Metamaterials & Chirality

Akhlesh Lakhtakia

Department of Engineering Science & Mechanics
Pennsylvania State University

1600 hrs, April 18, 2007

Department of Physics, Millersville University of Pennsylvania

ENGINEERING SCIENCE AND MECHANICS DEPARTMENT

ENGINEERED MATERIALS, STRUCTURES, DEVICES AND SYSTEMS

ESM – Engineering the Frontiers of Science

NANOSCIENCE AND TECHNOLOGY

THE PENN STATE NANOFABRICATION FACILITY

Prof Fonash: Director
Center for Nanotechnology Education and Utilization

CENTER FOR INNOVATIVE SINTERED PRODUCTS

Director: Prof. Ivi Smid

BOEING AIRLINER COMPONENT: NIST-ATP, INDUSTRY, CISP: computer models for sintering 3D components formed using molding.

FACULTY/STAFF

- 20 Full Professors
  - 3 Chairs, 2 Professorships, 4 Distinguished Professors
  - 8 Professors Emeriti
- 5 Associate Professors
- 3 Assistant Professors
- 10 Graduate Faculty (fixed term)
- Part-time instructors
- 10 Office Staff + 2.3 faculty support staff (centers and faculty support additional staff)

RECOGNITION

- **Prof. Fonash: Thomas D. Callinen Award, Electrochemical Society,** ***for contributions to Dielectric Science and Technology***
- **Profs. Bakis and Rose, Fellow ASME International**
- **Prof. Hayek, Trente-Crede Silver Medal, Acoustical Society of America**
- **Prof. Messier, Howard B. Palmer Faculty Mentoring Award, PSES Outstanding Advising Award**
- **Prof. Engel, ASEE Board of Directors**
- **Prof. Todd, VP Manufacturing, ASME; Franklin Institute Committee on Arts and Sciences, CIC Fellow**
- **Prof. Zamrik, ESM Outstanding Alumnus**
- **Prof. Pangborn, McKay Donkin Award**
- **Prof. Shaw, Executive Committee, NACE**
- **Profs. Costanzo, Gray, GE Learning Excellence Award**
- **Akhlesh Lakhtakia, Binder Endowed Professor**

STUDENTS

- ~100 UNDERGRADUATES (60-70 jr/sr)
- 116 GRADUATES (97M, 18F, 1M - 6IGDP)
- 2002-03: 92 REFEREED PUBLICATIONS CO-AUTHORED BY STUDENTS

STRATEGIC GOALS

1. **Develop new research, educational and outreach programs related to "*Bio-nano Science and Engineering*" in collaboration with the Materials Research Institute, Huck Life Sciences Institute, College of Engineering, College of Science and Hershey Medical Center.**

STRATEGIC GOALS

2. **Develop new research, educational and outreach programs related to "Systems Health Monitoring – *for structures, systems and people*" in collaboration with the College of Engineering, Applied Research Laboratory and Hershey Medical Center.**

STRATEGIC GOALS

3. **Develop a new "*Center for Multiscale Wave-Materials Interactions*" (CMWMI) and associated research, educational and outreach programs in collaboration with the Applied Research Laboratory, Electro-Optics Center, College of Engineering and Materials Research Institute.**

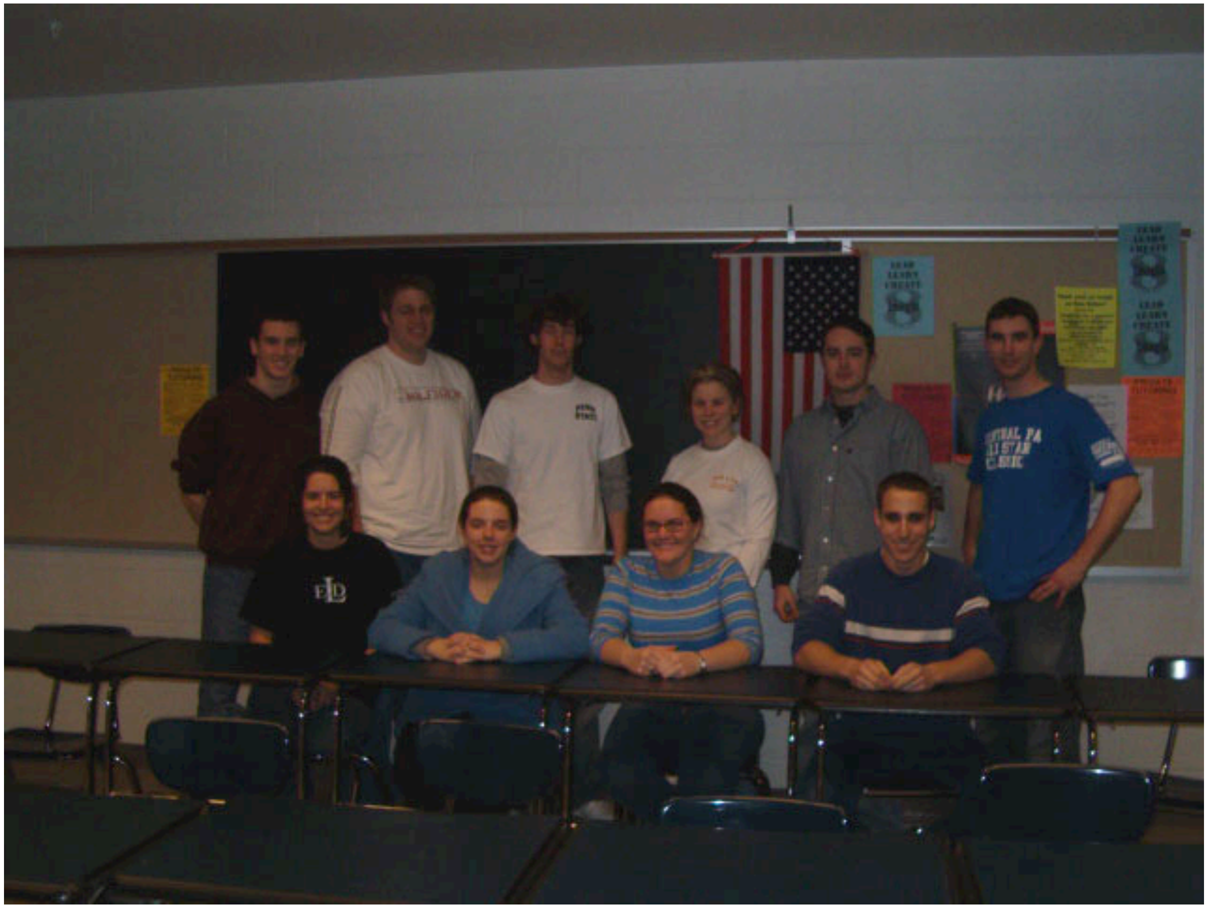
STRATEGIC GOALS

4. Develop new recruitment strategies to attract faculty, graduate and undergraduate students and enhance our placement strategies for our students.

5. Enhance our development activities, corporate and alumni relations to increase support for key ESM initiatives.

PENNSTATE

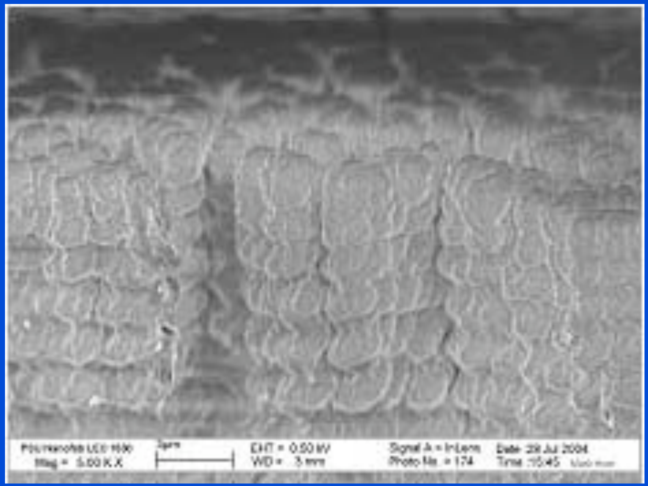
Engineering Science and Mechanics Department

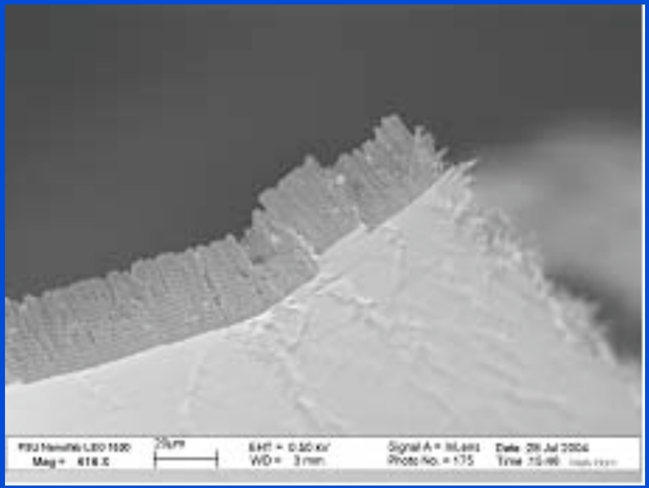


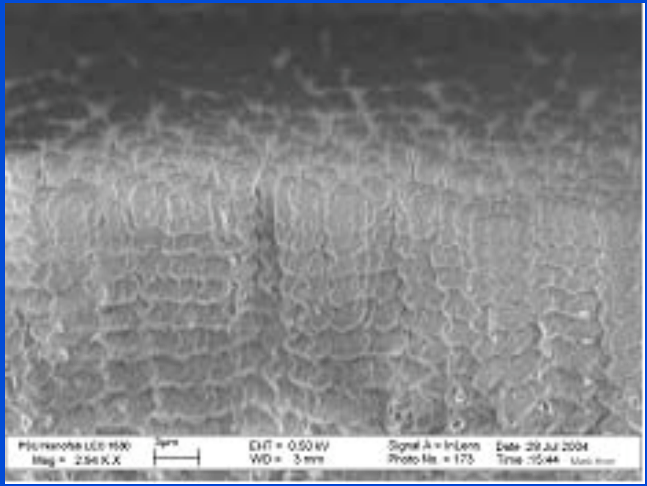
Presented by the Engineering Science Undergraduate Student Council

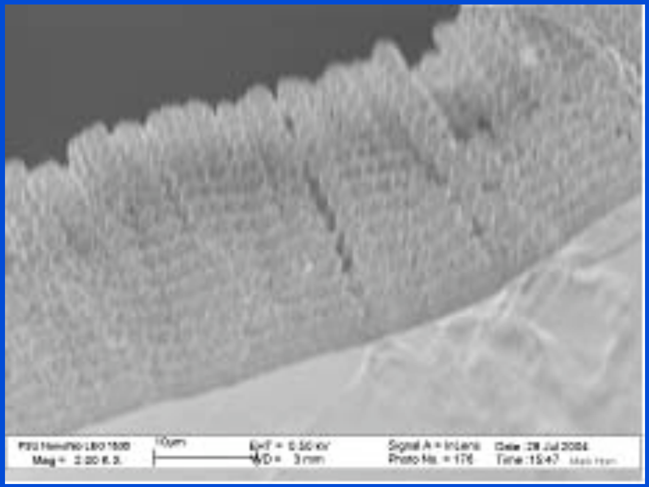
What does
Engineering Science do?

Penn State Engineering Science









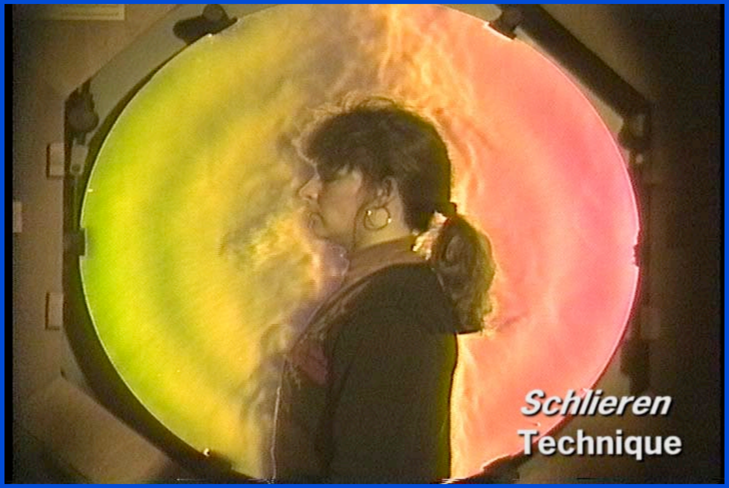
Sean Pursel uses a Scanning Electron Microscope (SEM) to view polymeric sculptured thin films

Engineering Science and Mechanics

engineering the frontiers of science . . .

Alex Robinson simulates nitrogen molecules in collision, and examines how those molecules breakdown

Penn State Engineering Science



Gabrielle Tremblay creates visuals of fluid mechanics. These will be used in a DVD to teach other undergraduate engineers.

Engineering Science and Mechanics

engineering the frontiers of science . . .

Jed Schober developed a new design for the rear suspension of a mountain bike. He is now building and testing that design.

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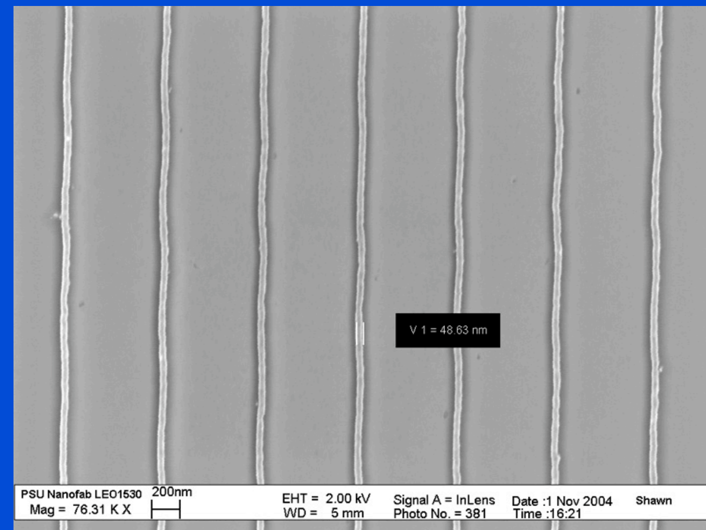

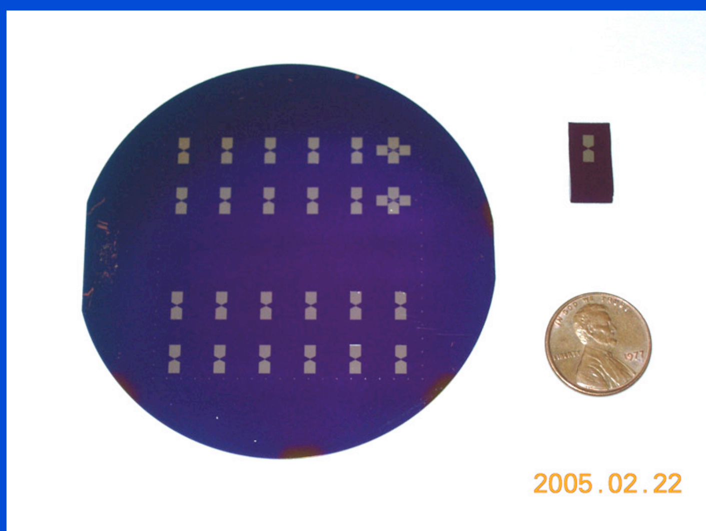

Myo Thein makes gas sensors that are based on nanowires.

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Ryan Melnychuk is studying the absorption of laser light in metal powders.

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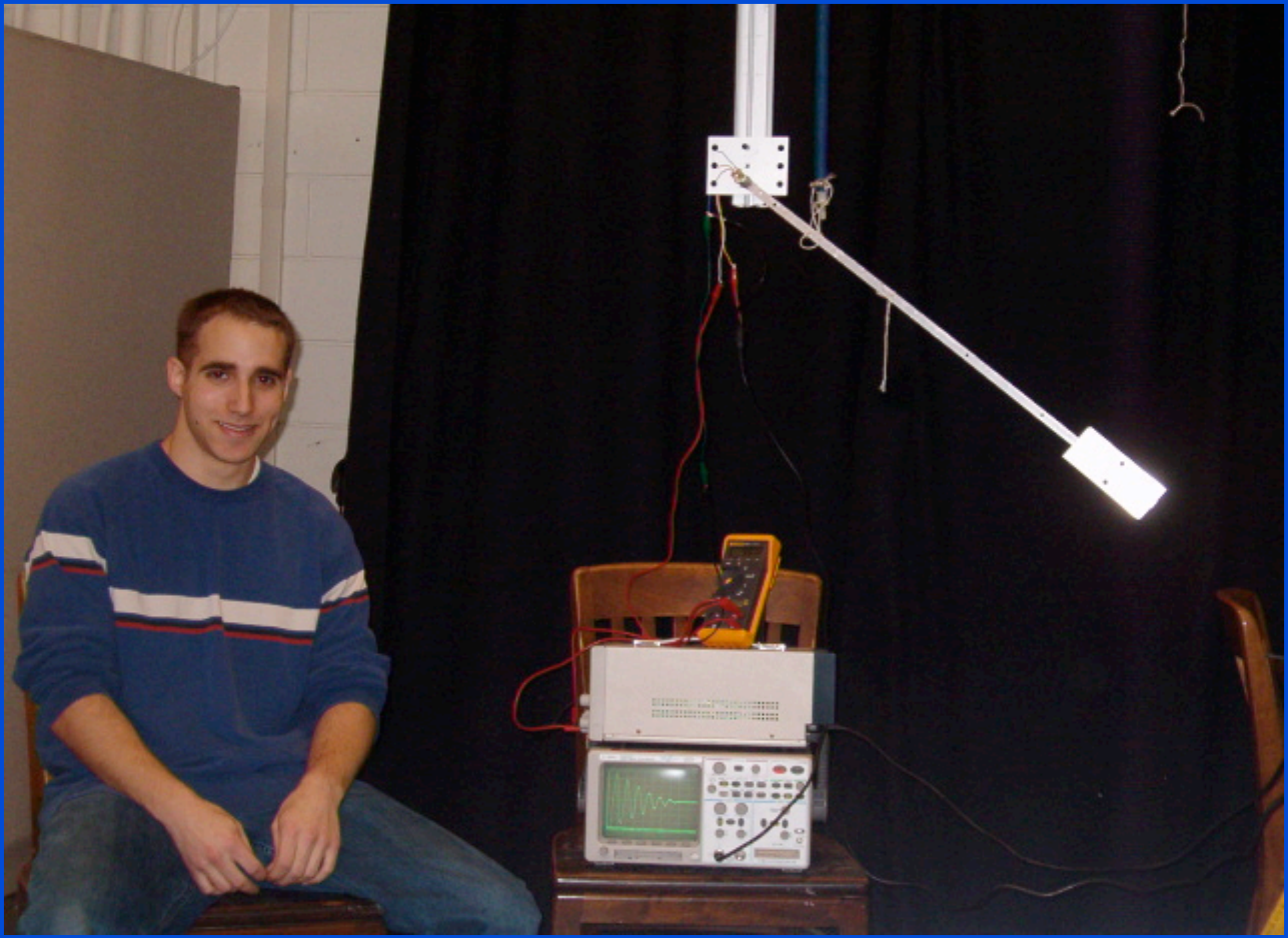
Tom Fina is searching for defects in the breech section of an army tank's gun barrel. To do this, he is using guided waves and ultrasonic technologies.

Engineering Science and Mechanics
engineering the frontiers of science . . .



Brett Shapiro is studying the methods for a semi-active damping control system.

Noninvasive Insulin Delivery and Glucose Monitoring Using a Low-Profile Ultrasound Array

Penn State University, University Park

Shelby Fidler helps develop a new method of drug delivery

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And yeah. . . we hang out too

What does
Engineering Science do?

Whatever you want it to. . . .

- Laser Absorption
- Fluid Visualization
- Material Testing
- Mountain bike suspension
- Sterling Engines
- Drug Transfusion
- Guided Waves
- Nanotechnology
- Thin Films
- Microscopy
- Etc. . . .

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J.B.S. Haldane

The Creator, if he exists, has ...

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J.B.S. Haldane

… an inordinate fondness for beetles.

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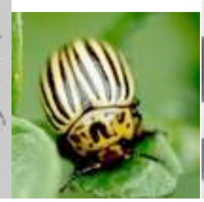
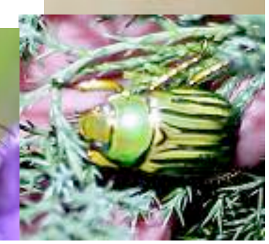
… an inordinate fondness for beetles.





Engineers

have had an inordinate fondness

for

composite materials…

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… right from the Bronze Age.

Composite Materials

Conspirator-in-Chief:
Tom G. Mackay

School of Mathematics, University of Edinburgh

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Frontiers of Materials Research

Evolution of *Materials Research Frontiers*

- Material Properties (< 1970)

Evolution of *Materials Research Frontiers*

- Design for Functionality (ca.1980)

Evolution of *Materials Research Frontiers*

- Design for System Performance (ca. 2000)

Multifunctionality

Thanks: Chuck Bakis

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Multifunctionality

Performance Requirements on the Fuselage

1. Light weight (for fuel efficiency)
2. High stiffness (resistance to deformation)
3. High strength (resistance to rupture)
4. High acoustic damping (quieter cabin)
5. Low thermal conductivity (less condensation; more humid cabin)

Multifunctionality

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Performance Requirements on the Fuselage

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4. High acoustic damping (quieter cabin)
5. Low thermal conductivity (less condensation; more humid cabin)

Future: Conducting fibers for

(i) reinforcement
(ii) antennas
(iii) environmental sensing
(iv) structural health monitoring
(iv) morphing

Evolution of *Materials Research Frontiers*

- Material Properties (< 1970)
- Design for Functionality (ca.1980)
- Design for System Performance (ca. 2000)

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Metamaterials

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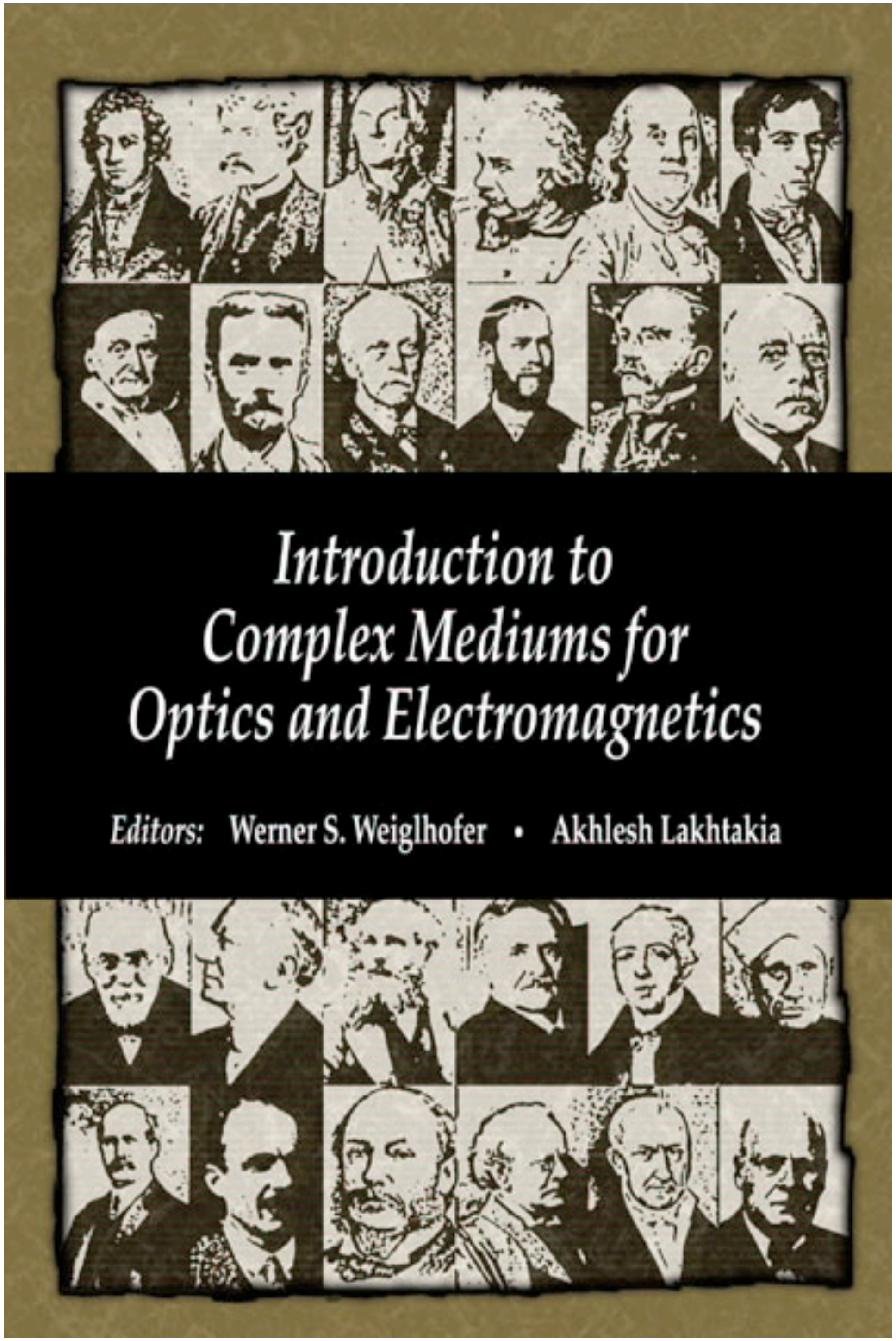
Metamaterials

Rodger Walser

SPIE Press (2003)



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Walser's Definition (2001/2)

- macroscopic composites having a manmade, three-dimensional, periodic cellular architecture designed to produce an optimized combination, not available in nature, of two or more responses to specific excitation

Walser's Definition (2001/2)

manmade

Walser’s Definition (2001/2)

three-dimensional

Walser's Definition (2001/2)

periodic

cellular

Walser's Definition (2001/2)

designed to
produce an optimized combination
of two or more
responses to specific excitation

Walser's Definition (2001/2)

not

available in nature

Walser's Definition (2001/2)

not

available in nature

D.G. Stavenga, Invertebrate superposition eye-structures that behave like metamaterial with negative refractive index, *JEOS-RP* **1**, 06010 (2006).

Walser’s Definition (2001/2)

- macroscopic composites having a manmade, three-dimensional, periodic cellular architecture designed to produce an optimized combination, not available in nature, of two or more responses to specific excitation

Working Definition

‘Metamaterial’

– composite which exhibits properties:

  * not observed in constituents

  or

  * enhanced relative to properties of constituents

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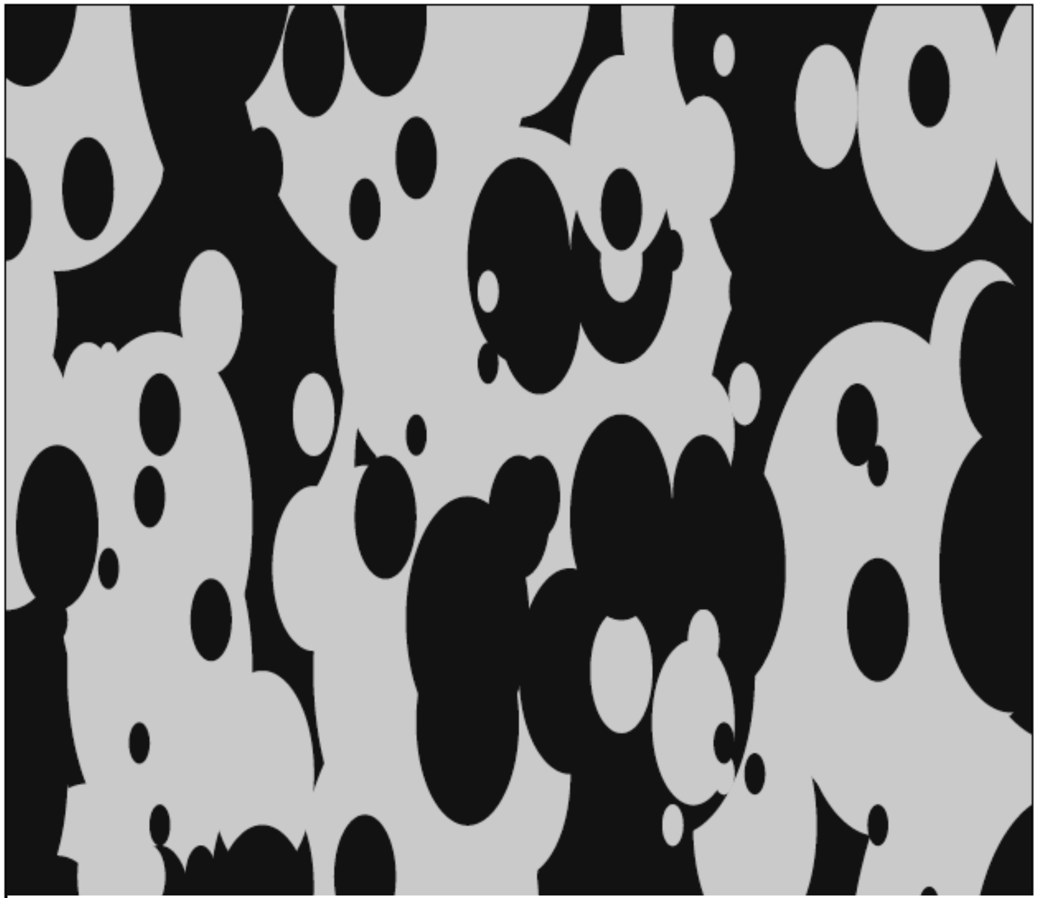
Examples:
Particulate Composite Materials with ellipsoidal inclusions



$\lambda \gg$ inclusion size

Homogenizable Metamaterials

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- Enhancement of group velocity

Homogenizable Metamaterials

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- Enhancement of nonlinearity

Homogenizable Metamaterials

- Voigt wave propagation (degenerate eigenvectors)

Homogenizable Metamaterials

- Bianisotropy (e.g., Faraday chiral medium)

Homogenizable Metamaterials

- Negative phase velocity (isotropy/anisotropy)

Homogenizable Metamaterials

- Enhancement of group velocity
- Enhancement of nonlinearity
- Voigt wave propagation
- Bianisotropy
- Negative phase velocity

http://www.esm.psu.edu/~axl4/lakhtakia/documents/Mackay_06_6MRI.pdf

Composite Materials with Viscoelastic Stiffness Greater Than Diamond

T. Jaglinski,[1] D. Kochmann,[2] D. Stone,[3] R. S. Lakes[4]*

We show that composite materials can exhibit a viscoelastic modulus (Young's modulus) that is far greater than that of either constituent. The modulus, but not the strength, of the composite was observed to be substantially greater than that of diamond. These composites contain barium-titanate inclusions, which undergo a volume-change phase transformation if they are not constrained. In the composite, the inclusions are partially constrained by the surrounding metal matrix. The constraint stabilizes the negative bulk modulus (inverse compressibility) of the inclusions. This negative modulus arises from stored elastic energy in the inclusions, in contrast to periodic composite metamaterials that exhibit negative refraction by inertial resonant effects. Conventional composites with positive-stiffness constituents have aggregate properties bounded by a weighted average of constituent properties; their modulus cannot exceed that of the stiffest constituent.

2 FEBRUARY 2007 VOL 315 SCIENCE

Negative Phase Velocity

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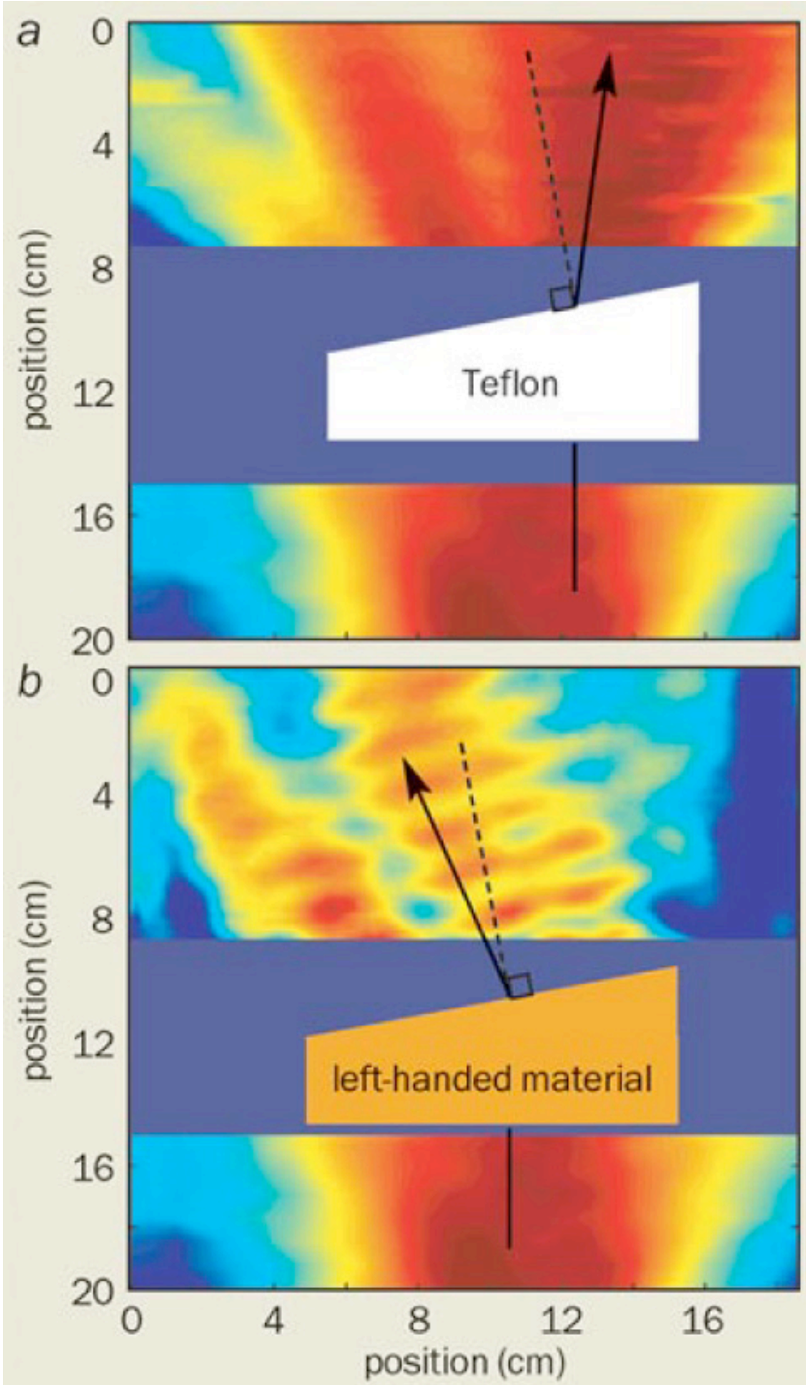

material with n > 0

material with n < 0

Adapted from David Smith's website

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What to make of it?

INSTITUTE OF PHYSICS PUBLISHING EUROPEAN JOURNAL OF PHYSICS

Eur. J. Phys. **23** (2002) 353–359 PII: S0143-0807(02)31789-6

The negative index of refraction demystified

Martin W McCall[1,4], Akhlesh Lakhtakia[2] and Werner S Weiglhofer[3]

Two Important Quantities

- Phase velocity vector
- Time-averaged Poynting vector
  = direction of energy flow & attenuation

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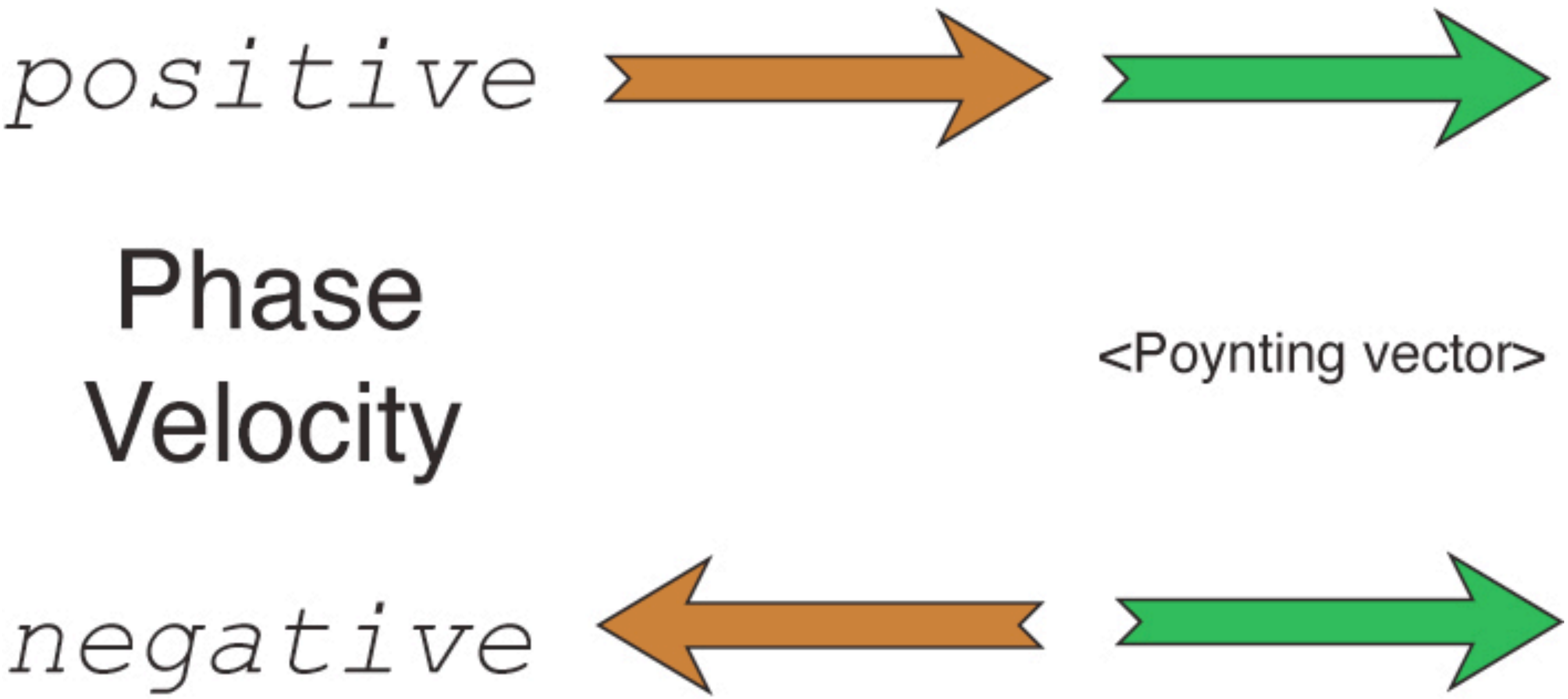
Positive/Negative *Phase Velocity Medium*



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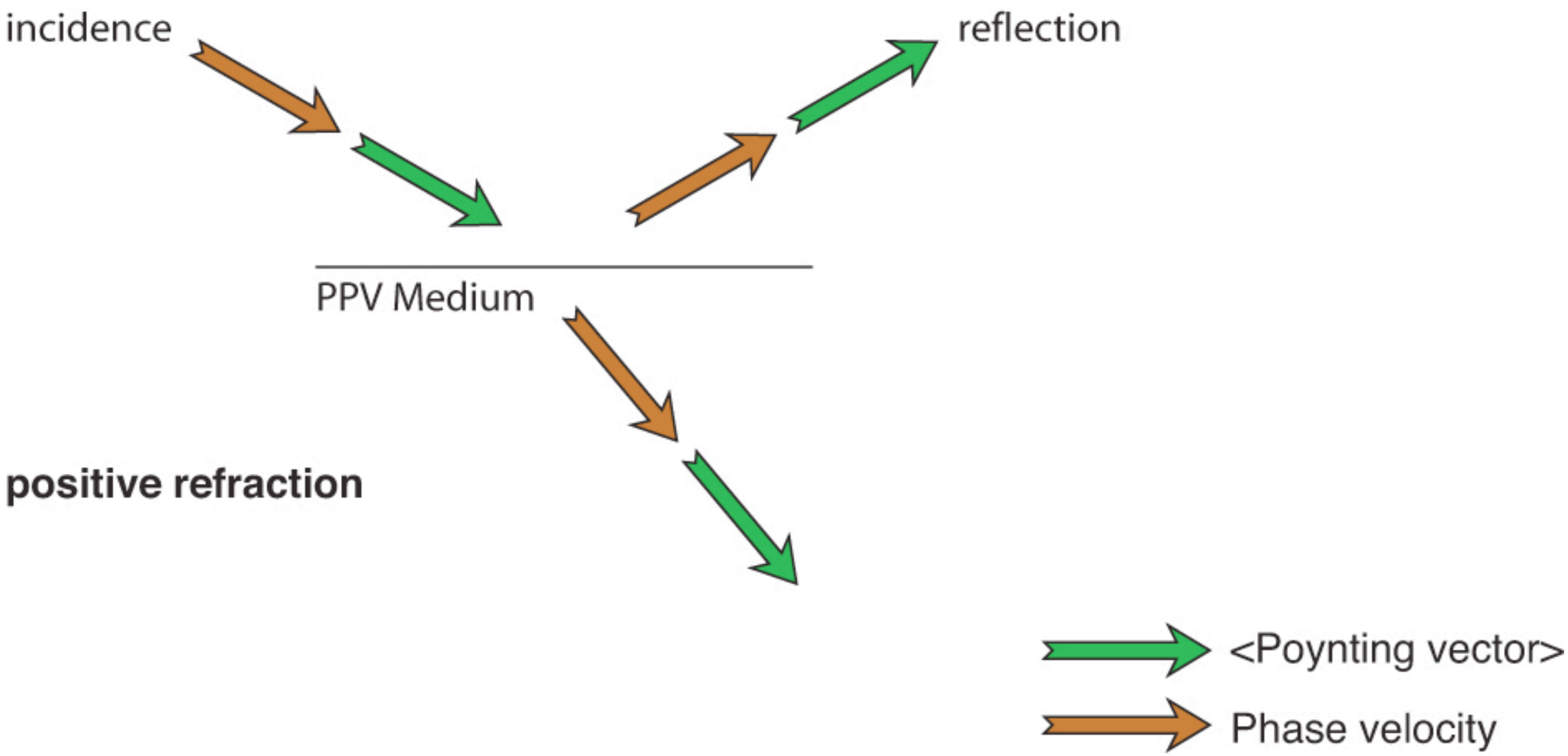
Positive *Refraction by Isotropic Medium*



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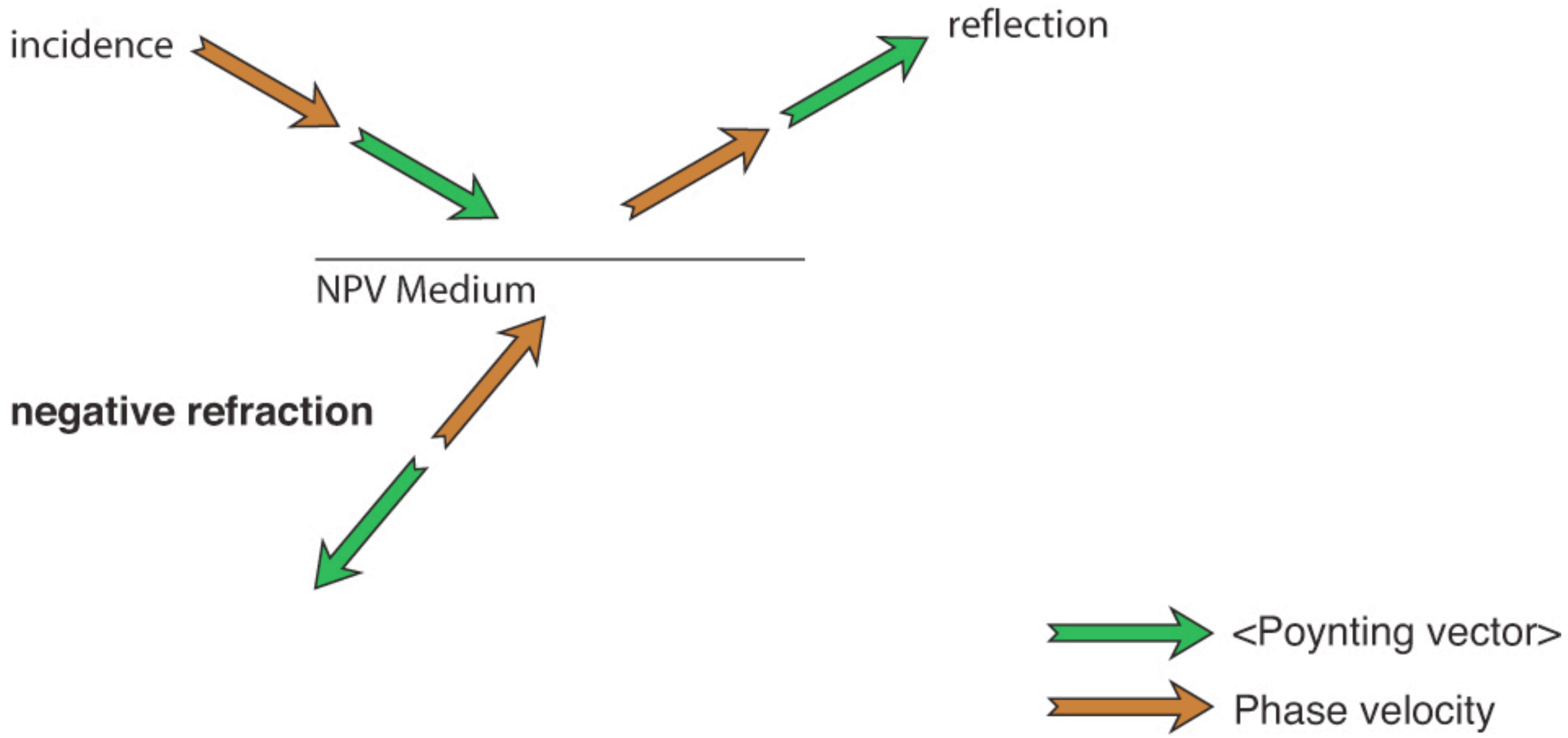
Negative Refraction by Isotropic Medium



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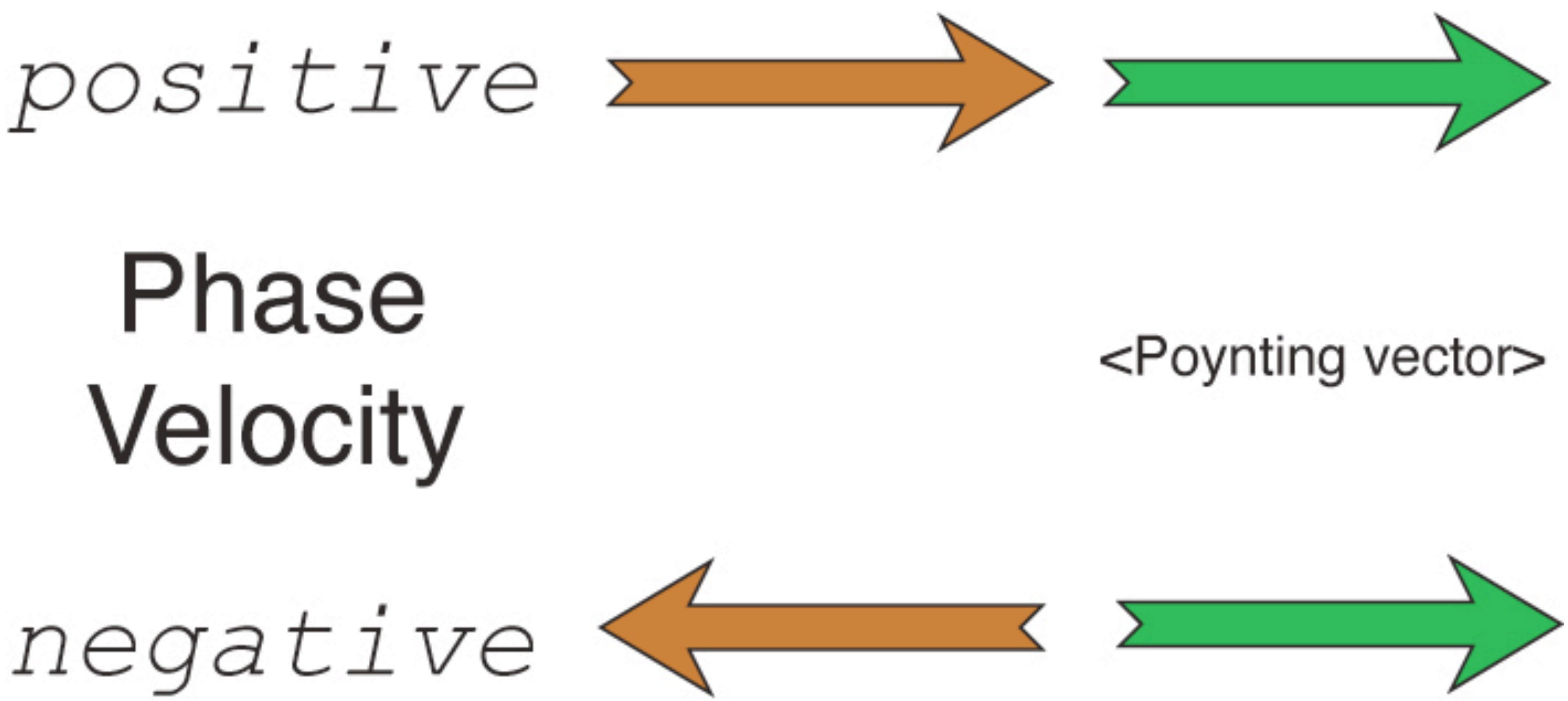
NPV in Simple Mediums



NPV in Bianisotropic Mediums

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PHYSICAL REVIEW E **69**, 026602 (2004)

Plane waves with negative phase velocity in Faraday chiral mediums

Tom G. Mackay*

School of Mathematics, James Clerk Maxwell Building, The King's Buildings, University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom

Akhlesh Lakhtakia†

CATMAS — Computational and Theoretical Materials Sciences Group, Department of Engineering Science and Mechanics, Pennsylvania State University, University Park, Pennsylvania 16802-6812, USA

(Received 18 July 2003; published 10 February 2004)

NPV in Bianisotropic Mediums

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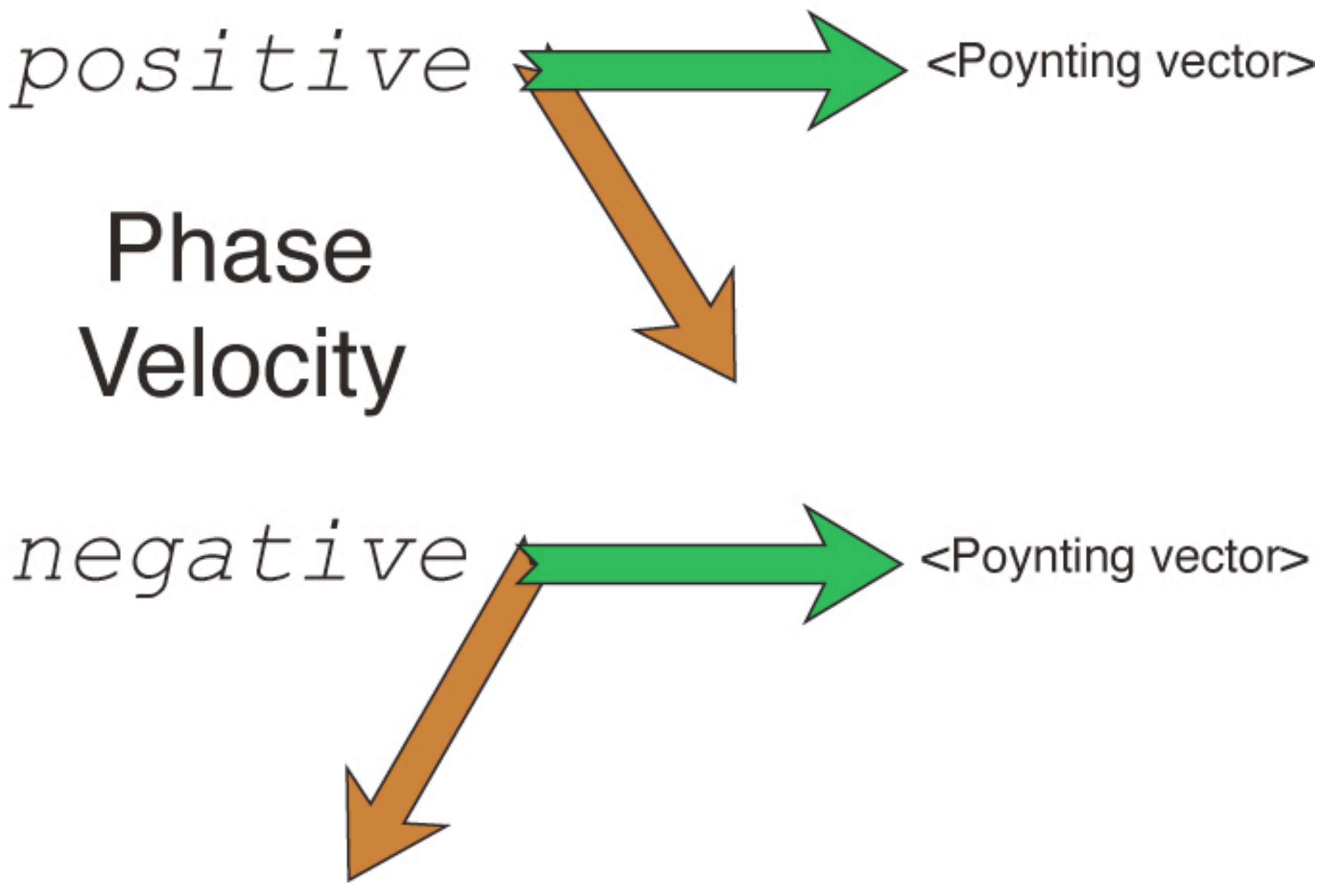

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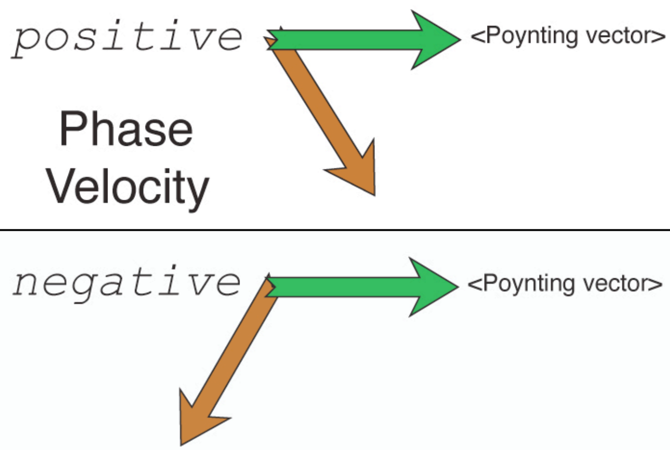
NPV in Bianisotropic Mediums



$$\mathrm{Re}\{\mathbf{k}\}\bullet<\mathbf{P}> \; > 0$$

$$\mathrm{Re}\{\mathbf{k}\}\bullet<\mathbf{P}> \; < 0$$

k = wave vector

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Chirality

Types of Chirality

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Types of Chirality

(a) Microscopic/Microstructural

(i) Isotropic

$$\underline{D}(\underline{r}) = \epsilon_0\,\epsilon\,\underline{E}(\underline{r}) + i\sqrt{\epsilon_0\mu_0}\,\xi\,\underline{H}(\underline{r})$$

$$\underline{B}(\underline{r}) = -i\sqrt{\epsilon_0\mu_0}\,\xi\,\underline{E}(\underline{r}) + \mu_0\,\mu\,\underline{H}(\underline{r})$$

Frequency-domain constitutive equations

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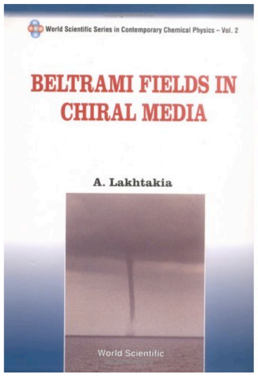
Types of Chirality

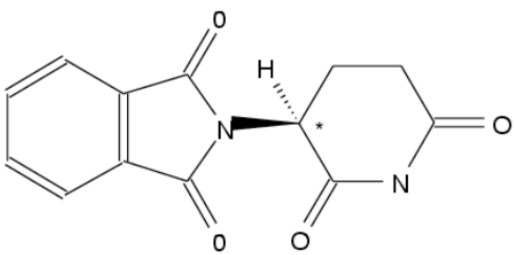
(a) Microscopic/Microstructural



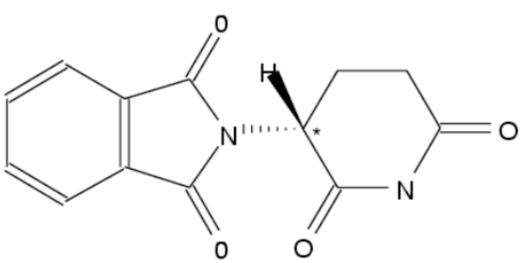
(i) Isotropic

$$\underline{D}(\underline{r}) = \epsilon_0\,\epsilon\,\underline{E}(\underline{r}) + i\sqrt{\epsilon_0\mu_0}\,\xi\,\underline{H}(\underline{r})$$

$$\underline{B}(\underline{r}) = -i\sqrt{\epsilon_0\mu_0}\,\xi\,\underline{E}(\underline{r}) + \mu_0\,\mu\,\underline{H}(\underline{r})$$

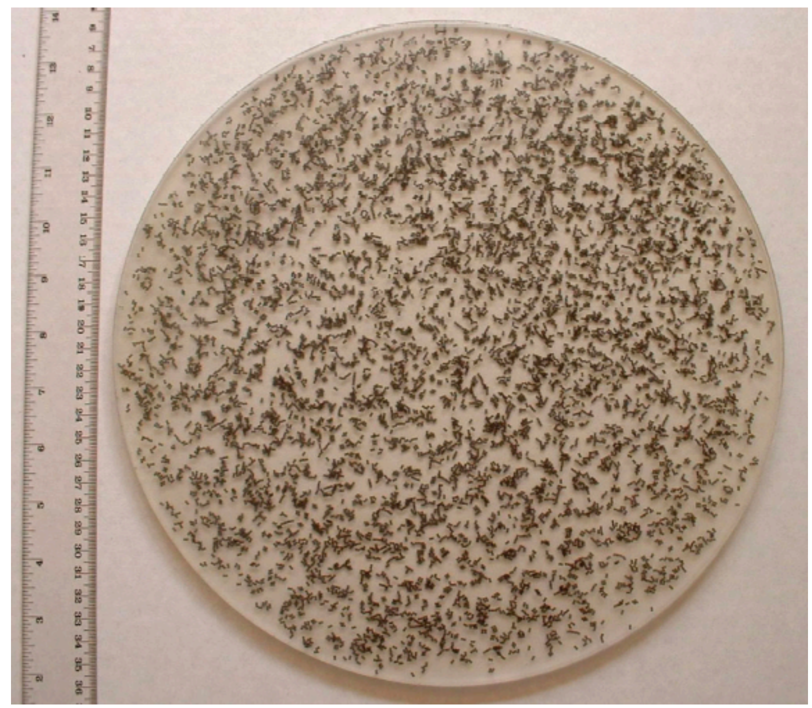


Enantiomère (S) : tératogène



Enantiomère (R) : Non–toxique

Courtesy:
Á. Gómez,
Univ. Cantabria



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Types of Chirality

(a) Microscopic/Microstructural

(i) Isotropic

$$\underline{D}(\underline{r}) = \epsilon_0\,\epsilon\,\underline{E}(\underline{r}) + i\sqrt{\epsilon_0\mu_0}\,\xi\,\underline{H}(\underline{r})$$
$$\underline{B}(\underline{r}) = -i\sqrt{\epsilon_0\mu_0}\,\xi\,\underline{E}(\underline{r}) + \mu_0\,\mu\,\underline{H}(\underline{r})$$

(ii) Faraday chiral

$$\underline{D}(\underline{r}) = \underline{\underline{\epsilon}} \bullet \underline{E}(\underline{r}) + \underline{\underline{\xi}} \bullet \underline{H}(\underline{r})$$
$$\underline{B}(\underline{r}) = -\underline{\underline{\xi}} \bullet \underline{E}(\underline{r}) + \underline{\underline{\mu}} \bullet \underline{H}(\underline{r})$$

$$\underline{\underline{\epsilon}} = \epsilon_0 \left[\epsilon\,\underline{\underline{I}} - i\epsilon_g\,\hat{\underline{z}} \times \underline{\underline{I}} + (\epsilon_z - \epsilon)\,\hat{\underline{z}}\,\hat{\underline{z}} \right]$$
$$\underline{\underline{\xi}} = i\sqrt{\epsilon_0\mu_0} \left[\xi\,\underline{\underline{I}} - i\xi_g\,\hat{\underline{z}} \times \underline{\underline{I}} + (\xi_z - \xi)\,\hat{\underline{z}}\,\hat{\underline{z}} \right]$$
$$\underline{\underline{\mu}} = \mu_0 \left[\mu\,\underline{\underline{I}} - i\mu_g\,\hat{\underline{z}} \times \underline{\underline{I}} + (\mu_z - \mu)\,\hat{\underline{z}}\,\hat{\underline{z}} \right]$$

Frequency-domain constitutive equations

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Types of Chirality

(a) Microscopic/Microstructural

(i) Isotropic

$$\underline{D}(\underline{r}) = \epsilon_0\,\epsilon\,\underline{E}(\underline{r}) + i\sqrt{\epsilon_0\mu_0}\,\xi\,\underline{H}(\underline{r})$$
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$$\underline{\underline{\xi}} = i\sqrt{\epsilon_0\mu_0} \left[\xi\,\underline{\underline{I}} - i\xi_g\,\hat{\underline{z}} \times \underline{\underline{I}} + (\xi_z - \xi)\,\hat{\underline{z}}\,\hat{\underline{z}} \right]$$
$$\underline{\underline{\mu}} = \mu_0 \left[\mu\,\underline{\underline{I}} - i\mu_g\,\hat{\underline{z}} \times \underline{\underline{I}} + (\mu_z - \mu)\,\hat{\underline{z}}\,\hat{\underline{z}} \right]$$

(iii) Nonhomogeneous Variants

Frequency-domain constitutive equations

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Types of Chirality

(b) Macrostructural

$$\underline{D}(\underline{r}) = \underline{\underline{S}}(z) \bullet \left[\underline{\underline{\epsilon}}_{ref} \bullet \underline{\underline{S}}^T(z) \bullet \underline{E}(\underline{r}) + \underline{\underline{\xi}}_{ref} \bullet \underline{\underline{S}}^T(z) \bullet \underline{H}(\underline{r}) \right]$$

$$\underline{B}(\underline{r}) = \underline{\underline{S}}(z) \bullet \left[\underline{\underline{\zeta}}_{ref} \bullet \underline{\underline{S}}^T(z) \bullet \underline{E}(\underline{r}) + \underline{\underline{\mu}}_{ref} \bullet \underline{\underline{S}}^T(z) \bullet \underline{H}(\underline{r}) \right]$$

Linear Bianisotropic Materials

$$\begin{aligned}
\underline{\underline{S}}_x(z) &= \mathbf{u}_x\mathbf{u}_x + (\mathbf{u}_y\mathbf{u}_y + \mathbf{u}_z\mathbf{u}_z)\cos\xi(z) \\
&\quad + (\mathbf{u}_z\mathbf{u}_y - \mathbf{u}_y\mathbf{u}_z)\sin\xi(z)\,, \\
\underline{\underline{S}}_y(z) &= \mathbf{u}_y\mathbf{u}_y + (\mathbf{u}_x\mathbf{u}_x + \mathbf{u}_z\mathbf{u}_z)\cos\tau(z) \\
&\quad + (\mathbf{u}_z\mathbf{u}_x - \mathbf{u}_x\mathbf{u}_z)\sin\tau(z)\,, \\
\underline{\underline{S}}_z(z) &= \mathbf{u}_z\mathbf{u}_z + (\mathbf{u}_x\mathbf{u}_x + \mathbf{u}_y\mathbf{u}_y)\cos\zeta(z) \\
&\quad + (\mathbf{u}_y\mathbf{u}_x - \mathbf{u}_x\mathbf{u}_y)\sin\zeta(z)\,.
\end{aligned}$$

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Types of Chirality

(b) Macrostructural

Dielectric Materials

$$
\begin{aligned}
\mathbf{D}(\mathbf{r},\omega) &= \epsilon_0\, \underline{\underline{\epsilon}}_{\,r}(z,\omega) \bullet \mathbf{E}(\mathbf{r},\omega) \\
&= \epsilon_0\, \underline{\underline{S}}(z) \bullet \underline{\underline{\epsilon}}_{\,ref}(\omega) \bullet \underline{\underline{S}}^{T}(z) \bullet \mathbf{E}(\mathbf{r},\omega)\,, \\
\mathbf{B}(\mathbf{r},\omega) &= \mu_0\, \mathbf{H}(\mathbf{r},\omega)\,.
\end{aligned}
$$

Local Orthorhombicity

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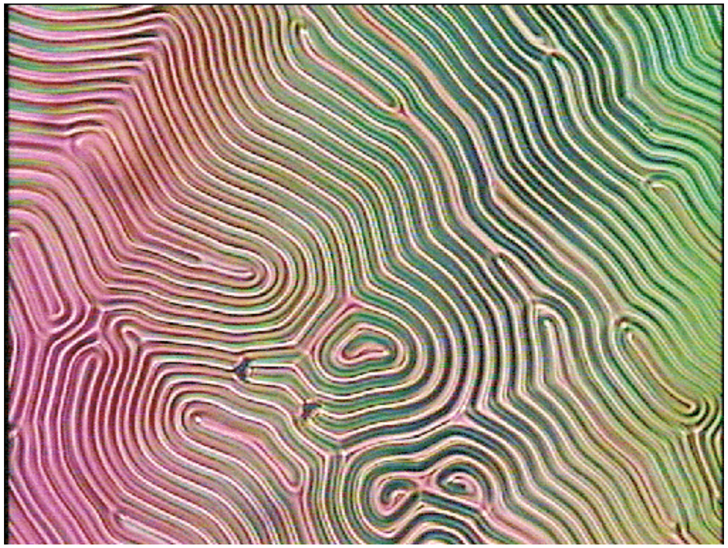
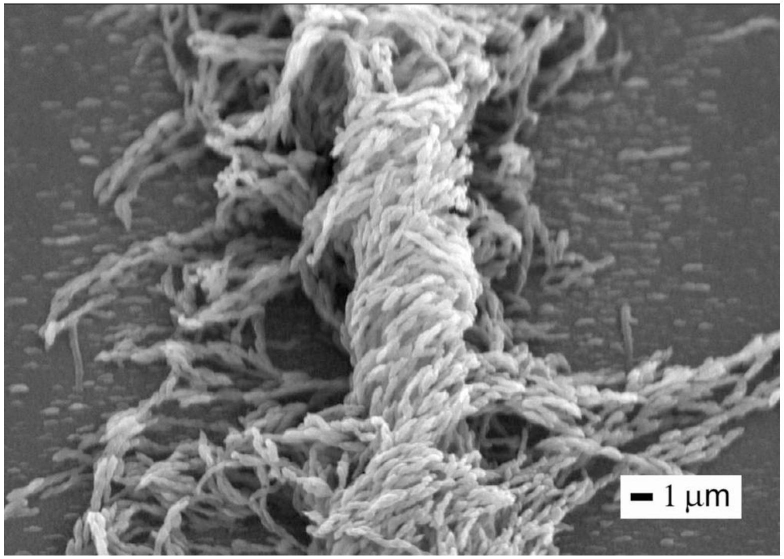
Types of Chirality

(b) Macrostructural



http://www.mc2.chalmers.se/pl/lc/engelska/gallery/fingerprint.html



http://www.lcd.kent.edu/images/4.htm

Cholesteric LC with helical axis in the substrate plane

Twisted-grain polymer morphology due to a choleesteric LC host

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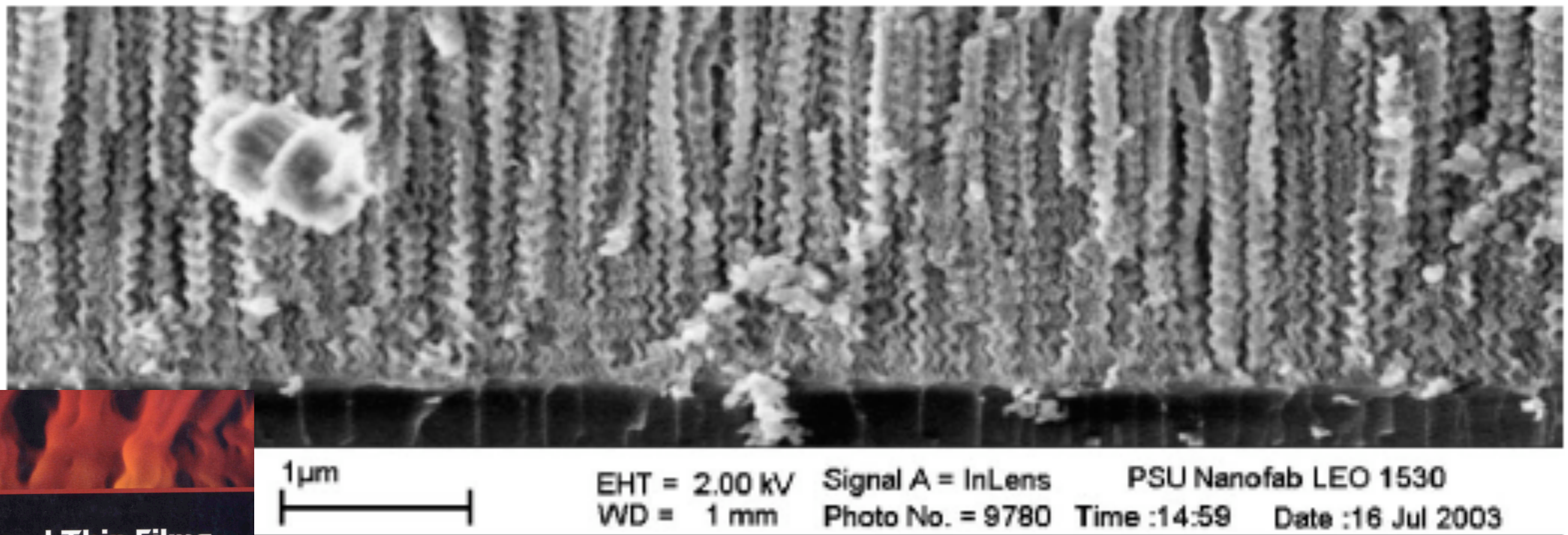
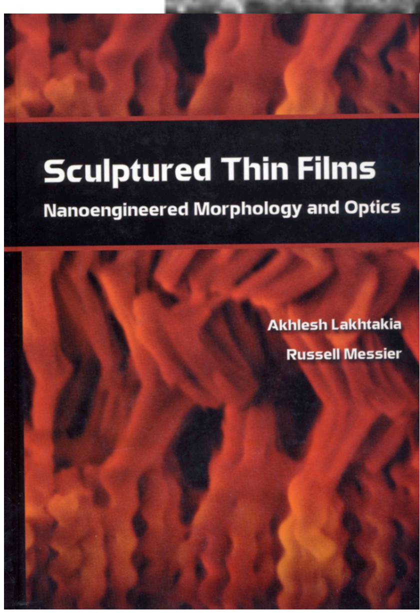
Types of Chirality

(b) Macrostructural





Chiral sculptured thin film

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Isotropic Chiral Medium

Isotropic Chiral Medium

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$$\underline{D}(\underline{r}) = \epsilon_0\,\epsilon\,\underline{E}(\underline{r}) + i\sqrt{\epsilon_0\mu_0}\,\xi\,\underline{H}(\underline{r})$$

$$\underline{B}(\underline{r}) = -i\sqrt{\epsilon_0\mu_0}\,\xi\,\underline{E}(\underline{r}) + \mu_0\,\mu\,\underline{H}(\underline{r})$$

PLANE WAVES WITH NEGATIVE PHASE VELOCITY IN ISOTROPIC CHIRAL MEDIUMS

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120 MICROWAVE AND OPTICAL TECHNOLOGY LETTERS / Vol. 45, No. 2, April 20 2005

Isotropic Chiral Medium

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Plane waves

$$\mathbf{E}(\mathbf{r}) = \mathbf{E}_0 \exp(ik\,\hat{\mathbf{k}} \bullet \mathbf{r})$$

$$\mathbf{H}(\mathbf{r}) = \mathbf{H}_0 \exp(ik\,\hat{\mathbf{k}} \bullet \mathbf{r})$$

NPV condition

$$\mathrm{Re}\,[\mathbf{k}] \bullet \langle \mathbf{P} \rangle < 0$$

4 wavenumbers

$$k^{(i)} = -\omega\sqrt{\epsilon_0\mu_0}\left(\sqrt{\epsilon\mu} + \xi\right)$$

$$k^{(ii)} = \omega\sqrt{\epsilon_0\mu_0}\left(\sqrt{\epsilon\mu} - \xi\right)$$

$$k^{(iii)} = -\omega\sqrt{\epsilon_0\mu_0}\left(\sqrt{\epsilon\mu} - \xi\right)$$

$$k^{(iv)} = \omega\sqrt{\epsilon_0\mu_0}\left(\sqrt{\epsilon\mu} + \xi\right)$$

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Isotropic Chiral Medium

2 NPV Conditions

$$\mathrm{Re}\left\{\sqrt{\epsilon\mu}+\xi\right\}\times\mathrm{Re}\left\{\sqrt{\frac{\epsilon^*}{\mu^*}}\right\}<0 \qquad \text{for} \qquad k=k^{(i),(iv)}$$

$$\mathrm{Re}\left\{\sqrt{\epsilon\mu}-\xi\right\}\times\mathrm{Re}\left\{\sqrt{\frac{\epsilon^*}{\mu^*}}\right\}<0 \qquad \text{for} \qquad k=k^{(ii),(iii)}$$

Negligible dissipation

$$\sqrt{\epsilon\mu}<-\xi \qquad \text{for} \qquad k=k^{(i),(iv)}$$

$$\sqrt{\epsilon\mu}<\xi \qquad \text{for} \qquad k=k^{(ii),(iii)}$$

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Isotropic Chiral Medium

Planewave propagation in a specific direction

2 Beltrami modes	
Both PPV	Re[k] > 0
Both NPV	Re[k] < 0
Both IPV	Re[k] = 0
1 NPV, 1 PPV	
1 IPV, 1 PPV	
1 IPV, 1NPV	

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Isotropic Chiral Medium

Advantage: Birefringence

Refraction can create two channels.

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Isotropic Chiral Medium

Advantage: **Birefringence**

Refraction can create two channels.

Challenge: Can ξ be large enough

so that

one channel is NPV,

the other PPV?

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Assessment

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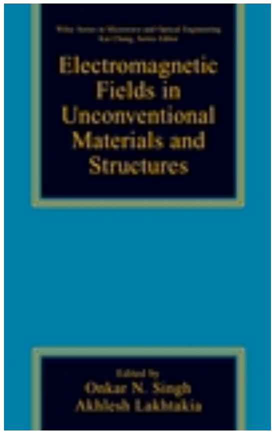
Assessment



- Anisotropy: the direction-dependent contraction of space and absorption
- Chirality: the twisting of space
- Nonhomogeneity: the redirection of energy into different directions by material interfaces
- Nonlinearity: the emission of absorbed energy at (generally) some other frequency

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Assessment

Geometry (structure) is integral to complex materials.

Assessment

Geometry (structure) is integral to complex materials.

Geometry begets chirality and anisotropy.

Assessment

Geometry (structure) is integral to complex materials.

Geometry begets chirality and anisotropy.

Question: How important are chirality and anisotropy?

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Assessment

Answer: **Isotropic Chiral Materials**
Faraday Chiral Materials

Polarization adjustment
like retro-rockets

Macrostructural Chiral Materials

Polarization filtering

Assessment

“Large” anisotropy is “easy” to design for and achieve.

“Large” isotropic chirality is not “easy” to design for and achieve.

PENNSTATE

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Curl Enhancer

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Assessment

"Large" isotropic chirality is not "easy" to design for and achieve.

Focus on nihility

$$\varepsilon = 0,\ \mu = 0$$

International Journal of Infrared and Millimeter Waves, Vol. 23, No. 6, June 2002 (© 2002)

AN ELECTROMAGNETIC TRINITY FROM "NEGATIVE PERMITTIVITY" AND "NEGATIVE PERMEABILITY"*

Akhlesh Lakhtakia


"That's all Folks!"