Sculptured Thin Films: Nanoengineered Metamaterials

Presented in the International Embryo Physics Course http://www.embryophysics.org

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By

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Sculptured Thin Films: Nanoengineered Metamaterials

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International Embryo Physics Course

June 16, 2010


• Nanotechnology
• Metamaterials
•Sculptured Thin Films

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Nanotechnology

Nanotechnology

promises to be

- pervasive
- ubiquitous

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Nanotechnology: Many Initiators

1850s	Colored glasses (nanoparticles)
1880s	Thin films
1910s	Colloidal chemistry
1960s	Integrated circuits
1970s	Supramolecular chemistry
1981	Scanning tunneling microscopy

Significant Attributes

- Large surface area per unit volume
- Quantum effects

Dimensionality

- **1 D**
  - Ultrathin coatings
- **2 D**
  - Nanowires and nanotubes
- **3 D**
  - Nanoparticles

Nanomaterials

- *Lots of potential applications*

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Metamaterials

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J.B.S. Haldane

The Creator, if he exists, has ...


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… an inordinate fondness for beetles.

Engineers

have had an inordinate fondness

for

composite materials

all through the ages

Evolution of *Materials Research*

- Material Properties (< ca.1970)

Evolution of *Materials Research*

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

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Evolution of *Materials Research*

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

Multifunctionality

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Multifunctionality

Multifunctionality

Performance Requirements on the Fuselage

1. Light weight (for fuel efficiency)
2. High stiffness (resistance to deformation)
3. High strength (resistance to rupture)

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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)

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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)

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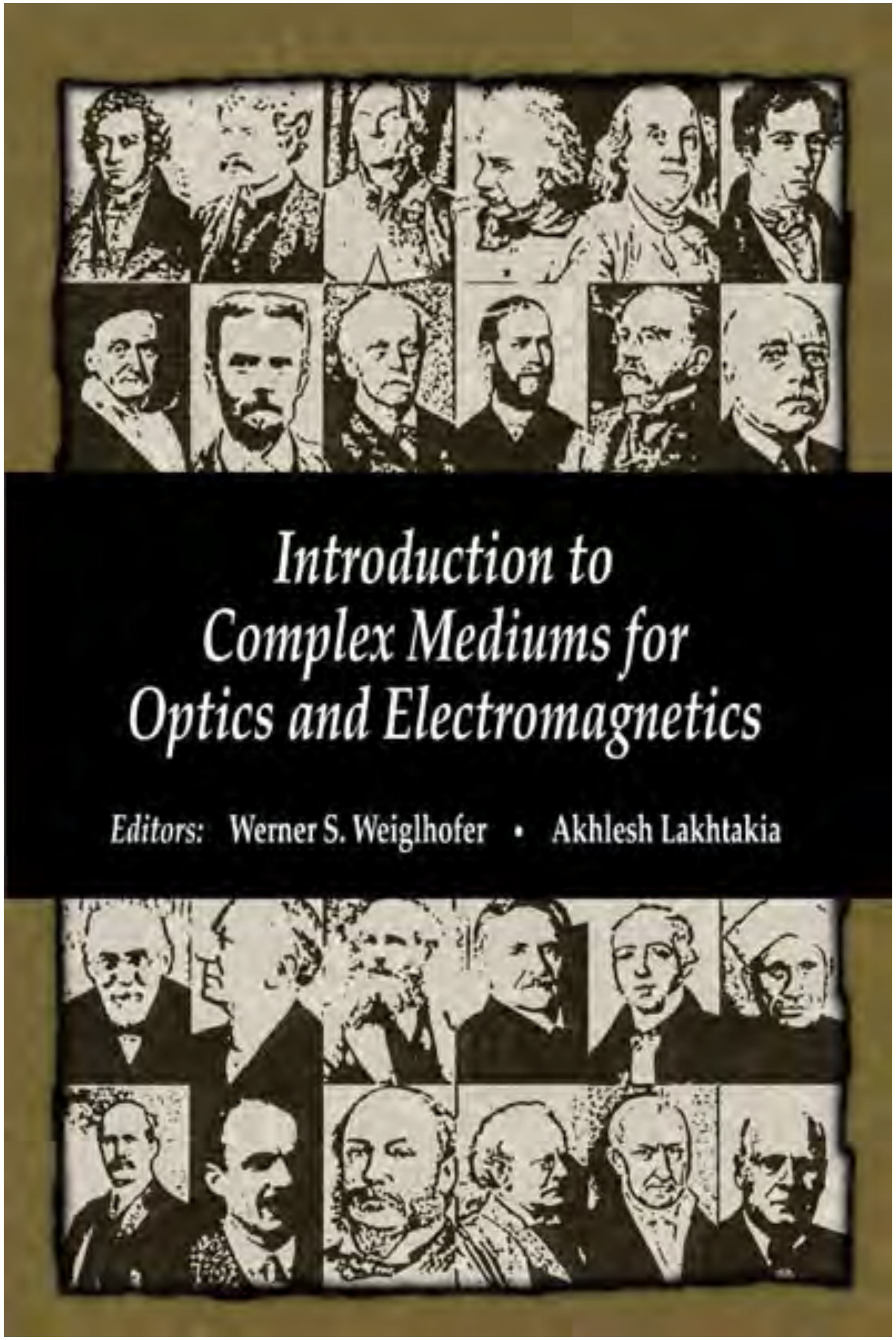
Metamaterials

Rodger Walser

SPIE Press (2003)



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"Updated" Definition

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

Cellularity

Nanoengineered Metamaterials

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Cellularity **Multifunctionality**

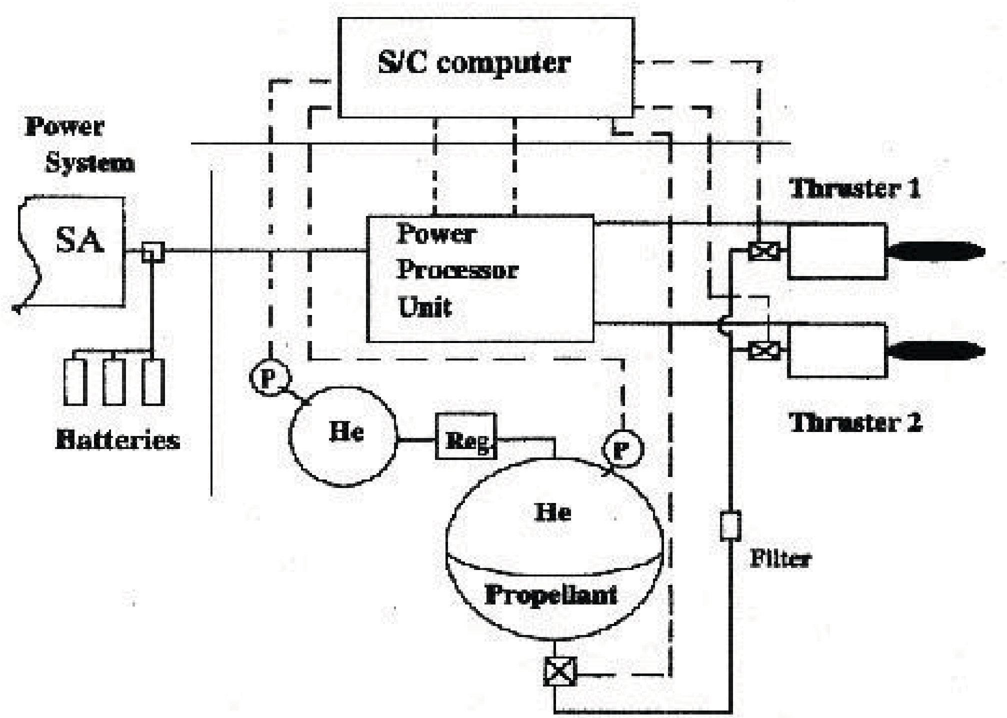
Morphology **Performance**

Nanoengineered Metamaterials

Multi-component system = Assembly of different components

Component:
Simple action

Assembly of components:
Complex action



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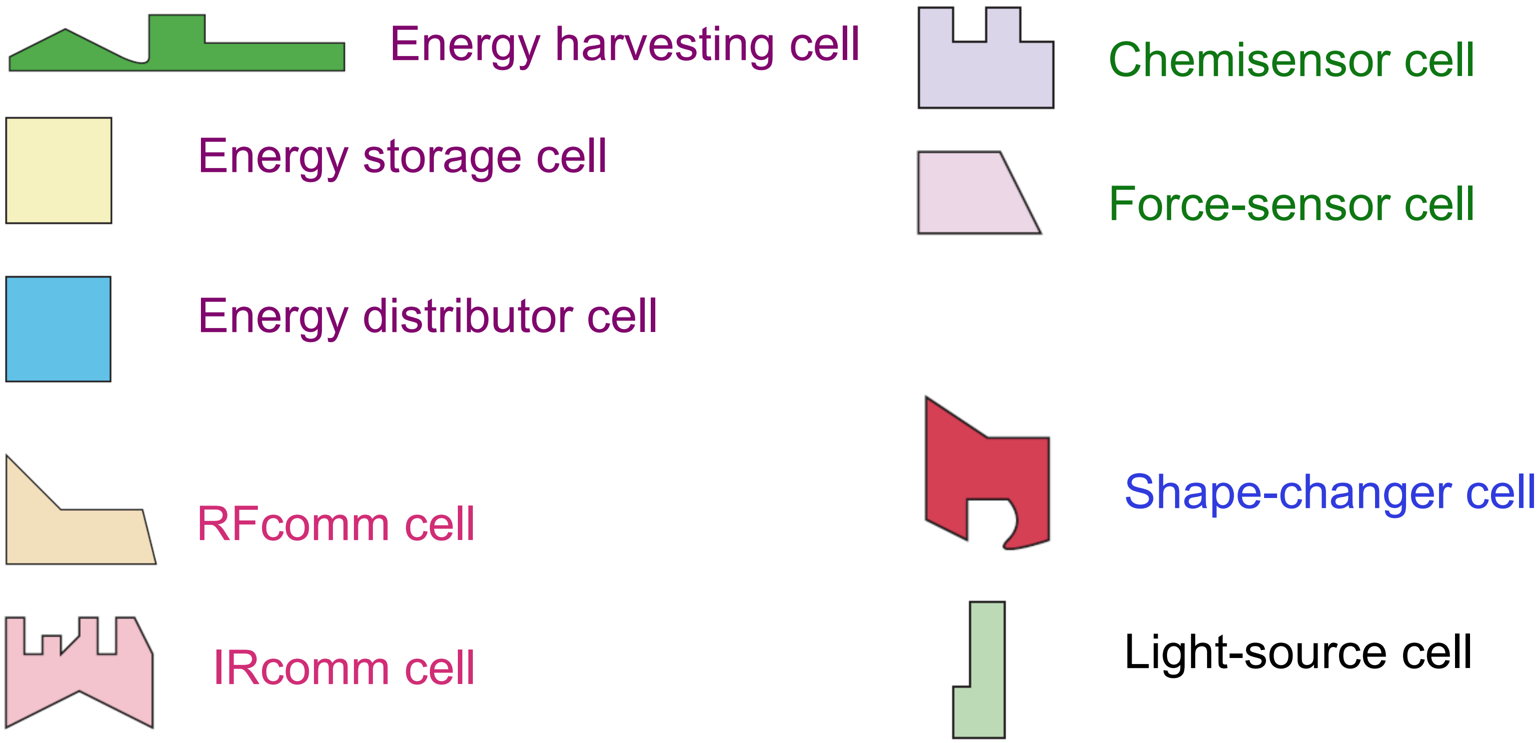
Nanoengineered Metamaterials



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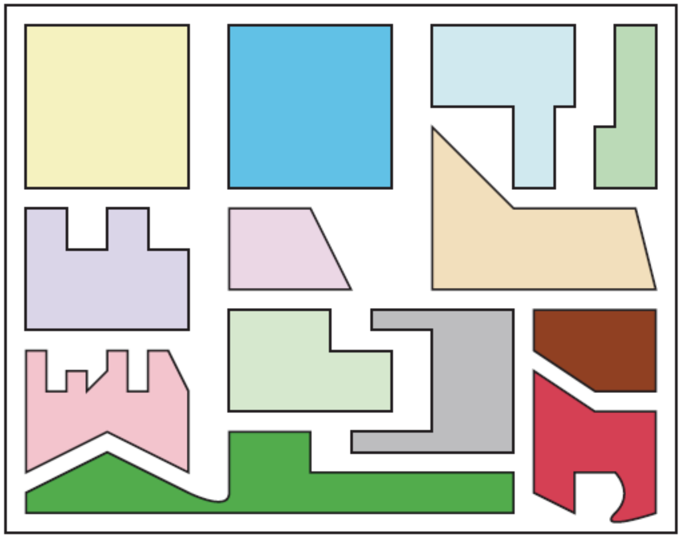
Supercell



Nanoengineered Metamaterials

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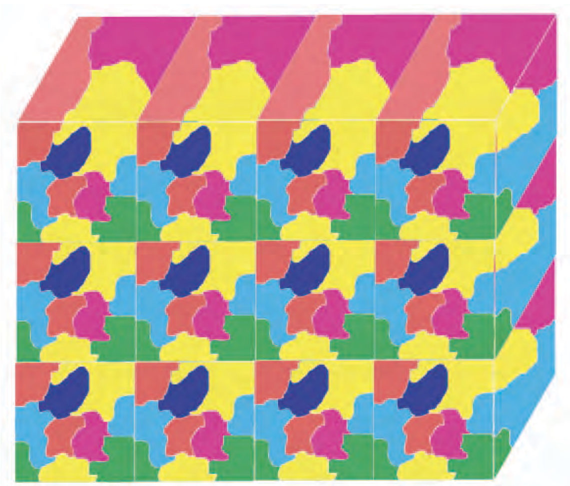
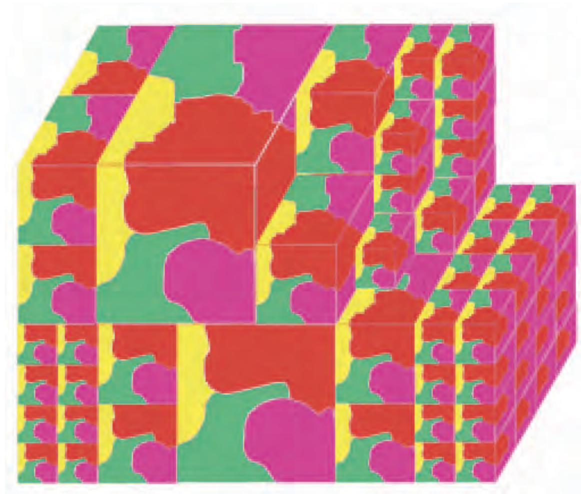
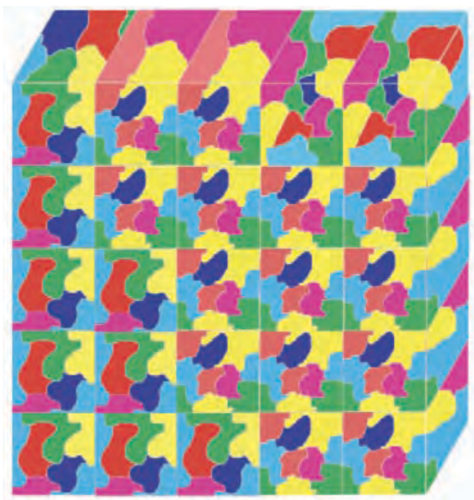
Periodic Arrangement of Supercells



Fractal Arrangement of Supercells

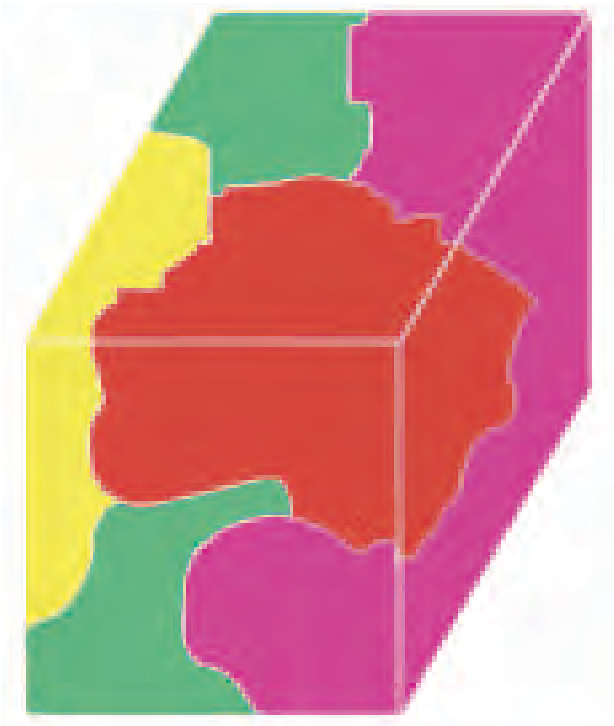


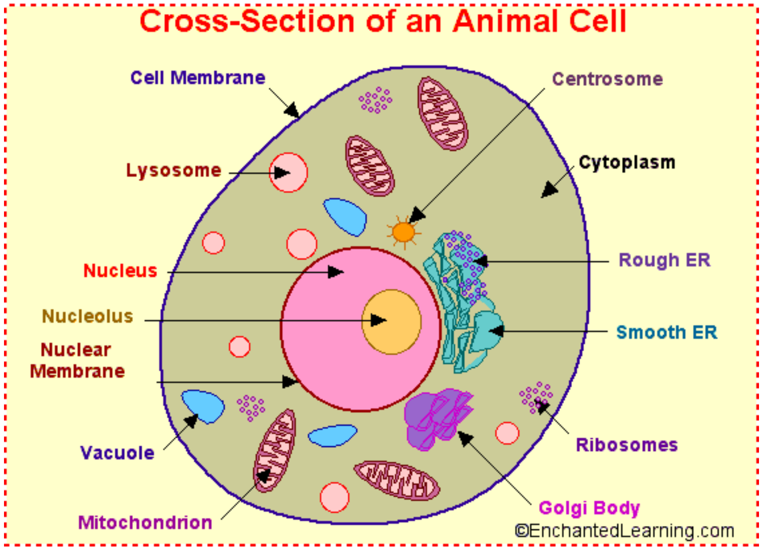
Functionally Graded Arrangement of Supercells



Nanoengineered Metamaterials

Biomimesis





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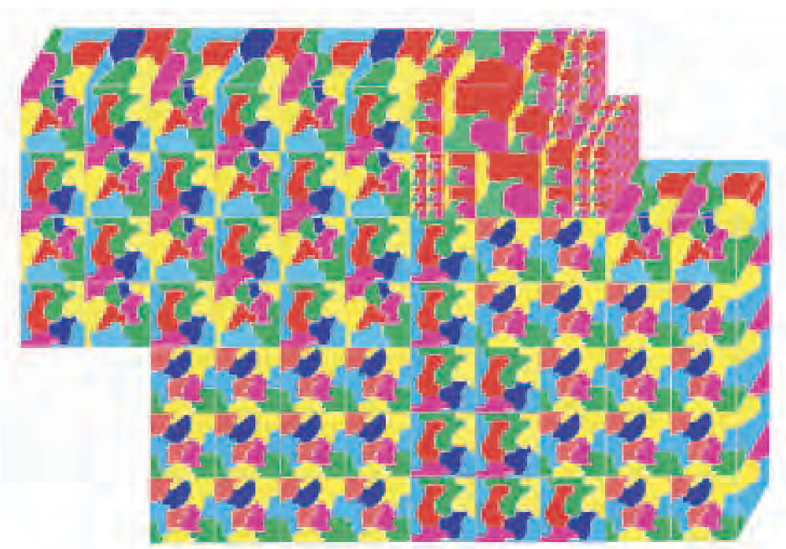
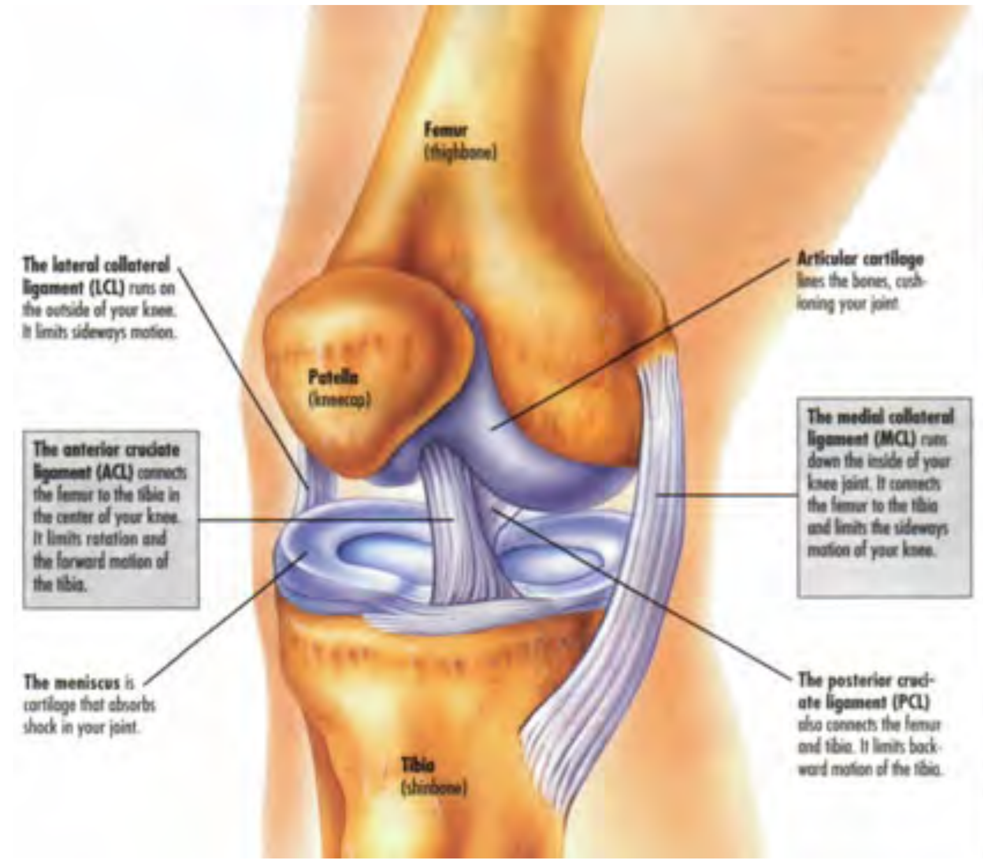
Biomimesis





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Nanoengineered Metamaterials

Fabrication

1. Self-assembly
2. Positional assembly
3. Lithography
4. Etching
5. Ink-jet printing
6. ….
7. ….
8. Hybrid techniques

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Sculptured Thin Films

Sculptured Thin Films

Sculptured Thin Films

Assemblies of Parallel Curved Nanowires/Submicronwires

Controllable Nanowire Shape

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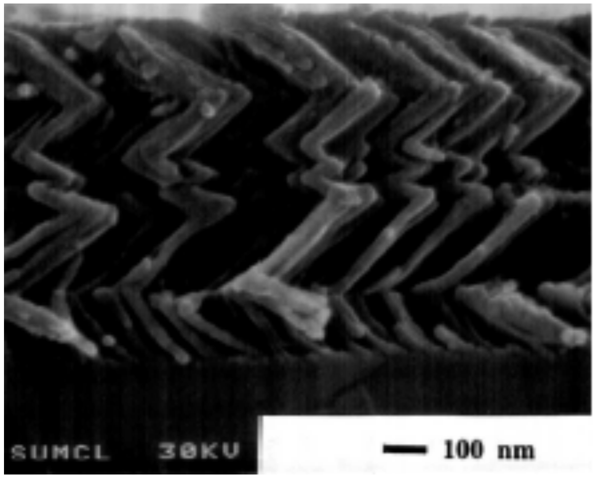
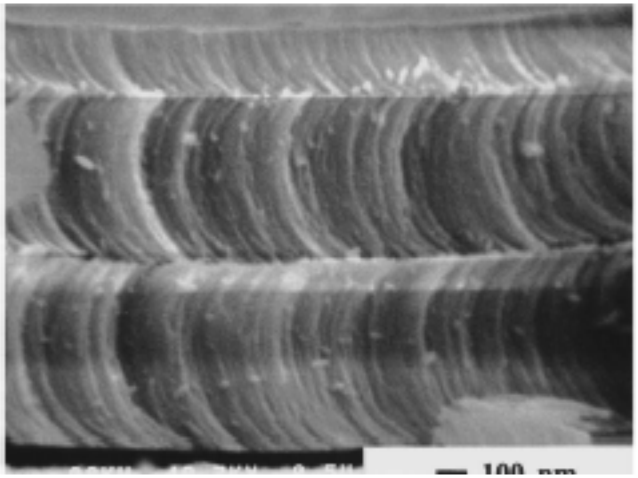
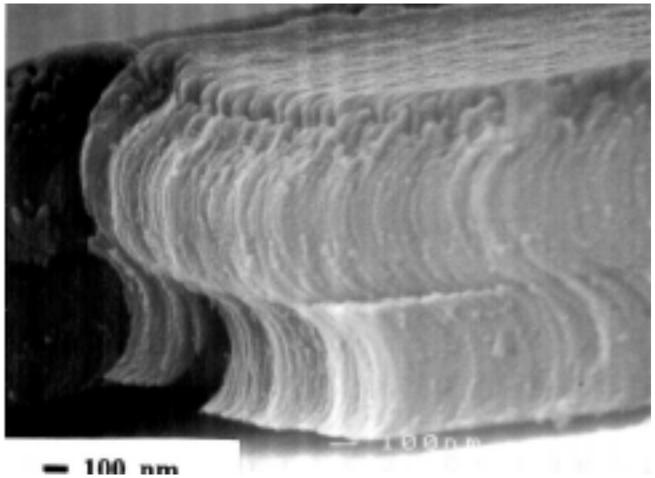
Sculptured Thin Films

Assemblies of Parallel Curved Nanowires/Submicronwires

Controllable Nanowire Shape







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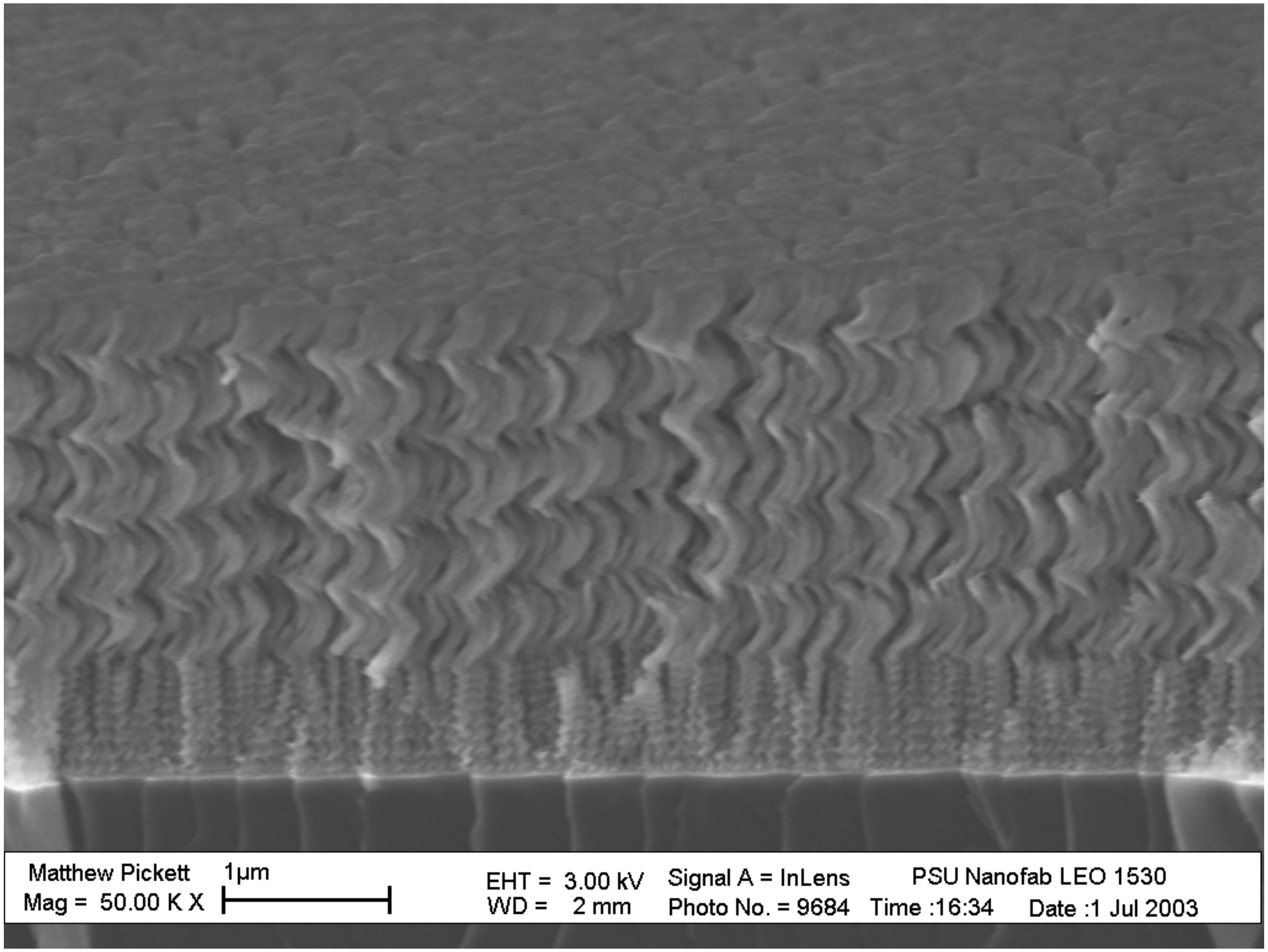
Sculptured Thin Films



Morphological Change

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Sculptured Thin Films

Assemblies of Parallel Curved Nanowires/Submicronwires

Controllable Nanowire Shape

2-D *morphologies*
3-D *morphologies*

vertical sectioning

Nanoengineered Materials (1-3 nm clusters)

Controllable Porosity (10-90 %)

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Sculptured Thin Films

Antecedents:

(i) Young and Kowal - 1959

(ii) Niuewenhuizen & Haanstra - 1966

(iii) Motohiro & Taga - 1989

Conceptualized by Lakhtakia & Messier (1992-1995)

Sculptured Thin Films

Research Groups

(i) Penn State
(ii) Edinboro University of Pennsylvania
(iii) Lock Haven University of Pennsylvania
(iv) Millersville University
(v) Rensselaer Polytechnic University
(vi) University of Arkansaa, Little Rock
(vii) University of Toledo
(viii) University of Georgia
(ix) University of South Carolina
(x) University of Nebraska at Lincoln
(xi) Pacific Northwest National Laboratory
(xii) University of Alberta
(xiii) Queen's University
(xiv) University of Moncton
(xv) National Autonomous University of Mexico
(xvi) Imperial College, London
(xvii) University of Glasgow
(xviii) University of Edinburgh
(xix) University of Leipzig
(xx) ENSMM, Besançon
(xxi) Toyota R&D Labs
(xxii) Kyoto University
(xxiii) Hanyang University
(xxiv) Inha University
(xxv) Dalian University of Technology
(xxvi) National Taipei University of Tech.
(xxvii) Indian Institute of Tech., Kanpur
(xxviii) University of Otago
(xxix) University of Canterbury
(xxx) Ben Gurion Univ. of the Negev
(xxxi) University of Campinas

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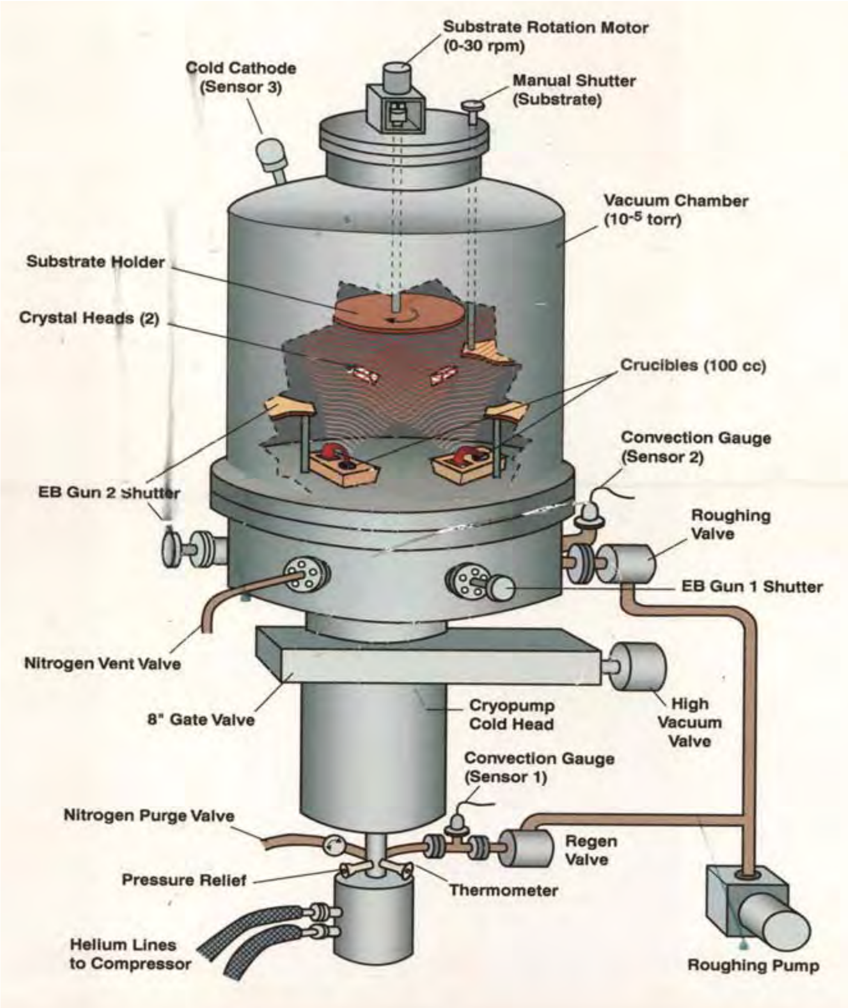
Physical Vapor Deposition



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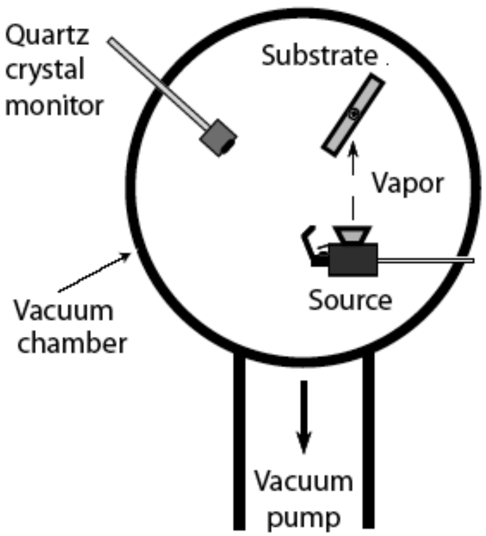
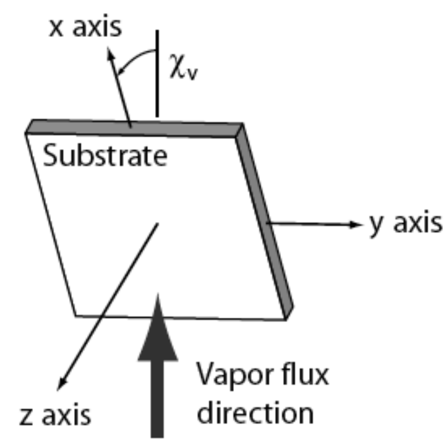
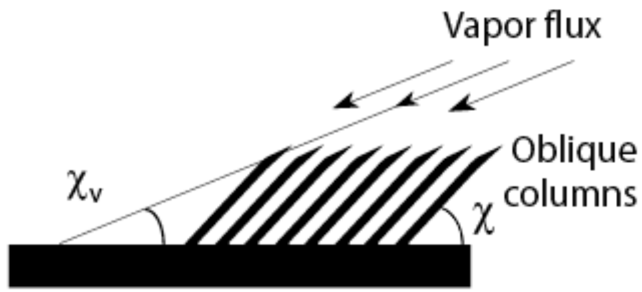
Physical Vapor Deposition
(Columnar Thin Films)







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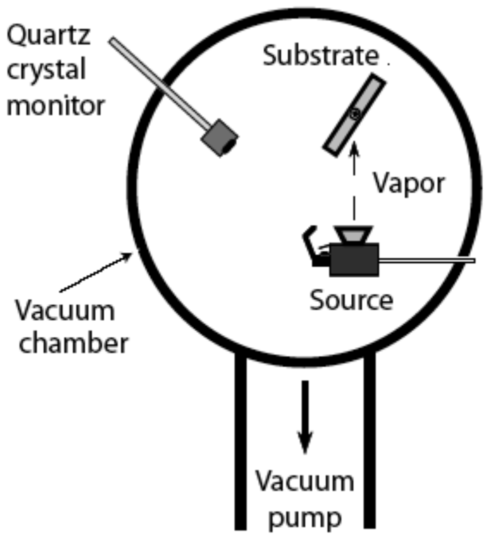
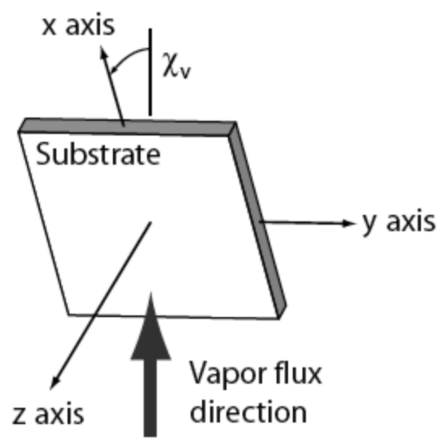
Physical Vapor Deposition
(Sculptured Thin Films)



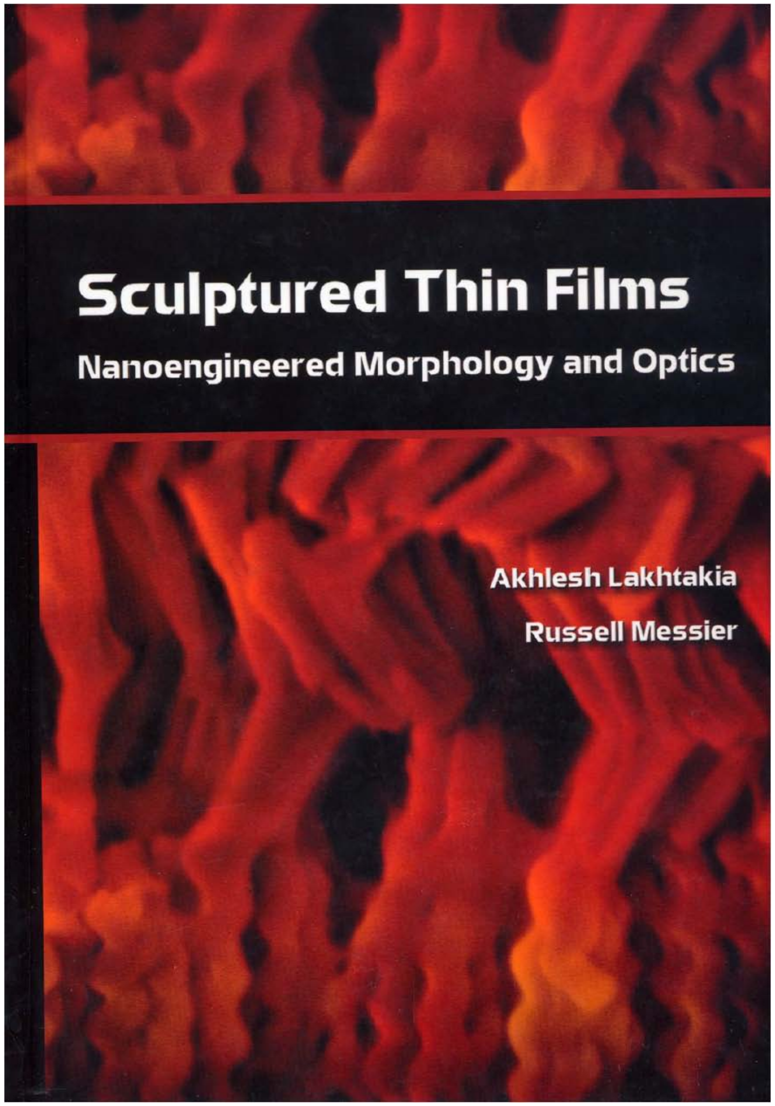


Rotate about y axis for nematic morphology

Rotate about z axis for helicoidal morphology

Combined rotations for complex morphologies

STF Optics


Sculptured Thin Films
Nanoengineered Morphology and Optics
Akhlesh Lakhtakia
Russell Messier

STF Optics

$$\mathbf{D}(\mathbf{r},\omega) = \epsilon_0 \, \underline{\underline{S}}(z) \bullet \Big[\underline{\underline{\epsilon}}_{ref}(\omega) \bullet \underline{\underline{S}}^T(z) \bullet \mathbf{E}(\mathbf{r},\omega) + \underline{\underline{\alpha}}_{ref}(\omega) \bullet \underline{\underline{S}}^T(z) \bullet \mathbf{H}(\mathbf{r},\omega) \Big] ,$$

$$\mathbf{B}(\mathbf{r},\omega) = \mu_0 \, \underline{\underline{S}}(z) \bullet \Big[\underline{\underline{\beta}}_{ref}(\omega) \bullet \underline{\underline{S}}^T(z) \bullet \mathbf{E}(\mathbf{r},\omega) + \underline{\underline{\mu}}_{ref}(\omega) \bullet \underline{\underline{S}}^T(z) \bullet \mathbf{H}(\mathbf{r},\omega) \Big] ,$$

Dielectric, Magnetic, & Magnetoelectric Properties

Substrate Motion

$$\underline{\underline{S}}_x(z) = \mathbf{u}_x\mathbf{u}_x + (\mathbf{u}_y\mathbf{u}_y + \mathbf{u}_z\mathbf{u}_z)\ \cos\,\xi(z) + (\mathbf{u}_z\mathbf{u}_y - \mathbf{u}_y\mathbf{u}_z)\ \sin\,\xi(z)\,,$$

$$\underline{\underline{S}}_y(z) = \mathbf{u}_y\mathbf{u}_y + (\mathbf{u}_x\mathbf{u}_x + \mathbf{u}_z\mathbf{u}_z)\ \cos\,\tau(z) + (\mathbf{u}_z\mathbf{u}_x - \mathbf{u}_x\mathbf{u}_z)\ \sin\,\tau(z)\,,$$

$$\underline{\underline{S}}_z(z) = \mathbf{u}_z\mathbf{u}_z + (\mathbf{u}_x\mathbf{u}_x + \mathbf{u}_y\mathbf{u}_y)\ \cos\,\zeta(z) + (\mathbf{u}_y\mathbf{u}_x - \mathbf{u}_x\mathbf{u}_y)\ \sin\,\zeta(z)\,.$$

STF Optics

Dielectric Materials

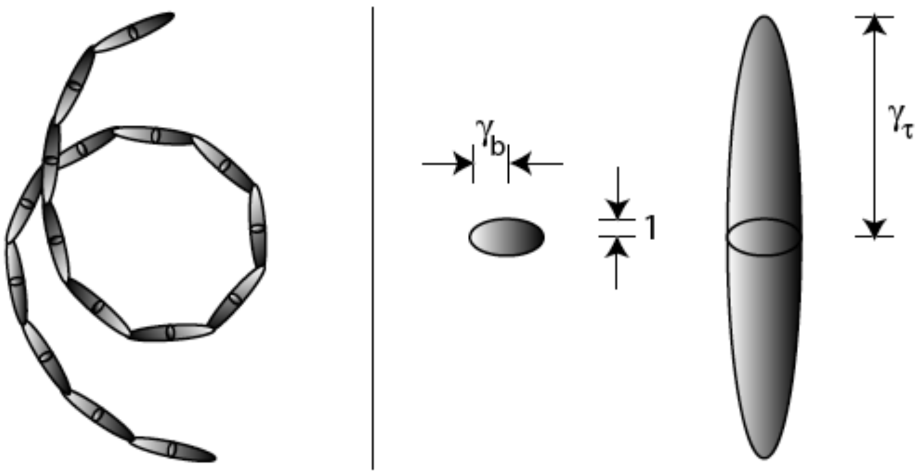
$$\begin{aligned}\mathbf{D}(\mathbf{r},\omega) &= \epsilon_0\,\underline{\underline{\epsilon}}_r(z,\omega)\bullet\mathbf{E}(\mathbf{r},\omega)\\ &= \epsilon_0\,\underline{\underline{S}}(z)\bullet\underline{\underline{\epsilon}}_{ref}(\omega)\bullet\underline{\underline{S}}^T(z)\bullet\mathbf{E}(\mathbf{r},\omega)\,,\\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

$$\underline{\underline{\epsilon}}_{ref}(\omega)=\underline{\underline{\hat{S}}}_y(\chi)\bullet\underline{\underline{\epsilon}}^o_{ref}(\omega)\bullet\underline{\underline{\hat{S}}}^T_y(\chi)$$

$$\underline{\underline{\epsilon}}^o_{ref}(\omega)=\underline{\underline{\epsilon}}_{ref}(\omega)\Big|_{\chi=0}=\epsilon_a(\omega)\,\mathbf{u}_z\mathbf{u}_z+\epsilon_b(\omega)\,\mathbf{u}_x\mathbf{u}_x+\epsilon_c(\omega)\,\mathbf{u}_y\mathbf{u}_y$$

$$\underline{\underline{\hat{S}}}_y(\chi)=\mathbf{u}_y\mathbf{u}_y+(\mathbf{u}_x\mathbf{u}_x+\mathbf{u}_z\mathbf{u}_z)\cos\chi+(\mathbf{u}_z\mathbf{u}_x-\mathbf{u}_x\mathbf{u}_z)\sin\chi$$

STF Optics



Homogenize a collection of parallel ellipsoids to get $\underline{\underline{\epsilon}}^{o}_{ref}(\omega)$

STF Optics

Wave Propagation

$$\mathbf{E}(\mathbf{r},\omega) = \mathbf{e}(z,\kappa,\psi,\omega)\ \exp\left[i\kappa(x\cos\psi + y\sin\psi)\right]$$

$$\mathbf{H}(\mathbf{r},\omega) = \mathbf{h}(z,\kappa,\psi,\omega)\ \exp\left[i\kappa(x\cos\psi + y\sin\psi)\right]$$

STF Optics

Wave Propagation

$$\mathbf{E}(\mathbf{r},\omega) = \mathbf{e}(z,\kappa,\psi,\omega)\ \exp\left[i\kappa(x\cos\psi + y\sin\psi)\right]$$
$$\mathbf{H}(\mathbf{r},\omega) = \mathbf{h}(z,\kappa,\psi,\omega)\ \exp\left[i\kappa(x\cos\psi + y\sin\psi)\right]$$

$$\nabla\times\mathbf{E}(\mathbf{r},\omega) = i\omega\mathbf{B}(\mathbf{r},\omega)\,,$$
$$\nabla\times\mathbf{H}(\mathbf{r},\omega) = -i\omega\mathbf{D}(\mathbf{r},\omega)\,,$$

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

STF Optics

Wave Propagation

$$\mathbf{E}(\mathbf{r},\omega) = \mathbf{e}(z,\kappa,\psi,\omega)\,\exp\left[i\kappa(x\cos\psi + y\sin\psi)\right]$$

$$\mathbf{H}(\mathbf{r},\omega) = \mathbf{h}(z,\kappa,\psi,\omega)\,\exp\left[i\kappa(x\cos\psi + y\sin\psi)\right]$$

$$\nabla\times\mathbf{E}(\mathbf{r},\omega) = i\omega\mathbf{B}(\mathbf{r},\omega)\,,$$
$$\nabla\times\mathbf{H}(\mathbf{r},\omega) = -i\omega\mathbf{D}(\mathbf{r},\omega)\,,$$

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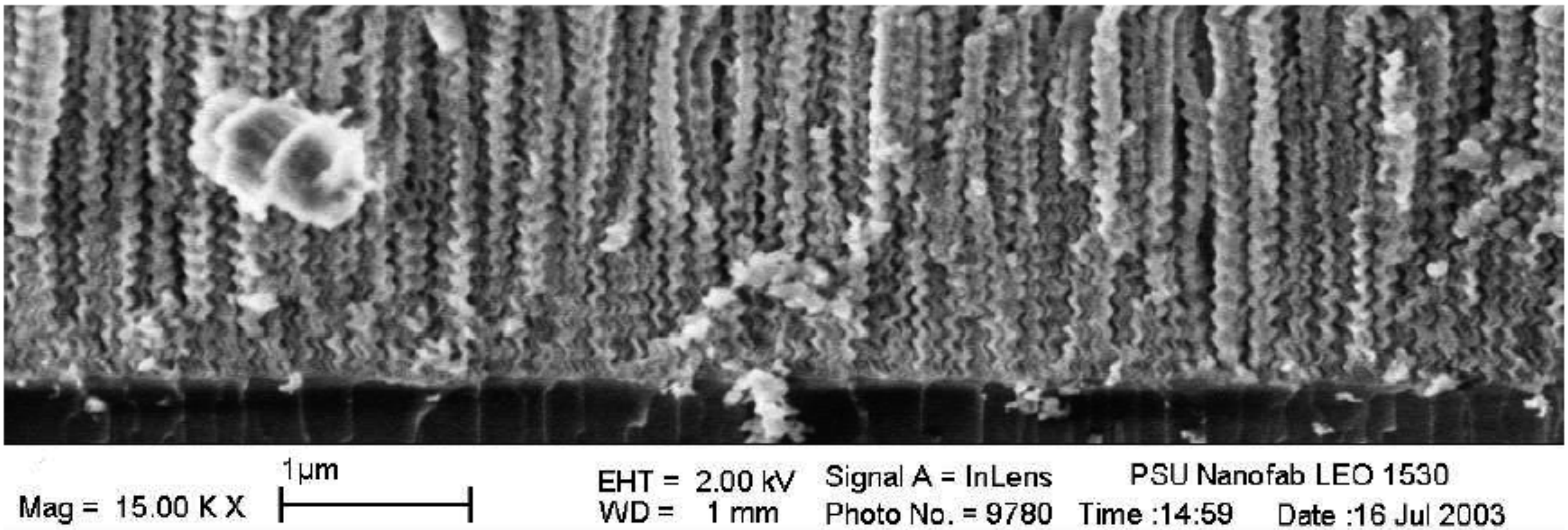
$$\frac{d}{dz}\left[\mathbf{f}(z,\kappa,\psi,\omega)\right] = i\left[\mathbf{P}(z,\kappa,\psi,\omega)\right]\left[\mathbf{f}(z,\kappa,\psi,\omega)\right].$$

$$\left[\mathbf{f}(z,\kappa,\psi,\omega)\right] = \begin{bmatrix} e_x(z,\kappa,\psi,\omega)\\ e_y(z,\kappa,\psi,\omega)\\ h_x(z,\kappa,\psi,\omega)\\ h_y(z,\kappa,\psi,\omega)\end{bmatrix}$$

Optical Filters

Chiral STF



Courtesy: Mark Horn

Optical Filters

Chiral STF as CP Filter

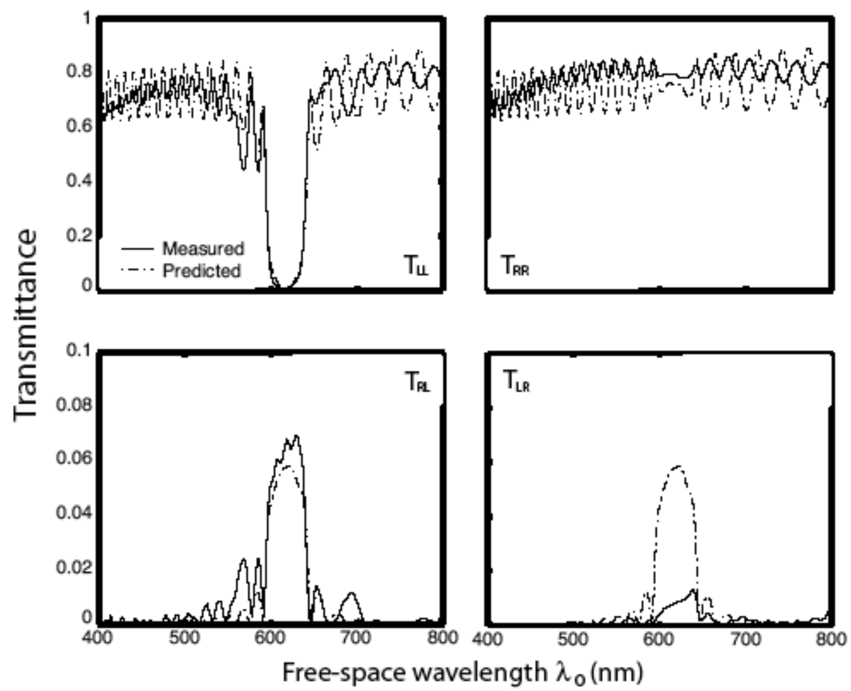
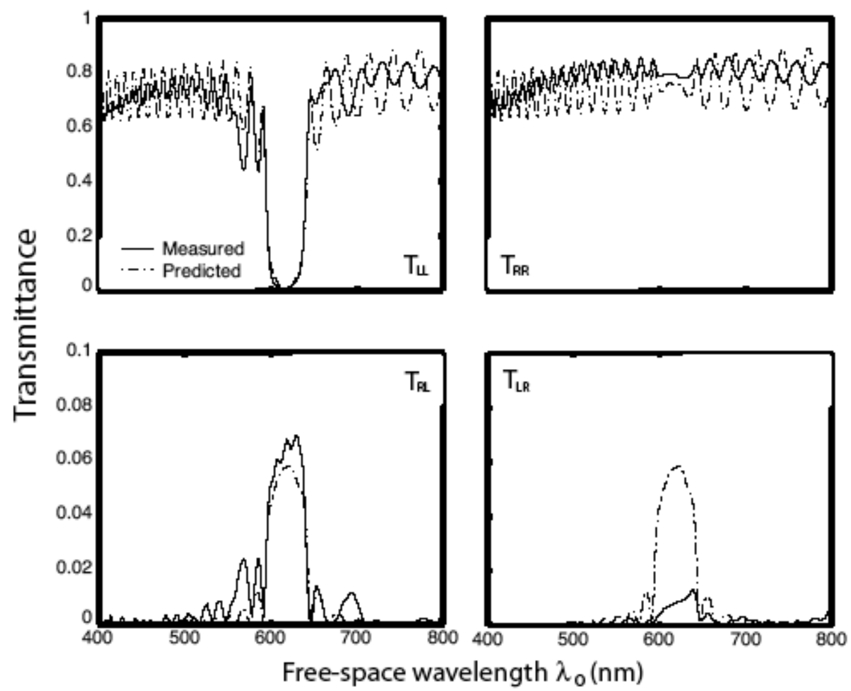


Figure 10.2: Predicted and measured transmittances of a circular polarization filter as functions of the free-space wavelength λ_0 for normal incidence. The filter is a chiral STF of patinal titanium oxide. The reference permittivity dyadic was predicted with $\epsilon_s = 6.3 + i0.012$, $\epsilon_v = 1$, $f_v = 0.421$, $\gamma_\tau^{(s)} = \gamma_\tau^{(v)} = 20$, and $\gamma_b^{(s)} = \gamma_b^{(v)} = 1.06$ set in Program 6.1. The other parameters are $\chi = 47$ deg, $h = -1$, $\Omega = 173$ nm, $L = 30\,\Omega$, and $\psi = 0$ deg. (Adapted from Sherwin et al. [109] with permission of Elsevier.)

Optical Filters

Chiral STF as CP Filter



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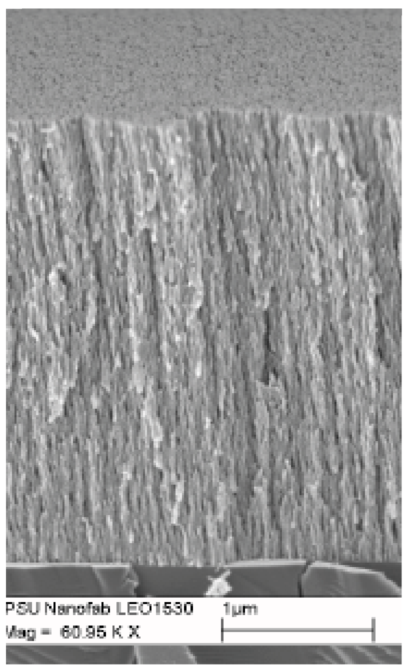
Optical Filters

Chiral STF as CP Filter

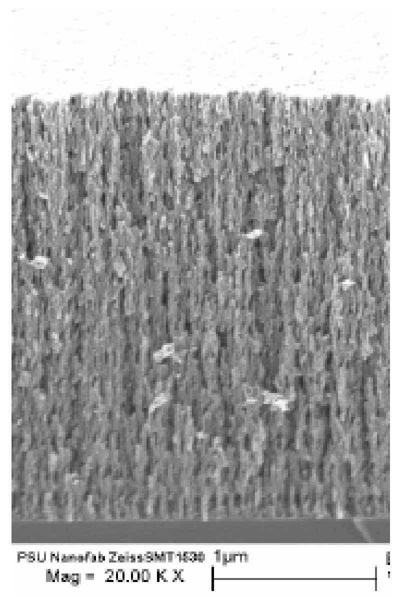
Post-Deposition Engineering of Bragg Regime

Annealing

before



after



Pursel, Horn and Lakhtakia. *Opt. Express* **14**, 8001 (2006)

Optical Filters

Chiral STF as CP Filter

Annealing

Blue-shift factors:

(i) Decreases pitch

(ii) Thins nanowires

Red-shift factors:

(i) Increases permittivity

Pursel, Horn and Lakhtakia, *Opt. Express* **14**, 8001 (2006)

Optical Filters

Chiral STF as CP Filter

Annealing

Blue-shift factors:

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Red-shift factors:

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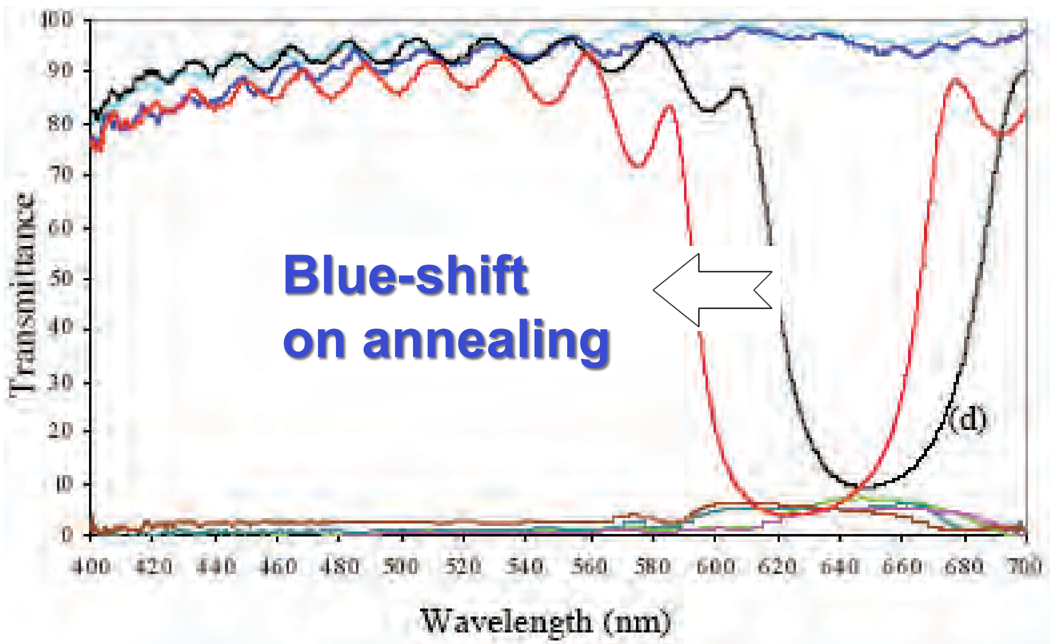
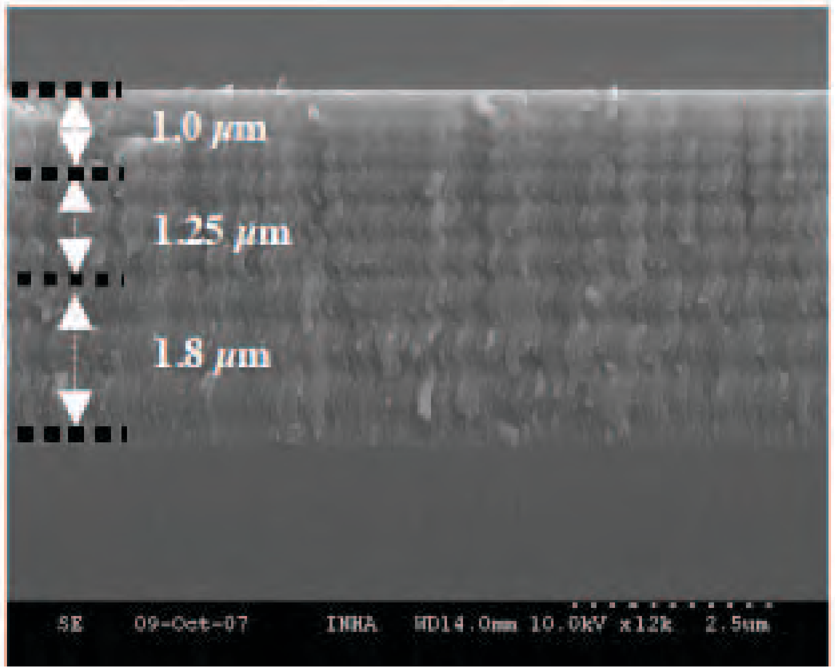


Pursel, Horn and Lakhtakia, *Opt. Express* **14**, 8001 (2006)

Optical Filters

Multiband CP Filter

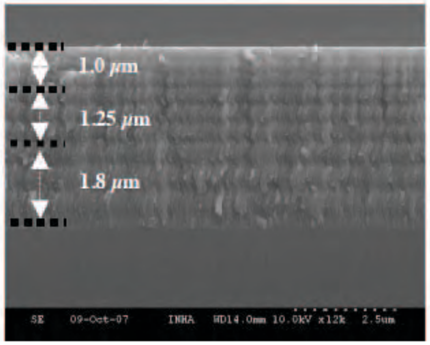


Stack of 3 chiral STFs

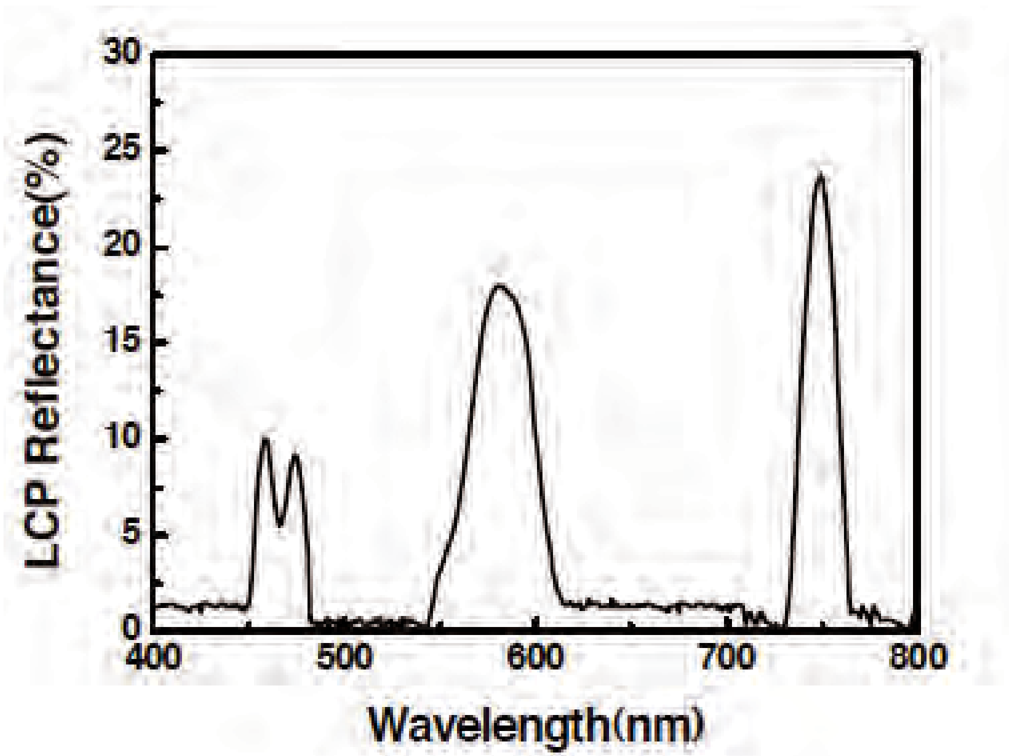
Park, Sobahan and Hwangbo, *Opt. Express* **15**, 5186 (2008)

Optical Filters

Multiband CP Filter



Stack of 3 chiral STFs



Park, Sobahan and Hwangbo, *Opt. Express* **15**, 5186 (2008)

Optical Filters

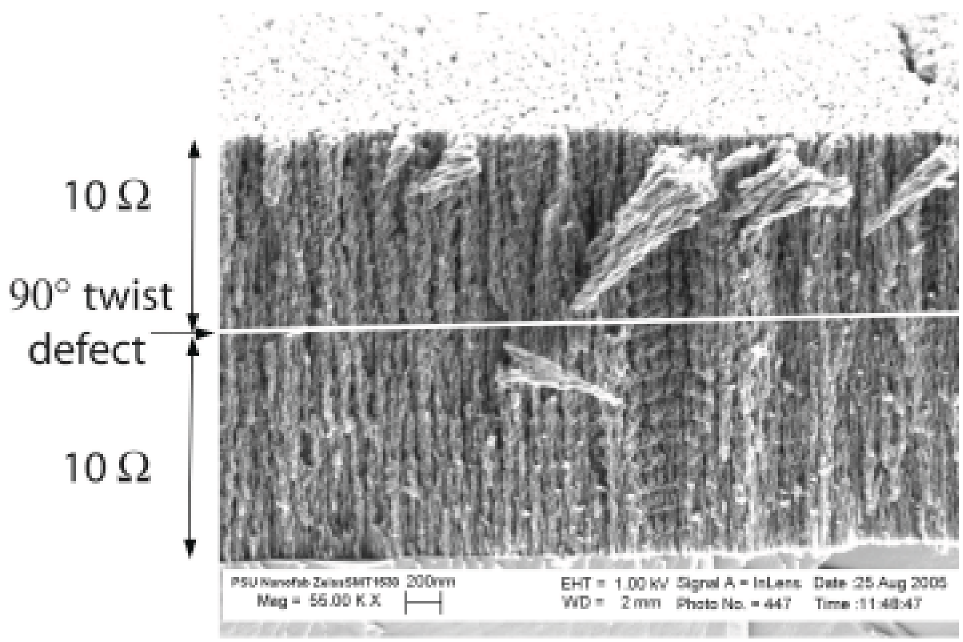
Spectral Hole Filter

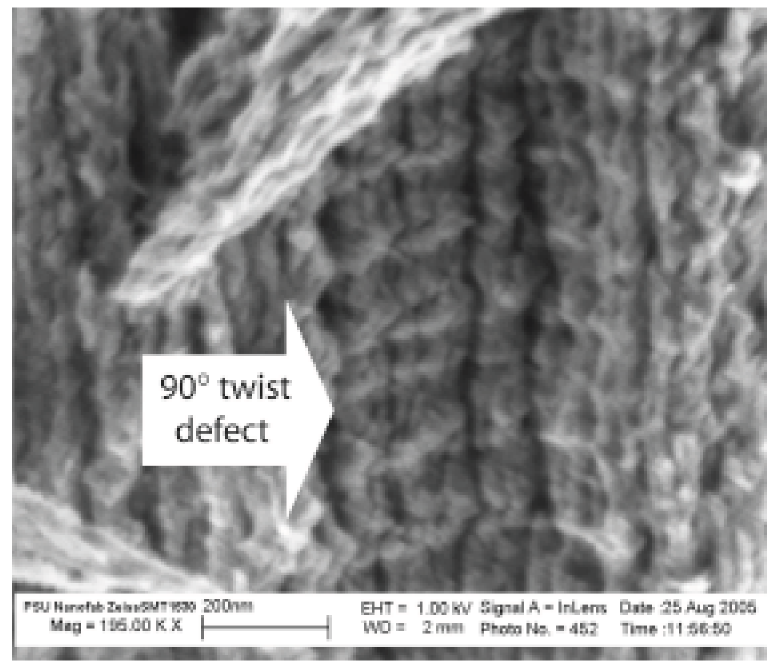
Central Phase Defect in a Chiral STF

- Homogeneous-layer defect
  - *Isotropic*
  - *Anisotropic*
- Twist defect
- Structurally-chiral-layer defect

Optical Filters

Spectral Hole Filter





Pursel, Horn and Lakhtakia, *Opt. Eng.* **45**, 040507 (2007)

Optical Filters

Spectral Hole Filter

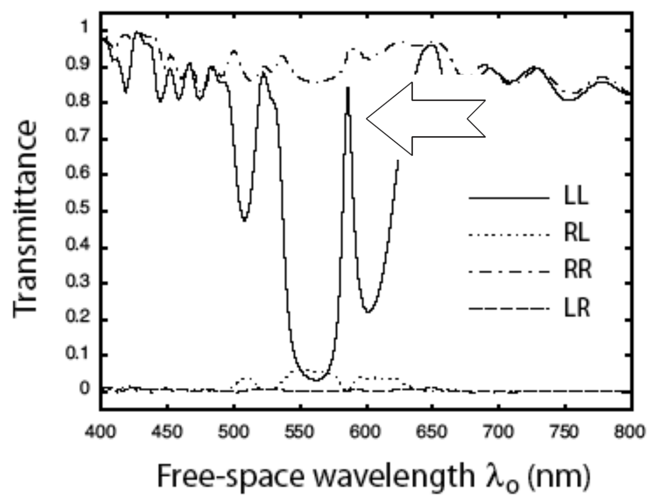
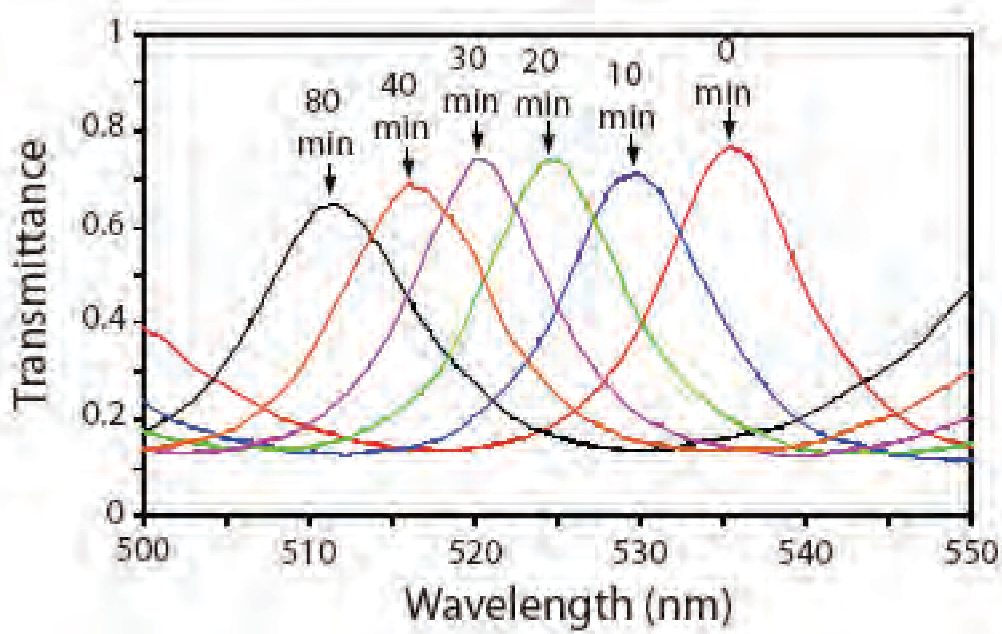


Figure 10.10: Measured transmittances of a narrow bandpass filter comprising an isotropic homogeneous spacer of hafnium oxide interposed between two identical, structurally left-handed, chiral STF sections of titanium oxide. Evidence of a hole in the spectrum of R_{LL} at 580-nm wavelength is provided by the spectrum of T_{LL}. (Adapted from Hodgkinson et al. [125] with permission of Elsevier.)

Optical Filters

Spectral Hole Filter

Chemical Etching Columnar Thinning Blue Shift



Pursel, Horn and Lakhtakia, *Opt. Eng*. **45**, 040507 (2007)

Snapshots

Snapshots

1. Fluid Concentration Sensor

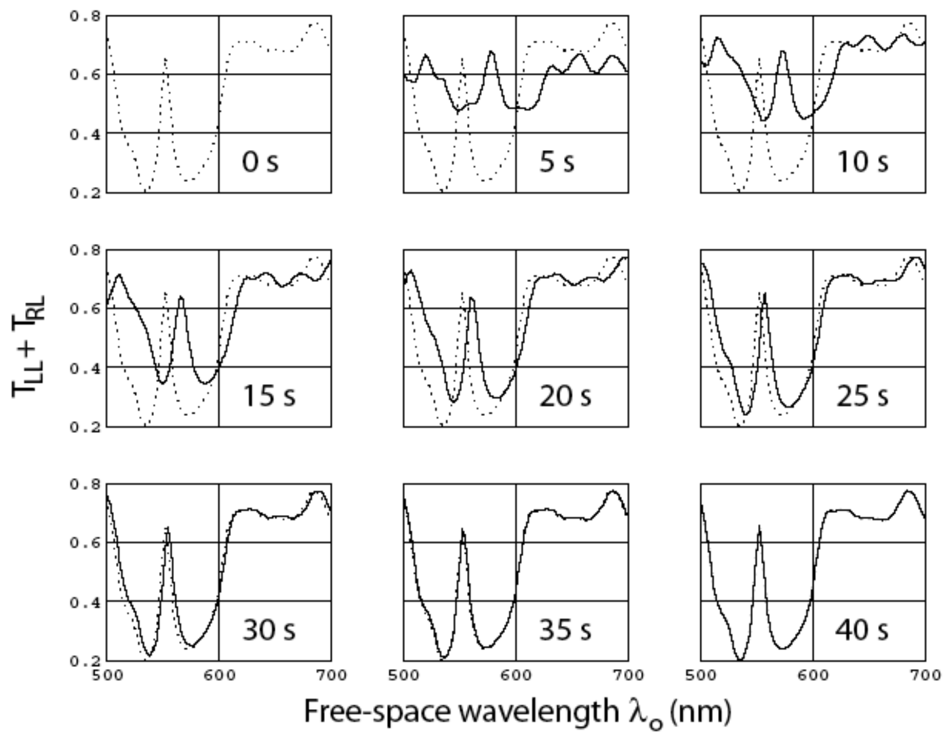
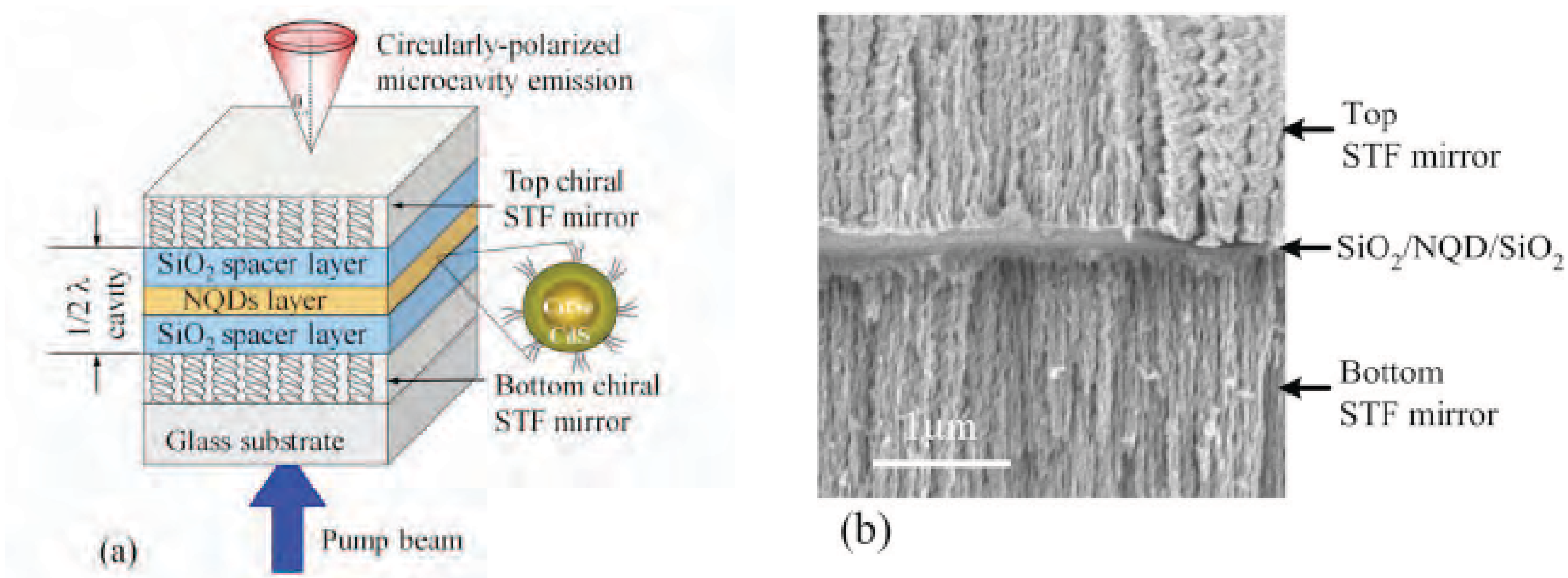


Figure 10.22: Optical response of a narrow bandpass filter, described by Eq. (10.17) and made of two structurally left-handed chiral STF sections, on infiltration by water vapor. The dotted lines indicate the measured transmittance spectrum when the filter was dry. The filter was flooded with water and then allowed to recover by evaporation in air. Transmittance spectrums recorded at 5-s intervals after the flooding are shown. (Adapted from Lakhtakia et al. [105] with permission of Elsevier.)

Snapshots

2. CP-Light Emitting Cavity

- Quantum dots inserted in a cavity between two left-handed chiral STFs



Zhang *et al*., *Appl. Phys. Lett.* **91,** 023102 (2007)

Snapshots

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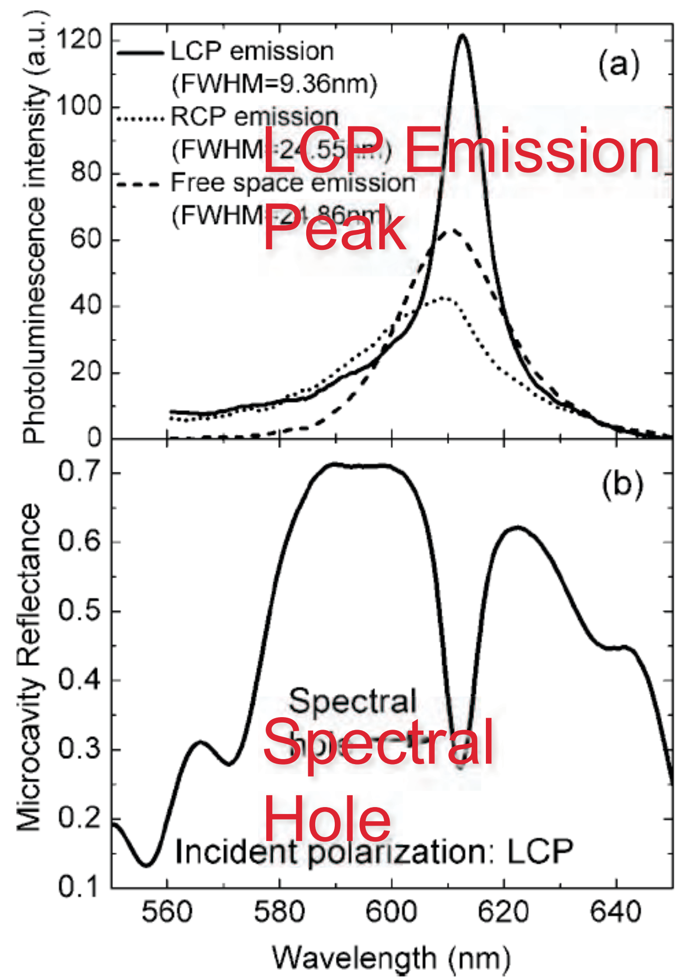
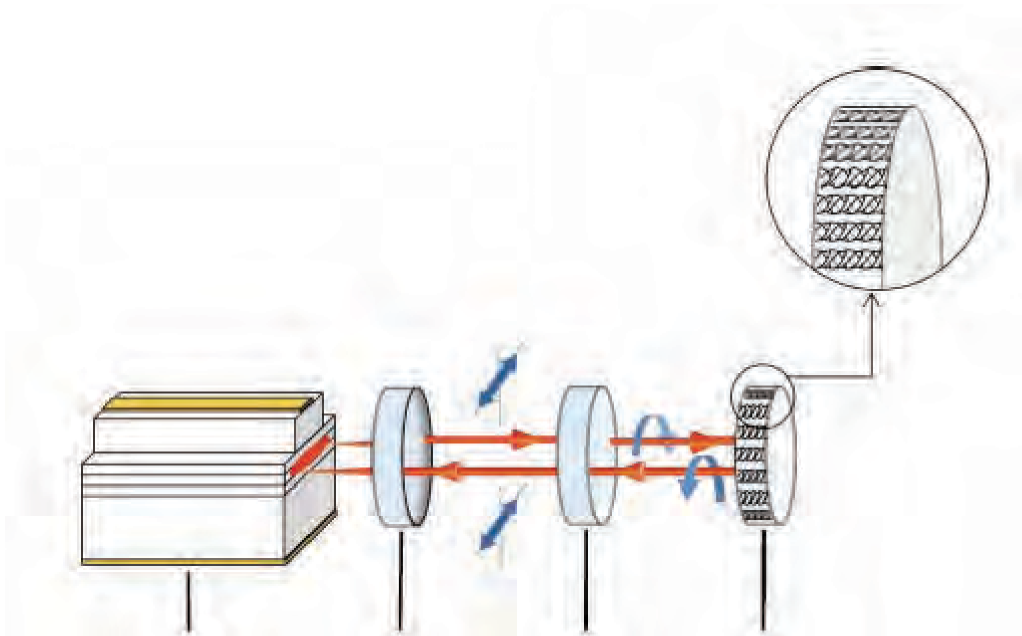


Zhang *et al.*, *Appl. Phys. Lett.* **91,** 023102 (2007)

Snapshots

3. CP-Light External Cavity Diode Laser



Zhang *et al.*, *Appl. Phys. Lett.* **92,** 111109 (2008)

Snapshots

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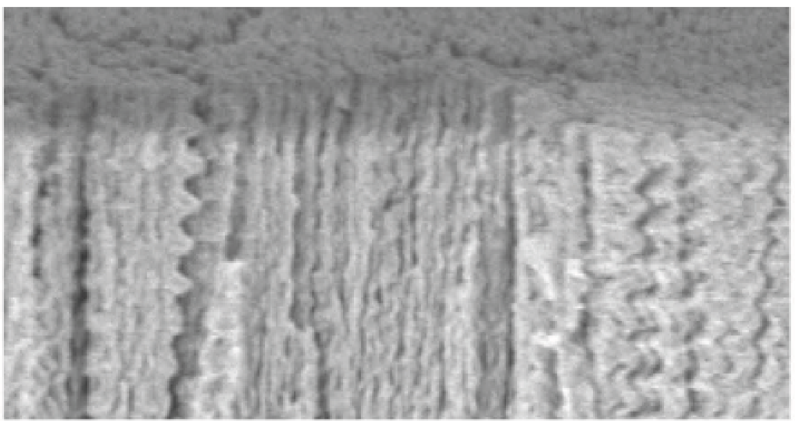

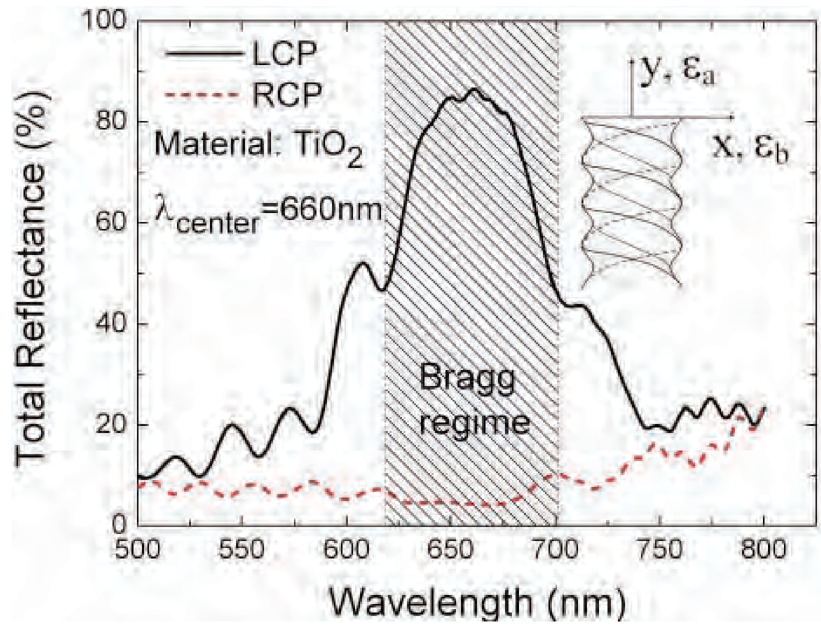

Zhang *et al*., *Appl. Phys. Lett.* **92,** 111109 (2008)

Snapshots

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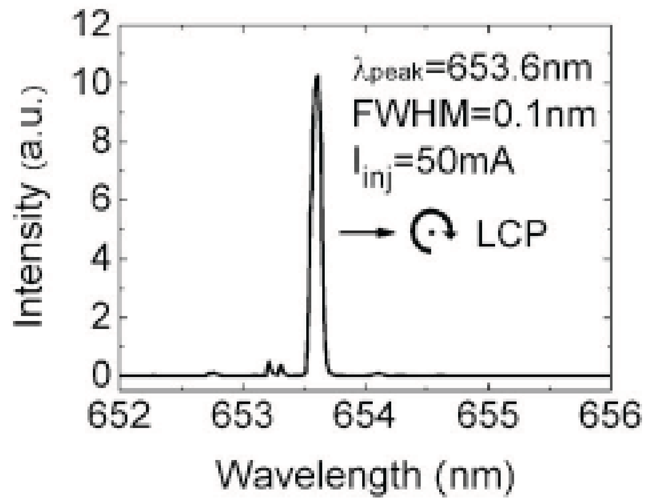


Zhang *et al.*, *Appl. Phys. Lett.* **92,** 111109 (2008)

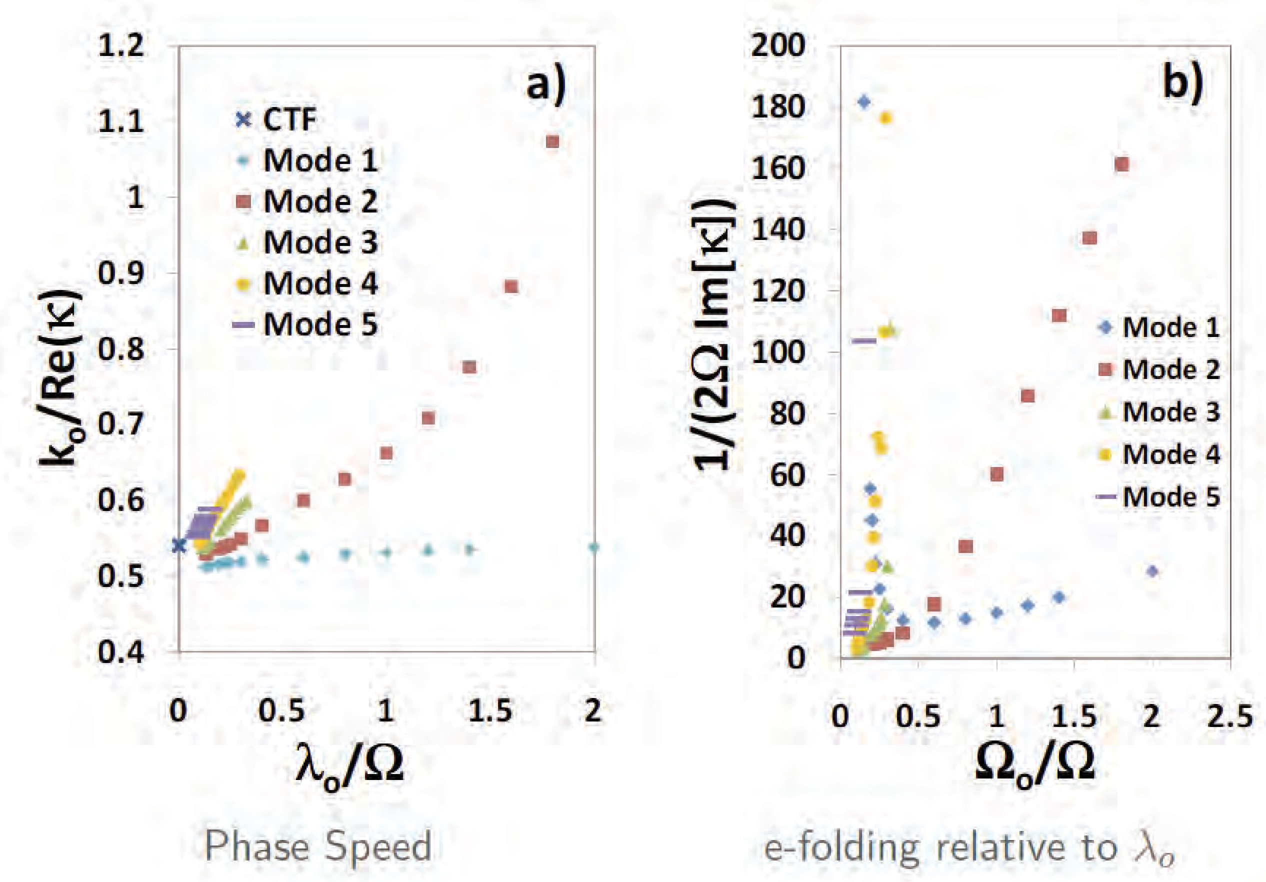
Snapshots

4. Multiple Surface-Plasmon-Polariton Waves

Polo and Lakhtakia, *Proc. R. Soc. Lond. A* **465**, 87 (2009)

Snapshots

4. Multiple Surface-Plasmon-Polariton Waves



Polo and Lakhtakia, *Proc. R. Soc. Lond. A* **465**, 87 (2009)

Snapshots

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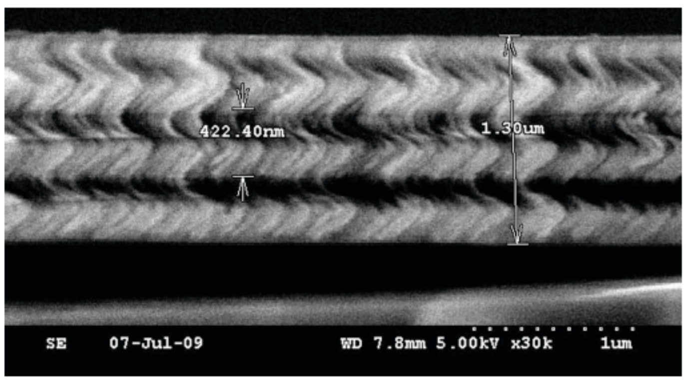
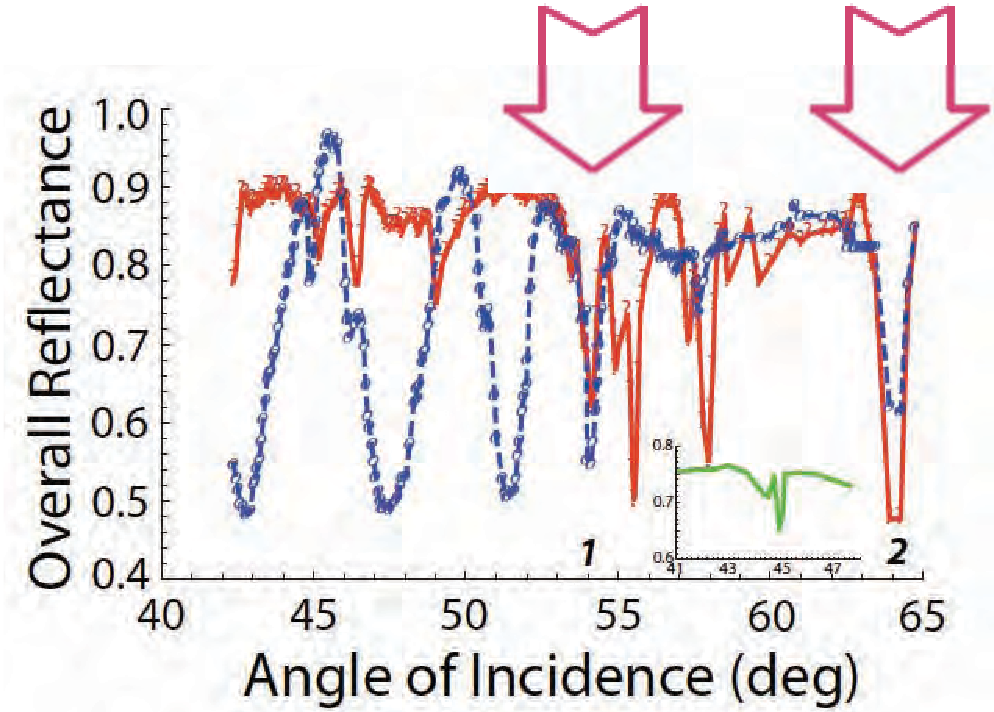




Devender, Pulsifer & Lakhtakia, *Electron. Lett.* **45**, 1137 (2009)

Snapshots

4. Multiple Surface-Plasmon-Polariton Waves

Multiple trains of same-color surface plasmon-polaritons guided by the planar interface of a metal and a sculptured nematic thin film

Michael A. Motyka[a] and Akhlesh Lakhtakia[b]

Journal of Nanophotonics, Vol. 2, 021910 (4 November 2008)

Snapshots

4. Multiple Surface-Plasmon-Polariton Waves

Multiple trains of same-color surface plasmon-polaritons guided by the planar interface of a metal and a sculptured nematic thin film. Part III: Experimental evidence

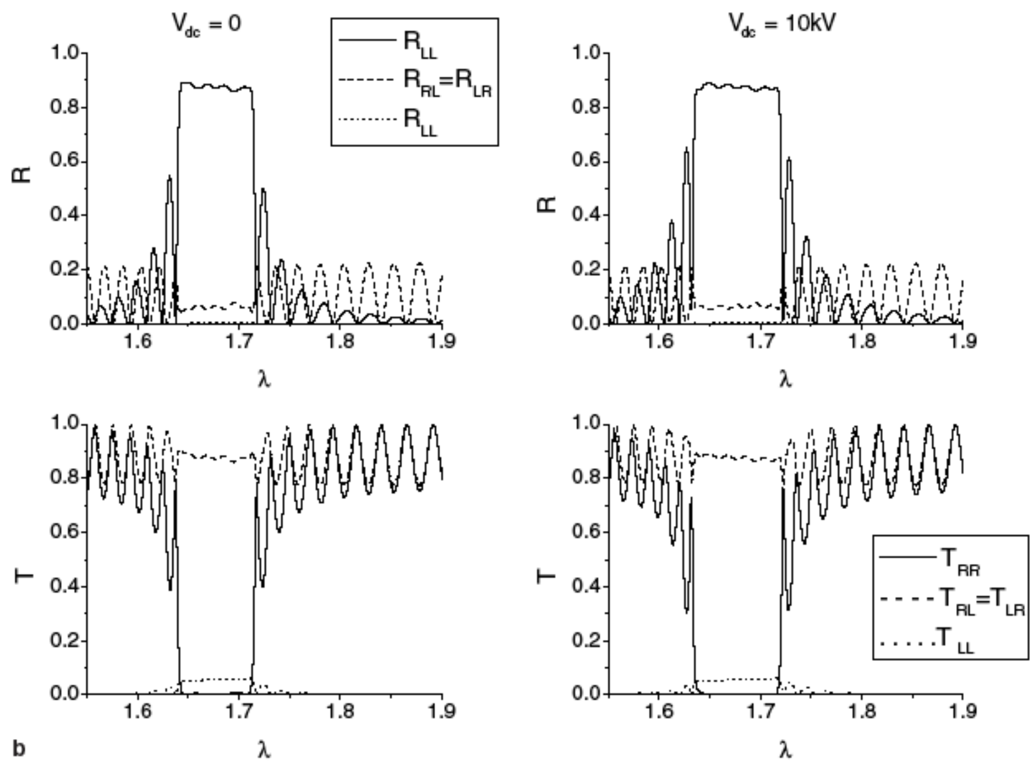
Akhlesh Lakhtakia,[a] Yi-Jun Jen,[b] and Chia-Feng Lin[c]

Journal of Nanophotonics, Vol. 3, 033506 (25 September 2009)

Snapshots

5. Electro-Optic Chiral STFs

$$\epsilon_1^{(0)} = 2.7, \epsilon_3^{(0)} = 3.2, r_{41} = 9 \times 10^{-12} \text{ mV}^{-1}, r_{63} = 3r_{41}, \text{ and } h = 1.$$



Without dc voltage

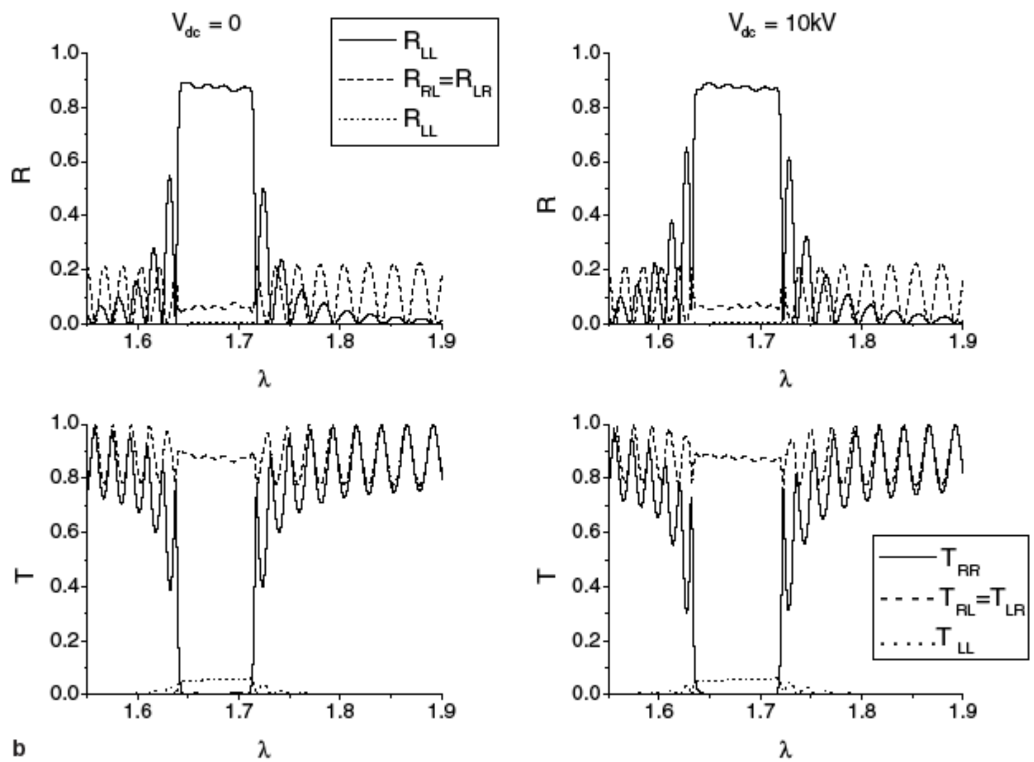
With dc voltage

Reyes and Lakhtakia, *Opt. Commun.* **259**, 164 (2006)

Snapshots

5. Electro-Optic Chiral STFs

$$\epsilon_1^{(0)} = 2.7, \epsilon_3^{(0)} = 3.2, r_{41} = 9 \times 10^{-12}\ \mathrm{mV}^{-1}, r_{63} = 3r_{41}, \text{ and } h = 1.$$



Without dc voltage

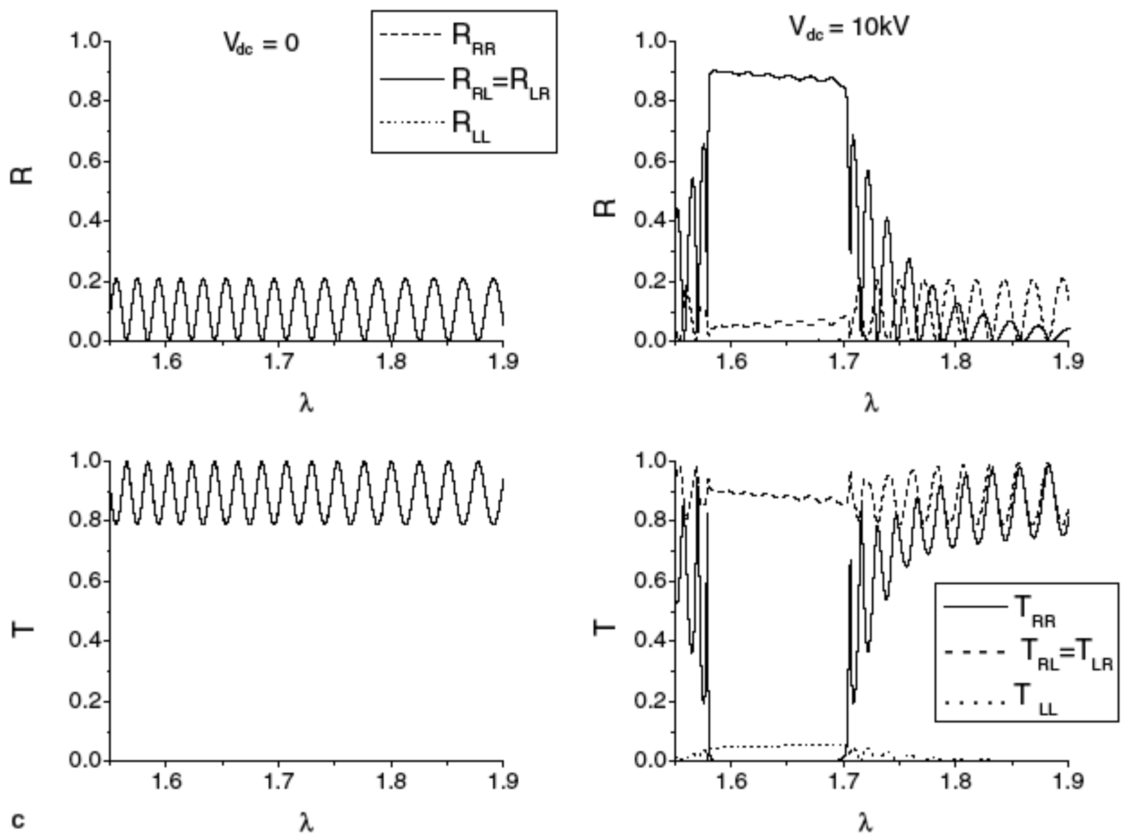
With dc voltage

Reyes and Lakhtakia, *Opt. Commun.* **259**, 164 (2006)

Snapshots

5. Electro-Optic Chiral STFs

Pseudo-
Isotropic
Point



Without dc voltage

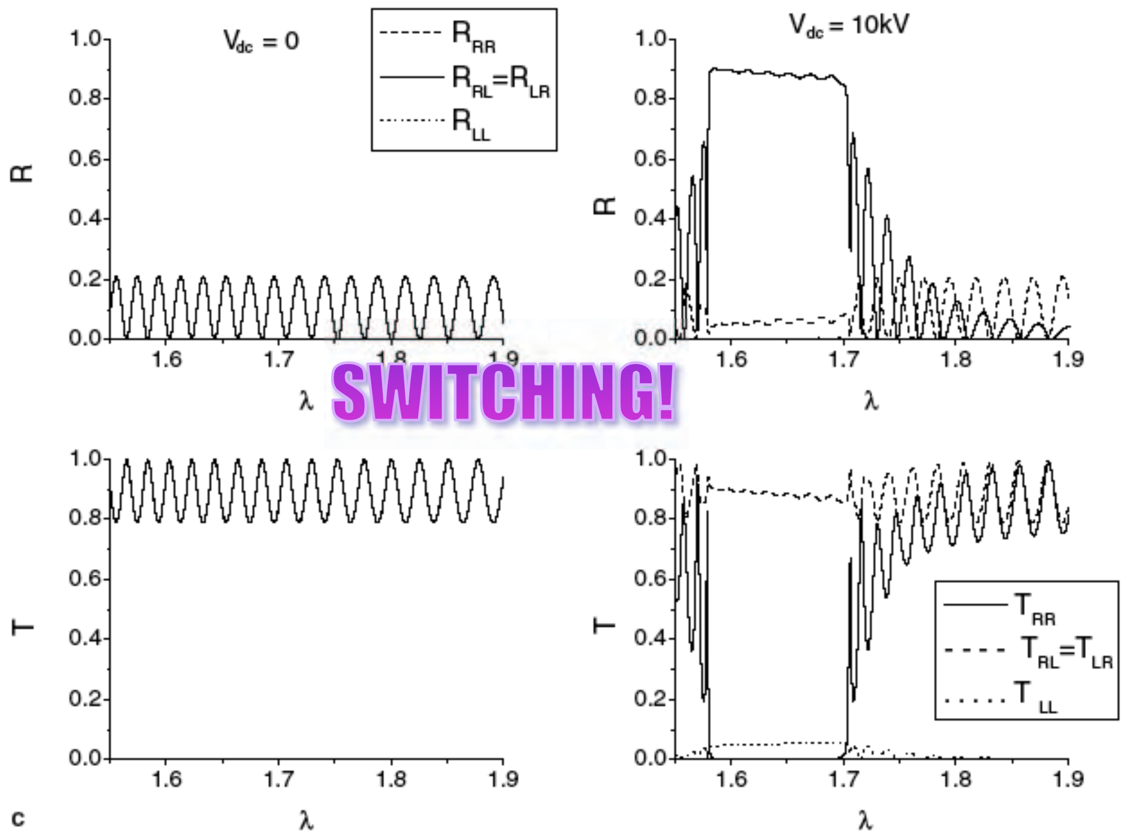
With dc voltage

Reyes and Lakhtakia, *Opt. Commun.* **259**, 164 (2006)

Snapshots

5. Electro-Optic Chiral STFs

Pseudo-Isotropic Point



Without dc voltage

With dc voltage

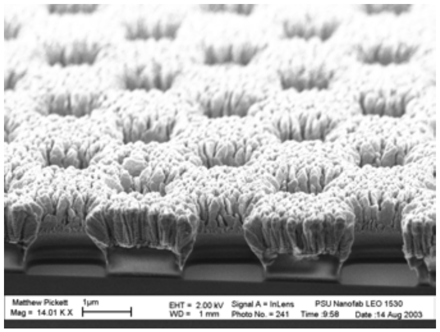
Reyes and Lakhtakia, *Opt. Commun.* **259**, 164 (2006)

Snapshots

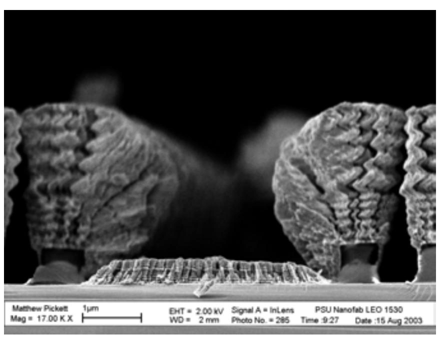
A. Lakhtakia

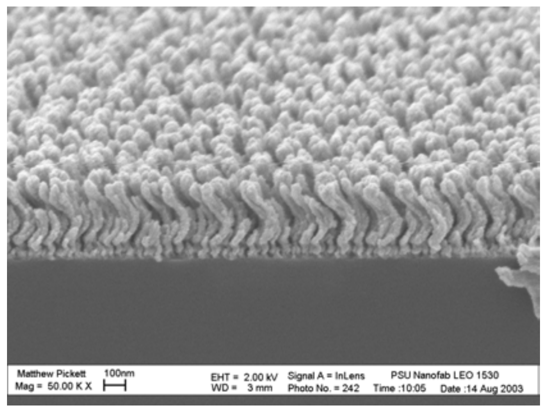
6. 2D and 3D Photonic Crystals

MetalS TFson Topographic Substrates

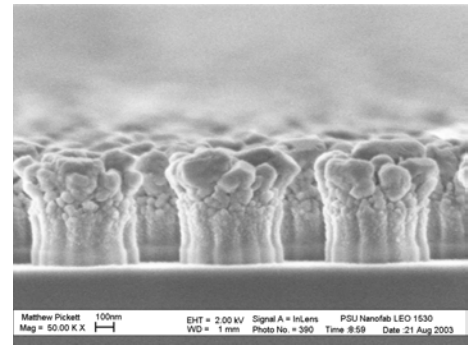


Chromium

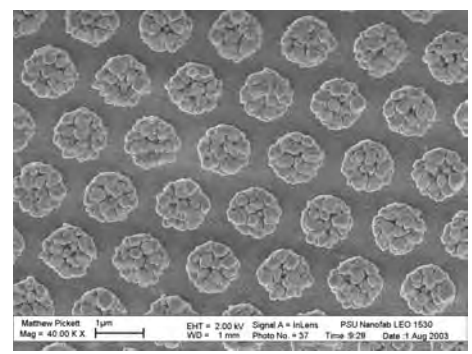




Molybdenum



Aluminum

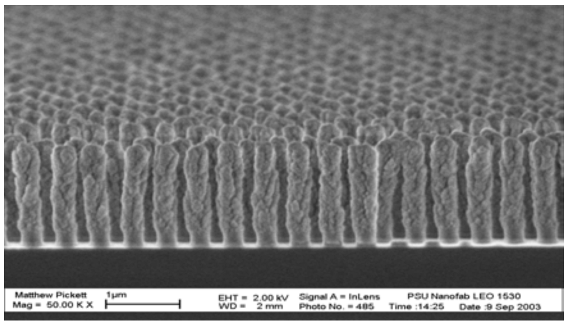


Horn *et al.*, *Nanotechnology* **15**, 303 (2004).

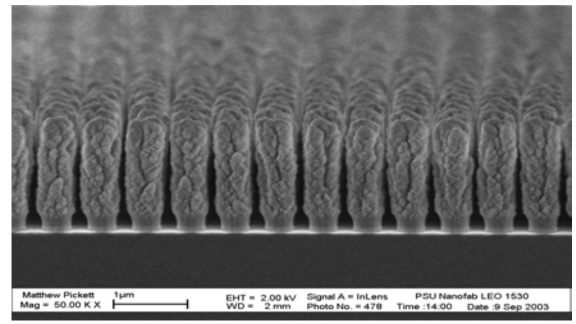
Snapshots

6. 2D and 3D Photonic Crystals

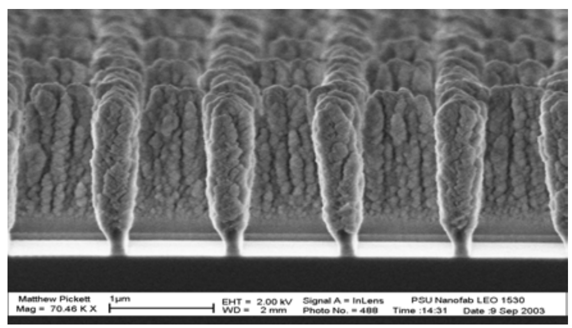
Dielectric STFs on Topographic Substrates



HCP array of SiOx nanocolumns



BCC array of SiOx nanocolumns



1um x 1um mesh of SiOx nanolines

Horn *et al.*, *Nanotechnology* **15**, 303 (2004).

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A. Lakhtakia

Snapshots

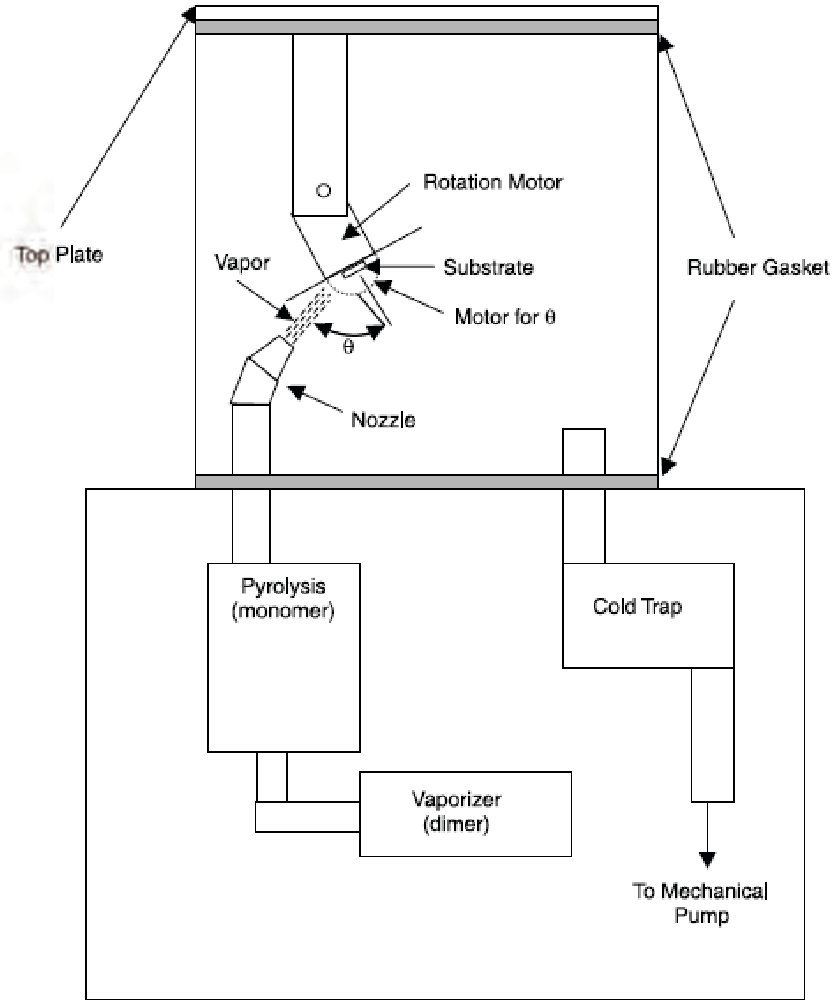
7. Bioreplication

Martín-Palma et al., *Nanotechnology* **19**, 355704 (2008)

Polymeric STFs

A. Lakhtakia

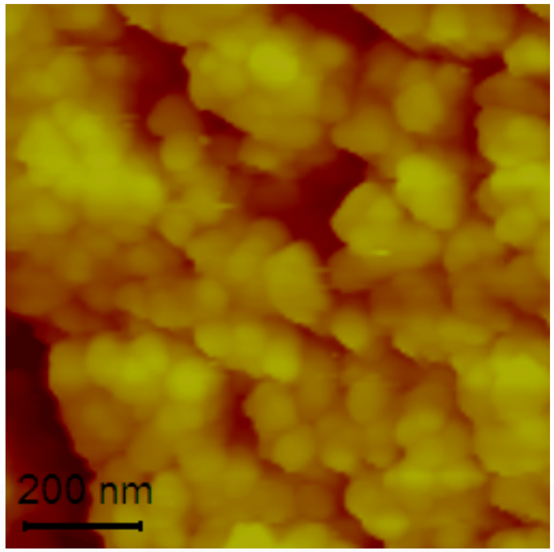
PARYLENE-C STFs:
COMBINED CVD+PVD TECHNIQUE



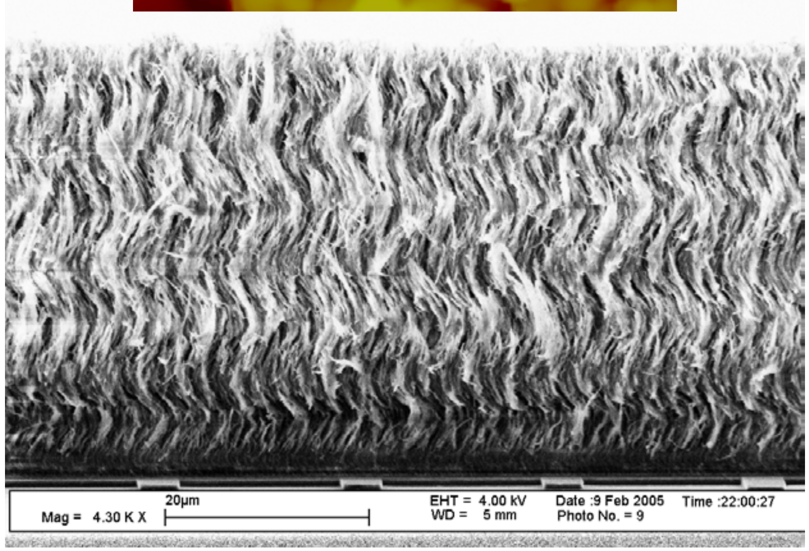
Pursel *et al.*, *Polymer* **46**, 9544 (2005)

A. Lakhtakia

PARYLENE-C STFs:
COMBINED CVD+PVD TECHNIQUE



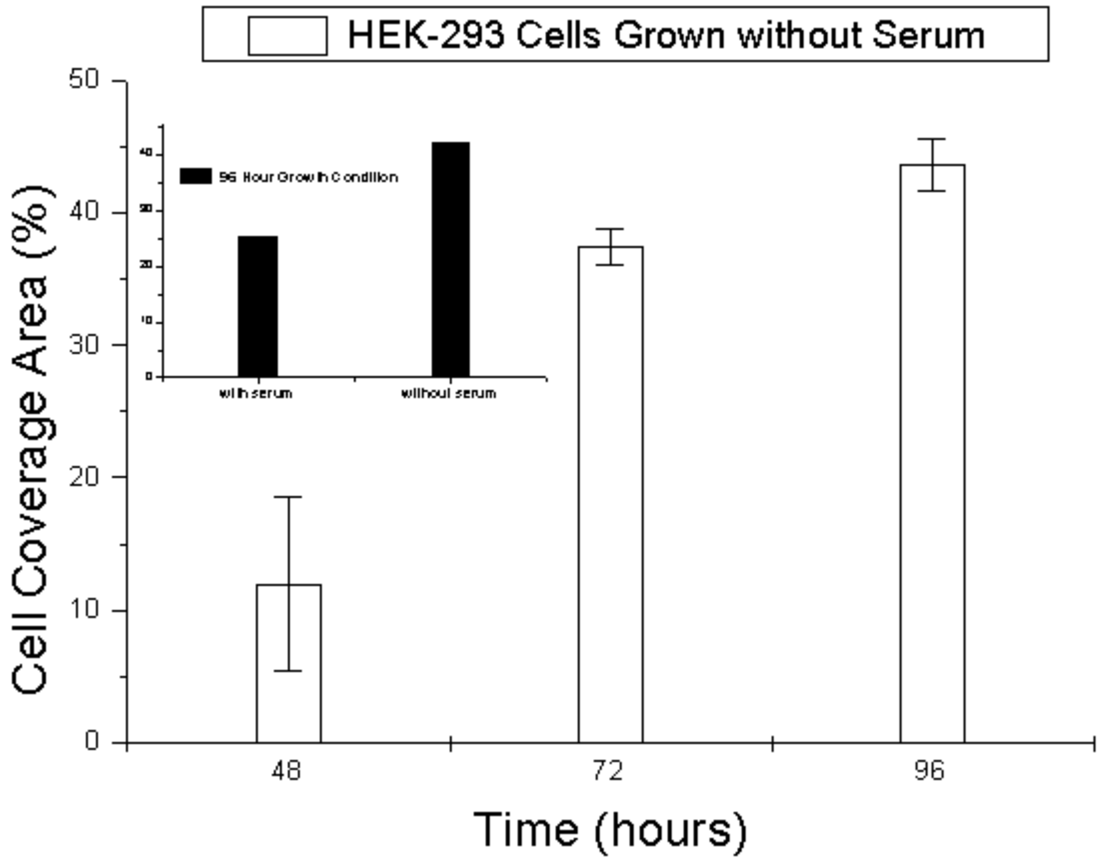
Nanoscale Morphology



Ciliary Structure

A. Lakhtakia

BIOSCAFFOLDS



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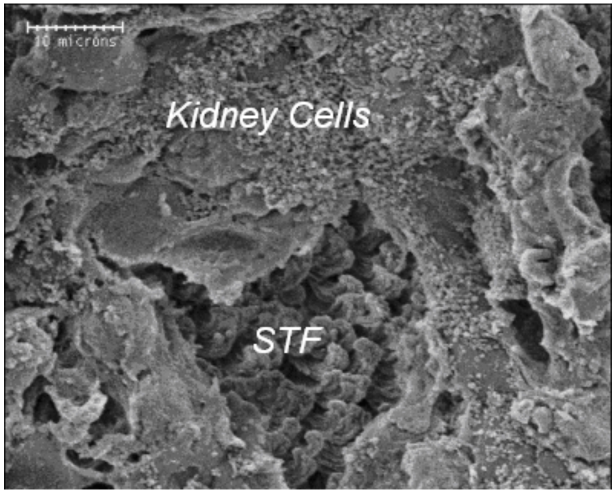
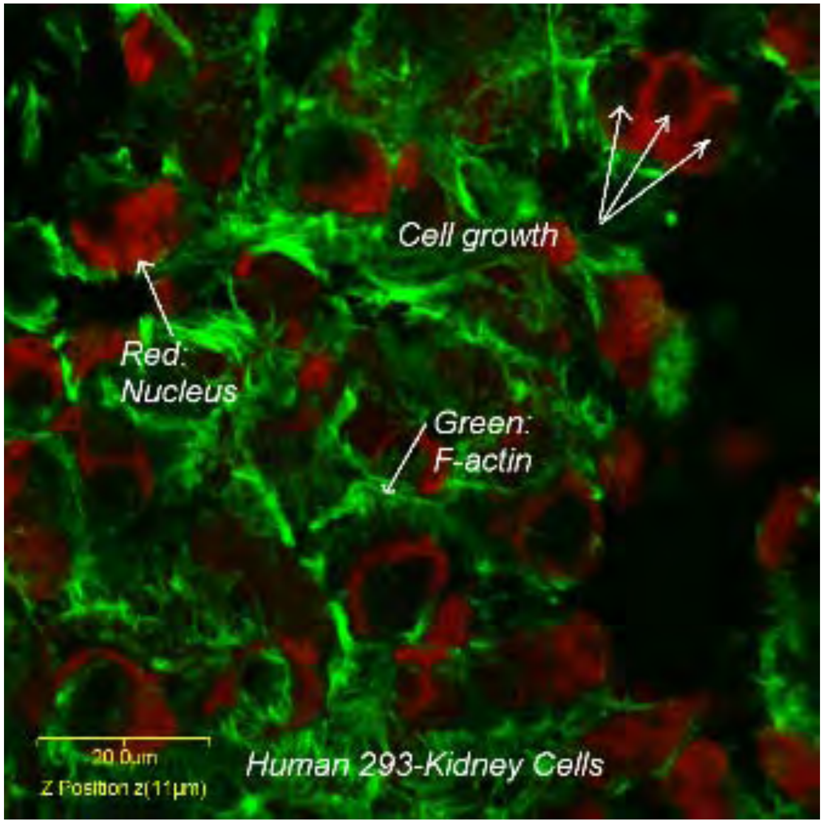
BIOSCAFFOLDS





Lakhtakia *et al.*, *Adv. Solid State Phys.* **46,** 295 (2008).

A. Lakhtakia

Applications of Parylene STFs

- Cell-culture substrates
- Coatings for prostheses (e.g. stents)
- Coatings for surgical equipment (e.g., catheters)
- Biosensors
- Tissue engineering for controlled drug release

Volumetric functionalization

IR monitoring

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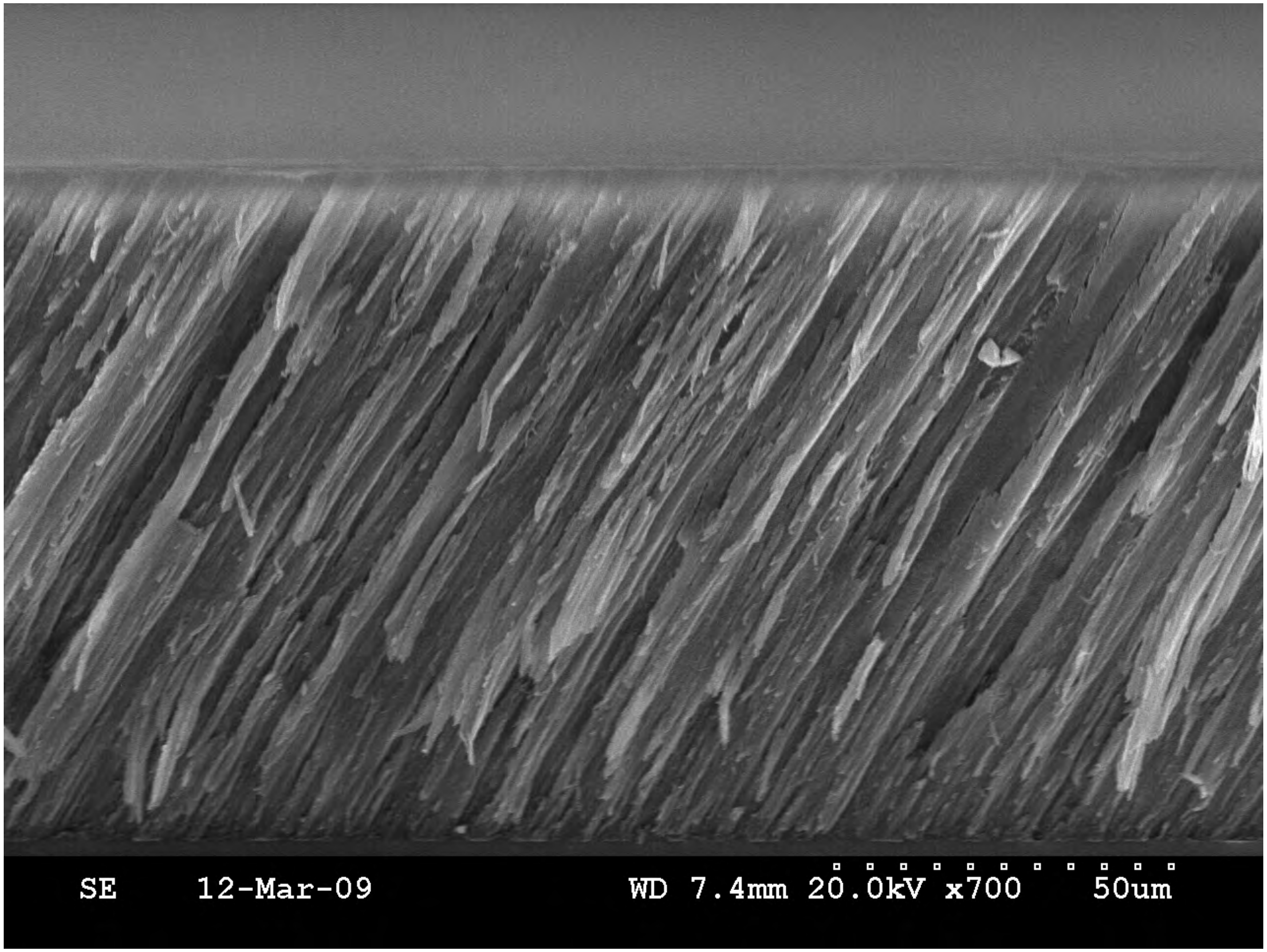
A. Lakhtakia

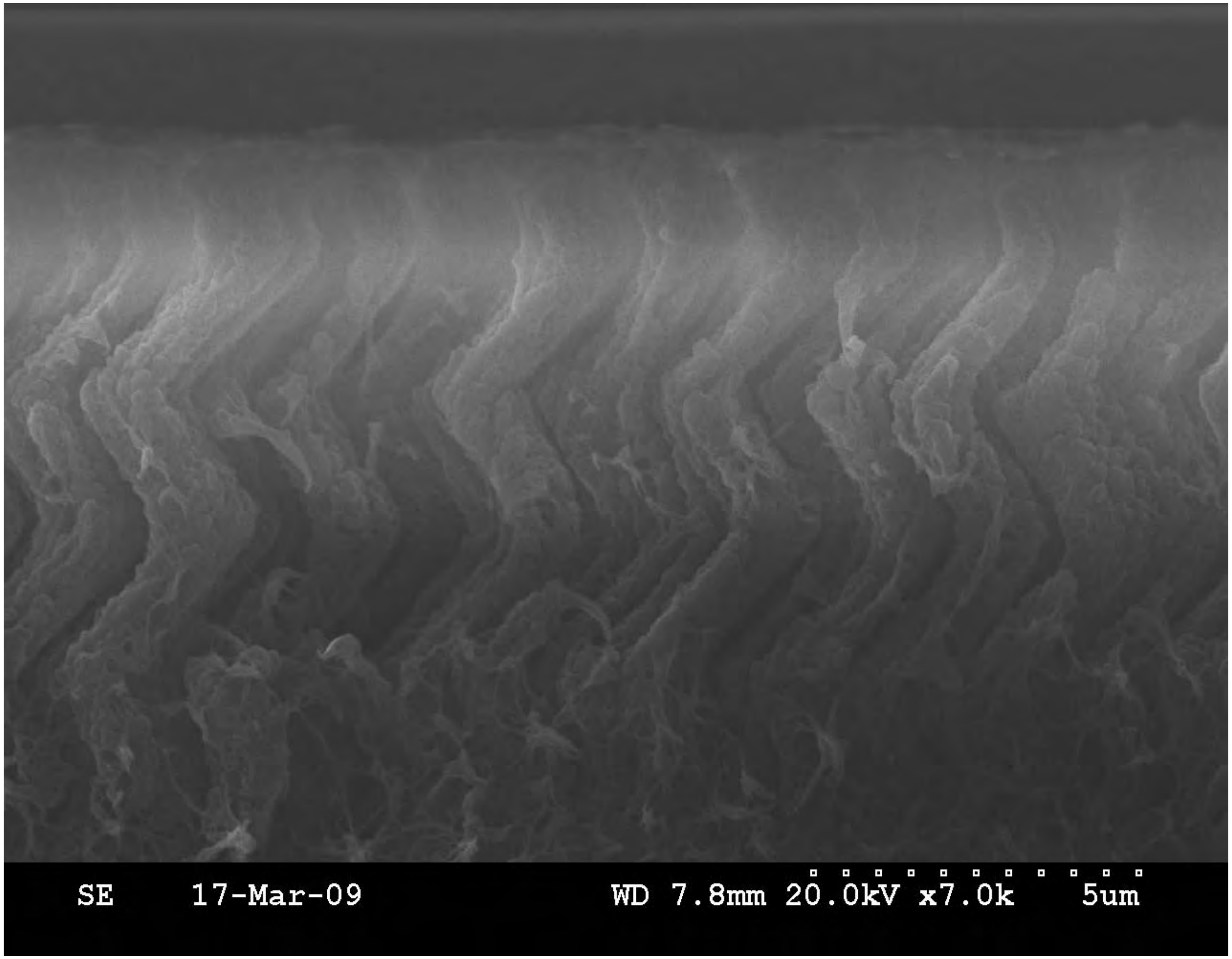
STFs for Ultrasonics

STFs for Ultrasonics



80-micron thick parylene CTF

STFs for Ultrasonics



15-micron thick parylene chevronic STF

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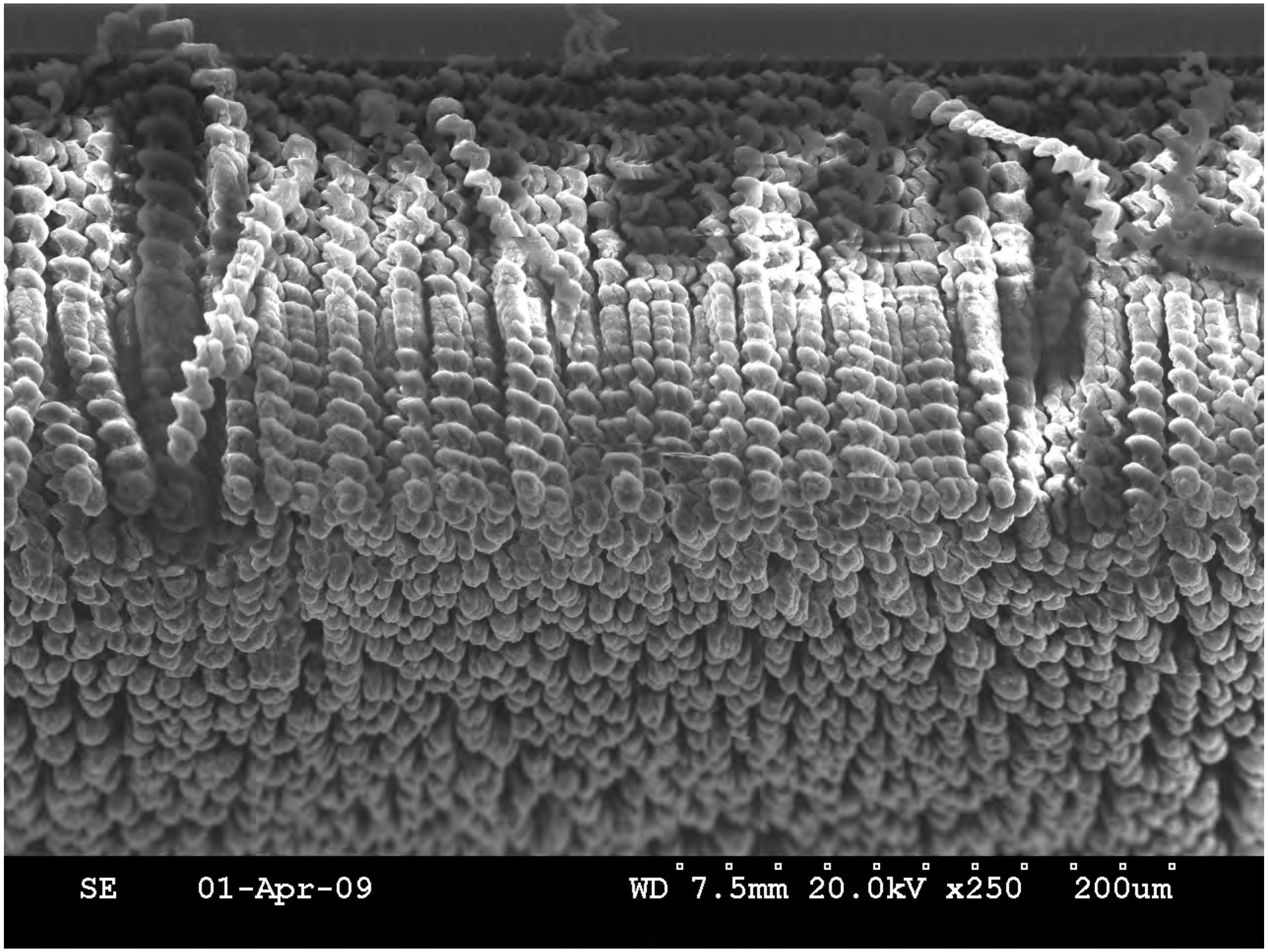
STFs for Ultrasonics



200-micron thick parylene chiral STF

A. Lakhtakia

A. Lakhtakia