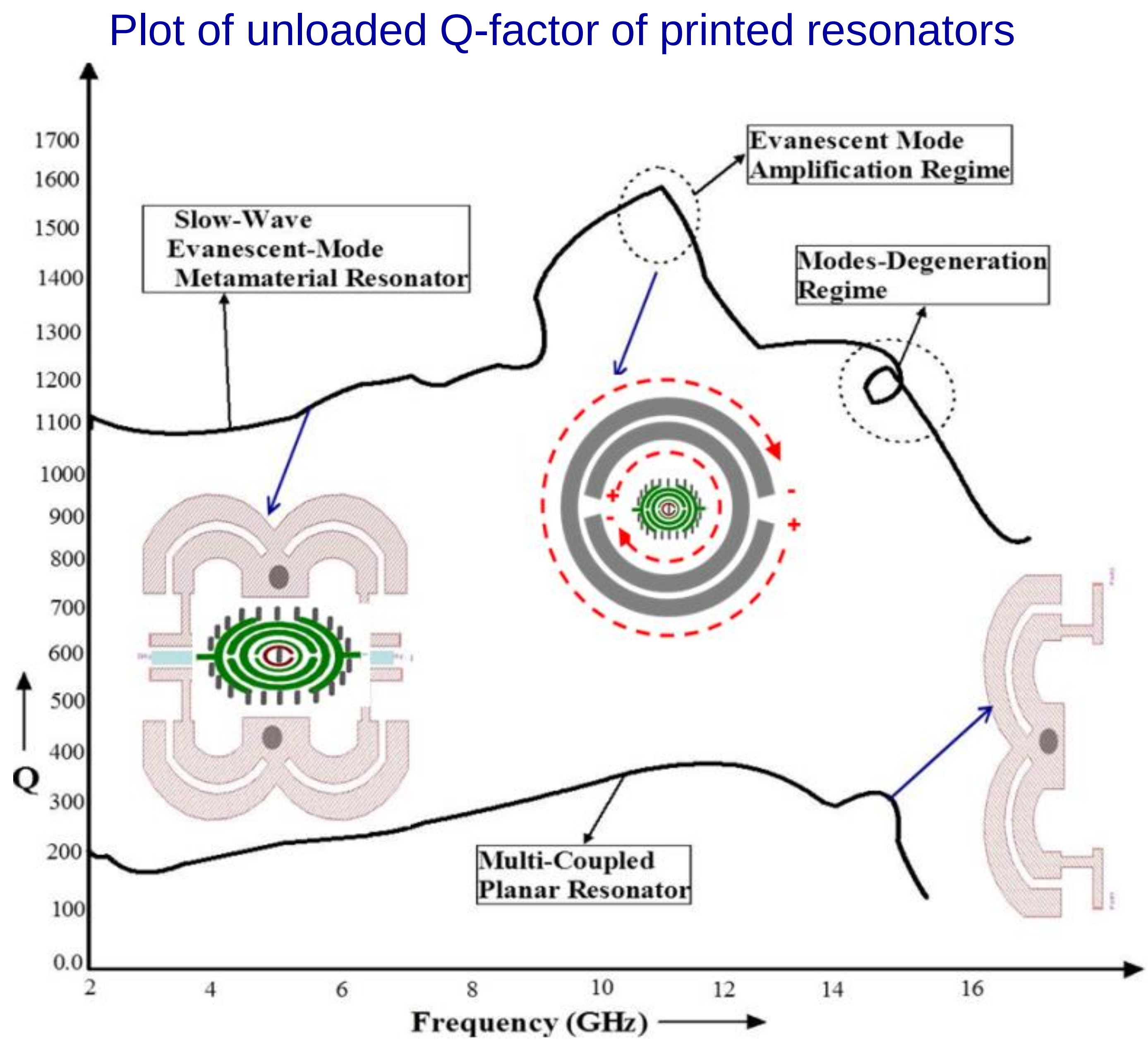


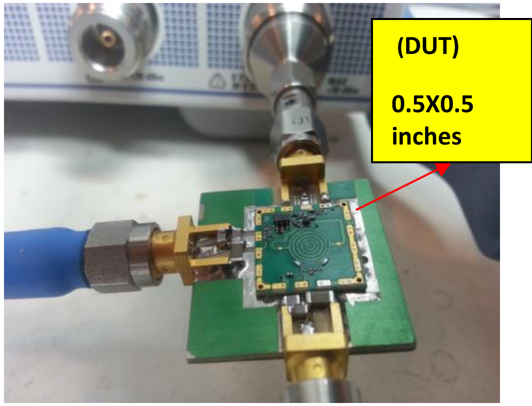
Figure shows the Metamaterial Möbius strips formed Graphene nano-ribbons behave as a topological insulator and possess topology-induced thermal and magnetic properties.

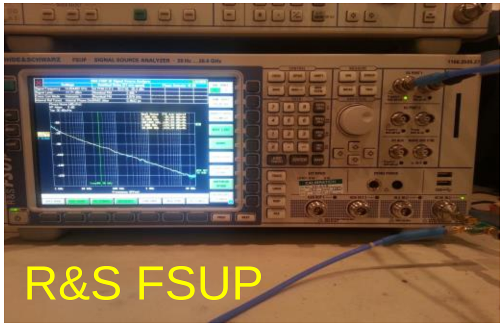
Wang[1] investigated the stability and total magnetic moment (TMM) of Möbius strips with fixed length and different widths, the Möbius strips formed by Graphene nanoribbons found extraordinarily stable. These unique magnetic properties make the Möbius strips Graphene building blocks in spintronic devices.

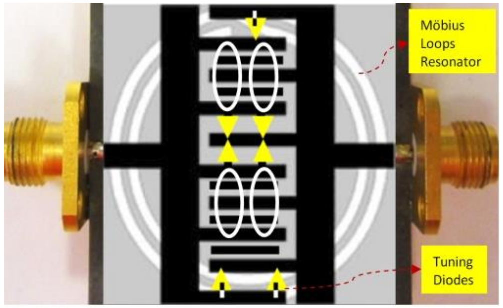
[1] Wang et al, "Theortical investifgation of Mobous strips formed from Graphene", Applied Physics Letters 2010.

Q-factor: Printed Möbius Resonator





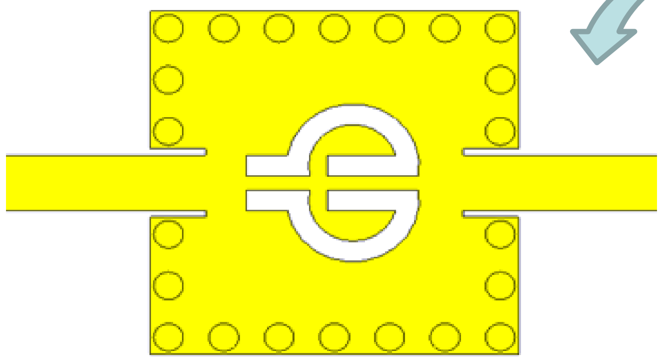


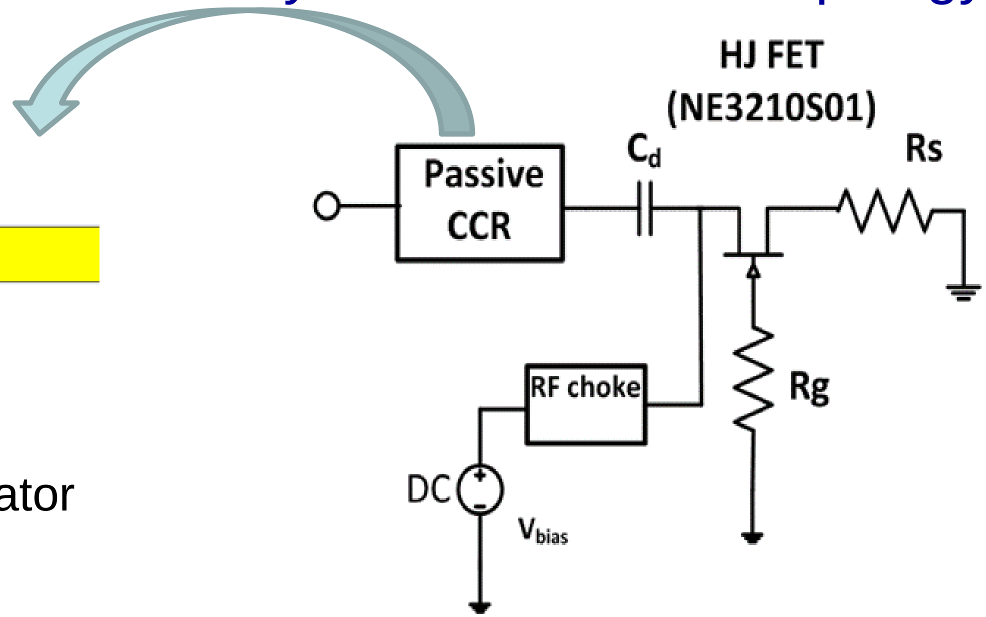


Example: SIW CCR

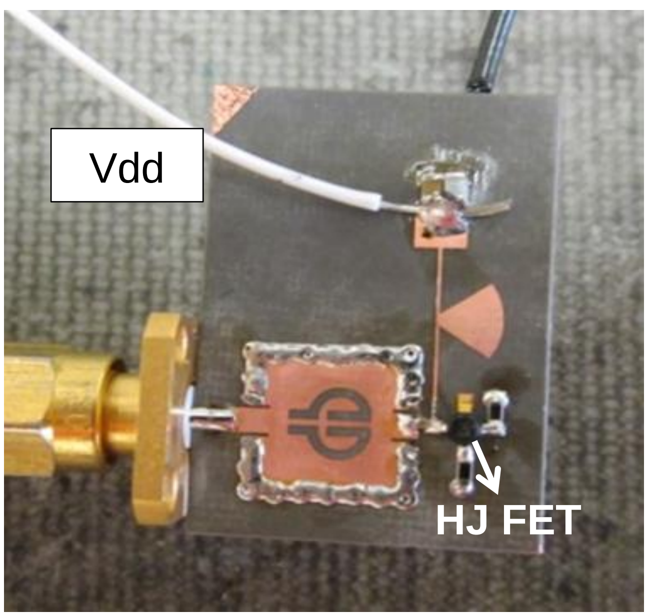
The Q of **SIW** resonator can be enhanced by Active resonator topology

SIW CCR





CCR: Complementary Coupled Resonator



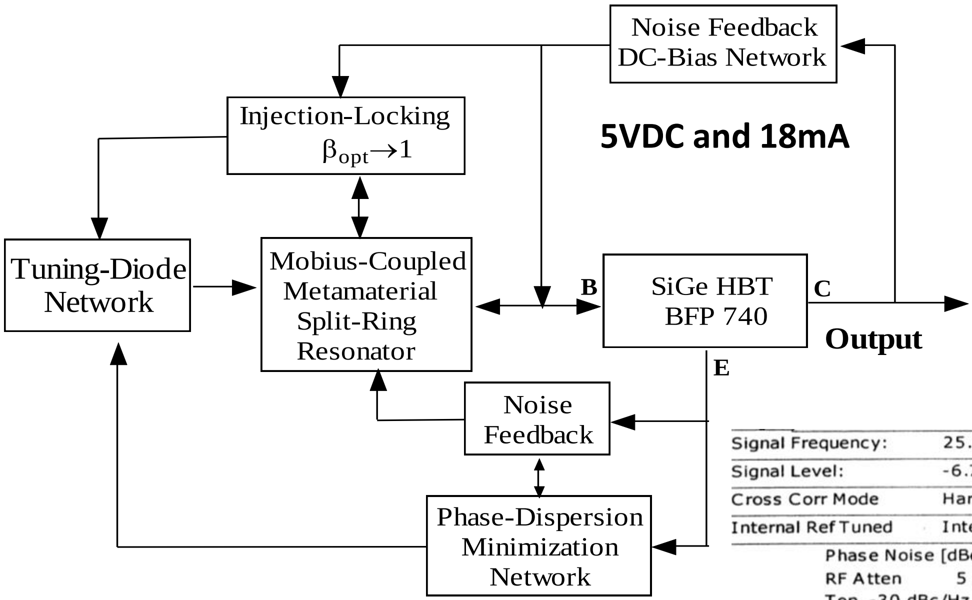
Vdd	0V	0.65V	1V	1.2V
Unloaded Q	130.7	95.6	706.3	1913.1
Vdd	1.4V	1.6V	1.8V	2.0V
Unloaded Q	3,390	7,249	**21,172**	6,938.5

Pros: High Q-Factor

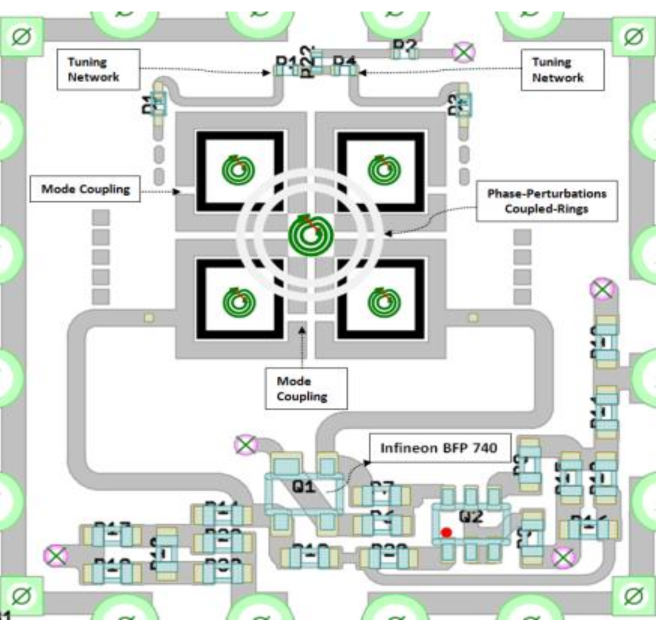
Cons: Power Consumption and Noise

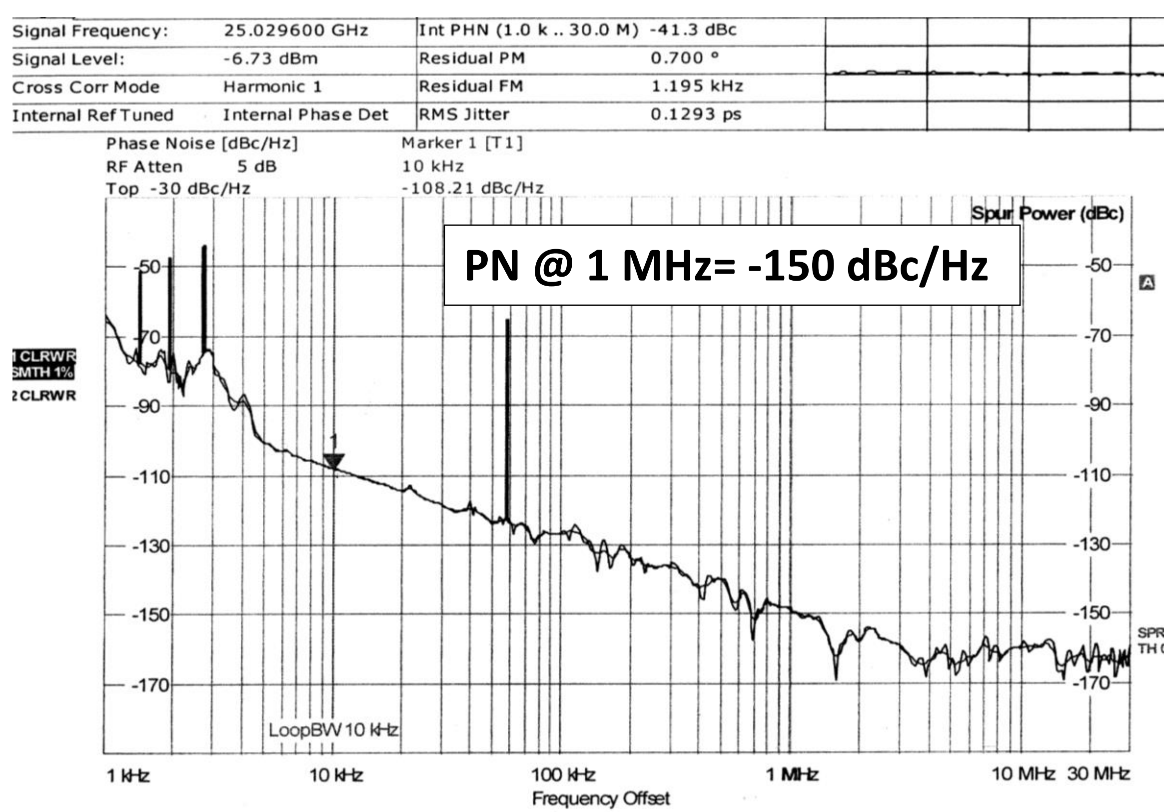
Ref: Wu, Poddar, Rohde, Itoh, IMS 2013

Example: 25 GHz Möbius Resonator VCO



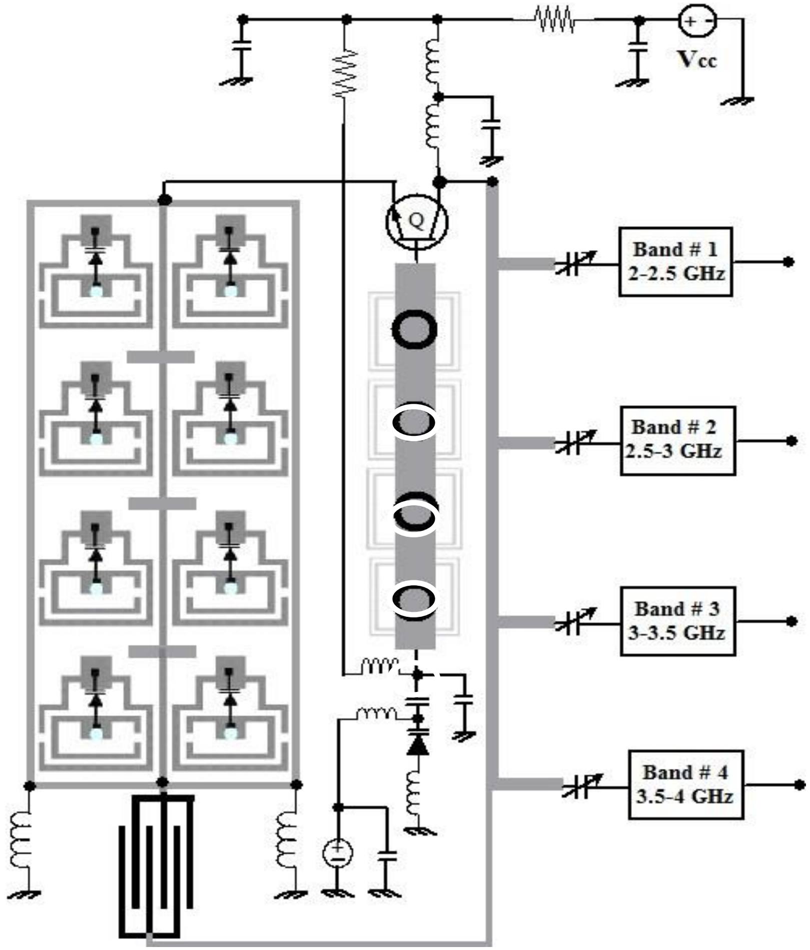
To overcome mode-jumping issues and tuning problems, mode stabilization (manipulating the phase velocity by introducing *Mode-Suppression Ring* that allows multi-mode-self-injection injection into the Mobius Strips cavity, improves the stability) technique.





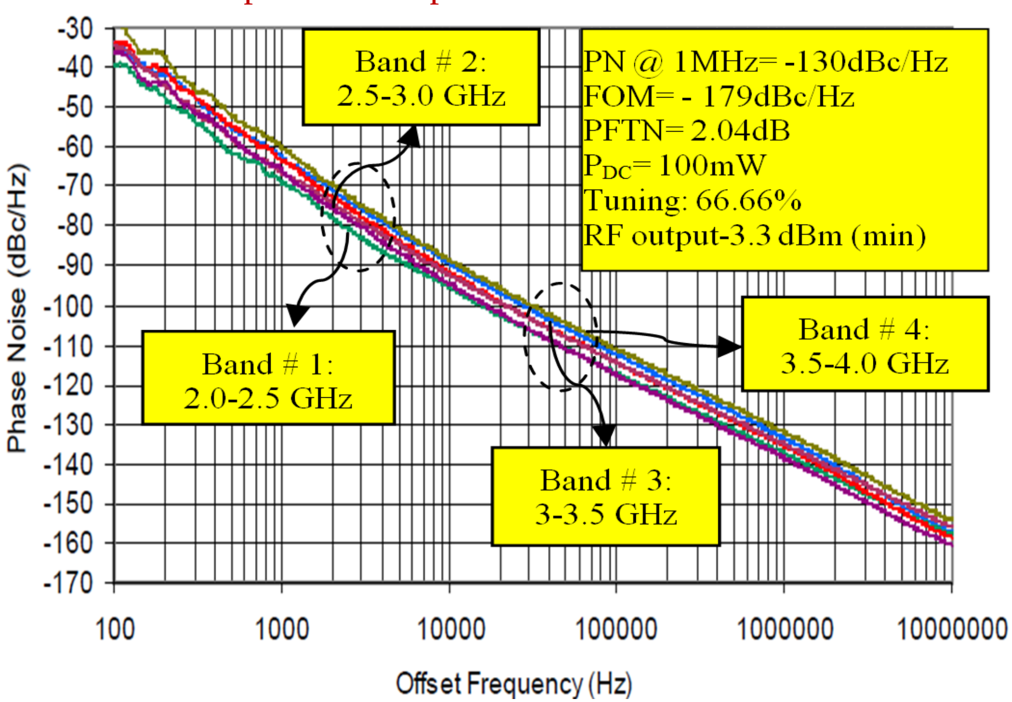
Multi-Band Möbius Resonator VCO

Multi-band oscillator using slow-wave Möbius resonator Topology



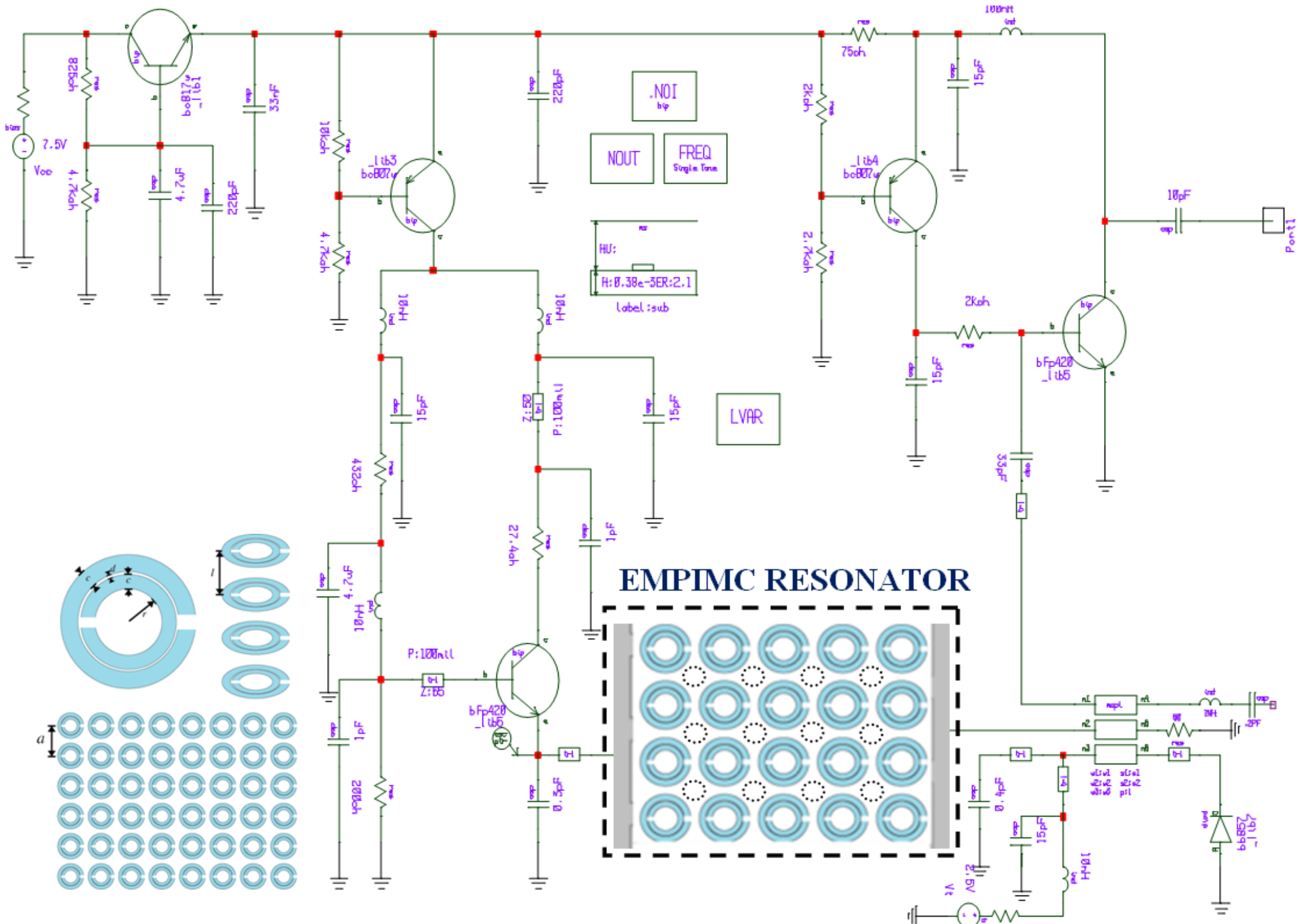
5 VDC and 20 mA, and delivers +3 dBm

The proposed oscillator circuit works without multipliers or switching from among resonators and/or oscillators, for reduced complexity, size, and power consumption compared to other multiple-signal-generation methods, and with excellent phase-noise performance.



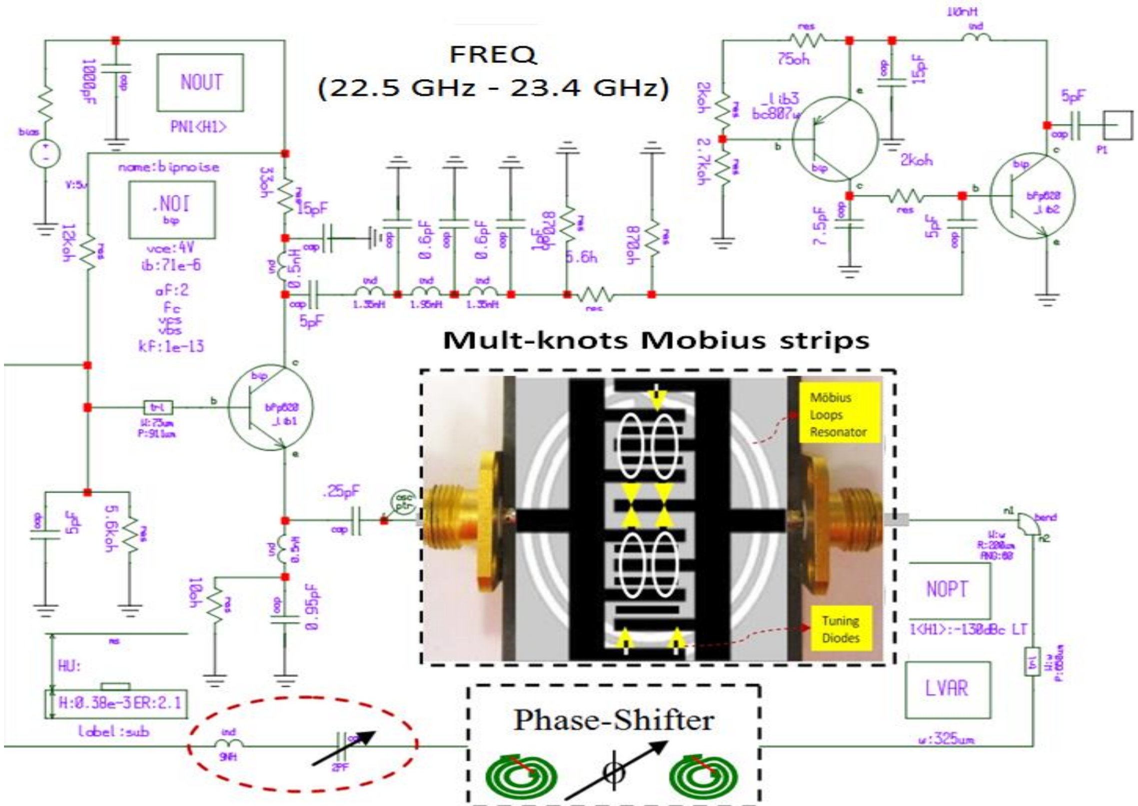
Measured Phase Noise Plot of multi-band evanescent mode metamaterial resonator oscillator circuit

Example: Tunable Möbius Resonator VCO



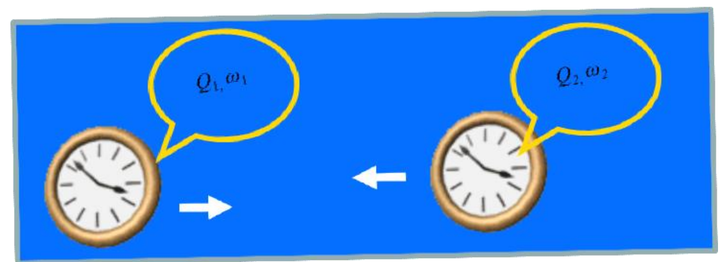
$$\overline{Q_a(\omega)}_{\omega\to\omega_0} = \left[\frac{\omega}{2(I_{max} - I_{min})}\int_{I_{min}}^{I_{max}} Q_a(\omega.i)\, di\right]_{\omega\to\omega_0}$$

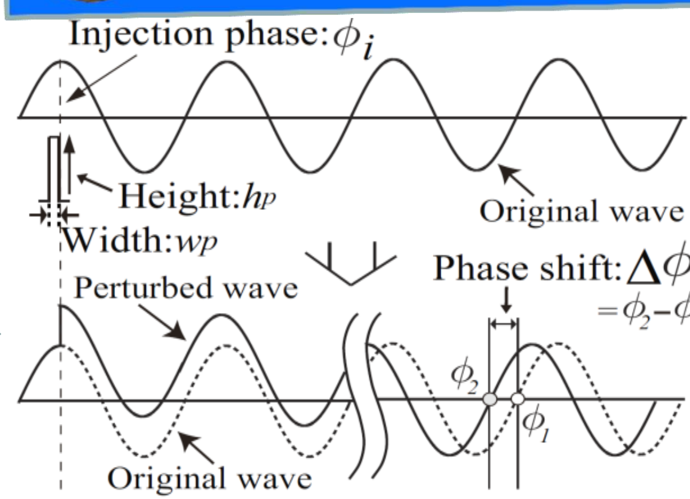
Tunable Möbius Resonator VCO



EMPIMC : Evanescent Mode Phase Injection Mode-Coupled

Figures show the typical circuit schematic, injection locking scheme, and phase perturbation dynamics.





3rd Harmonic Injection

Phase shift due to impulse perturbation at $\phi_{i.}$

$$Q_L = \frac{\omega_0}{2}\left|\frac{d\varphi(\omega)}{d\omega}\right|_{\omega=\omega_0} = \frac{\omega_0}{2}\tau_d; \quad \tau_d = \left|\frac{d\varphi(\omega)}{d\omega}\right|_{\omega=\omega_0} \qquad \tau_d = \left.\frac{d\varphi(\omega)}{d\omega}\right|_{\omega=\omega_0} = \frac{\varphi(\omega_0+\Delta\omega)-\varphi(\omega_0-\Delta\omega)}{2\Delta\omega}$$

where $\varphi(\omega)$ is the phase of the oscillator's loop transfer function at steady state and τ_d *is the group delay of the metamaterial Möbius strips resonator.*

Tunable (12-18 GHz) EMMSR VCO

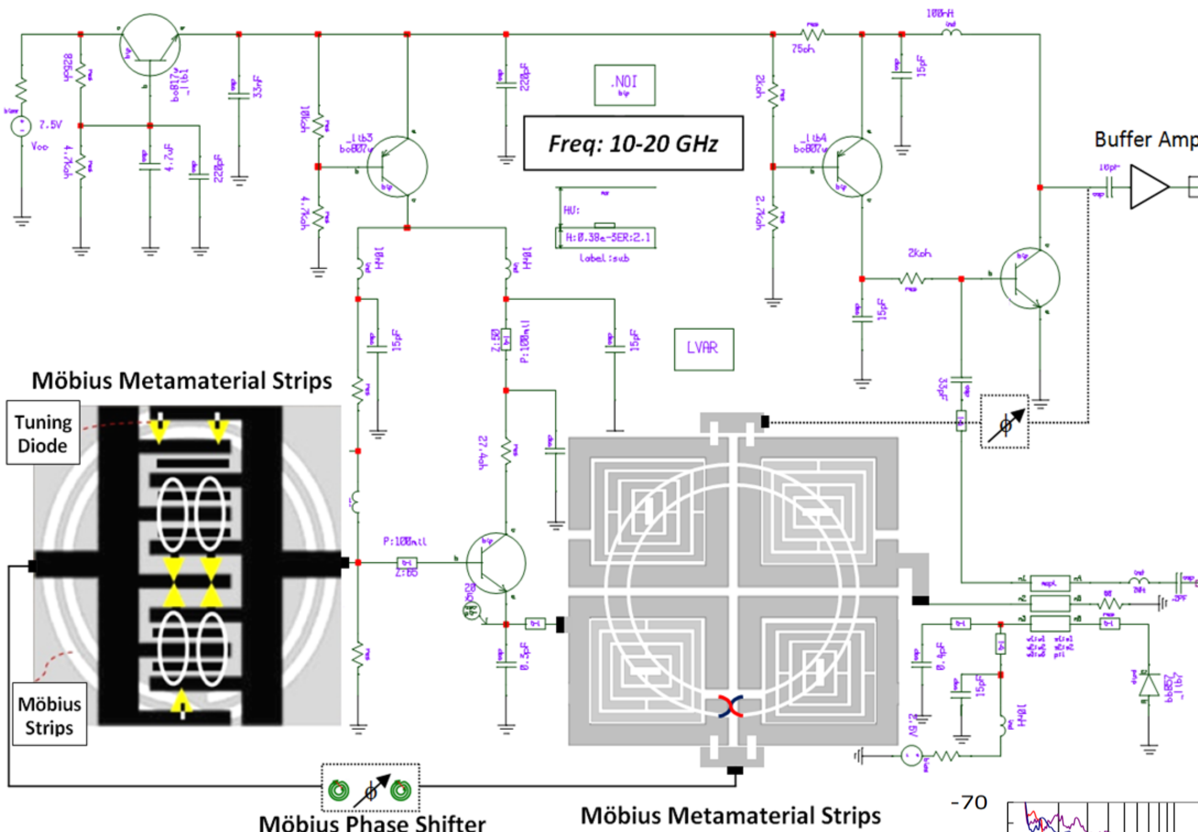
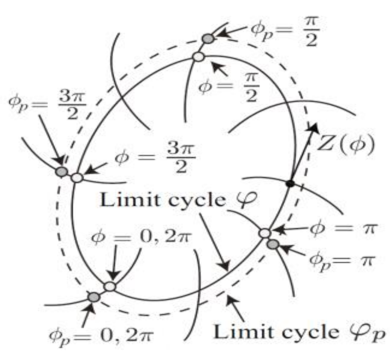
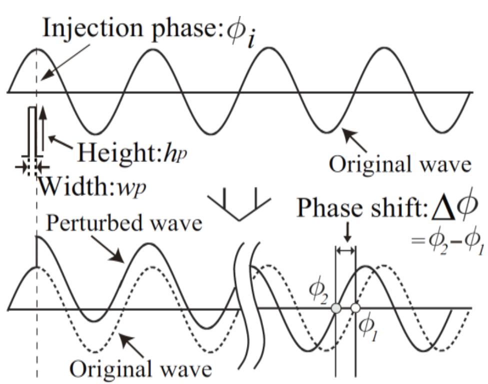
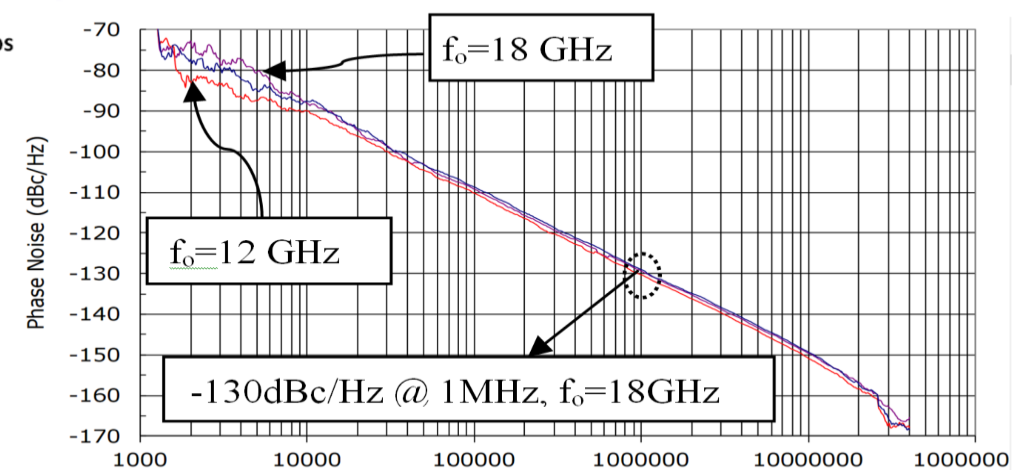


Table 1: Recent published oscillator's performance

Ref.	f_o GHz	P_{DC} mW	P_o dBm	Tuning GHz	$L(f)$ dBc/Hz	FOM dBc/Hz
[1]	22.1	11.1	-11	20.6%	-109	-181
[2]	9.5	37	7.5	4.8%	-117	-180.9
[3]	11.16	20	2.9	4.1%	-125.1	-193
[4]	10	10.5	-2	1.8%	-105	-174.8
[5]	12.4	30	7	2.5%	-122	-189.1
This work	23.12	300	5.1	3.8 %	-152.4	-214.5

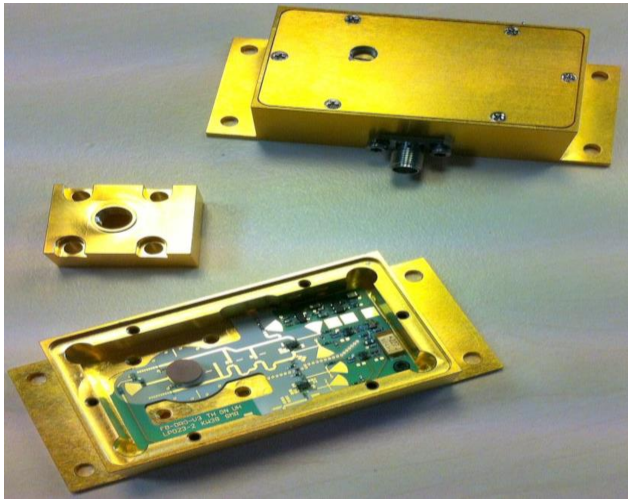




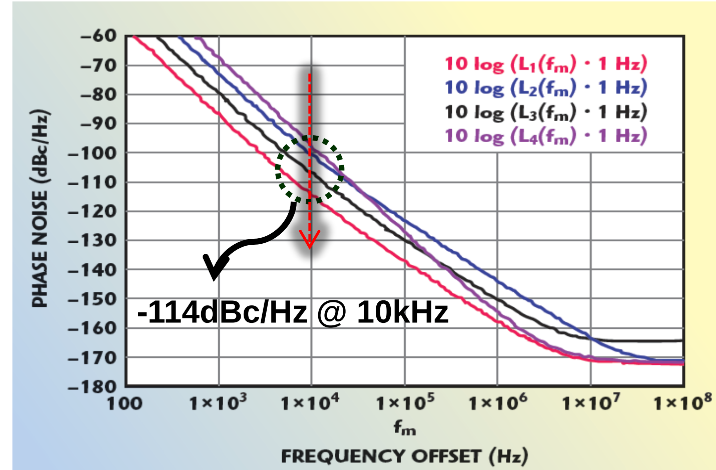


Cost-Effective DRO Alternative

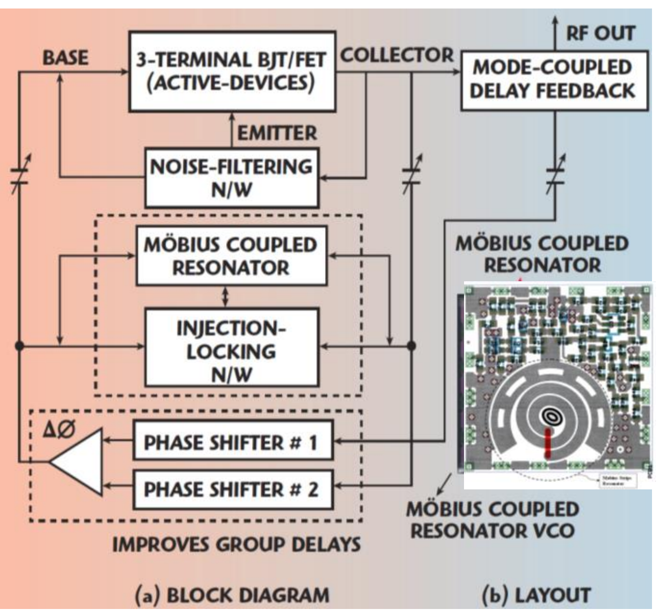
Size: 3.1" × 1.34" × 0.788” inches



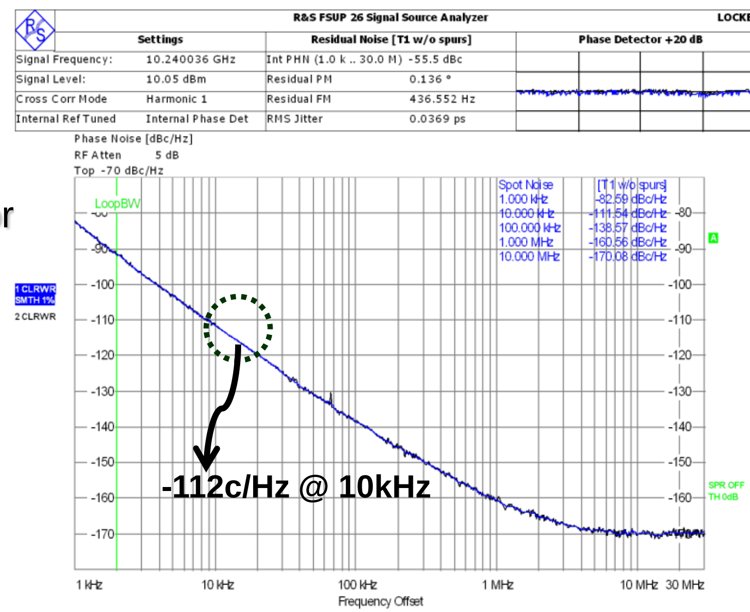
Connectorized 3-D Disc resonator based 10.24 GHz Oscillator
5V, 80 mA



0.5"x 0.5" inches

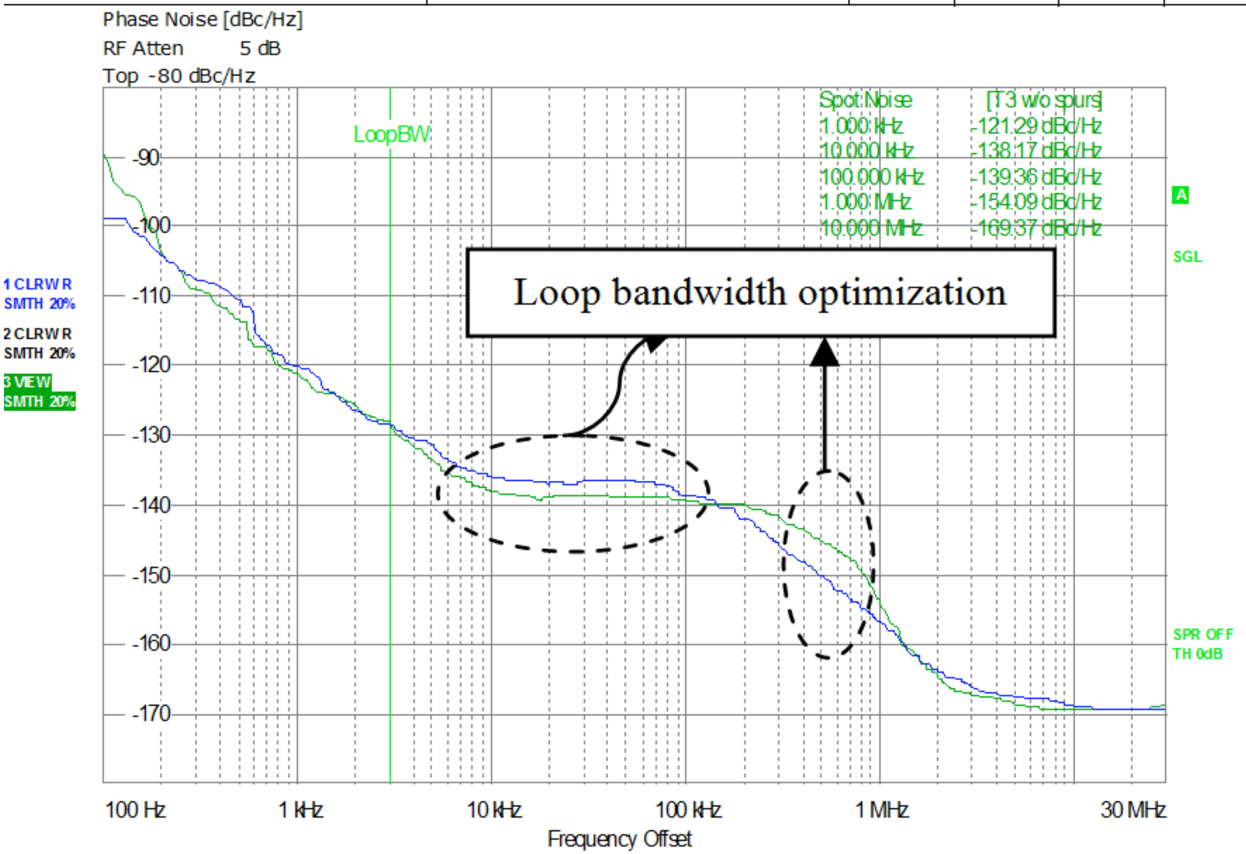


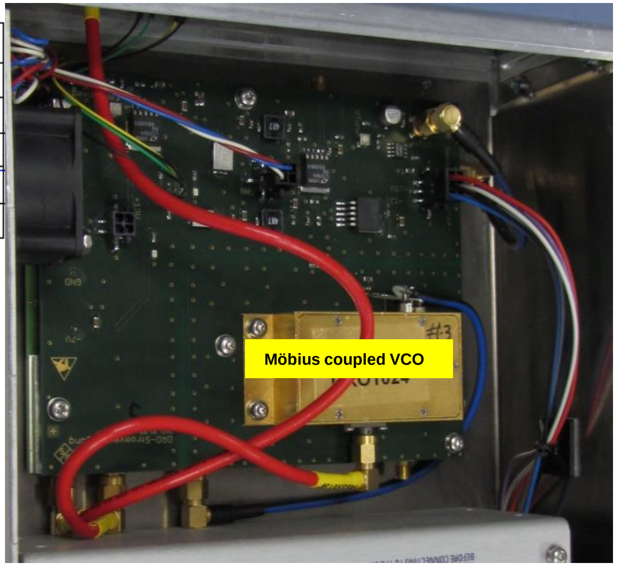
Printed Möbius Resonator Based 10.24 GHz Oscillator with DC bias of 5V, 30 mA



High Performance 10.24 GHz Synthesizer

R&S FSUP 26 Signal Source Analyzer				LOCKED
Settings		Residual Noise [T3 w/o spurs]		Phase Detector +20 dB
Signal Frequency:	10.239955 GHz	Int PHN (100.0 .. 30.0 M)	-74.2 dBc	
Signal Level:	7.9 dBm	Residual PM	15.735 m°	
Cross Corr Mode	Harmonic 1	Residual FM	468.955 Hz	
Internal Ref Tuned	Internal Phase Det	RMS Jitter	0.0043 ps	



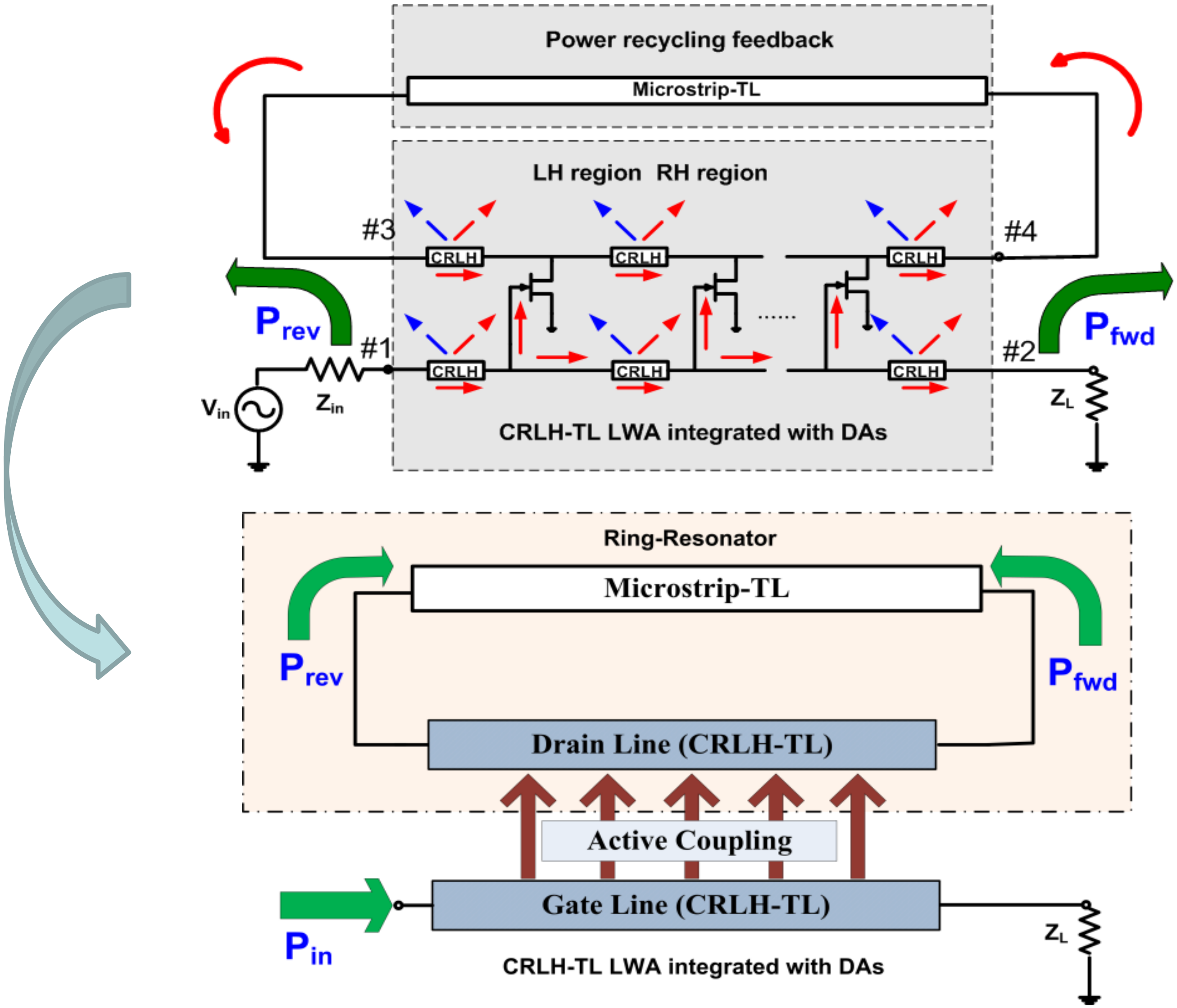


A typical measured phase noise plot of the 10.24 GHz synthesized signal source (lowest phase noise source reported for a given cost and FOM

R&S FSUP 50: phase noise measurements

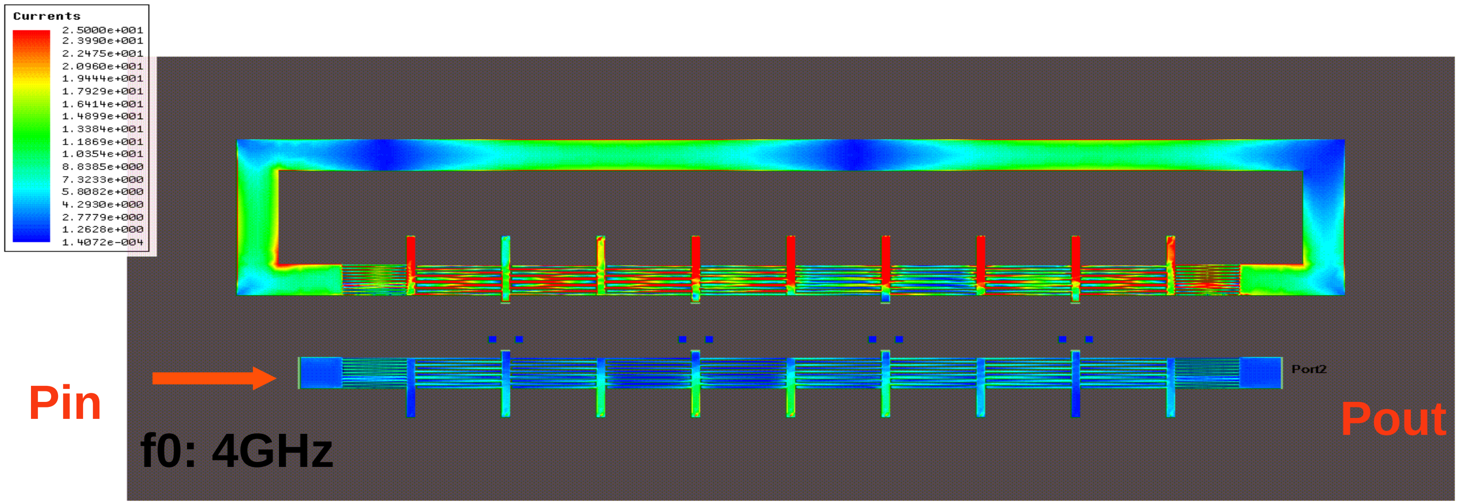
Power Recycling: Metamaterial Möbius Strips

Unradiated power can be redirected to the LWA again!



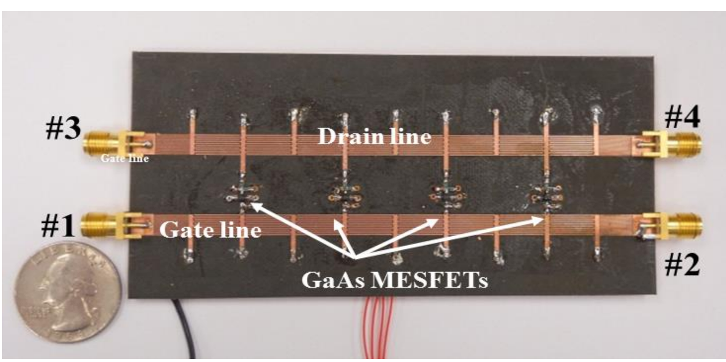
C.-T. M. Wu et al, "Ring-Resonator-Inspired Power Recycling Scheme for Gain-Enhanced Distributed Amplifier-Based CRLH-Transmission Line Leaky Wave Antennas," *IEEE Trans. on Microwave Theory and Techniques*, pp.1027-1037, April 2012.

Metamaterial: Go Green (Power Recycling)

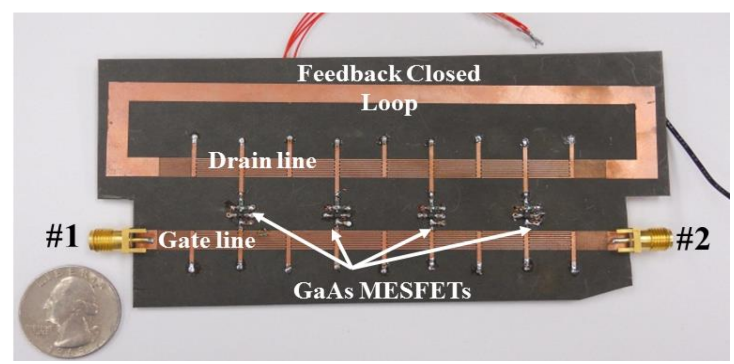


Unradiated power can be redirected

Without power feedback

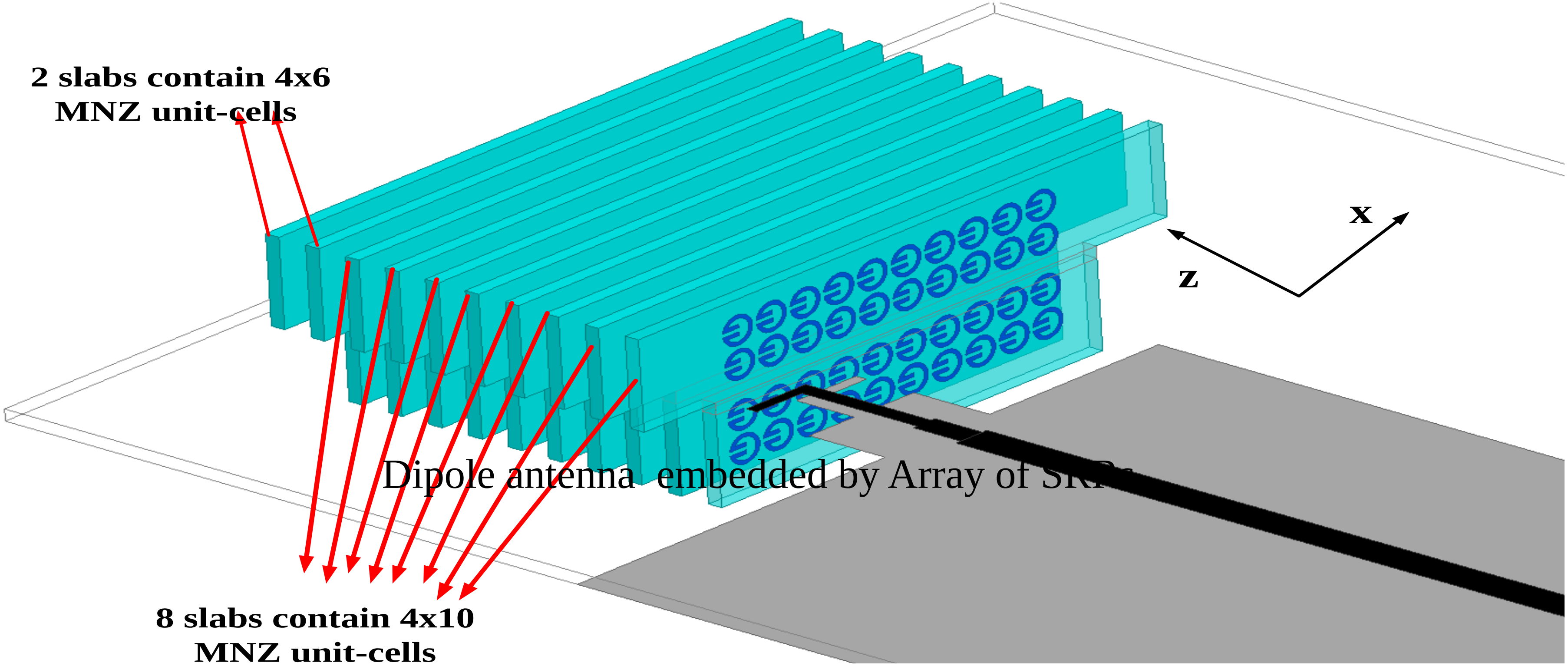


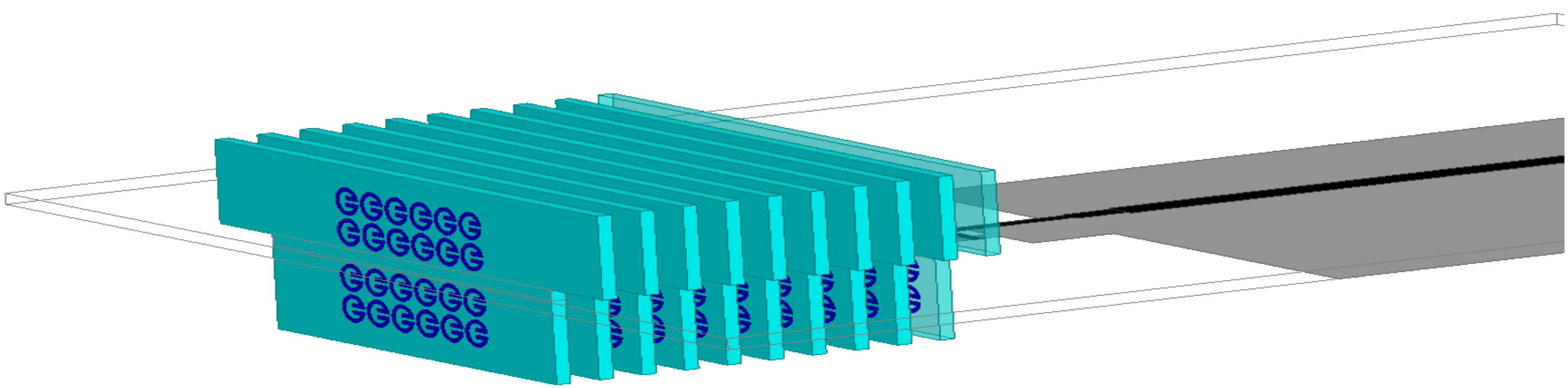
With power feedback



- **Significant increase in gain (42%)**
- **Maintaining beam-scanning capability**

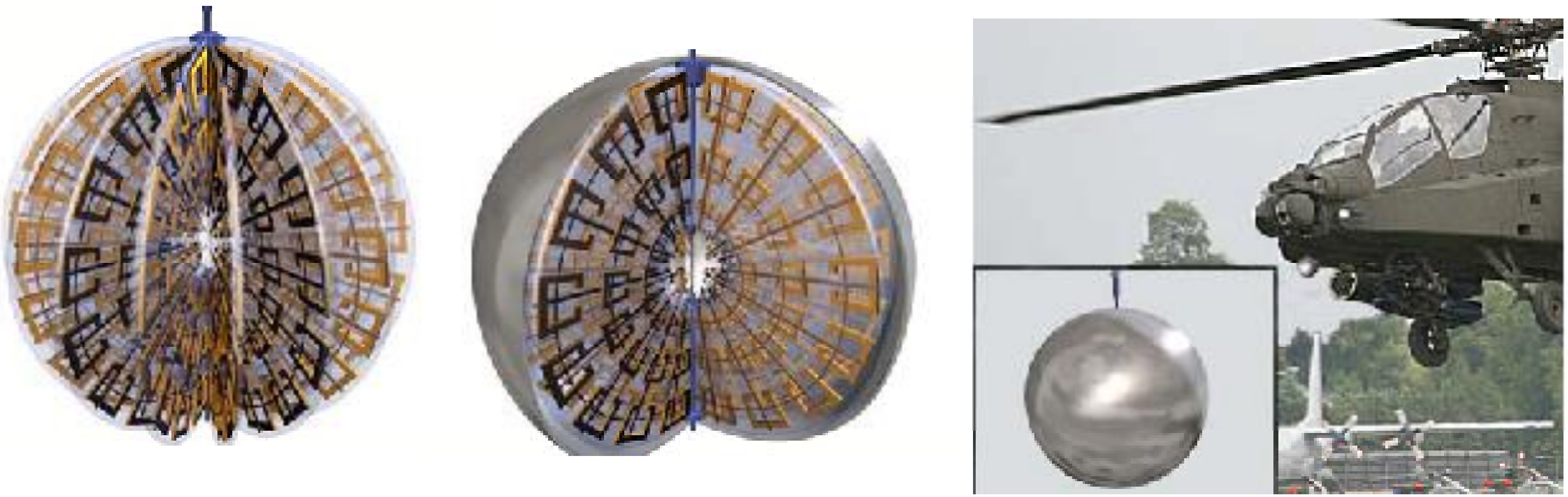
Dipole antenna embedded by Array of SRRs





Möbius Metamaterial : Compact Antenna

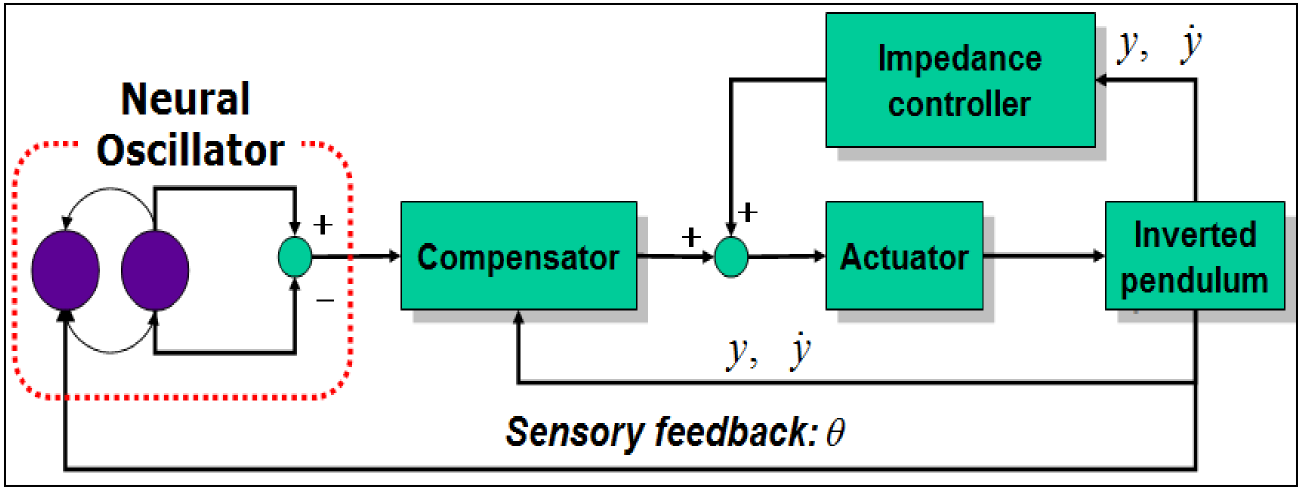
Negative-Index Mobius Materials: Miniaturizing Everything!

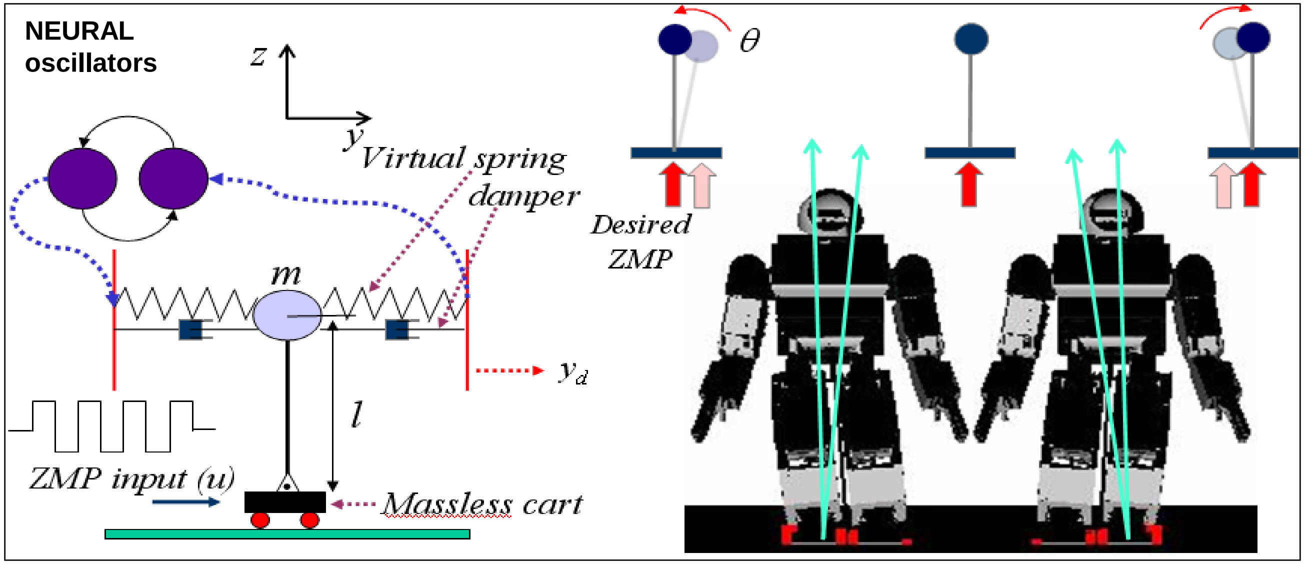


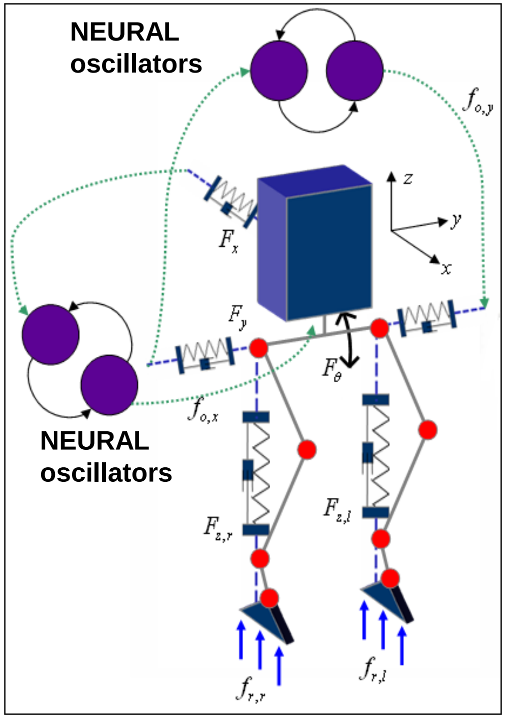
A sub-wavelength antenna embedded in a negative index shell

Neural Oscillator: MMR Couple Mode Oscillator

Analogy to Human/Robotic Systems





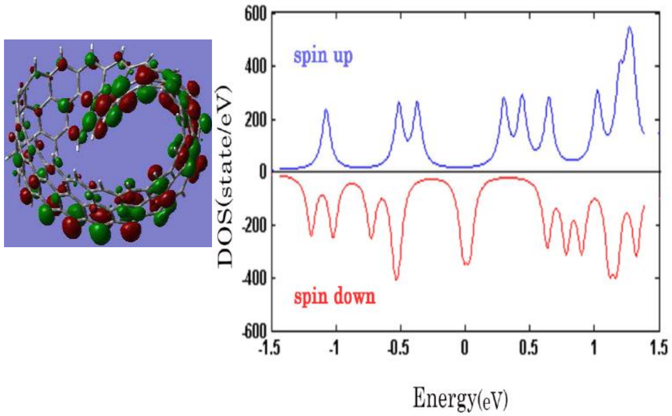


Matsuoka's neural oscillator model

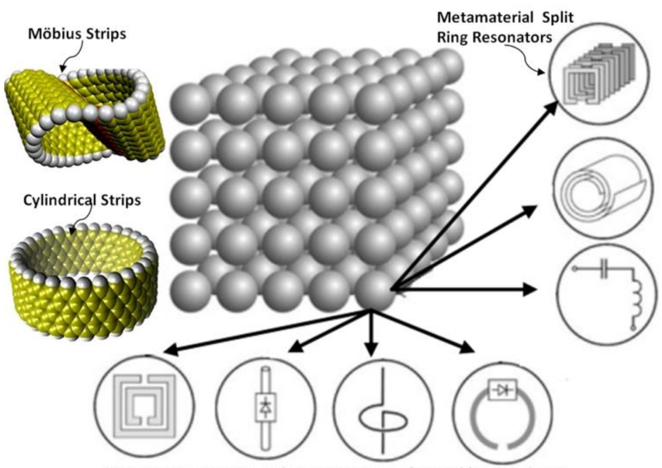
Coupled mode neural oscillator: inverted pendulum model

Conclusions

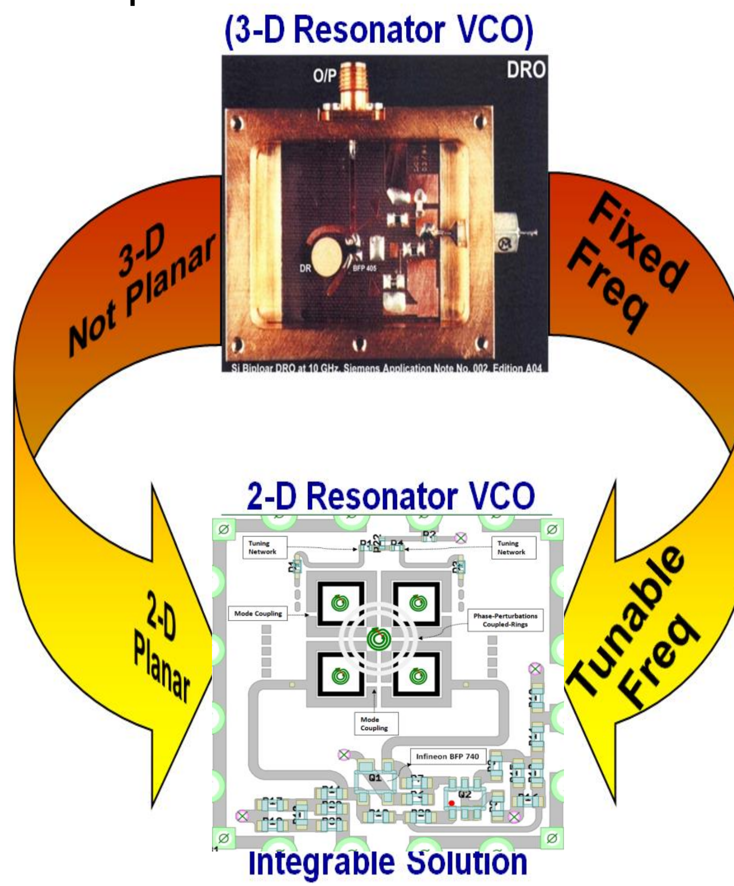
- The new approach of designing tunable oscillators with Metamaterial Mobius strips resonators yields compact VCOs with excellent phase-noise performance, can be readily adapted to modern RF integrated circuit (RFIC) and MMIC semiconductor manufacturing processes.



Spintronic device and quantum oscillations

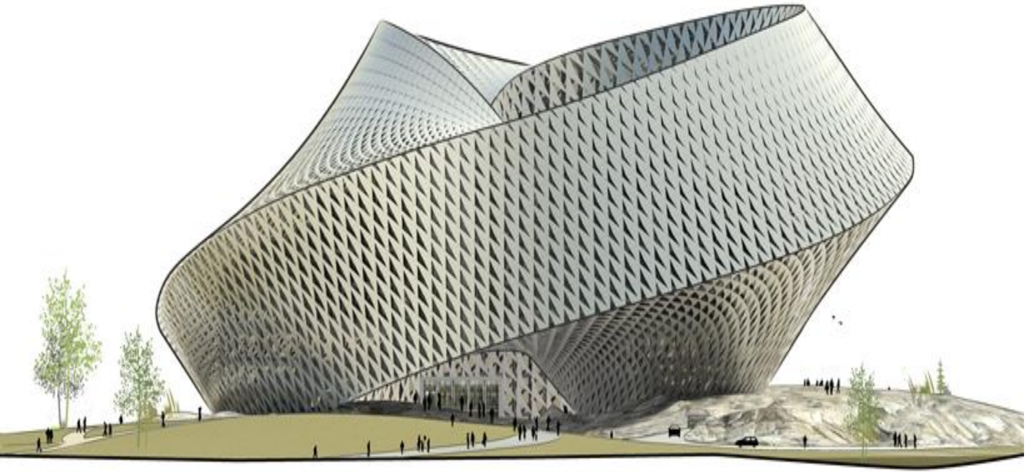


- ✓ Configurability
- ✓ Integrability
- ✓ Tunability
- ✓ Low Cost
- ✓ Compact Size
- ✓ Power-Efficient
- ✓ User-Definable

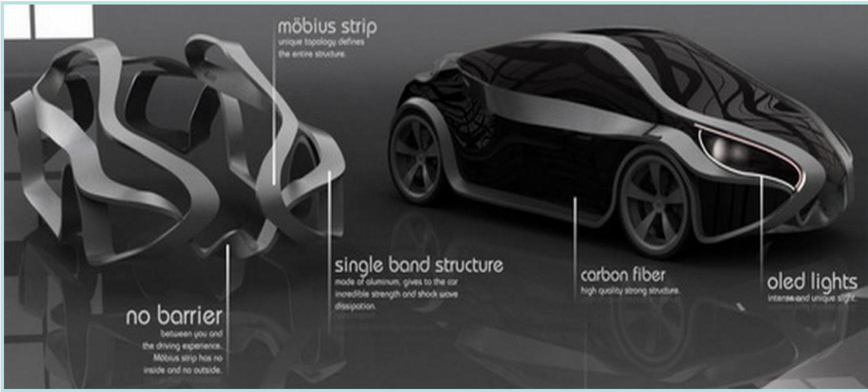


Möbius Strip: RF & MW Beyond Application

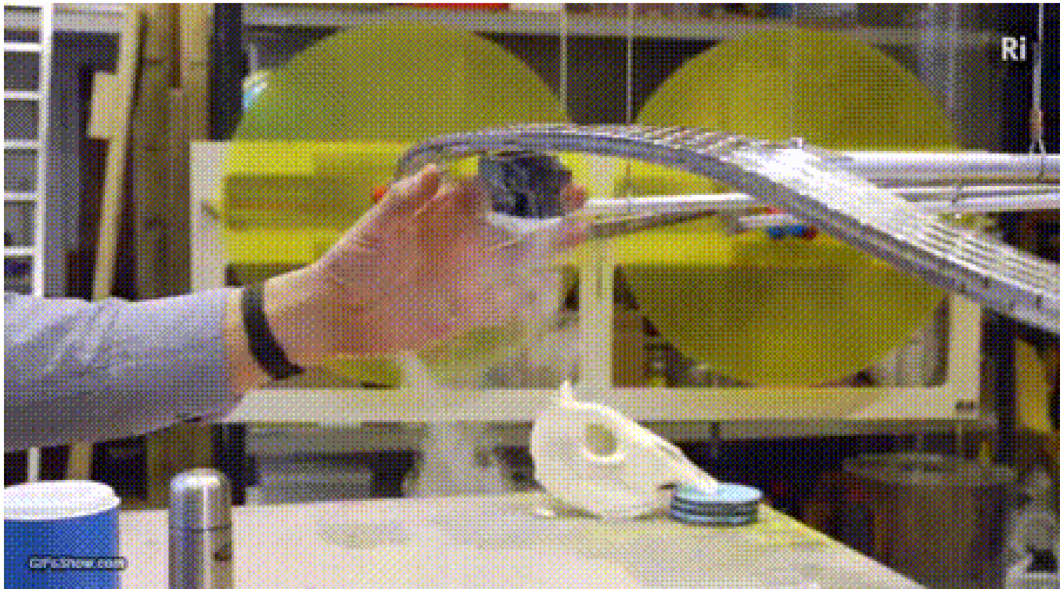
3D view of the Mobius style National Library building in Kazakhstan: Won best architectural prize award



Möbius car designed by Tommaso Gecchelin



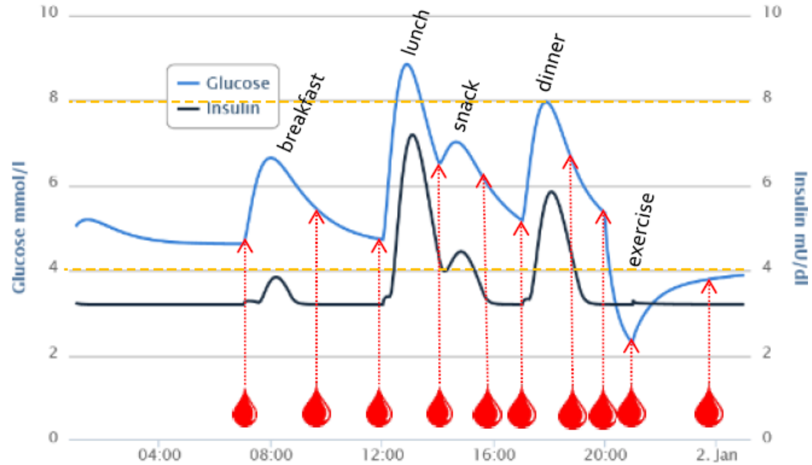
Magnetic Levitation of a Superconductor Over a Mobius Strip



Thank You !

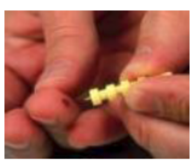
Questions ?

Diabetes management – todays solutions are not optimal

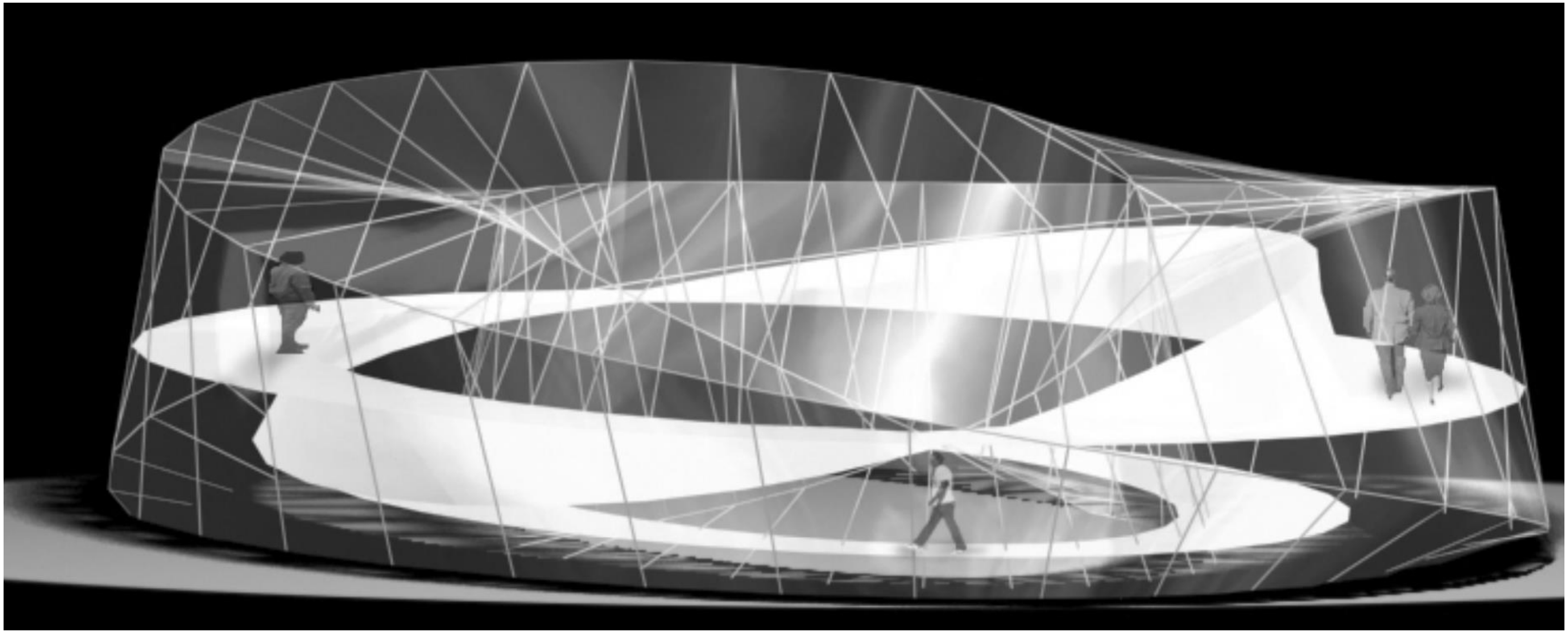


- Must be managed daily to avoid diseases and death:
  - Blood glucose monitoring
  - Diet management
  - Insulin injection

- The dominant method is blood sampling:



Non invasive Blood sugar monitoring solution



Proposed Möbius strips Musueum building :Taiwan

Metamaterial Waveguide Confirms Theoretical Prediction

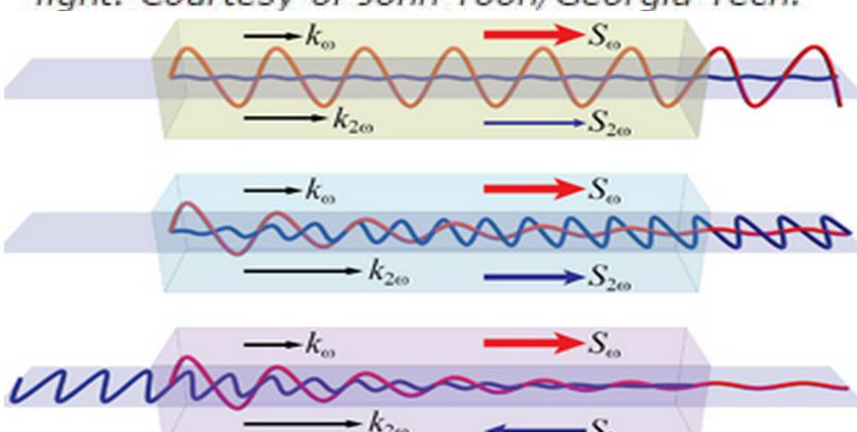
June 2015

ATLANTA, June 16, 2015 — A metamaterial waveguide has demonstrated opposite refractive indices at the fundamental and harmonic frequencies of light, confirming for the first time a decade-old theoretical prediction.

The experimental verification of backward phase matching – a phenomenon also known as the "nonlinear mirror" – may have few immediate practical applications, according to the Georgia Institute of Technology team that created the waveguide. But it is a milestone that could also lead to new areas of study, they said.

"Nonlinear optics is critically important to controlling light for information processing, sensing and signal generation," said Wenshan Cai, an associate professor in Georgia Tech's School of Electrical and Computer Engineering, who led the research team. "Our effort substantially expands the scope of nonlinear light-matter interactions in artificially structured media with engineered, unconventional linear and high-order material parameters."

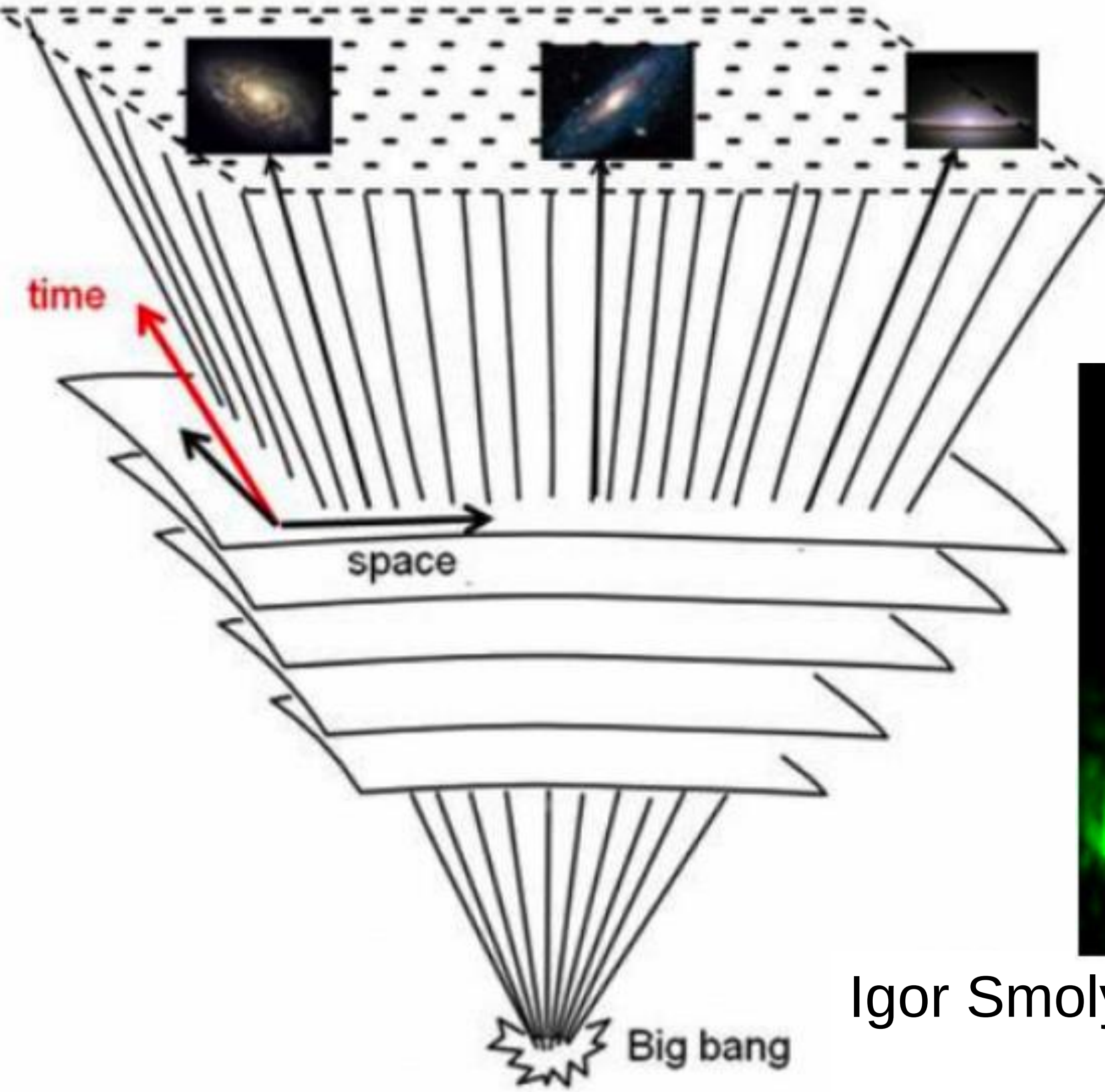
A metamaterial waveguide at the center of a silicon chip has opposite refractive indices at the fundamental and harmonic frequencies of light. Courtesy of John Toon/Georgia Tech.



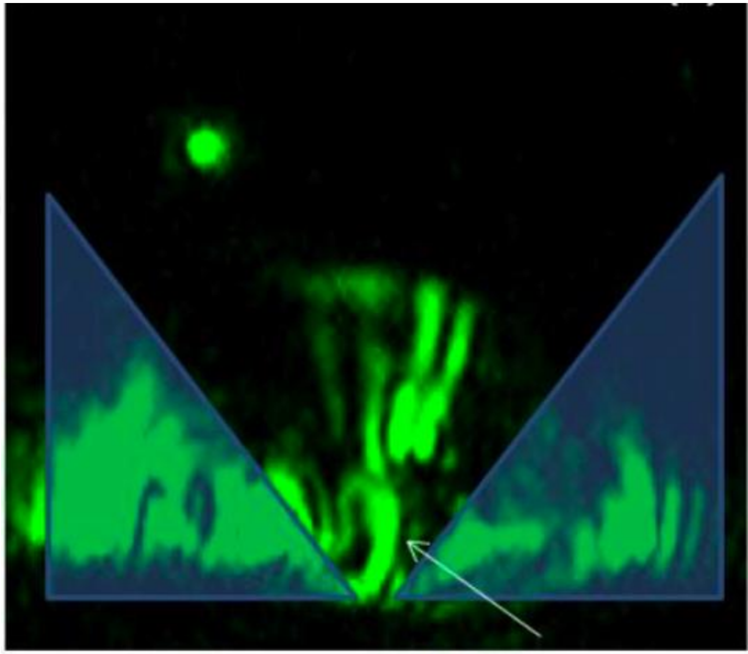
Silicon Chip

Acoustic Invisibility Cloak made of metamaterial makes objects unhearable

The research is reported in the journal *Physical Review Letters, Feb 2011*



Igor Smolyaninov Model: mapping light distribution in a metamaterial can serve as a model for the flow of time. The model shows that the forward direction of time is unrelenting; you cannot curve back on time and go back to where you started.

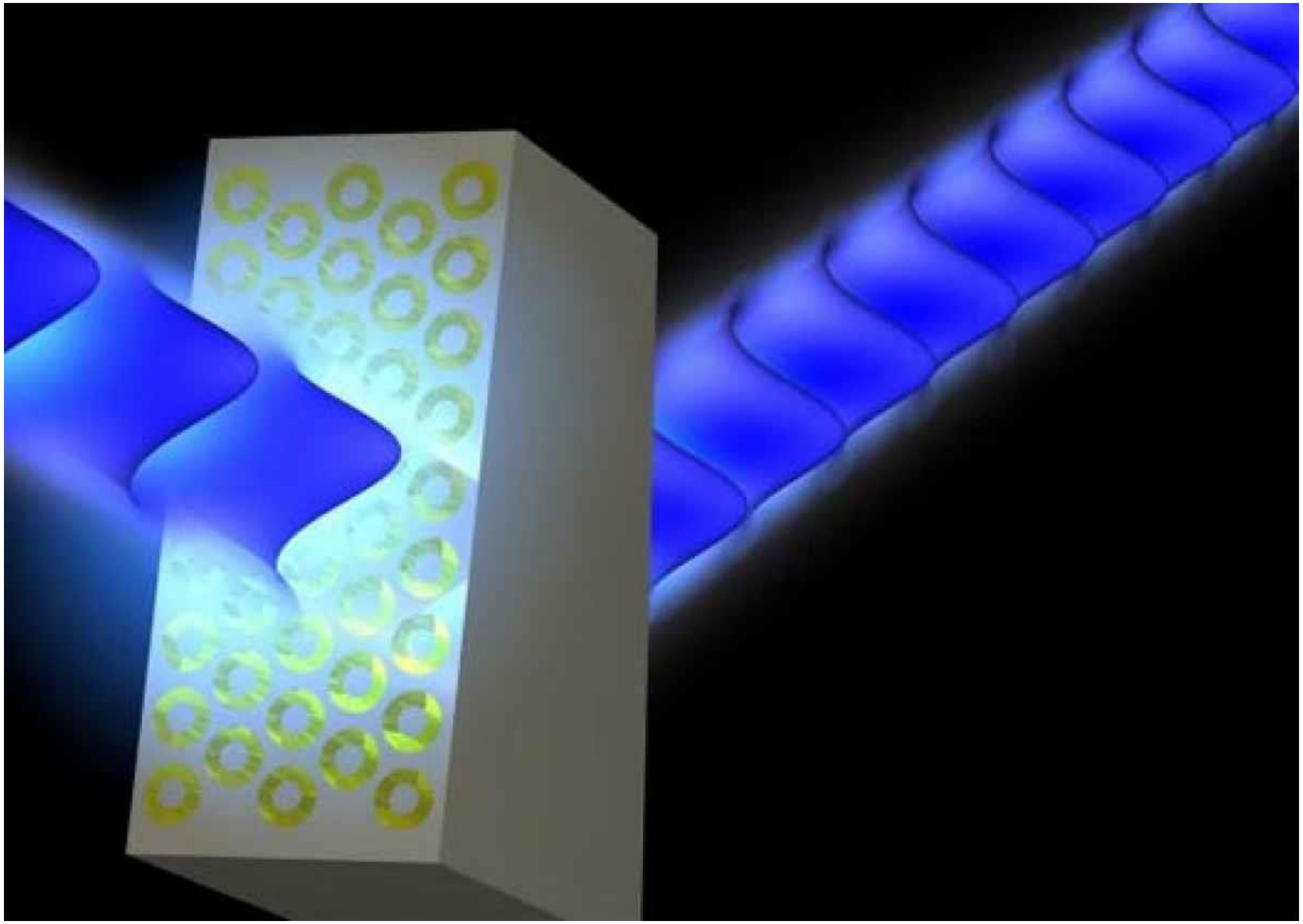


Igor Smolyaninov Big Bang Model

A B-2 Spirit bomber flying over Guam. A team of researchers from Purdue University and Norfolk State University in Virginia designed a new metamaterial that absorbs almost all the light that hits it, heralding a new wave of stealth technology. The material could be applied to all parts of the electromagnetic spectrum, meaning it could be used to make materials invisible to radar.

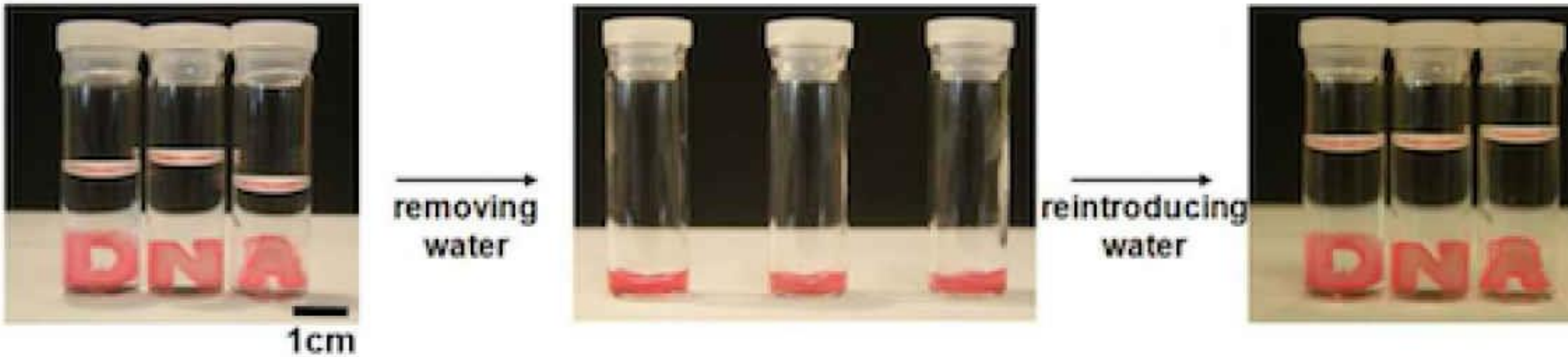
www.newscientist.com/article/mg20627645.000-radiationsoaking-metamaterial-puts-black-in-the-shade

Metamaterial: Light Bending in Visible Spectrum

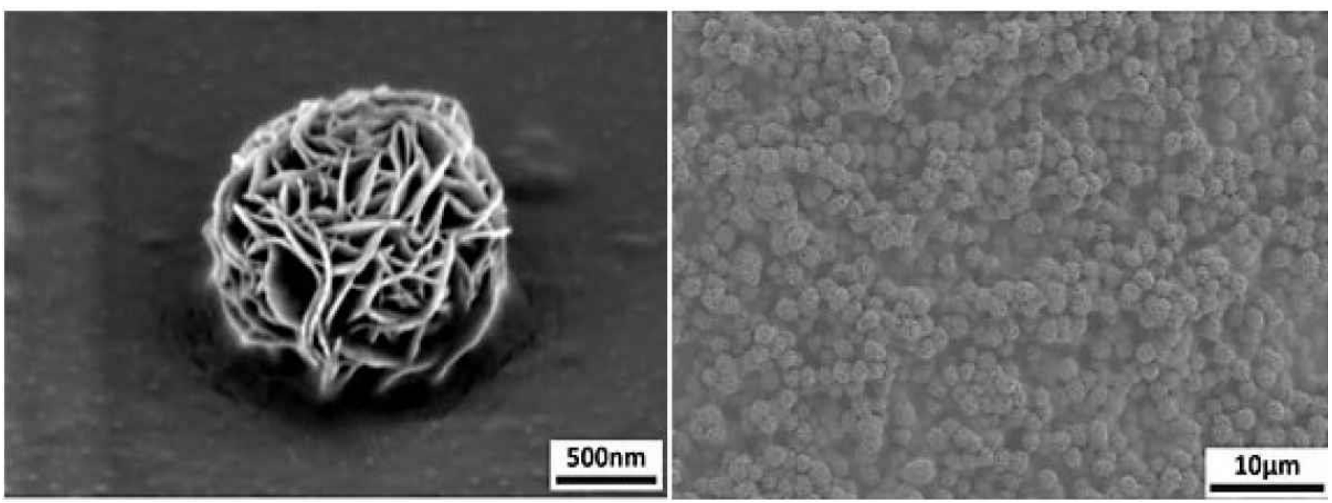


New Metamaterial: Bending light in the visible spectrum: Ares Rosakis, chair of the Division of Engineering and Applied Science at Caltech and Theodore von Kármán Professor of Aeronautics and Mechanical Engineering.
"A single-layer wide-angle negative index metamaterial at visible frequencies," *Nature Materials*, April 2010.

Shapes Shifting Metamaterial could revolutionize how we treat wounds



When a drug can flow into a cavity then conform to the shape of the cavity and stay there, it offers unprecedented opportunities delivery of drugs. Cornell researchers invented hydro gel metamaterial soft that it can flow like a liquid and then, strangely, return to its original shape.



IMG_0991.MOV

http://www.news.cornell.edu/stories/2012/12/hydrogel-remembers-its-shape

http://www.popsci.com/technology/article/2012-12/new-metamaterial-hydrogel-flows-liquid-remembers-its-shape#ooid=s4dncwYjqyRzpxExYFJ1TQyGwch7LiV_

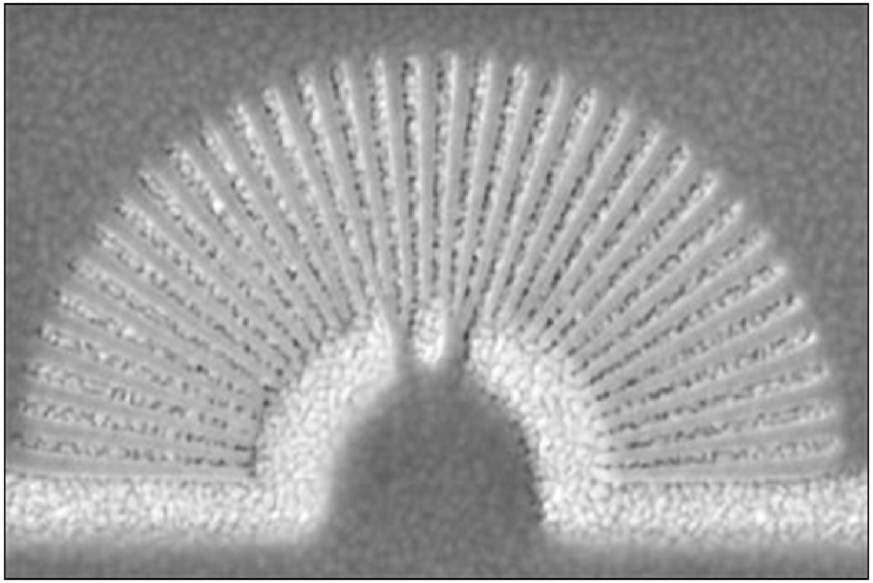
Metamaterial Hyperlens Breaks Diffraction Limit

May 2015

BUFFALO, N.Y., May 26, 2015 — A new metamaterial design has enabled a hyperlens capable of imaging details smaller than the wavelengths of visible light.

Developed at The State University of New York at Buffalo, the new device relies on a nonresonant, waveguide-coupled design to overcome the losses previous hyperlenses suffered at optical wavelengths.

"There is a great need in health care, nanotechnology and other areas to improve our ability to see tiny objects that elude even the most powerful optical systems," said Natalia Litchinitser, professor of electrical engineering at Buffalo. "The hyperlens we are developing is, potentially, a giant step toward solving this problem."

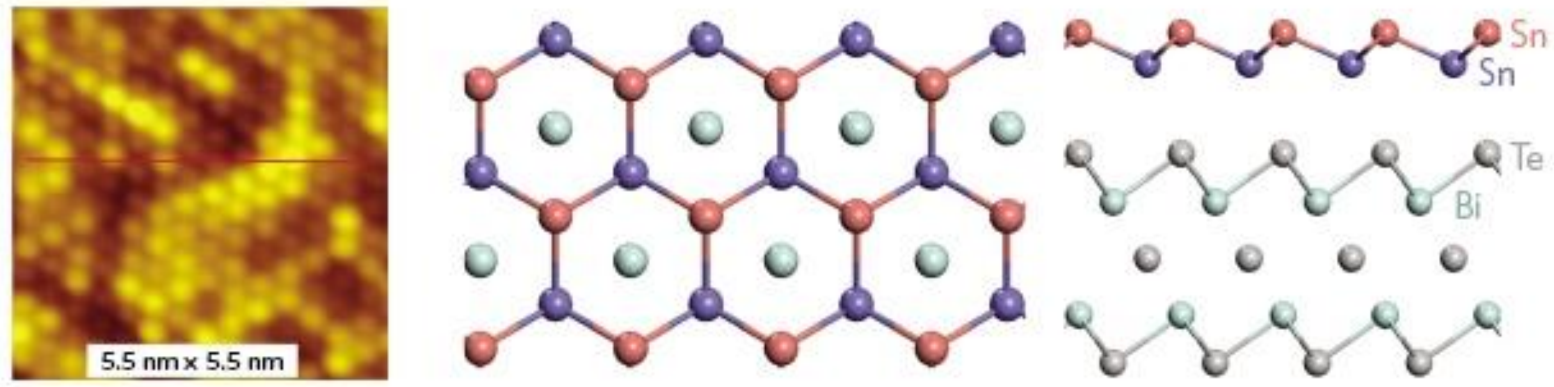


A metamaterial hyperlens. The light-colored slivers are gold, and the darker ones are PMMA. Courtesy of University at Buffalo.

Diffraction sets a fundamental limit to the resolution of optical systems, but metamaterials provide a potential route around this barrier.

Typically optical metamaterials are arranged in repetitive patterns, often smaller in scale than the wavelengths of the phenomena they influence. Metamaterial hyperlenses overcome the diffraction limit by transforming decaying evanescent waves into propagating waves.

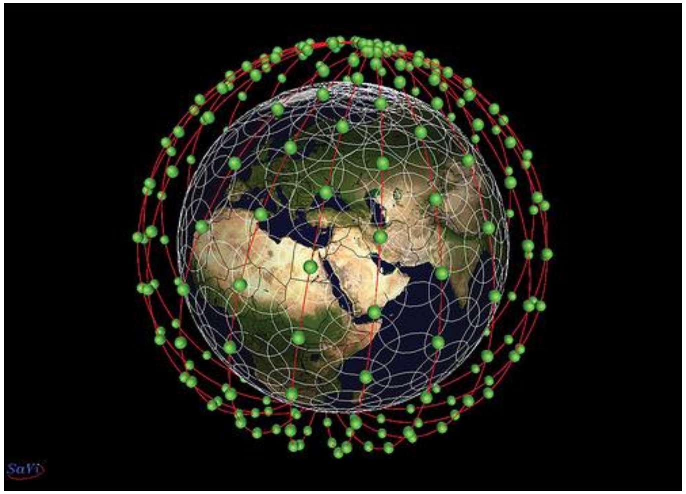
May 2015

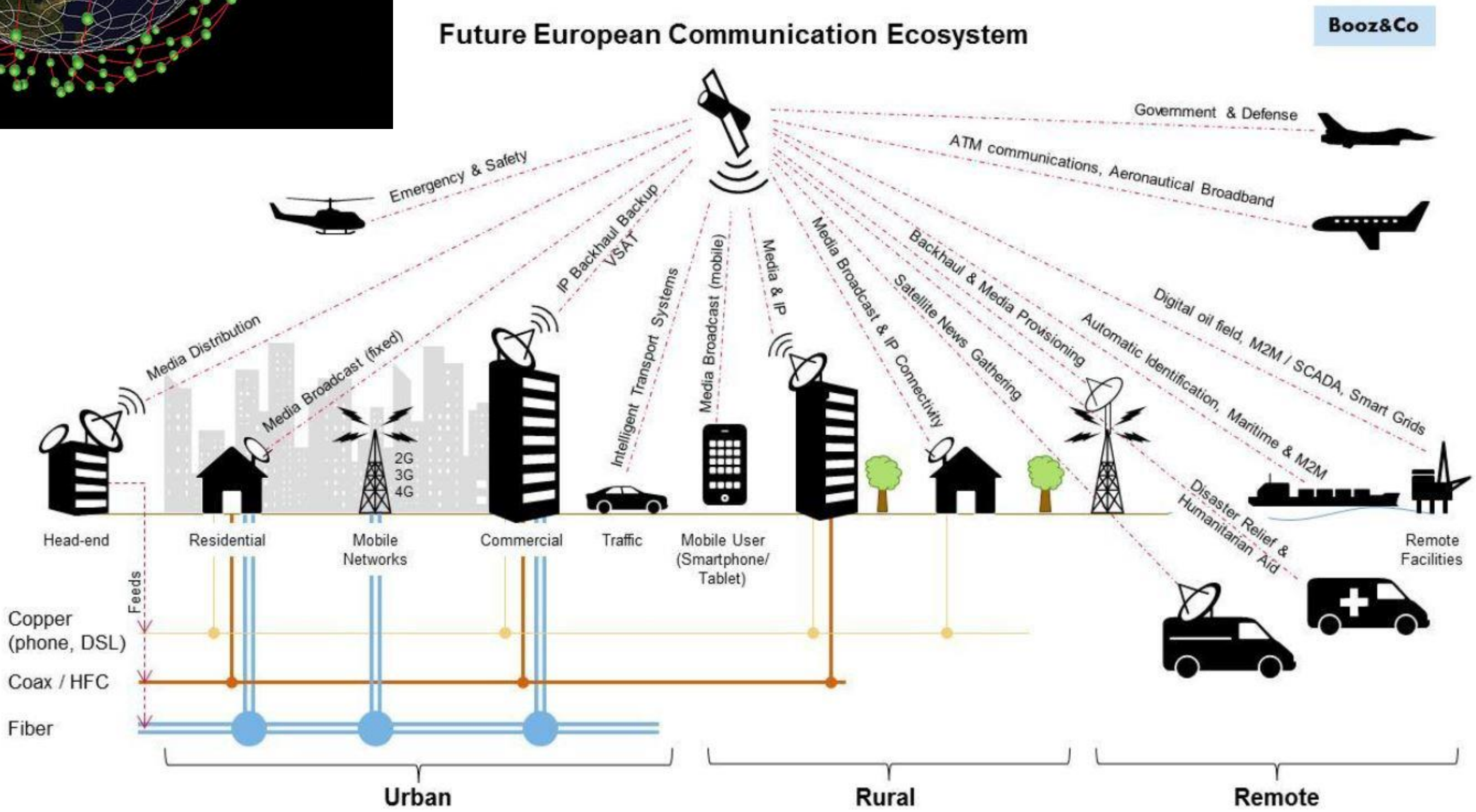


Physicists announce Graphene’s latest cousin: Stanene

First observation of 2D tin can't confirm whether material can conduct electricity without heat loss.

/ 2015

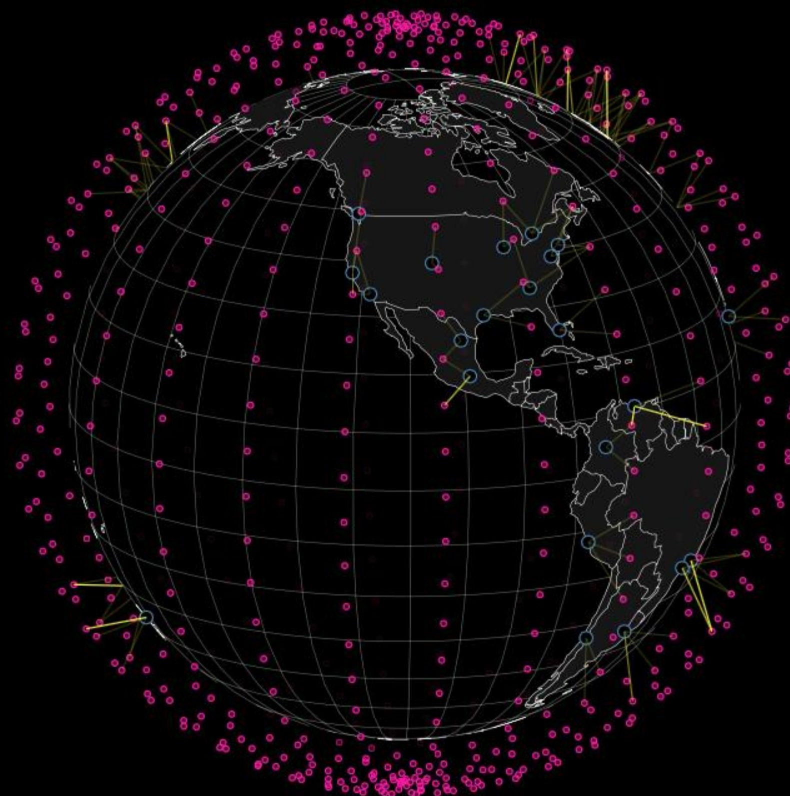



Future European Communication Ecosystem
Booz&Co
Government & Defense
ATM communications, Aeronautical Broadband
Emergency & Safety
IP Backhaul Backup
VSAT
Media Distribution
Media Broadcast (fixed)
Intelligent Transport Systems
Media Broadcast (mobile)
Media & IP
Media Broadcast & IP Connectivity
Satellite News Gathering
Backhaul & Media Provisioning
Automatic Identification, Maritime & M2M
Digital oil field, M2M / SCADA, Smart Grids
Disaster Relief & Humanitarian Aid
2G
3G
4G
Head-end
Residential
Mobile Networks
Commercial
Traffic
Mobile User (Smartphone/ Tablet)
Remote Facilities
Feeds
Copper (phone, DSL)
Coax / HFC
Fiber
Urban
Rural
Remote

Expected

648 Satellites in 2018

750 miles above earth

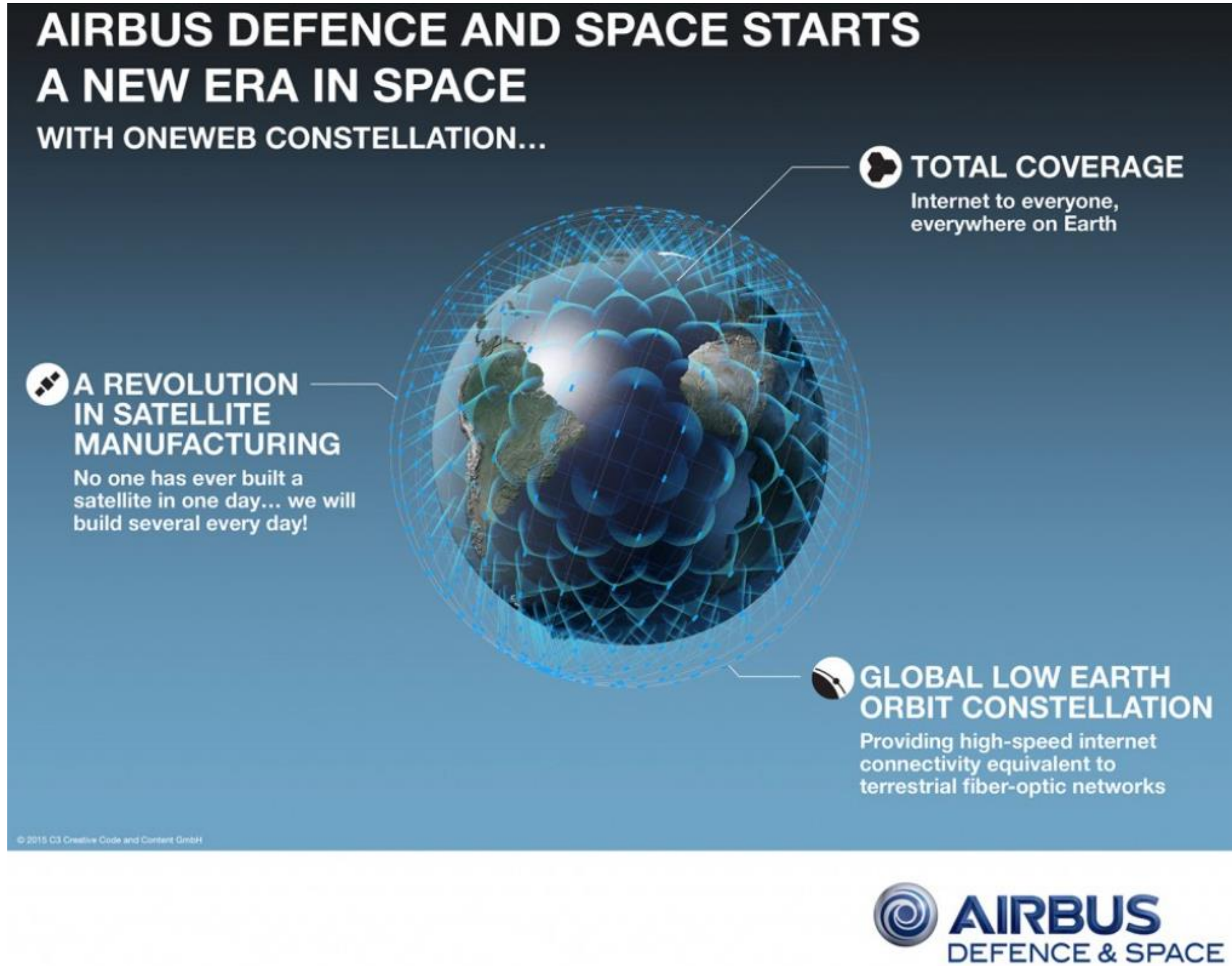


Think of OneWeb, Greg Wyler's newest startup, as a supercharged O3b. The company intends to launch hundreds of satellites into low-earth orbit by 2018. Assuming it works (a lot can go wrong), OneWeb will provide extremely high-speed Internet access everywhere on earth.

The Guardian, 6/15/2015

http://www.theguardian.com/science/2015/jun/16/airbus-to-build-900-satellites-for-oneweb-internet-from-space-project

Airbus to build 900 satellites for OneWeb internet-from-space project



replacements were needed, said OneWeb, based in Britain's Channel Islands.

http://spaceflightnow.com/2015/06/15/oneweb-selects-airbus-to-build-900-internet-satellites/

First CubeSats Planned for Mars

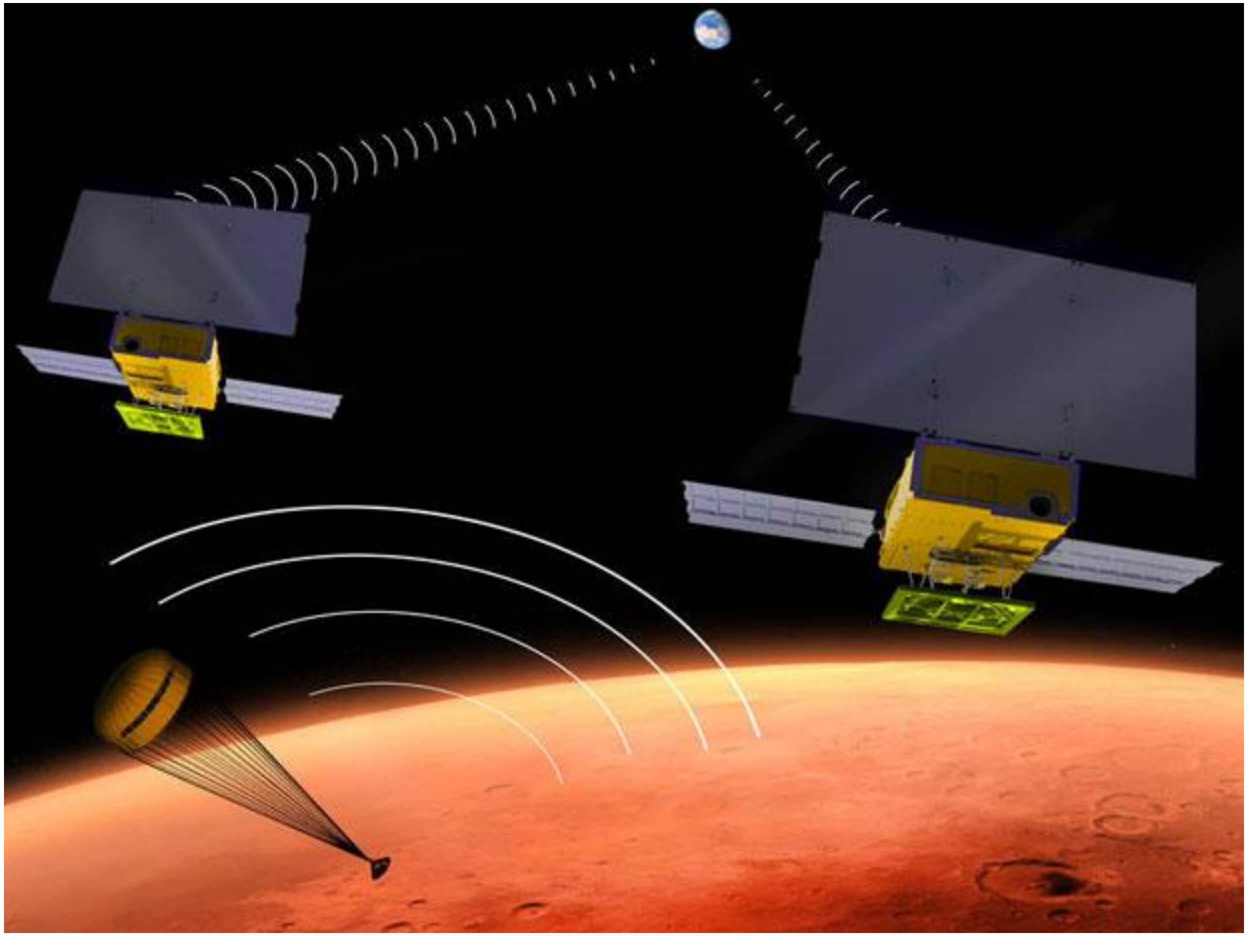
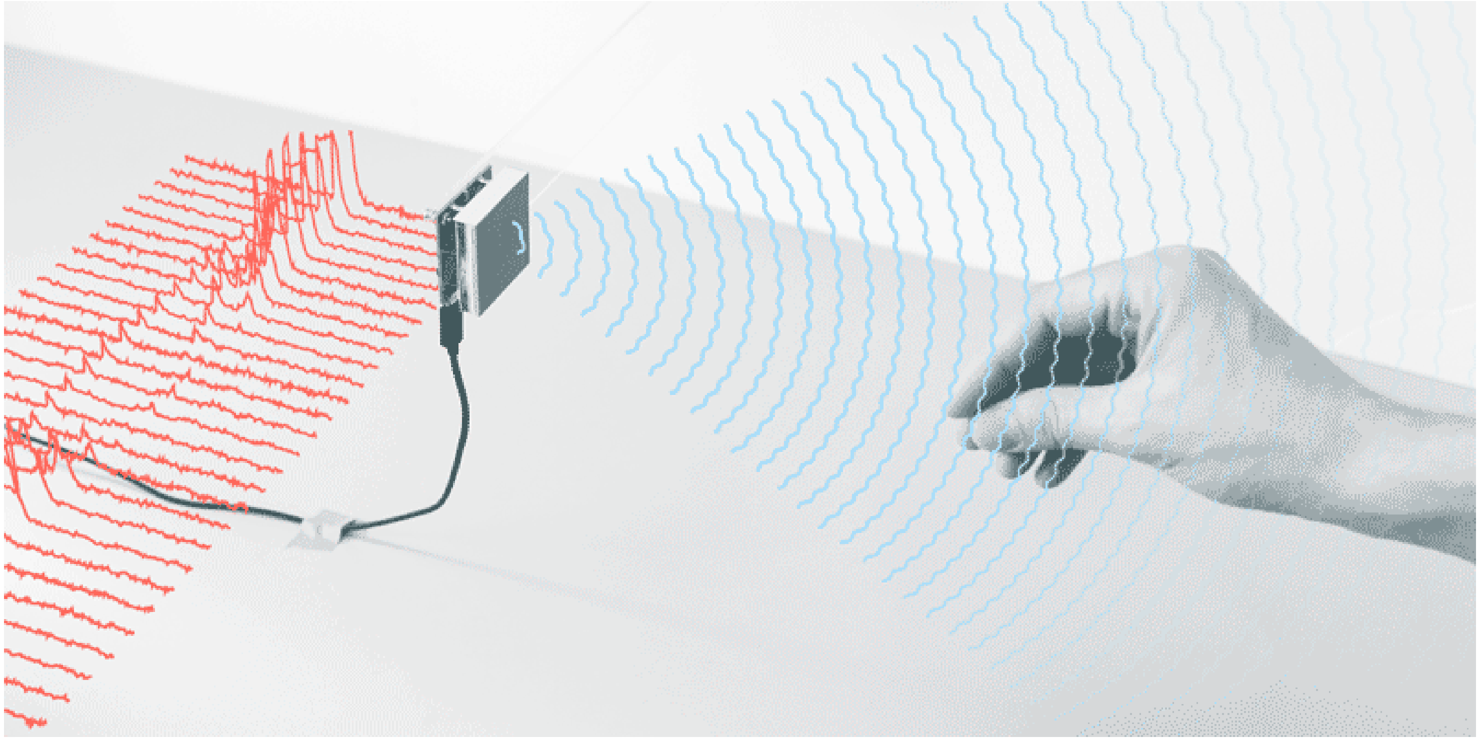
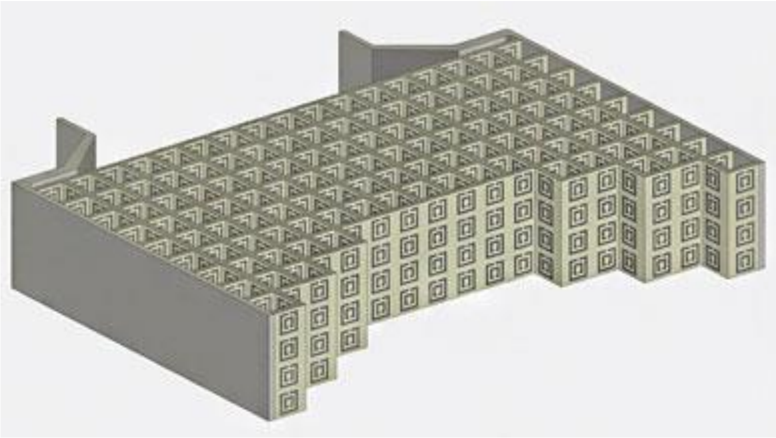
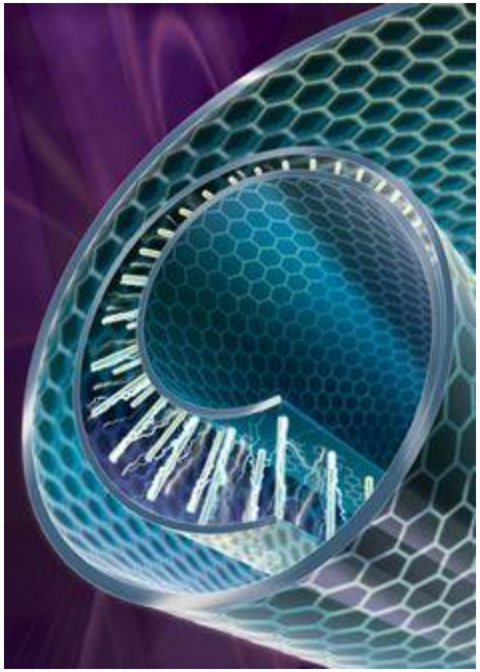


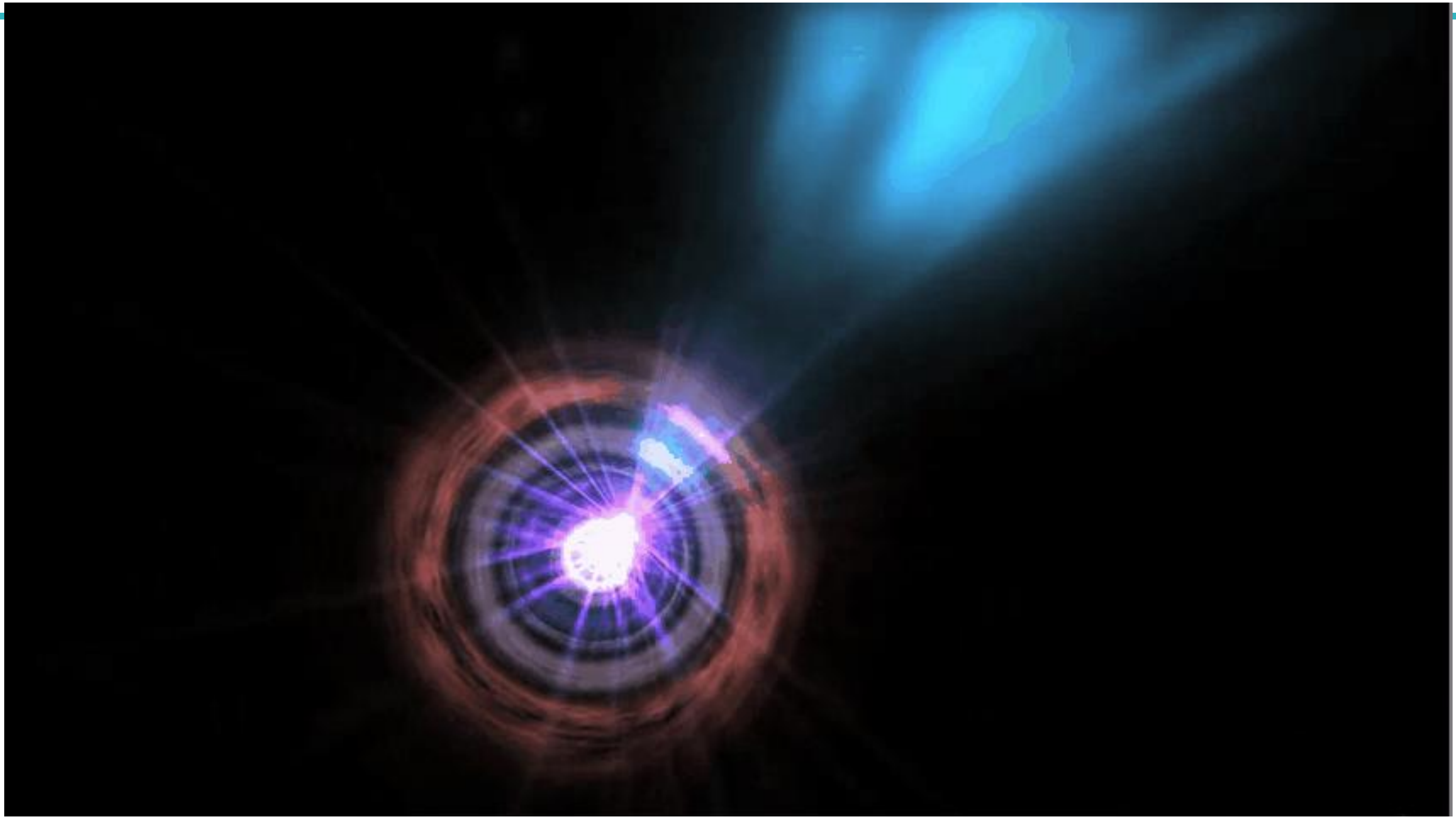
Illustration: JPL-Caltech/NASA 16 Jun 2015

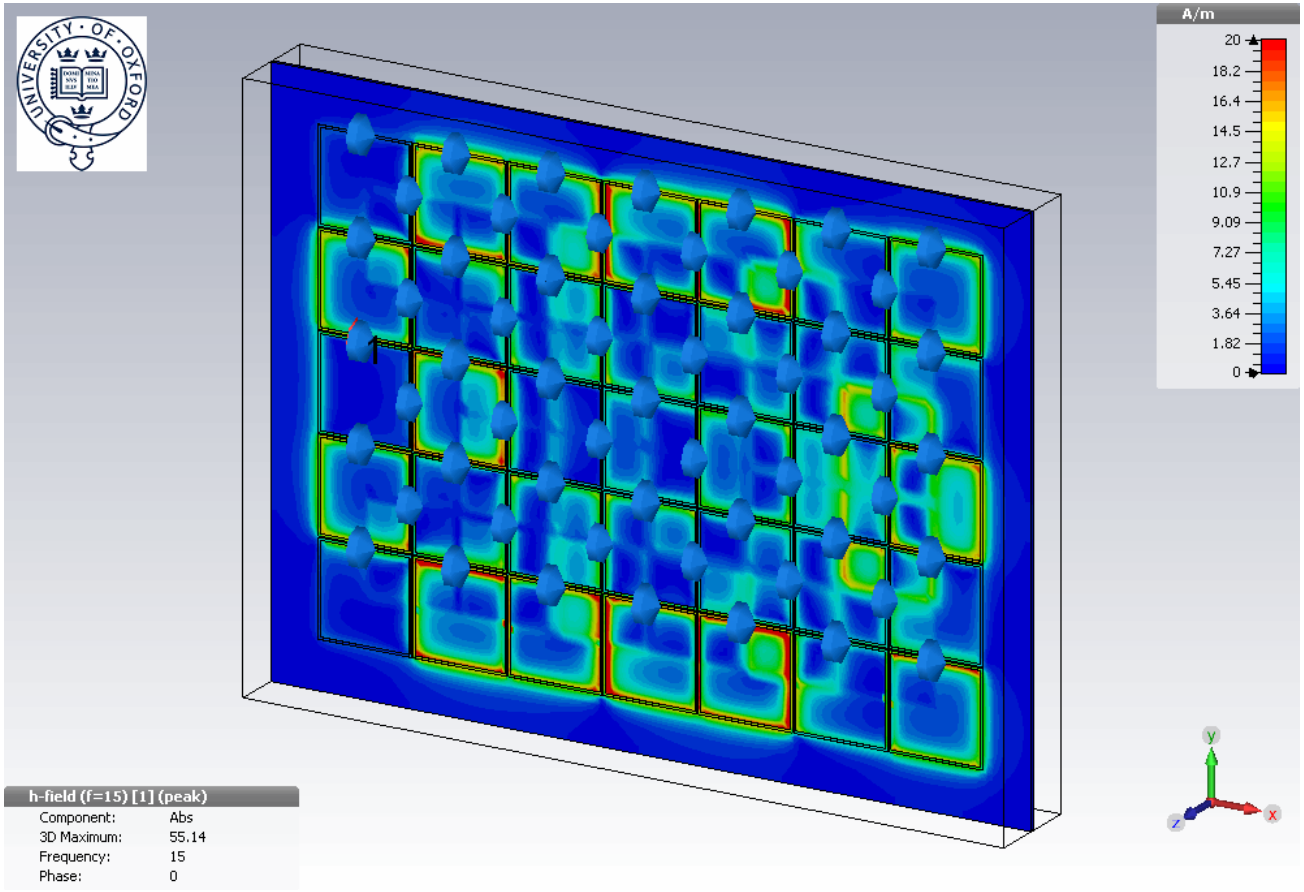
Google's Project Soli to bring gesture control to wearables

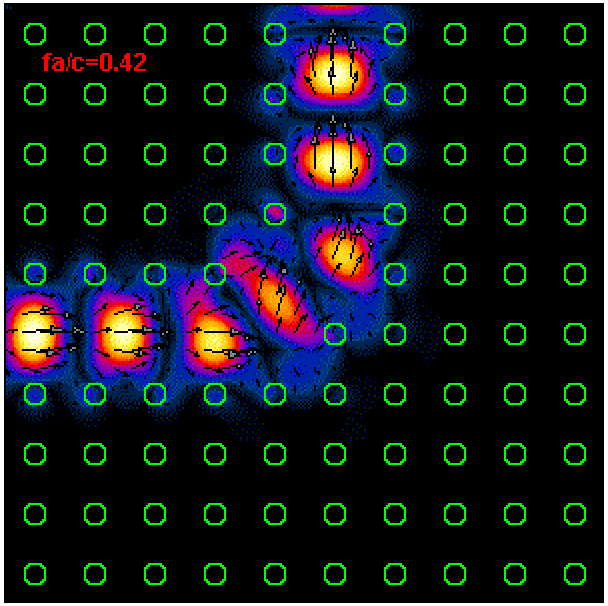


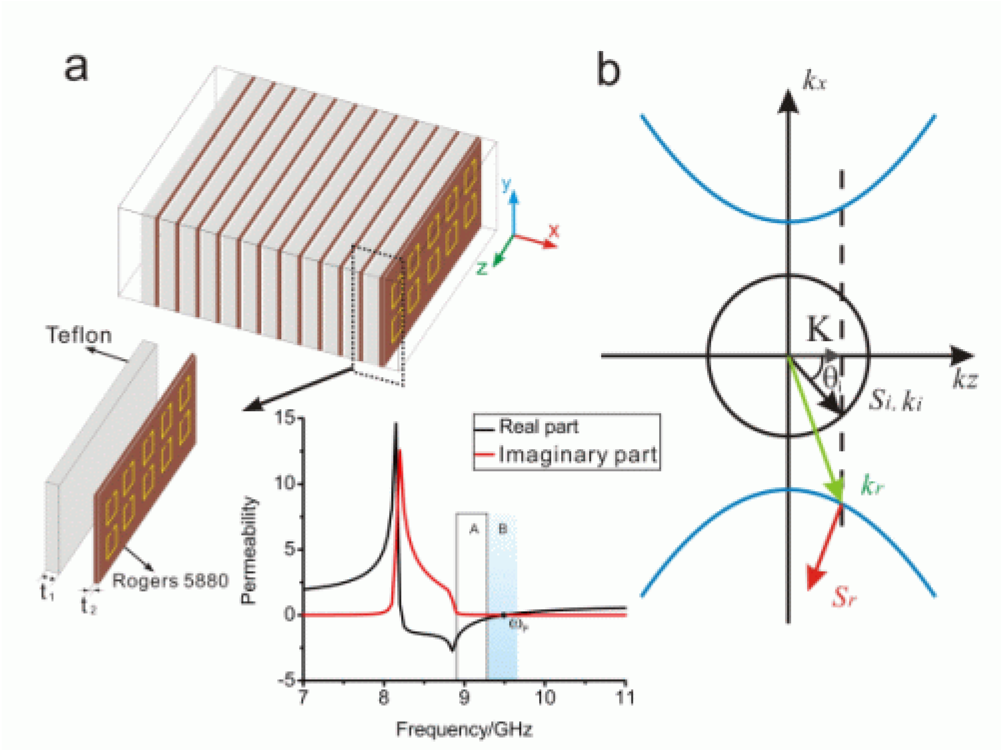


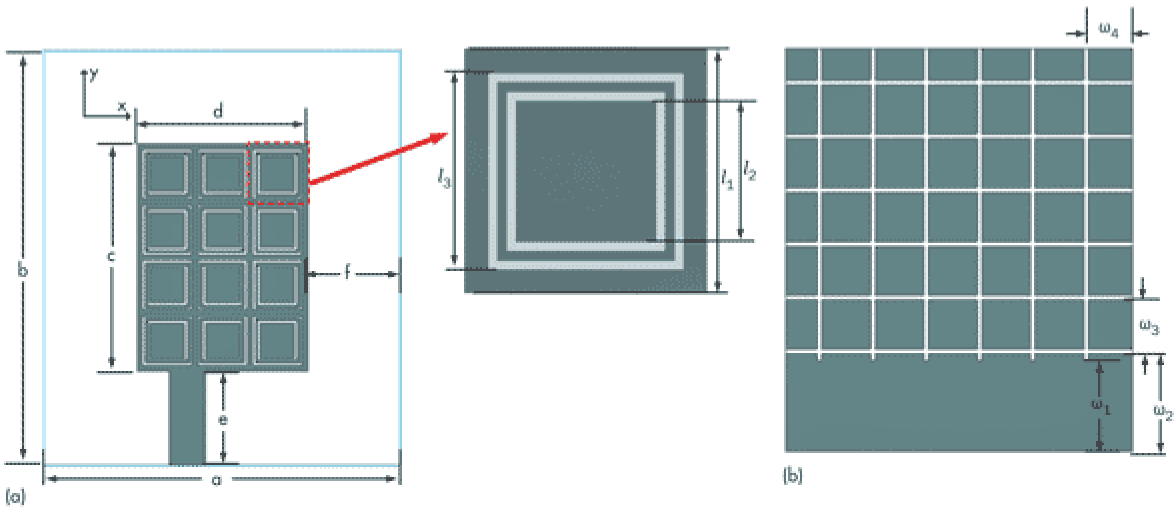


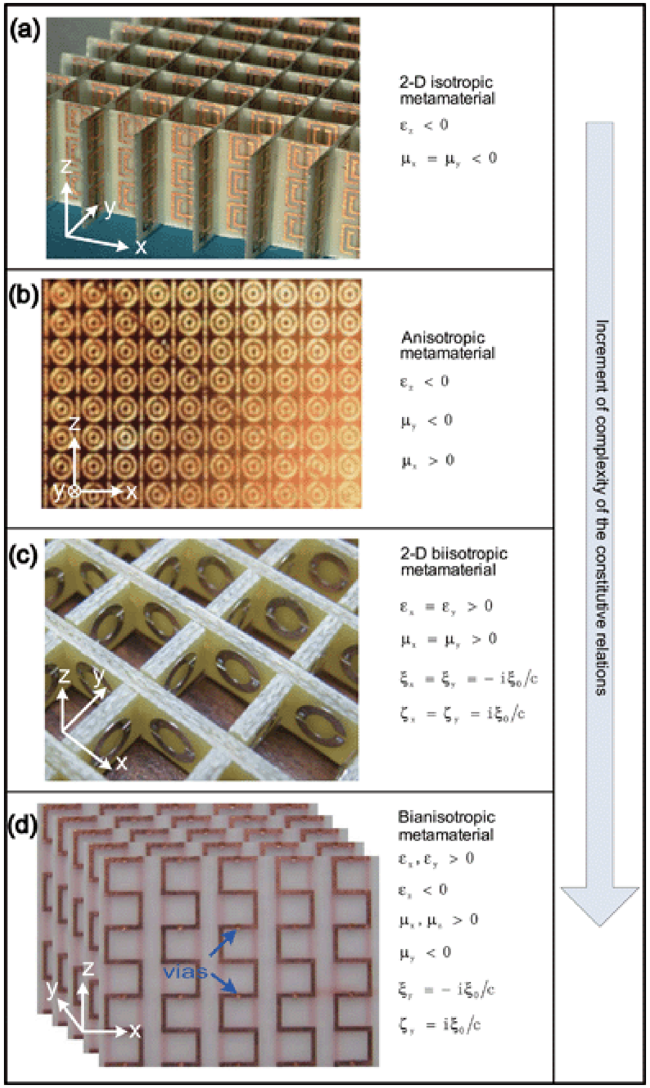


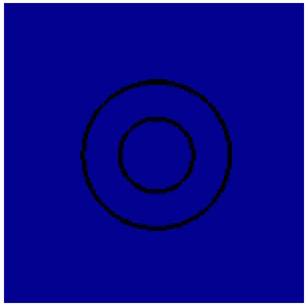

A/m
20
18.2
16.4
14.5
12.7
10.9
9.09
7.27
5.45
3.64
1.82
0
h-field (f=15) [1] (peak)
Component: Abs
3D Maximum: 55.14
Frequency: 15
Phase: 0
y
z
x

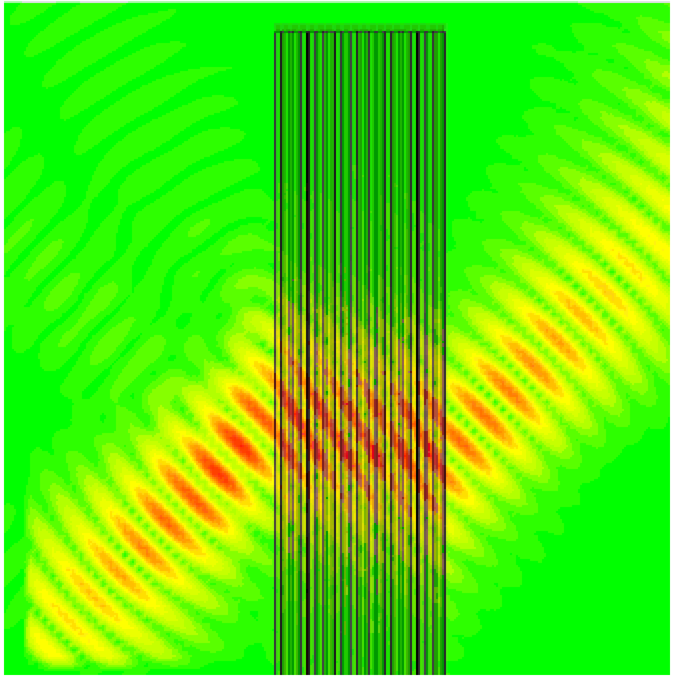

fa/c=0.42

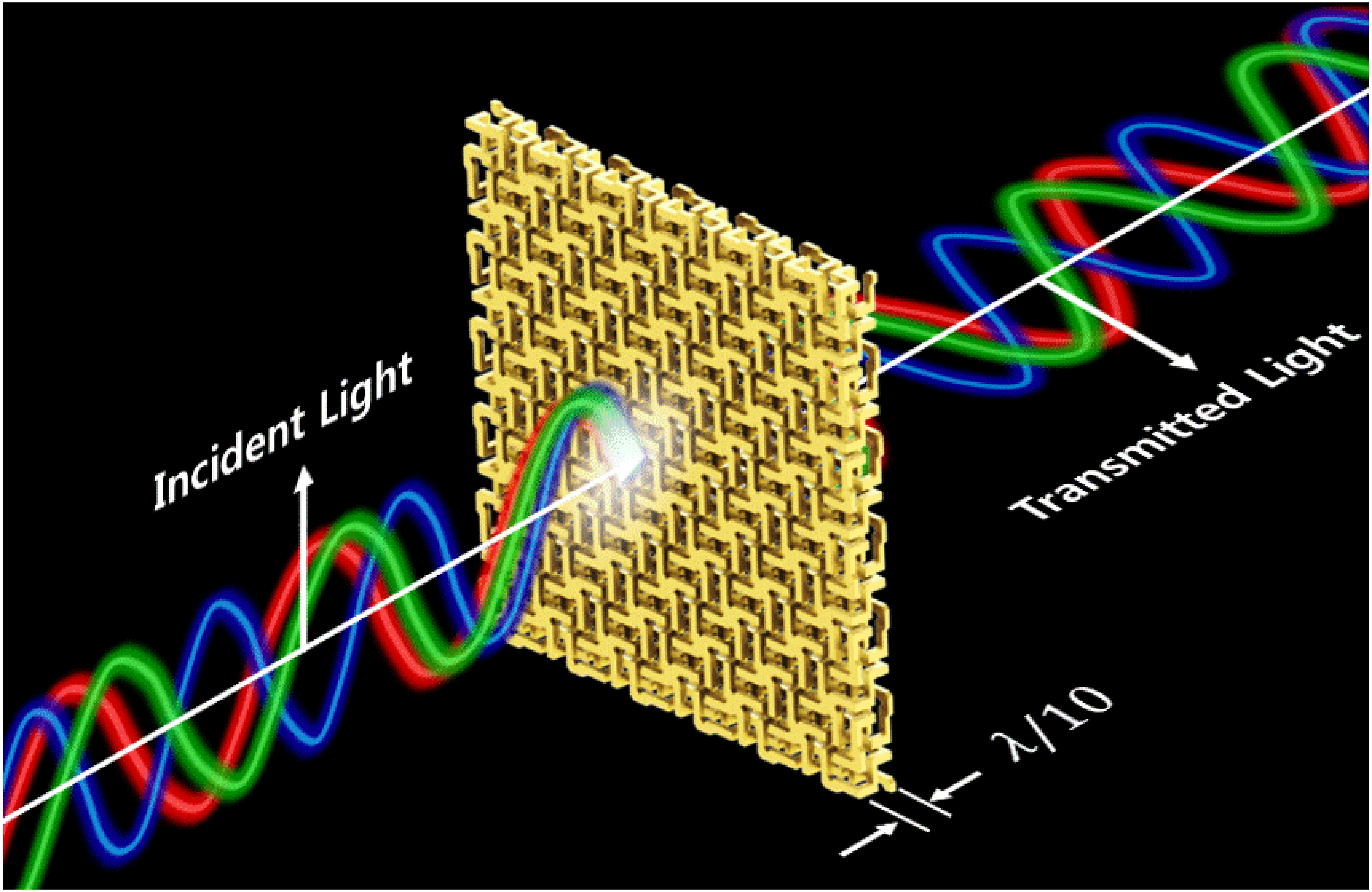

a
b
Teflon
Rogers 5880
t_1
t_2
y
x
z
Real part
Imaginary part
A
B
Permeability
Frequency/GHz
ω_p
kx
kz
K
θ
S_i, k_i
k_r
S_r

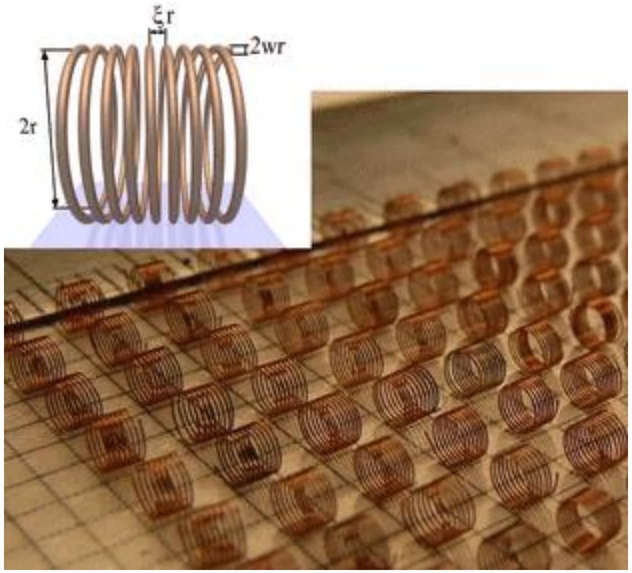

y
x
d
b
c
f
e
a
(a)
l_3
l_1
l_2
ω_4
ω_3
ω_1
ω_2
(b)


(a)
2-D isotropic metamaterial
$\varepsilon_z < 0$
$\mu_x = \mu_y < 0$
(b)
Anisotropic metamaterial
$\varepsilon_z < 0$
$\mu_y < 0$
$\mu_x > 0$
(c)
2-D biisotropic metamaterial
$\varepsilon_x = \varepsilon_y > 0$
$\mu_x = \mu_y > 0$
$\xi_x = \xi_y = -i\xi_0/c$
$\zeta_x = \zeta_y = i\xi_0/c$
(d)
Bianisotropic metamaterial
$\varepsilon_x, \varepsilon_y > 0$
$\varepsilon_z < 0$
$\mu_x, \mu_z > 0$
$\mu_y < 0$
$\xi_y = -i\xi_0/c$
$\zeta_y = i\xi_0/c$
vias
Increment of complexity of the constitutive relations



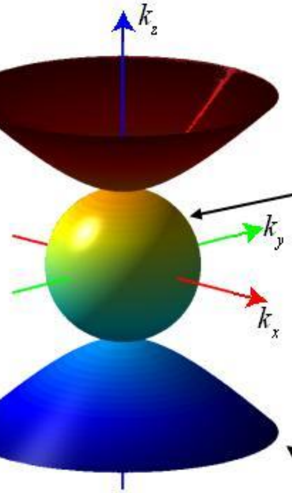



Incident Light
Transmitted Light
λ/10


ξr
2wr
2r

Hyperbolic Metamaterials (HMMs)

A metamaterial has hyperbolic dispersion relation



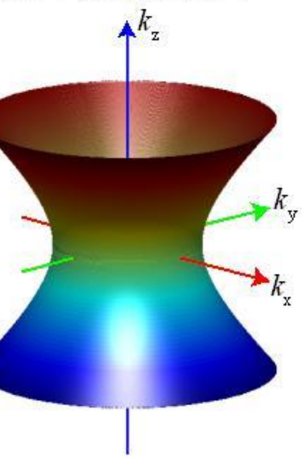
normal dispersion

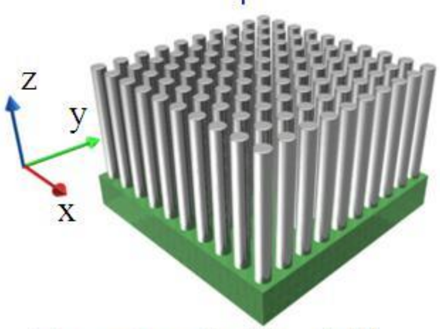
$$\frac{k_x^2 + k_y^2 + k_z^2}{\varepsilon} = \left(\frac{\omega}{c}\right)^2$$

hyperbolic dispersion

$$\frac{k_x^2 + k_y^2}{\varepsilon_{\parallel}} - \frac{k_z^2}{|\varepsilon_{\perp}|} = \left(\frac{\omega}{c}\right)^2$$

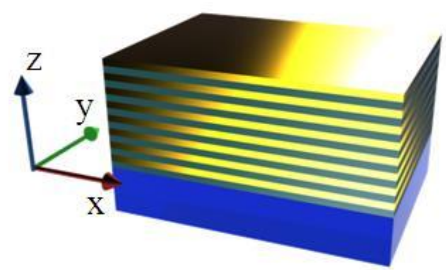
$$-\frac{k_x^2 + k_y^2}{|\varepsilon_{\parallel}|} + \frac{k_z^2}{\varepsilon_{\perp}} = \left(\frac{\omega}{c}\right)^2$$



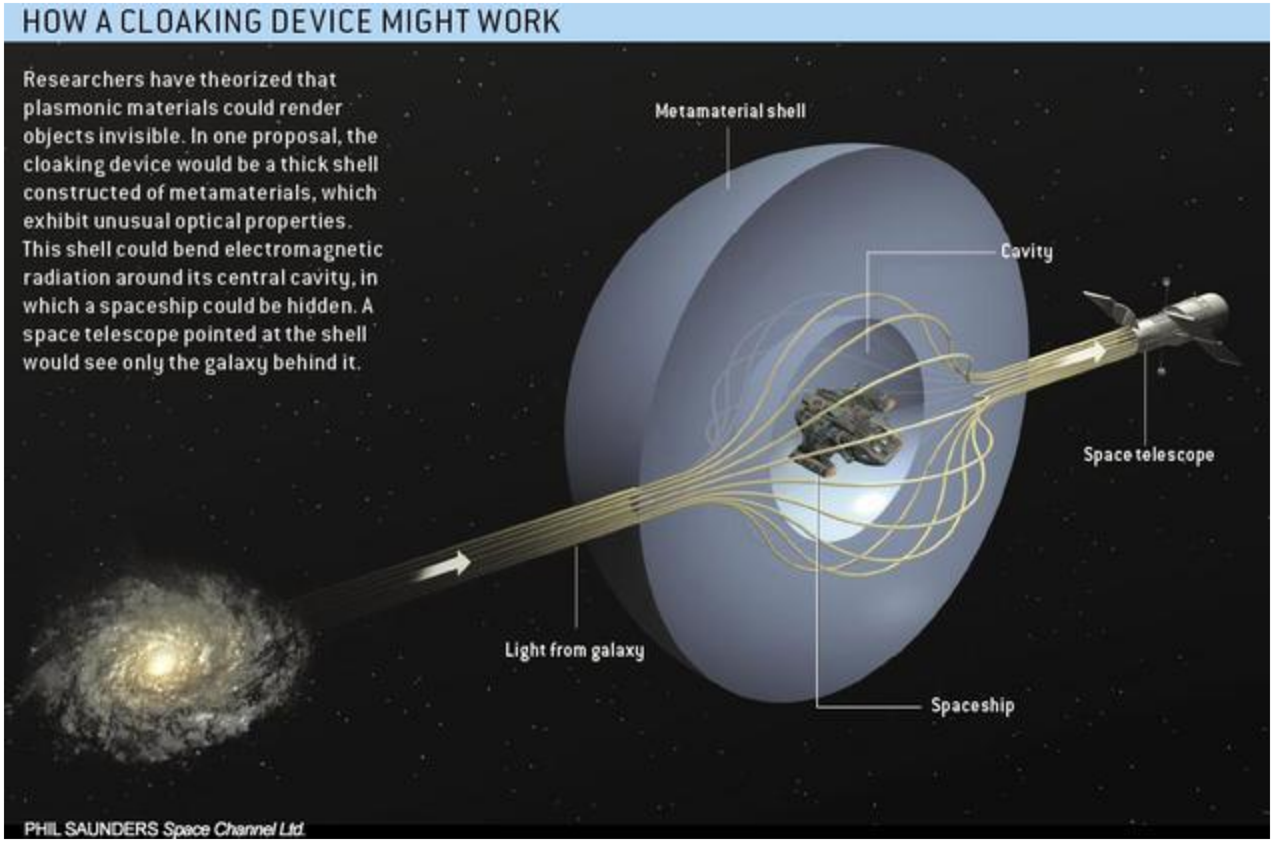


Transverse Positive (TP)

Jacob, et al., Opt. Express, 2006



Transverse Negative (TN)

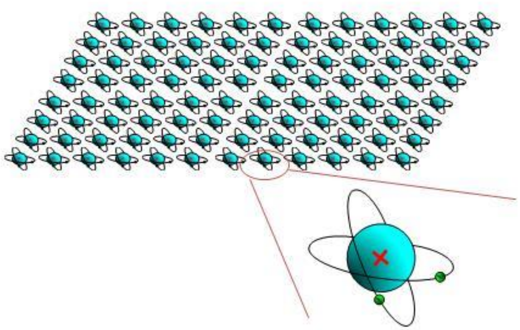

HOW A CLOAKING DEVICE MIGHT WORK
Researchers have theorized that plasmonic materials could render objects invisible. In one proposal, the cloaking device would be a thick shell constructed of metamaterials, which exhibit unusual optical properties. This shell could bend electromagnetic radiation around its central cavity, in which a spaceship could be hidden. A space telescope pointed at the shell would see only the galaxy behind it.
Metamaterial shell
Cavity
Space telescope
Light from galaxy
Spaceship
PHIL SAUNDERS Space Channel Ltd.


UNIVERSITY of
ROCHESTER

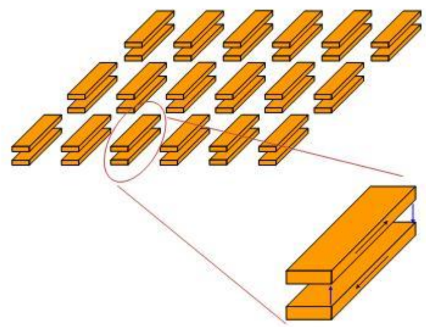
What is a metamaterial?

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

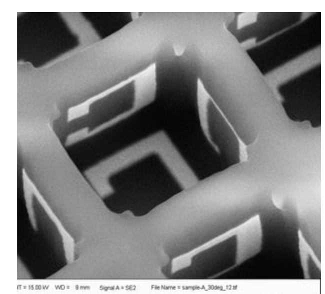
$\mu\varepsilon\tau\alpha$ = meta = beyond (Greek)

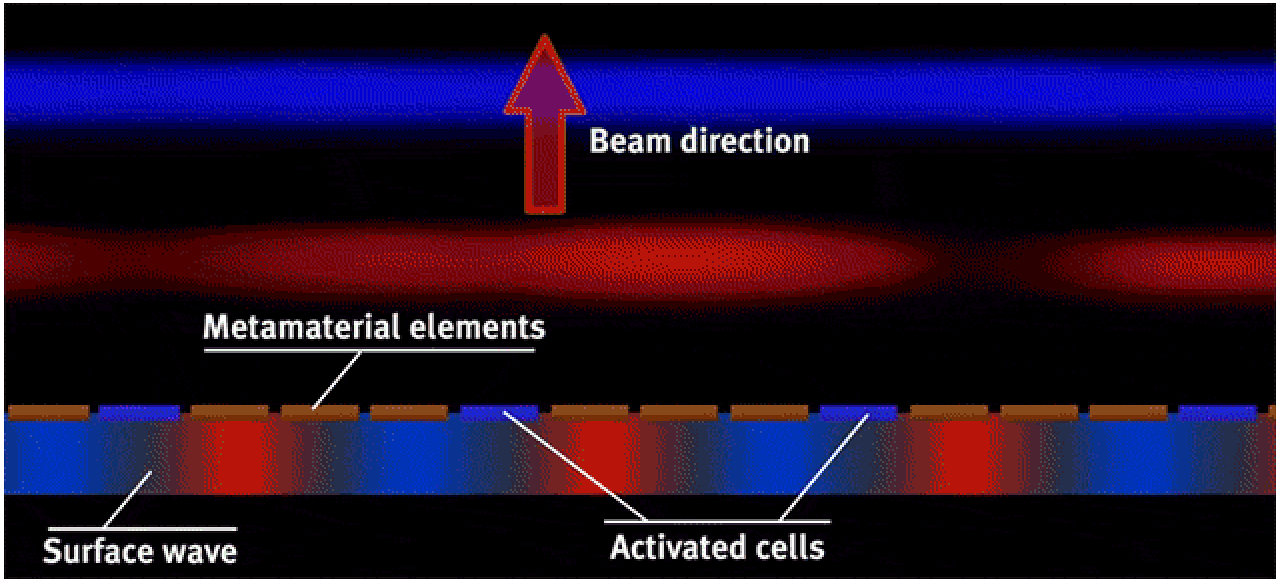


A natural material with its atoms

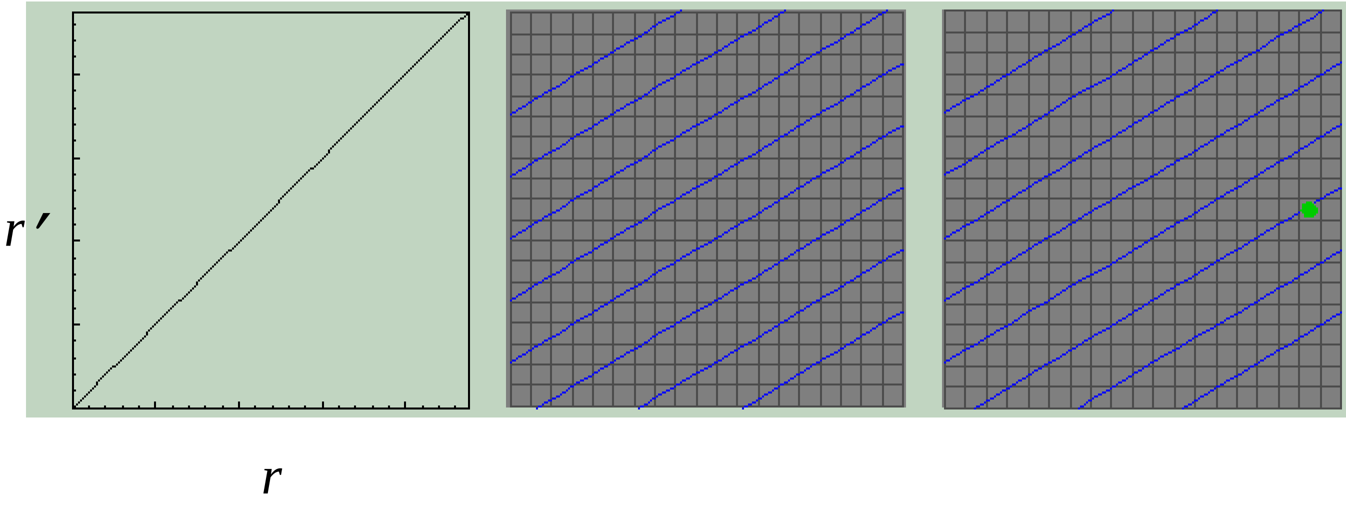


A metamaterial with artificially structured "atoms"

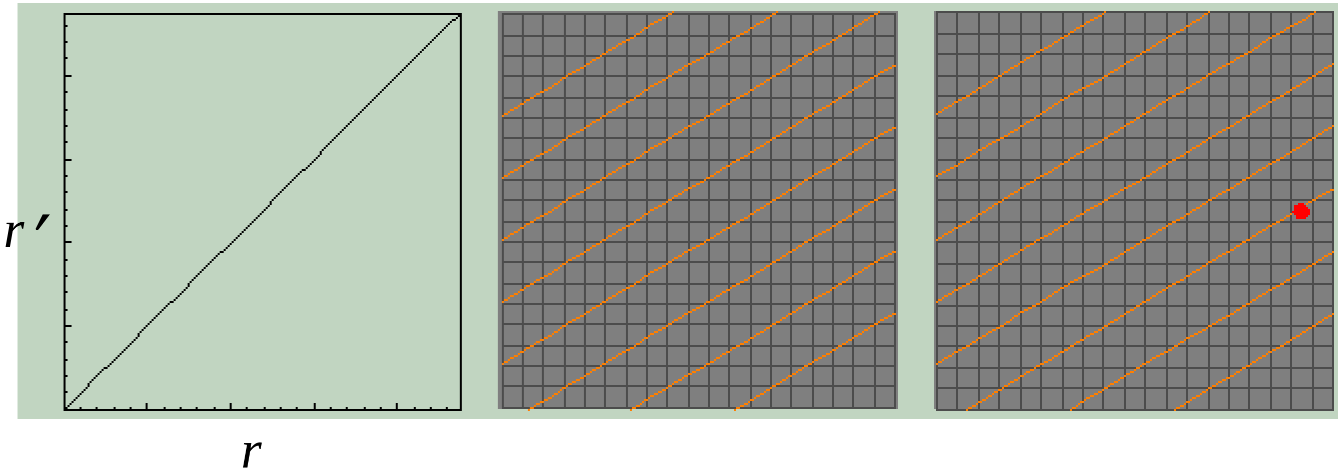



Beam direction
Metamaterial elements
Surface wave
Activated cells

Metamaterial-Invisibility Dynamics

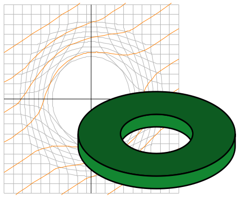


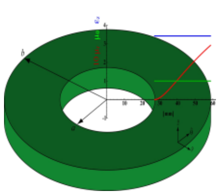
$$\begin{pmatrix} 1.00 & 0.00 & 0.00 \\ 0.00 & 1.00 & 0.00 \\ 0.00 & 0.00 & 1.00 \end{pmatrix}$$

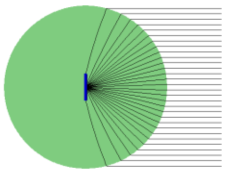


$$\begin{pmatrix} 1.00 & 0.00 & 0.00 \\ 0.00 & 1.00 & 0.00 \\ 0.00 & 0.00 & 1.00 \end{pmatrix}$$

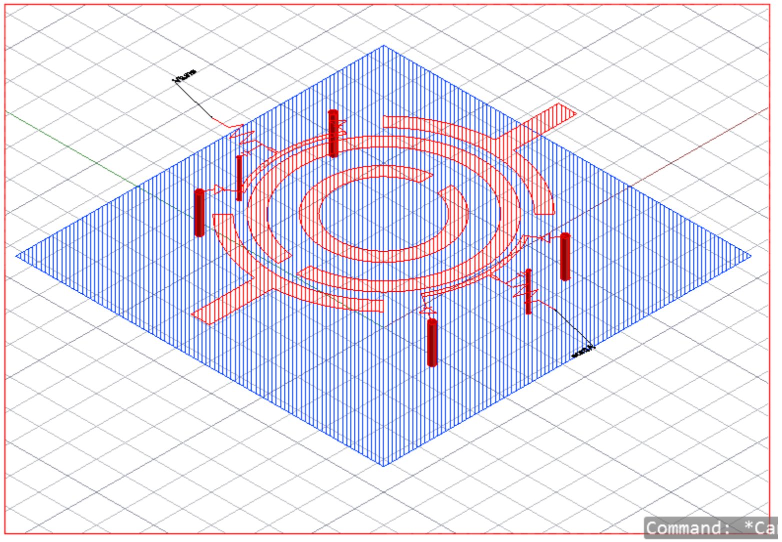
Cloaking

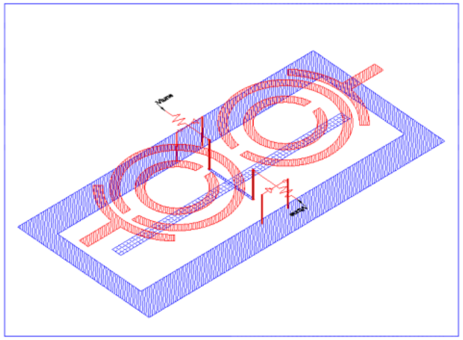


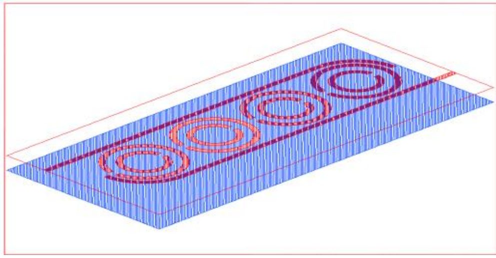


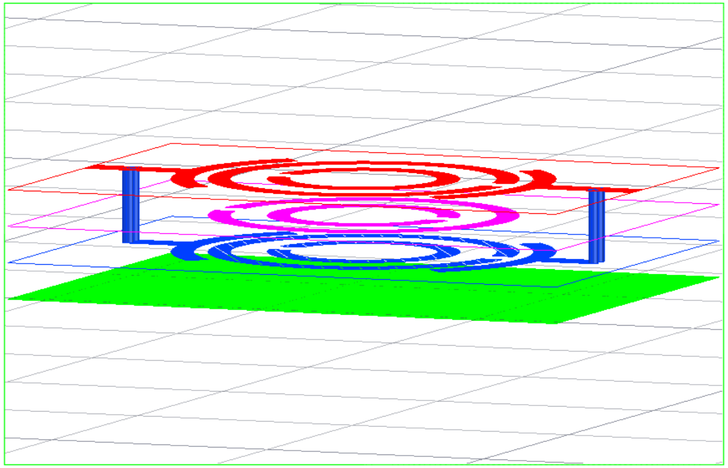


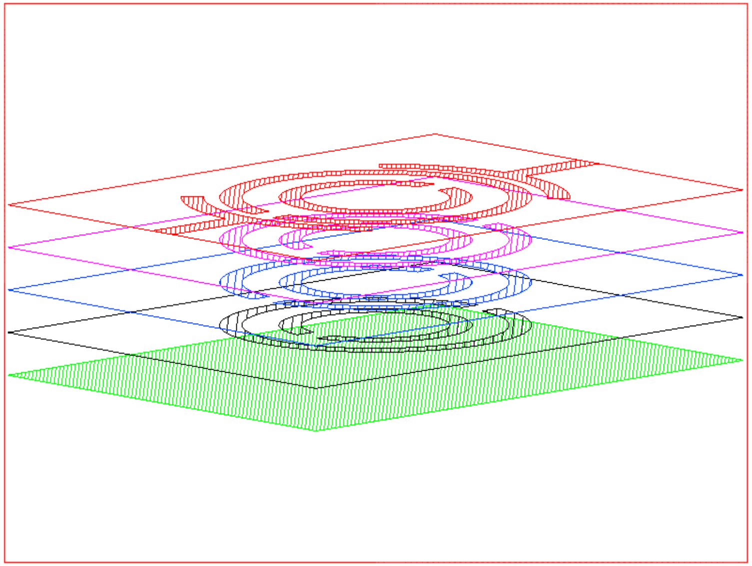
With Ground plane: These figures are not to scale.





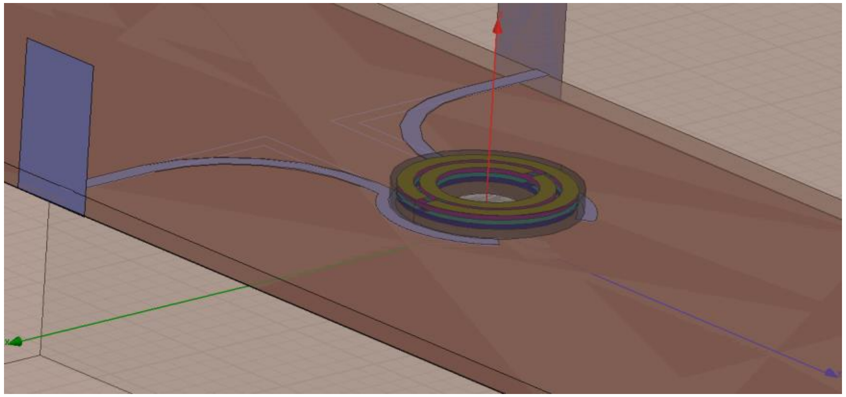


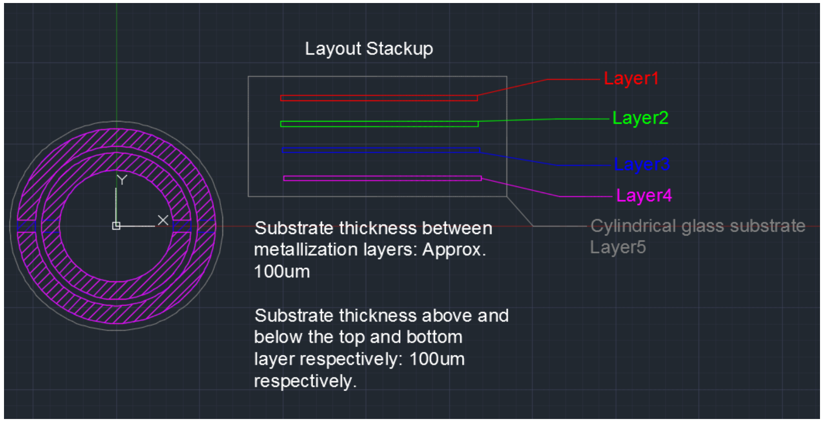


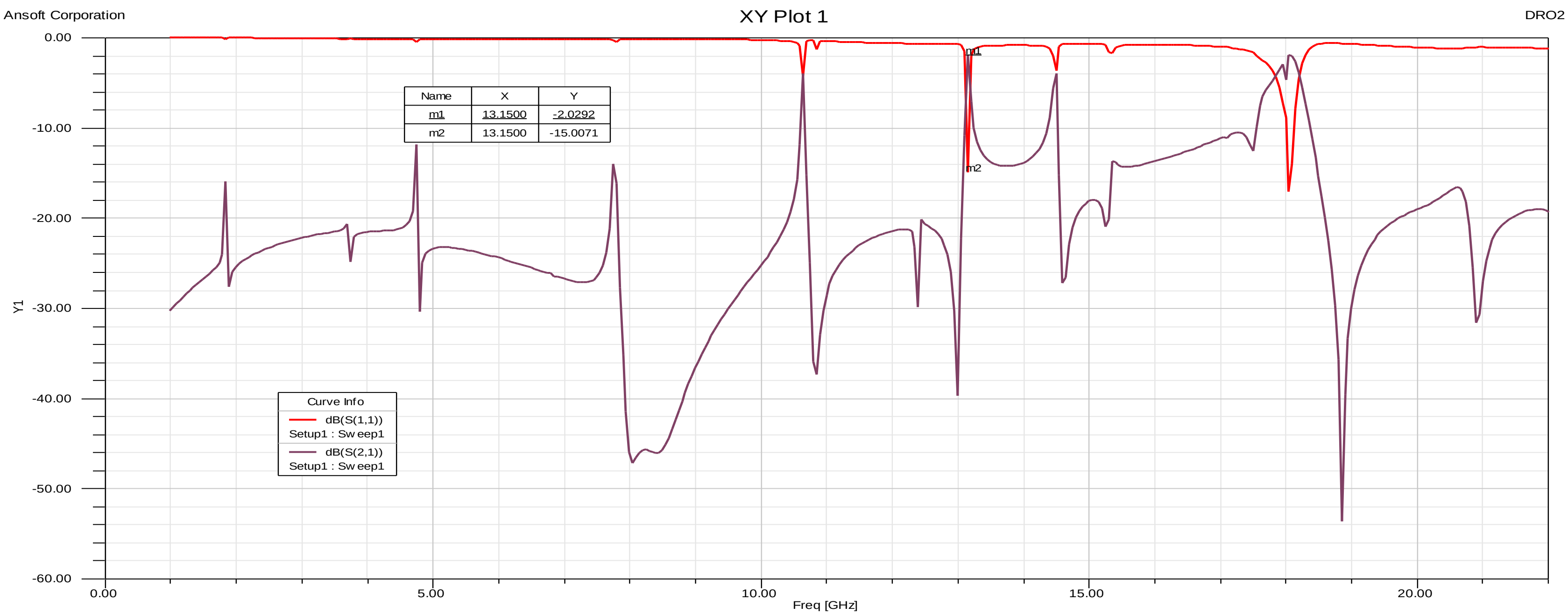


Without Ground plane

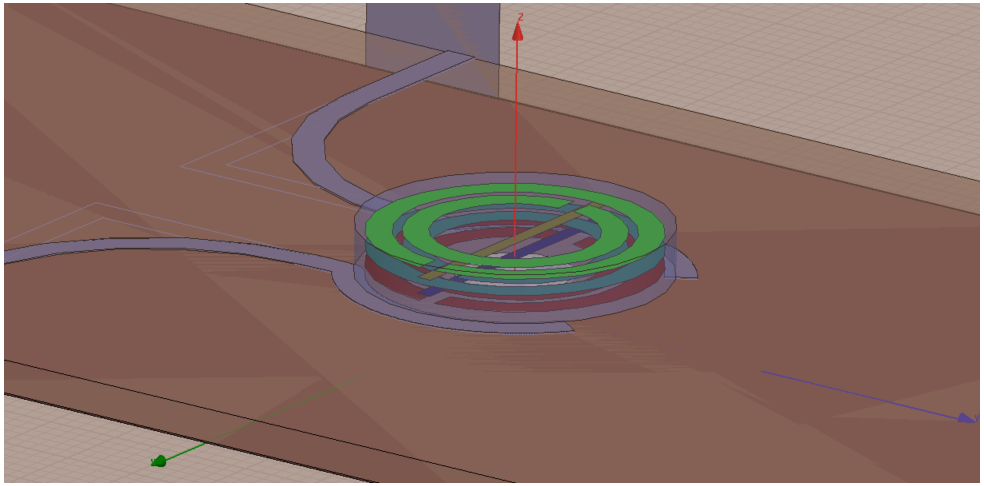
SRR_DRO

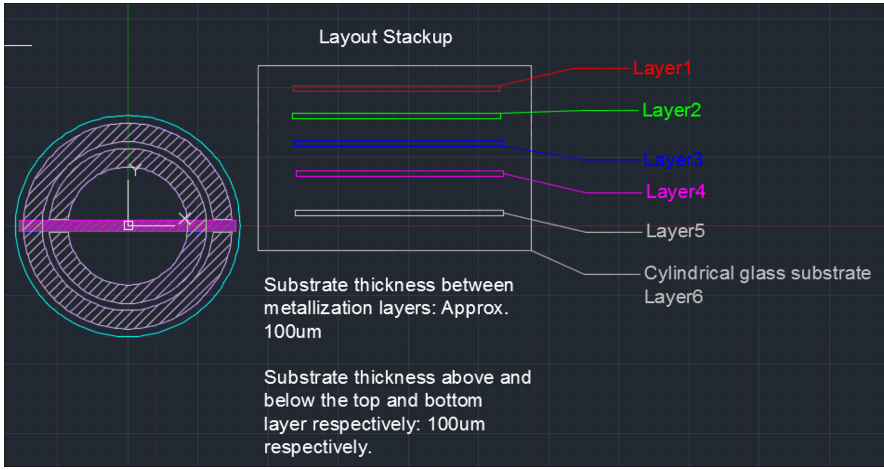


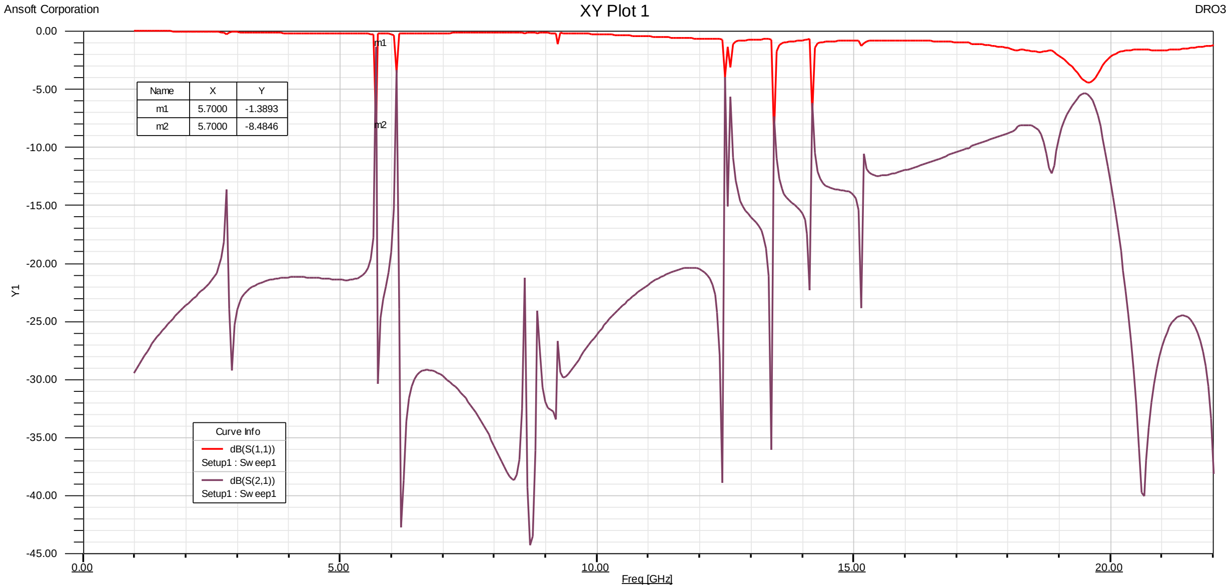




SRR_DRO_wmstrip







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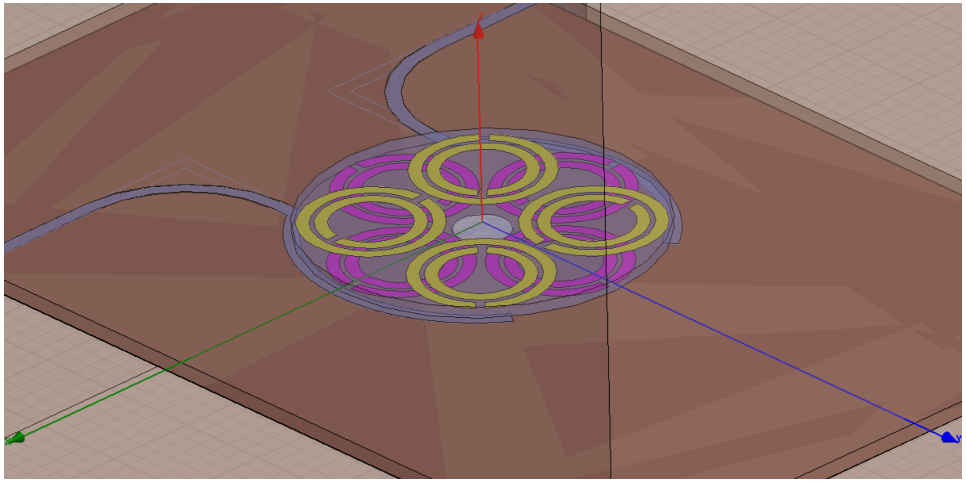

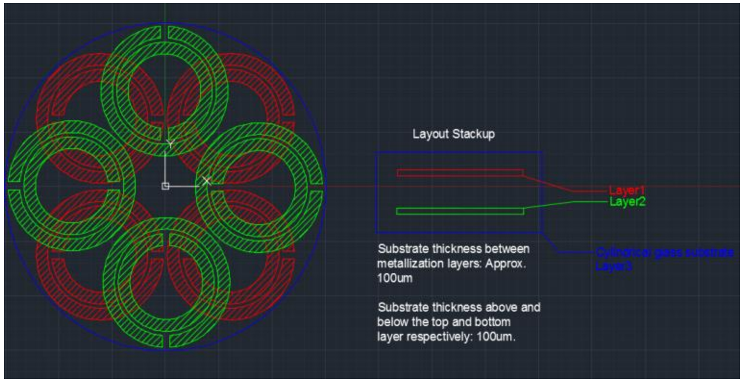

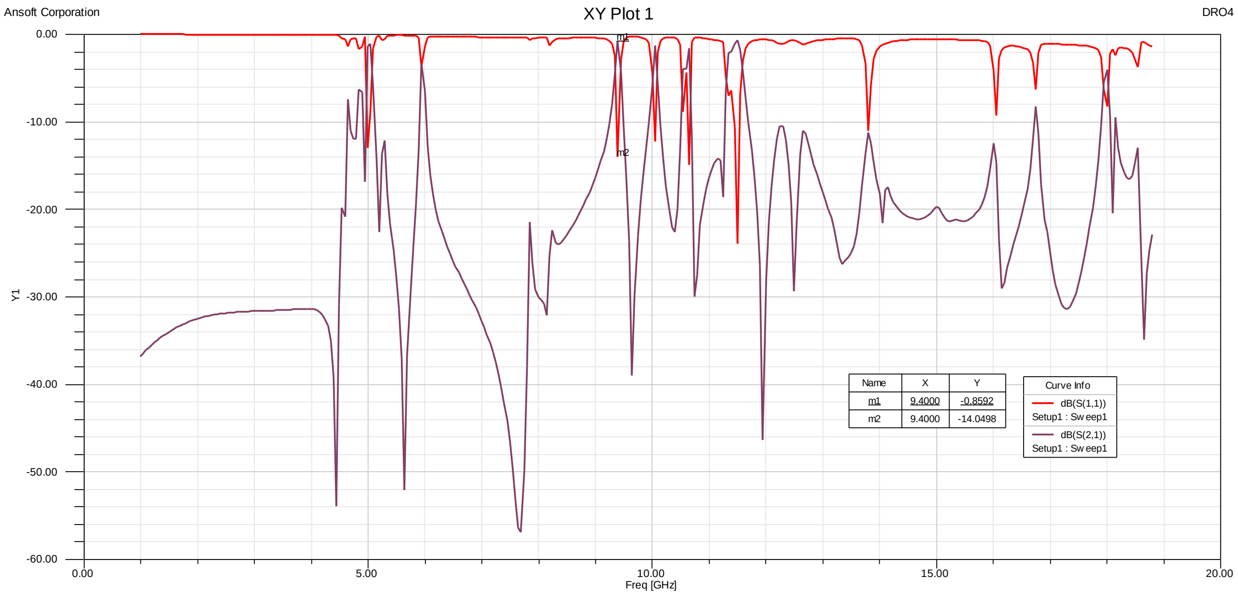

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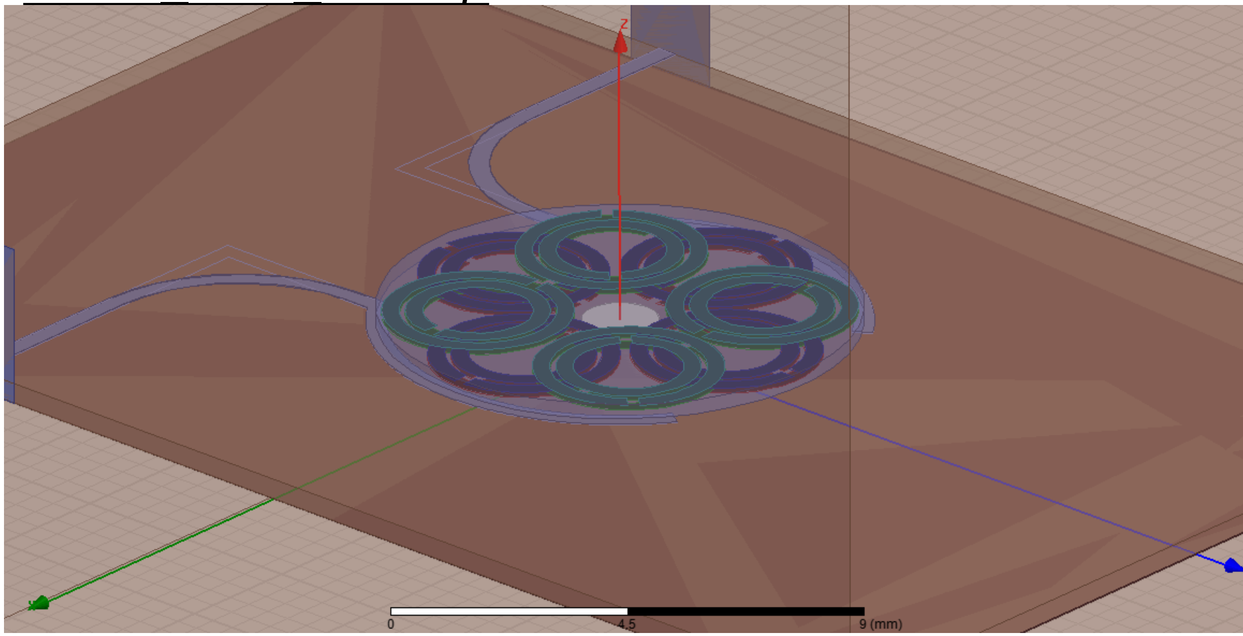

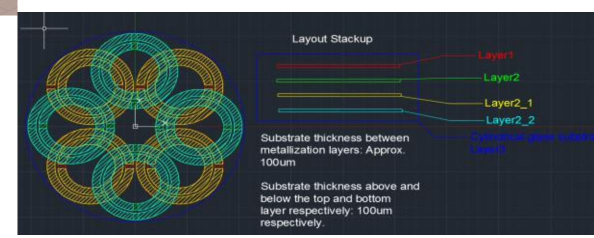

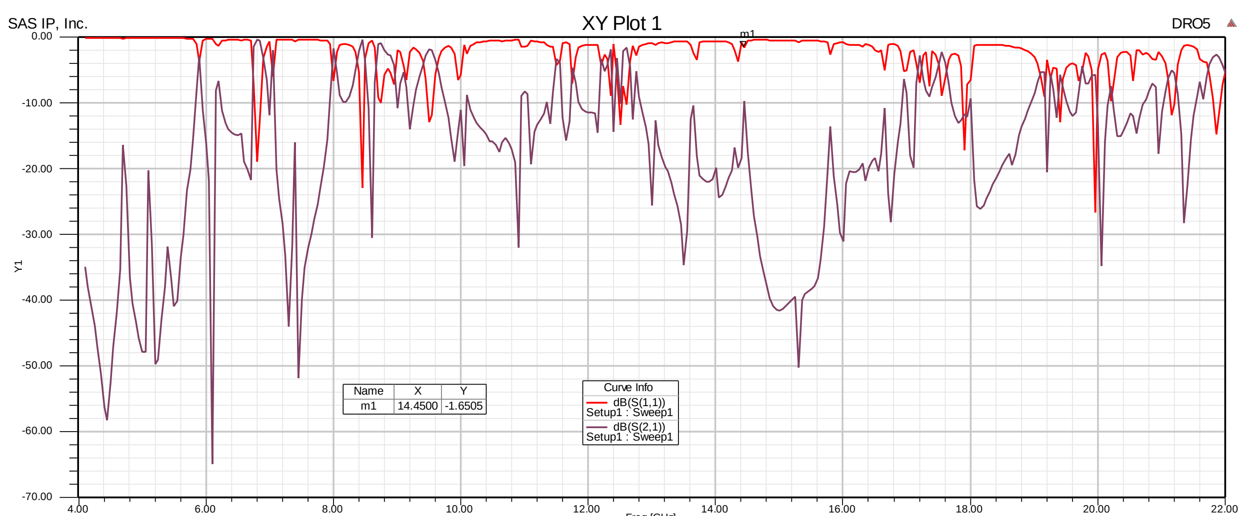

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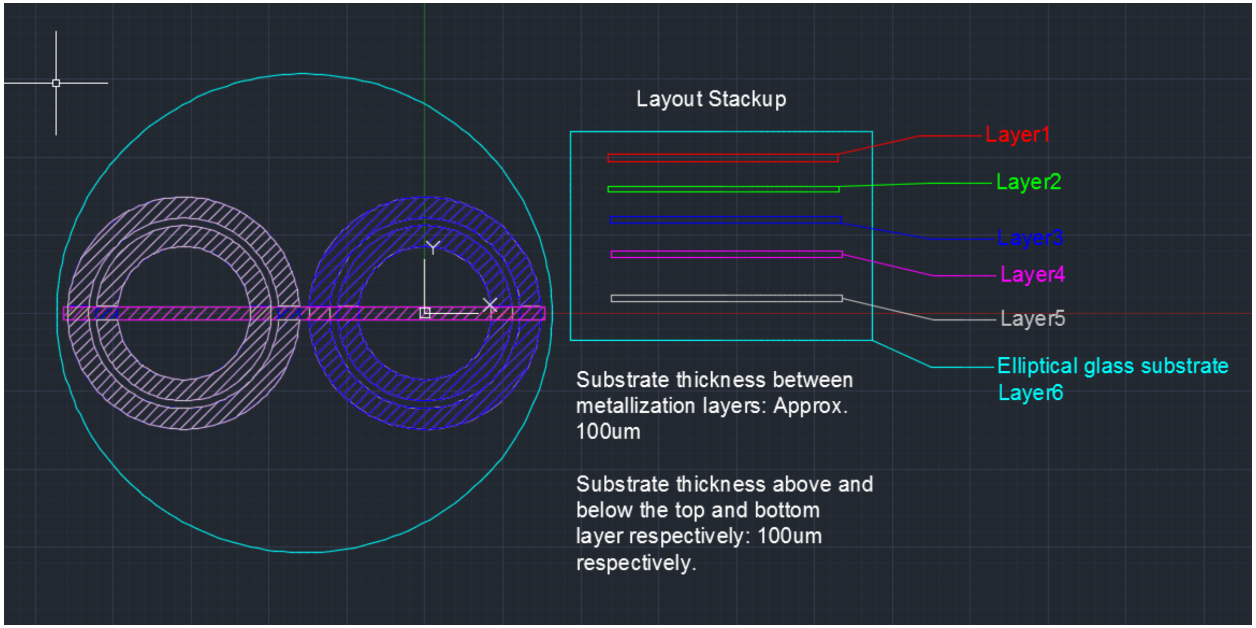

SRR_DRO_w_perpendicular_mstrip