Polarization Engineering *through* Nanoengineered Morphology

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Electromagnetics, Remote Sensing, and Space Sciences
Seminar
Department of Electrical Engineering
Penn State

Optics Practice

Control of

- Intensity
- Operating frequency band
- Polarization state

Optics Practice

Long History

– Intensity

– Operating frequency band

Short History

– Polarization state

Optics Practice

Polarization

– Discovered in 1809

Etienne-Louis Malus
1775 - 1812

Optics Practice

Polarization

– Discovered in 1809

Etienne-Louis Malus
1775 - 1812

– **"Do not disturb" designs**

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Polarization Engineering

- Anisotropic materials
- *Uniaxial and biaxial crystals*
- *Piezoelectric materials*

- Bianisotropic materials
- *Chiral materials*
- *Magnetoelectric materials*

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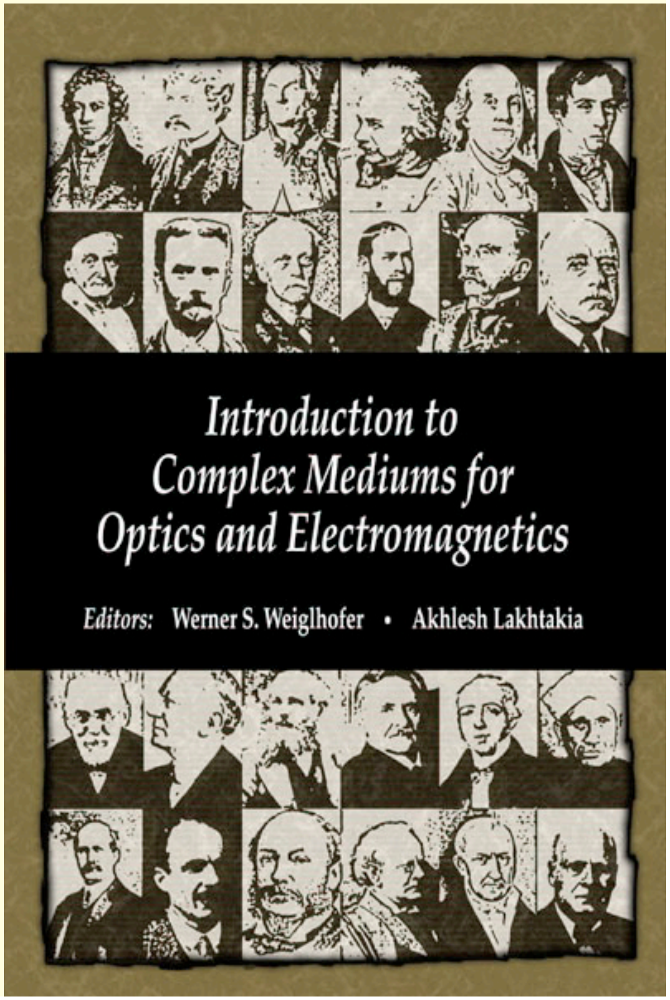
Polarization Engineering

– Anisotropic materials
– Bianisotropic materials



SPIE Press (2003)

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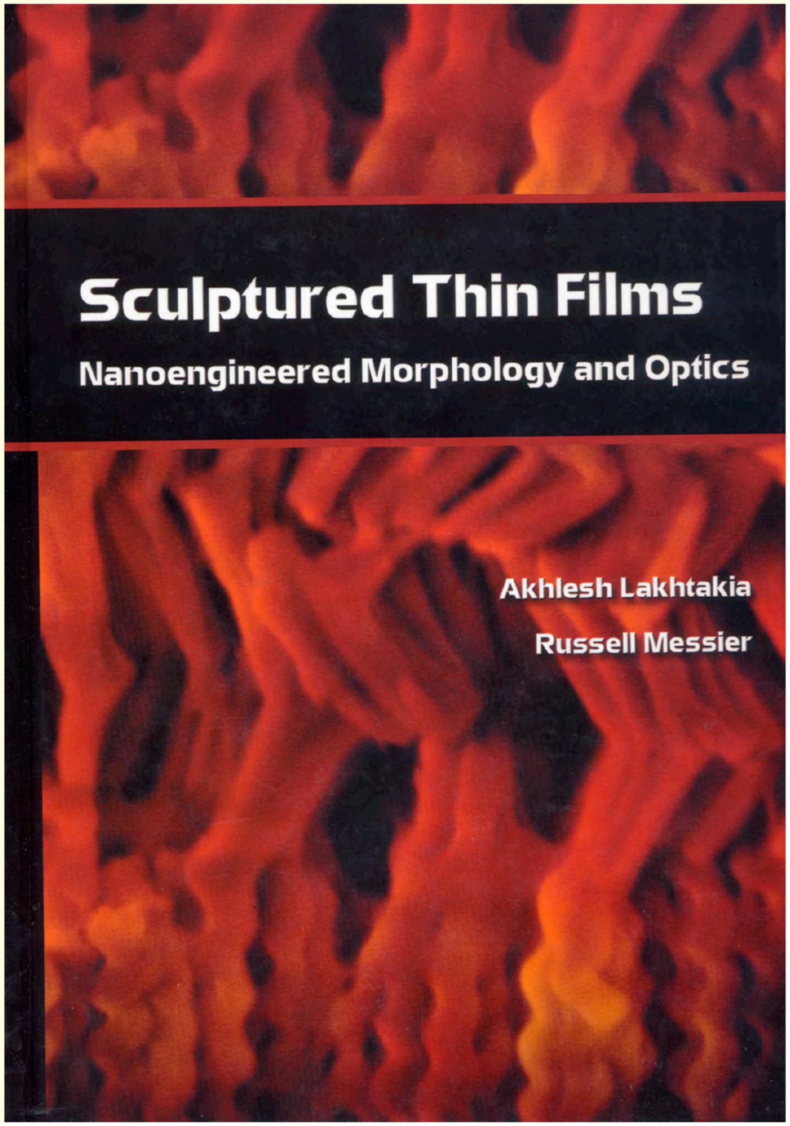
Polarization Engineering

– Sculptured Thin Films



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Students & Collaborators

- Joseph Sherwin, Sean Pursel, Benjamin Ross, Fei Wang (Penn State)

- Mark Horn, Jian Xu (Penn State)
- Ian Hodgkinson (Otago)
- Martin McCall (Imperial)
- John Polo (Edinboro)

Outline

- Introduction
- Optical Modeling
- Examples of Polarization Engineering
- More Examples
- What’s next?

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INTRODUCTION

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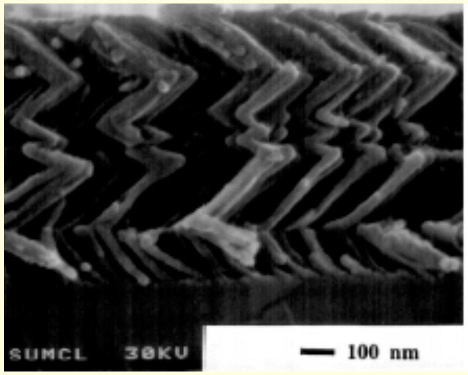

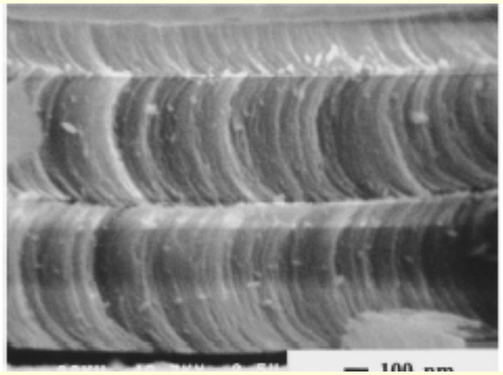

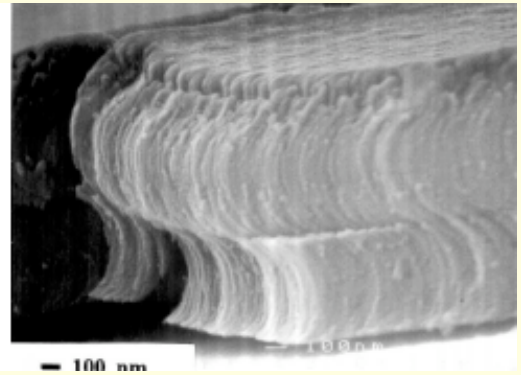

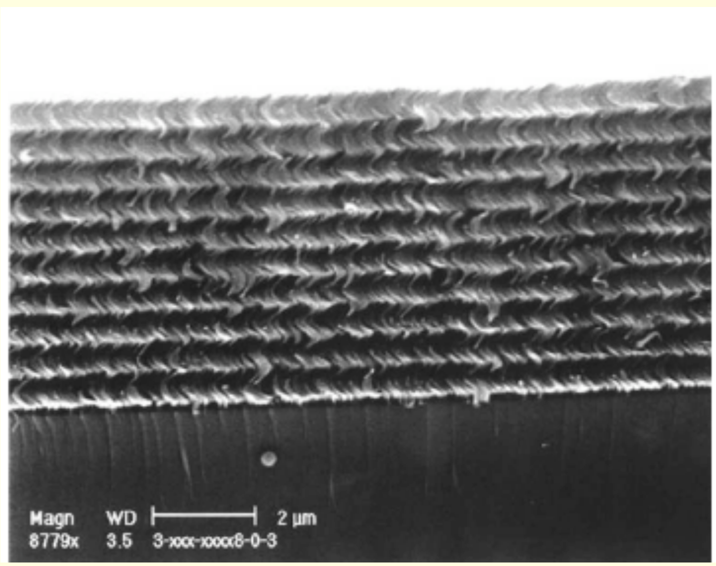

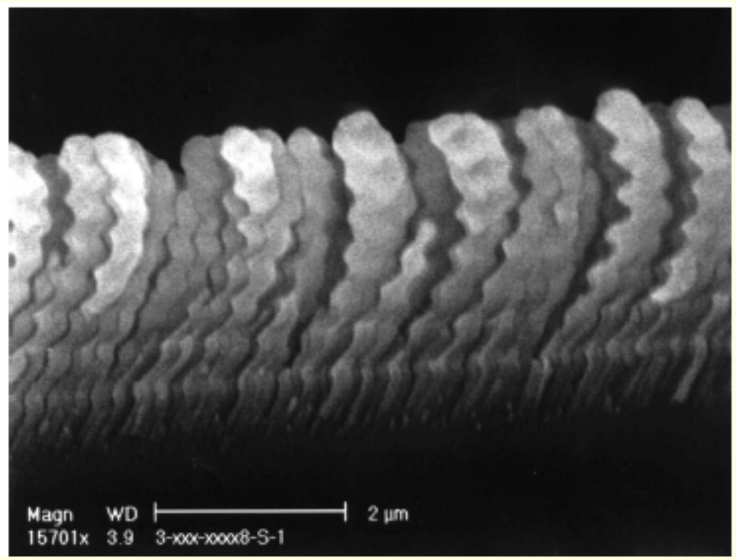

Sculptured Thin Films

Assemblies of Parallel Curved Nanowires/Submicronwires

Controllable Nanowire Shape

2-D - nematic
3-D - helicoidal
combination morphologies

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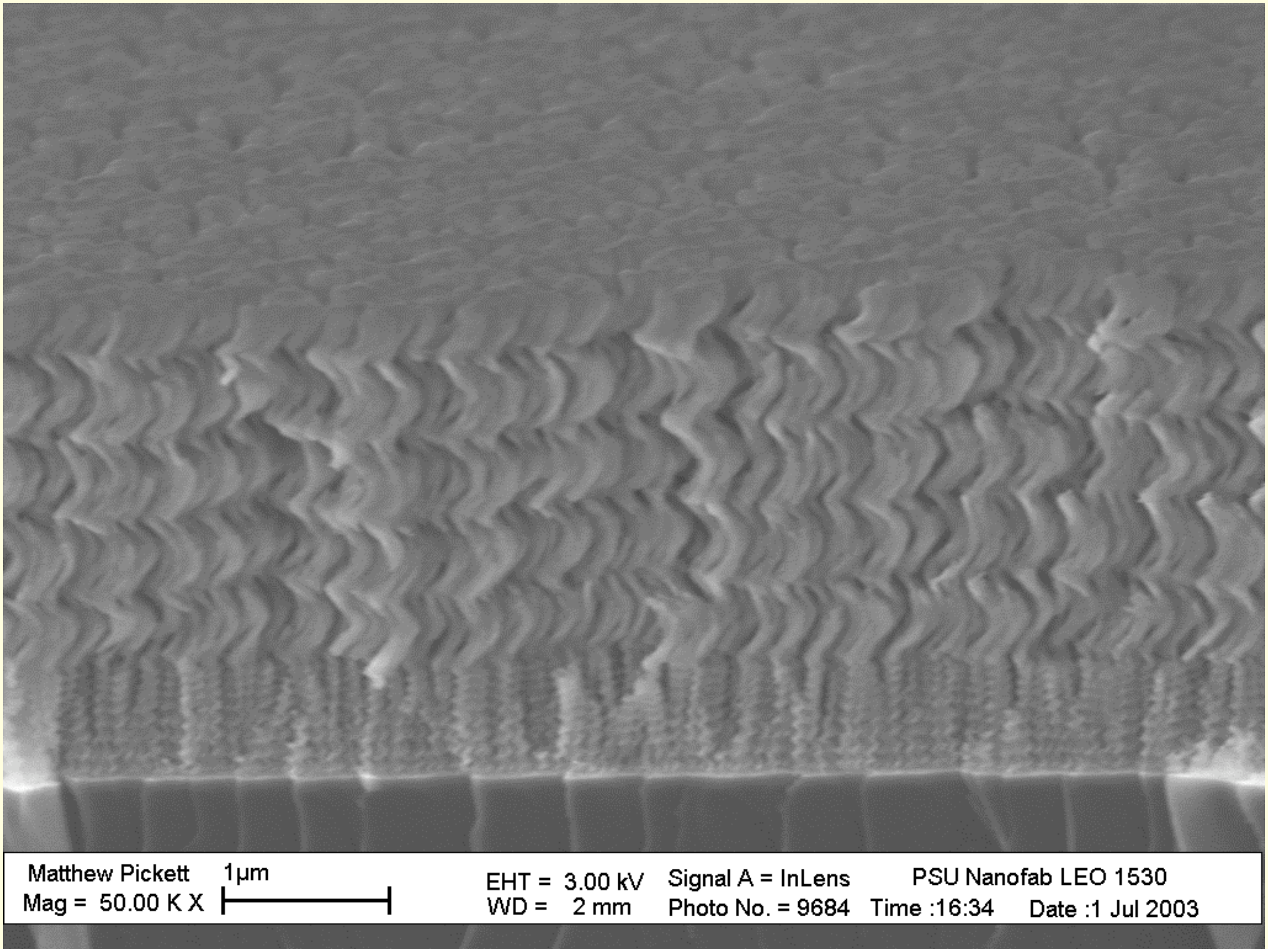

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Sculptured Thin Films

Assemblies of Parallel Curved Nanowires/Submicronwires

Controllable Nanowire Shape

2-D - nematic
3-D - helicoidal
combination morphologies
vertical sectioning

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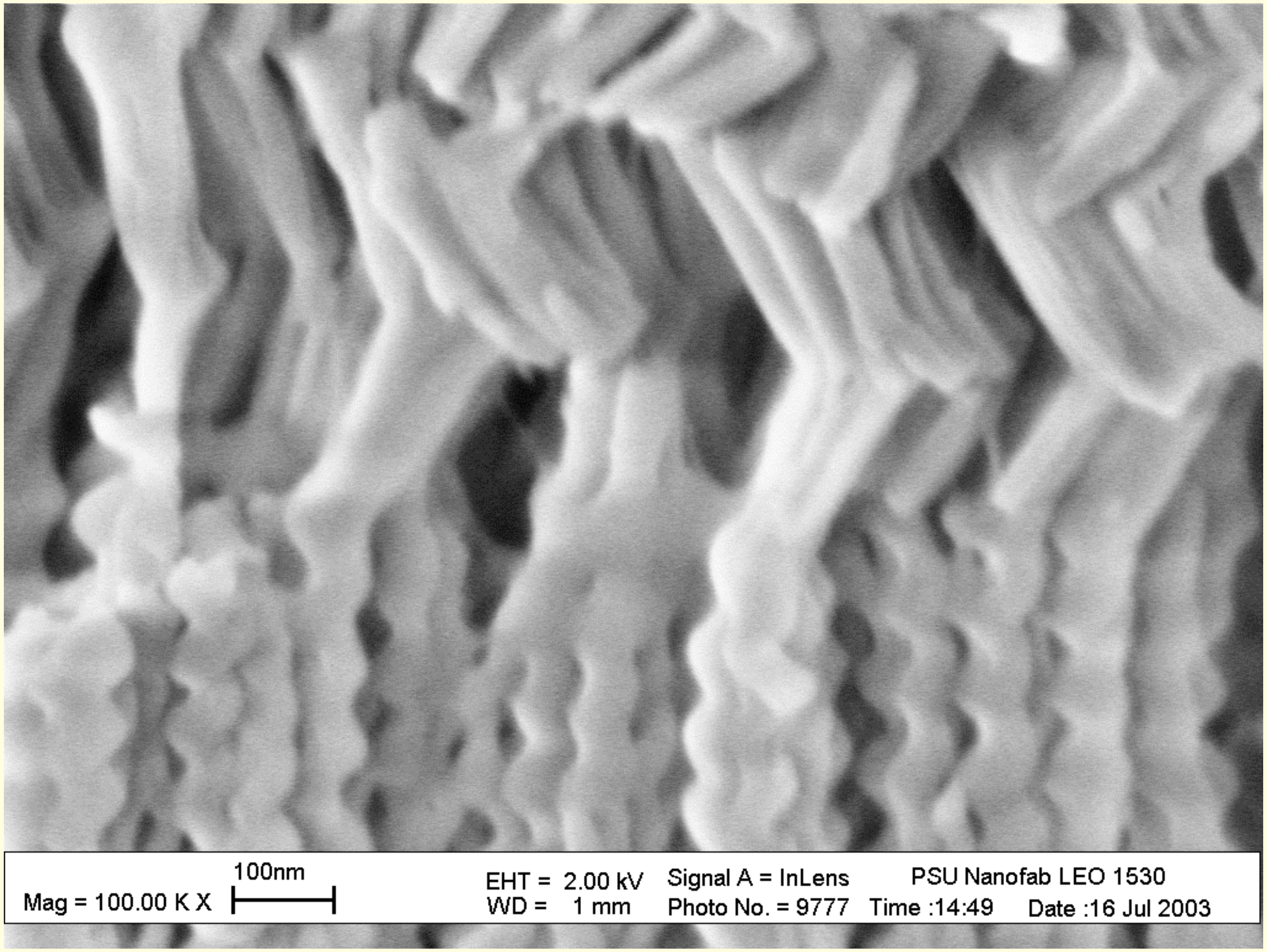
100nm
Mag = 100.00 K X
EHT = 2.00 kV
WD = 1 mm
Signal A = InLens
Photo No. = 9777
PSU Nanofab LEO 1530
Time :14:49
Date :16 Jul 2003

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Sculptured Thin Films

Assemblies of Parallel Curved Nanowires/Submicronwires

Controllable Nanowire Shape

2-D - nematic
3-D - helicoidal
combination 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)

Optical applications (1992-)

Biological applications (2003-)

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Sculptured Thin Films

Collaborators:

(i) Weiglhofer, University of Glasgow

(ii) Robbie & Brett, University of Alberta

(iii) McCall, Imperial College London

(iv) Hodgkinson, University of Otago

(v) Polo, Edinboro University

(vi) Reyes, UNAM, Mexico

(vii) Penn State Colleagues & Students

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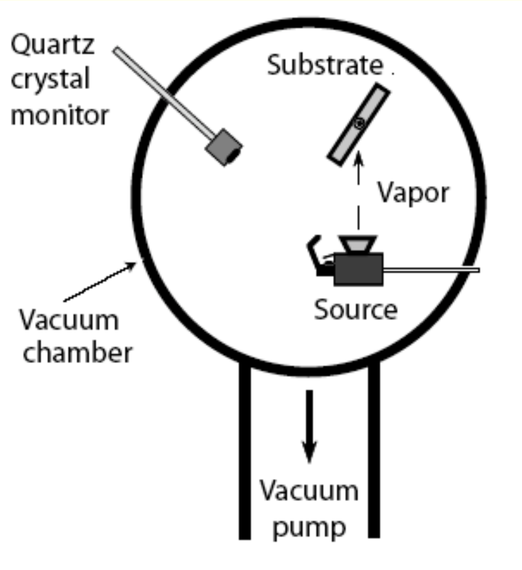
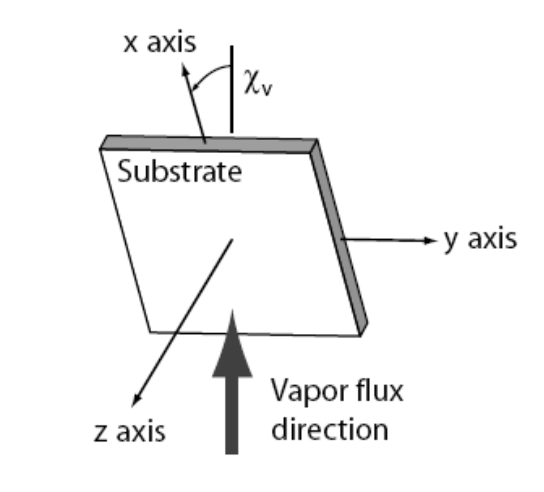
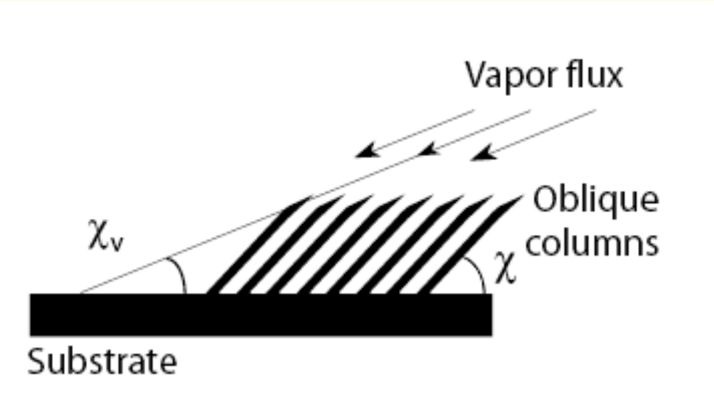
Physical Vapor Deposition
(Columnar Thin Films)







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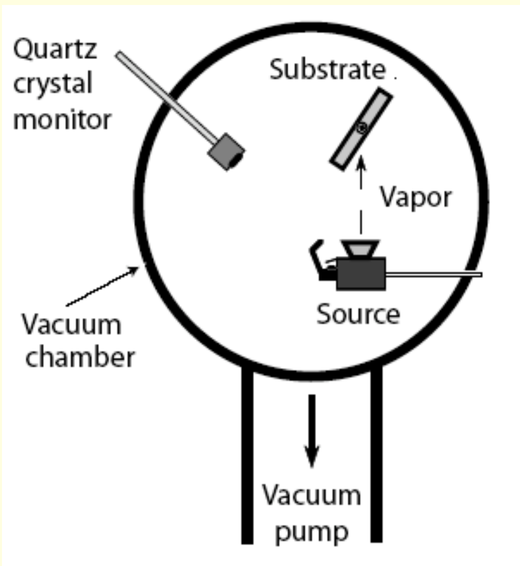
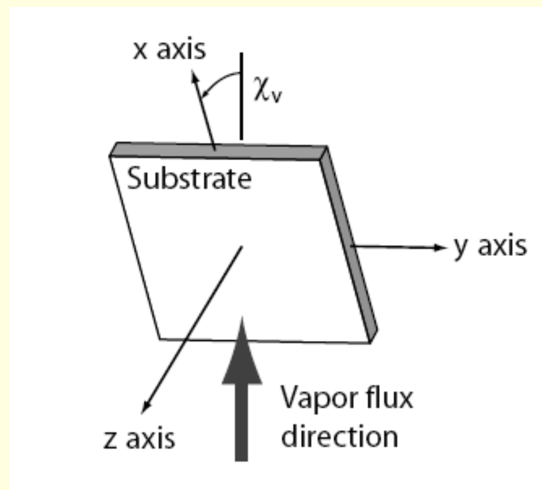
Physical Vapor Deposition
(Sculptured Thin Films)





Rotate about y axis for nematic morphology

Rotate about z axis for helicoidal morphology

Mix and match rotations for complex morphologies

Physical Vapor Deposition

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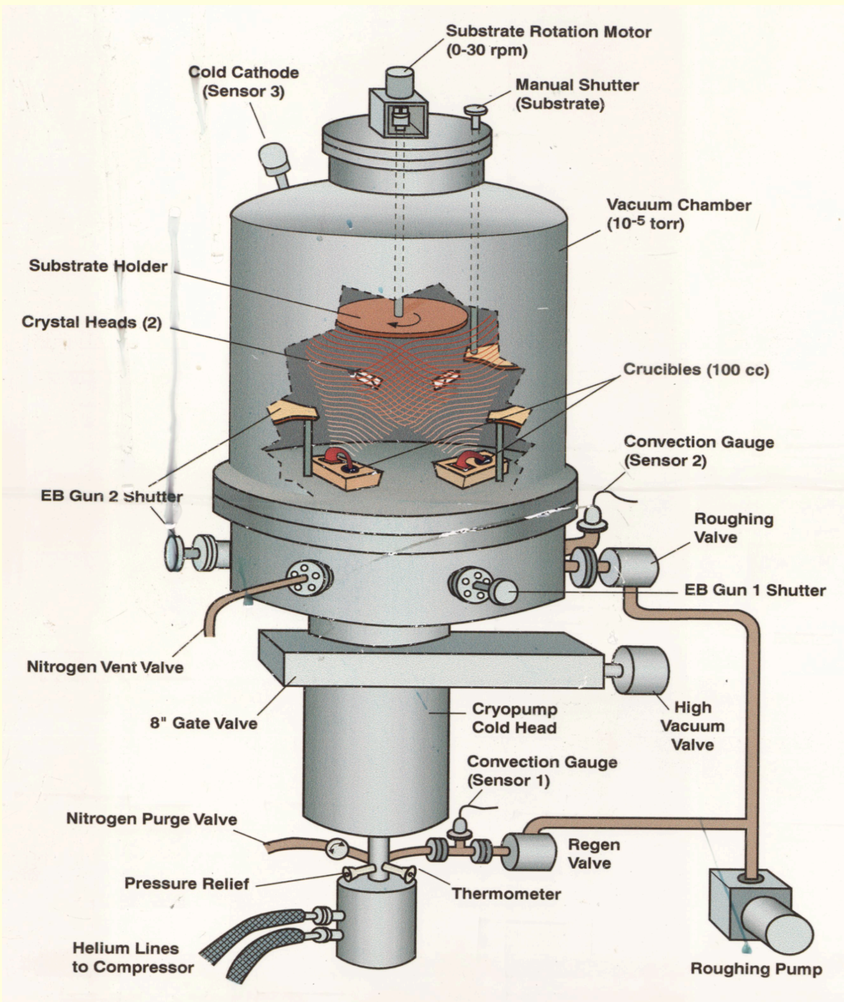
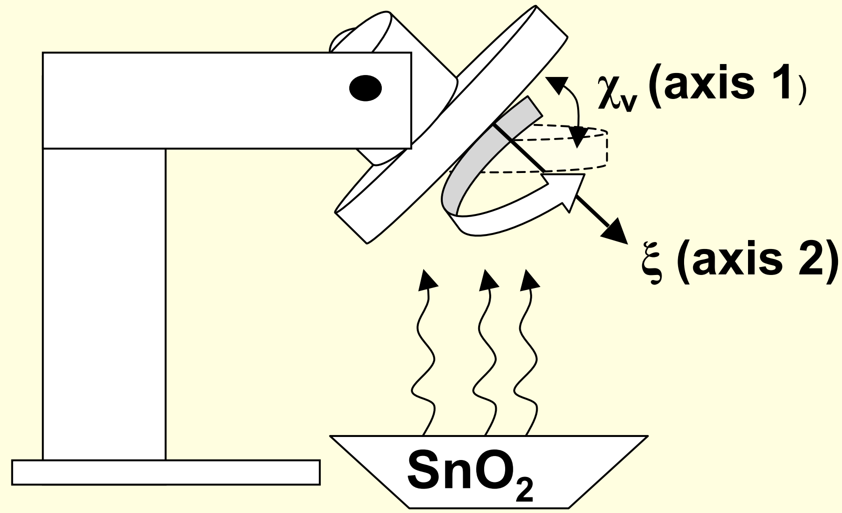
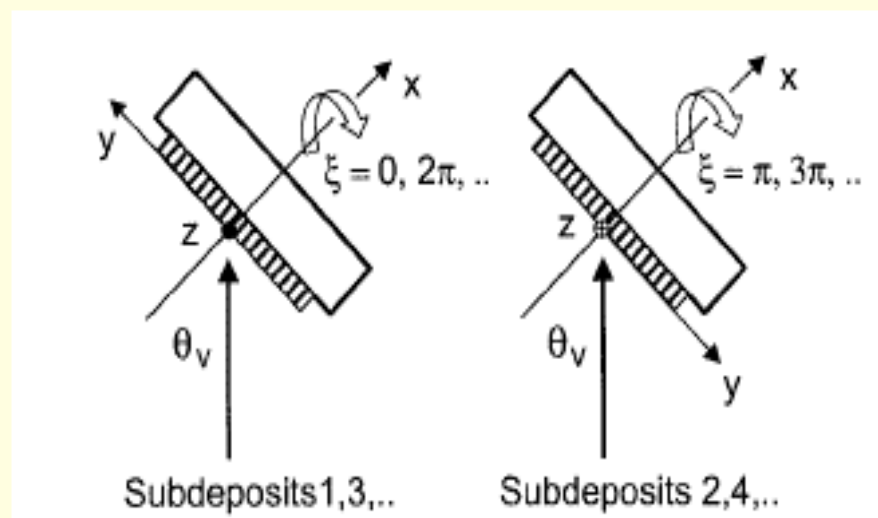
(Serial Bideposition)







Adapted for STFs by Hodgkinson

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Sculptured Thin Films

Optical Devices:
- Polarization Filters
- Bragg Filters
- Ultranarrowband Filters
- Fluid Concentration Sensors
- Bacterial Sensors (Penn State)
- Light Sources (Penn State)

Biomedical Applications:
- Tissue Scaffolds (Penn State)
- Stents (Penn State)
- Bone Repair (Penn State)

Other Applications:
- Photocatalysis (Toyota)
- Thermal Barriers (Alberta)
- Energy Harvesting (Penn State, Toledo)

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OPTICAL MODELING

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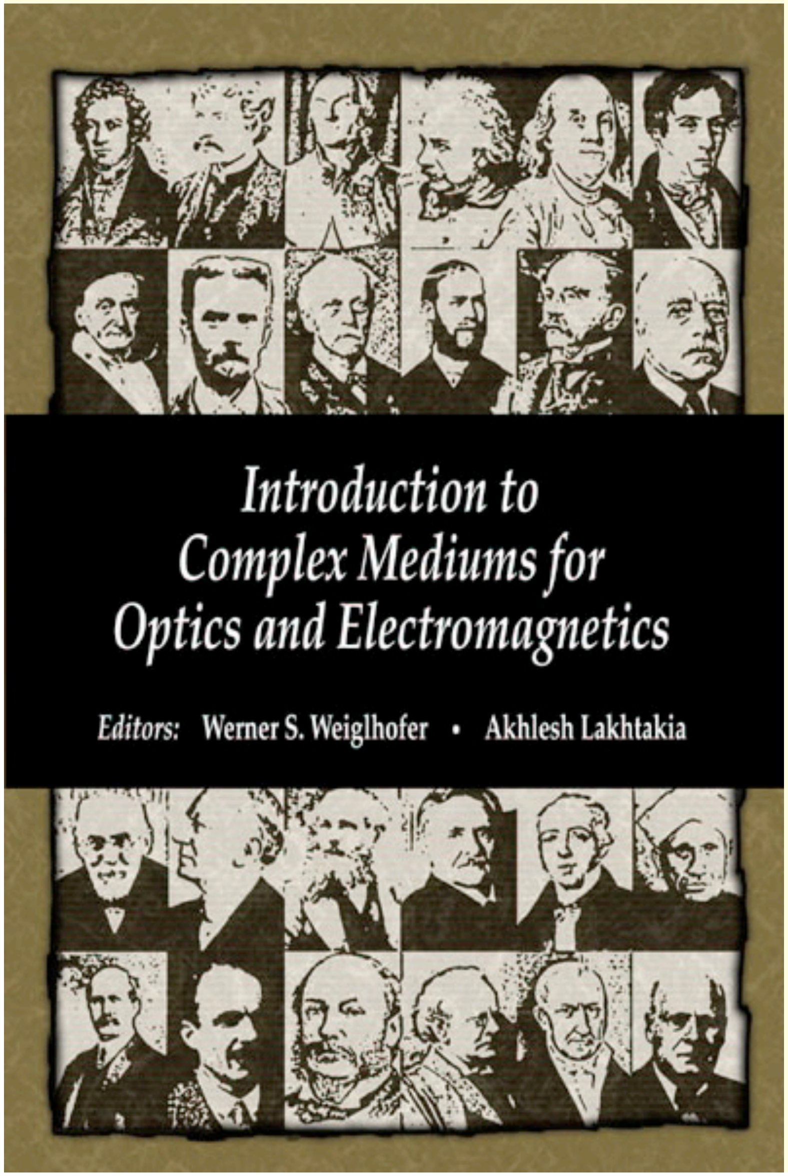
Optical Modeling of STFs



Linear
Bianisotropic
Materials

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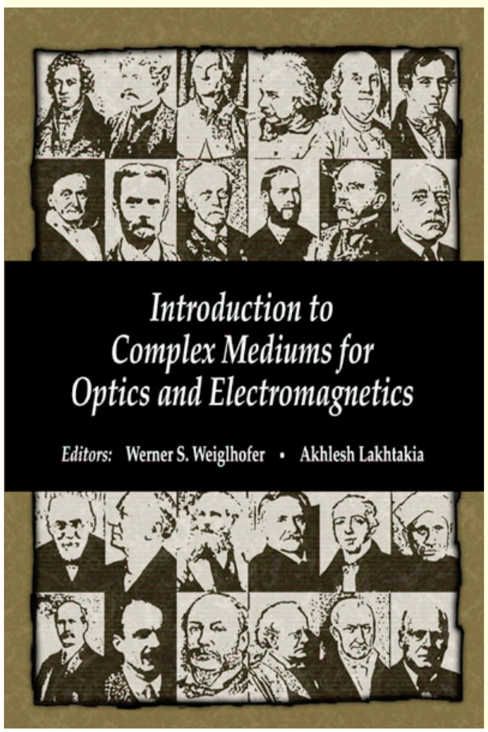
Optical Modeling of STFs

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

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

Linear
Bianisotropic
Materials



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

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

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

SPIE Press (2003)

Optical Modeling of STFs

Dielectric Materials

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

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Optical Modeling of STFs

Locally Orthorhombic Materials

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

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

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

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

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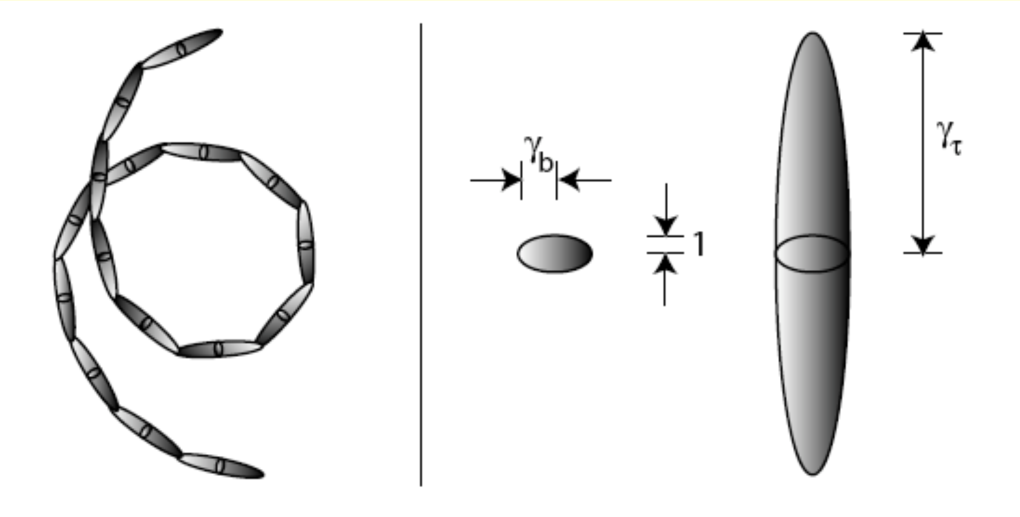
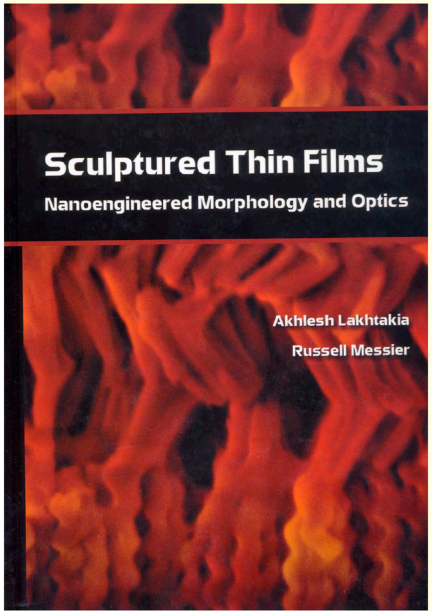
Optical Modeling of STFs



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



Mathematica Program

Sherwin and Lakhtakia (2001-2003): Bruggeman formalism

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Optical Modeling of STFs

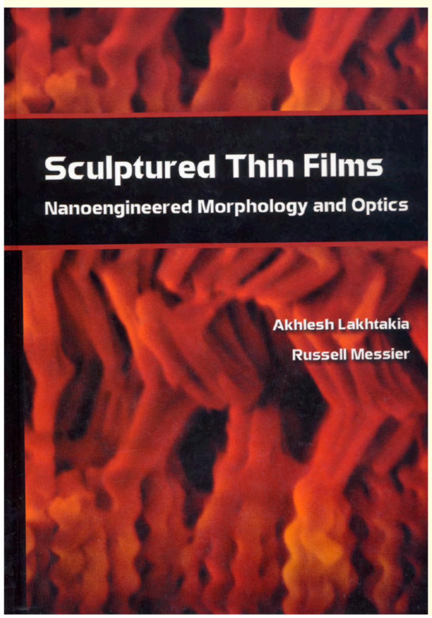
Wave Propagation

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

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

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

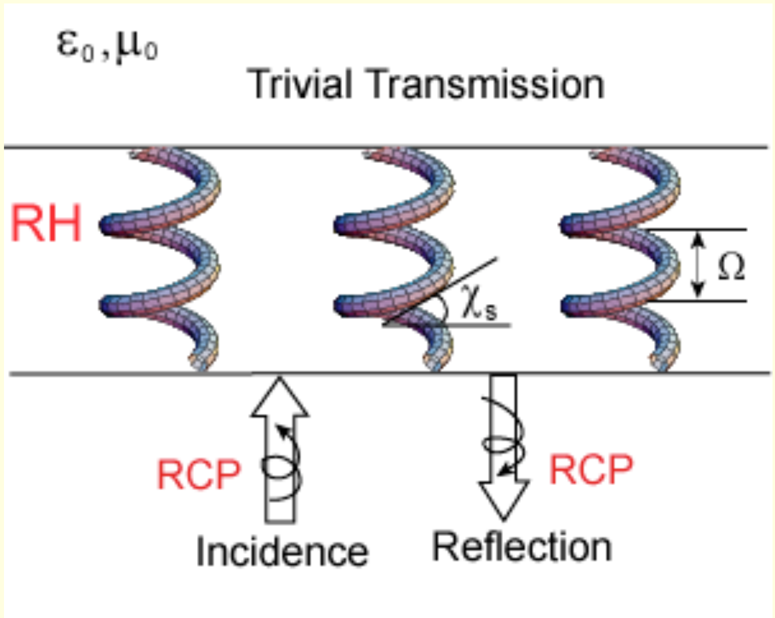
$$\left[\mathbf{f}(z,\kappa,\psi,\omega)\right] = \begin{bmatrix} e_x(z,\kappa,\psi,\omega) \\ e_y(z,\kappa,\psi,\omega) \\ h_x(z,\kappa,\psi,\omega) \\ h_y(z,\kappa,\psi,\omega) \end{bmatrix}$$

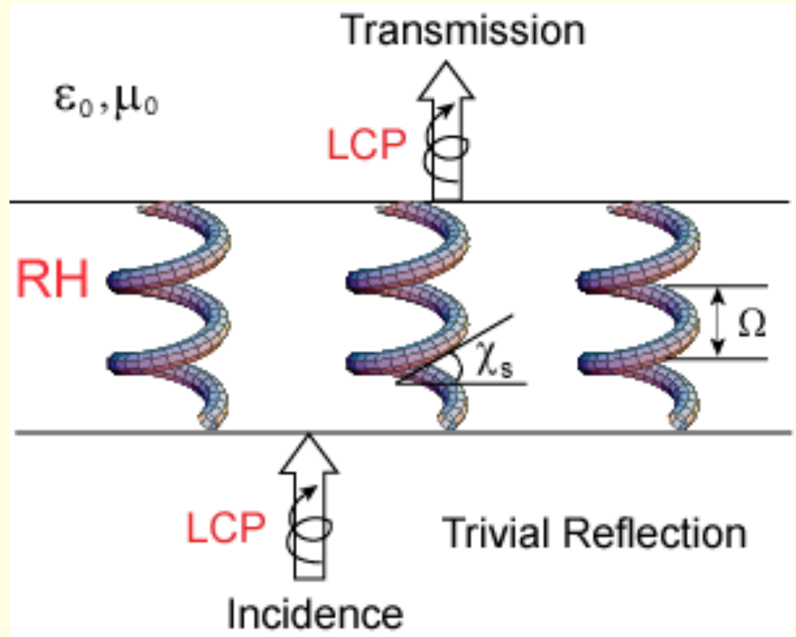


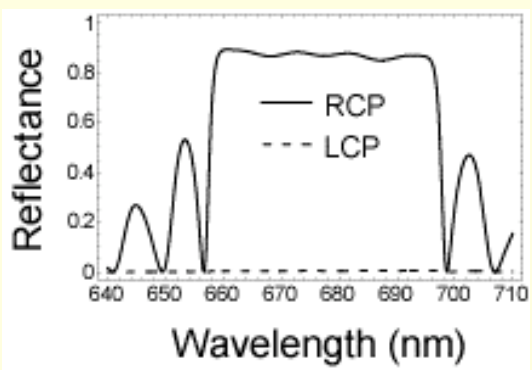
Mathematica
Program

EXAMPLES OF POLARIZATION ENGINEERING

Chiral STFs: Circular Bragg Phenomenon







A simple explanation (Coupled-Wave Theory):

- Co-handed wave: Scalar Bragg grating
- Cross-handed wave: Homogeneous bulk medium

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Chiral STF as CP Filter

442. J.A. Sherwin, **A. Lakhtakia** & I.J. Hodgkinson, 'On calibration of a nominal structure--property relationship model for chiral sculptured thin films by axial transmittance measurements,' *Optics Communications*, **209**, 2002, 369–375.

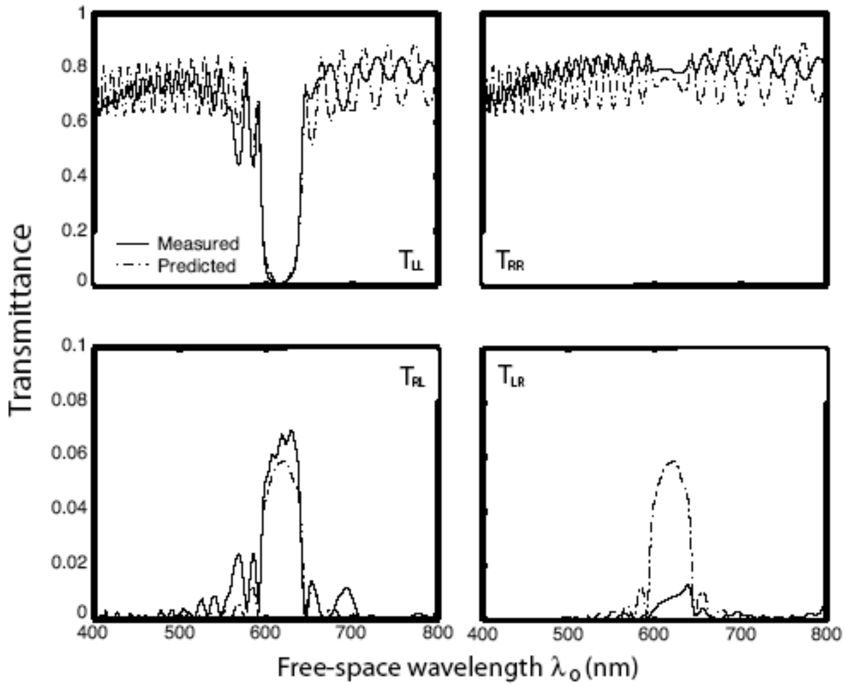

Figure 10.2: Predicted and measured transmittances of a circular polarization filter as functions of the free-space wavelength λ_0 for normal incidence. The filter is a chiral STF of patinal titanium oxide. The reference permittivity dyadic was predicted with $\epsilon_s = 6.3 + i0.012$, $\epsilon_v = 1$, $f_v = 0.421$, $\gamma_\tau^{(s)} = \gamma_\tau^{(v)} = 20$, 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.)

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Chiral STF as CP Filter

Engineering of Bragg Regime and CP State

$$\underline{\underline{\epsilon}}_{chiral}(z,\omega) = \underline{\underline{S}}_z(z) \bullet \underline{\underline{S}}_y(\chi) \bullet \left[\epsilon_a(\omega)\,\hat{\mathbf{u}}_z\hat{\mathbf{u}}_z + \epsilon_b(\omega)\,\hat{\mathbf{u}}_x\hat{\mathbf{u}}_x + \epsilon_c(\omega)\,\hat{\mathbf{u}}_y\hat{\mathbf{u}}_y\right] \bullet \underline{\underline{S}}_y^{-1}(\chi) \bullet \underline{\underline{S}}_z^{-1}(z)$$

$$\underline{\underline{S}}_z(z) = (\hat{\mathbf{u}}_x\hat{\mathbf{u}}_x + \hat{\mathbf{u}}_y\hat{\mathbf{u}}_y)\cos(\pi z/\Omega) + h(\hat{\mathbf{u}}_y\hat{\mathbf{u}}_x - \hat{\mathbf{u}}_x\hat{\mathbf{u}}_y)\sin(\pi z/\Omega) + \hat{\mathbf{u}}_z\hat{\mathbf{u}}_z$$

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

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Chiral STF as CP Filter

Engineering of Bragg Regime and CP State

$$\underline{\underline{\epsilon}}_{chiral}(z,\omega) = \underline{\underline{S}}_z(z) \bullet \underline{\underline{S}}_y(\chi) \bullet \left[\epsilon_a(\omega)\,\hat{\mathbf{u}}_z\hat{\mathbf{u}}_z + \epsilon_b(\omega)\,\hat{\mathbf{u}}_x\hat{\mathbf{u}}_x + \epsilon_c(\omega)\,\hat{\mathbf{u}}_y\hat{\mathbf{u}}_y\right] \bullet \underline{\underline{S}}_y^{-1}(\chi) \bullet \underline{\underline{S}}_z^{-1}(z)$$

$$\underline{\underline{S}}_z(z) = (\hat{\mathbf{u}}_x\hat{\mathbf{u}}_x + \hat{\mathbf{u}}_y\hat{\mathbf{u}}_y)\cos(\pi z/\Omega) + h(\hat{\mathbf{u}}_y\hat{\mathbf{u}}_x - \hat{\mathbf{u}}_x\hat{\mathbf{u}}_y)\sin(\pi z/\Omega) + \hat{\mathbf{u}}_z\hat{\mathbf{u}}_z$$

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

Rotational Speed: Controls Ω

Rotational Sense: Controls h

Vapor Incidence Angle: Controls $\epsilon_{a,b,c}$ and χ

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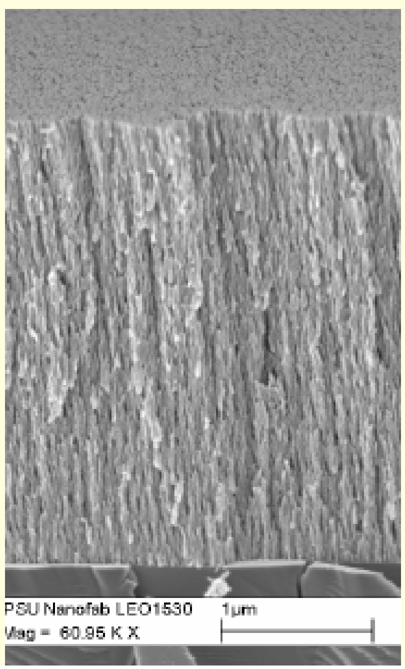
Chiral STF as CP Filter

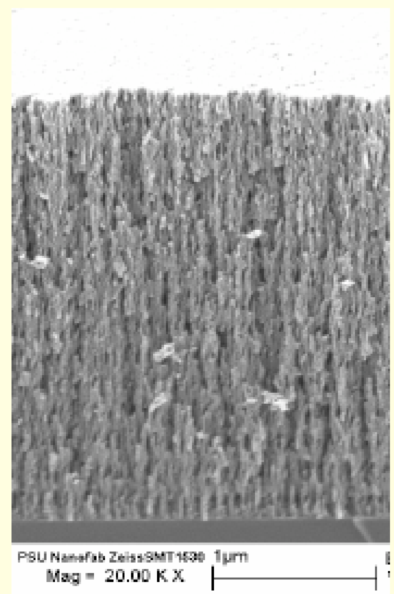
Post-Deposition Engineering of Bragg Regime

558. S.M. Pursel, M.W. Horn & **A. Lakhtakia**, Blue–shifting of circular Bragg phenomenon by annealing of chiral sculptured thin films,' *Optics Express*, **14**, 2006, 8001 – 8012.

Annealing

before *after*





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Chiral STF as CP Filter

Post-Deposition Engineering of Bragg Regime

Annealing

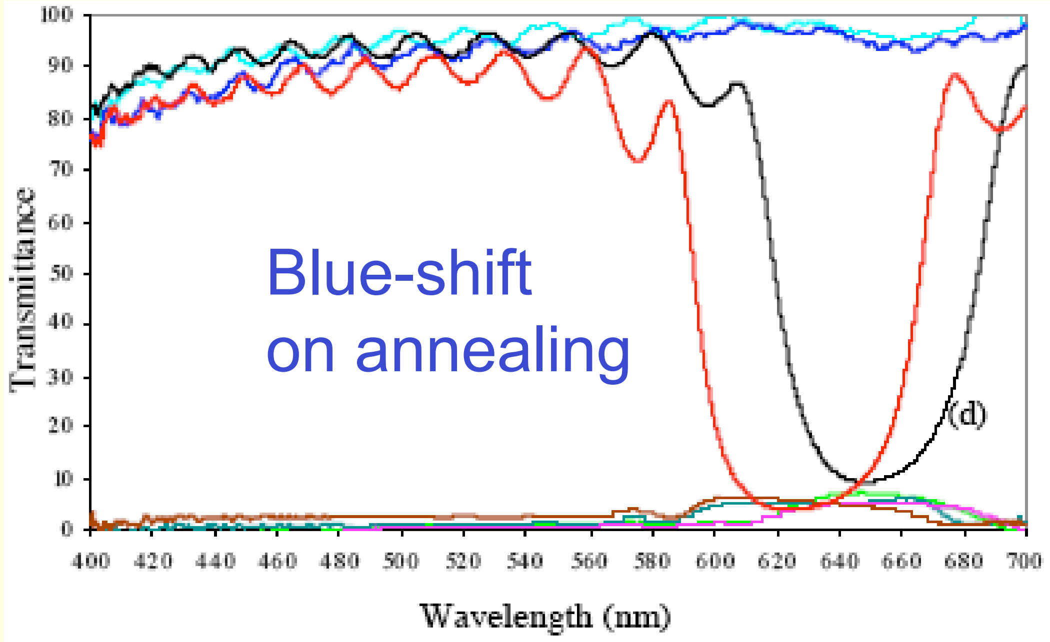
Blue-shift factors:

(i) Decreases pitch

(ii) Thins nanowires

Red-shift factors:

(i) Increases permittivity



Spectral Hole Filter

Central Phase Defect in a Chiral STF

- Homogeneous-layer defect
    - *Isotropic*
    - *Anisotropic*

- Twist defect

- Structurally-chiral-layer defect

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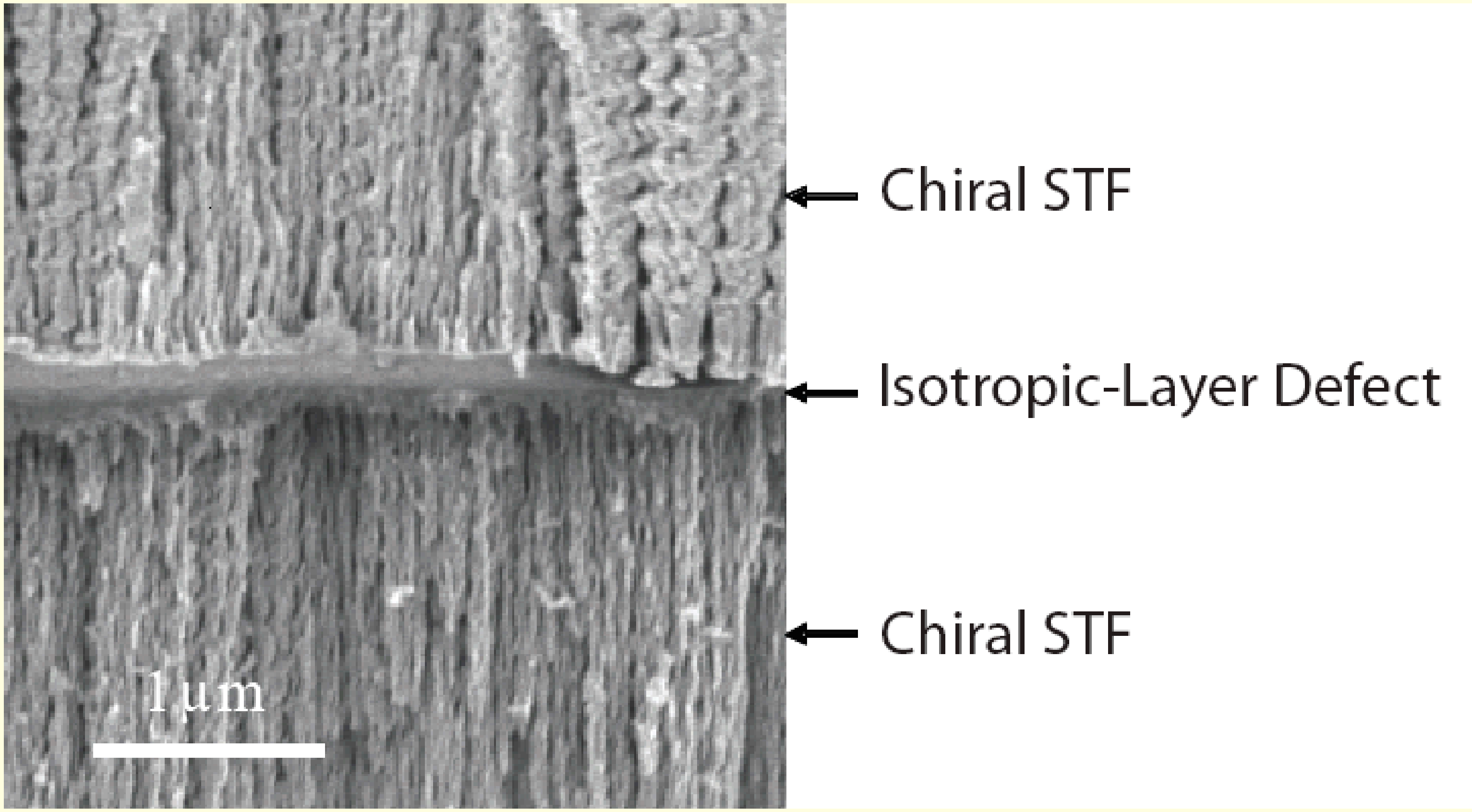
Spectral Hole Filter



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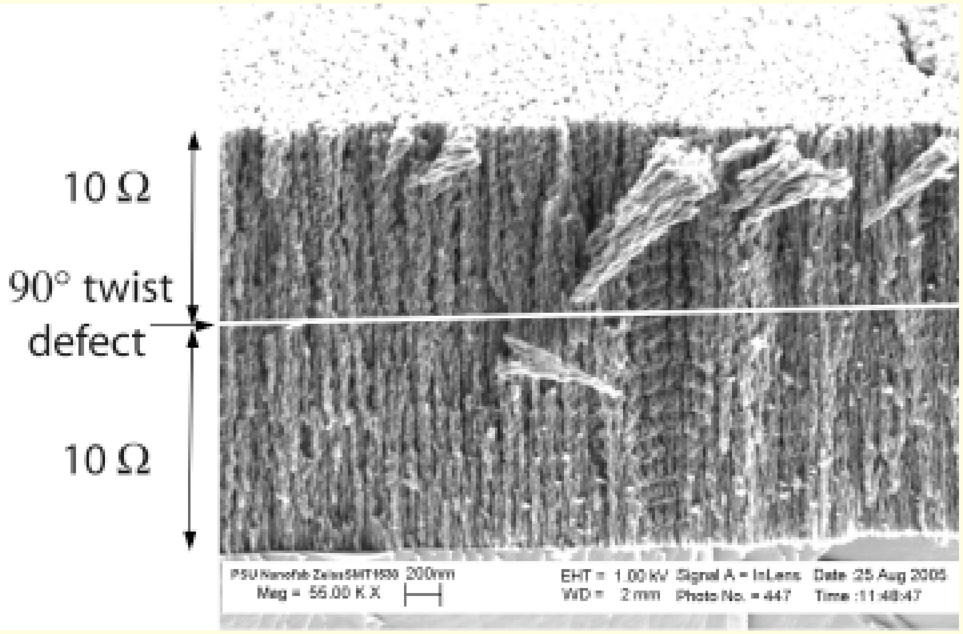
Spectral Hole Filter



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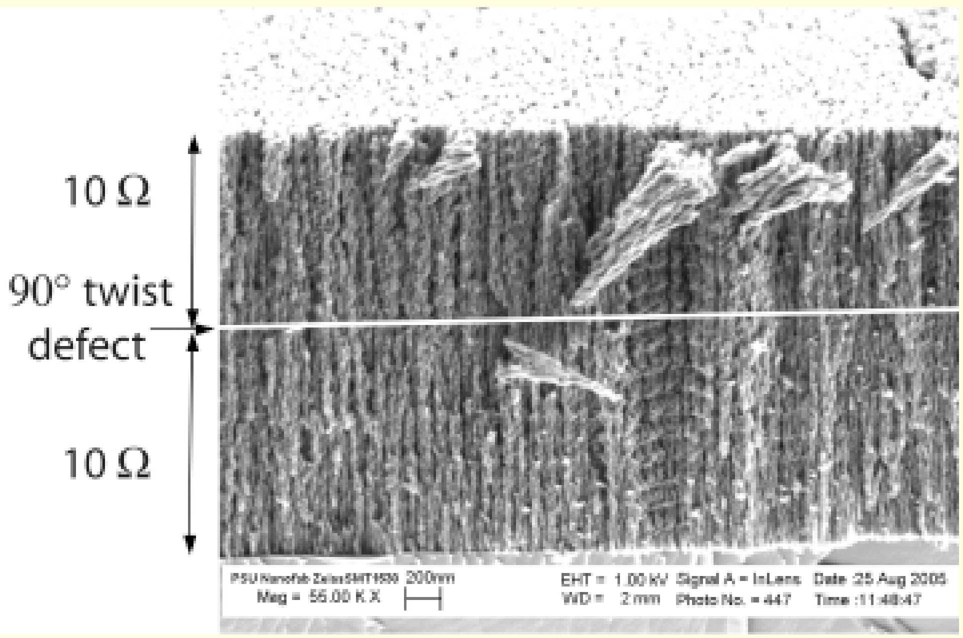
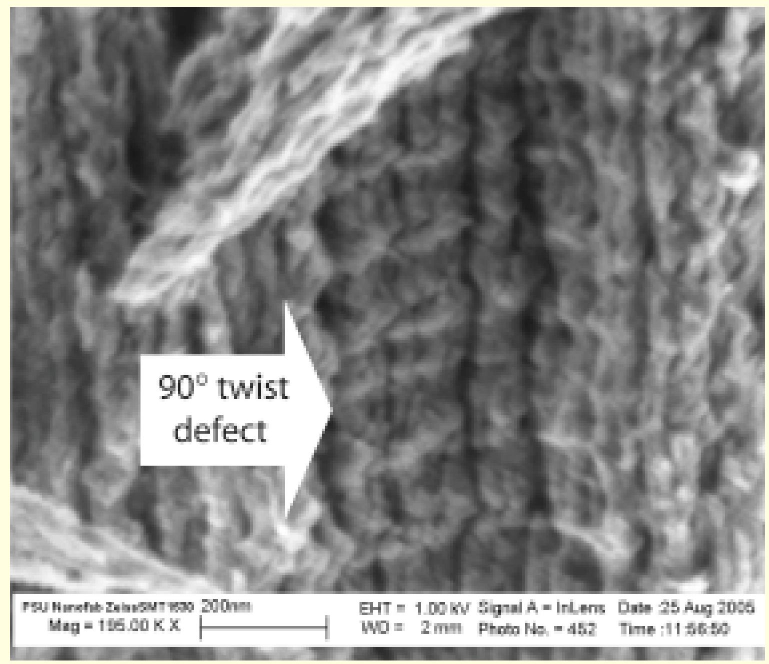
Spectral Hole Filter





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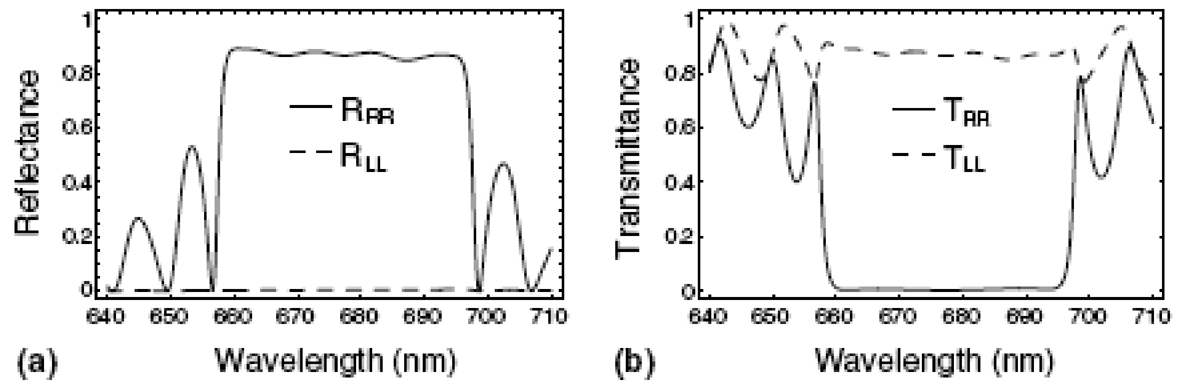
Spectral Hole Filter

Defect-free



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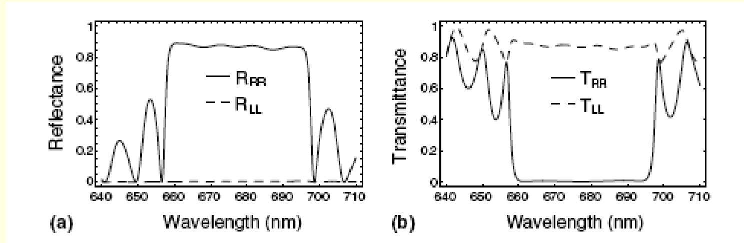
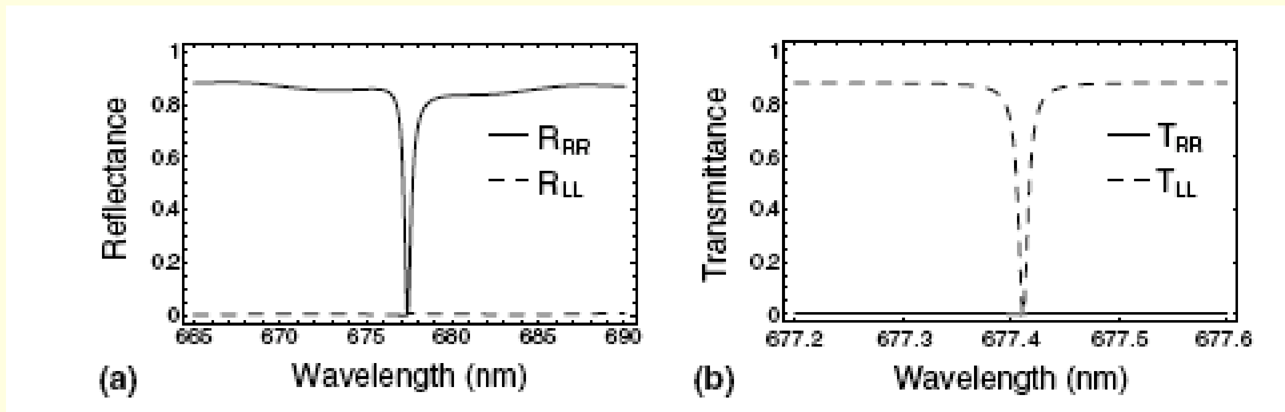
Spectral Hole Filter

Defect-free



With defect



Thin Chiral STF	Thick Chiral STF
Reflection Hole	Transmission Hole
Co-handed	Cross-handed
Theory/Experiment	Theory only

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Spectral Hole Filter

Isotropic-layer defect

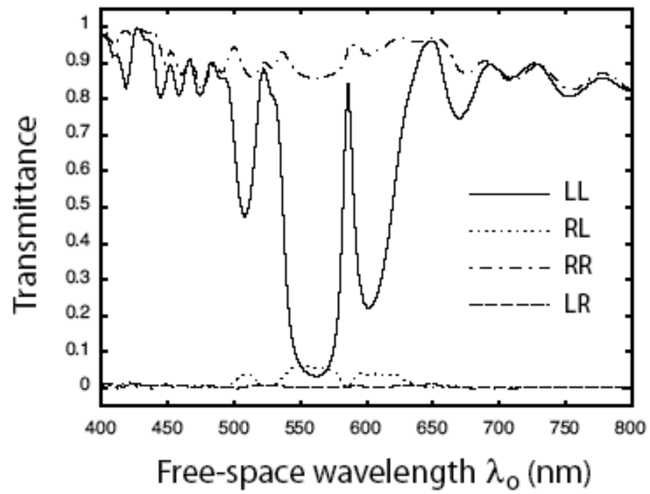


Figure 10.10: Measured transmittances of a narrow bandpass filter comprising an isotropic homogeneous spacer of hafnium oxide interposed between two identical, structurally left-handed, chiral STF sections of titanium oxide. Evidence of a hole in the spectrum of R_{LL} at 580-nm wavelength is provided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

377. I.J. Hodgkinson, Q.h. Wu, **A. Lakhtakia** & M.W. McCall, 'Spectral–hole filter fabricated using sculptured thin–film technology,' *Optics Communications*, **177**, 2000, 79–84.

A. Lakhtakia

Spectral Hole Filter

Twist defect

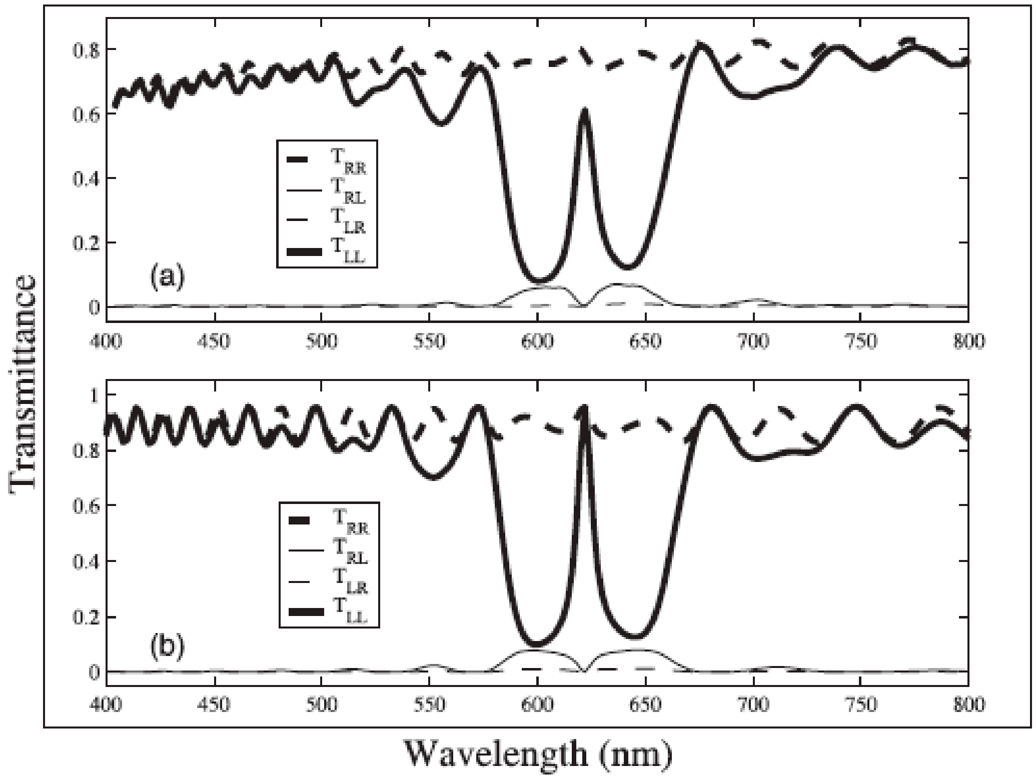


Fig. 7. (a) Measured spectra of the transmittances, T_{RR}, T_{RL}, T_{LR} and T_{LL} of the spacerless filter sp290200 with twist $\psi_t = 90°$. (b) Transmittance spectrums simulated for the above filter using the parameters $h = -1$, $N = 6$, $\Omega = 163$ nm, $n_{av} = 1.914$ and $\Delta n = 0.116$, so that $\lambda_0^{Br} = 622$ nm.

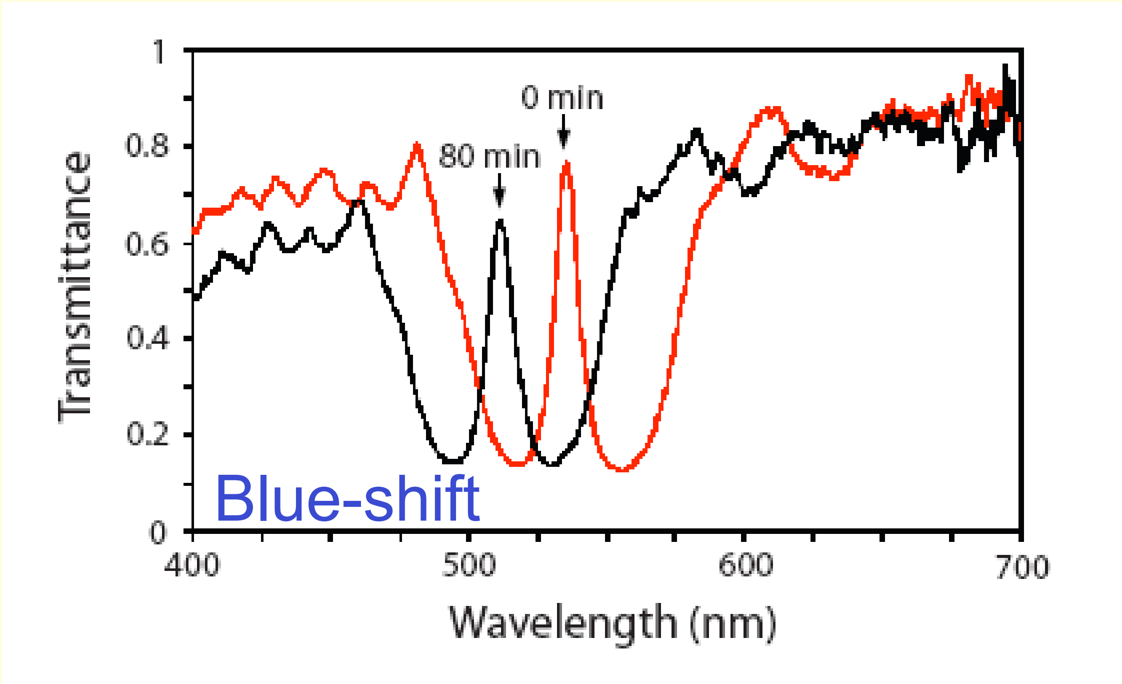
388. I.J. Hodgkinson, Q.h. Wu, K.E. Thorn, **A. Lakhtakia** & M.W. McCall, 'Spacerless circular–polarization spectral–hole filters using chiral sculptured thin films: theory and experiment,' *Optics Communications*, **184**, 2000, 57–66.

A. Lakhtakia

Spectral Hole Filter

Post-Deposition Engineering

Chemical Etching



Pursel, Lakhtakia, and Horn, Optical Engineering (2007)

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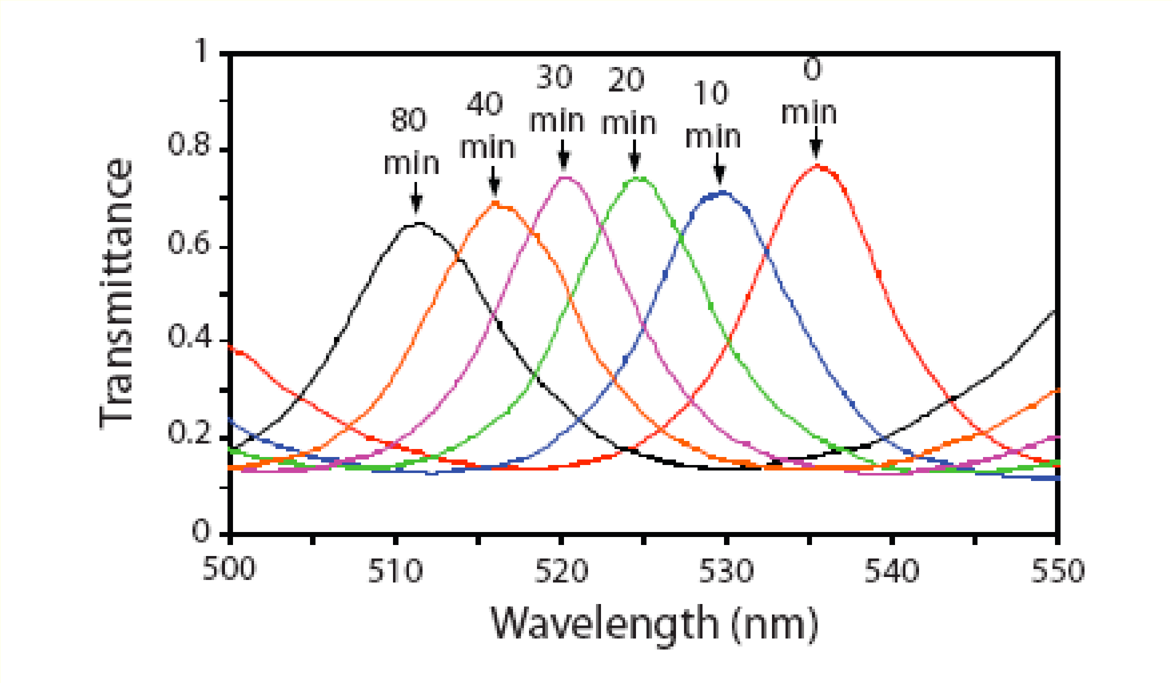
Spectral Hole Filter

Post-Deposition Engineering

Chemical Etching Columnar Thinning Blue Shift



Pursel, Lakhtakia, and Horn, Optical Engineering (2007)

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Fluid Concentration Sensor

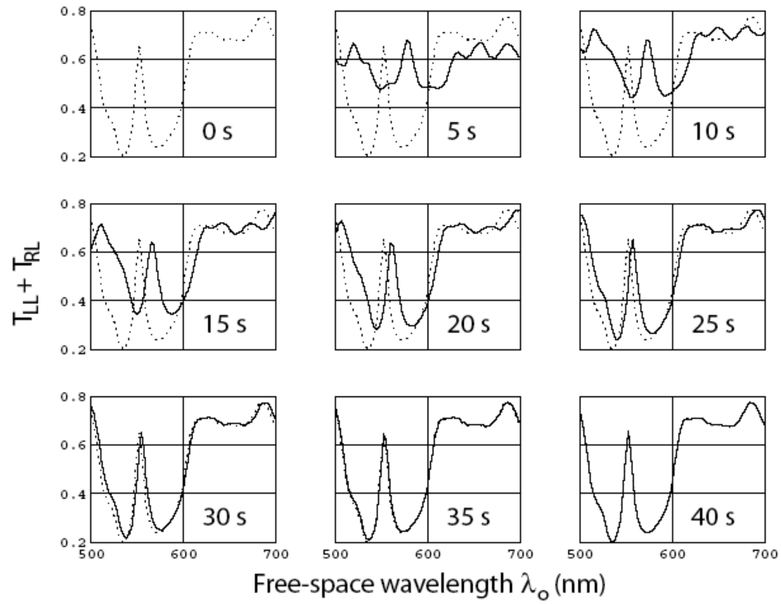

Figure 10.22: Optical response of a narrow bandpass filter, described by Eq. (10.17) and made of two structurally left-handed chiral STF sections, on infiltration by water vapor. The dotted lines indicate the measured transmittance spectrum when the filter was dry. The filter was flooded with water and 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.)

410. **A. Lakhtakia**, M.W. McCall, J.A. Sherwin, Q.H. Wu & I.J. Hodgkinson, 'Sculptured–thin–film spectral holes for optical sensing of fluids,' *Optics Communications*, **194**, 2001, 33–46.

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MORE EXAMPLES OF POLARIZATION ENGINEERING

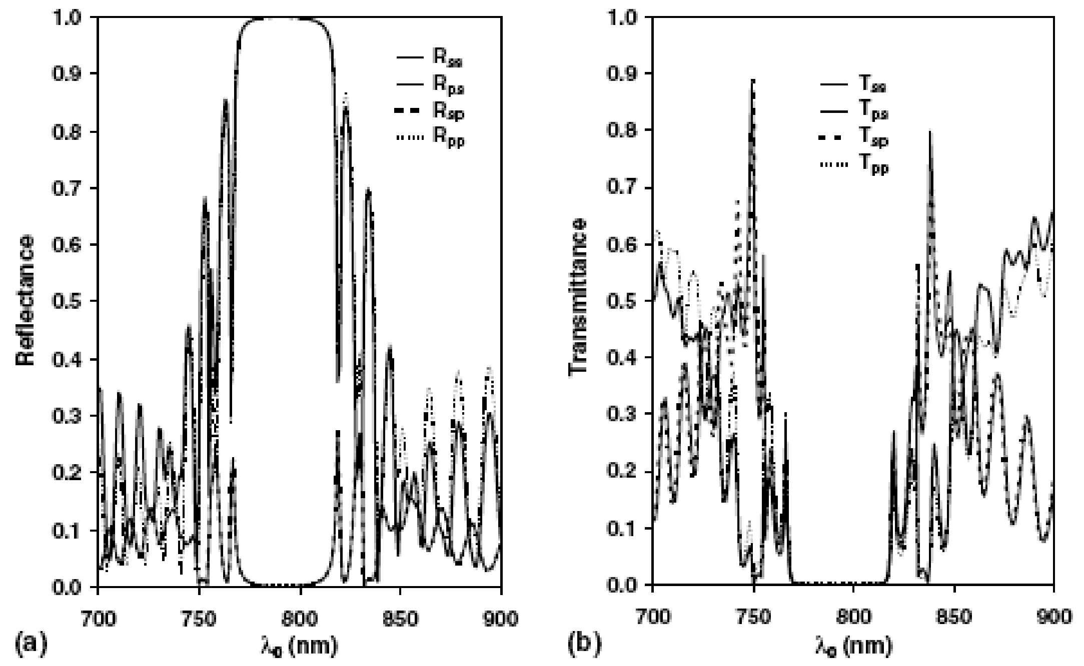
A. Lakhtakia

Tilt-Modulated Chiral STF

$$\underline{\underline{\epsilon}}_{tmc}(z,\omega) = \underline{\underline{S}}_z(z) \bullet \underline{\underline{S}}_y[\chi(z)] \bullet \left[\epsilon_a(z,\omega)\,\hat{\mathbf{u}}_z\hat{\mathbf{u}}_z + \epsilon_b(z,\omega)\,\hat{\mathbf{u}}_x\hat{\mathbf{u}}_x + \epsilon_c(z,\omega)\,\hat{\mathbf{u}}_y\hat{\mathbf{u}}_y\right] \bullet \underline{\underline{S}}_y^{-1}[(\chi(z)] \bullet \underline{\underline{S}}_z^{-1}(z)$$

$$\chi_v(z) = \tilde{\chi}_v + \delta_v \sin(2\pi z/\Omega)$$

$\delta_v = 10°,\ \tilde{\chi}_v = 35°$

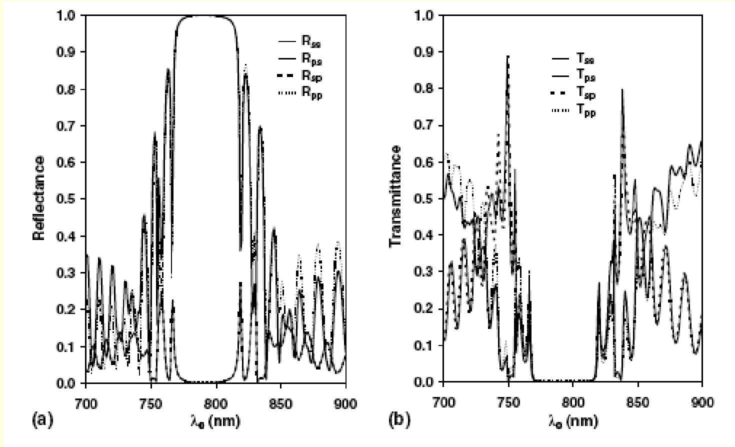


500. J.A. Polo, Jr. & **A. Lakhtakia**, 'Tilt–modulated chiral sculptured thin films: an alternative to quarter–wave stacks,' *Optics Communications*, **242**, 2004, 13 – 21.

A. Lakhtakia

Tilt-Modulated Chiral STF

Ordinary Dielectric Mirror



Advantages:

(1) Single material

(2) Bragg FWHM governed by tilt-modulation amplitude

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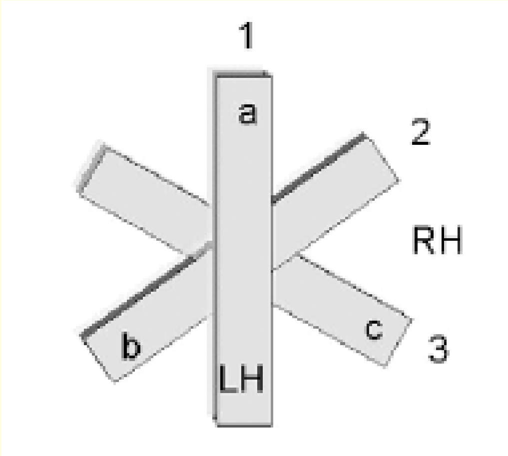
Ambichiral STF

Reusch 1869

$$\underline{\underline{\epsilon}}_n(\omega) = \underline{\underline{R}}_z\left[2h\frac{(n-1)\pi}{N}\right] \bullet \underline{\underline{S}}_y(\chi) \bullet \left[\epsilon_a(\omega)\,\hat{\mathbf{u}}_z\hat{\mathbf{u}}_z + \epsilon_b(\omega)\,\hat{\mathbf{u}}_x\hat{\mathbf{u}}_x + \epsilon_c(\omega)\,\hat{\mathbf{u}}_y\hat{\mathbf{u}}_y\right] \bullet \underline{\underline{S}}_y^{-1}(\chi) \bullet \underline{\underline{R}}_z^{-1}\left[2h\frac{(n-1)\pi}{N}\right] \quad (1$$

$$\underline{\underline{R}}_z(\zeta) = (\hat{\mathbf{u}}_x\hat{\mathbf{u}}_x + \hat{\mathbf{u}}_y\hat{\mathbf{u}}_y)\,\cos\zeta + (\hat{\mathbf{u}}_y\hat{\mathbf{u}}_x - \hat{\mathbf{u}}_x\hat{\mathbf{u}}_y)\,\sin\zeta + \hat{\mathbf{u}}_z\hat{\mathbf{u}}_z$$



$$d_n = d_1\left\{1 + a\sin\left[4\frac{(n-1)\pi}{N}\right]\right\}, \quad 0 \le a \le 1$$

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Ambichiral STF

All layers of equal thickness.

2 Bragg regimes

Different CP states reflected

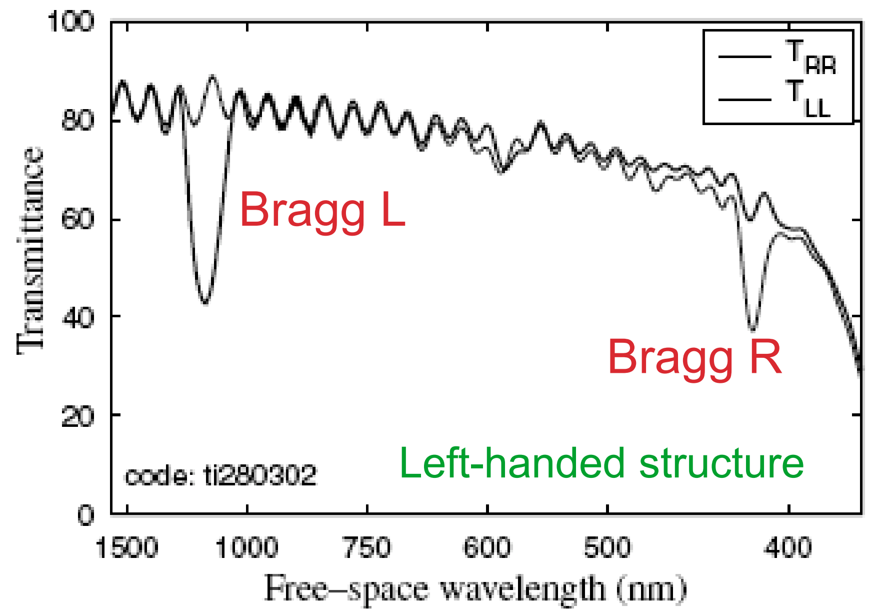


Fig. 4. Measured co-polarized transmittances of an ambichiral layered structure characterized by $h=-1$, $N=10q$, and $q=4$. This structure of titanium oxide was created using the serial bideposition technique.

497. I.J. Hodgkinson, **A. Lakhtakia**, Q.h. Wu, L. De Silva & M.W. McCall, 'Ambichiral, equichiral and finely chiral layered structures,' *Optics Communications*, **239**, 2004, 353 – 358.

A. Lakhtakia

Ambichiral STF

Layers of
unequal thickness.

$$d_n = d_1 \left\{ 1 + a \sin \left[4 \frac{(n-1)\pi}{N} \right] \right\} , \quad 0 \leq a \leq 1$$

1 Bragg regime

544. B.M. Ross, **A. Lakhtakia** & I.J. Hodgkinson, 'Towards the design of elliptical–polarization rejection filters,' *Optics Communications*, **259**, 2006, 479 – 483.

A. Lakhtakia

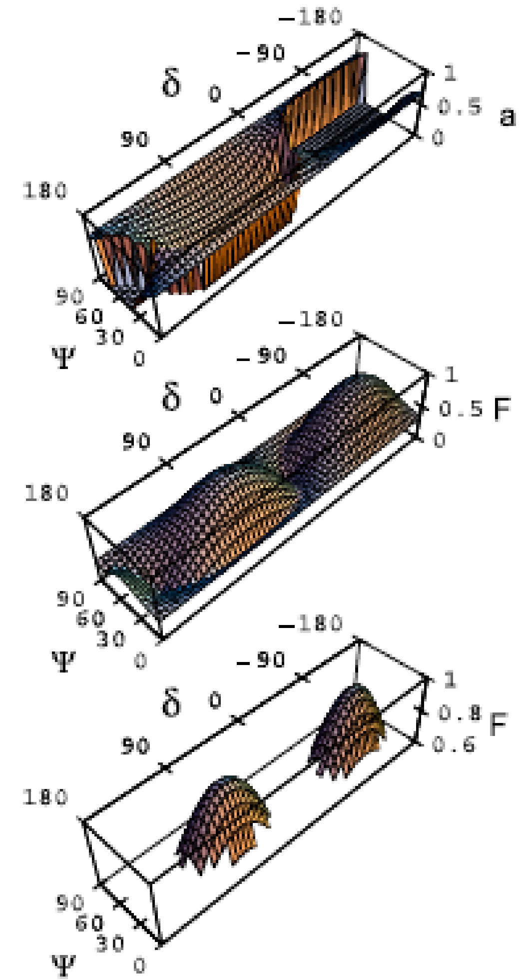
Ambichiral STF

Layers of
unequal thickness.

1 Bragg regime

EP states (Ψ and δ) reflected

Better for CP and nearly CP states



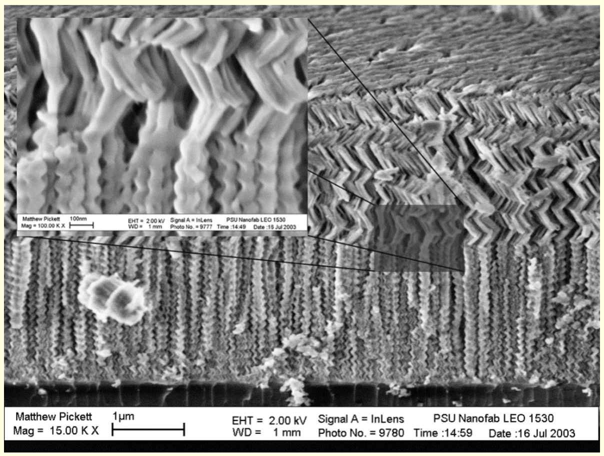
544. B.M. Ross, **A. Lakhtakia** & I.J. Hodgkinson, 'Towards the design of elliptical–polarization rejection filters,' *Optics Communications*, **259**, 2006, 479 – 483.

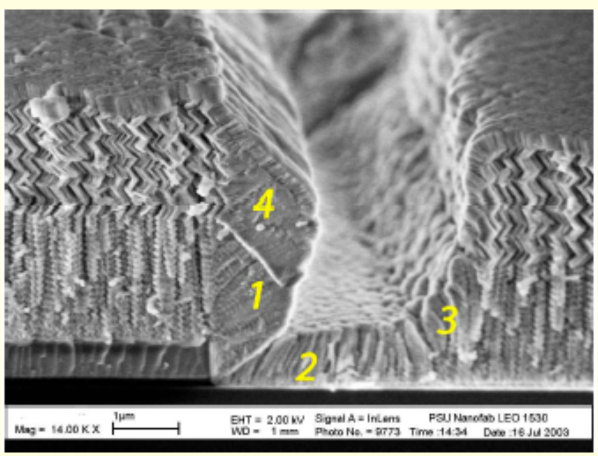
WHAT’s NEXT?

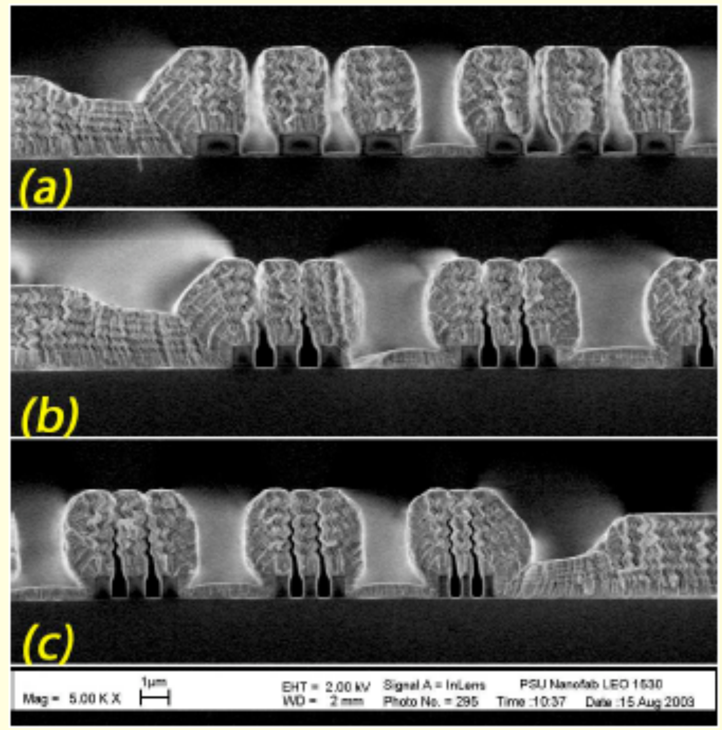
STFs WITH TRANSVERSE ARCHITECTURE

STFs on Microscale Topography

(Cross-sectional SEMs of SiOx STFs)







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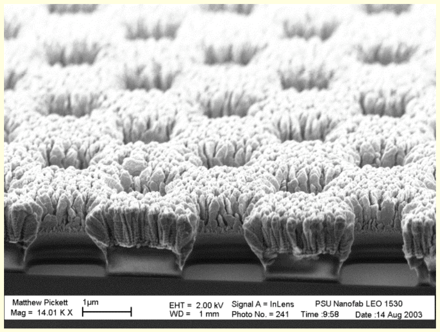
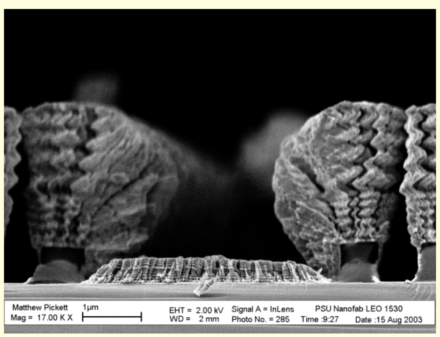
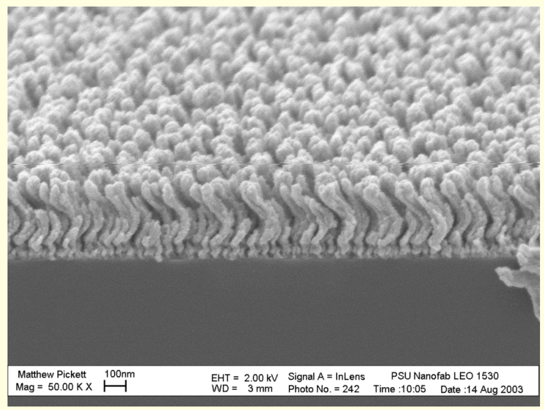
STFs WITH TRANSVERSE ARCHITECTURE

Metal STFs on Topography

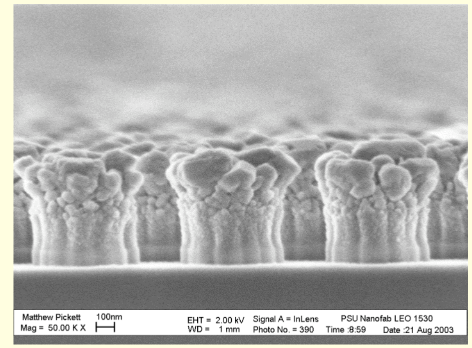


Chromium

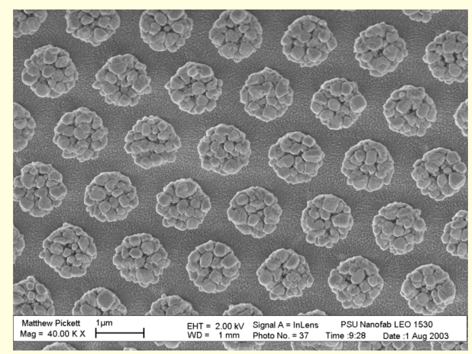




Molybdenum



Aluminum



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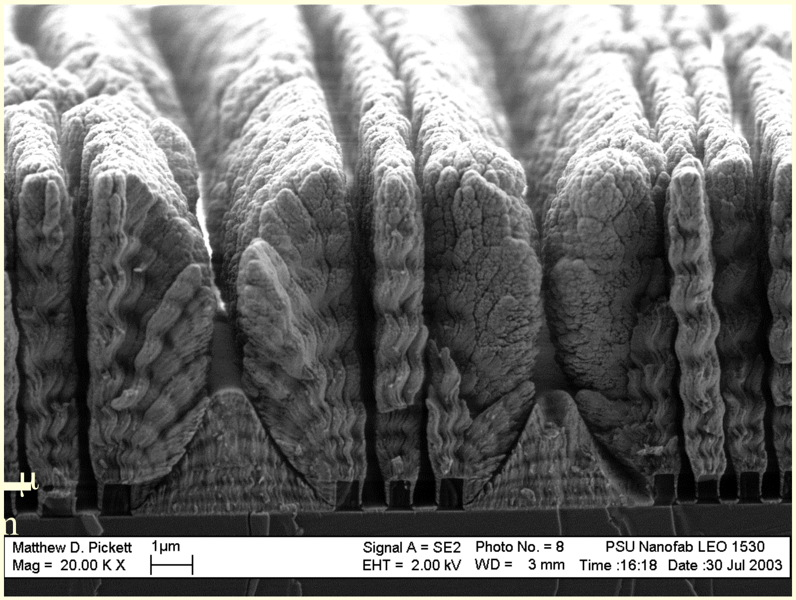
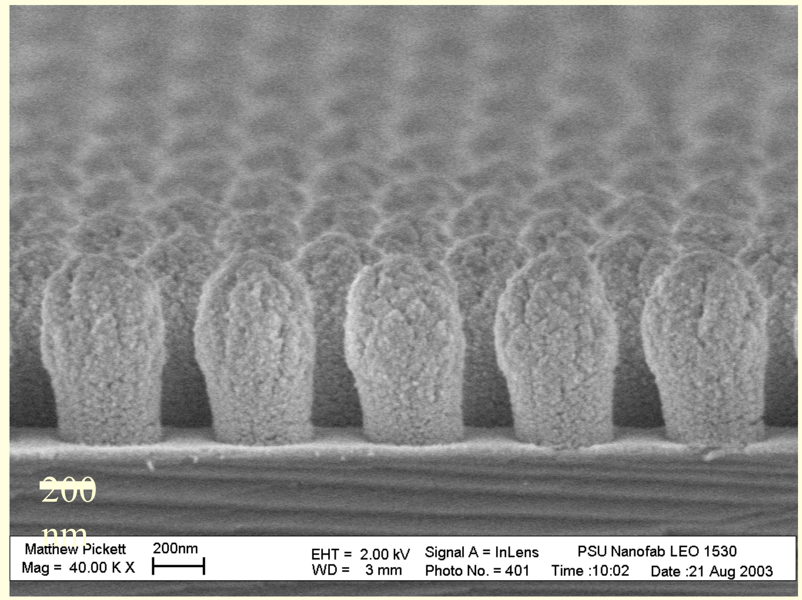
STFs WITH TRANSVERSE ARCHITECTURE

Semiconductor STFs on Micro and Nanoscale Topography





SnO_x STFs grown on photoresist patterns

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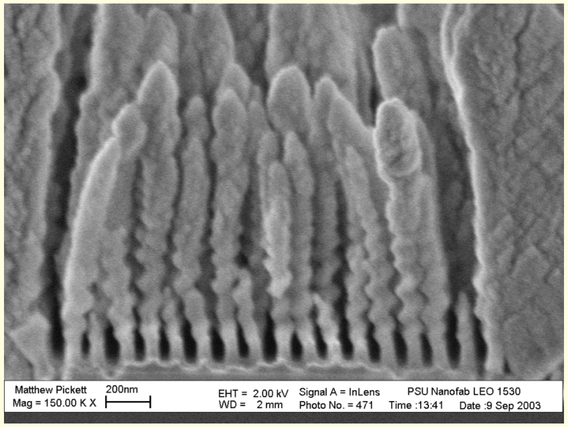
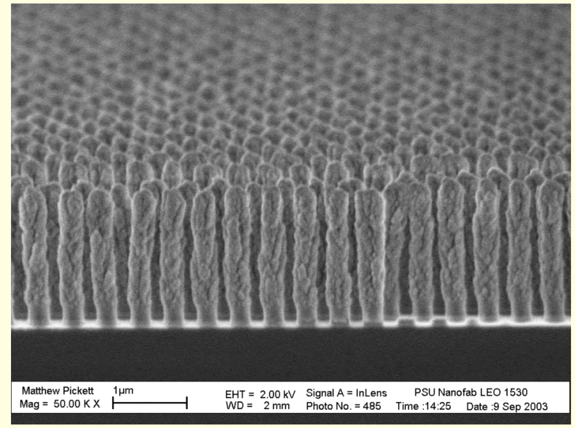
STFs WITH TRANSVERSE ARCHITECTURE

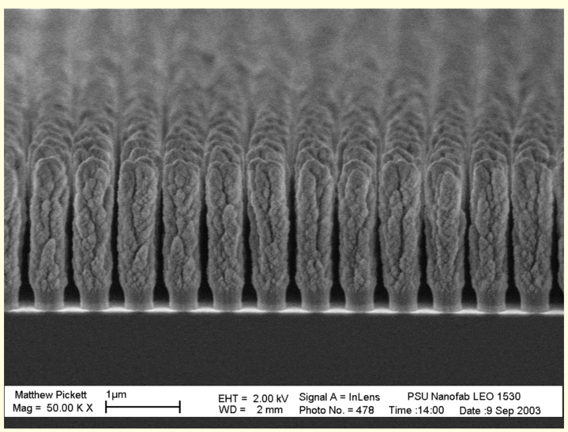
Sculptured Nanowires on Nanoscale Topography



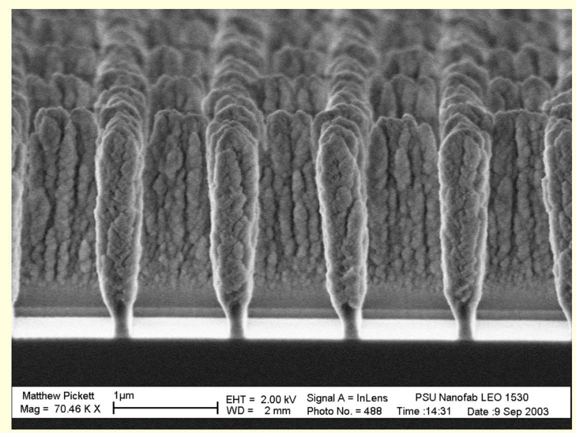
Single SiOx nanowire array grown on 60 nm e-beam resist



HCP array of SiOx nanocolumns



BCC array of SiOx nanocolumns



1um x 1um mesh of SiOx nanolines

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STFs WITH TRANSVERSE ARCHITECTURE

INSTITUTE OF PHYSICS PUBLISHING NANOTECHNOLOGY

Nanotechnology 15 (2004) 303–310 PII: S0957-4484(04)69259-2

Blending of nanoscale and microscale in uniform large-area sculptured thin-film architectures

Mark W Horn, Matthew D Pickett, Russell Messier and Akhlesh Lakhtakia[1]

Selective growth of sculptured nanowires on microlithographic lattices

Mark W. Horn,[a)] Matthew D. Pickett, Russell Messier, and Akhlesh Lakhtakia
Department of Engineering Science and Mechanics, Pennsylvania State University, University Park, Pennsylvania 16802

(Received 25 June 2004; accepted 4 October 2004; published 14 December 2004)

We have grown helicoidal nanowire assemblies on a variety of topographic substrates with regular microlithographic patterns, thereby demonstrating that sculptured thin films with transversely latticed architecture can be grown by physical vapor deposition. The transverse feature-separations are as low as 100–300 nm, and mesa regions are circular posts as small as 60 nm in diameter. The initial as well as the subsequent stages of growth on topographic substrates can be understood using simple geometric shadowing arguments.

Thesis

Morphology can be nanoengineered

to obtain

desired polarization

&

operating frequency band

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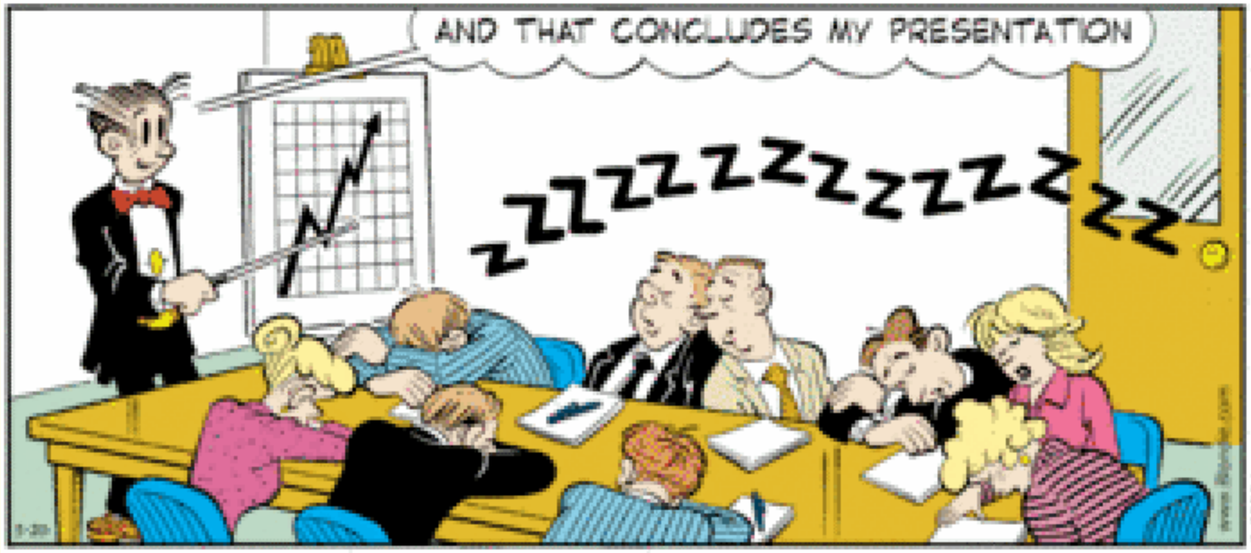

Thank You