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Preparatory School to the Winter College on Optics and the Winter College on Optics: Advances in Nano-Optics and Plasmonics

30 January - 17 February, 2012

BLOCH SURFACE WAVES ON PHOTONIC CRYSTALS APPLICATIONS TO GAS SENSING AND BIOPHOTONICS

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BLOCH SURFACE WAVES ON PHOTONIC CRYSTALS

APPLICATIONS TO
GAS SENSING AND BIOPHOTONICS

SAPIENZA Università di Roma
Department of Basic and Applied Sciences for Engineering
Molecular Photonics Laboratory

Francesco Michelotti

International Centre for Theoretical Physics, Trieste, February 2010

Collaboration and Credits

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ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

IMT- Ecole Polytechnique Fédérale de Lausanne (EPFL) - Neuchatel
T. Sfez, L. Yu, and H.-P. Herzig
NAM- Ecole Polytechnique Fédérale de Lausanne (EPFL)
D. Brunazzo and O. J. F. Martin

Fraunhofer

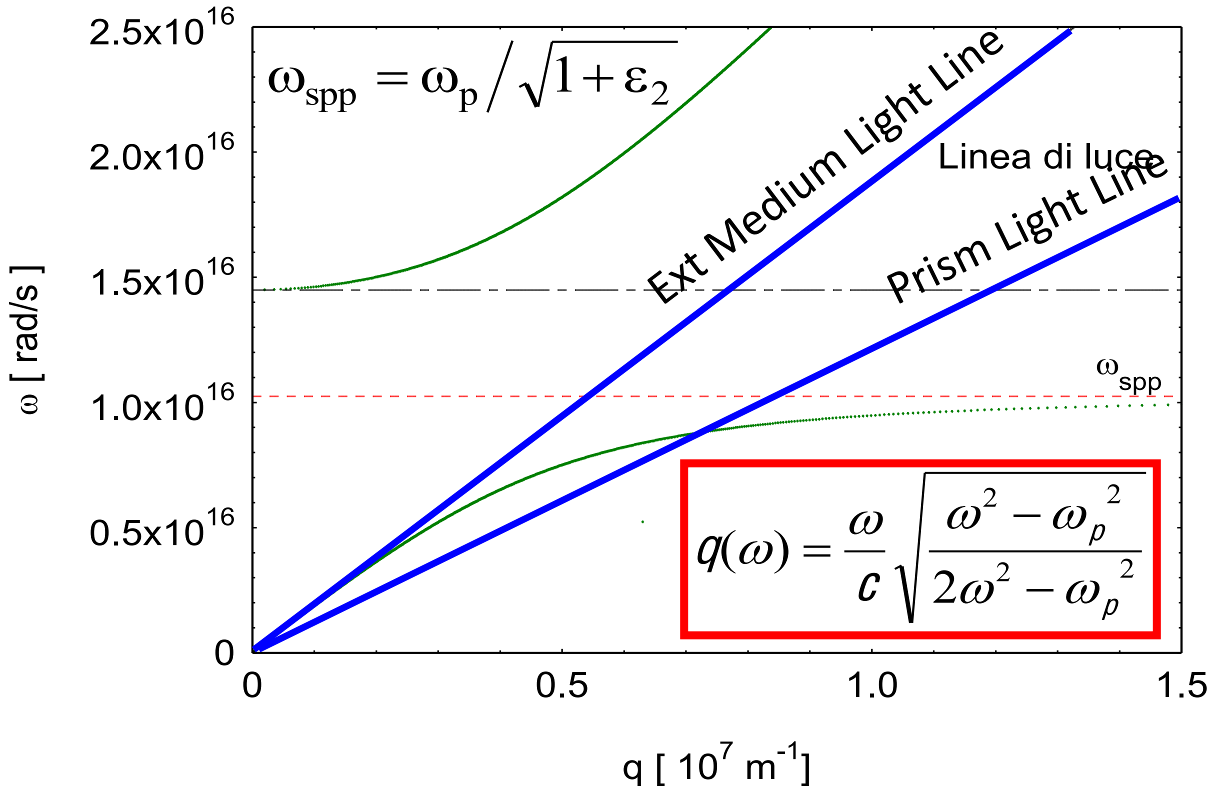
IOF - Applied Optics and Fine Mechanics – Jena
N.Danz
IWS - Materials and Beam Technology – Dresden
F.Sonntag

Plasmonics

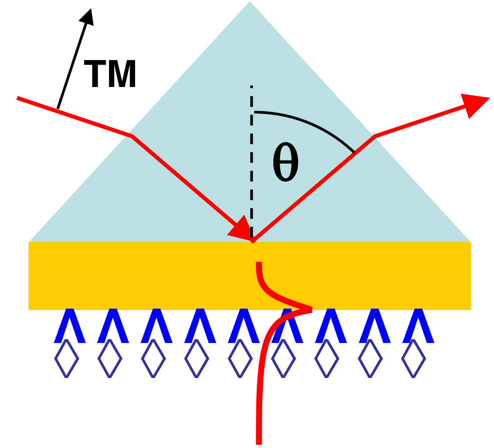
- DURING THESE TWO WEEKS MANY PLASMONICS EXPERIMENTS AND APPLICATIONS WERE OR WILL BE DESCRIBED
- PLASMONICS RECENTLY BECAME A VERY HOT RESEARCH FIELD. SO POPULAR THAT ….
- APPLICATIONS BASED ON PLASMONS SHOW SOME LIMITATIONS WHICH CAN BE OVERCOME ADOPTING ALTERNATIVE APPROACHES

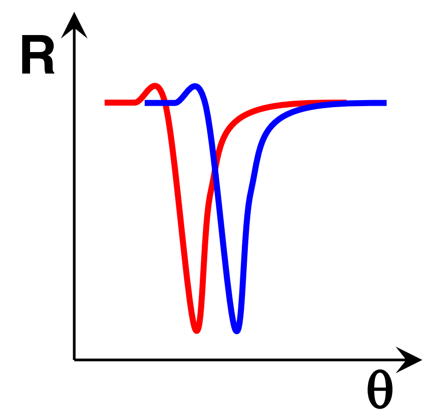
ONE OF THE POSSIBLE APPROACHES ARE BLOCH SURFACE WAVES ON PHOTONIC CRYSTALS

Examples – SPR Biosensing

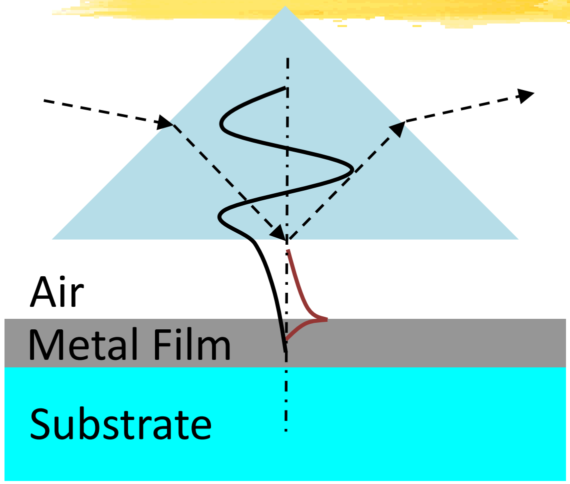


SPP dispersion at a metal(ideal)/dielectric interface

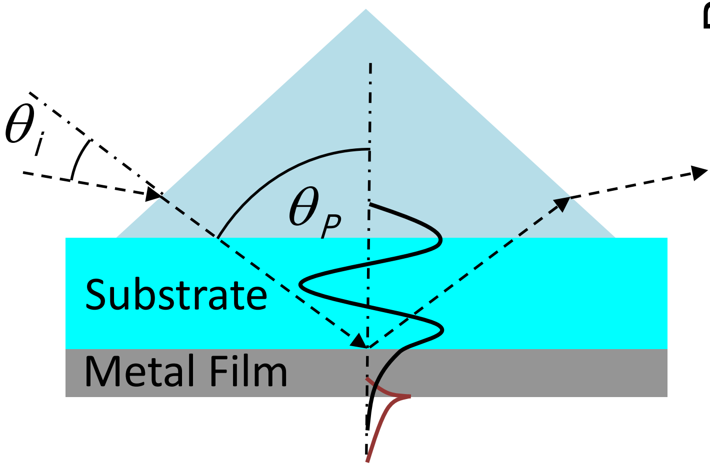




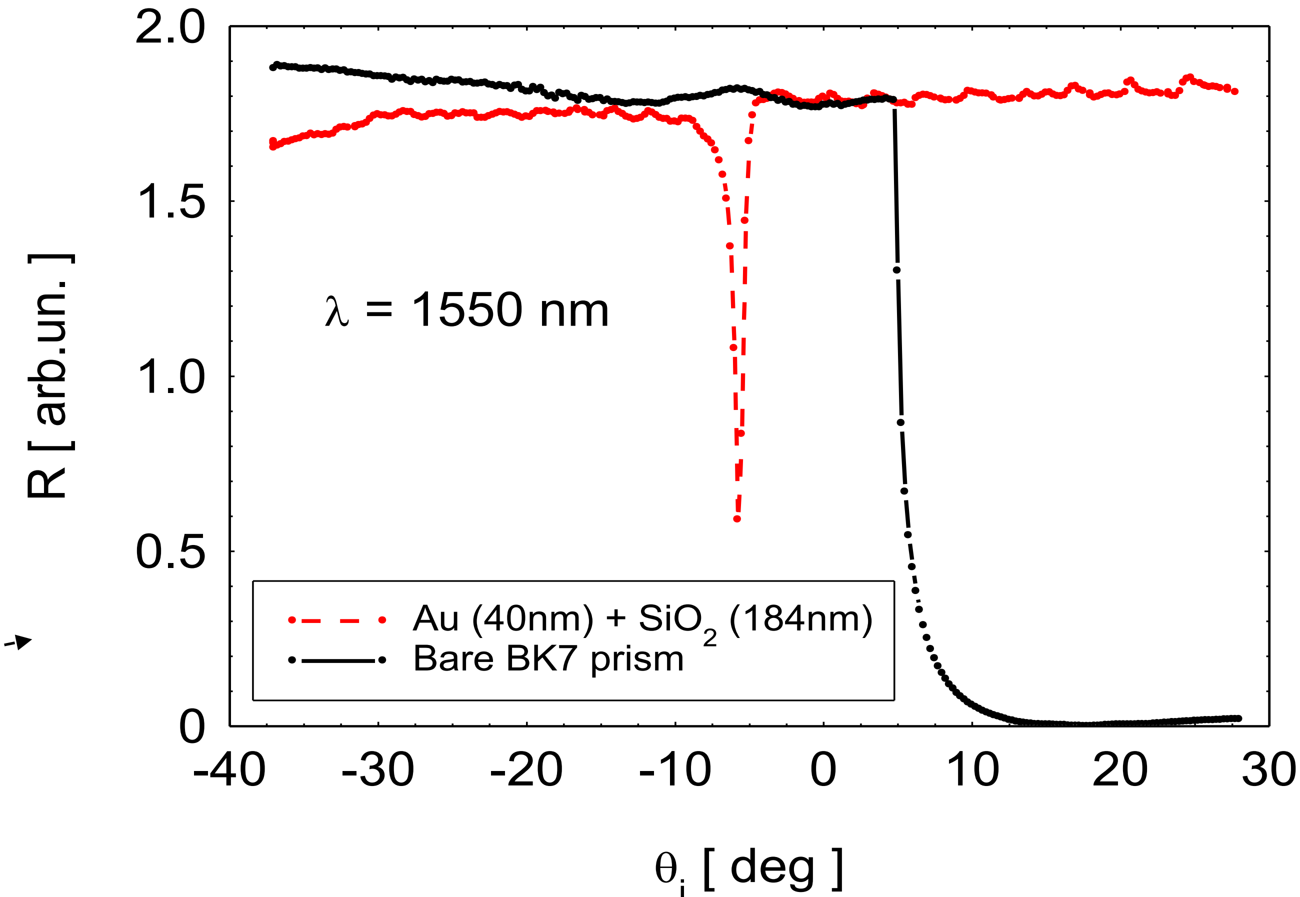
Examples – SPR Biosensing



PAM, Otto



PMA, Kretschmann

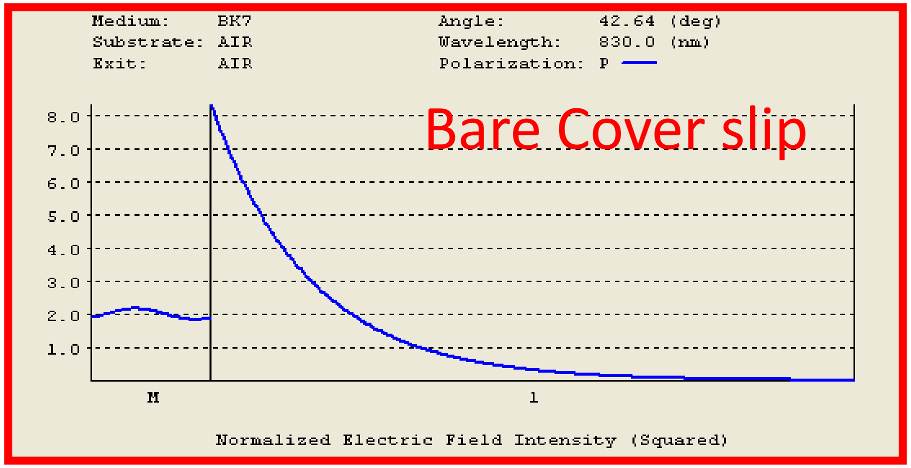


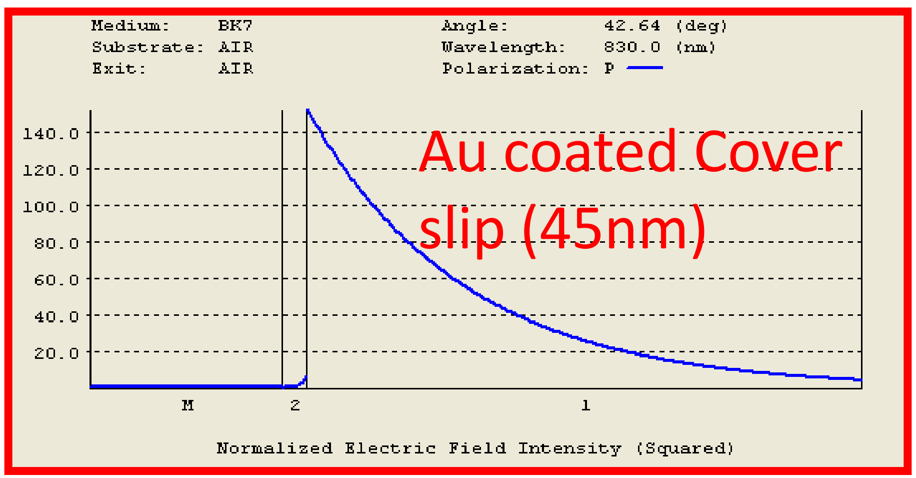
Examples – SPR Biosensing

Examples – SPR Biosensing

- Absorption losses in metal layers give rise to broad resonances and limit the sensitivity of SPR devices
- The limit of resolution is $\Delta n=2\cdot 10^{-7}$ RIU (Biacore)
- The resolution does not permit to detect small molecules (<250 dalton)
- SPR devices never really accessed the Point-of-Care level
- The sensitivity can be improved by making use of long range surface plasmon polaritons but problems due to the symmetry of dielectric layers arise.

Examples – Fluorescence Imaging





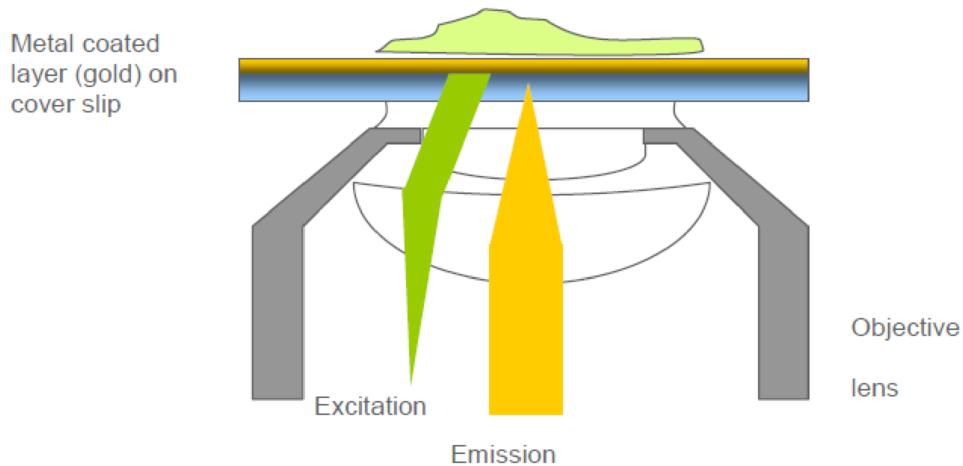
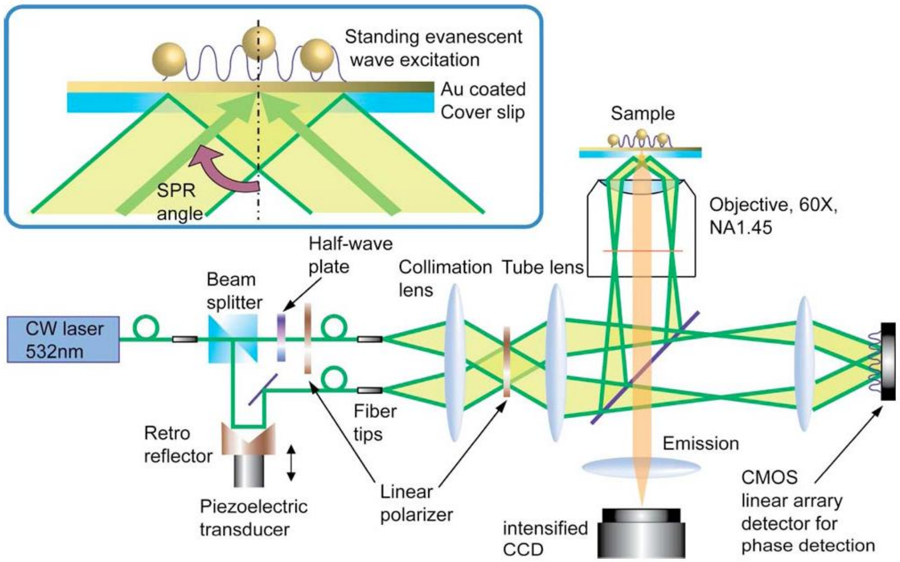
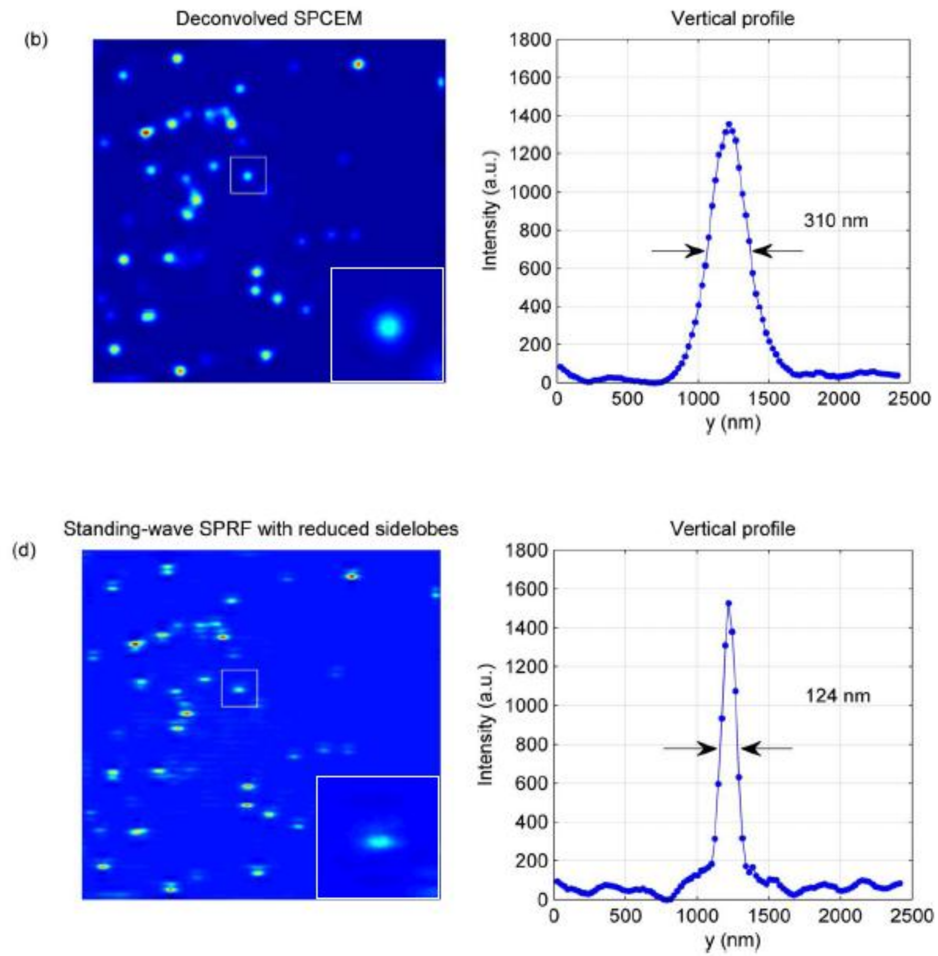


Figure 2-2. An objective-launched set-up for SPCE imaging.

Surface Plasmon Coupled Emission (SPCE)
and
Surface Plasmon Field-enhanced Fluorescence (SPFS)

Examples – SW-SPCF Fluorescence Imaging





2366 OPTICS LETTERS / Vol. 34, No. 15 / August 1, 2009

Wide-field extended-resolution fluorescence microscopy with standing surface-plasmon-resonance waves

Euiheon Chung,[1,2] Yang-Hyo Kim,[1] Wai Teng Tang,[3] Colin J. R. Sheppard,[4] and Peter T. C. So[1,5,*]

Examples – DLSPPW and LRSPP Waveguiding

Dielectric thickness 500nm

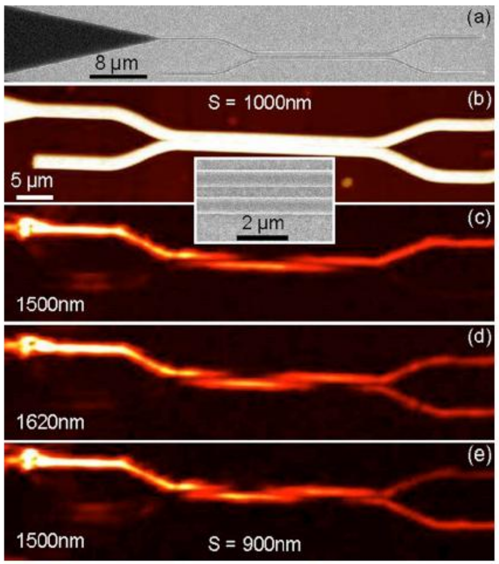


Fig. 1. (Color online) (a) Scanning electron microscope image of the fabricated DC showing the funnel structure facilitating the DLSPPW excitation. (b) Topographical and (c)–(e) near-field optical [λ=(c) 1500, (d) 1620, and (e) 1500 nm] SNOM images of 45 μm long DCs with the separations (b)–(d) $S=1000$ nm along with an inset showing SEM image of the coupling region and (e) $S=900$ nm.

310 OPTICS LETTERS / Vol. 34, No. 3 / February 1, 2009

Wavelength-selective directional coupling with dielectric-loaded plasmonic waveguides

Zhuo Chen,[1] Tobias Holmgaard,[1] Sergey I. Bozhevolnyi,[1,2,*] Alexey V. Krasavin,[3] Anatoly V. Zayats,[3] Laurent Markey,[4] and Alain Dereux[4]

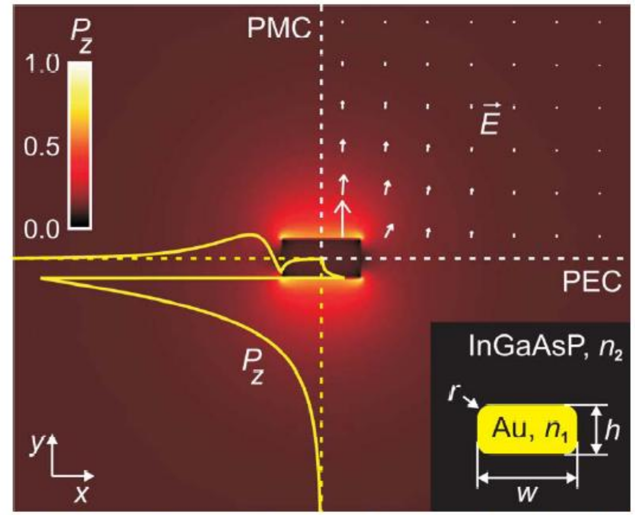


Fig. 1. (Color online) Field map of power flow P_z of the long-range SPP mode supported by a 200 nm × 100 nm waveguide at $\lambda = 1550$ nm. Solid curves correspond to the vertical and horizontal cross sections of the power flow P_z. Arrows show the direction of the electric field. Inset: studied Au($n_1 = 0.55$–$11.5i$)/InGaAsP($n_2 = 3.3737$) metallic wire waveguide with width w and height h, having corners rounded with $r = 5$ nm.

OPTICS LETTERS / Vol. 35, No. 13 / July 1, 2010

Numerical analysis of long-range surface plasmon polariton modes in nanoscale plasmonic waveguides

Alexey V. Krasavin* and Anatoly V. Zayats

Can we do similar things in a different way?

We can exploit the propagation of surface electromagnetic waves (SEW) at the truncation interface of finite one dimensional photonic crystals (1DPC)

We shall refer to such waves with the name

Bloch Surface Waves (BSW)

To demonstrate such possibility in the following we will describe the:

Mon	$10^{??} – 11^{00}$	General properties of BSW on 1DPC (Theory)
Tue	10^{00} - 11^{00}	Experimental techniques for the detection of SPP and BSW (Experimental)
Tue	$11^{30} – 12^{30}$	Applications of BSW to gas sensing (Experimental)
Wed	14^{30} - 15^{30}	Applications of BSW to biophotonics (Experimental)

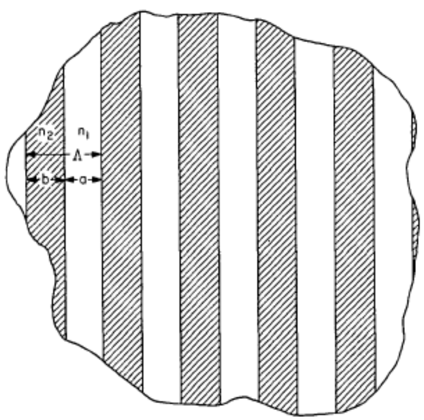
Lecture 1
General properties of BSW on 1DPC
(Theory)

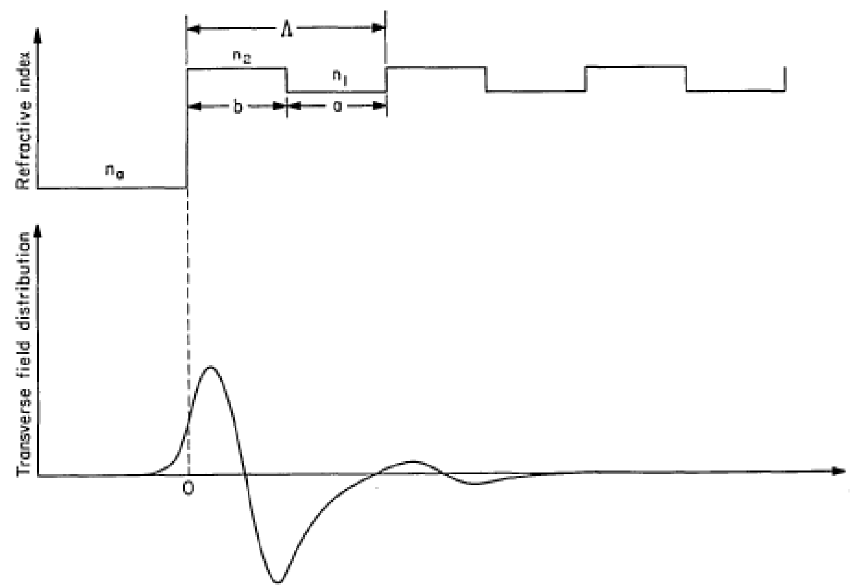
BSW at the truncation interface of 1DPC

Electromagnetic propagation in periodic stratified media. I. General theory*

Pochi Yeh, Amnon Yariv, and Chi-Shain Hong
California Institute of Technology, Pasadena, California 91125
(Received 8 November 1976)

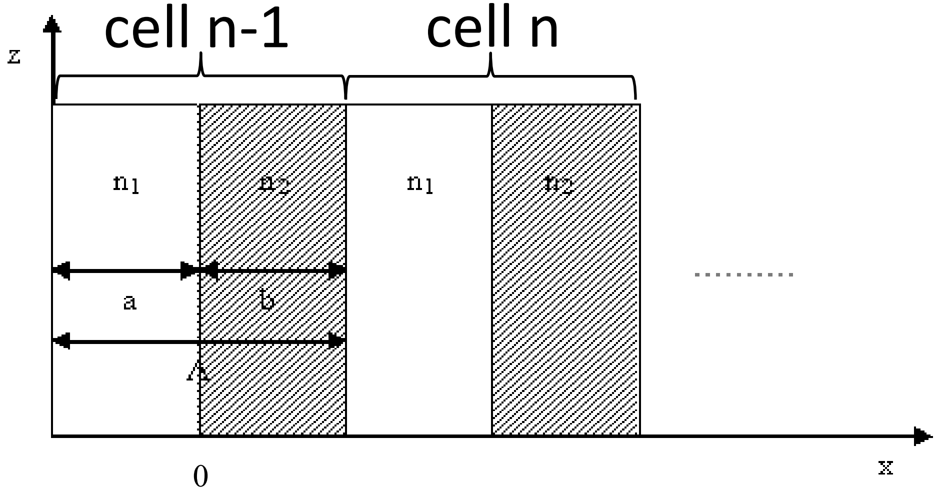
The propagation of electromagnetic radiation in periodically stratified media is considered. Media of finite, semi-infinite, and infinite extent are treated. A diagonalization of the unit cell translation operator is used to obtain exact solutions for the Bloch waves, the dispersion relations, and the band structure of the medium. Some new phenomena with applications to integrated optics and laser technology are presented.





J. Opt. Soc. Am., Vol. 67, No. 4, April 1977

Propagation of light in infinite 1DPC



$n(x) = n_2$ for $0 < x < b$
$n(x) = n_1$ for $b < x < \Lambda$

with $n(x + \Lambda) = n(x)$

$$E(x,z) = E(x)e^{i\beta z}$$

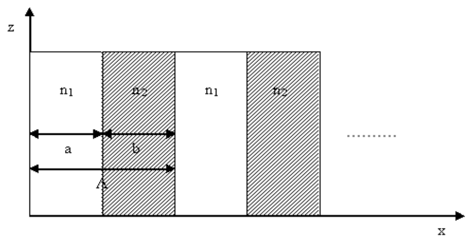
In each layer the field can be expressed as the superposition of forward and backward propagating waves

$$E(x,z) = \left(a_n^{(\alpha)} e^{ik_{\alpha x}(x-n\Lambda)} + b_n^{(\alpha)} e^{-ik_{\alpha x}(x-n\Lambda)}\right)e^{i\beta z}$$

With $k_{\alpha x} = \left\{\left[(\omega / c)n_\alpha\right]^2 - \beta^2\right\}^{\frac{1}{2}}$, α=1,2

In a vectorial representation → $\begin{pmatrix} a_n^{(\alpha)} \\ b_n^{(\alpha)} \end{pmatrix}$

Propagation of light in infinite 1DPC



For the sake of notation simplicity

$$\begin{pmatrix} a_n^{(1)} \\ b_n^{(1)} \end{pmatrix} = \begin{pmatrix} a_n \\ b_n \end{pmatrix} \qquad \begin{pmatrix} a_n^{(2)} \\ b_n^{(2)} \end{pmatrix} = \begin{pmatrix} c_n \\ d_n \end{pmatrix}$$

$$\begin{pmatrix} a_{n-1} \\ b_{n-1} \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} a_n \\ b_n \end{pmatrix} \qquad \begin{pmatrix} A & B \\ C & D \end{pmatrix} = T$$

The unit cell Λ translation operator is unimodular AD-CB=1

TE case

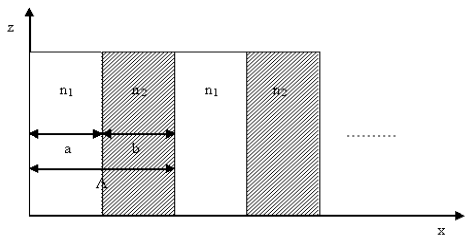
$$A = e^{-ik_{1x}a}\left[\cos k_{2x}b - \frac{1}{2}i\left(\frac{k_{2x}}{k_{1x}} + \frac{k_{1x}}{k_{2x}}\right)\sin k_{2x}b\right]$$

$$B = e^{ik_{1x}a}\left[-\frac{1}{2}i\left(\frac{k_{2x}}{k_{1x}} - \frac{k_{1x}}{k_{2x}}\right)\sin k_{2x}b\right]$$

$$C = e^{-ik_{1x}a}\left[\frac{1}{2}i\left(\frac{k_{2x}}{k_{1x}} - \frac{k_{1x}}{k_{2x}}\right)\sin k_{2x}b\right]$$

$$D = e^{ik_{1x}a}\left[\cos k_{2x}b + \frac{1}{2}i\left(\frac{k_{2x}}{k_{1x}} + \frac{k_{1x}}{k_{2x}}\right)\sin k_{2x}b\right]$$

Propagation of light in infinite 1DPC



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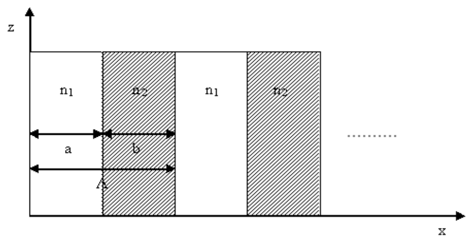
The unit cell Λ translation operator is unimodular AD-CB=1

TM case

$$A = e^{-ik_{1x}a}\left[\cos k_{2x}b - \frac{1}{2}i\left(\frac{n_2^2 k_{1x}}{n_1^2 k_{2x}} + \frac{n_1^2 k_{2x}}{n_2^2 k_{1x}}\right)\sin k_{2x}b\right] \qquad B = e^{ik_{1x}a}\left[-\frac{1}{2}i\left(\frac{n_2^2 k_{1x}}{n_1^2 k_{2x}} - \frac{n_1^2 k_{2x}}{n_2^2 k_{1x}}\right)\sin k_{2x}b\right]$$

$$C = e^{-ik_{1x}a}\left[\frac{1}{2}i\left(\frac{n_2^2 k_{1x}}{n_1^2 k_{2x}} - \frac{n_1^2 k_{2x}}{n_2^2 k_{1x}}\right)\sin k_{2x}b\right] \qquad D = e^{ik_{1x}a}\left[\cos k_{2x}b + \frac{1}{2}i\left(\frac{n_2^2 k_{1x}}{n_1^2 k_{2x}} + \frac{n_1^2 k_{2x}}{n_2^2 k_{1x}}\right)\sin k_{2x}b\right]$$

Propagation of light in infinite 1DPC



Only one vector is independent

$$\begin{pmatrix} a_n \\ b_n \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix}^{-n} \begin{pmatrix} a_0 \\ b_0 \end{pmatrix} = \begin{pmatrix} D & -B \\ -C & A \end{pmatrix}^{n} \begin{pmatrix} a_0 \\ b_0 \end{pmatrix}$$

Note that: $\begin{pmatrix} c_n \\ d_n \end{pmatrix} = \begin{pmatrix} A' & B' \\ C' & D' \end{pmatrix}^{-n} \begin{pmatrix} c_0 \\ c_0 \end{pmatrix}$ and that: $\begin{pmatrix} A' & B' \\ C' & D' \end{pmatrix} \neq \begin{pmatrix} A & B \\ C & D \end{pmatrix}$

The unit cell translation operator is such that:

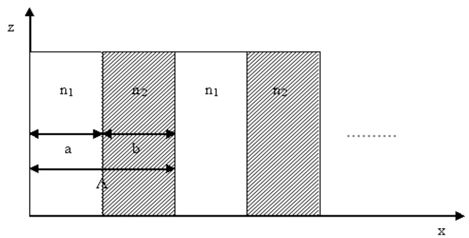
$$Tx = x + l\Lambda \qquad T \cdot E(x) = E(T^{-1}x) = E(x - l\Lambda).$$

Floquet theorem for a wave propagating in a periodic medium:

$$\begin{cases} E_K(x,z) = E_K(x) e^{iKx} e^{i\beta z} \\ E_K(x+\Lambda) = E_K(x) \end{cases}$$

K := Bloch wavenumber

Propagation of light in infinite 1DPC



Periodicity

$$\begin{pmatrix} a_n \\ b_n \end{pmatrix} = e^{iK\Lambda} \begin{pmatrix} a_{n-1} \\ b_{n-1} \end{pmatrix} \Rightarrow \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} a_n \\ b_n \end{pmatrix} = e^{-iK\Lambda} \begin{pmatrix} a_n \\ b_n \end{pmatrix}$$

Eigenvalues

$$e^{-iK\Lambda} = \frac{1}{2}(A+D) \pm \left\{ \left[\frac{1}{2}(A+D) \right]^2 - 1 \right\}^{1/2}$$

Eigenvectors

$$\begin{pmatrix} a_0 \\ b_0 \end{pmatrix} = \begin{pmatrix} B \\ e^{-iK\Lambda} - A \end{pmatrix}$$

Unimodularity of T implies that:

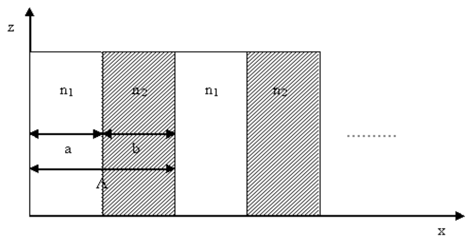
$$K(\beta, \omega) = \frac{1}{\Lambda} \cos^{-1} \left[\frac{1}{2}(A+D) \right]$$

Dispersion relation

The field in the n_1 layer of the n-th cell is:

$$E_K(x) e^{iKx} = \left[\left(a_0 e^{ik_{1x}(x-n\Lambda)} + b_0 e^{-ik_{1x}(x-n\Lambda)} \right) e^{-iK(x-n\Lambda)} \right] e^{iKx}$$

Propagation of light in infinite 1DPC



$$\left|\frac{1}{2}(A+D)\right| < 1 \quad \Rightarrow \quad K \in R$$

Propagating waves (permitted)

$$\left|\frac{1}{2}(A+D)\right| > 1 \quad \Rightarrow \quad K = \frac{m\pi}{\Lambda} + iK_i \in C$$

Evanescent waves (forbidden in ∞ 1DPC)

$$\left|\frac{1}{2}(A+D)\right| = 1$$

Band edges

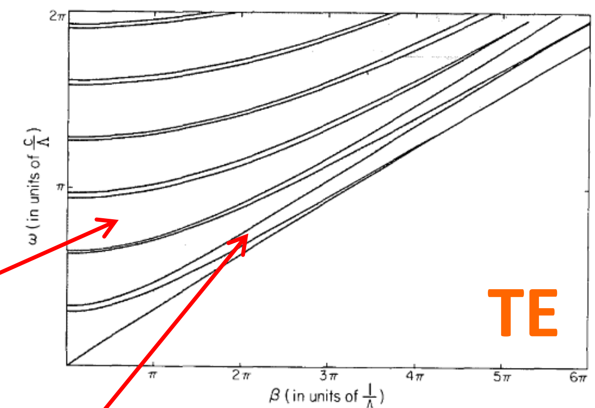


FIG. 3. TE waves (E perpendicular to the direction of periodicity) band structure in the ω–β plane. The dark zones are the allowed bands.

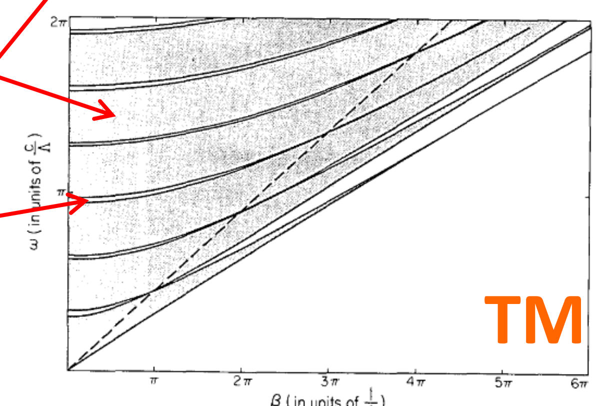
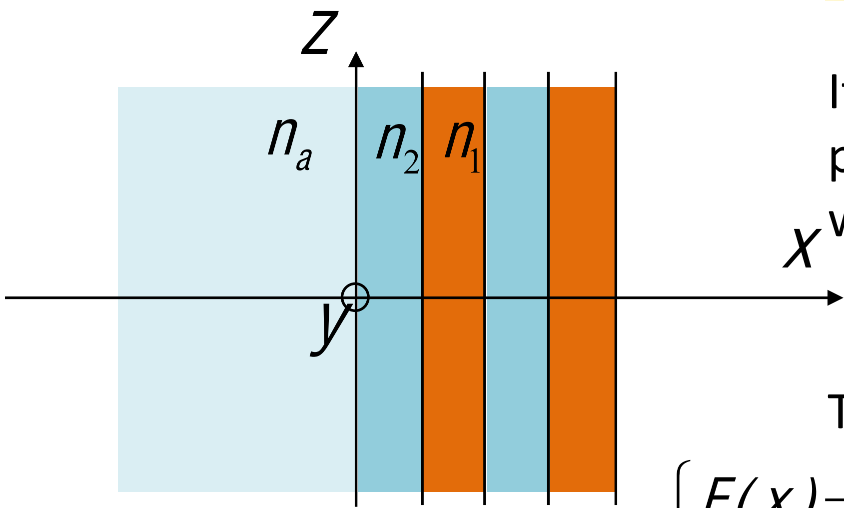


FIG. 4. TM waves (H perpendicular to the direction of periodicity) band structure in the ω–β plane. The dashed line is $\beta=(\omega/c)n_2\sin\phi_B$. The dark zones are the allowed bands.

BSW at the truncation interface of 1DPC



If the 1DPC is finite the evanescent solutions are permitted at the interface and decay in the 1DPC with an envelope (Bloch Surface Wave - BSW):

$$e^{-K_i x}$$

The BSW field has the transverse structure:

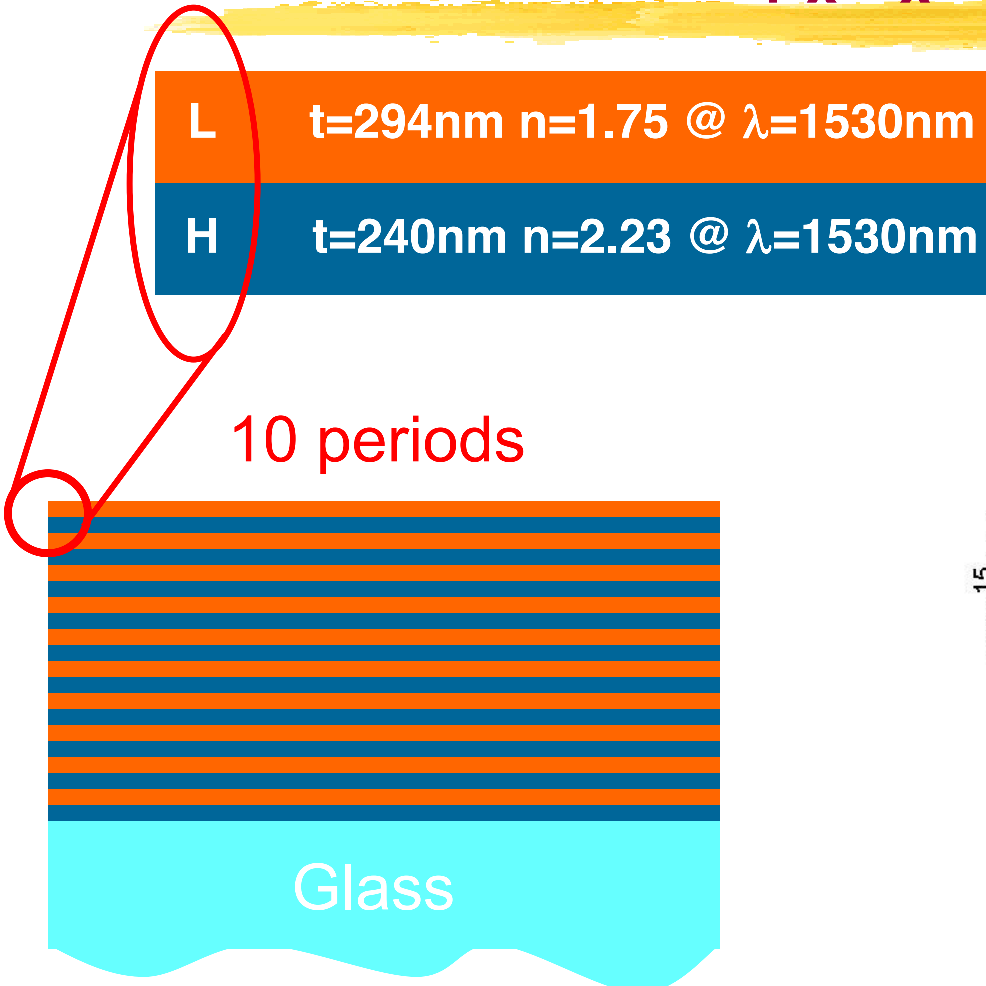
$$\begin{cases} E(x) = \alpha e^{q_a x} & x \leq 0 \\ E(x) = E_K(x) e^{iKx} & x \geq 0 \end{cases} \quad \text{with} \quad q_a = \left\{\beta^2 - [(\omega / c) n_a]^2\right\}^{1/2}$$

$K \in$ C → BSW live in the forbidden bands

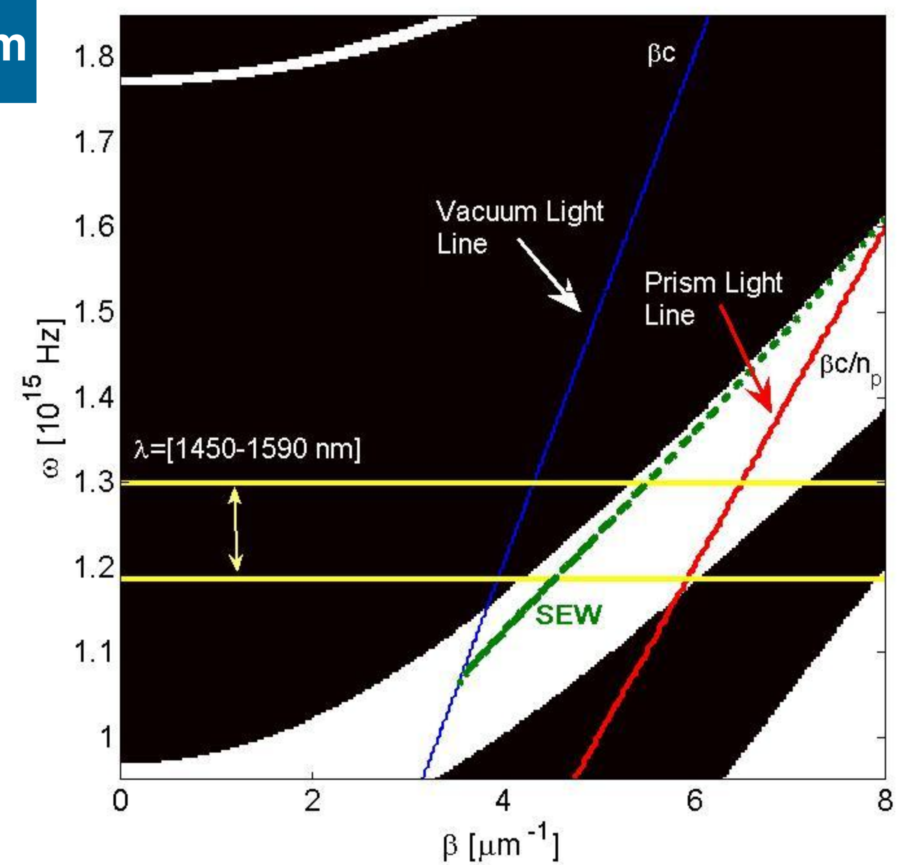
Continuity of E and $\partial E / \partial x$ → BSW dispersion relation

$$q_a = q\left(e^{-iK\Lambda} - A - B\right) / \left(e^{-iK\Lambda} - A + B\right)$$

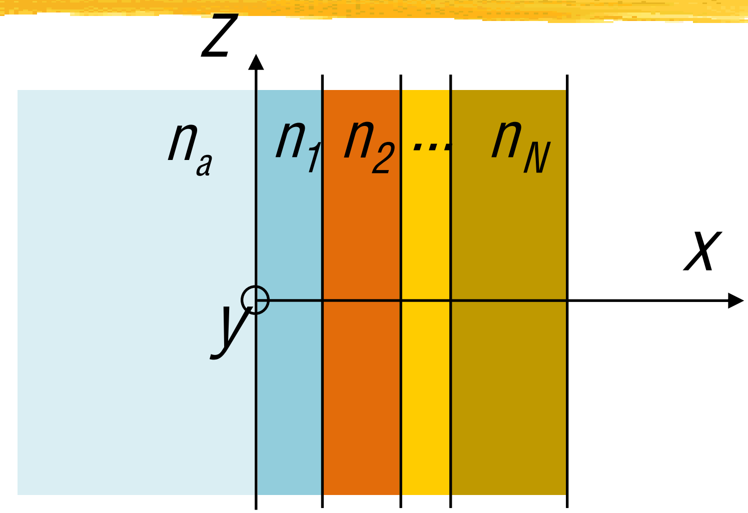
EXAMPLE: a-$Si_{1-x}N_x$:H 1DPC



Band Diagram



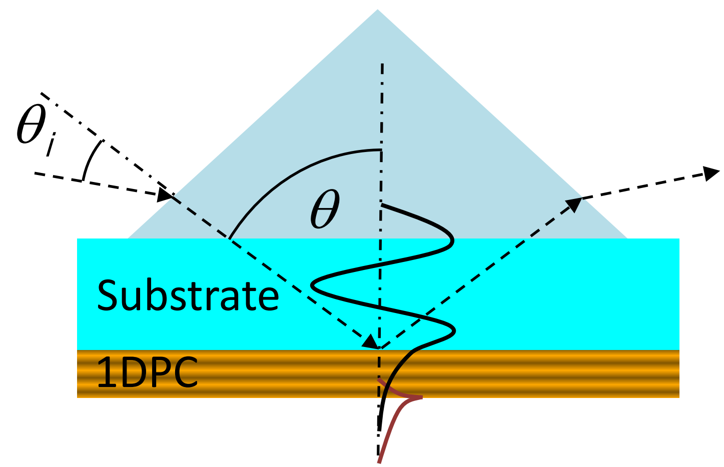
Finite and non periodic 1DPC



In the case the 1DPC is finite and/or non periodic the analytical approach from Yariv cannot be applied. The solution must be seeked numerically.

We can applied the Transfer Matrix Method (TMM) to calculate the reflectance of an arbitrary structure.

Suppose we wish to calculate the reflectance of a finite 1DPC in the Kretschmann prism coupling configuration.

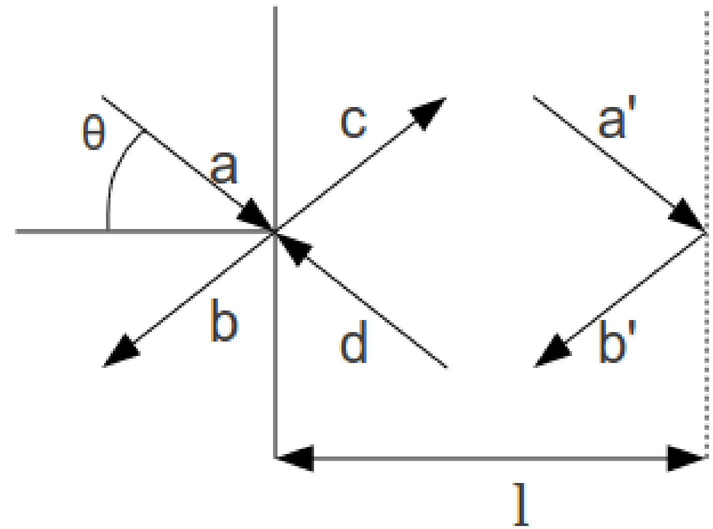


PMA, Kretschmann

Finite and non periodic 1DPC

Step 1 – The single layer transfer matrix is:

$$\begin{pmatrix} a \\ b \end{pmatrix} = \underbrace{\frac{1}{t_{12}} \begin{pmatrix} 1 & r_{12} \\ r_{12} & 1 \end{pmatrix}}_{\text{Interface matrix}} \underbrace{\begin{pmatrix} e^{jkl} & 0 \\ 0 & e^{-jkl} \end{pmatrix}}_{\text{Propagation matrix}} \begin{pmatrix} a' \\ b' \end{pmatrix}$$



$$\begin{cases} c = t_{12} a + r_{21} d \\ b = r_{12} a + t_{21} d \end{cases}$$

TE case

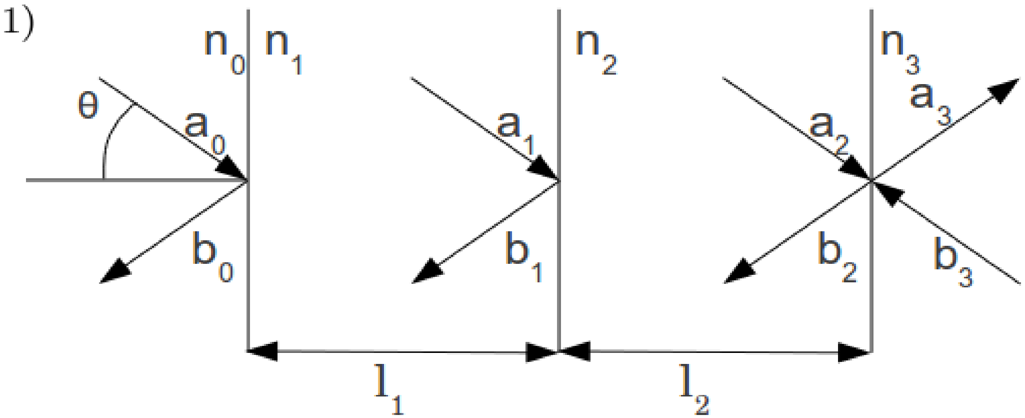
$$r_{ij} = \frac{n_i \sin(\vartheta_i) - n_j \sin(\vartheta_j)}{n_i \sin(\vartheta_i) + n_j \sin(\vartheta_j)} \qquad i,j = 1,2 \qquad i \neq j$$

$$t_{ij} = 1 + r_{ij} \qquad \vartheta_j = \arcsin\left(\frac{n_i}{n_j} \sin(\vartheta_i)\right)$$

Finite and non periodic 1DPC

Step 2 – The multilayer transfer matrix is:

$$\bar{M} = \left(\prod_{k=1}^{N} M_{(k-1)k} T_k \right) M_{N(N+1)}$$



$$M_{ij} = \frac{1}{t_{ij}} \begin{pmatrix} 1 & r_{ij} \\ r_{ij} & 1 \end{pmatrix}$$

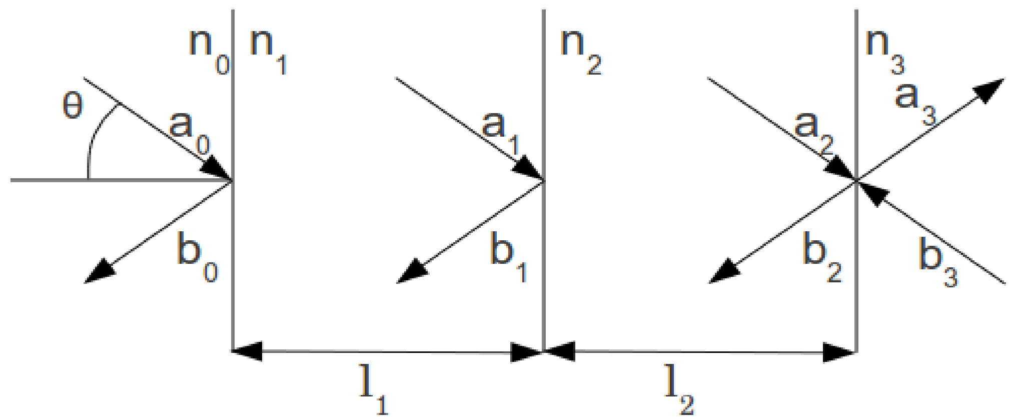
$$T_j = \begin{pmatrix} e^{jk_j l_j} & 0 \\ 0 & e^{-jk_j l_j} \end{pmatrix}$$

$$\begin{pmatrix} a_0 \\ b_0 \end{pmatrix} = \bar{M} \begin{pmatrix} a_{N+1} \\ b_{N+1} \end{pmatrix}$$

Finite and non periodic 1DPC

Step 3 – The reflectance and transmittance are calculated imposing that $b_{N+1}=0$:

$$\begin{pmatrix} a_0 \\ b_0 \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} \begin{pmatrix} a_{N+1} \\ 0 \end{pmatrix}$$



$$r = \frac{b_0}{a_0} = \frac{m_{21}}{m_{11}}$$

$$t = \frac{a_{N+1}}{a_0} = \frac{1}{m_{11}}$$

$$R = |r|^2$$

$$T = |t|^2$$

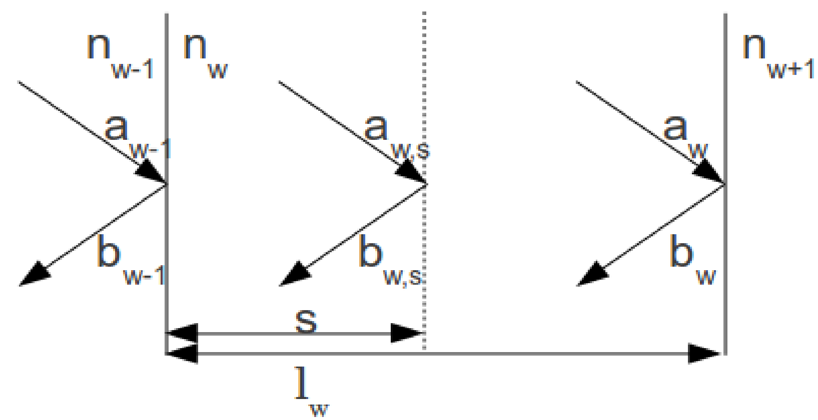
Finite and non periodic 1DPC

Step 4 – The field distribution at any position inside the structure is calculated imposing that a_0=1 and b_0=r:

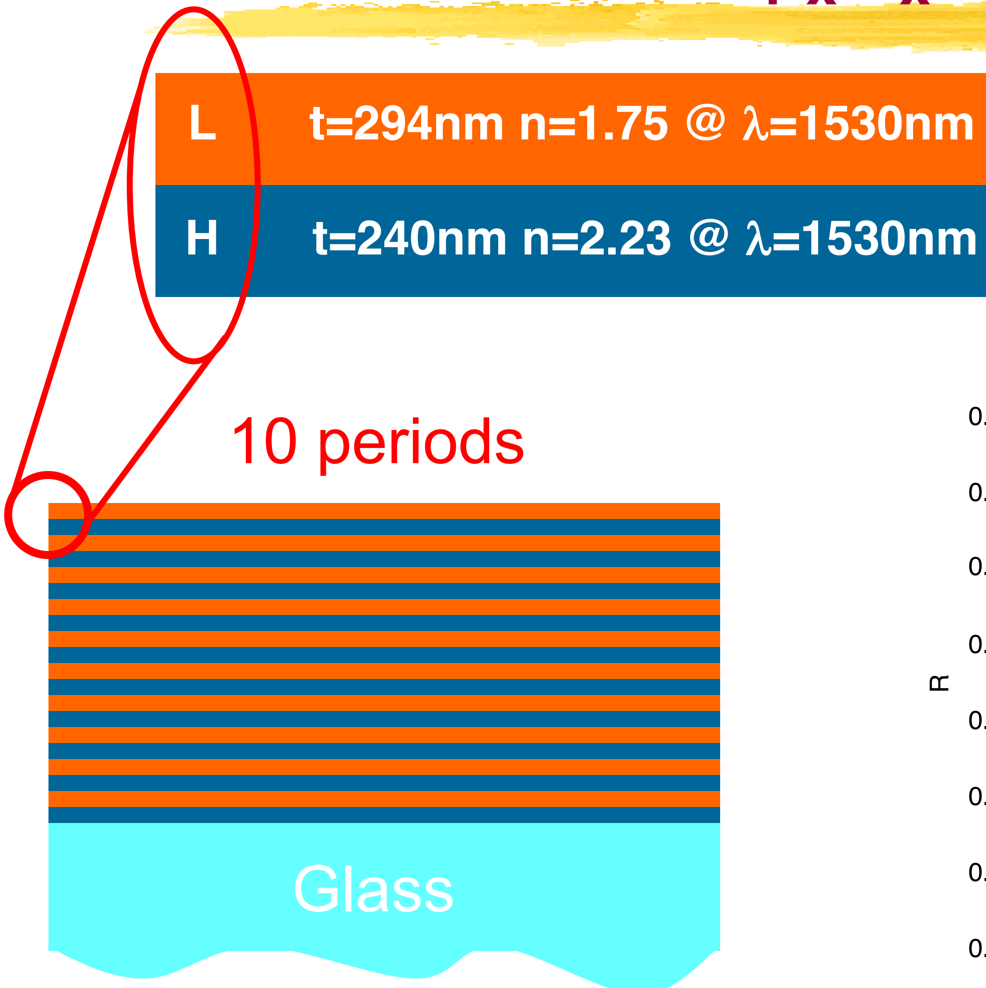
$$\begin{pmatrix} a_{w,s} \\ b_{w,s} \end{pmatrix} = \widehat{T}_w(s) \left(\prod_{k=1}^{w-1} \widehat{M}_{(w-k)(w-k+1)} \, \widehat{T}_{w-k}(l_{w-k}) \right) \widehat{M}_{0\,1} \begin{pmatrix} 1 \\ r \end{pmatrix}$$

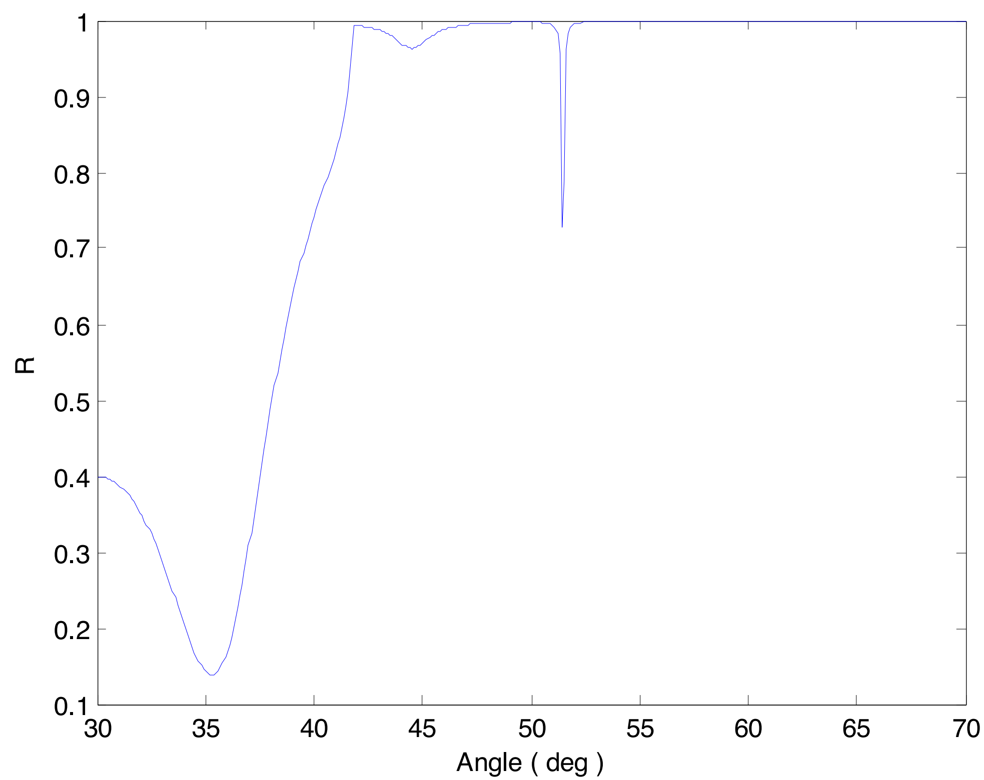
$$\widehat{T}_j(s) = \begin{pmatrix} e^{-jk_j s} & 0 \\ 0 & e^{jk_j s} \end{pmatrix}$$

$$\widehat{M}_{ij} = M_{ij}^{-1} = \frac{1}{1 - r_{ij}} \begin{pmatrix} 1 & -r_{ij} \\ -r_{ij} & 1 \end{pmatrix}$$

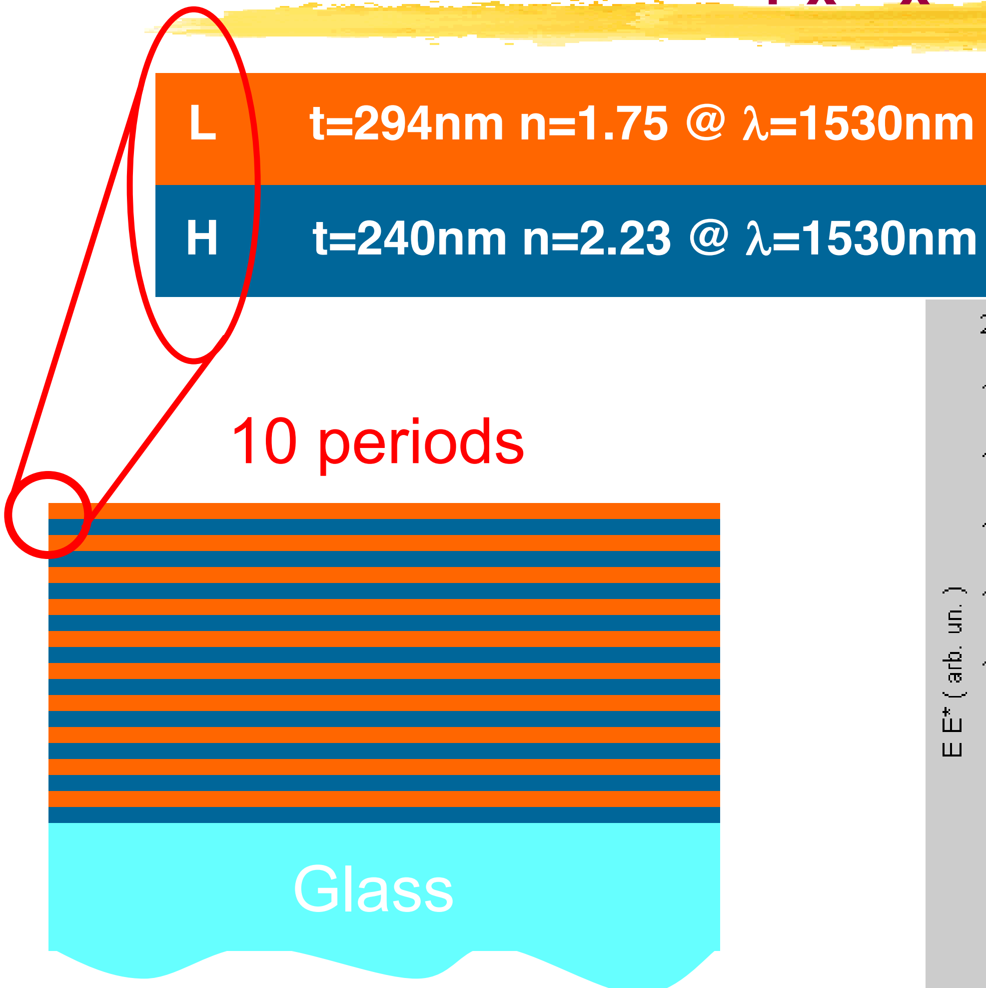


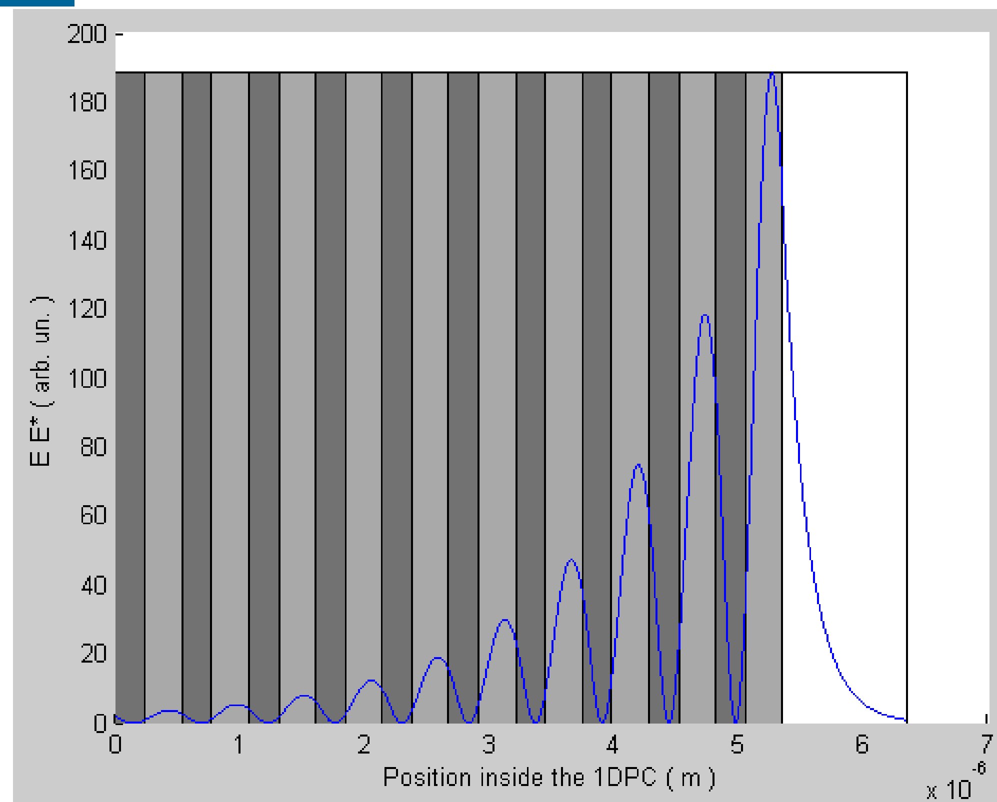
EXAMPLE: a-$Si_{1-x}N_x$:H 1DPC



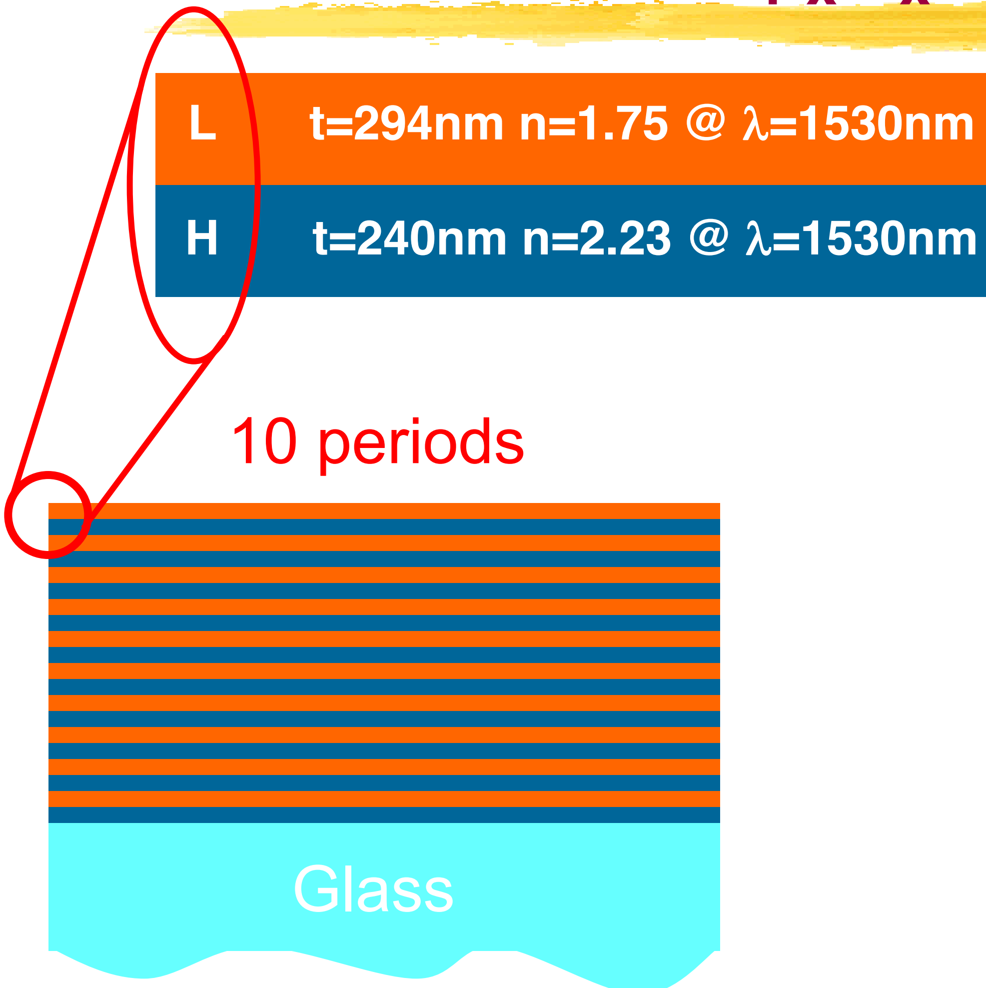


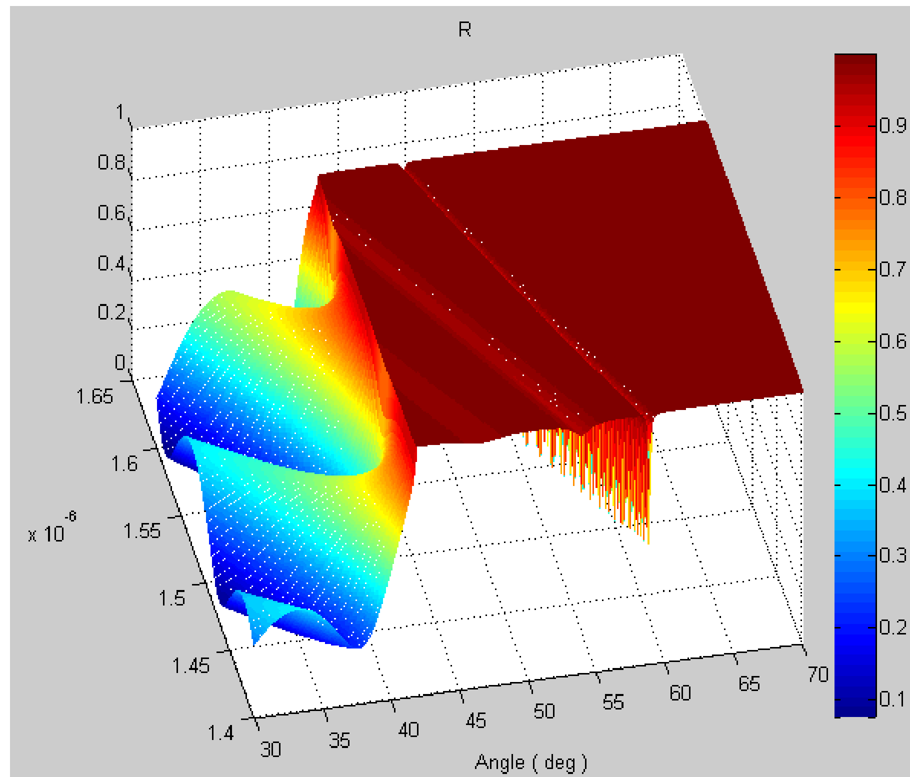
EXAMPLE: a-$Si_{1-x}N_x$:H 1DPC



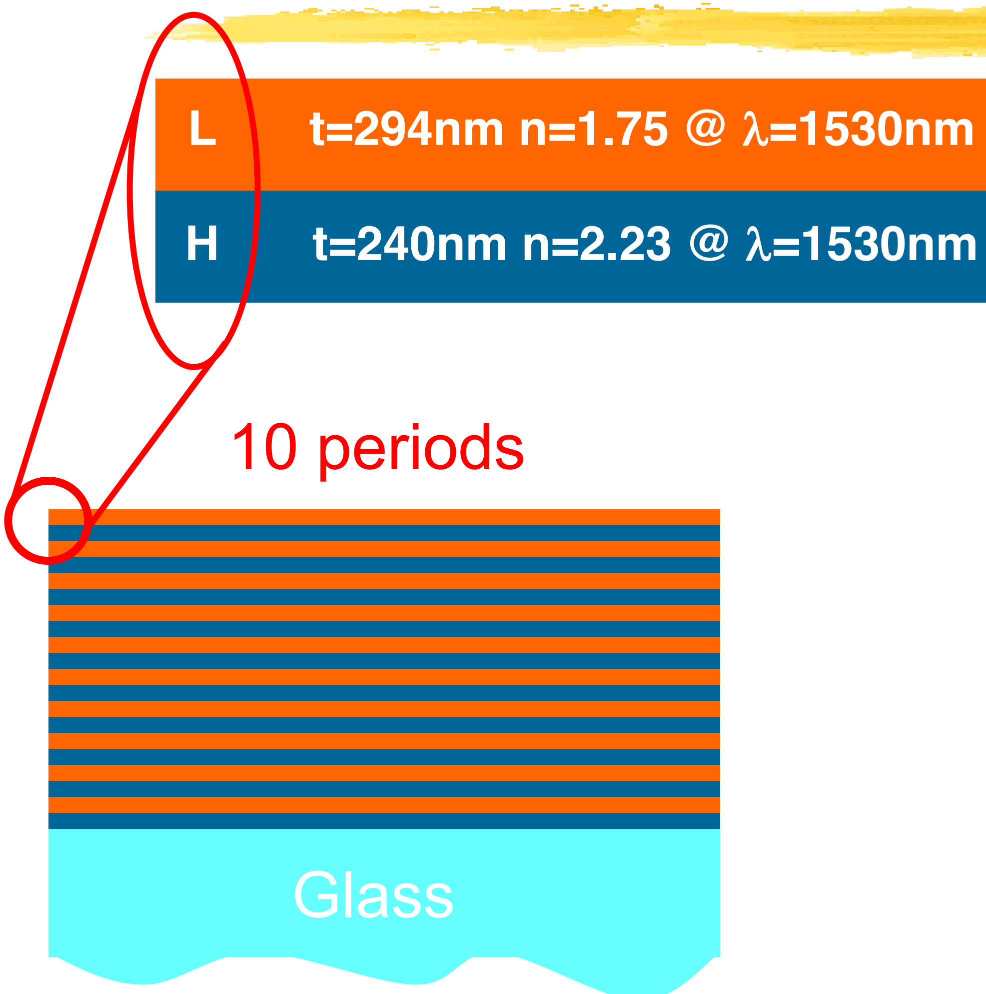


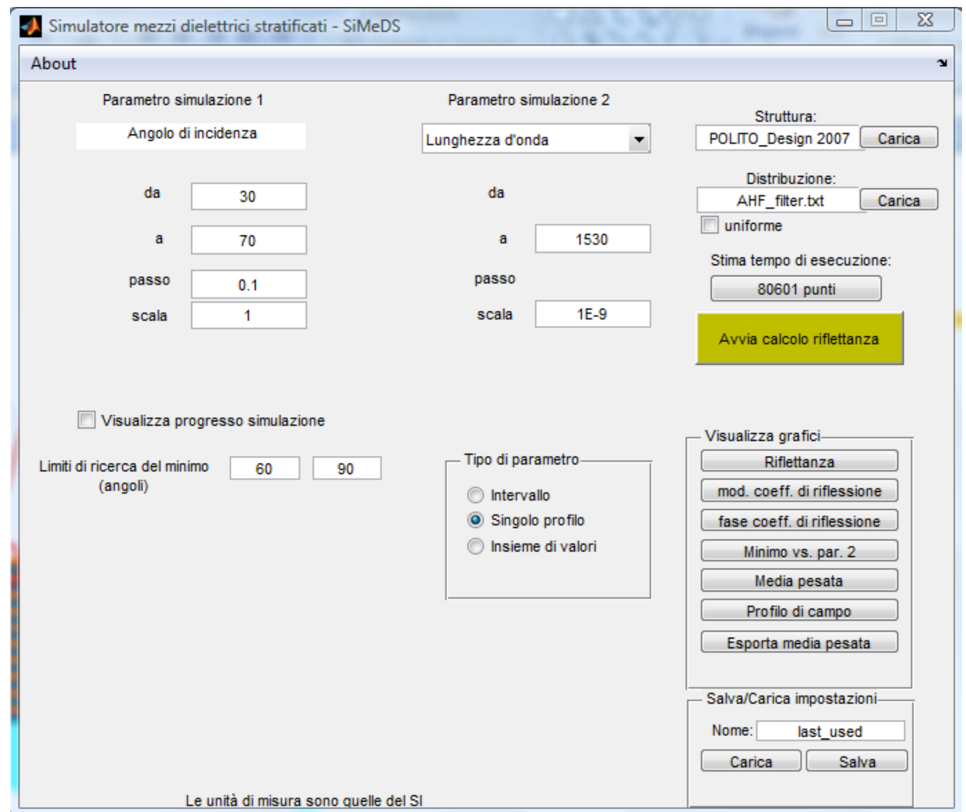
EXAMPLE: a-$Si_{1-x}N_x$:H 1DPC



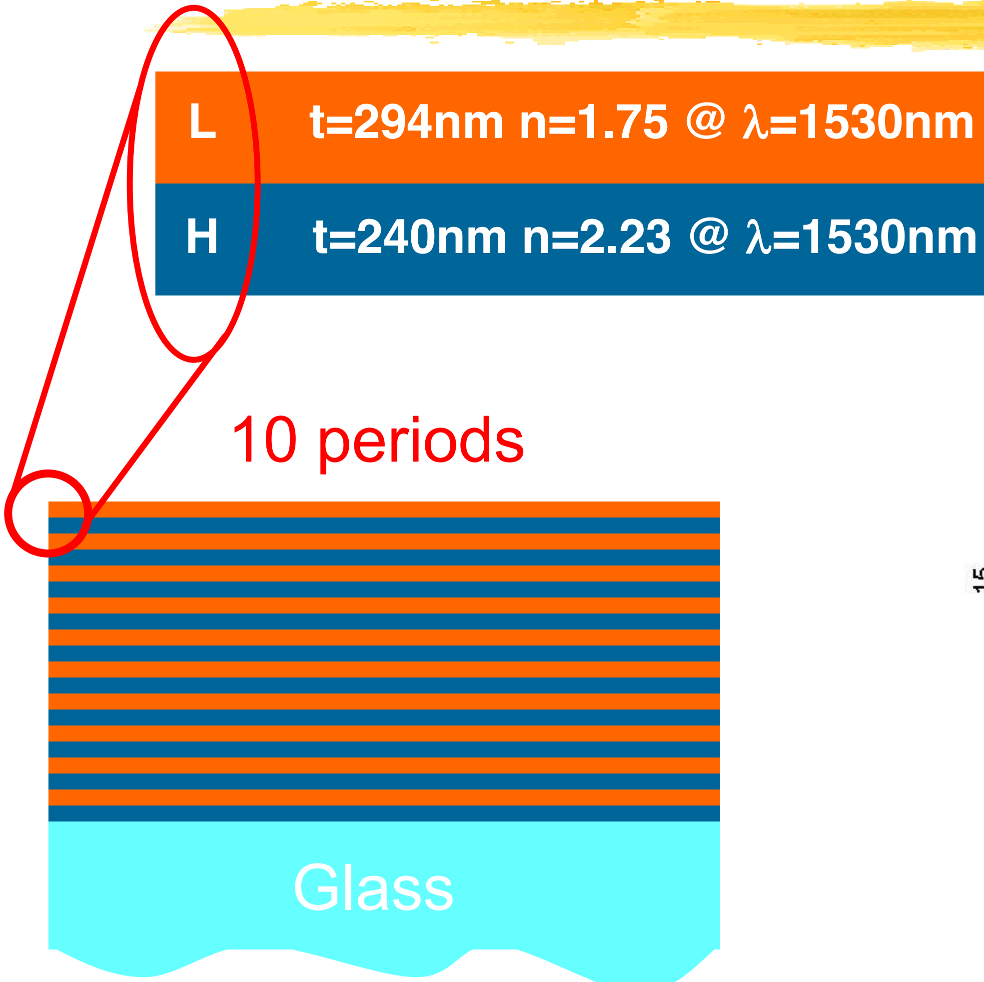


Transfer Matrix Method on MATLAB

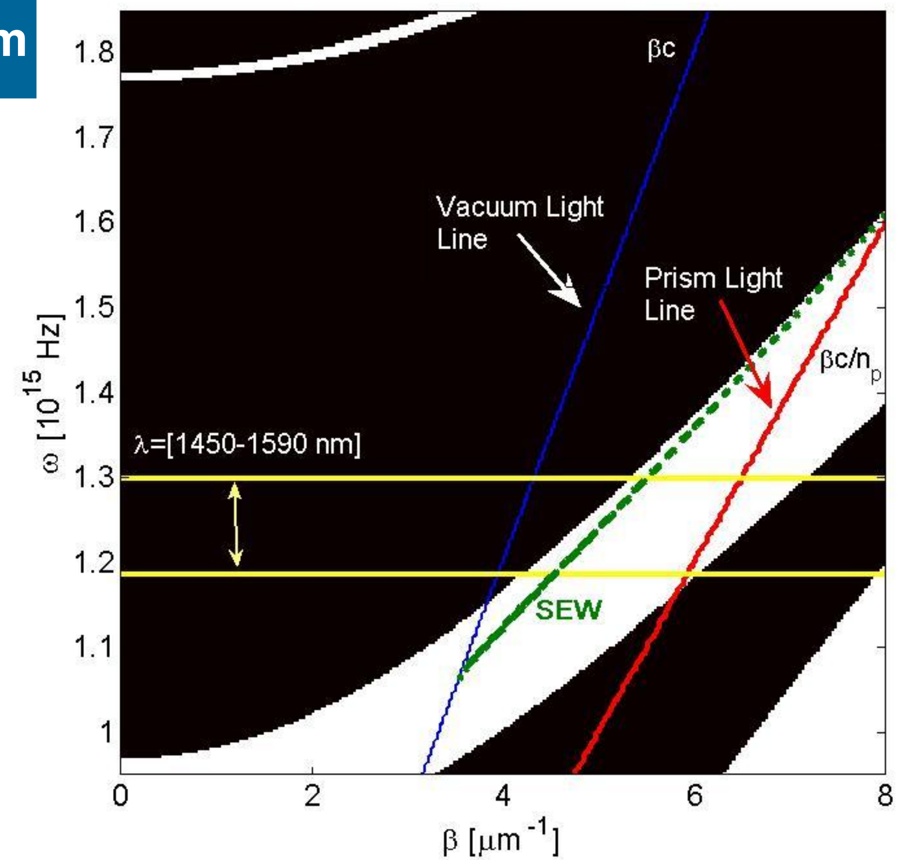




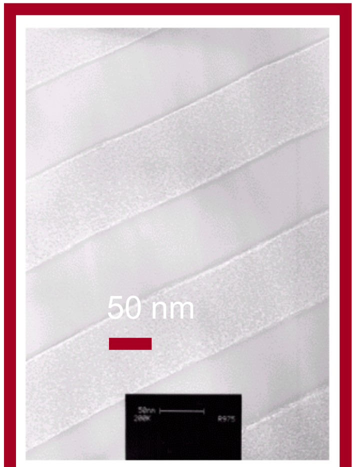
…. a small preview of Lecture 2

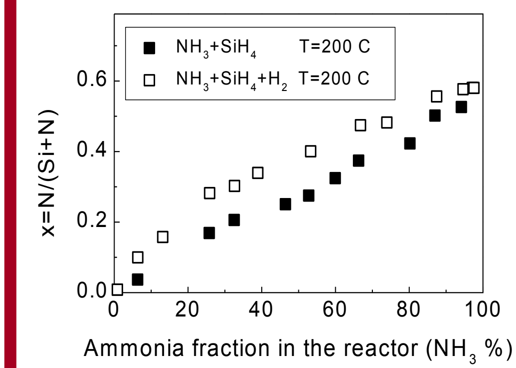


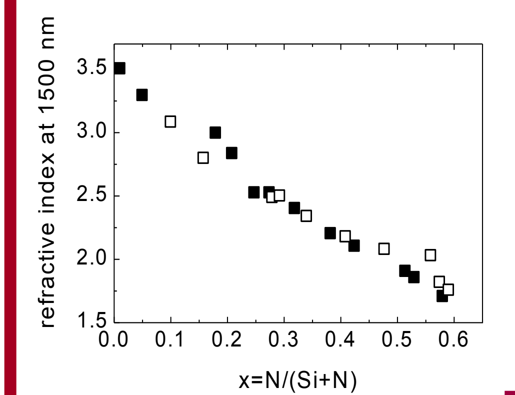
Band Diagram



Hydrogenated amorphous silicon nitride ($Si_{1-x}N_x$:H) by PECVD





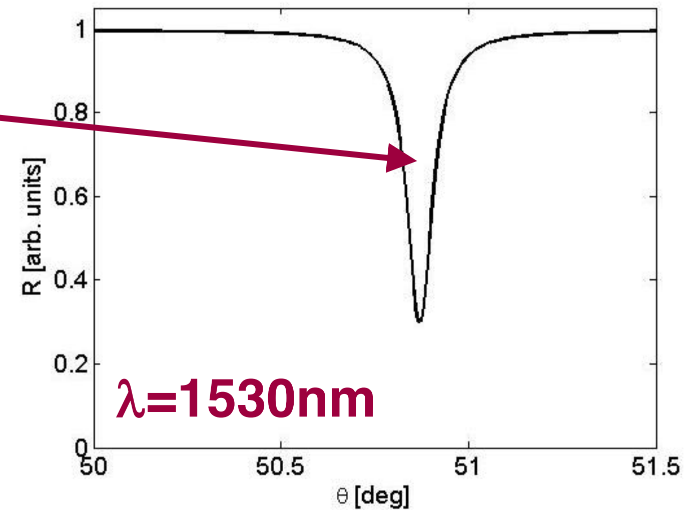


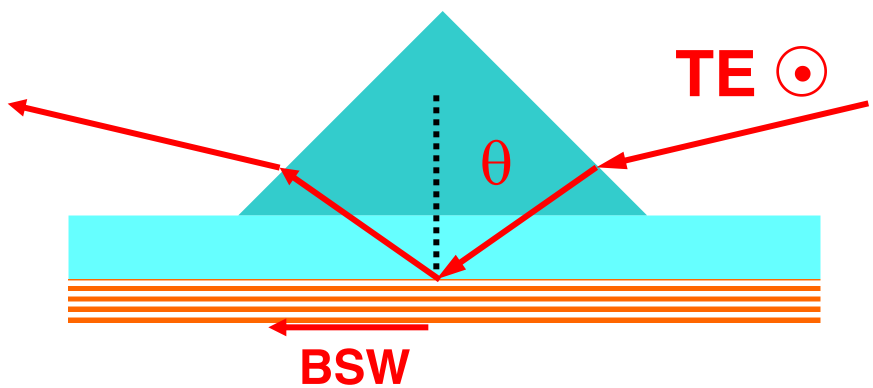
a-$Si_{1-x}N_x$:H alloy — material with tunable optical gap and refractive index varying the N content

13.56 MHz PECVD (SiH_4+NH_3) — growth of a-$Si_{1-x}N_x$:H thin films and multilayers with an excellent control of the thickness and composition

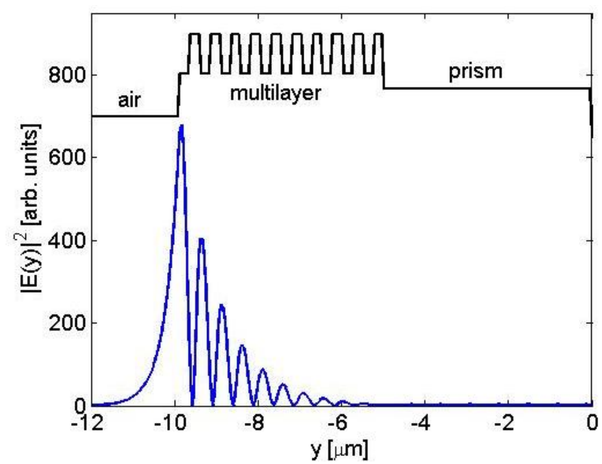
a-$Si_{1-x}N_x$:H based 1D Photonic Crystal

Linewidths are smaller than observed for SPPs

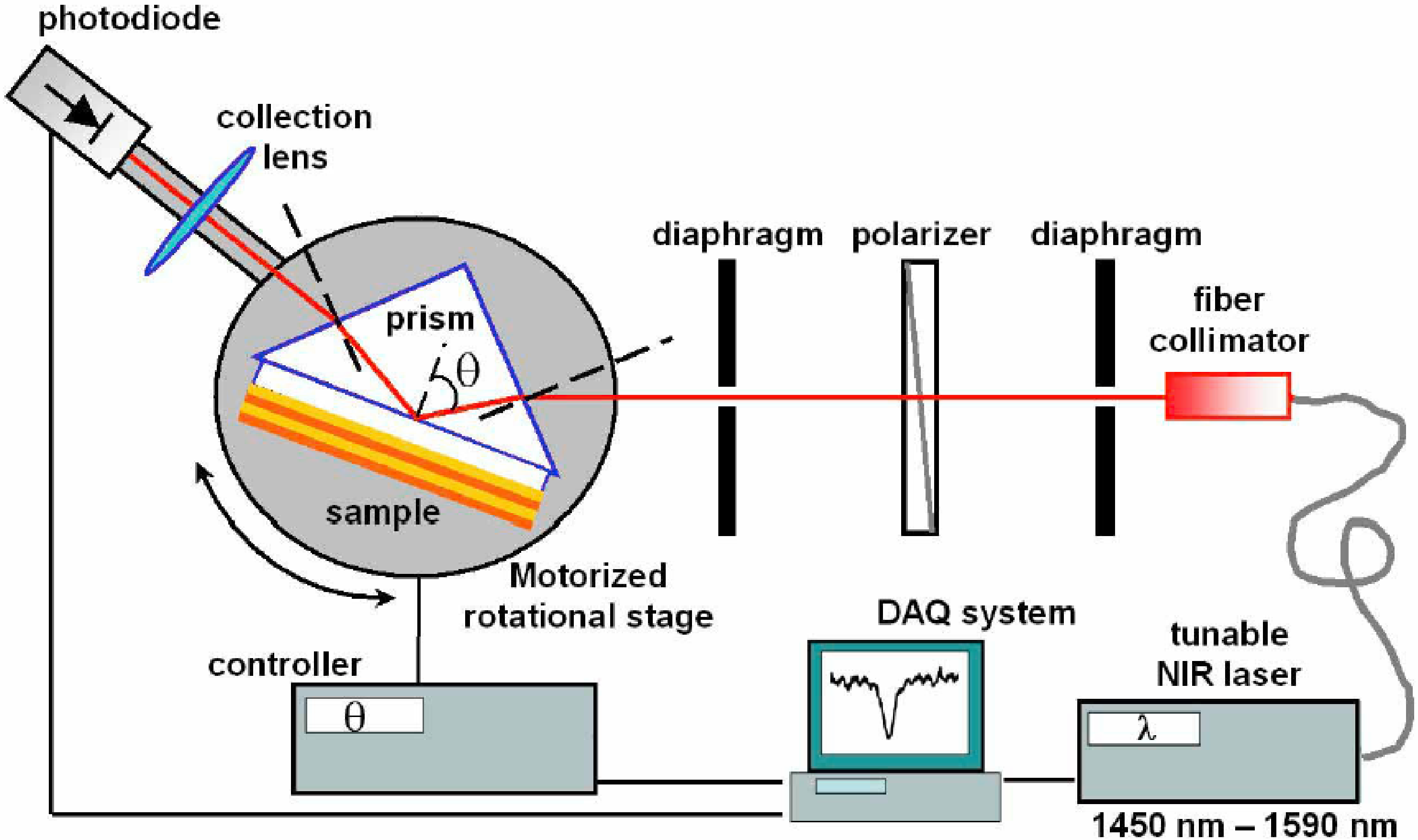




Kretschmann

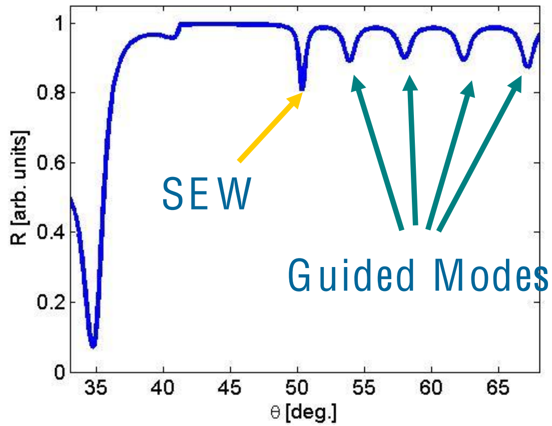


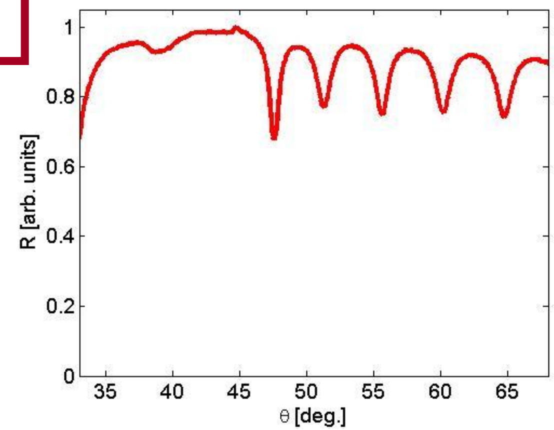
a-$Si_{1-x}N_x$:H based 1D Photonic Crystal



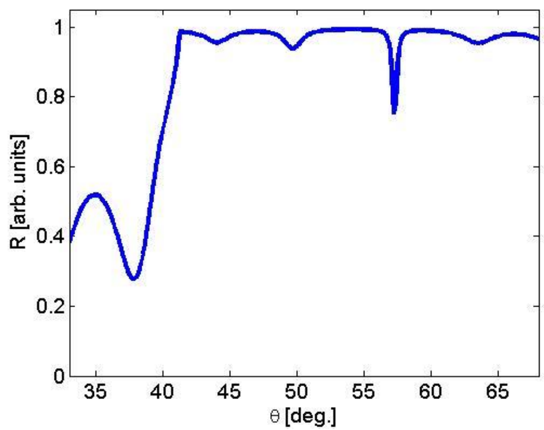
a-$Si_{1-x}N_x$:H – Kretschman reflectance

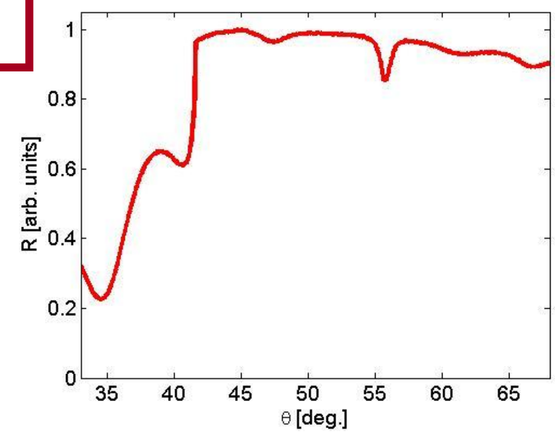
633 nm





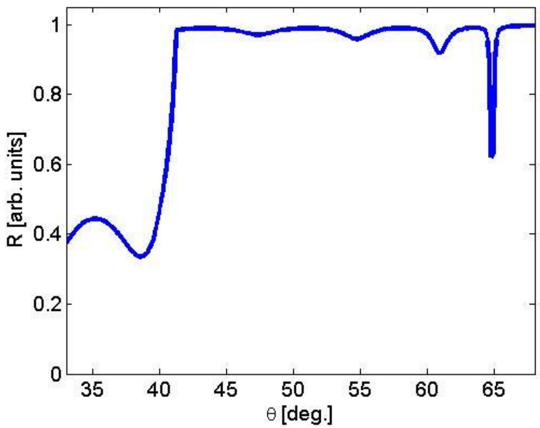
830 nm

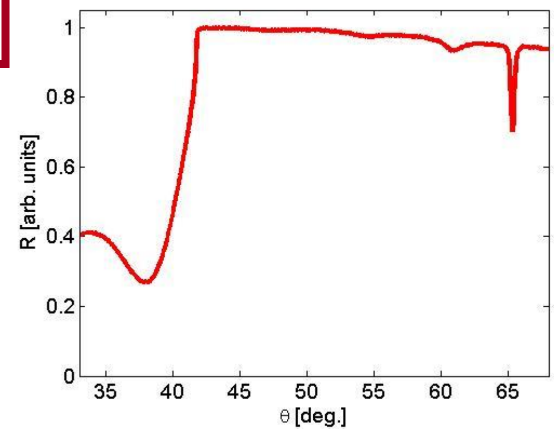




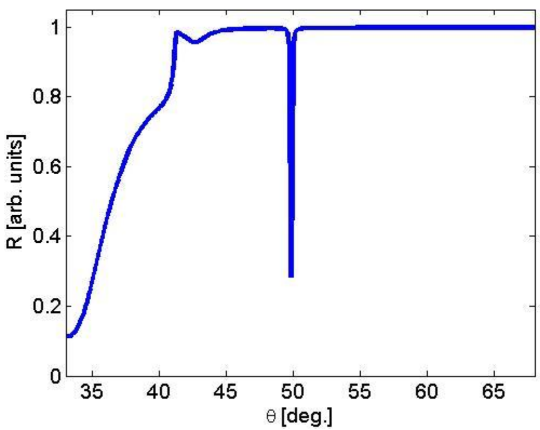
a-$Si_{1-x}N_x$:H – Kretschman reflectance

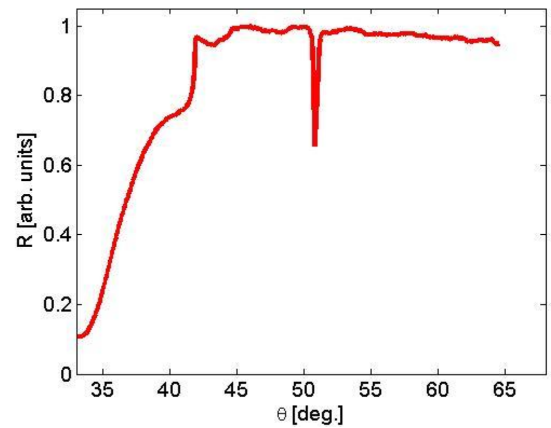
1300 nm



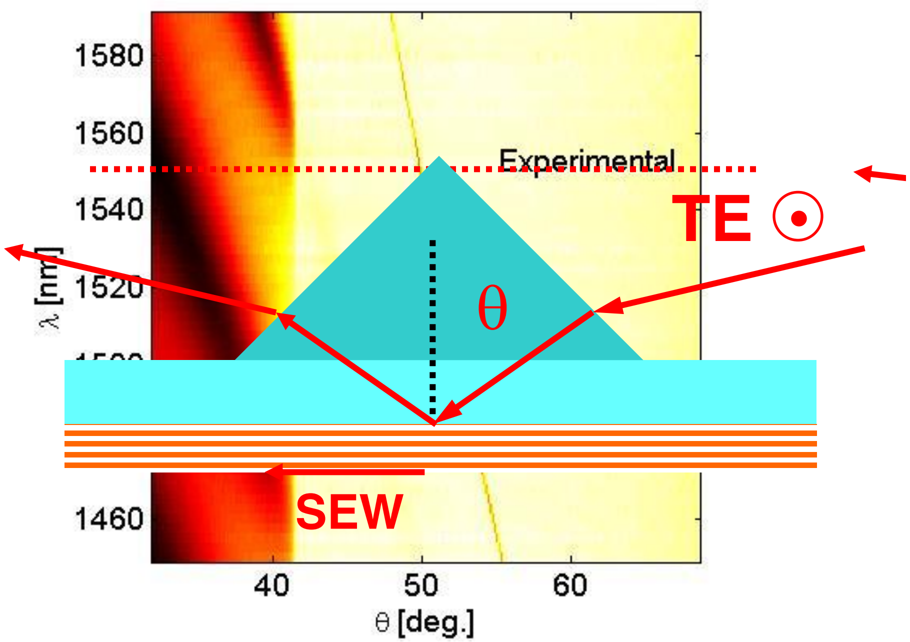


1550 nm





Kretschman Reflectance Map



Kretschmann