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Full-Wave Simulation of an Optofluidic Transmission-Mode Biosensor

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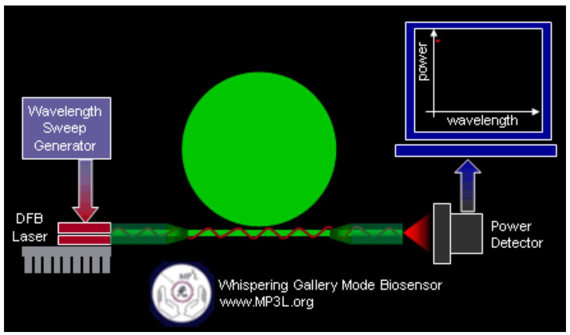
Outline

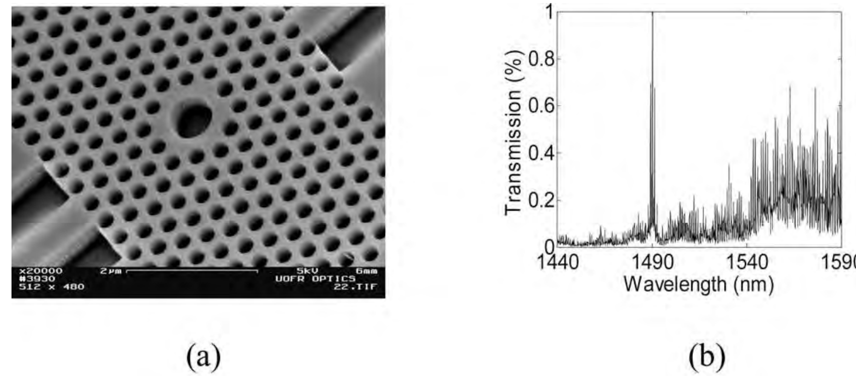
- Transverse Waveguide-based Biosensors
- Novel Optofluidic Biosensor
- Antiresonant Reflecting Optical Waveguides
- Device Simulation
- Conclusions

Transverse – Waveguide Based Biosensors

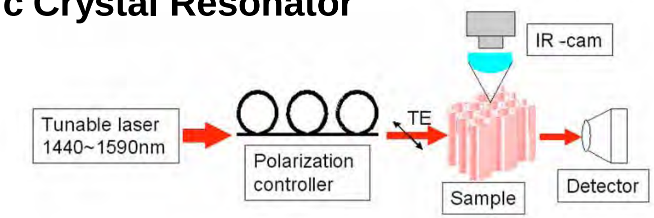
Whispering Gallery Mode Sensor



F. Vollmer et al. App. Phys. Lett. 80, 4057 -4059 (2002).

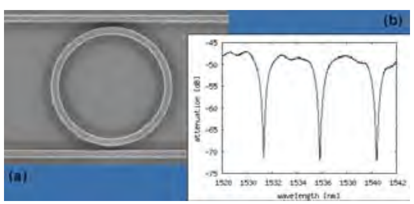


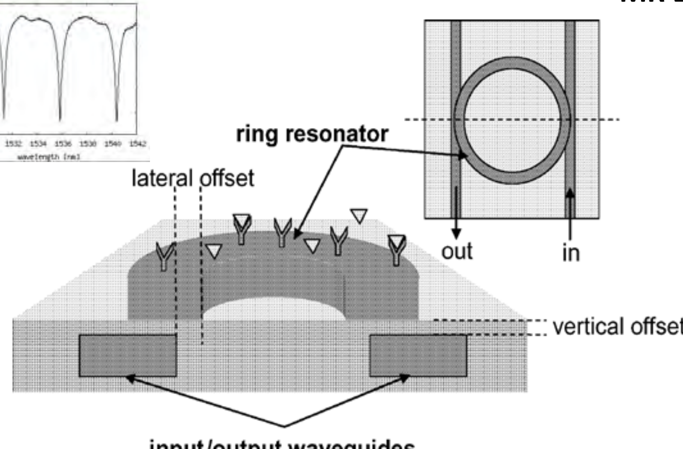
Photonic Crystal Resonator



MR Lee and P. Fauchet, Opt. Exp. (2007)

Microring Resonator





A. Yalcin et al. IEEE J. Sel. Topics Quant. Elec. (2006)

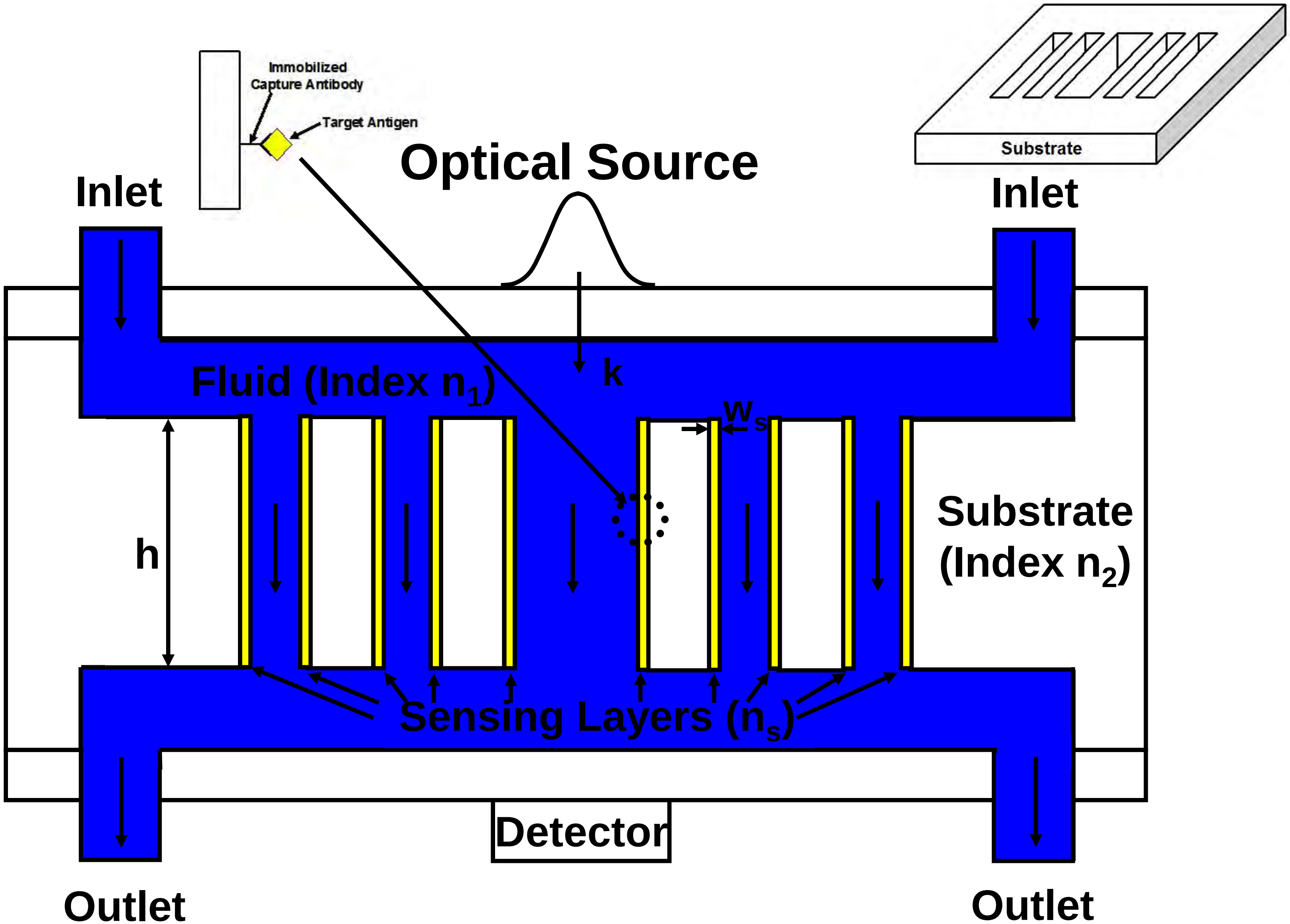
Advantages:

High Sensitivity

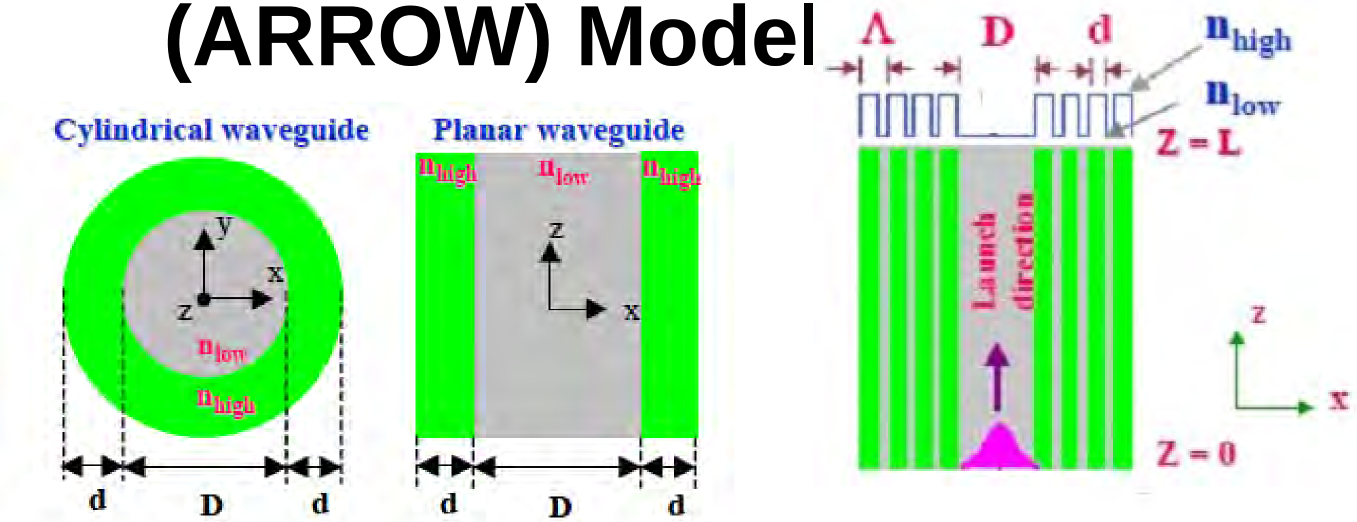
Disadvantages:

- **Difficult multiplexing for array applications**
- **Sensitive alignment coupling - awkward for POS applications**

Optofluidic Biosensor



Antiresonant Reflecting Optical Waveguide (ARROW) Model



Antiresonant Reflecting Optical Waveguide (ARROW) model

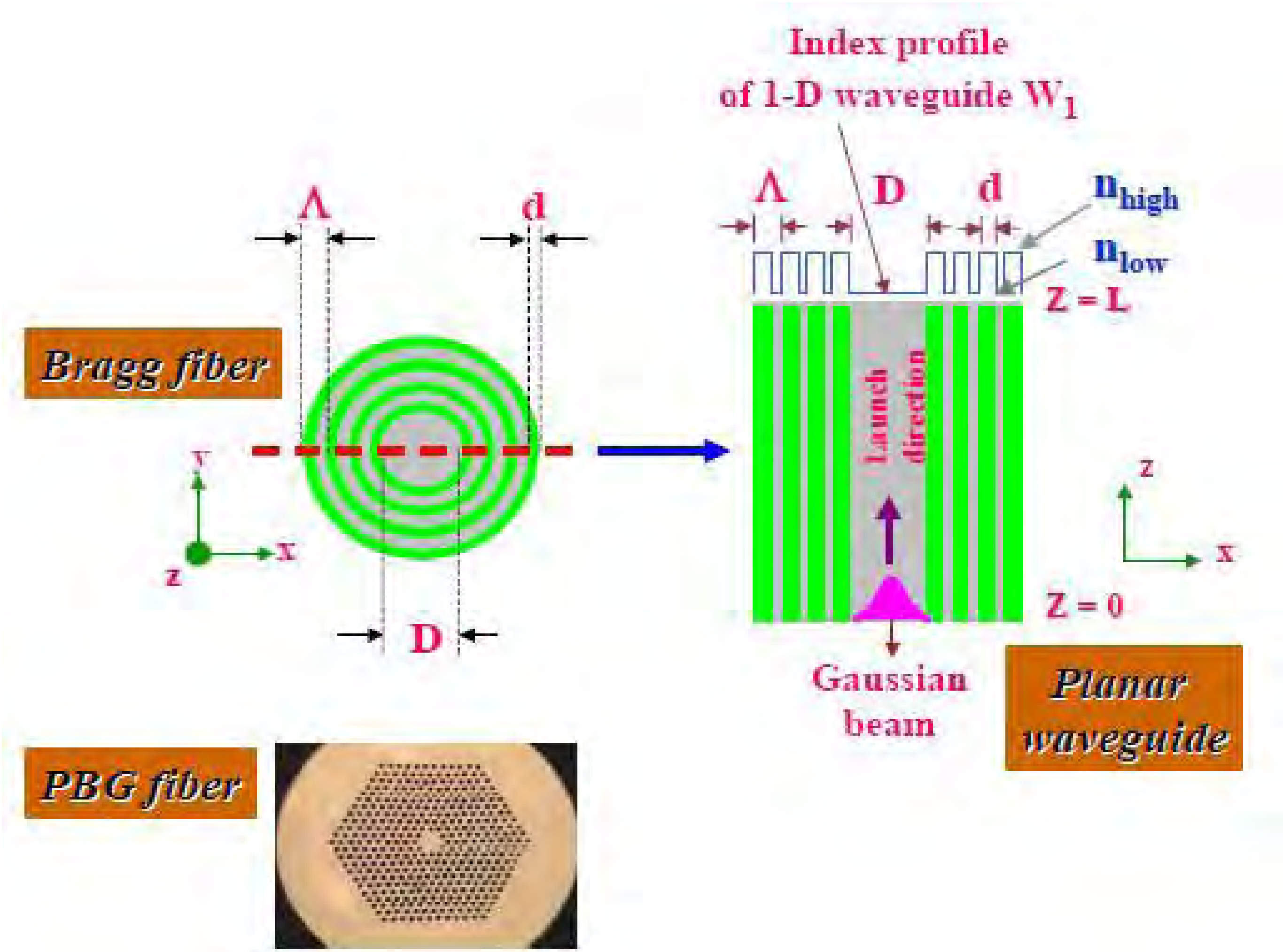
The high-index layer on either side of the low-index core behaves as a Fabry-Perot resonator in the ARROW model.

A standing wave builds up in the high-index layer when $k_{ex}d = \pi m$, m = 1, 2,…, where k_{ex} is the propagation constant. This corresponds to a resonant condition in the high-index layer so that light leaks out of the core, thus giving rise to the transmission minima.

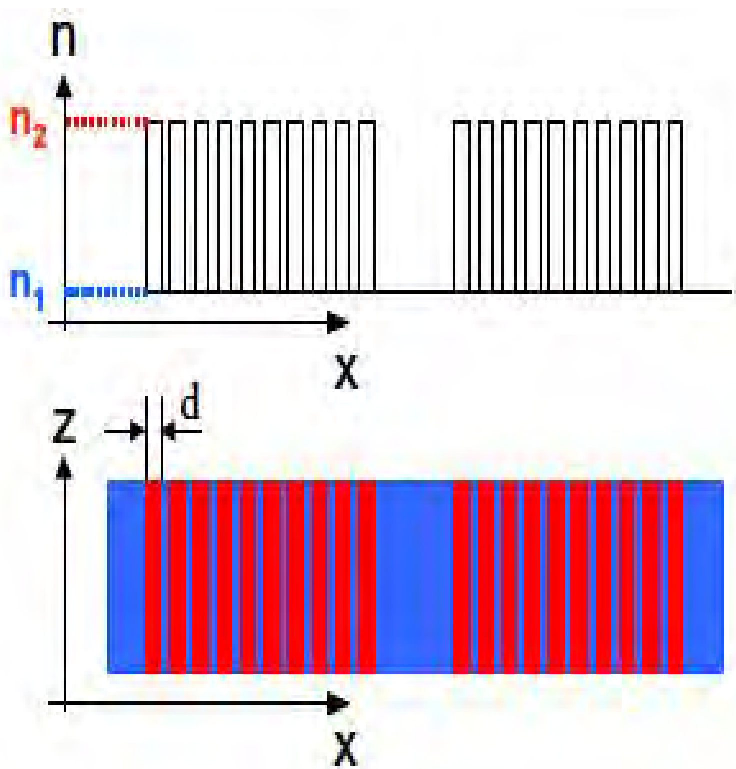
The transmission maxima result from antiresonant wavelengths that experience destructive interference within the high-index layer so that light is confined in the low-index core.

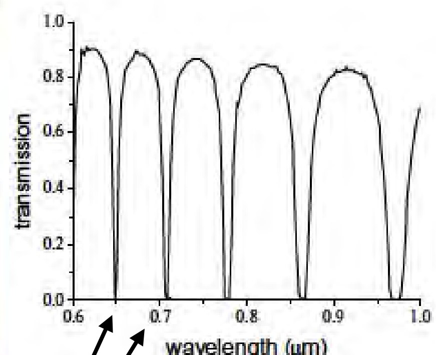
A. K. Abeeluck 2002 / Vol. **10** 23 Optics Express 2002

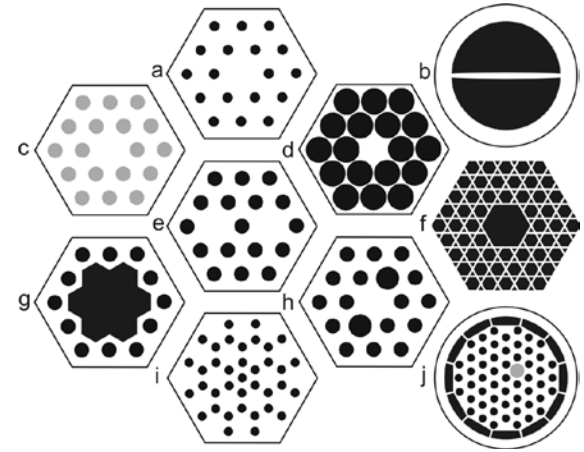
Microstructured Optical Fibers

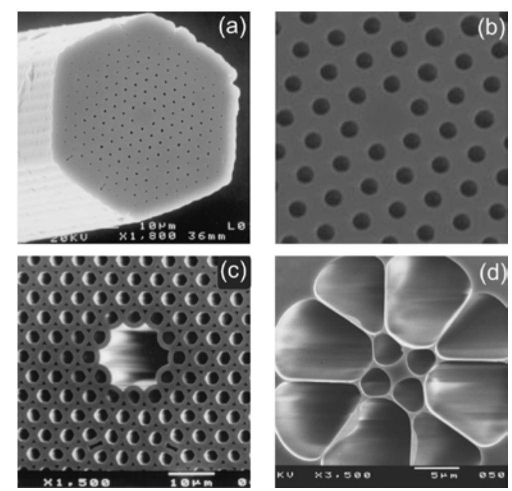


Microstructured Optical Fiber (MOF)
(Photonic Crystal Fibers)









Transmission Minima λ_m

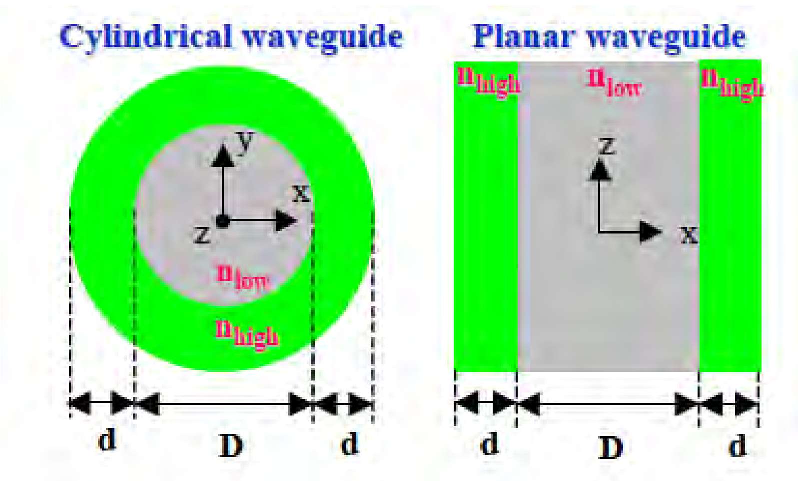
$$\lambda_m = \frac{2n_1 d}{m}\left[\left(\frac{n_2}{n_1}\right)^2 - 1\right]^{\frac{1}{2}} \qquad (m = 1, 2, \ldots)$$

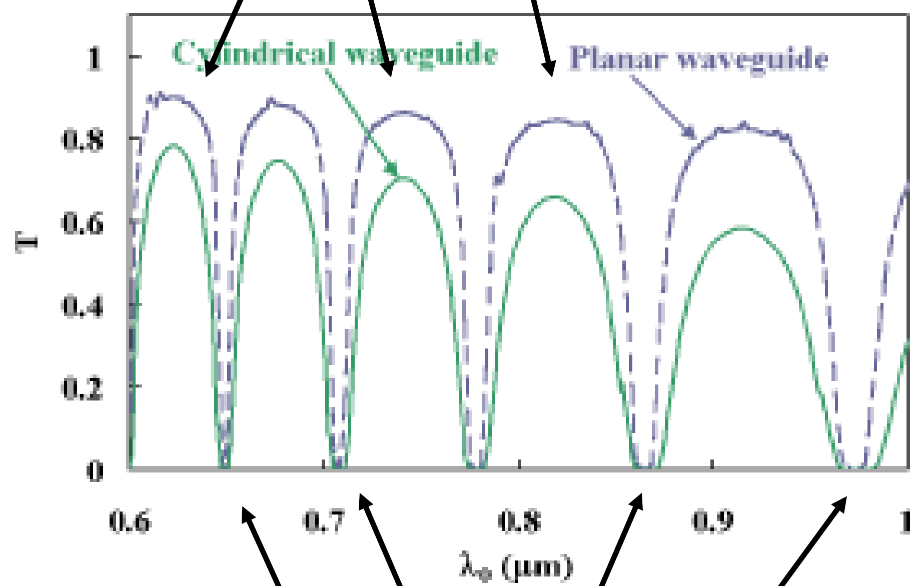
P. J. Russel, Light Wave Tech. 2006

Analysis of Transmission Spectrum

Antiresonant Reflecting Optical Waveguide (ARROW) model

Maxima $$\lambda_l = \frac{4n_{low}d}{(2l+1)}\left[\left(\frac{n_{high}}{n_{low}}\right)^2 - 1\right]^{\frac{1}{2}} \qquad (l = 0,1,2,\ldots)$$





Analytical analysis applies when

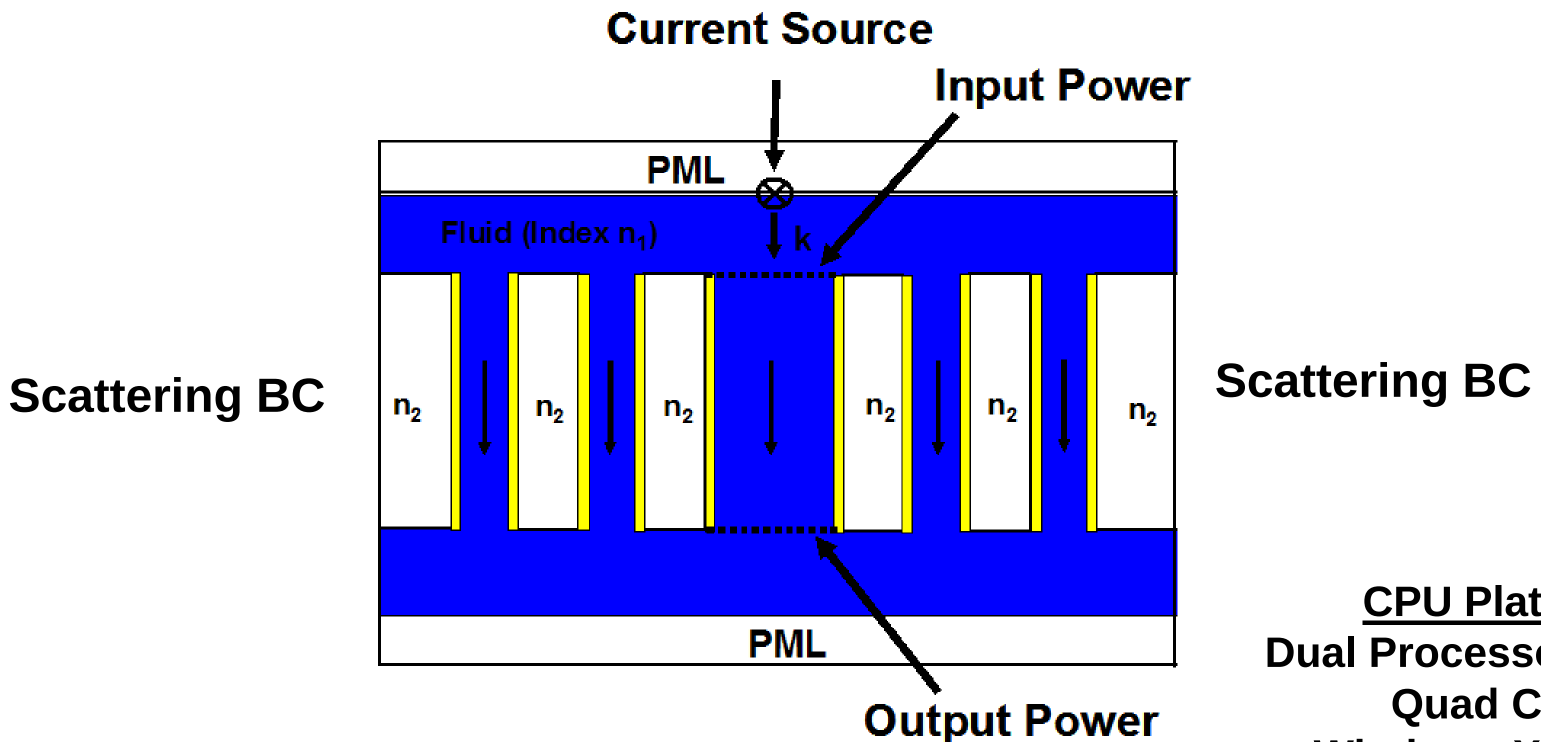
$$\frac{\lambda}{D} \ll 1$$

Minima $$\lambda_m = \frac{2n_{low}d}{m}\left[\left(\frac{n_{high}}{n_{low}}\right)^2 - 1\right]^{\frac{1}{2}} \qquad (m = 1,2,\ldots)$$

A. K. Abeeluck 2002 / Vol. **10** 23 Optics Express 2002

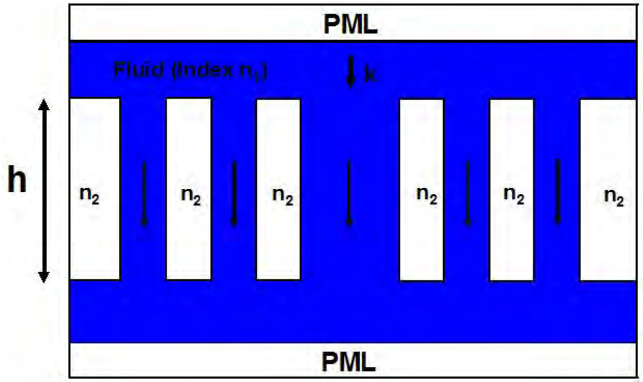
Time-Harmonic Analysis Computational Domain

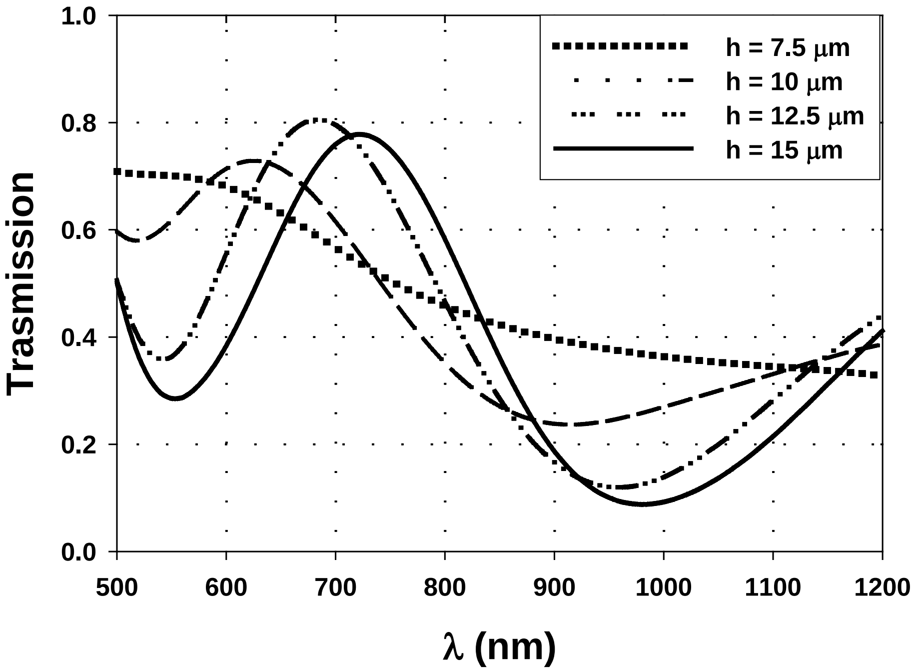
$$\nabla \times \left(\mu_r^{-1} \nabla \times \boldsymbol{E} \right) - \left(\varepsilon_r - \frac{j\sigma}{\omega \varepsilon_0} \right) k^2 \boldsymbol{E} = 0$$

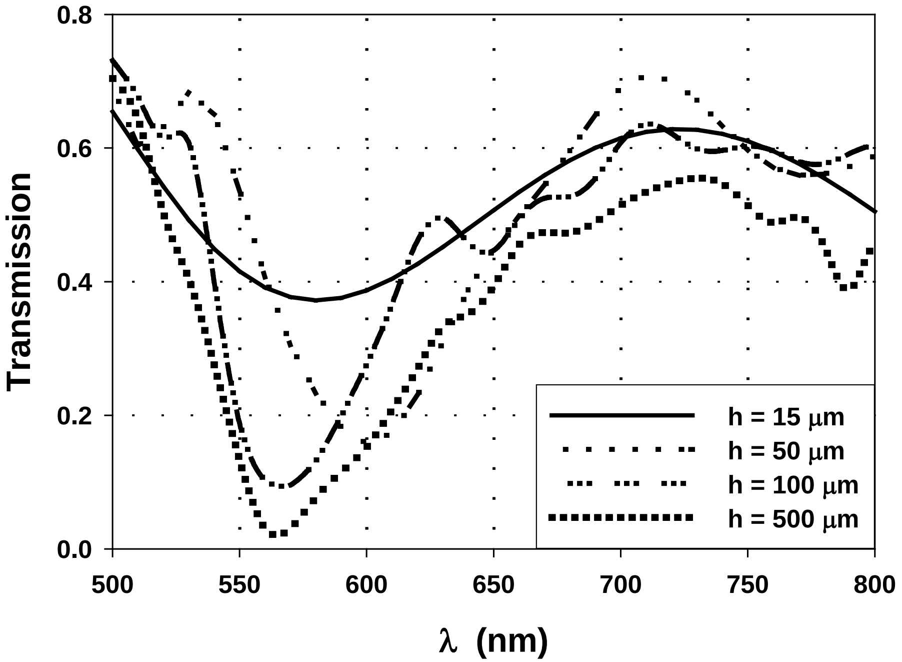


CPU Platform
Dual Processor (3 GHz)
Quad Core
Windows XP 64 Bit
32 GB RAM

Transmission Spectra vs. Substrate Thickness (h)

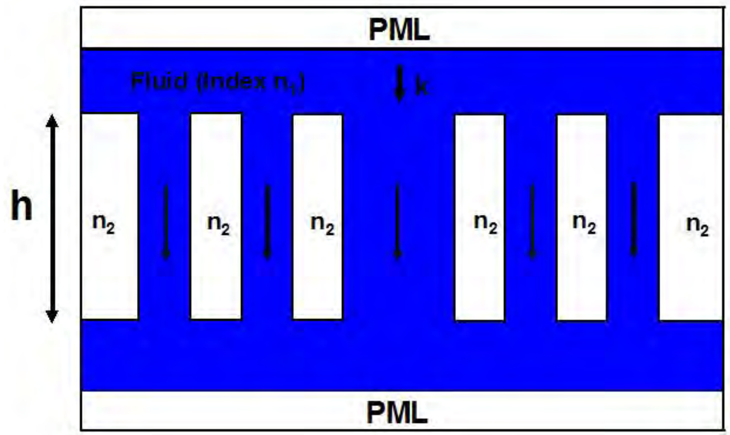




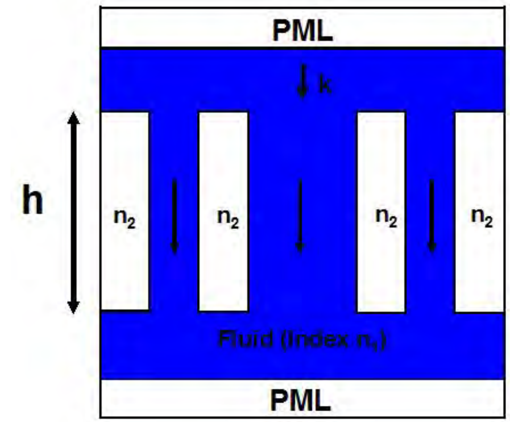


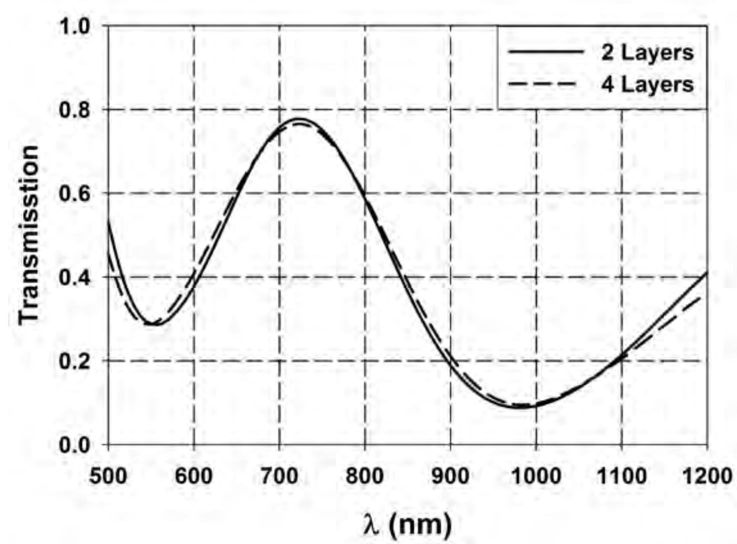
Transmission vs. Number of Layers

Four Layers



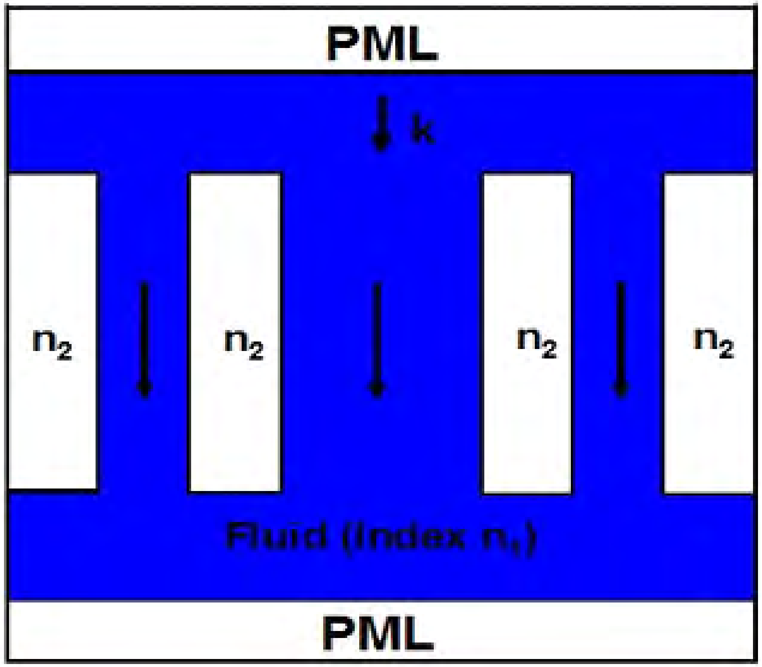
Two Layers



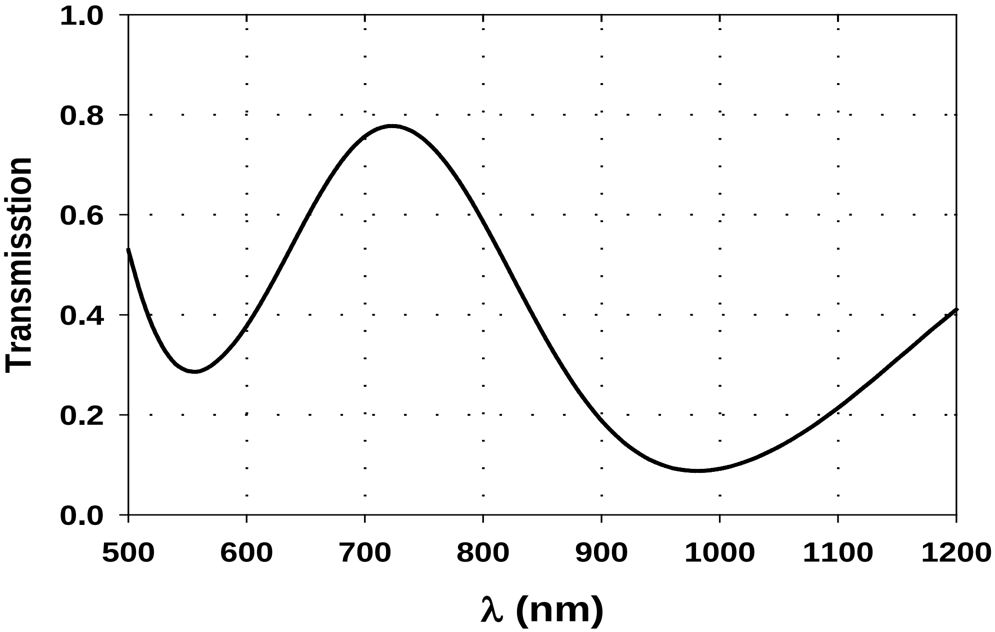


Time-Harmonic Full-Wave Analysis
Device Design

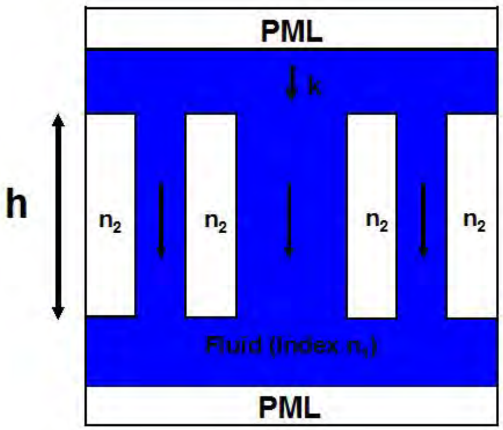
Reduced Computational Domain
Mesh: 48,306 cubic elements

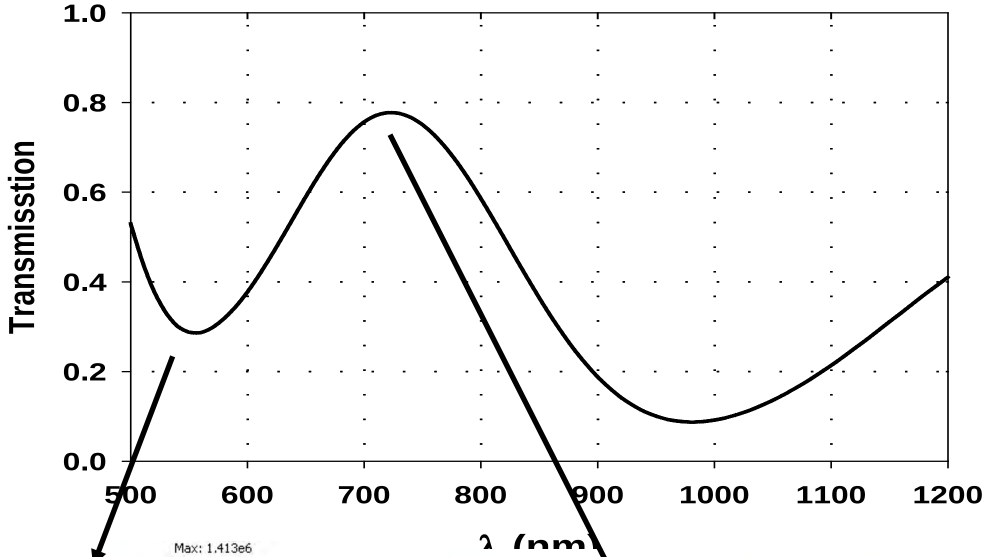


Parametric Analysis: It takes approximately 15 min to compute a transmission spectrum using a dual quad-core workstation (Windows XP 64 bit) with 24 GB of RAM

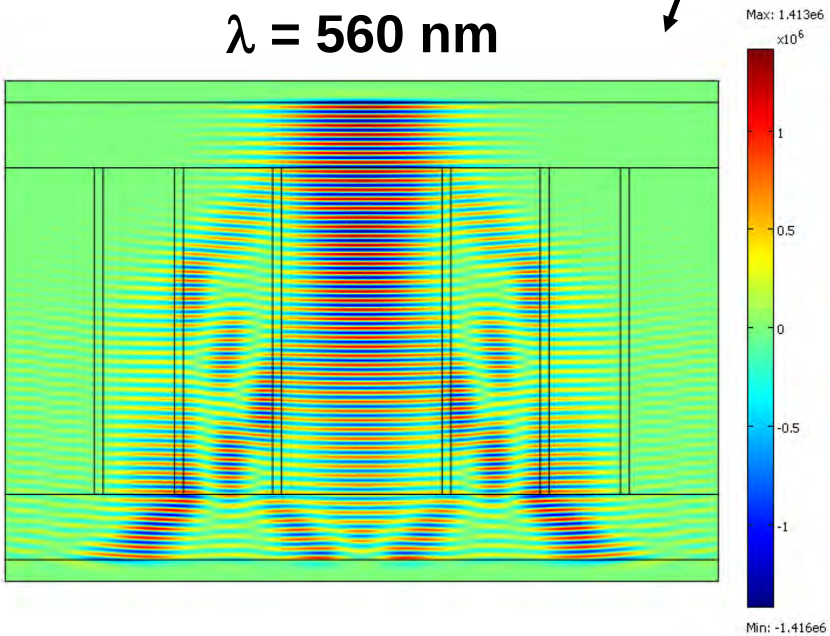


Analysis of Transmission Spectrum

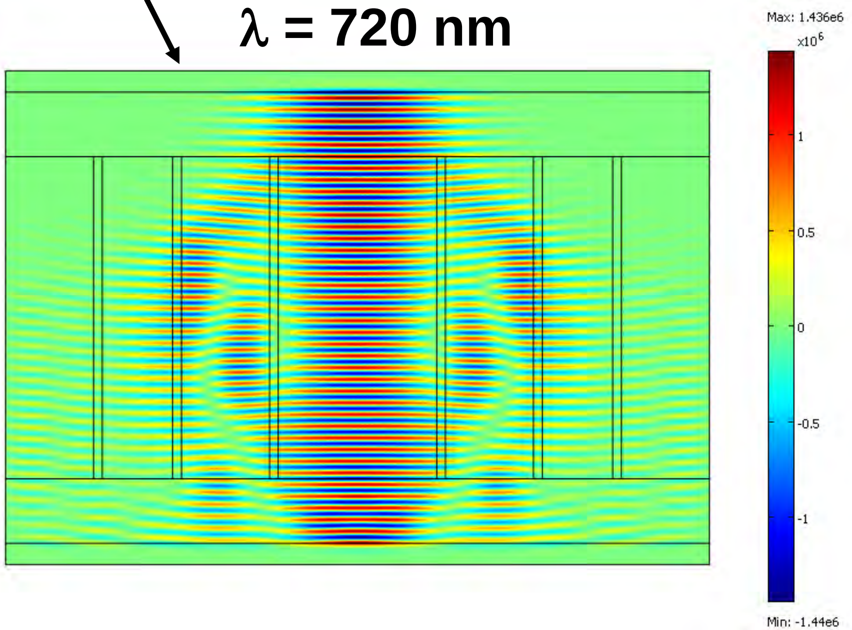




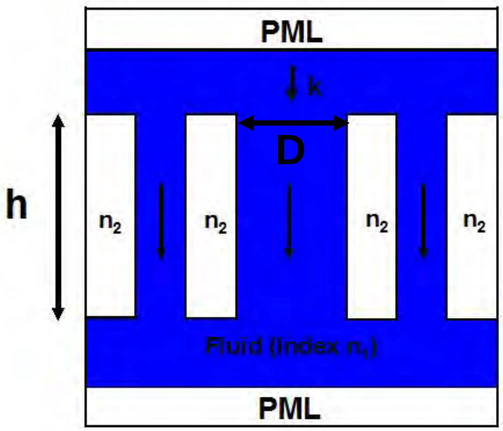
λ = 560 nm



λ = 720 nm



Comparison with Analytical Analysis



Maxima $$\lambda_l = \frac{4 n_{low} d}{(2l+1)} \left[\left(\frac{n_{high}}{n_{low}} \right)^2 - 1 \right]^{\frac{1}{2}} \quad (l = 0, 1, 2, \ldots)$$

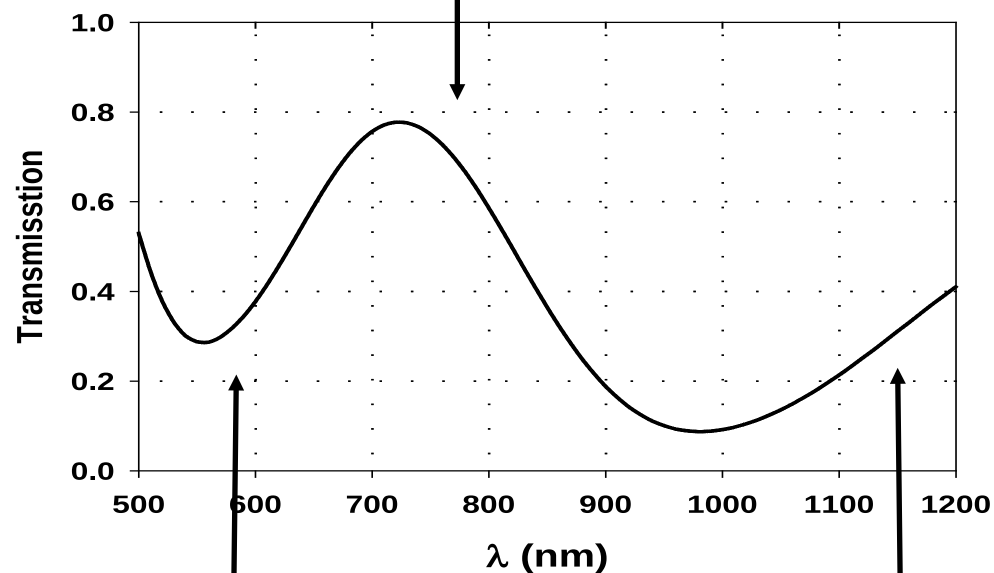
$\lambda_{1,max}$ = 770 nm **$\lambda_{0,max}$ = 2310 nm**

Analytical analysis applies when $\frac{\lambda}{D} \ll 1$

d = 1 μm

n_1 = 1.33 (H_2O)

n_2 = 1.45 (SiO_2)

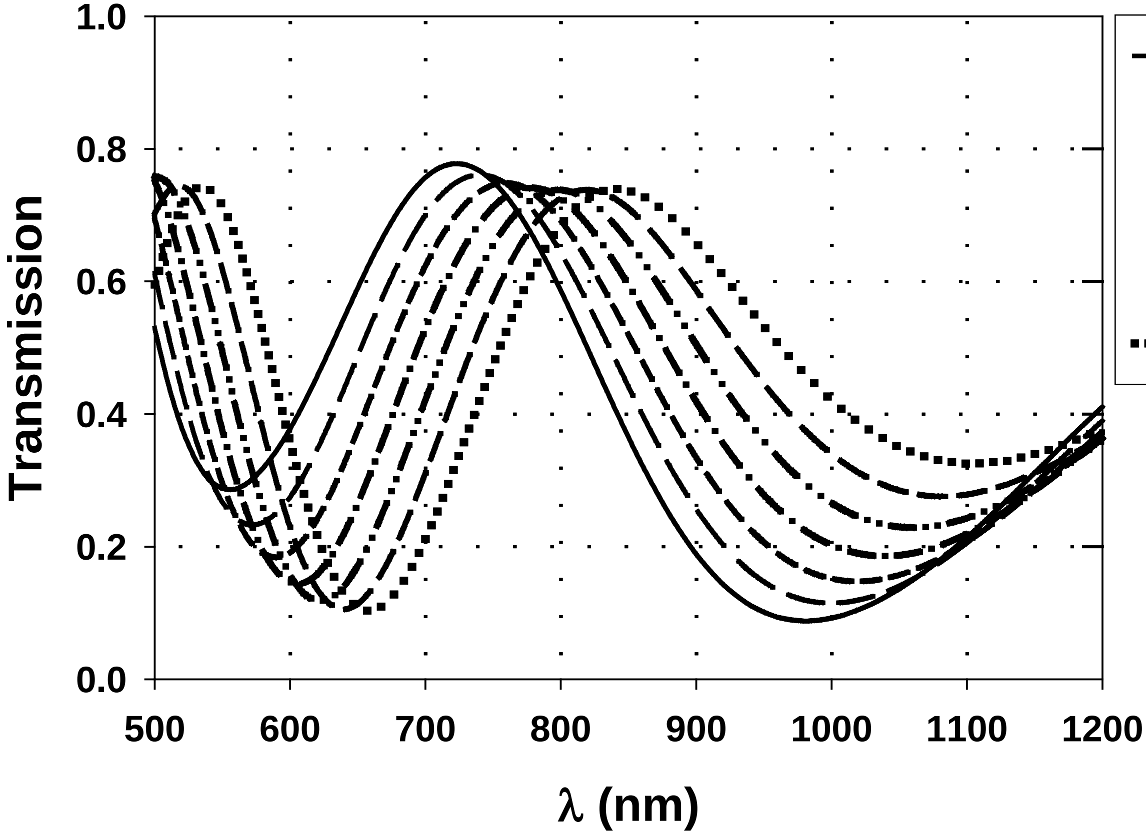


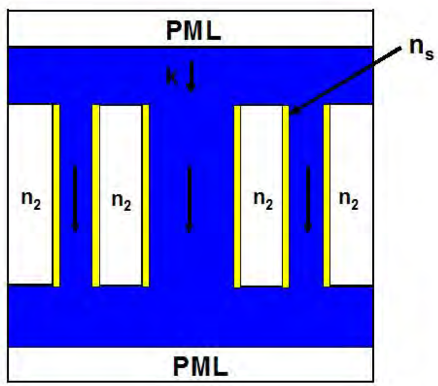
Minima

$$\lambda_m = \frac{2 n_{low} d}{m} \left[\left(\frac{n_{high}}{n_{low}} \right)^2 - 1 \right]^{\frac{1}{2}} \quad (m = 1, 2, \ldots)$$

$\lambda_{2,min}$ = 578 nm **$\lambda_{1,min}$ = 1155 nm**

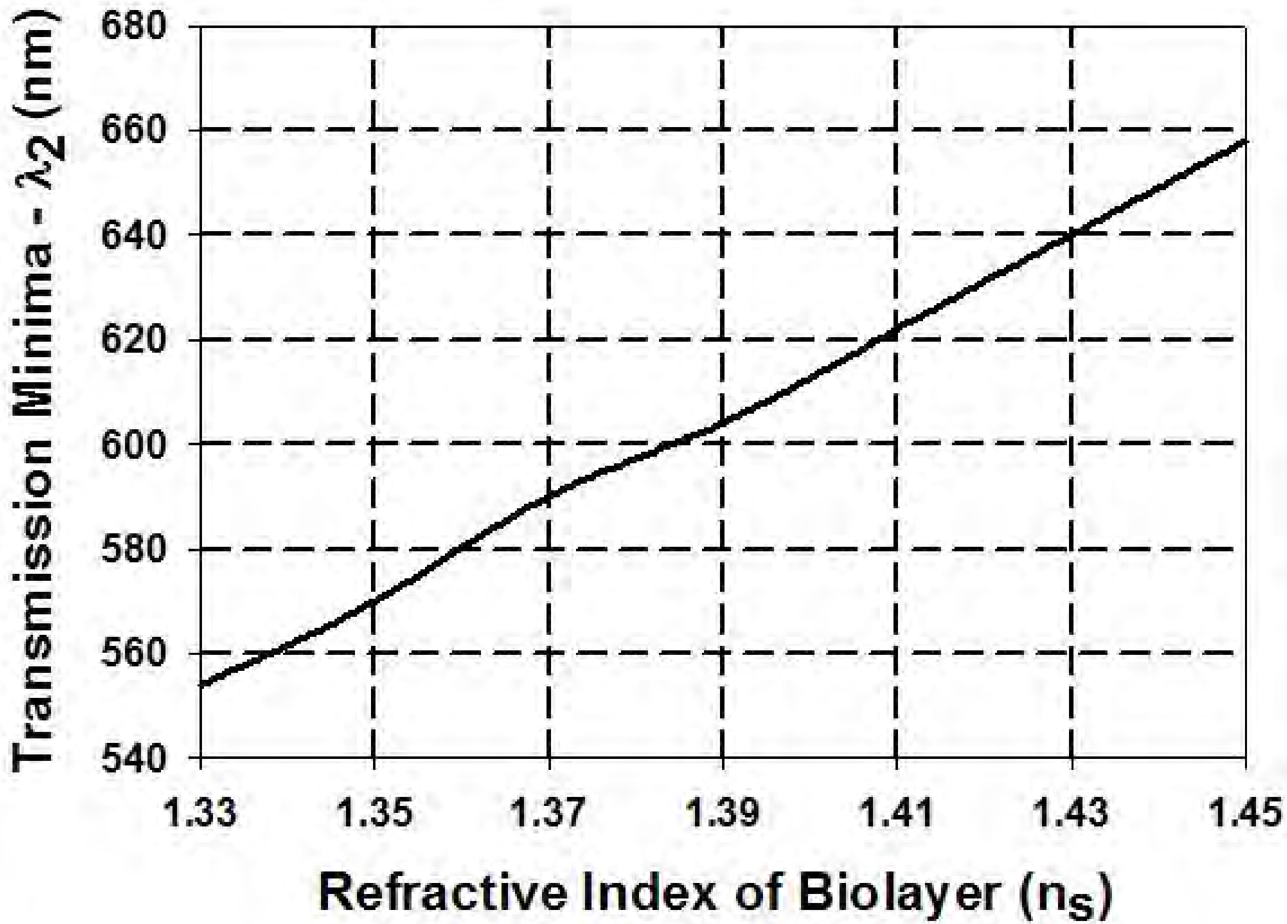
Transmission Spectra vs. Refractive Index of Sensing Layer n_s



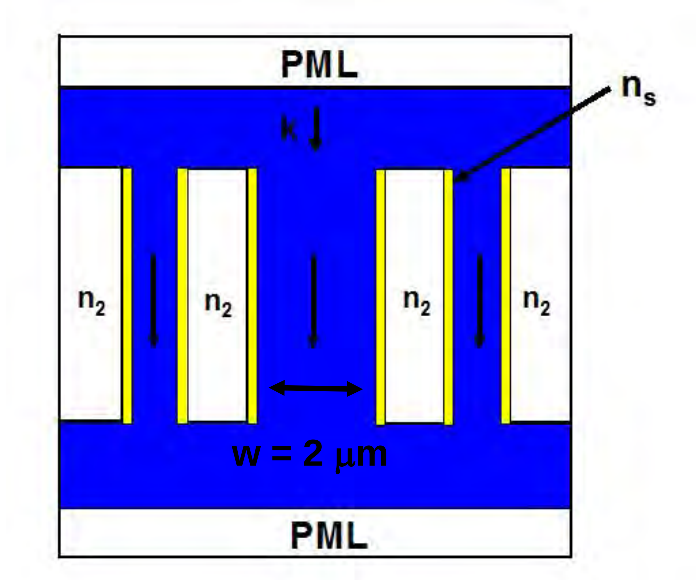


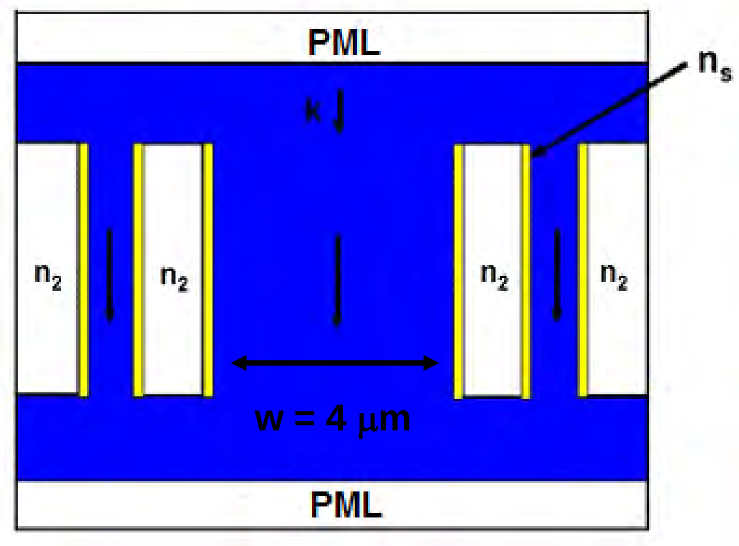
Transmission Spectra vs. n_s.

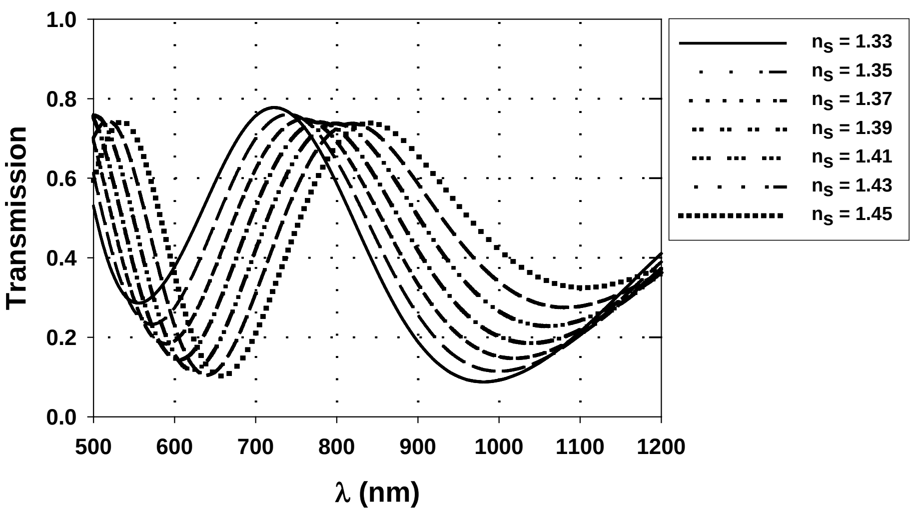
Shift in λ_2 Transmission Minima vs. Refractive Index of Sensing Layer n_s

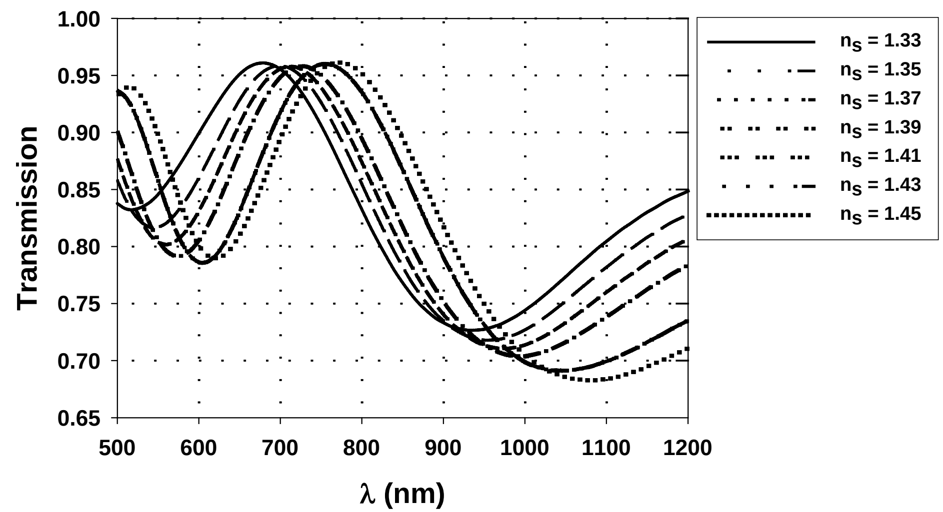


Transmission vs. Channel Width



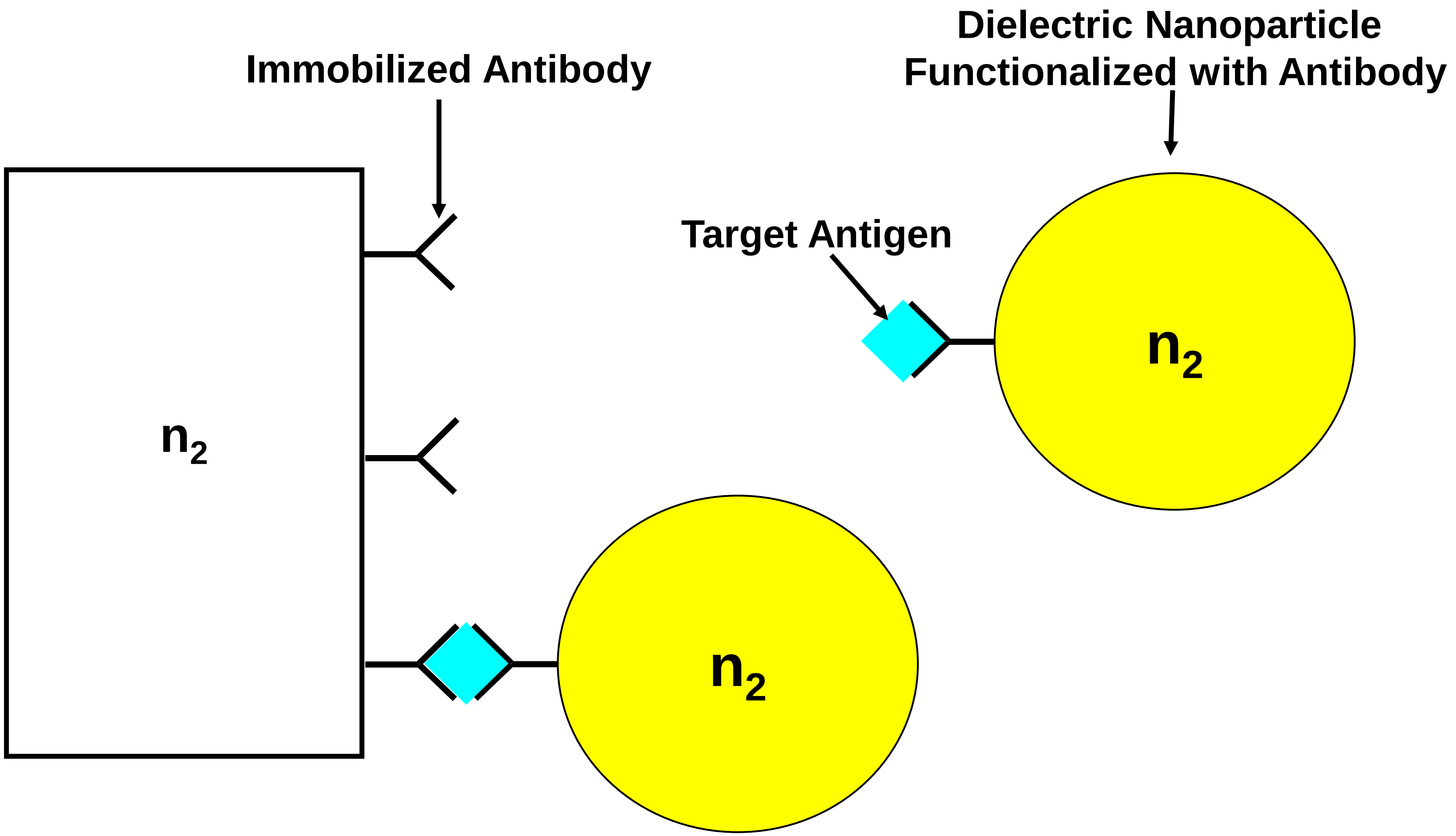






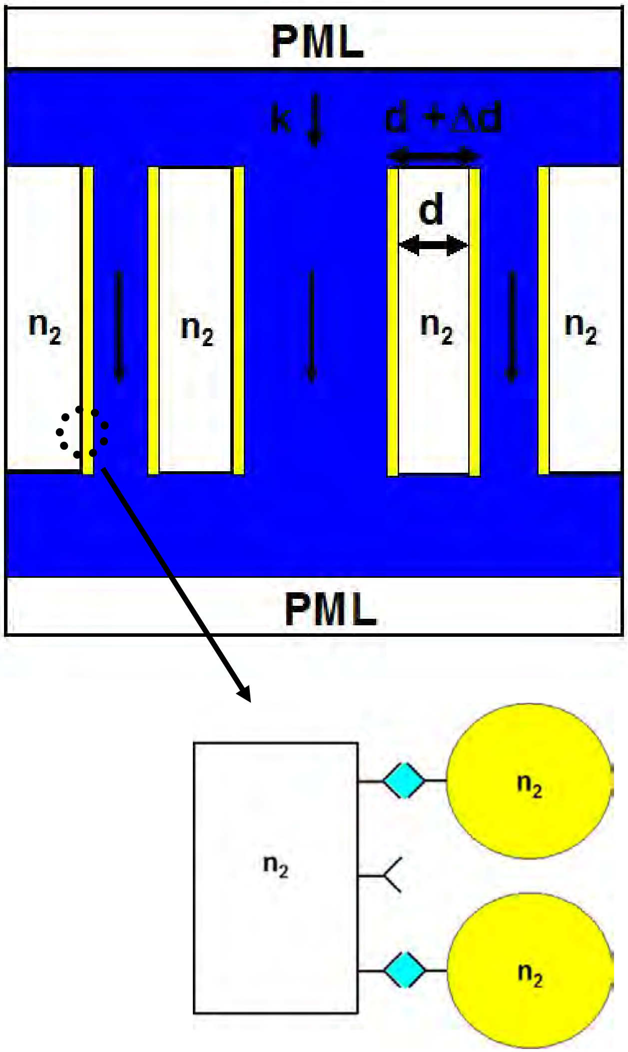
Detection Sensitivity
(Spectral Shift vs. Biolayer Thickness w_s)

Nanoparticle-Based Immunoassay



Sensitivity – Spectral Shift vs. Biolayer Thickness w_s

$$\Delta d = 2\, w_s$$



Transmission Minima

$$\lambda_m = \frac{2 n_1 d}{m}\left[\left(\frac{n_2}{n_1}\right)^2 - 1\right]^{\frac{1}{2}} \qquad (m = 1, 2, \ldots)$$

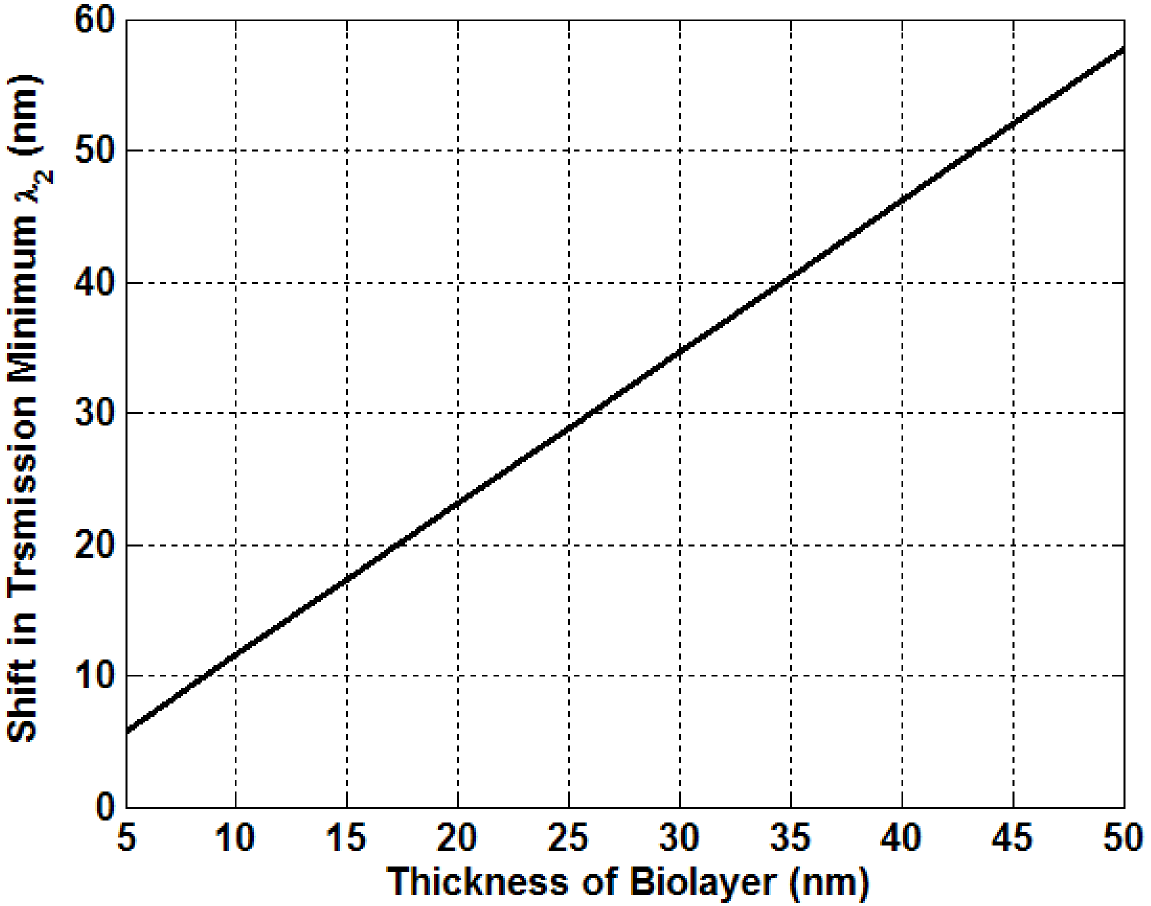
$$\Delta\lambda_m = \frac{2 n_1 \Delta d}{m}\left[\left(\frac{n_2}{n_1}\right)^2 - 1\right]^{\frac{1}{2}} \qquad (m = 1, 2, \ldots)$$

$$\Delta\lambda_2 = n_1 \Delta d\left[\left(\frac{n_2}{n_1}\right)^2 - 1\right]^{\frac{1}{2}} \qquad (m = 2)$$

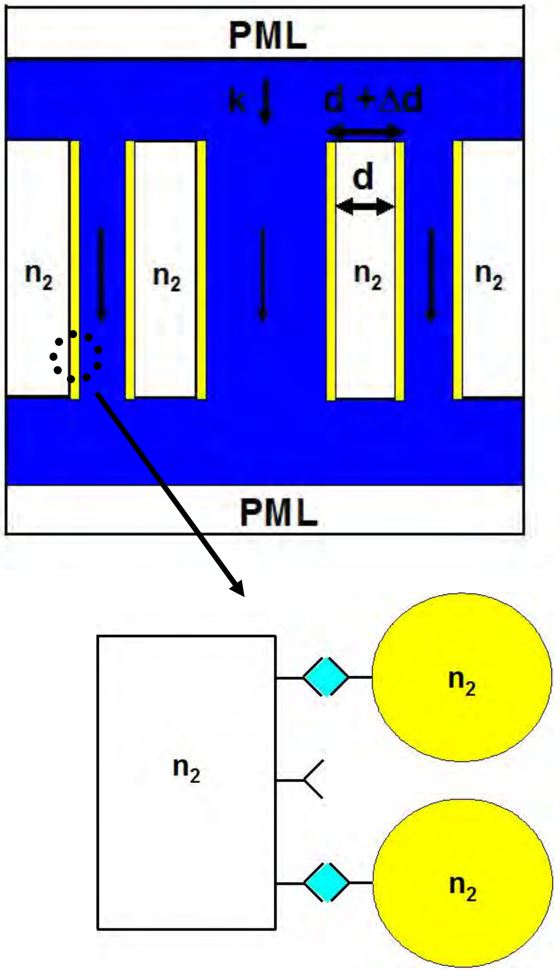
$$\Delta\lambda_2 = 2 n_1 w_s\left[\left(\frac{n_2}{n_1}\right)^2 - 1\right]^{\frac{1}{2}} \qquad (m = 2)$$

Sensitivity – Spectral Shift vs. Biolayer Thickness w_s

$$\Delta\lambda_2 = 2n_1 w_s \left[\left(\frac{n_2}{n_1}\right)^2 - 1\right]^{\frac{1}{2}} \qquad (m = 2)$$



$\Delta d = 2\ w_s$



Conclusions

- **Introduction of a novel Optofluidic Transmission- Mode Biosensor.**
- **Biosensing based on contrast in refractive index between target biomaterial and carrier fluid.**
- **The presence of target biomaterial causes a detectable shift in transmission spectrum of sensor.**
- **Transmission mode operation facilitates array sensing with potential for multiple target antigens detected on a single chip.**
- **Device design and optimization can be completed in a few days using Comsol RF solver,**
- **Sensor architecture holds potential for low cost POS clinical diagnostic applications.**