جہانِ تازہ کی افکارِ تازہ سے ہے نمود
کہ سنگ و خشت سے ہوتے نہیں جہاں پیدا
(اقبالؒ)

Meta/Flat-Optics: Enabling Novel Science and Applications

Dr. Muhammad Qasim Mehmood

Associate Professor & Chairperson: Department of Electrical Engineering,
Director: Innovative Systems & Solution Laboratories
Information Technology University of the Punjab (ITU), 54000 Lahore, Pakistan.

INFORMATION TECHNOLOGY UNIVERSITY

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WeChat: M_Qasim_Mehmood

www.itu.edu.pk

Myself

About Me

2011 – 2016
PhD Degree

Light Manipulation and Structuring Via Nanofabricated Flat Metasurfaces

2016 – Date
Assistant/Associate Professor

Research, Mentorship, Teaching, Curriculum Design & Outreach in Electronics & Photonics [Printed Electronics, Antenna & Microwave Engineering, Optics & Photonics]

INFORMATION TECHNOLOGY UNIVERSITY

2016 – Date
Director, IS&S Labs

Modelling & Design, Device & system-level Research & Innovations for Healthcare, Communication, Agriculture etc.

micronano

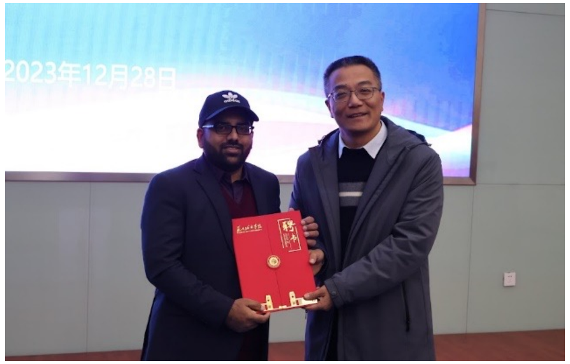
http://micronano.itu.edu.pk/

ICO-ICTP Gallieno Denardo Award Golden Book

ICTP
MICRO2019 FELLOWSHIP

SUZHOU CITY UNIVERSITY
INFORMATION TECHNOLOGY UNIVERSITY OF THE PUNJAB

SZCU - ITU
BIO-PHOTONICS RESEARCH CENTRE



Associate Editorships
Optics EXPRESS
IEEE Photonics Journal
Emerging Leaders, 2024

IEEE APS/CAS/MTT/SSC Joint Chapter Lahore Section

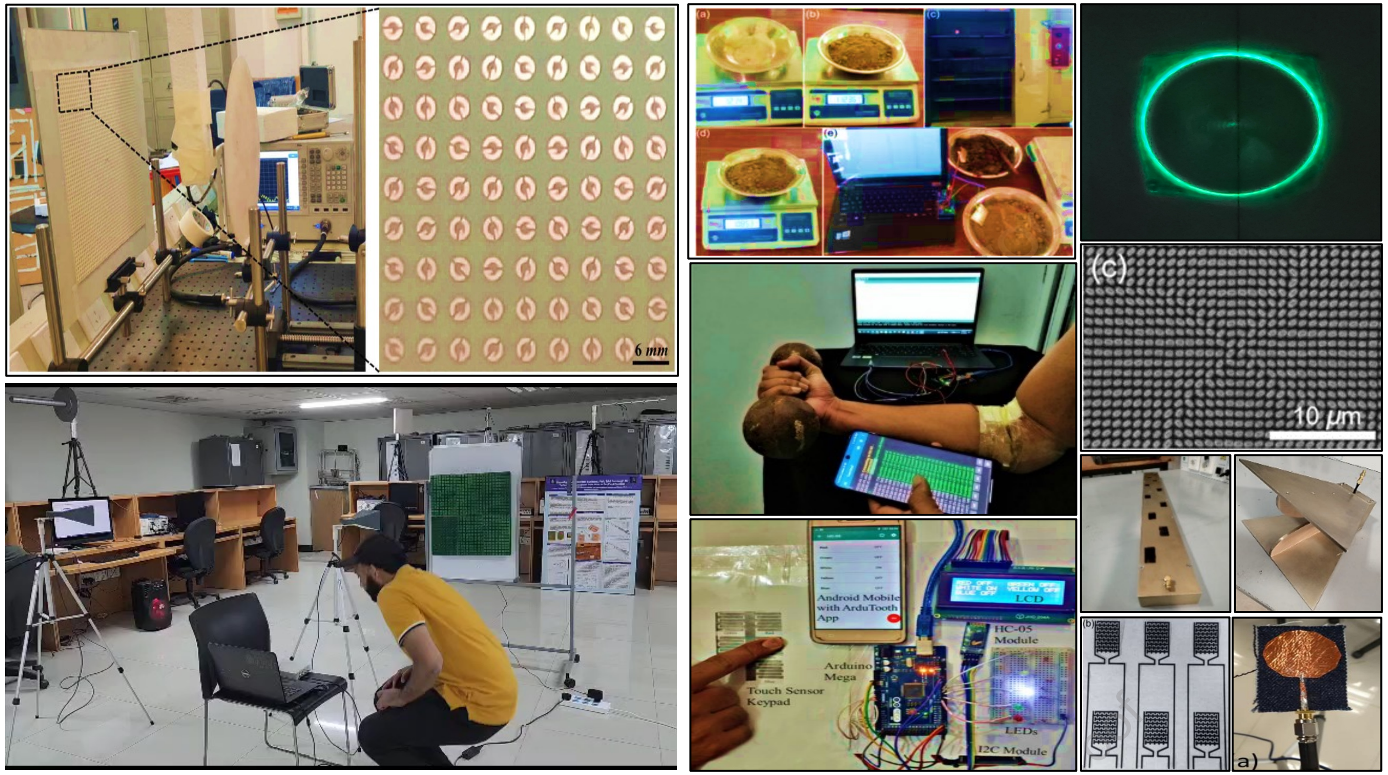
OPTICA & SPIE STUDENT CHAPTERS
INFORMATION TECHNOLOGY UNIVERSITY OF THE PUNJAB

IS&S Labs

INFORMATION TECHNOLOGY
UNIVERSITY OF THE PUNJAB

Innovative Systems & Solutions Labs @ ITU

1) Strategic Organizations: Customized Designs in RF & MW
2) Healthcare: Optical System Design & Bio-imaging
3) Education: Portable Smart STEM Solutions, Training Materials, Policy Frameworks
4) Flexible & Printed Sensors



IS&S Labs

INFORMATION TECHNOLOGY UNIVERSITY OF THE PUNJAB

Fabless Ecosystem: Capabilities to Outsourcing

Existing Capabilities	Hybridization	Outsourcing
PROVEN HISTORY OF RUNNING FABLESS ECOSYSTEM	CHARACTERIZATION & TESTING	FABRICATION
TRAINED HUMAN RESOUCRE ON DESIGN	DEVICE & SYSTEM-LEVEL PROTOTYPING	INDUSTRIAL LINKAGES
COMPUTATIONAL RESOURCES	COMMERCIAL DESING TOOLS	TECHNOLOGY READINESS

Optics & It's Impact

Teaching & Training Plan (Lectures & Lab Sessions)

Team

Lectures

Flat optics: Enabling Novel Science & Applications

Dr. Muhammad Qasim Mehmood
Chairperson Electrical Engineering Dept. & Director of Micronano Lab,
Information Technology of the Punjab, Pakistan

Computational EM & Photonics: Conventional solvers to fractional Formulations

Dr. Muhammad Zubair
Associate Professor,
Information Technology of the Punjab, Pakistan

AI-Driven Biomedical imaging for Smart Diagnostics

Dr. Waqas Sultani
Associate Professor,
Information Technology of the Punjab, Pakistan

Team

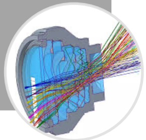
Laboratory Sessions on Modelling & Design

- Essentials of system level packaging for optical devices

CAD

- Open-source Ray Tracing Optimization for Conventional Optics

Ray tracing (Part-I)



- Open-source Ray Tracing Optimization for Meta-Optics

EM Solvers

- Design & Optimization of Meta-Optical Devices Through Computational Solvers

Ray tracing (Part-I)

- Design & Optimization of Meta-Optical Devices Through AI

Meta-Mogus

- Artificial Intelligence For Disease Diagnosis

Biomedical Imaging

MicroNano Team @ ITU-Pak

Optics & It's Impact

Optics: its Impact, Markets & Technologies

Optics & it's Market Impact

- **Optics:** is the **branch of physics** that **studies light and its behaviors**.
- **Optics Markets:** There are many **applications** of optical systems integrated within different fields of study such as **medical, materials & manufacturing, and communications applications**.

Aeronautics

Optics and photonics are paying an increasing role in aircraft and aviation.

Agrifood

Photonics is becoming a major player in the agri-food industry contributing to more efficient, sustainable, and safer food production, and to enable smart farming.

AR/VR

Improvements in display design and development are enhancing augmented and virtual reality systems, providing increased capabilities across the retail market.

Automotive

Photonics technologies are a source of increasing innovation for both vehicle automation and production.

Beauty & Cosmetics

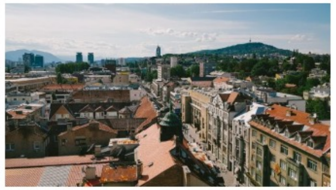
Thanks to the rapid development of laser and UV applications, light is now widely used for beauty and cosmetics applications.

Civil

Solid-state lighting (SSL) has civil applications like traffic lights, vehicle, street and parking lot lights, train marker lights, building exteriors or remote controls.

Communication

Global internet traffic is growing exponentially, and increasing fast, secure broadband connectivity is now a top priority for governments, industry, and providers of critical infrastructure.

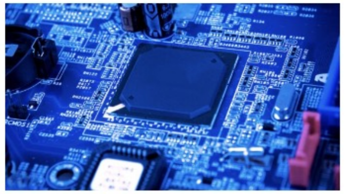


Construction & Civil Engineering

The construction industry is a growing market for lighting and photonic sensing technologies to enable smart buildings and smart cities.

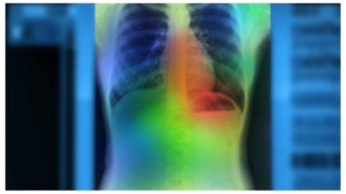
Display

Photonics-based displays are a critical enabling technology for the information age.



Electronic

Optoelectronic devices are used in a wide variety of application areas such as optical fiber communications, laser technology, and all kinds of optical metrology.



Healthcare

Optical technologies and photonics are playing a key role in non-invasive methods for the early detection, monitoring and improved treatment of cancer, diabetes, Alzheimer, and many other diseases.

Industrial

Photonic sensing technologies are increasingly used in the wind, oil & gas, nuclear and conventional power generation, and the chemical industries.

Optics & it's Market Impact

EPIC
EUROPEAN PHOTONICS INDUSTRY CONSORTIUM

- ***Optics:*** is the **branch of physics** that **studies light and its behaviors**.
- ***Optics Markets:*** There are many **applications** of optical systems integrated within different fields of study such as **medical, materials & manufacturing, and communications applications**.

Instrumentation

Instruments based on advanced photonics technology and devices are used in a wide area of applications.

Life Science

Photonics plays a major role in life science devices.

Lighting

While LEDs have been around for several years, they are beginning to be replaced by OLEDs (organic light emitting diodes), which provide improved colour fidelity, efficiency and operation stability and substantial energy savings.

Manufacturing

Photonics technologies are used extensively in advanced manufacturing to reduce costs and improve manufacturing processes.

Measurements

Optical metrology is used for fast, highly precise, non-contact measurements for a wide range of applications.

Medical

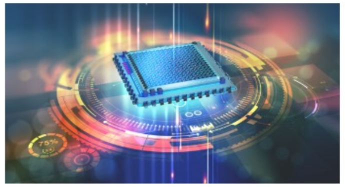
Optical technologies and photonics are increasingly used for treatment and early diagnosis as they are minimally invasive, reduce the length of hospital stay and reduce recovery times.

Ophthalmology

Nowadays, lasers and optics are indispensable tools for ophthalmologists.

Photovoltaic

Photonics is playing a crucial role in the next generation of more efficient and lower loss photovoltaic (PV) energy production and storage systems.



Quantum

Although most quantum applications are still over a decade away, the following segments provide some concrete opportunities for photonics.

Scientific

Government recognition of photonics as a key enabling technology is driving photonics research in academia and industry.

Security & Defence

Photonics and optics are playing key roles in sensing, communications and weapon systems for security and defence, as well as for Critical Infrastructure Protection due to the increase in use of unmanned vehicles that can be used as spy or attack devices.

Space

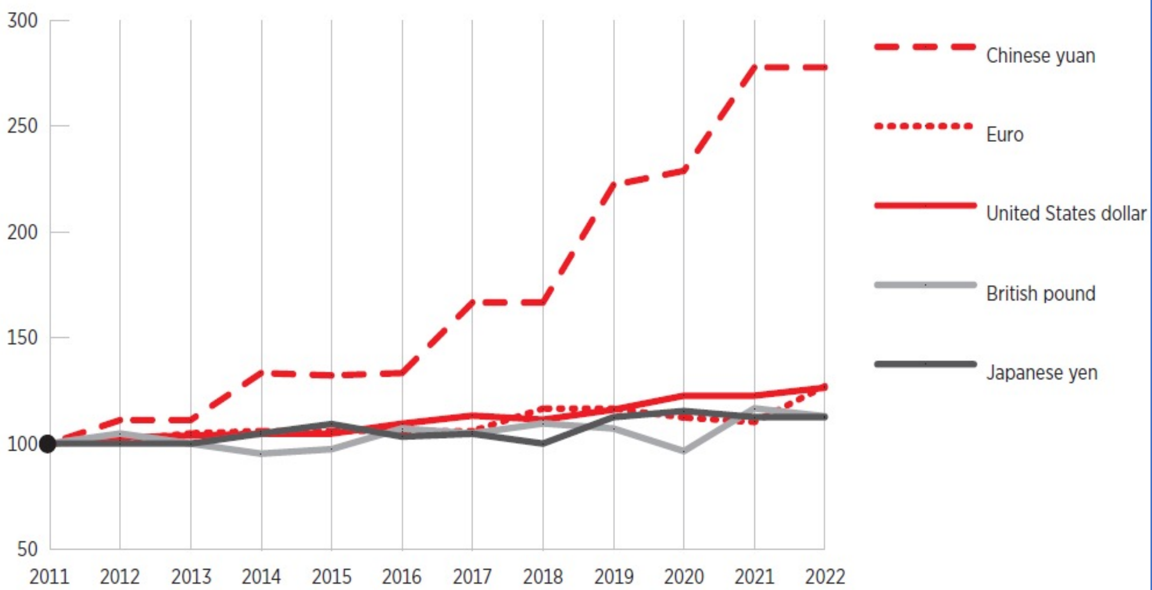
Photonics are making a big impact in space applications.

Career Potential in Optics

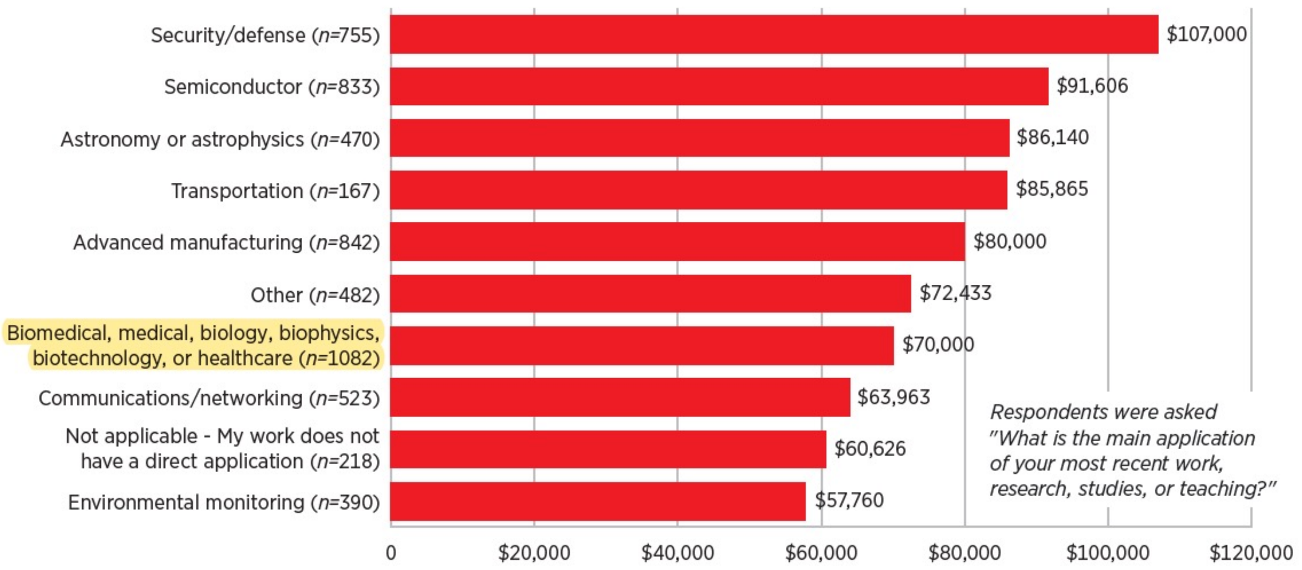
OPTICS & PHOTONICS GLOBAL SALARY REPORT 2023

SPIE. THE INTERNATIONAL SOCIETY FOR OPTICS AND PHOTONICS

"OPTICS IS AN AMAZING FIELD TO BE INVOLVED IN."



Change in median salaries, 2011-21, main currency groups



Median salary by application area

Career Potential in Optics

OPTICS & PHOTONICS GLOBAL SALARY REPORT 2023

SPIE. THE INTERNATIONAL SOCIETY FOR OPTICS AND PHOTONICS

"OPTICS HAS A GREAT FUTURE.
MAKE SURE YOU DON'T SHY AWAY FROM ASKING THINGS YOU DON'T KNOW."

Median salary by years employed and region

	Asia, Lower Income	Europe, Lower Income	Latin America & Caribbean	Middle East	Europe, Higher Income	Asia, Higher Income	North America
Less than one year	$7,651				$33,185	$40,477	$90,000
1-2 years	$6,680		$18,922	$6,396	$35,938	$42,608	$75,000
3-5 years	$11,173	$13,798	$15,652	$24,924	$51,826	$51,129	$100,000
6-10 years	$13,360	$25,000	$24,809	$45,302	$65,216	$58,585	$114,000
11-15 years	$17,610	$17,937	$26,634	$47,950	$69,443	$66,540	$129,000
16-20 years	$15,852	$13,074	$37,214	$61,351	$75,703	$68,172	$140,000
21-25 years	$21,188	$19,443	$37,084	$52,310	$81,520	$85,215	$160,000
26-30 years	$32,792	$20,696	$95,314	$60,038	$87,008	$95,867	$175,000
More than 30 years	$12,656	$14,487	$32,157	$108,350	$79,442	$85,215	$180,000

Blank cells result from sample size below 5 respondents. Gold numbers indicate sample size of 5-9.

Optics & It's Impact

EM Wave & It's Solution

Optical Constants of Materials

Refractive Index (Optical Constants: n &, k) of Materials:

- Refractive index is a **complex number**

$$\mathcal{N}^2 = (n + ik)^2 = \varepsilon_r \mu_r$$

- $n = c/v$. It quantifies the *Veclocity & Phase* of an EM wave through the medium.
- **Phase constant**: $\beta = \beta_0\, n = \frac{\omega}{c}\, n$, **Extinction Coefficient** $= k$, Absorption Coefficient: $\alpha = 2\beta_0 k = 2\frac{\omega}{c}k$
- Mathematically, there are **two solutions for the refractive index**

$$\mathcal{N} = n + ik = \pm\sqrt{\varepsilon_r \mu_r} = \pm\sqrt{(1 + \chi_e)(1 + \chi_m)}$$

Where, χ_e and χ_e are electric and magnetic susceptibilities

The **four possible sign combinations** in the pair (ε_r, μ_r) are $(+,+)$, $(+,-)$, $(-,+)$, and $(-,-)$.

Optical Constants of Materials

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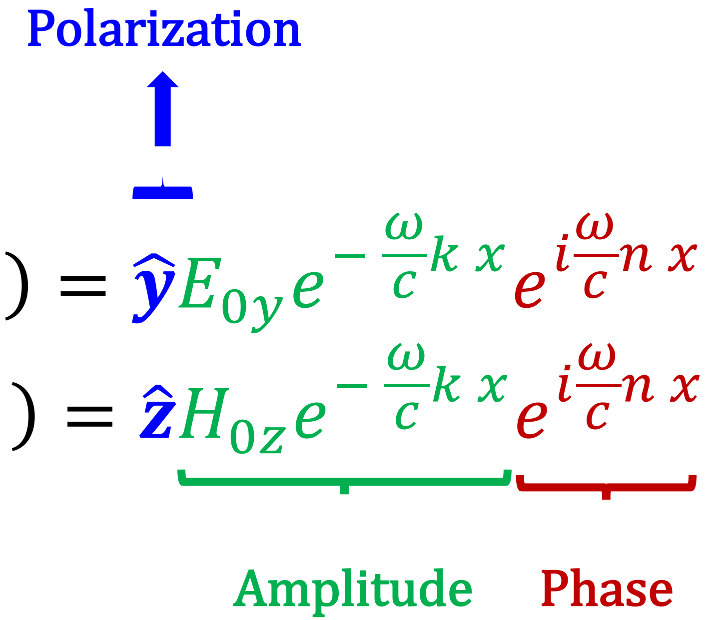
Relationship between $\mathcal{N}$ and permittivity & permeability:

- For now, we ignore the magnetic response

$$n + ik = \pm\sqrt{\varepsilon_r' + i\varepsilon_r''} \quad \Longrightarrow (n+ik)^2 = \varepsilon_r' + i\varepsilon_r'' \Longrightarrow (n^2 - k^2) + i2nk = \varepsilon_r' + i\varepsilon_r''$$

- Equating real and imaginary parts, we get

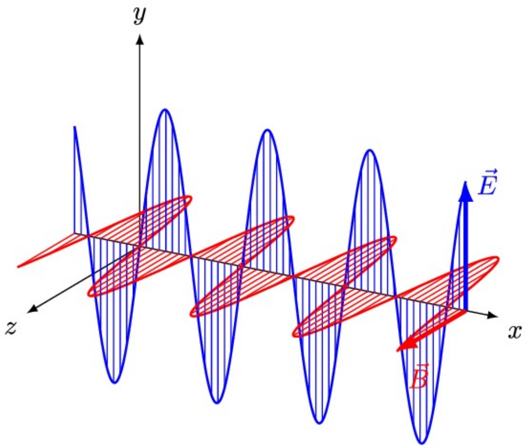
$$\varepsilon_r' = n^2 - k^2, \qquad \varepsilon_r'' = 2nk$$



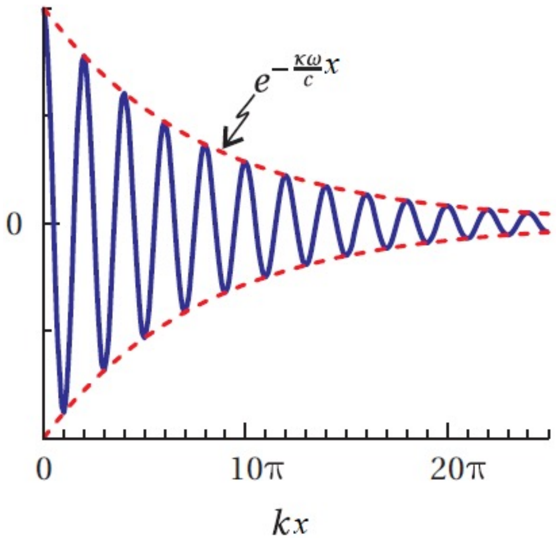
$$\boldsymbol{\mathcal{E}_y}(x,t) = \hat{\mathbf{y}} E_{0y} e^{-\frac{\omega}{c}k\,x} e^{i\frac{\omega}{c}n\,x} e^{-i\omega t}$$

$$\boldsymbol{H_z}(x,t) = \hat{\mathbf{z}} H_{0z} e^{-\frac{\omega}{c}k\,x} e^{i\frac{\omega}{c}n\,x} e^{-i\omega t}$$

For, $k = 0$



For, $k \neq 0$



Optical Constants of Materials

Refractive Index (Optical Constants: *n* &, *k*) of Materials:

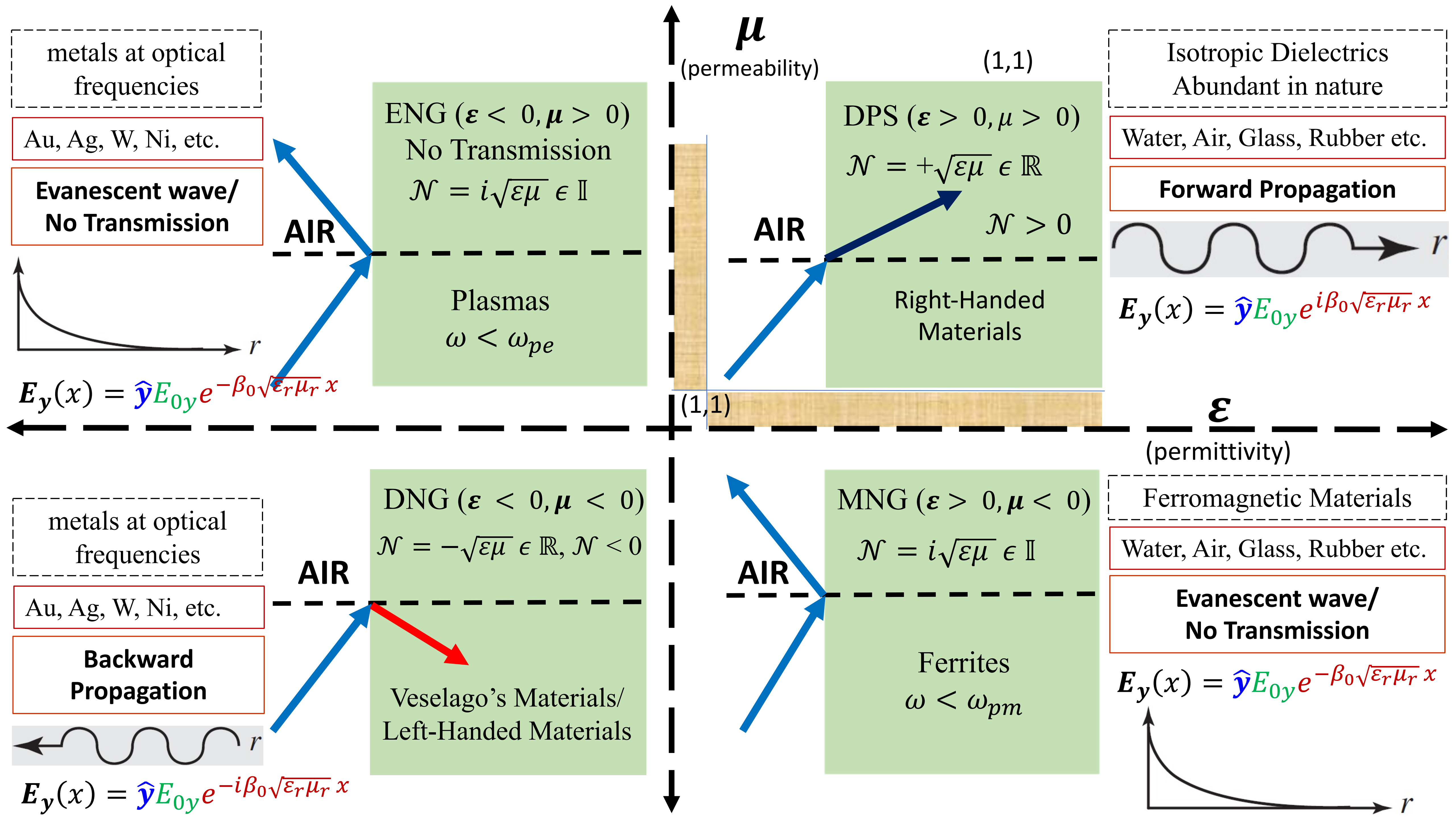
- For a lossless medium, $\mathcal{N} = n + ik = \pm\sqrt{\varepsilon_r \mu_r}$, wave expressions for four possible sign combinations in the pair (ε_r, μ_r) are (+,+), (+,−), (−,+), and (−,−).

$$(+,+) \Rightarrow (\varepsilon_r > 0,\ \mu_r > 0) \ \Rightarrow\ \mathcal{E}_y(x,t) = \hat{\boldsymbol{y}} E_{0y} e^{i\frac{\omega}{c}\left(\sqrt{\varepsilon_r \mu_r}\right) x} e^{-i\omega t} \ \Rightarrow$$

$$(-,+) \Rightarrow (\varepsilon_r < 0,\ \mu_r > 0) \ \Rightarrow\ \mathcal{E}_y(x,t) = \hat{\boldsymbol{y}} E_{0y} e^{-\frac{\omega}{c}\left(\sqrt{\varepsilon_r \mu_r}\right) x} e^{-i\omega t} \ \Rightarrow$$

$$(+,-) \Rightarrow (\varepsilon_r > 0,\ \mu_r < 0) \ \Rightarrow\ \mathcal{E}_y(x,t) = \hat{\boldsymbol{y}} E_{0y} e^{-\frac{\omega}{c}\left(\sqrt{\varepsilon_r \mu_r}\right) x} e^{-i\omega t} \ \Rightarrow$$

$$(-,-) \Rightarrow (\varepsilon_r < 0,\ \mu_r < 0) \ \Rightarrow\ \mathcal{E}_y(x,t) = \hat{\boldsymbol{y}} E_{0y} e^{-i\frac{\omega}{c}\left(\sqrt{\varepsilon_r \mu_r}\right) x} e^{-i\omega t} \ \Rightarrow$$



metals at optical frequencies
Au, Ag, W, Ni, etc.
Evanescent wave/ No Transmission
AIR
$E_y(x) = \hat{y}E_{0y}e^{-\beta_0\sqrt{\varepsilon_r\mu_r}\,x}$
ENG ($\varepsilon < 0, \mu > 0$)
No Transmission
$\mathcal{N} = i\sqrt{\varepsilon\mu} \in \mathbb{I}$
Plasmas
$\omega < \omega_{pe}$
μ
(permeability)
(1,1)
DPS ($\varepsilon > 0, \mu > 0$)
$\mathcal{N} = +\sqrt{\varepsilon\mu} \in \mathbb{R}$
$\mathcal{N} > 0$
AIR
Right-Handed Materials
Isotropic Dielectrics Abundant in nature
Water, Air, Glass, Rubber etc.
Forward Propagation
$E_y(x) = \hat{y}E_{0y}e^{i\beta_0\sqrt{\varepsilon_r\mu_r}\,x}$
(1,1)
ε
(permittivity)
metals at optical frequencies
Au, Ag, W, Ni, etc.
Backward Propagation
AIR
$E_y(x) = \hat{y}E_{0y}e^{-i\beta_0\sqrt{\varepsilon_r\mu_r}\,x}$
DNG ($\varepsilon < 0, \mu < 0$)
$\mathcal{N} = -\sqrt{\varepsilon\mu} \in \mathbb{R}, \mathcal{N} < 0$
Veselago's Materials/ Left-Handed Materials
MNG ($\varepsilon > 0, \mu < 0$)
$\mathcal{N} = i\sqrt{\varepsilon\mu} \in \mathbb{I}$
AIR
Ferrites
$\omega < \omega_{pm}$
Ferromagnetic Materials
Water, Air, Glass, Rubber etc.
Evanescent wave/ No Transmission
$E_y(x) = \hat{y}E_{0y}e^{-\beta_0\sqrt{\varepsilon_r\mu_r}\,x}$
r

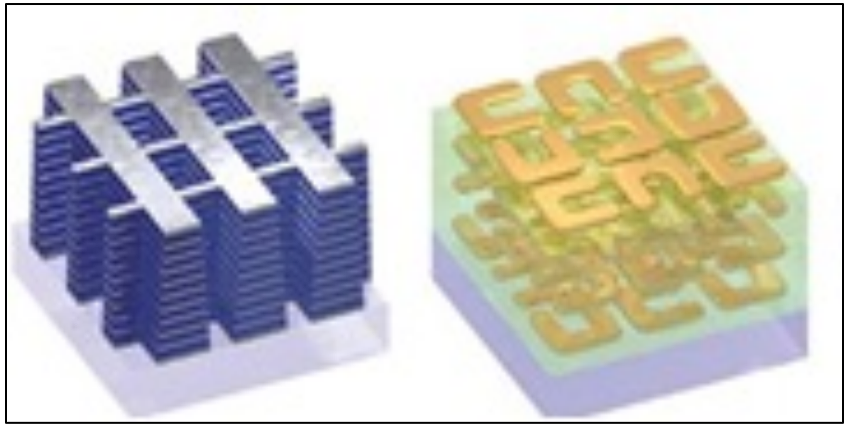
Optics & It's Impact

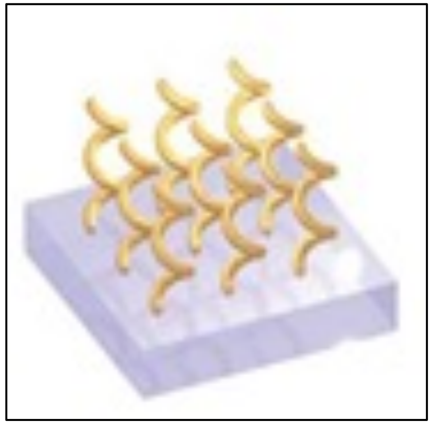
Metamaterials

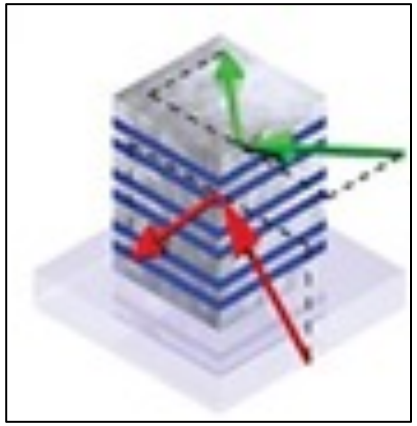
Metamaterials
A New Paradigm of Science and Engineering

Metamaterials: from the Greek word ***meta***, meaning "**beyond**" or "**after**", and the Latin word ***materia***, meaning "matter" or "material") is **any material engineered** to have a property **that is not found in naturally occurring materials**.

- They are made from repeated **patterns of multiple sub-wavelength elements** (fashioned from composite materials such as metals and plastics).
- They derive their properties not from the properties of the base materials, but from their newly designed structures.







Metamaterials

A New Paradigm of Science and Engineering

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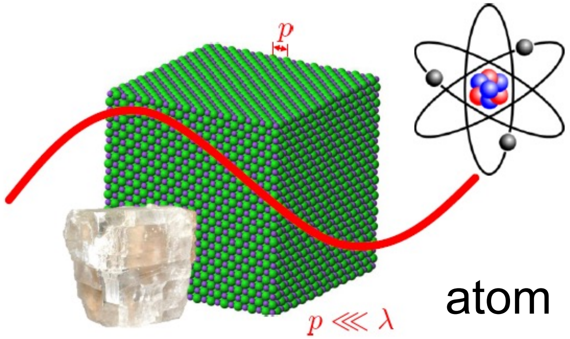
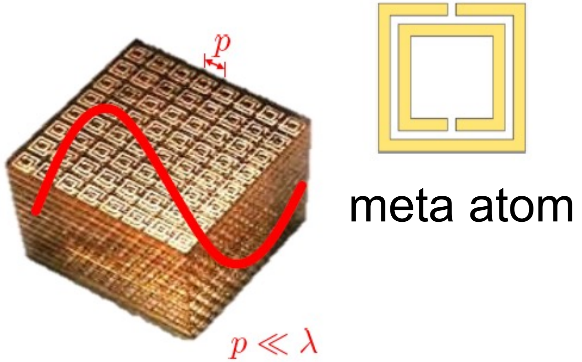
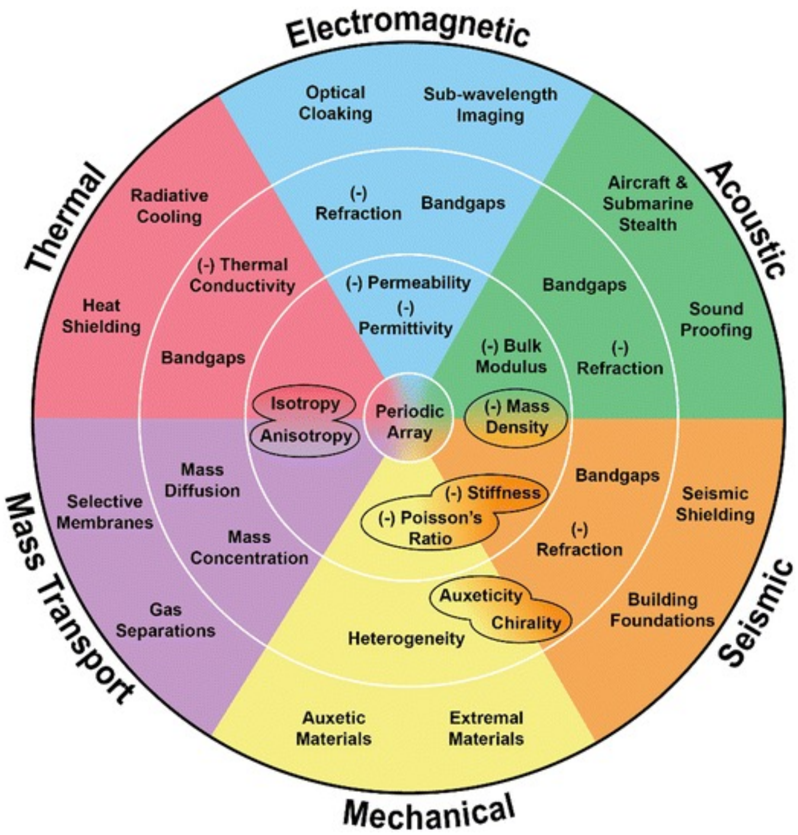


Natural Material



Metamaterial (artificial)



Effective Constitutive Parameters:

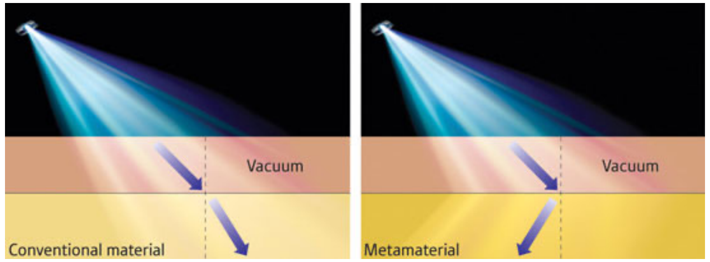
Permeability ($\boldsymbol{\varepsilon_{eff}}$), Permittivity ($\boldsymbol{\mu_{eff}}$), Mass density ($\boldsymbol{\rho_{eff}}$), Bulk modulus ($\boldsymbol{K_{eff}}$), etc.

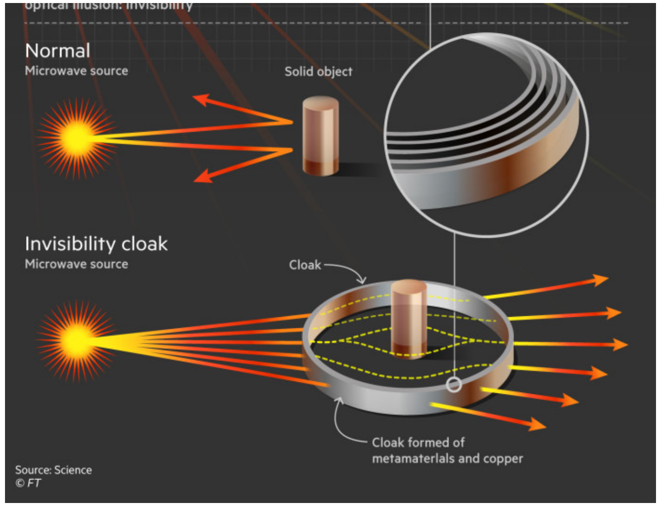
Metamaterials

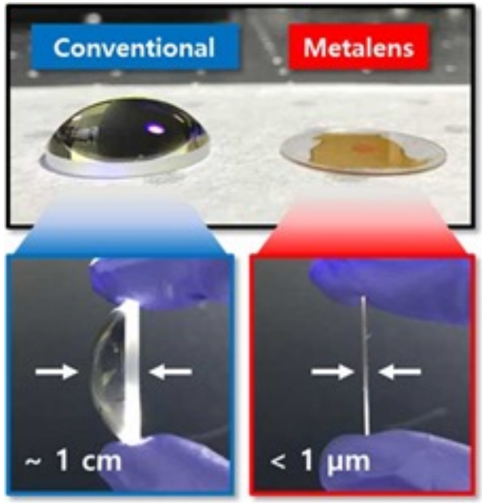
Metamaterials

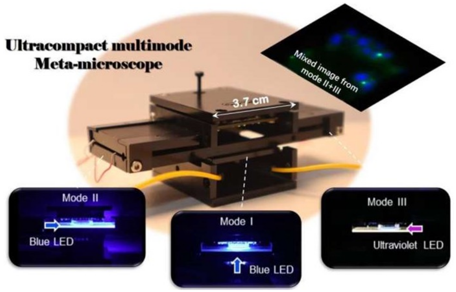
A New Paradigm of Science and Engineering

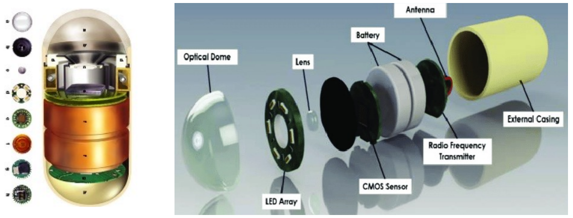
Anomalous Response: Like Negative Refraction & Invesibiltiy (Cloaking), Compactnes, Enhanced Performance









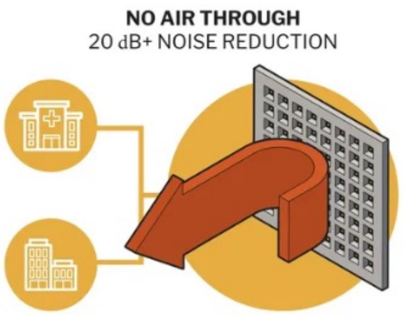


How Metamaterials Could Lead to Invisible Tanks and Super-Stealthy Submarines

New construction materials made of composites could make military vehicles—and even soldiers—invisible to radar, sonar, and even the naked eye.

China Is Getting Closer to a New Type of Stealth Aircraft

Traditional stealth aircraft rely on geometry to deflect radar, but metamaterials used in the construction of an aircraft could absorb radar waves.



Next-generation acoustic metamaterial absorbs low-frequency sound

When it comes to low-frequency noise, traditional sound-absorbing materials tend to be undesirably thick and heavy. Now, EU-funded entrepreneurs designed a breakthrough lightweight material specifically targeted for low-frequency sound waves.

Sonoblind   Metasonixx   Metablocker   KINETICS Noise Control

Metamaterials
Companies & Market

METAVC partners

Bill Gates backed VC firm specifically for metamaterials

62 Million USD Fund

LUMOTIVE

LEAD OPTIK

IMAGIA

Neurophos

A METACEPT spinoff

MANGATA

META® Go Beyond.

Kingwills

metalenz

迈塔兰斯®

MetaLenX®

PlanOpSim

Enlightened Planar Optics

Hot Product | Consumer electronics | LIDAR | Optical communication | Customization

End Users: Automotive, Aerospace & Defense, Medical Instrumentation, telecommunication, and Optics.

WORLD ECONOMIC FORUM

Global Agenda

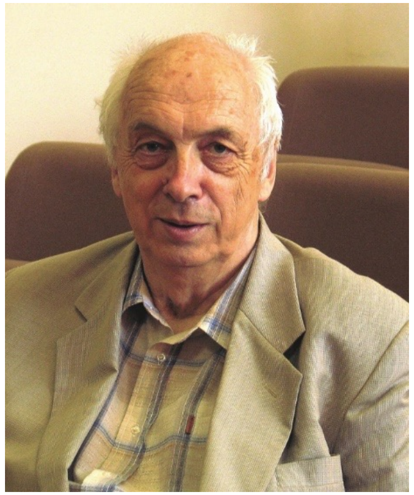
Top 10 Emerging Technologies 2018

Market Size in 2022	*Market Forecast in 2030*	*CAGR (in %)*	*Base Year*
USD 330.8 Million	*USD 10053.9 Million*	*53.23%*	*2022*

CAGR: compound annual growth rate

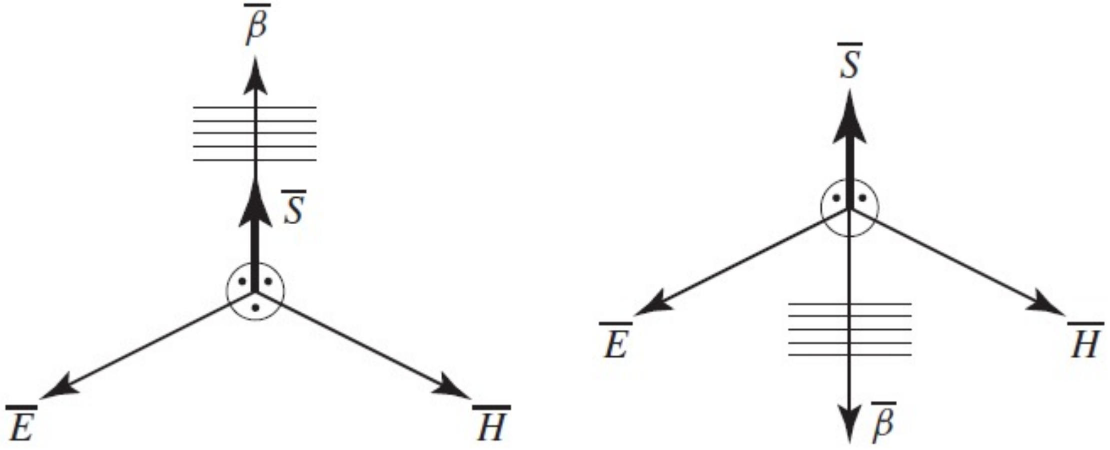
Zion Market Research

Meta/Flat-Optics → Entry to Industry

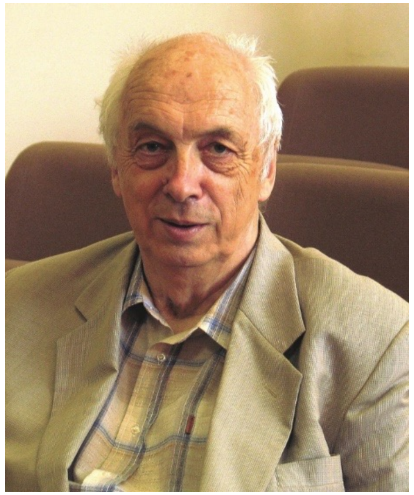


Victor Georgievich Veselago
1929 - 2018

- In 1967, Viktor Veselago **visionary speculation** on the existence of "***substances with simultaneously negative values of ε and μ***".
- He called these **"substances" LH** to express the fact that they would **allow the propagation** of electromagnetic waves with ***E***, ***H***, and wave vector building a **left-handed triad**.
- He recognized, "**Unfortunately, . . . , we do not know of even a single substance which could be isotropic and have μ < 0.**" thereby pointing out how difficult it seemed to realize a practical LH structure.



Meta/Flat-Optics → Entry to Industry



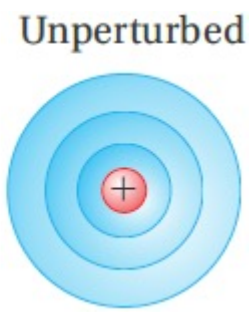
Victor Georgievich Veselago
1929 - 2018

Several fundamental phenomena occurring in or in association with LH media were predicted by Veselago

- Reversal of the boundary conditions relating the **normal components** of the electric and magnetic fields at the interface between a conventional/right-handed (RH) medium and an LH medium.
- Reversal of **Snell's law**.
- Subsequent **negative refraction** at the interface between a RH medium and a LH medium.
- Transformation of a **point source into a point image** by a LH slab.
- **Interchange of convergence and divergence effects** in convex and concave lenses.

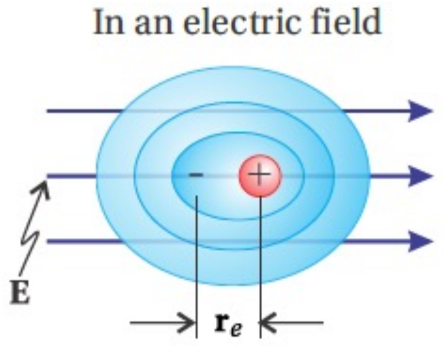
Lorentz Oscillator Model for Dielectrics

The Lorentz model uses **Newton's equation of motion to describe an electron displacement** from equilibrium within an atom.

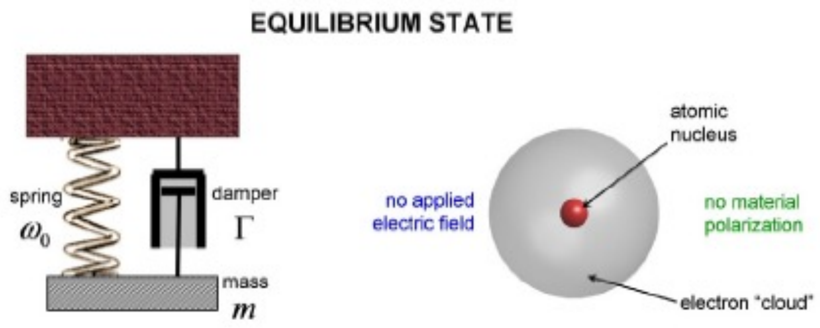


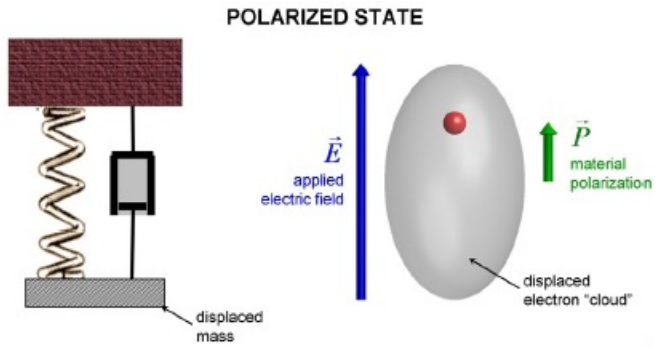
$$F_{accelerating} = F_{Electric} - F_{Damping} - F_{Restoring/Spring}$$

$$m_e \frac{\partial^2 \boldsymbol{r_e}}{\partial t^2} = q_e \boldsymbol{E} - m_e \gamma \frac{\partial \boldsymbol{r_e}}{\partial t} - k_{Hooke} \boldsymbol{r_e} = q_e \boldsymbol{E} - m_e \gamma \frac{\partial \boldsymbol{r_e}}{\partial t} - m_e \omega_0^2 \boldsymbol{r_e}$$



Where, $\omega_0 = \sqrt{k_{Hooke}/m_e}$ is the **natural oscillation frequency** (or resonant frequency) associated with the electron mass and the spring constant.





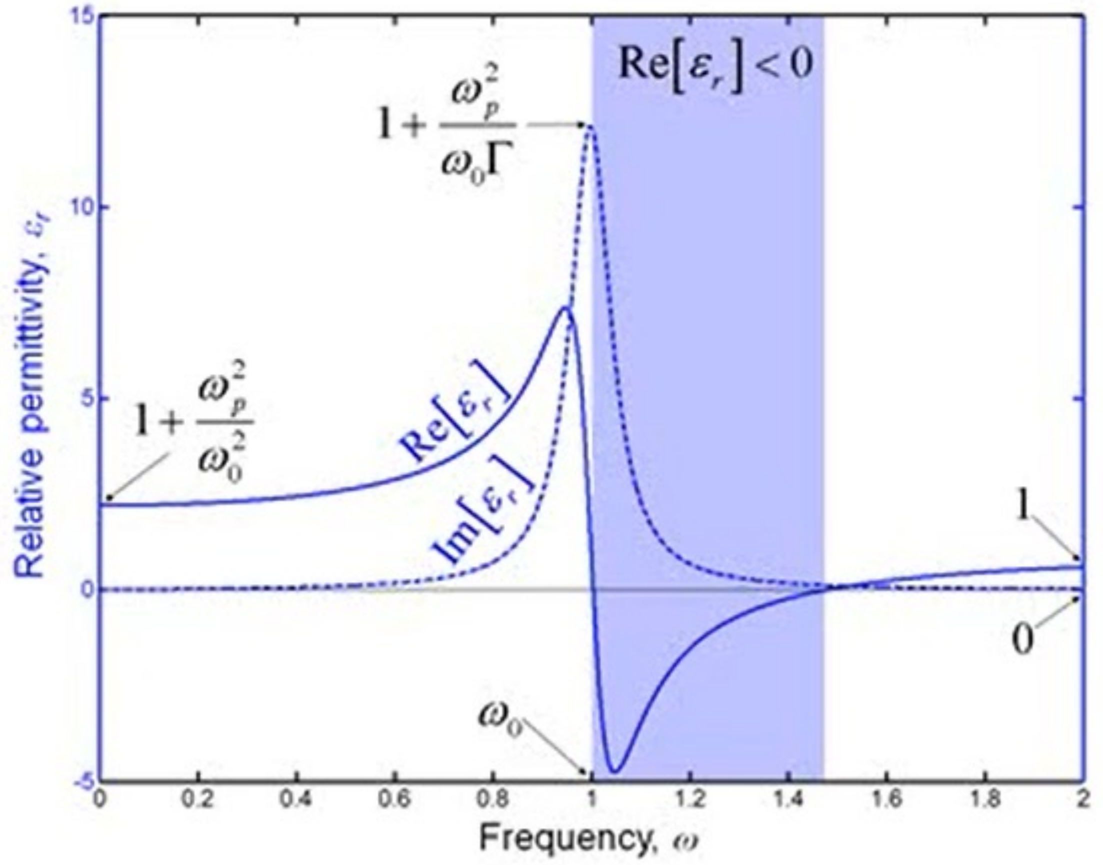
Lorentz Oscillator Model for Dielectrics

$$(n + ik)^2 = \varepsilon_r' + i\varepsilon_r'' = 1 + \chi_e = 1 + \frac{\omega_p^2}{\omega_0^2 - \omega^2 - i\omega\gamma},$$

$$\boldsymbol{n^2 - k^2 = \varepsilon_r' = 1 + \omega_p^2 \frac{\omega_0^2 - \omega^2}{(\omega_0^2 - \omega^2)^2 + \omega^2\gamma^2},}$$

$$\boldsymbol{2nk = \varepsilon_r'' = \omega_p^2 \frac{\omega\gamma}{(\omega_0^2 - \omega^2)^2 + \omega^2\gamma^2}}$$

$$\omega_p = \sqrt{\frac{Nq_e^2}{\varepsilon_0 m_e}}$$



Drude Model for Metals

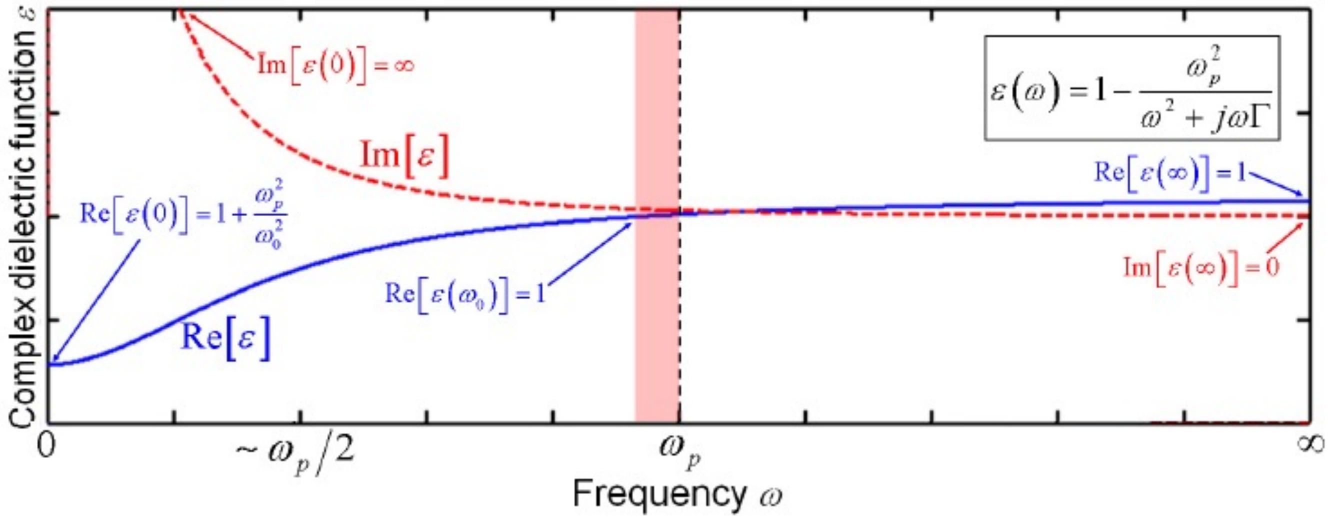
$$m_e \frac{\partial^2 \boldsymbol{r_e}}{\partial t^2} = q_e \boldsymbol{E} - m_e \gamma \frac{\partial \boldsymbol{r_e}}{\partial t} - \cancel{k_{Hooke} \boldsymbol{r_e}}$$

$$= q_e \boldsymbol{E} - m_e \gamma \frac{\partial \boldsymbol{r_e}}{\partial t} - \cancel{m_e \omega_0^2 \boldsymbol{r_e}}$$

$$(n + ik)^2 = \varepsilon_r' + i\varepsilon_r'' = 1 + \chi_e = 1 - \frac{\omega_p^2}{\omega^2 + i\omega\gamma}$$

$$\boldsymbol{n^2 - k^2 = \varepsilon_r' = 1 - \omega_p^2 \frac{\omega^2}{\omega^4 + \omega^2\gamma^2}}$$

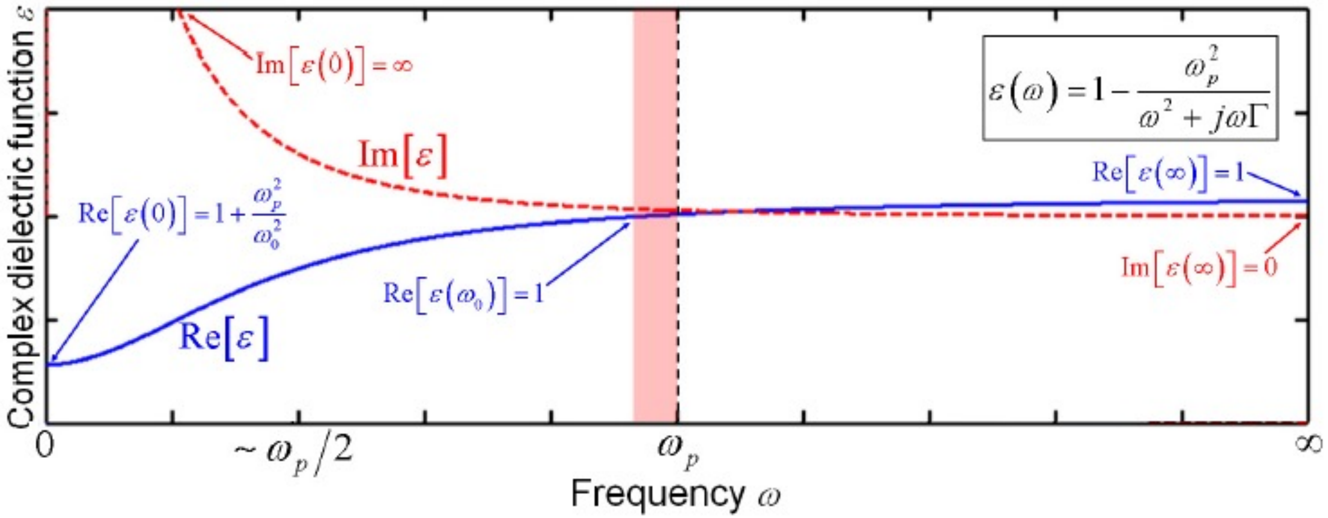
$$\boldsymbol{2nk = \varepsilon_r'' = \omega_p^2 \frac{\omega\gamma}{\omega^4 + \omega^2\gamma^2}}$$



- **<u>Below the plasma frequency</u>**, the dielectric constant is mostly imaginary, and **<u>metals behave like good conductors</u>**.

- Near the plasma frequency, both the real and imaginary parts of permittivity are significant, and metals are very lossy.
- **<u>At very high frequencies</u>** above the plasma frequency, **<u>loss vanishes, and metals become transparent.</u>**

Drude Model for Metals



The plasma frequency for typical metals lies in the ultra-violet.

Metal	Symbol	Plasma Wavelength	Plasma Frequency
Aluminum	Al	82.78 nm	3624 THz
Chromium	Cr	115.35 nm	2601 THz
Copper	Cu	114.50 nm	2620 THz
Gold	Au	137.32 nm	2185 THz
Nickel	Ni	77.89 nm	3852 THz
Silver	Ag	137.62 nm	2180 THz

- **Below the plasma frequency**, the dielectric constant is mostly imaginary, and **metals behave like good conductors**.
- **At very high frequencies** above the plasma frequency, **loss vanishes, and metals become transparent.**

Artificial Plasma Frequency & Permittivity

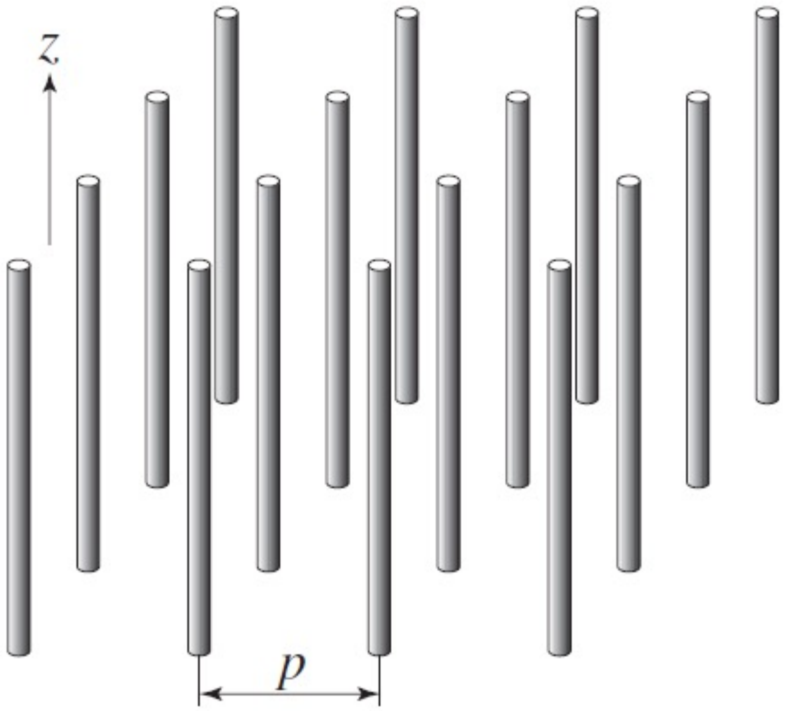
Negative: ε_r Positive: μ_r $\varepsilon_r < 0, \quad \mu_r > 0$

J B Pendry *et al* 1998 *J. Phys.: Condens. Matter* **10** 4785

For, ***E*** parallel to the wire axis induces a current along them and generates equivalent electric dipole moments, exhibiting a **plasmonic-type permittivity** frequency function.

$$\varepsilon_r(\omega) = 1 - \frac{\omega_{pe}^2}{\omega^2 - i\omega\gamma} = 1 - \frac{\omega_{pe}^2}{\omega^2 + \gamma^2} - i\frac{\gamma\omega_{pe}^2}{\omega(\omega^2 + \gamma^2)}$$

$$\omega_{pe} = electric\ plasma\ frequency = \sqrt{2\pi c^2/[p^2 ln(p/a)]}$$



a: radius of the wires, γ = damping factor $= \varepsilon_0 \left(p\omega_{pe}/a\right)^2/\pi\sigma$
It clearly appears in this formula that

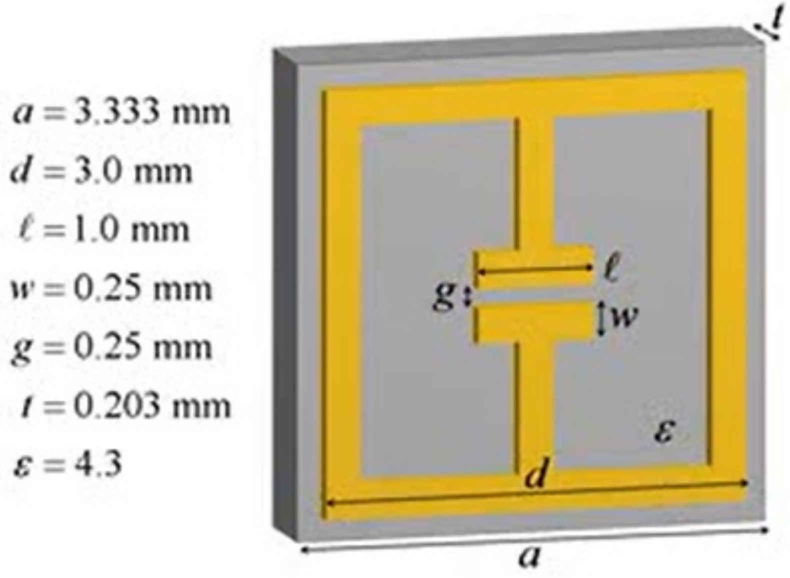
$$\mathrm{Re}(\varepsilon_r) < 0, \qquad \omega^2 < \omega_{pe}^2 - \gamma^2$$

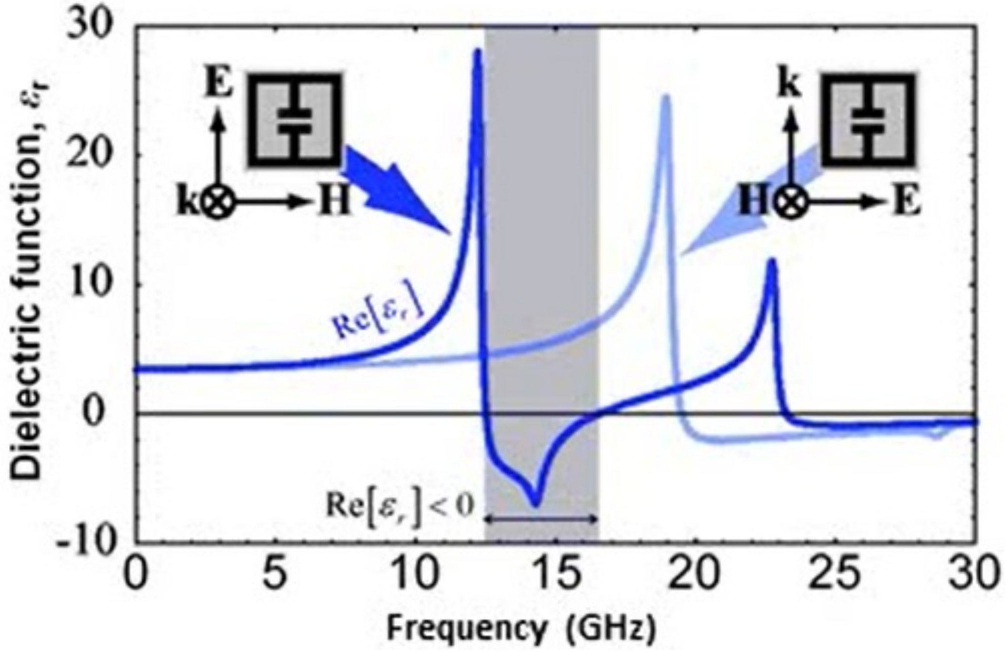
Which, for $\gamma = 0$, reduces to

$$\varepsilon_r < 0, \qquad for \quad \omega < \omega_{pe}$$

On the other hand, permeability is simply $\mu = \mu_0$ since no magnetic material is present and no magnetic dipole moment is generated.

Artificial Permittivity





D. Schurig et al, Appl. Phys. Lett. 88, 041109 (2006)

Artificial Plasma Frequency (SRR)

Positive: ε_r Negative: μ_r i.e., $\varepsilon_r < 0, \quad \mu_r > 0$

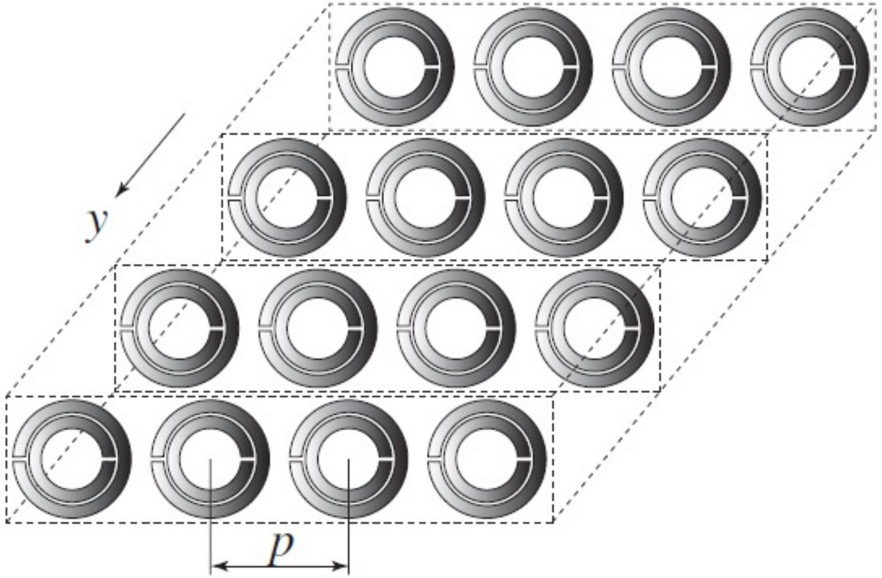
J. B. Pendry, "IEEE Transactions on Microwave Theory and Techniques, vol. 47, no. 11, pp. 2075-2084, Nov. 1999.

For, ***H*** perpendicular to the plane of the rings induces resonating currents in the loop and generate equivalent magnetic dipole moments, exhibiting a **plasmonic-type permeability** frequency function.

$$\mu_r(\omega) = 1 - \frac{F\omega^2}{\omega^2 - \omega_{0m}^2 + i\omega\gamma}$$

$$= 1 - \frac{F\omega^2(\omega^2 - \omega_{0m}^2)}{(\omega^2 - \omega_{0m}^2)^2 + (\omega\gamma)^2} - i\frac{F\omega^2\gamma}{(\omega^2 - \omega_{0m}^2)^2 + (\omega\gamma)^2}$$

$$\omega_{om} = c\sqrt{3p/[\pi ln(2wa^3/\delta)]},$$

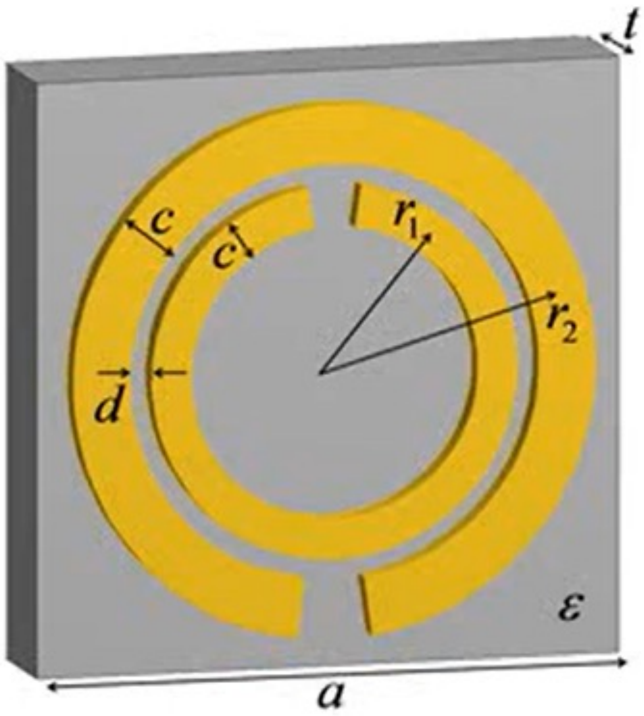


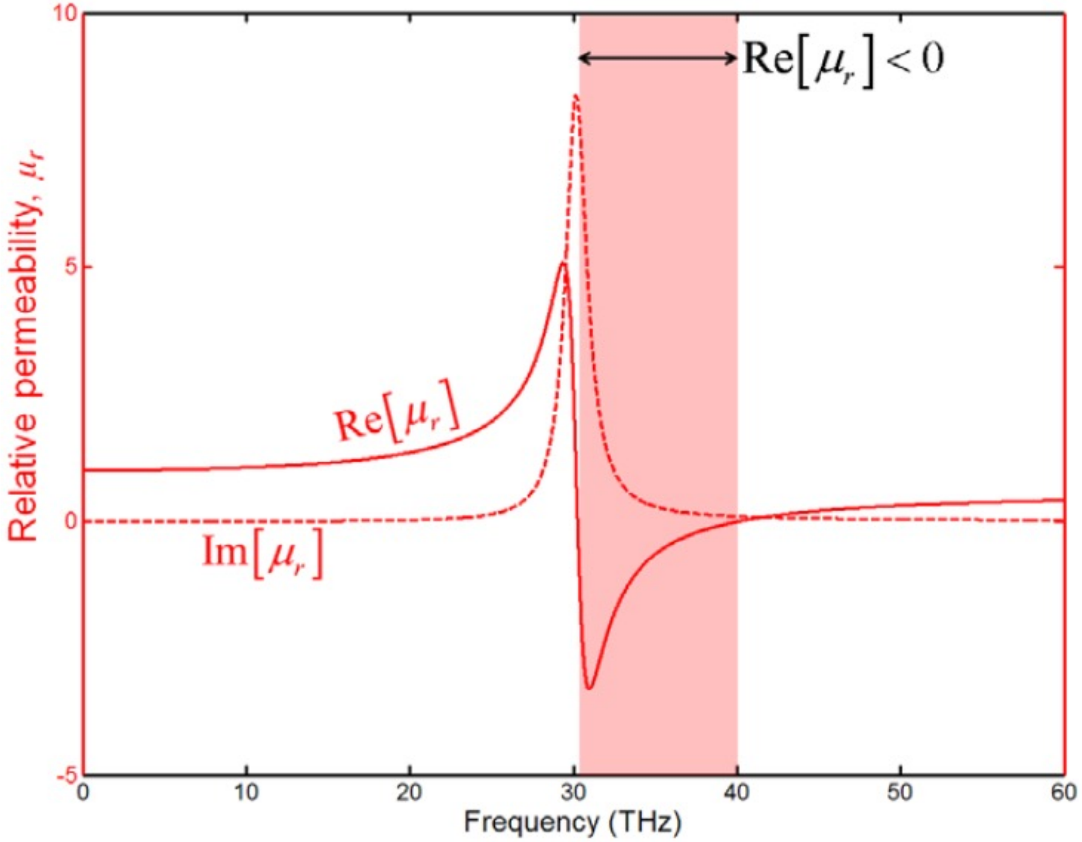
ω_{om}: magnetic resonance frequency, w: width of the ring,
δ: $radial\ spacing$, $F = \pi(a/p)^2$, a: inner radius of the smaller ring, $\gamma = 2pR'/\mu_0$

Hence, a frequency range can exist in which $\text{Re}(\mu_r) < 0$

$$\mu_r < 0, \qquad for \ \ \omega_{0m} < \omega < \frac{\omega_{0m}}{\sqrt{1-F}} = \omega_{pm} = \text{magnetic plasma frequency}$$

Artificial Permeability

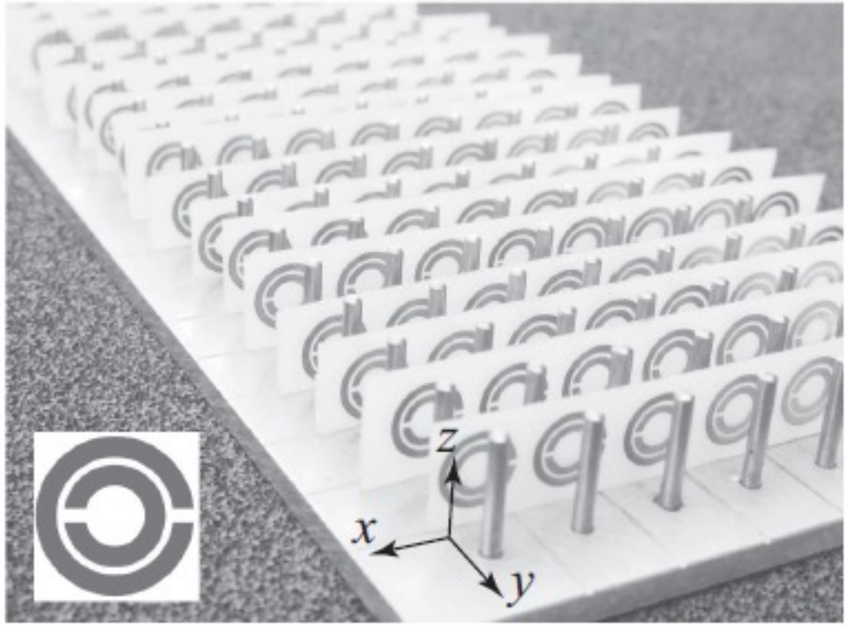


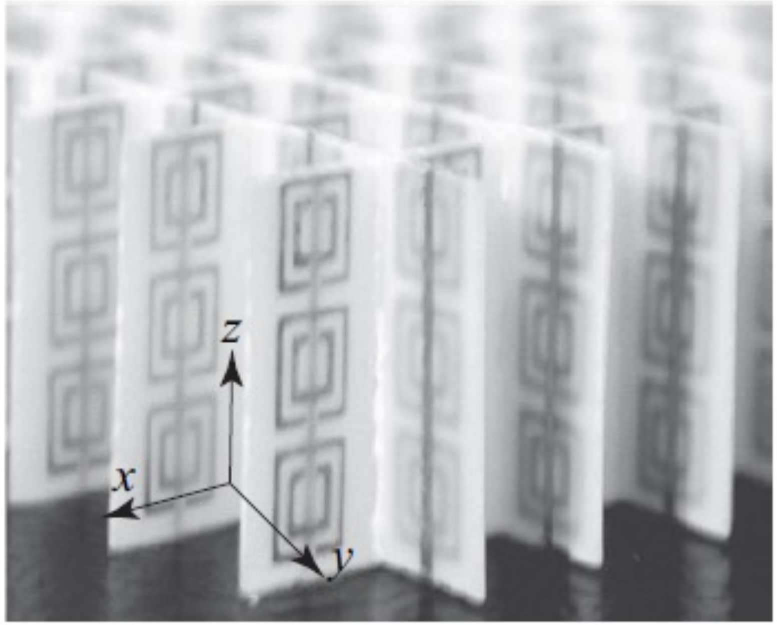


J. B. Pendry, IEEE Transactions on Microwave Theory and Techniques, vol. 47, no. 11, pp. 2075-2084, Nov. 1999.

Experimental Demonstration Of Left-handedness

Smith et al. combined the TW and SRR structures of Pendry into the composite structure, which represented the **first experimental LH MTM prototype**.

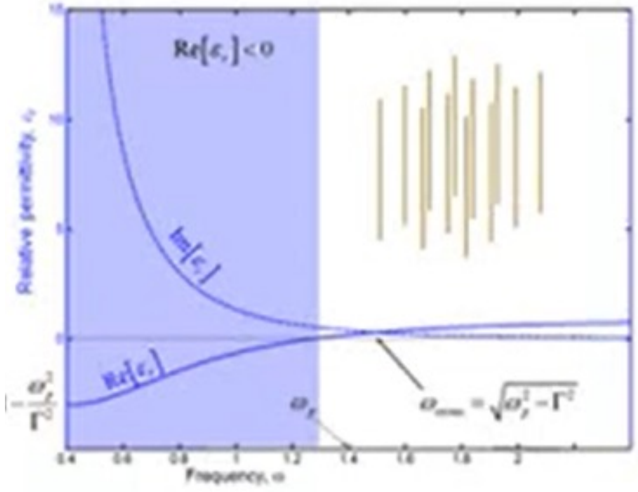


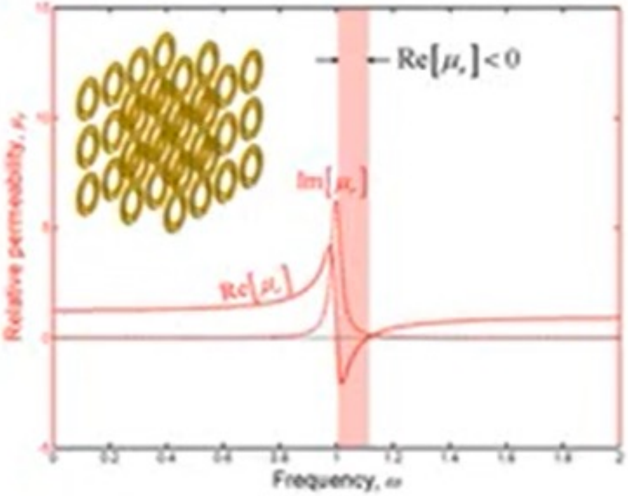


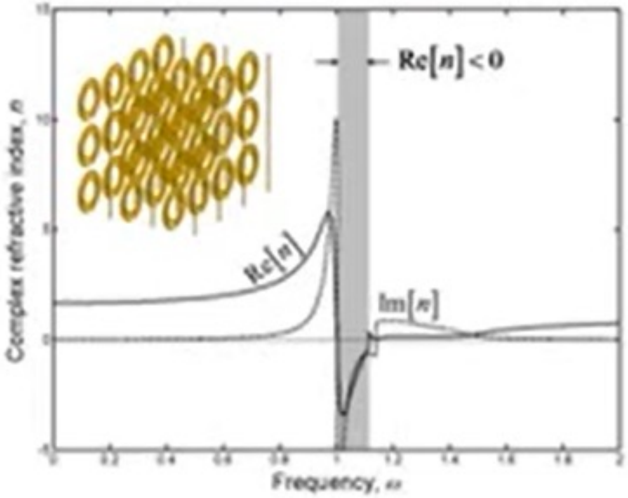
D. R. Smith et al." *Phys. Rev. Lett.*, vol. 84, no. 18, pp. 4184–4187, May 2000.
R. A. Shelby et. al," *Science*, vol. 292, pp. 77–79, April 2001

Experimental Demonstration Of Left-handedness

Credit Slide: Dr. Raymond C. Rumpf University of Texas at El Paso (UTEP)



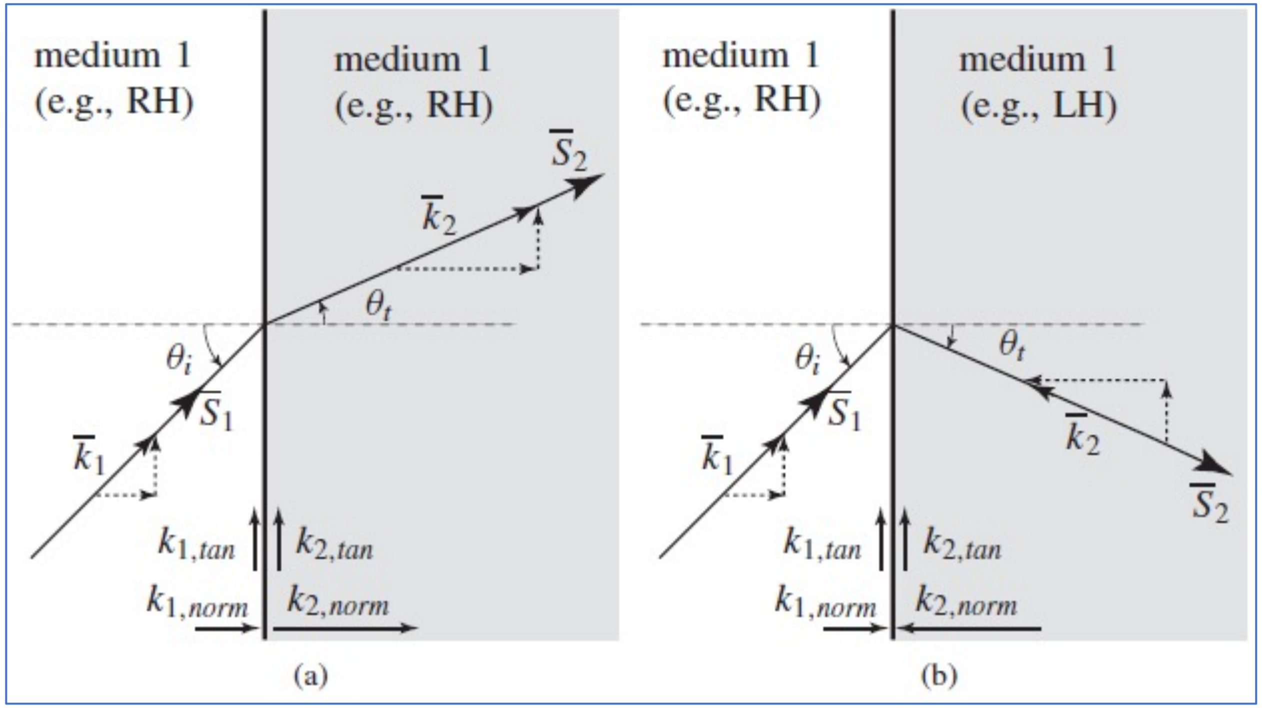




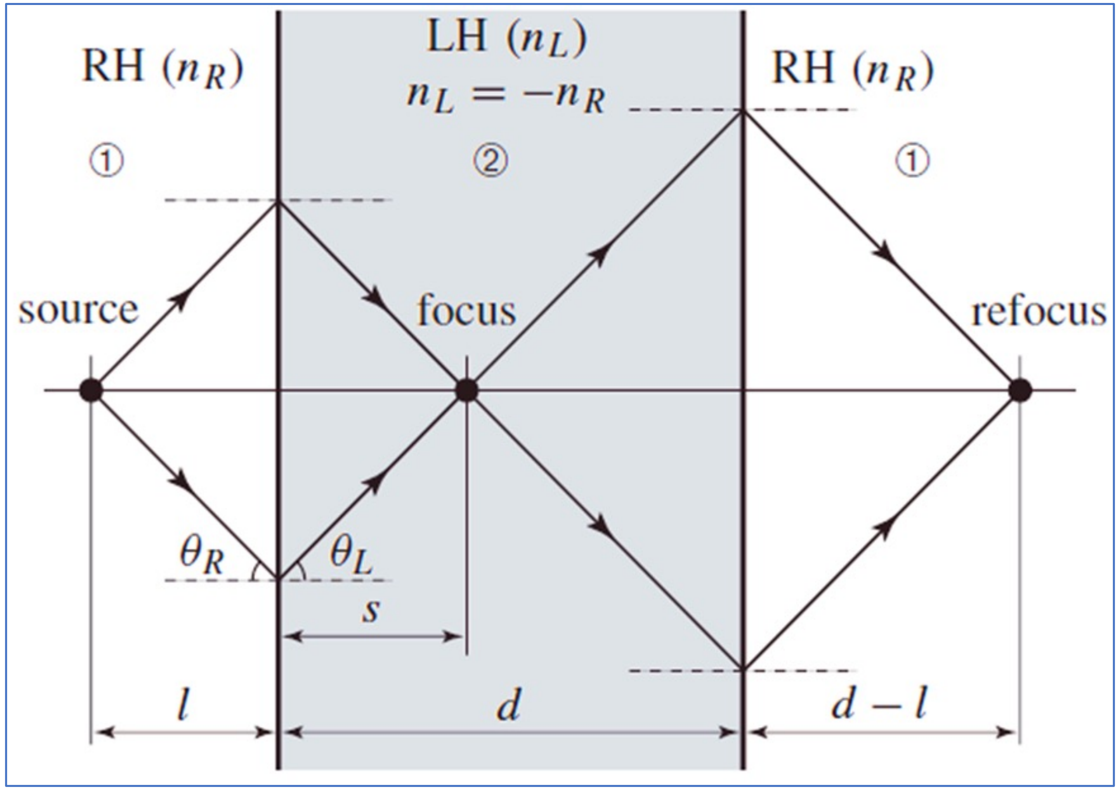
Smith et al., Phys. Rev. Lett. 84, 4184–4187 (2000).

Experimental Demonstration Of Left-handedness

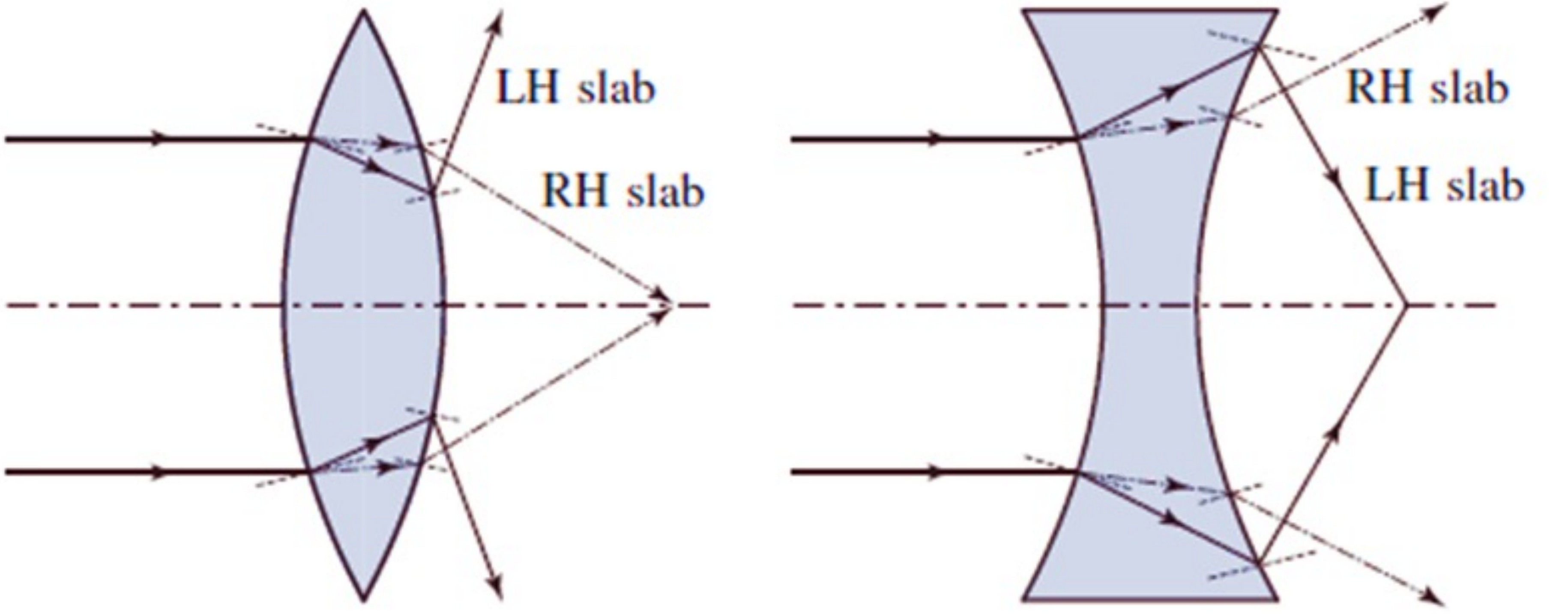
Negative Refraction



"FLAT LH LENS"



Experimental Demonstration Of Left-handedness



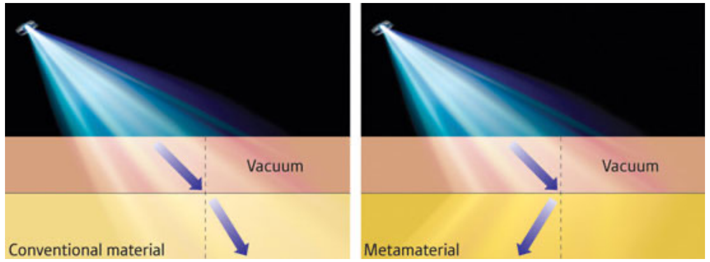
(a) (b)

Metamaterials

Metamaterials

A New Paradigm of Science and Engineering

Anomalous Response: Like Negative Refraction & Invesibiltiy (Cloaking), Compactnes, Enhanced Performance

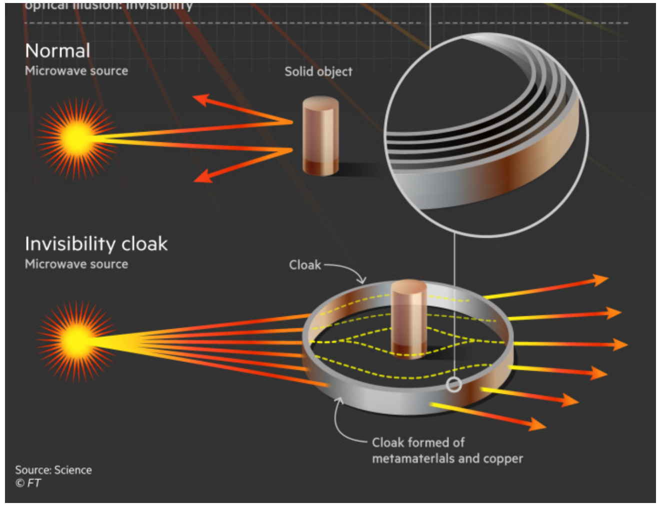


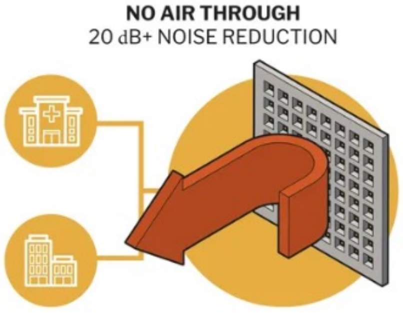
How Metamaterials Could Lead to Invisible Tanks and Super-Stealthy Submarines

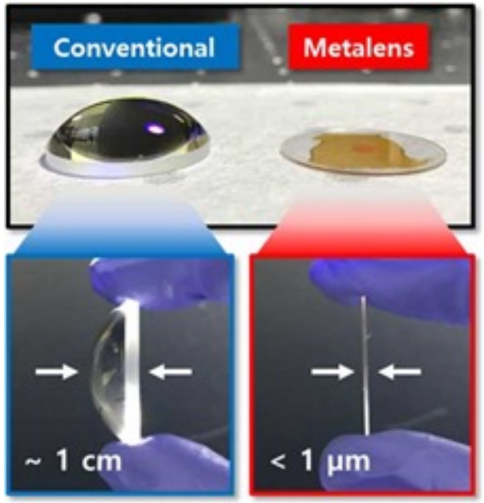
New construction materials made of composites could make military vehicles—and even soldiers—invisible to radar, sonar, and even the naked eye.

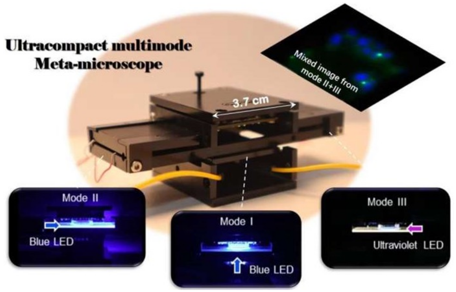
China Is Getting Closer to a New Type of Stealth Aircraft

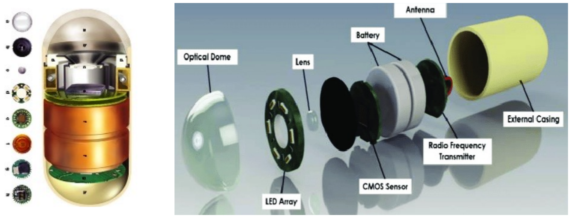
Traditional stealth aircraft rely on geometry to deflect radar, but metamaterials used in the construction of an aircraft could absorb radar waves.











Next-generation acoustic metamaterial absorbs low-frequency sound

When it comes to low-frequency noise, traditional sound-absorbing materials tend to be undesirably thick and heavy. Now, EU-funded entrepreneurs designed a breakthrough lightweight material specifically targeted for low-frequency sound waves.

Sonoblind Metasonixx Metablocker KINETICS Noise Control

Experimental Demonstration Of Left-handedness

Extra Slides

Lorentz Oscillator Model for Dielectrics

Taking the Fourier transform,

$$[m_e(i\omega)^2 + m_e\gamma(i\omega) + m_e\omega_0^2]\boldsymbol{r_e} = q_e\boldsymbol{E}$$

$$\boldsymbol{r_e} = \left(\frac{q_e}{m_e}\right)\frac{\boldsymbol{E}}{\omega_0^2 - \omega^2 - i\omega\gamma}, \qquad P = N\times(dipole\ moment) = Nq_e\boldsymbol{r_e} = \left(\frac{Nq_e^2}{m_e}\right)\frac{\boldsymbol{E}}{\omega_0^2 - \omega^2 - i\omega\gamma} = \varepsilon_0\chi_e\boldsymbol{E}$$

$$\chi_e = \left(\frac{Nq_e^2}{\varepsilon_0 m_e}\right)\frac{1}{\omega_0^2 - \omega^2 - i\omega\gamma} = \frac{\omega_p^2}{\omega_0^2 - \omega^2 - i\omega\gamma}, \qquad \omega_{\boldsymbol{p}} = \sqrt{\frac{Nq_e^2}{\boldsymbol{\varepsilon_0} m_e}}$$

$$(n + ik)^2 = \varepsilon_r' + i\varepsilon_r'' = 1 + \chi_e = 1 + \frac{\omega_p^2}{\omega_0^2 - \omega^2 - i\omega\gamma}, \qquad \omega_{\boldsymbol{p}} = \sqrt{\frac{Nq_e^2}{\boldsymbol{\varepsilon_0} m_e}}$$

$$\boldsymbol{n^2 - k^2 = \varepsilon_r' = 1 + \omega_p^2\frac{\omega_0^2 - \omega^2}{(\omega_0^2 - \omega^2)^2 + \omega^2\gamma^2}}, \qquad \boldsymbol{2nk = \varepsilon_r'' = \omega_p^2\frac{\omega\gamma}{(\omega_0^2 - \omega^2)^2 + \omega^2\gamma^2}}$$