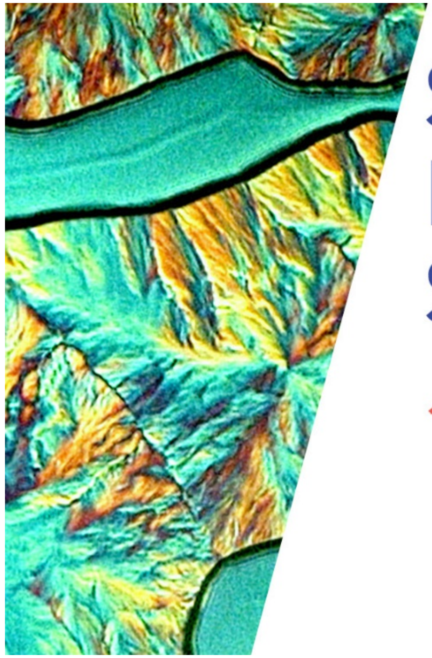
Surface Plasmon Resonance Sensors: Science and Technology

Presented by:

OSA Optical Biosensors Technical Group

The OSA Optical Biosensors (BB) Technical Group Welcomes You!



SURFACE PLASMON RESONANCE SENSORS: SCIENCE & TECHNOLOGY

10 October 2018 • 10:30 EDT

OSA Optical Biosensors Technical Group

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Ben Gurion University of the Negev

Technical Group at a Glance

- **Focus**
  - This group's interests are related to optical technologies for the targeted detection of biological compounds for medical diagnostics, healthcare, environmental and food safety applications.
  - Over 2,000 members within OSA.
- **Mission**
  - Promotion of the developments in the field to the society through webinars, social media, publications, technical and outreach events…
  - Create a platform to enhance the community network.
  - Interested in presenting your research? Have ideas for TG events? Contact: filizyesilkoy@gmail.com
- **Find us here**
  - Website: www.osa.org/OpticalBiosensorsTG
  - LinkedIn: https://www.linkedin.com/groups/8260947/
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Today’s Webinar

Surface Plasmon Resonance Sensors: Science & Technology

Prof. Ibrahim S. Abdulhalim

Head of Applied Nano-Photonics Group

Department of Electro-Optic Engineering

Ben Gurion University of the Negev, Israel

Surface Plasmon Resonance Sensors: Science and Technology

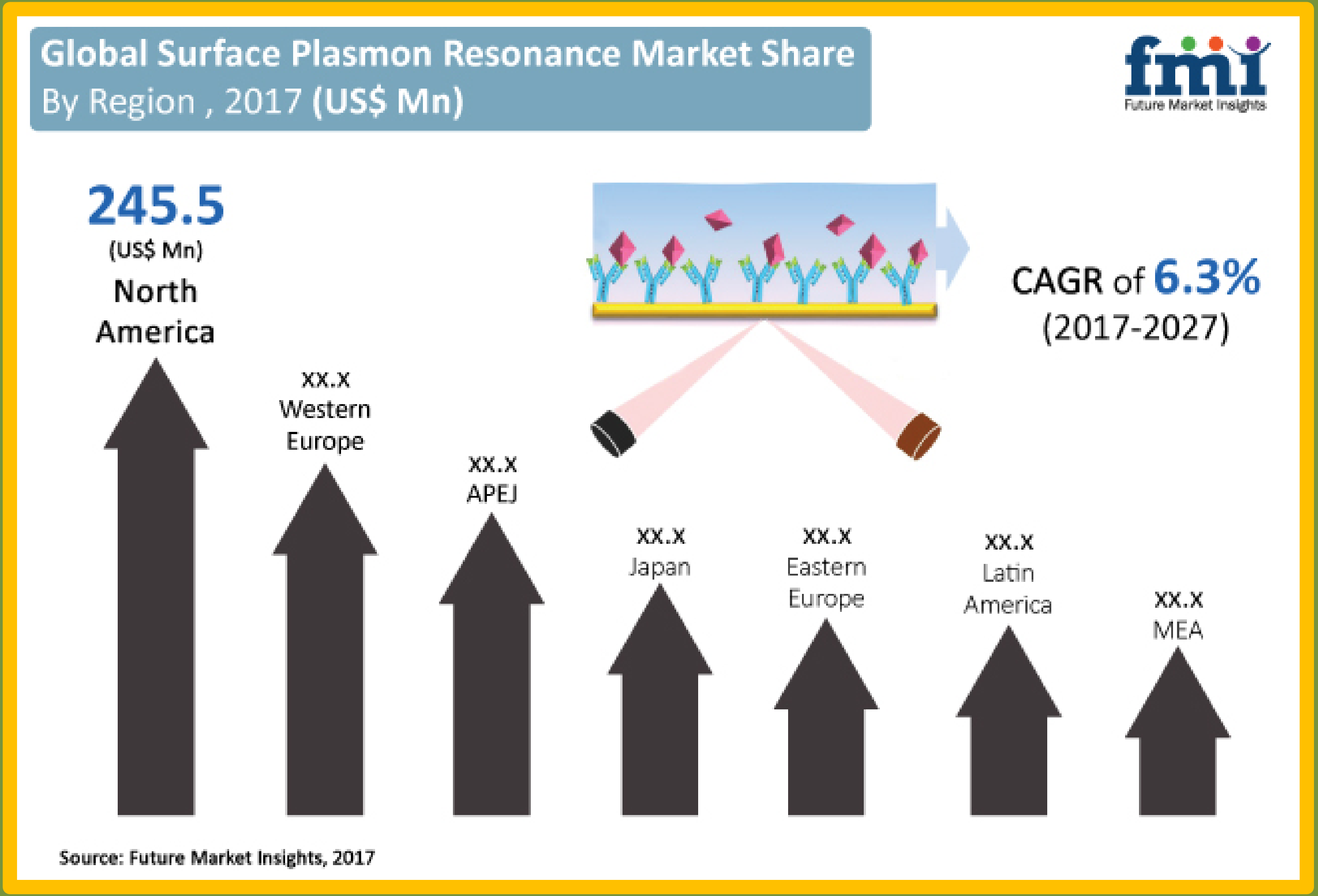
Prof. Ibrahim Abdulhalim

abdulhlm@bgu.ac.il

http://aizena.wix.com/abdulhalim-group

Department of Electro-Optics and Photonics Engineering
Ilse Katz Institute for Nanoscale Science and Technology,
Ben-Gurion University of the Negev, Be’er Sheva, Israel

Motivation
Global SPR Market



https://www.futuremarketinsights.com/reports/surface-plasmon-resonance-spr-systems-market

Motivation
Importance to Human Health

- ❑ Environmental pollutants detection
- ❑ Blood analytes detection
- ❑ Biomarkers identification/detection
- ❑ Drug discovery
- ❑ Food inspection

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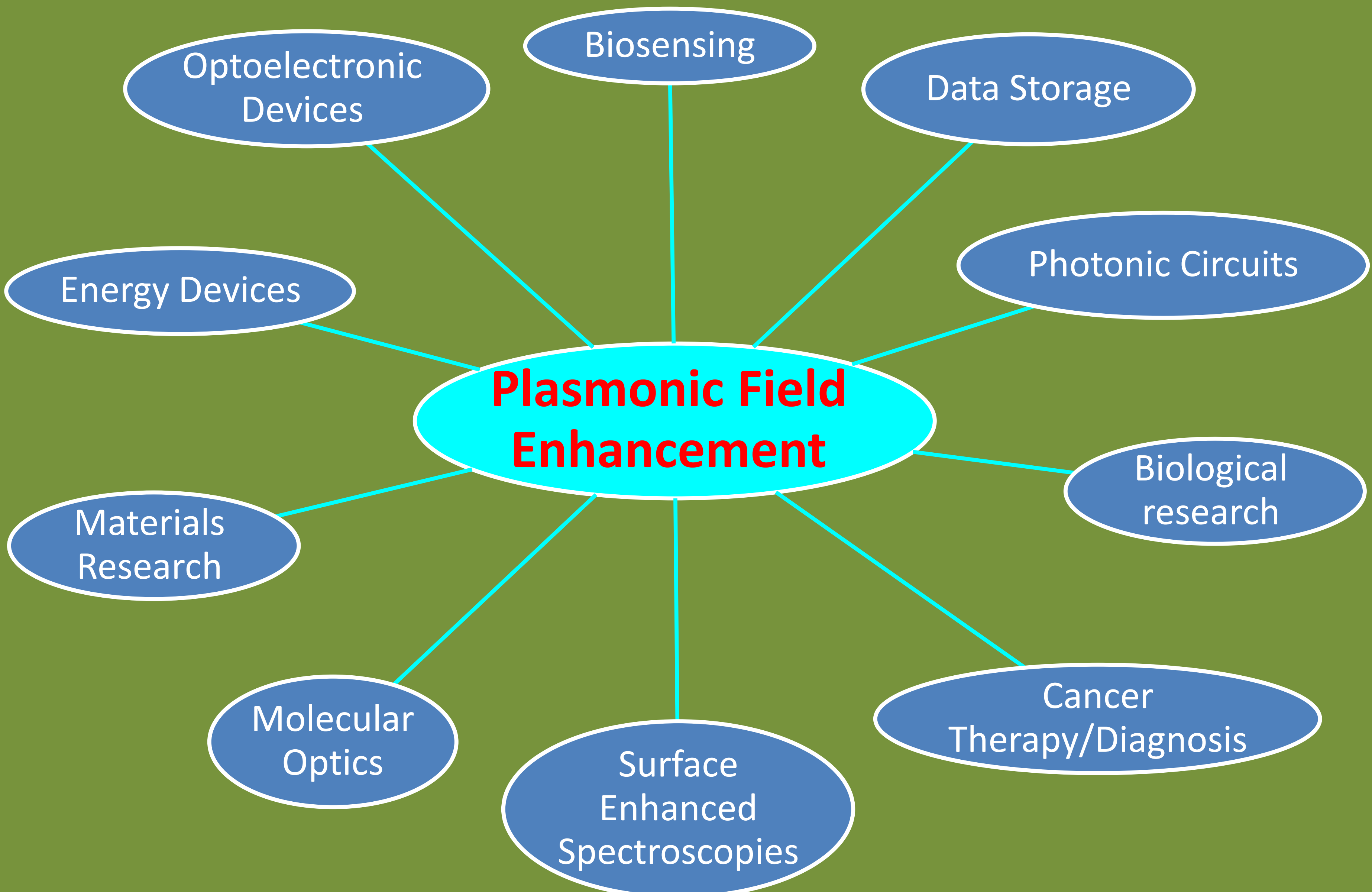
- ❑ .....

Key Points to be Covered

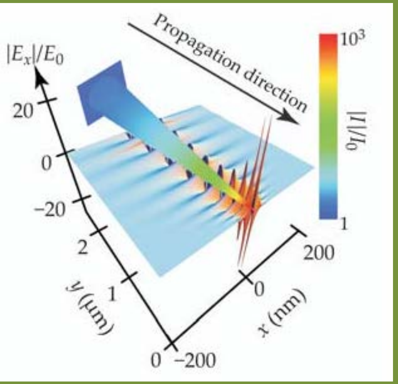
- Motivation ✓
- SPR Sensing:
  - Physics of Plasmonic Sensing
  - Resolution improvement with Optics/Physics
  - Penetration depth enhancement
  - Self referencing
  - Reading Methodologies-System
- Extended versus Localized SPR
- Summary and Future

Plasmonic Field Enhancement is a Key Factor



Factors Influencing Field Enhancement

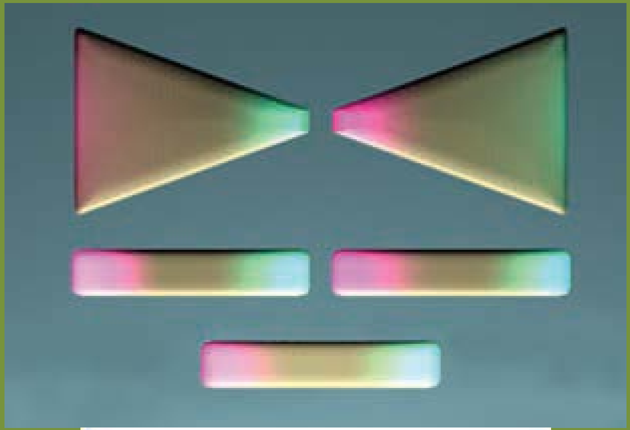
- **Material factor:** $\left(\dfrac{\varepsilon_{mr}}{\varepsilon_{mi}}\right)^2$

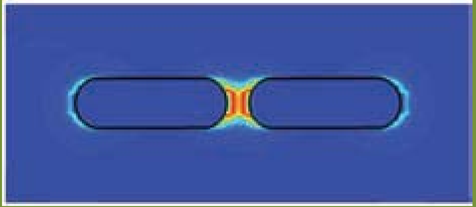


M.I. Stockman., Physics Today 64, 39 (2011)

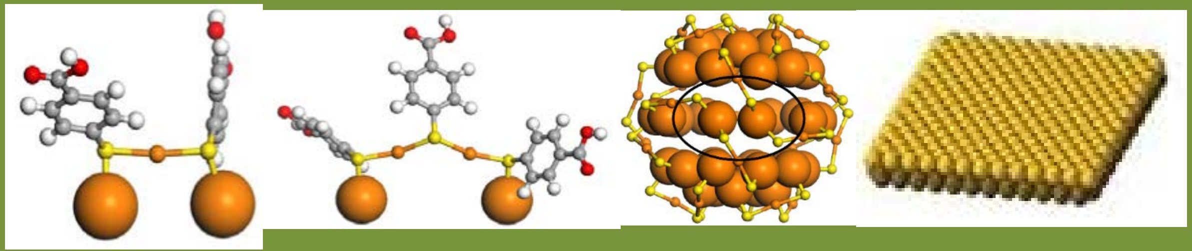
- **Geometry:** $\left(\dfrac{1}{L_j}\right)^2$

- **Interference:**
- **Optical Antenna Effect:**
- **Arrangement of NPs:**



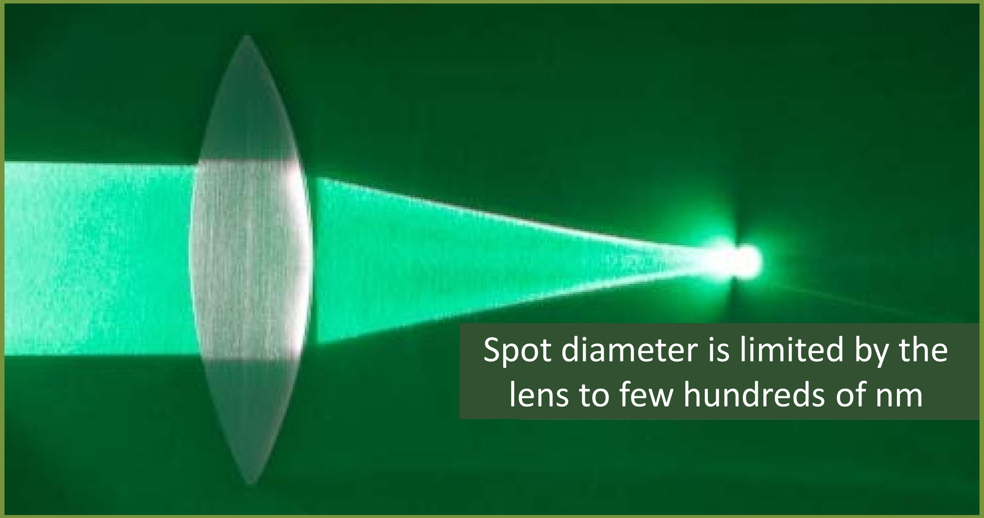


F. Capasso et.al., OPN, May 2009

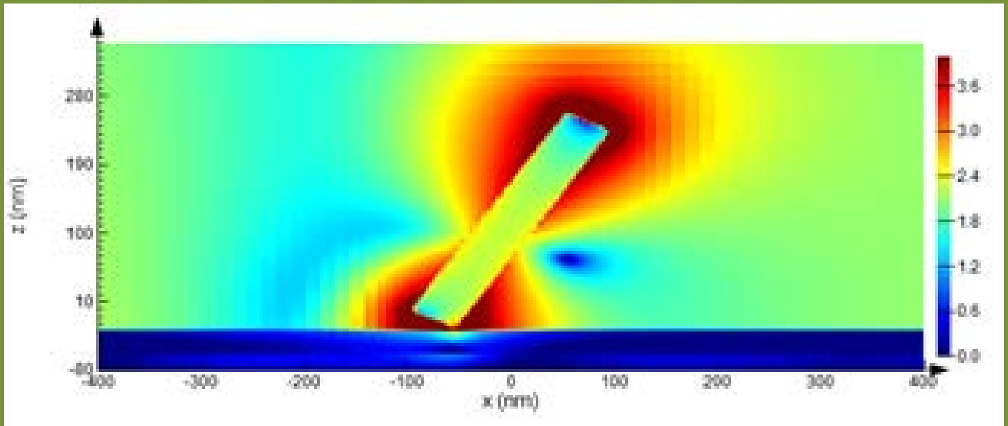


Plasmonics Allow the Nanoscale Enhancement

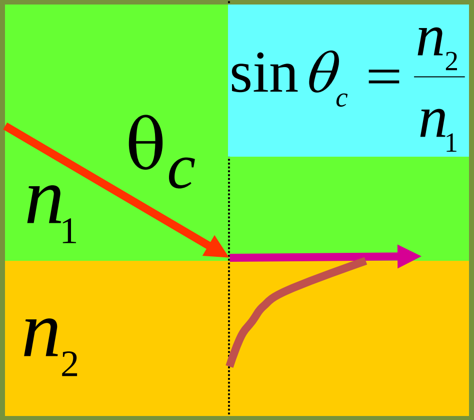
Limitations of Standard Optics



Field Intensity is Enhanced nearly 10 Million Times Near the Tip of a Silver Nanorod on Metal Film



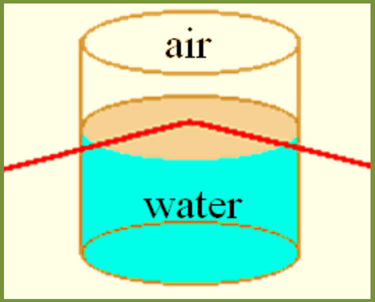
Surface Waves and Sensing

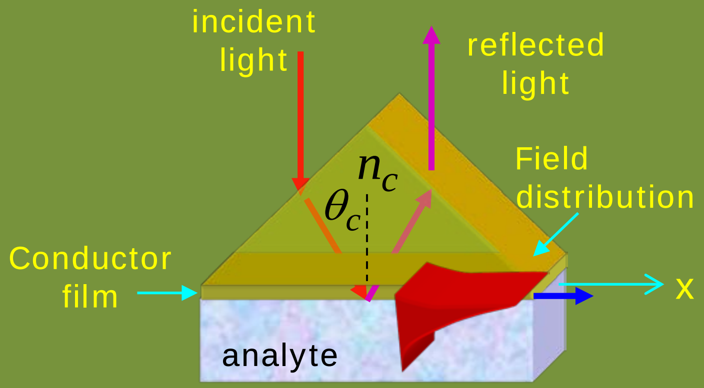


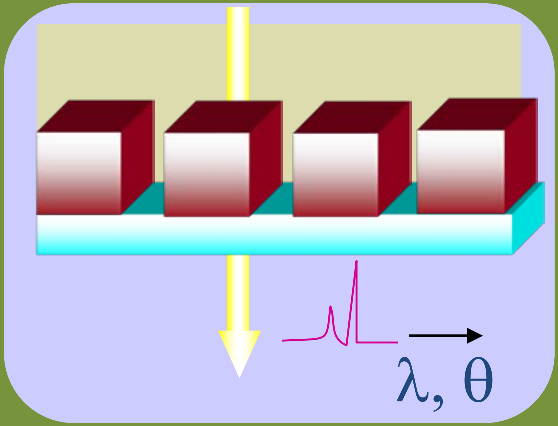
The simplest example:
Total Internal Reflection

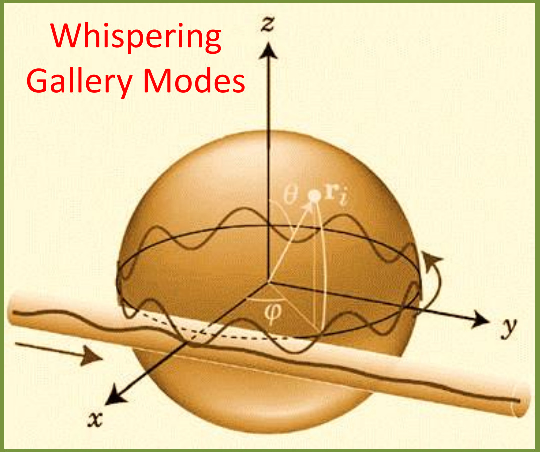
$$E \propto \exp(-z/\delta_e)$$

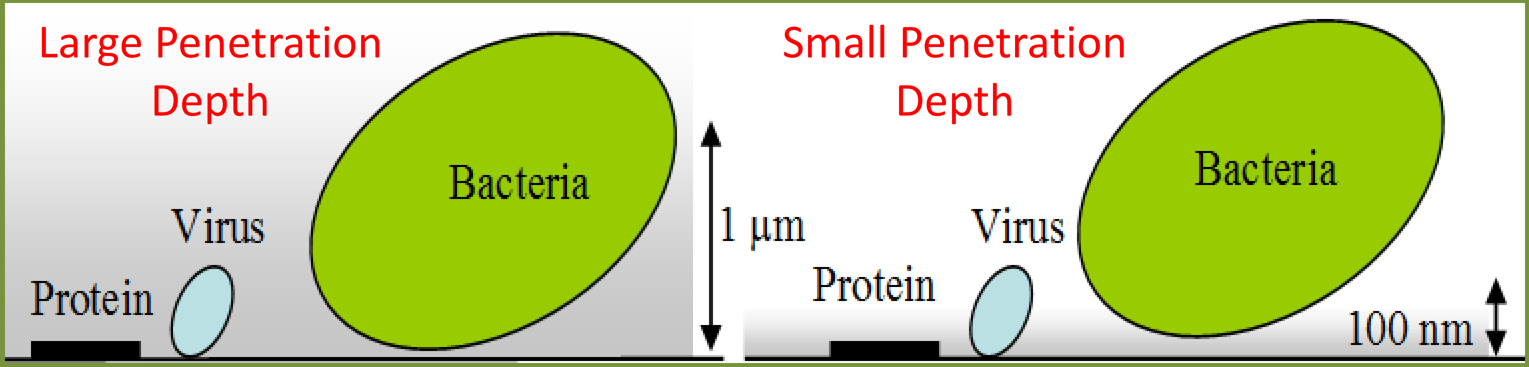
$$\delta_e = \lambda_0 / (2\pi\sqrt{n_1^2 \sin^2\theta_i - n_2^2})$$





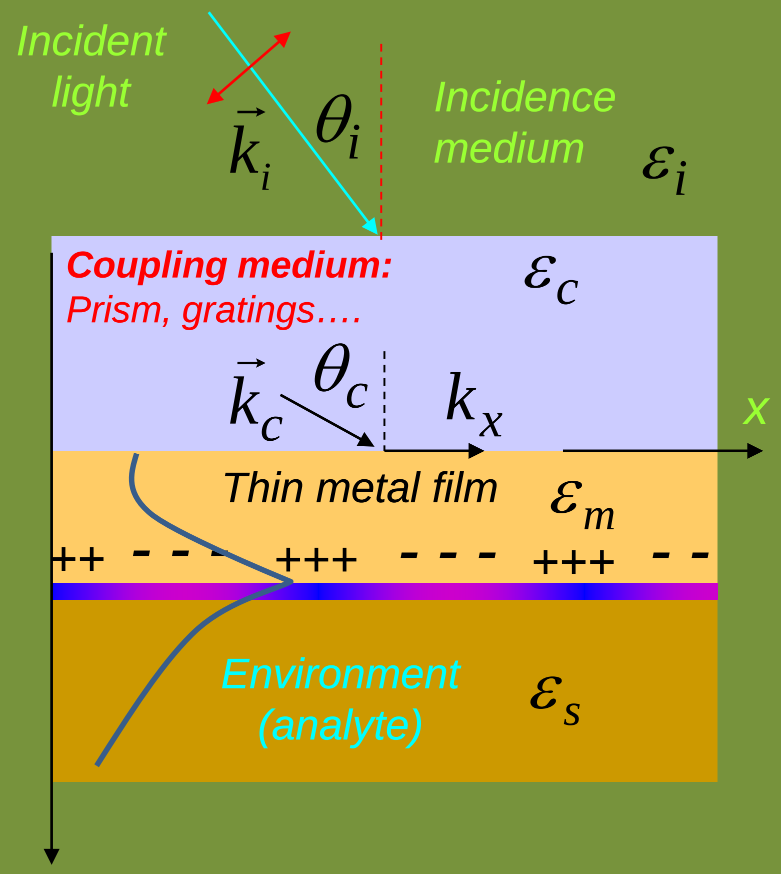






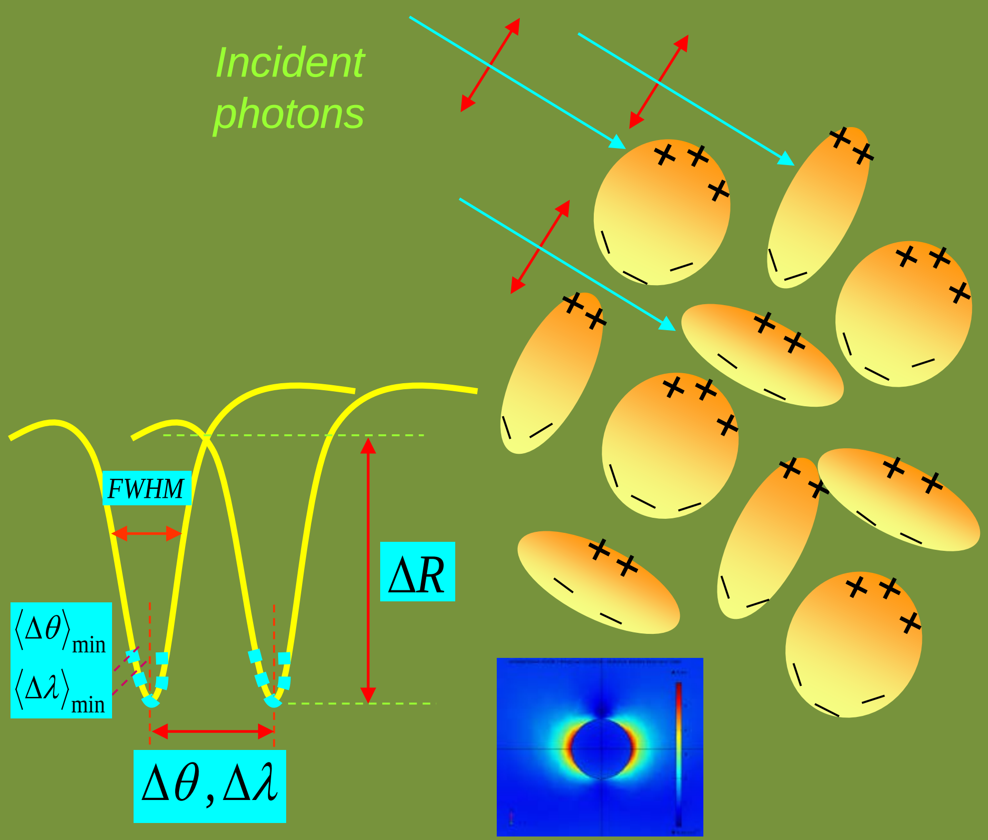
Two Main Types of Plasmonic Waves

Extended SPW



- Field penetrates few hundred nm and more in the analyte!
- Field enhancement at the interface ~x10-20
- Sensitivity ~1000-50000nm/RIU

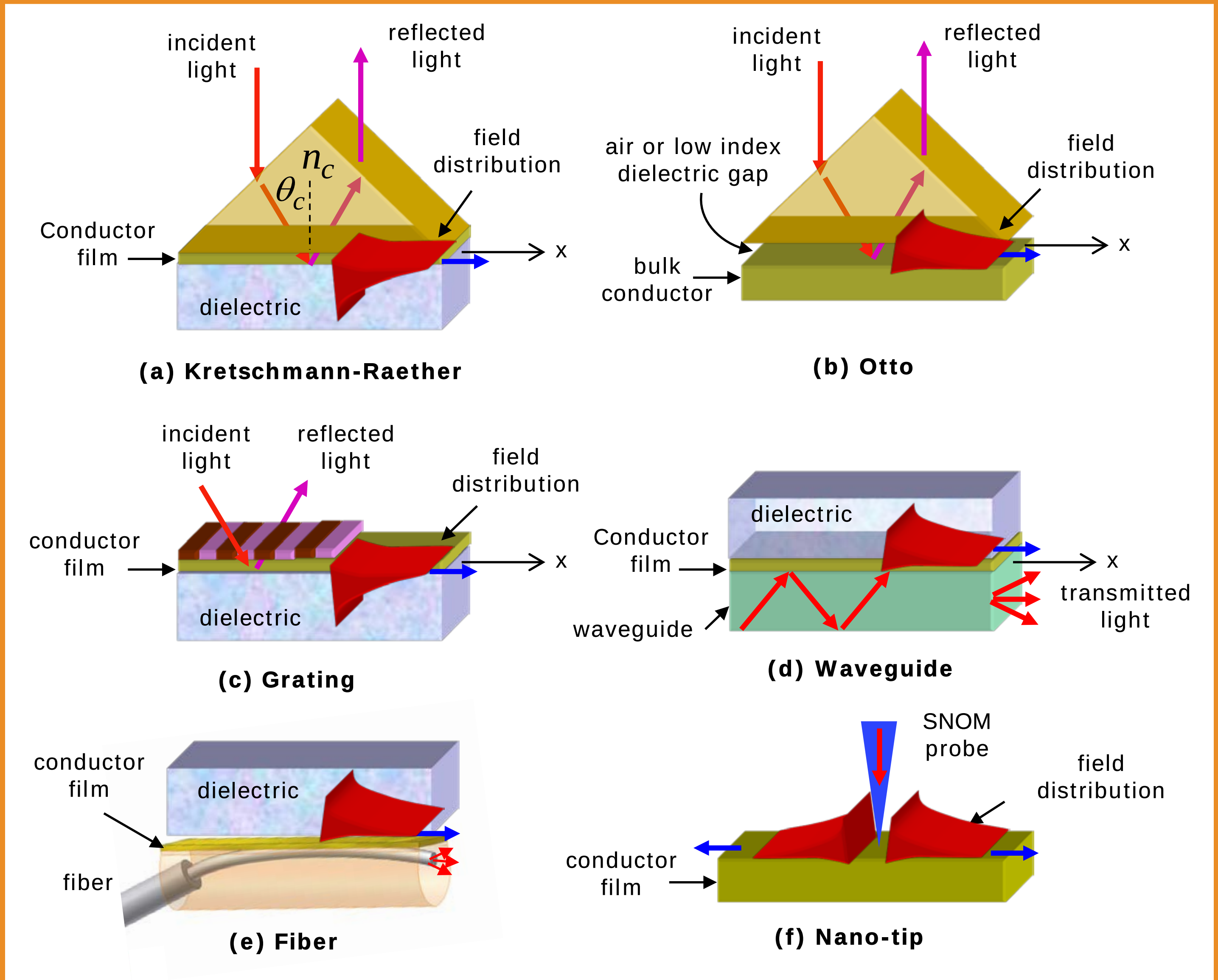
Localized SPW



- Field penetrates few nm in the analyte. Highly localized!
- Field enhancement at the interface is ~x20-100
- Sensitivity ~100-500nm/RIU

Extended Plasmonic Waves

$$k_x = \frac{2\pi}{\lambda} n_c \sin\theta_c \pm \frac{2\pi}{\Lambda} j = \frac{2\pi}{\lambda} \mathrm{Re}\left\{ \left(\frac{n_m^2 n_{a,s}^2}{n_m^2 + n_{a,s}^2} \right)^{1/2} \right\} = \mathrm{Re}\left\{ k_{sp} \right\}$$



Plasmonics is the Science and Technology Dealing with Surface Plasmon Waves

SPW- (Surface Plasmon Wave) : Is a charge density wave occurring at the interface between a metal and a dielectric.

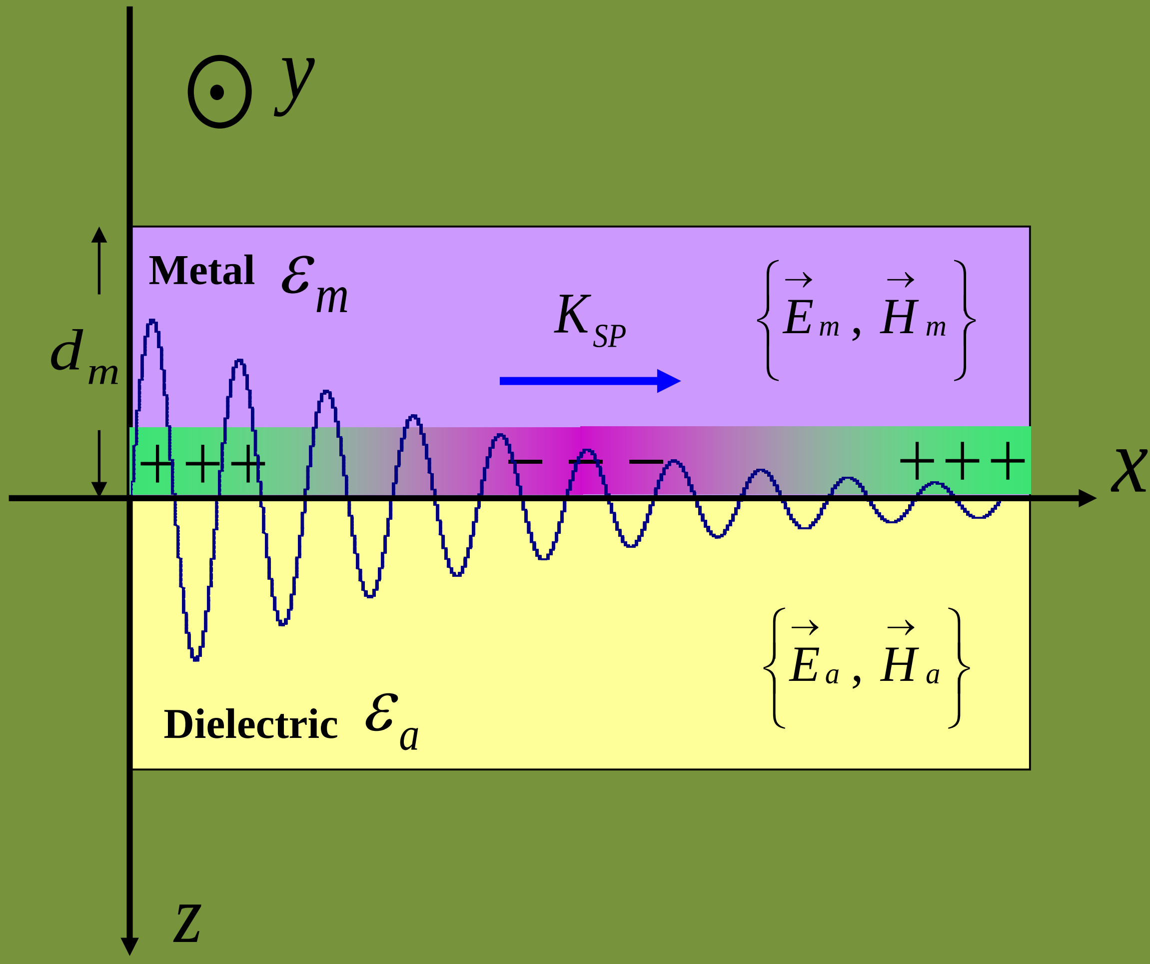
To generate charge density:

$$\vec{H}_i = (0, H_{yi}, 0)$$

$$\vec{E}_i = (E_{xi}, 0, E_{zi})$$

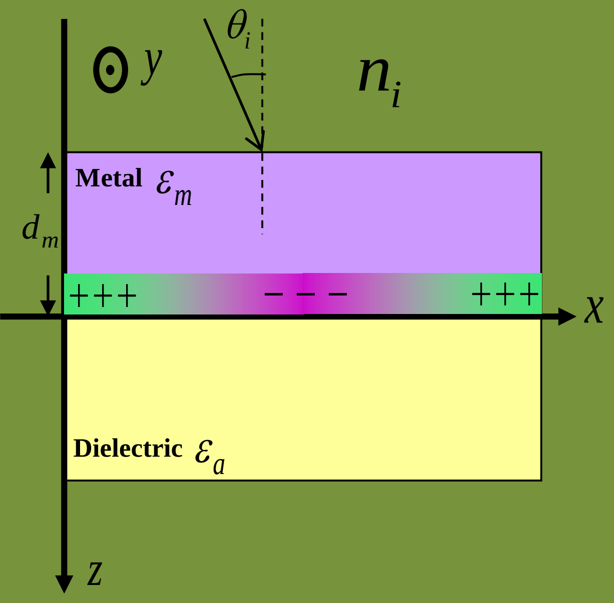
TM polarization only!

1st condition!



Momentum of Propagating SP

Plasmon propagation K vector:



In the infinite metal thickness limit:

$$H_{yi} = H_{0i} \cdot \exp i(k_x x - \omega t) \cdot \exp(ik_i z)$$

$$\textit{medium } i: \quad E_{xi} = \frac{H_{0i}}{\omega\varepsilon_0}\left(\frac{k_i}{\varepsilon_i}\right) \cdot \exp i(k_x x - \omega t) \cdot \exp(ik_i z)$$

$$E_{zi} = \frac{-H_{0i} \cdot k_x}{\omega\varepsilon_0}\left(\frac{1}{\varepsilon_i}\right) \cdot \exp i(k_x x - \omega t) \cdot \exp(ik_i z)$$

Applying the continuity relations of the tangential field's components (E_{xi}, H_{yi}):

$$k_{sp} = k_0 \operatorname{Re}\left\{\sqrt{\frac{\varepsilon_m \varepsilon_a}{\varepsilon_m + \varepsilon_a}}\right\} \Rightarrow k_x = \operatorname{Re}\{k_{sp}\} = k_0 \sqrt{\frac{\varepsilon_{mr}\varepsilon_a}{\varepsilon_{mr} + \varepsilon_a}}$$

2nd condition!

$$k_x = k_0 n_i \sin\theta_i \Rightarrow \sin\theta_{spr} = \frac{1}{n_i}\sqrt{\frac{\varepsilon_{mr}\varepsilon_a}{\varepsilon_{mr} + \varepsilon_a}}$$

Since $\varepsilon_{mr} < 0$ hen the

3rd condition! is: $|\varepsilon_{mr}| > \varepsilon_a$

Two Important Parameters

Penetration Depths

$$\delta_m = \frac{\lambda}{2\pi} \cdot \sqrt{\frac{\varepsilon_a + \varepsilon_{mr}}{-\varepsilon_{mr}^2}}$$

$$\delta_d = \frac{\lambda}{2\pi} \cdot \sqrt{\frac{\varepsilon_a + \varepsilon_{mr}}{-\varepsilon_a^2}}$$

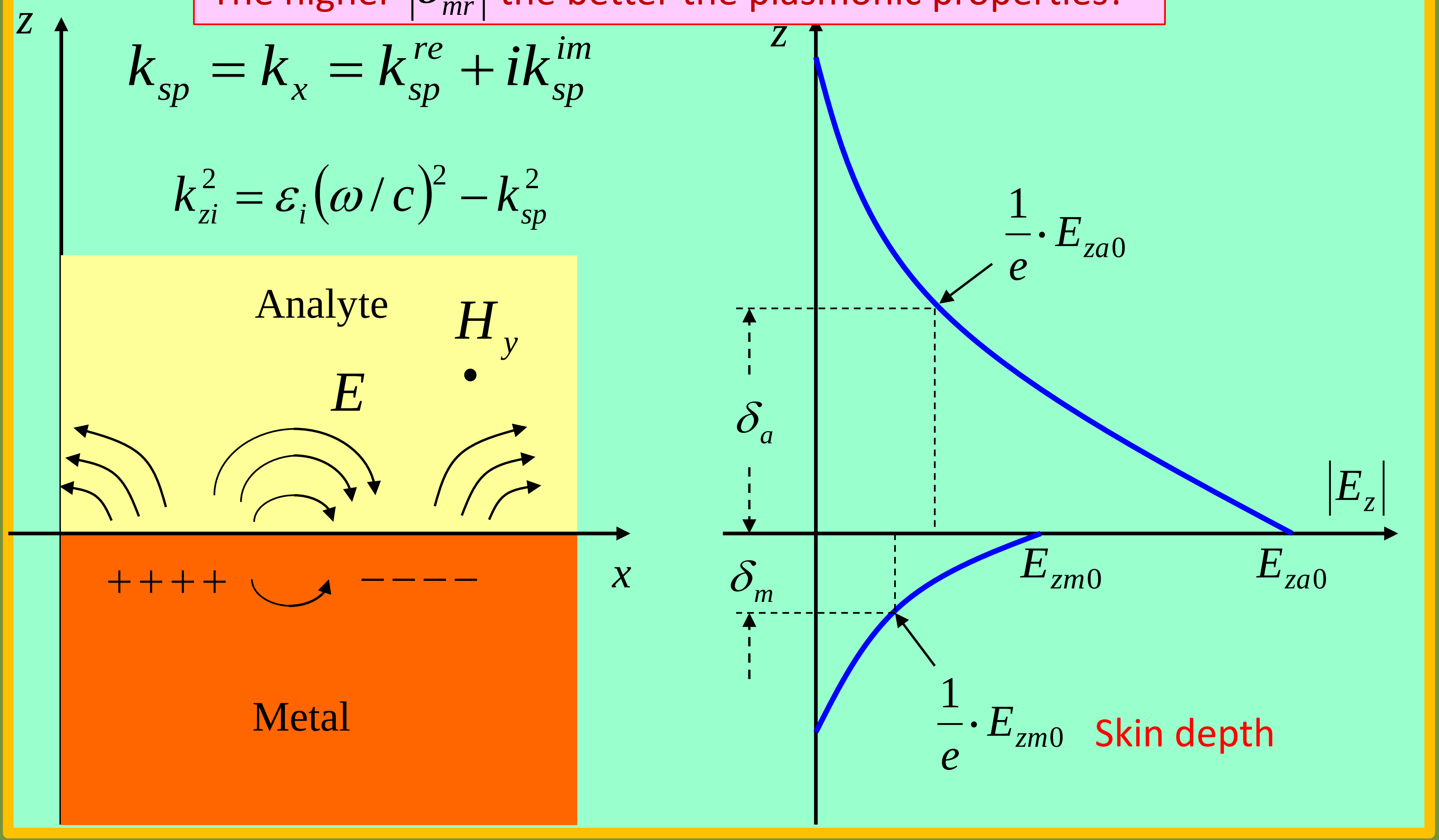
Propagation Length

$$L_x = \frac{1}{2\left|k_x''\right|} = \frac{\lambda}{2\pi} \frac{\varepsilon_{mr}^2}{\varepsilon_{mi}} \left[\frac{\varepsilon_a + \varepsilon_{mr}}{\varepsilon_a \varepsilon_{mr}}\right]^{3/2}$$

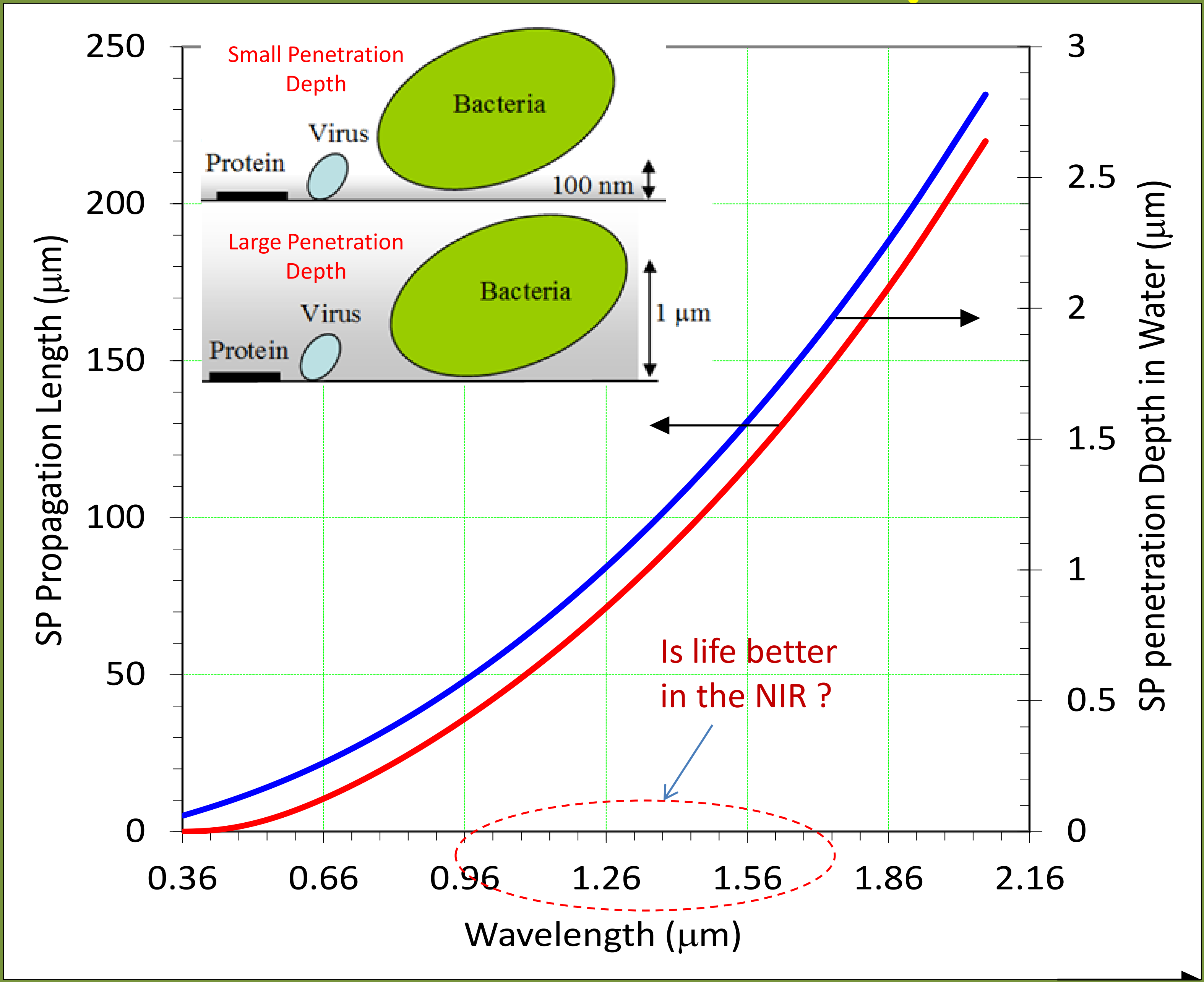
The higher $\left|\varepsilon_{mr}\right|$ the better the plasmonic properties!

$$k_{sp} = k_x = k_{sp}^{re} + ik_{sp}^{im}$$

$$k_{zi}^2 = \varepsilon_i (\omega / c)^2 - k_{sp}^2$$



Silver as an Example

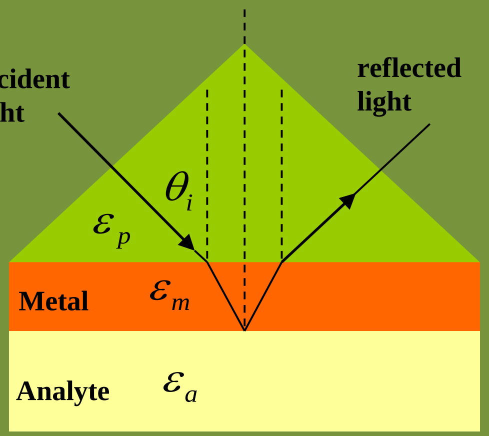


Exciting SPR- Prism Coupling

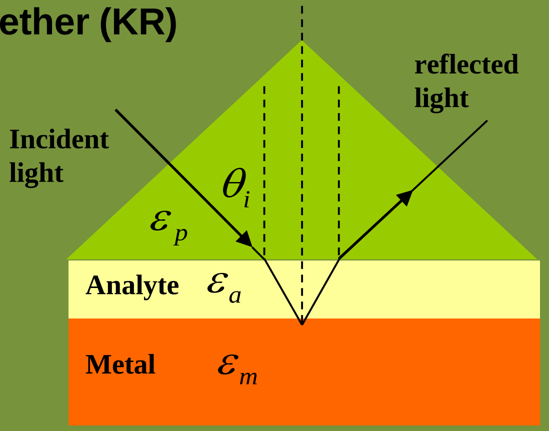
Introducing the Drude model for the metal permittivity gives the dispersion relation of the SP:

$$\varepsilon_m = 1 - \frac{\omega_p^{\;2}}{\omega(\omega + i\eta)} \Rightarrow k_{spr} = k_0 \sqrt{\frac{\varepsilon_{mr}\varepsilon_a}{\varepsilon_{mr} + \varepsilon_a}}$$

4th condition! $n_p \sin\theta_i > 1$ TIR

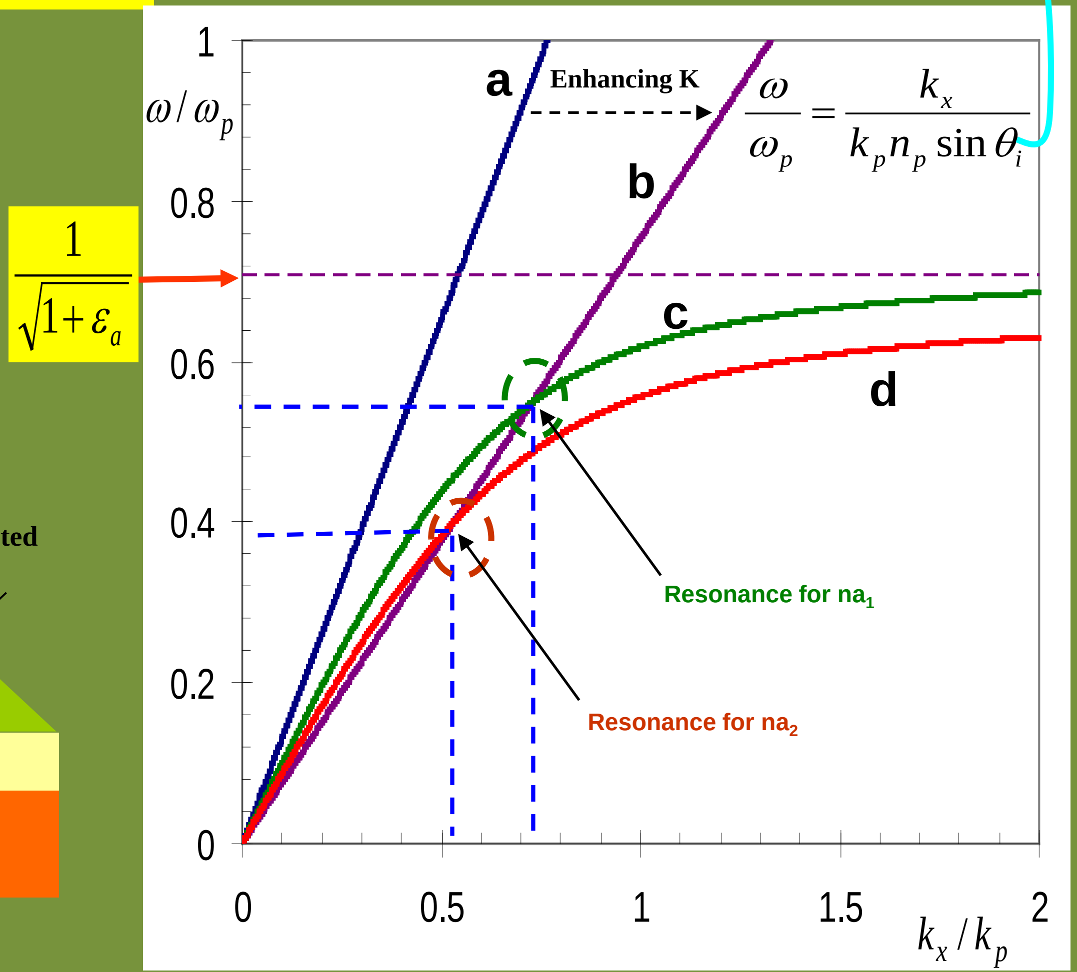


Kretschmann-Raether (KR)

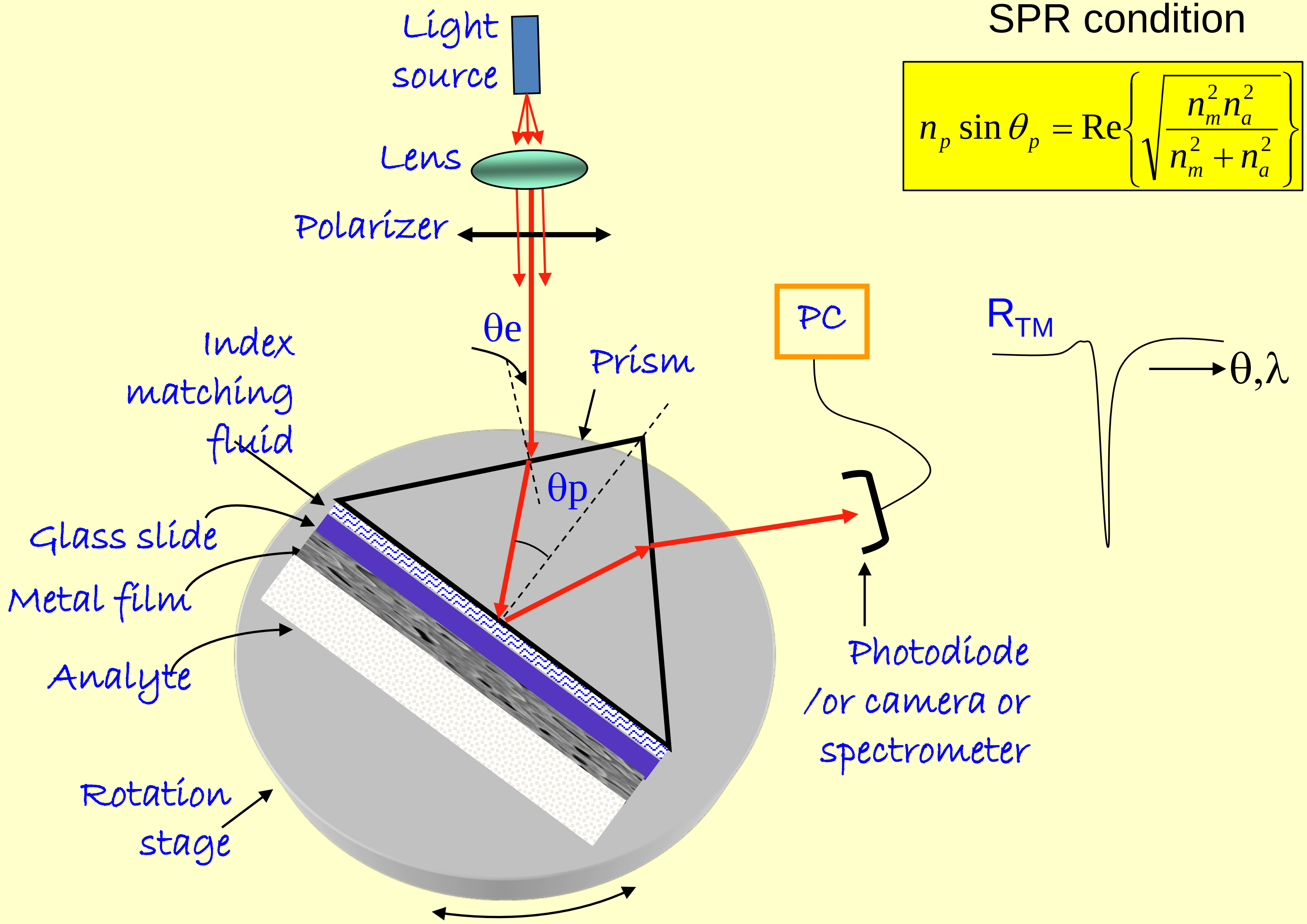


Otto

Dispersion relation of SP



Prism Coupling-General Setup

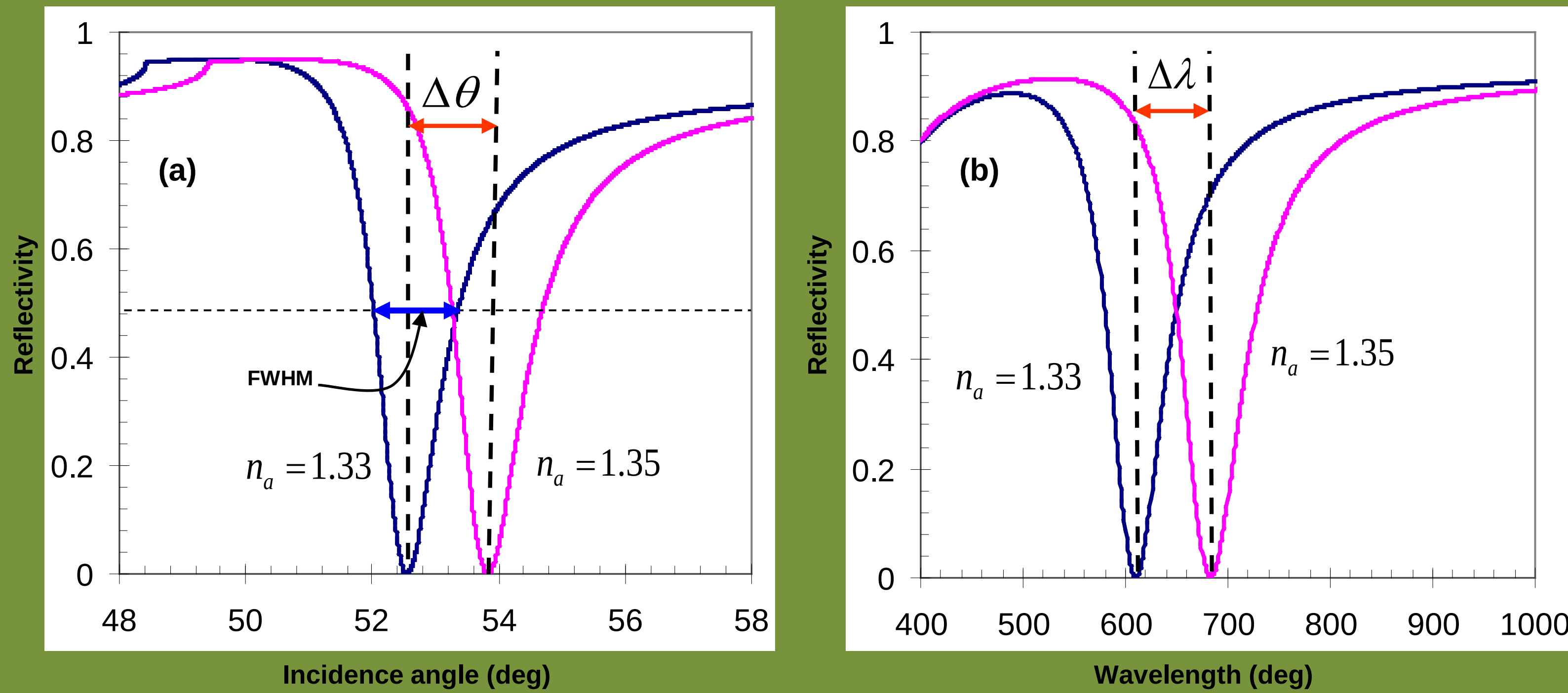


SPR condition

$$n_p \sin\theta_p = \mathrm{Re}\left\{\sqrt{\frac{n_m^2 n_a^2}{n_m^2 + n_a^2}}\right\}$$

Angular and Spectral Modes for Sensing

Sensing in the KR configuration



$$S_\theta = \frac{\partial \theta_{dip}}{\partial n_a} = \frac{\varepsilon_{mr}\sqrt{-\varepsilon_{mr}}}{(\varepsilon_{mr}+n_a^2)\sqrt{\varepsilon_{mr}(n_a^2-n_p^2)-n_p^2 n_a^2}}$$

$$FOM \equiv \frac{S_{\theta,\lambda}}{FWHM}$$

- Angular Sensitivity: ~100-200 deg/RIU

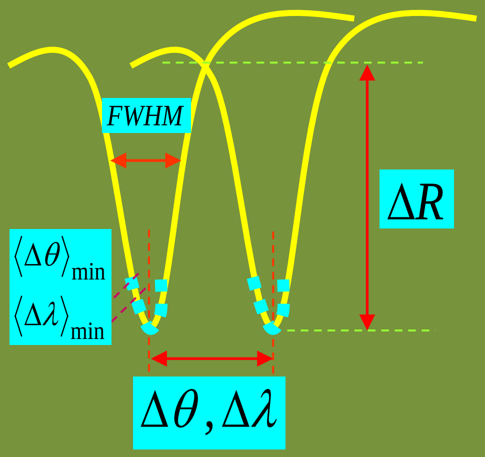
$$S_\lambda = \frac{\partial \lambda}{\partial n_a} = \frac{\varepsilon_{mr}^2}{\frac{n_a^3}{\lambda}\left|\frac{d\varepsilon_{mr}}{d\lambda}\right| + (n_a^2+\varepsilon_{mr})\varepsilon_{mr}\frac{dn_p}{d\lambda}\frac{n_a}{n_p}}$$

- Spectral sensitivity: ~1000-30000nm/RIU

→ $\delta n \sim 10^{-7}$ RIU ($1 pg/mm^2$)

Sensitivity and Detection Limit (Resolution)

$$S_\theta = \frac{\Delta\theta}{\Delta n}, \quad S_\lambda = \frac{\Delta\lambda}{\Delta n}, \quad S_R = \frac{\Delta R}{\Delta n}$$



$$DL_\theta = \langle \Delta n \rangle_{\min} = \frac{\langle \Delta\theta \rangle_{\min}}{S_\theta}$$

$$DL_\lambda = \langle \Delta n \rangle_{\min} = \frac{\langle \Delta\lambda \rangle_{\min}}{S_\lambda}$$

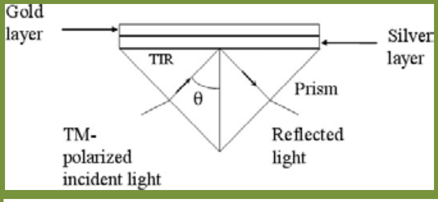
$$DL_R = \langle \Delta n \rangle_{\min} = \frac{\langle \Delta R \rangle_{\min}}{S_R}$$

$$FoM = \frac{S_{\lambda,\theta,R}}{FWHM}$$

$S_\theta, \; S_\lambda$ → **Physics / Optics / Materials**

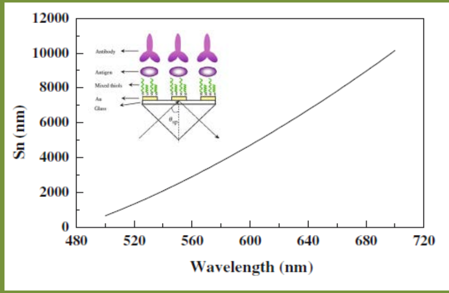
$\langle \Delta\theta \rangle_{\min}, \langle \Delta\lambda \rangle_{\min}$ → **System**

Existing Methods for Sensitivity Enhancement of SPR Sensors



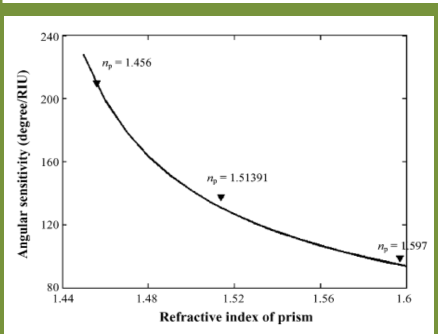
Double-metal layer

J. Opt. A: Pure Appl. Opt. **8** (2006) 959–963



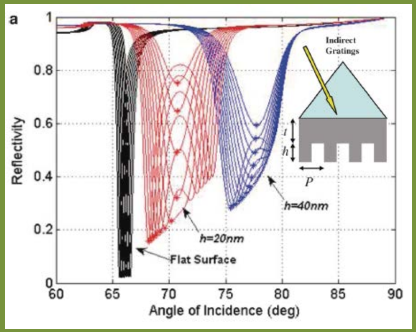
Prism RI- Spectral

J. S. Yuk, et al. Eur. Biophys. J 35, 469–476 (2006).



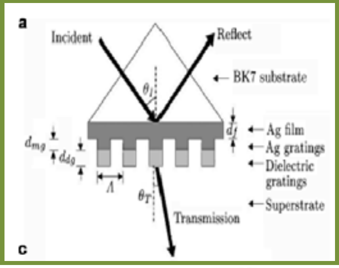
Prism RI- Angular

G. Gupta, and J.Kondoh, Sens. Actuators B, 122, 381–388 (2007).



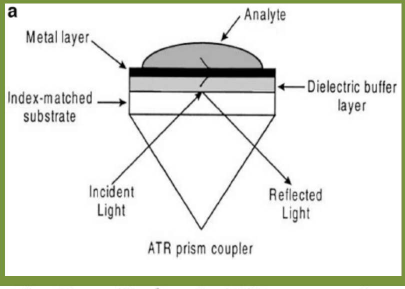
Gratings (Reflection)

C. J. Alleyne et. al., Opt. Express 15, 8163–8169 (2007).



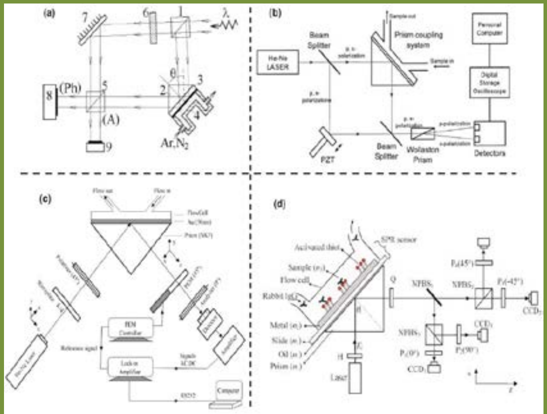
Gratings (Transmission)

W. Bin, and W. Q. Kang, Chin. Phys. Lett. 25, 1668–1671 (2008).



Long Range SPR

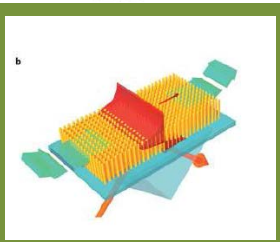
G. G. Nenninger, P. Tobiˇska, J. Homola, and S. S. Yee, Sens. Actuators B 74, 145–151 (2001).



Phase sensitive SPR

A.V. Kabashin, and P. I. Nikitin, Opt. Commun. 150, 5–8 (1998).

S.Y. Wu, H. P. Ho, W. C. Law, C. Lin, and S. K. Kong, Opt. Lett. 29, 2378–2380 (2004).



Metamaterials

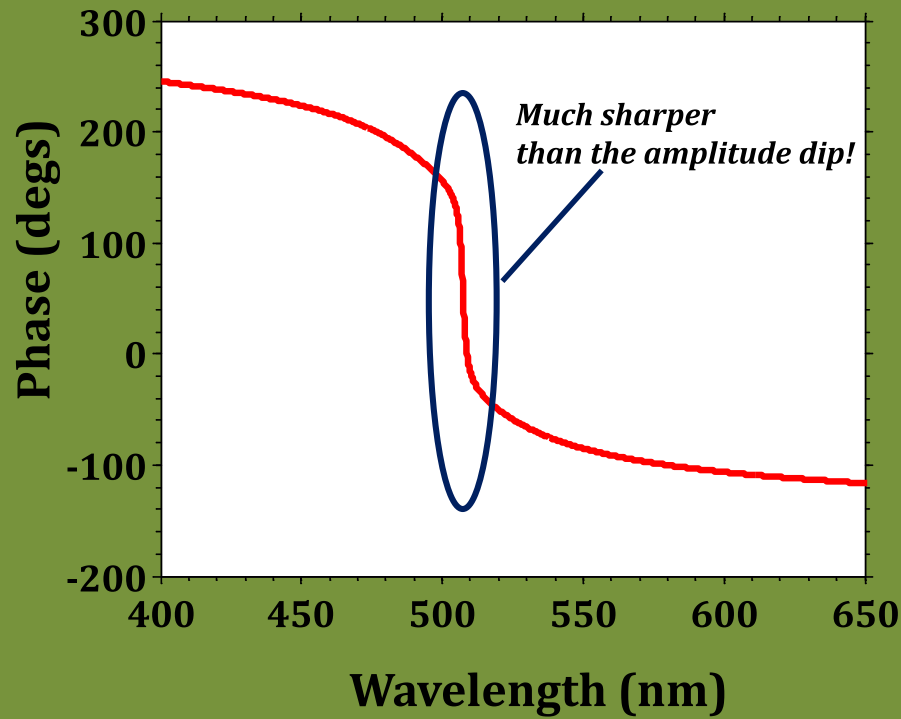
A.V. Kabashin, et al., Nature Mater. 8, 867–71 (2009).

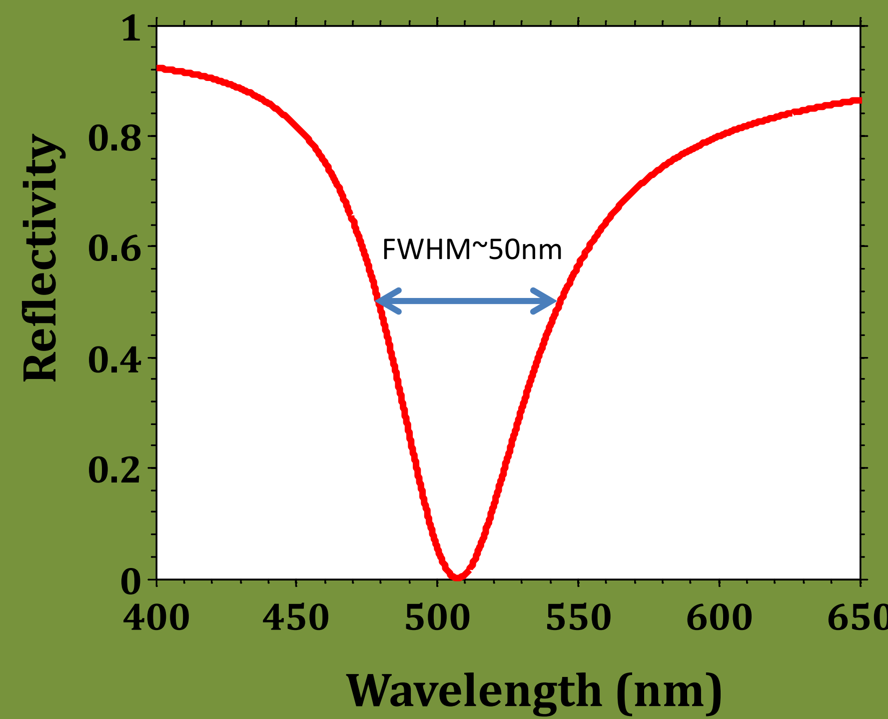
Phase SPR (Polarimetric, Ellipsometric)

$$r_{TM,TE} = |r_{TM,TE}| \exp(i\varphi_{TM,TE})$$

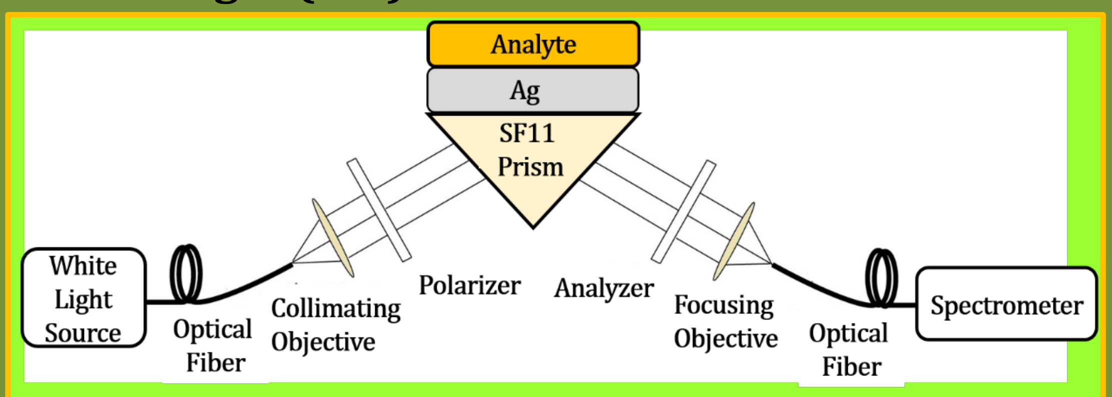
Amplitude Phase

$$\tan\psi = \left|\frac{r_{TM}}{r_{TE}}\right| \qquad \Delta = \varphi_{TM} - \varphi_{TE}$$





Ibrahim Watad et.al., Spectropolarimetric Surface Plasmon Resonance Sensor and the Selection of the Best Polarimetric Function, IEEE J. Selected Topics in Quantum Electronics, 23, 4600609 (2017). DOI: 10.1109/JSTQE.2016.2575543

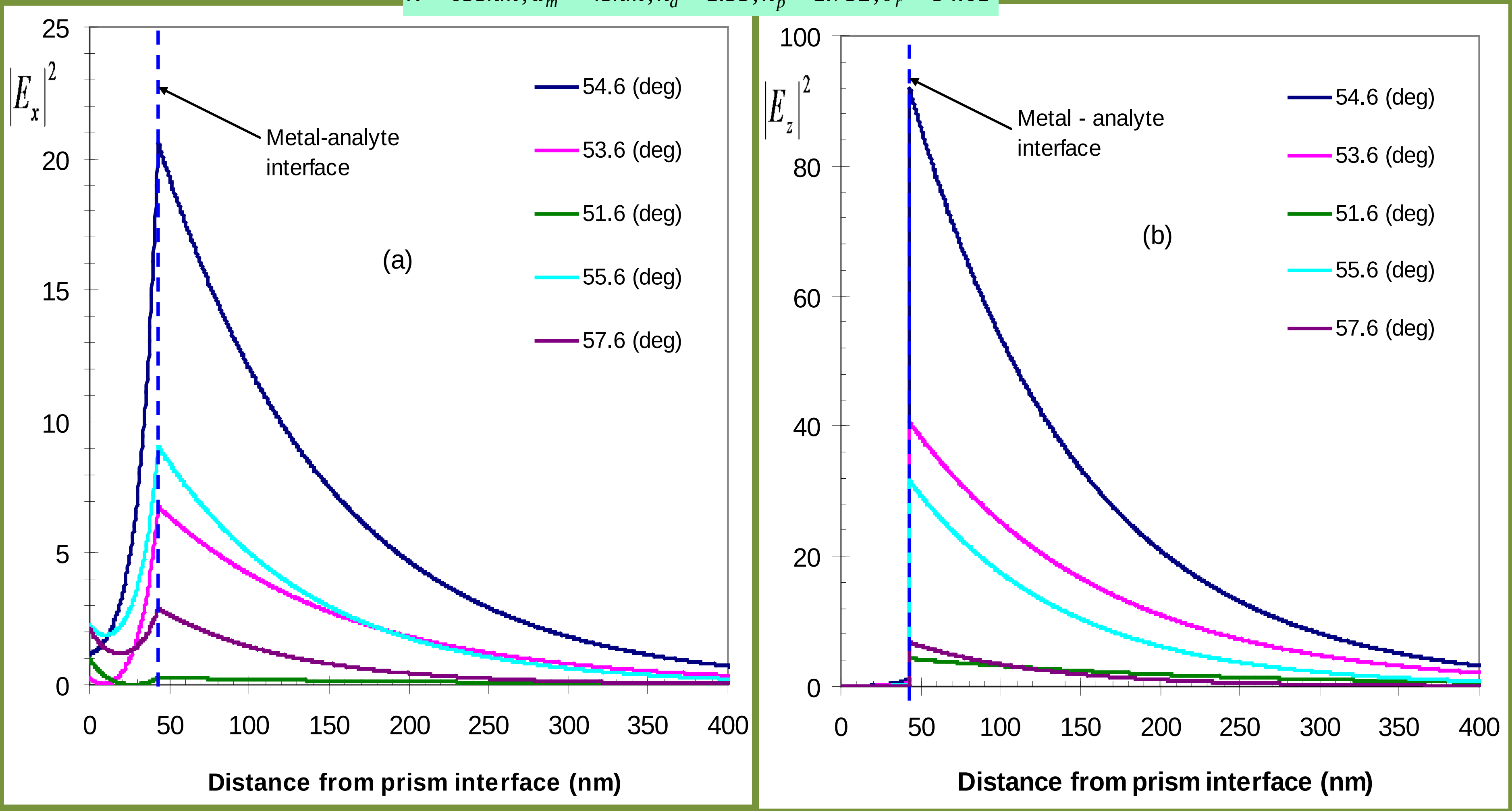


$$\tan\psi = \sqrt{\frac{I_{45}}{I_{\parallel} + I_{\perp} - I_{45}}}$$

$$\cos\Delta = \frac{1}{2\tan\psi}\,\frac{I_{\parallel} - I_{\perp}}{I_{\parallel} + I_{\perp} - I_{45}}$$

EM Field Enhancement at the Resonance

$\lambda = 633nm, d_m = 43nm, n_a = 1.33, n_p = 1.732, \theta_r = 54.61^\circ$



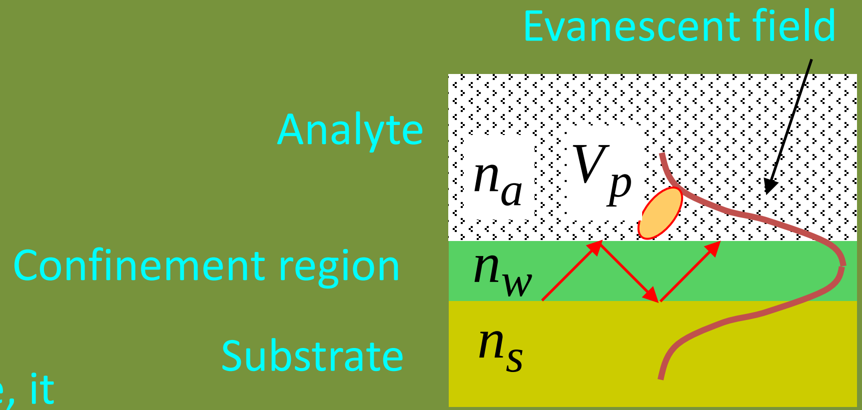
Transfer matrix calculation:

$$\begin{bmatrix} H_{yj}(z) \\ -E_{xj}(z) \end{bmatrix} = P_j(z) \cdot \left(\prod_{l=j-1}^{1} P_l \right) \cdot \begin{bmatrix} (1+r) \\ q_1(1-r) \end{bmatrix} \qquad , Z_j \le z \le Z_{j+1}$$

A. Shalabney and I. Abdulhalim, Sensors and Actuators A, 159, 24-32 (2010).

Evanescent Field Sensing

$$\varepsilon = \begin{cases} n_w^2 & r \in V_w \\ n_{a,s}^2 & r \notin V_w \end{cases}$$



Assuming a particle is added to the analyte, it creates a variation in the dielectric function:

$$\delta\varepsilon = \begin{cases} n_p^2 - n_a^2 & r \in V_p \\ 0 & otherwise \end{cases}$$

The wave vector will change by: $\delta k = k_f - k_i$ and the field from: E_i to E_f

Evanescent Field Sensing

Wave equation before the perturbation:

$$\nabla x \nabla x E_i = k_i^2 \varepsilon E_i$$

The wave equation after the particle is added:

$$\nabla x \nabla x E_f = k_f^2 (\varepsilon + \delta\varepsilon) E_f$$

Multiplying by E_i^* and integrating over the entire volume and subtracting yields:

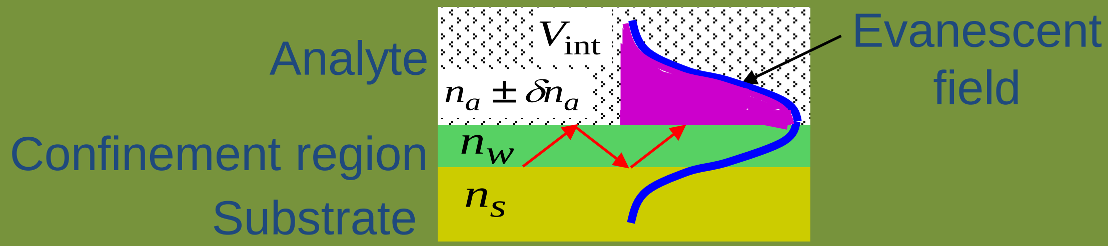
$$(k_i^2 - k_f^2) \int_V E_f . \varepsilon E_i^* dr = k_f^2 \int_{V_{\text{int}}} E_i^* . \delta\varepsilon E_f dr$$

➡ Up to the first order in δk

$$\delta k \approx -\frac{k_i}{2} \frac{\int_{V_{\text{int}}} \delta\varepsilon E_i^* . E_f dr}{\int_V \varepsilon E_i^* . E_i dr}$$

The shift in the wave vector is equal to the overlap integral normalized by the mode energy integral. ➡ Sensing in the evanescence region!

Correlation Between EM Intensity and Sensitivity Enhancement



$$\frac{\delta k}{k_i} = \frac{\delta n_{eff}}{n} = \frac{\delta \lambda}{\lambda} \approx -\frac{1}{2} \frac{\int_{V_{int}} \delta \varepsilon E_i^* . E_f \, dr}{\int_V \varepsilon E_i^* . E_i \, dr}$$

A. Shalabney and I. Abdulhalim, Sensors and Actuators A:physical, 159 (2010) 24-32

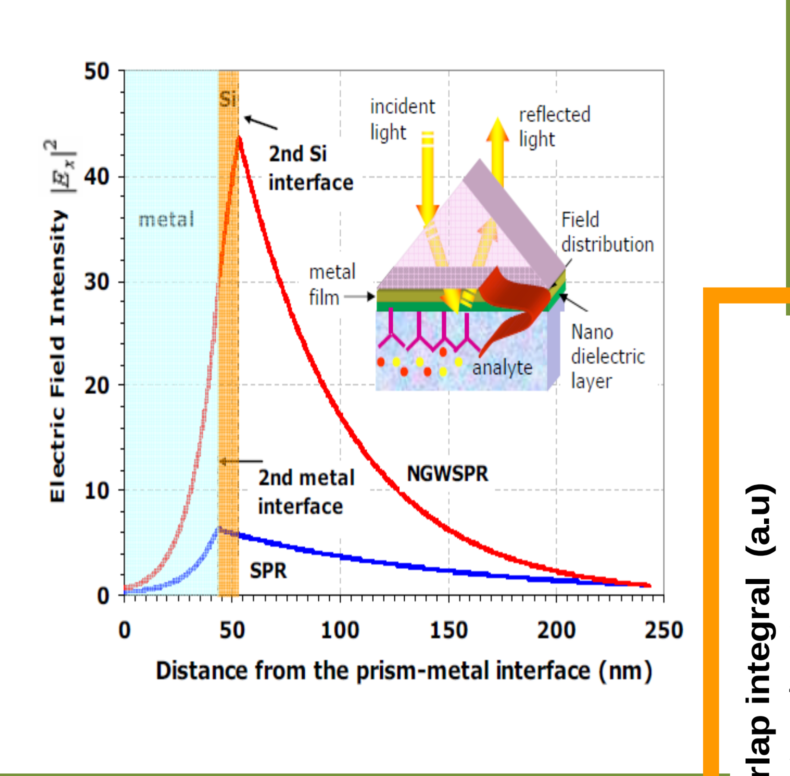
Field Strength

Sensors geometry, nano-structures, localization, band gaps, material parameters

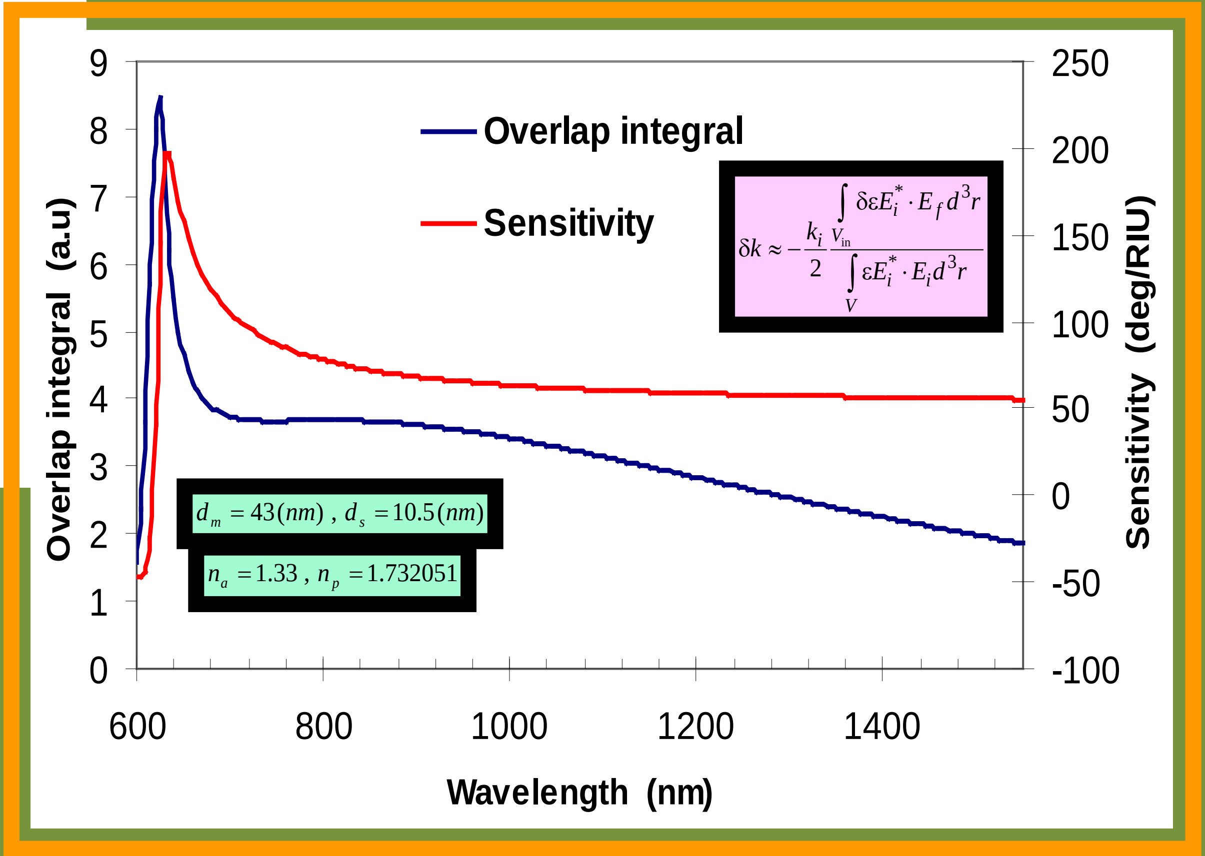
Interaction volume

Evanescence region, lateral propagation length, porosity

Correlation Between EM Intensity and Sensitivity Enhancement

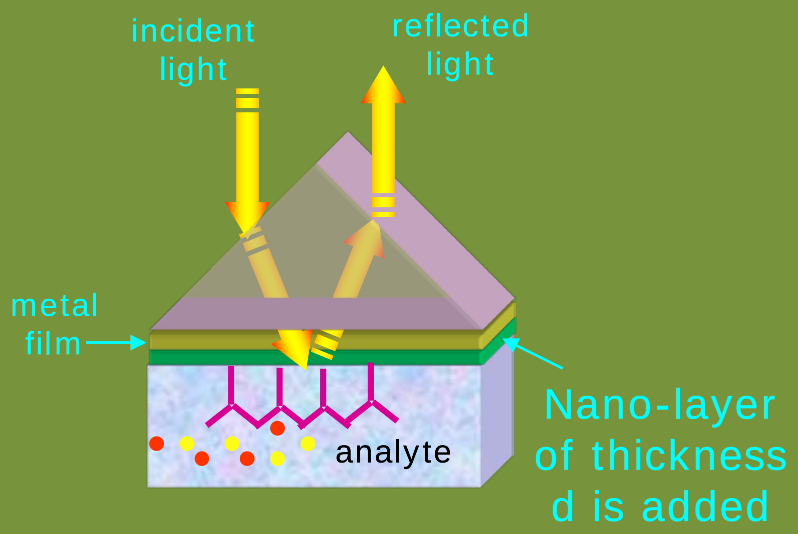


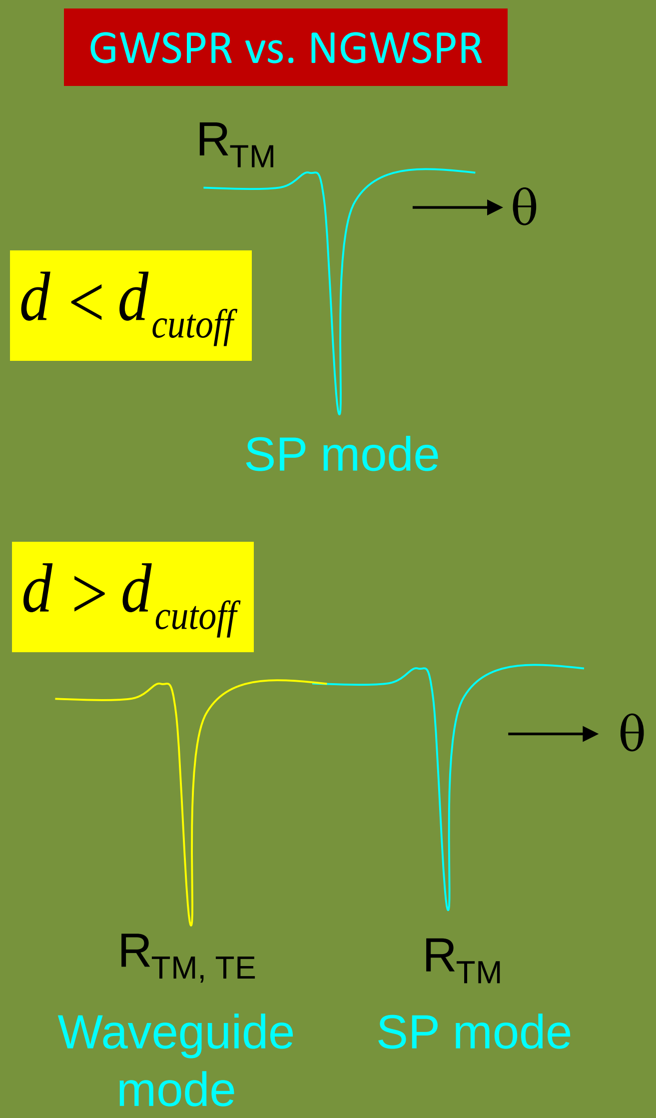
Case of adding nano-overlayer with high refractive index on top of the metal layer!



A. Shalabney and I. Abdulhalim, Sensors and Actuators A:physical, 159 (2010) 24-32

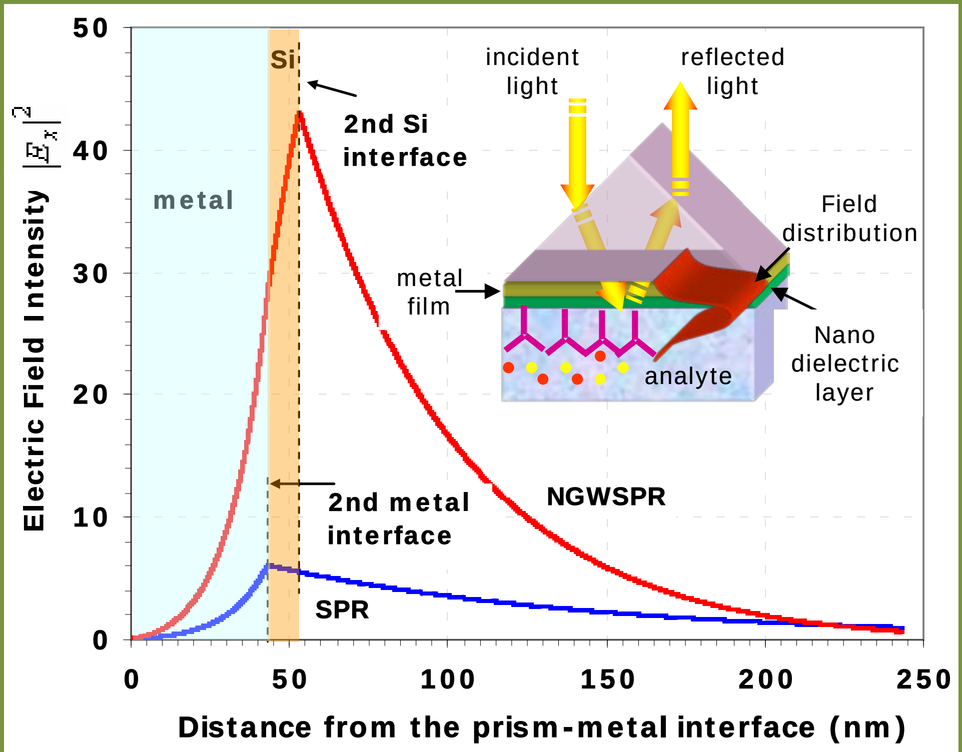
1st case: Adding top nano-dielectric Layer

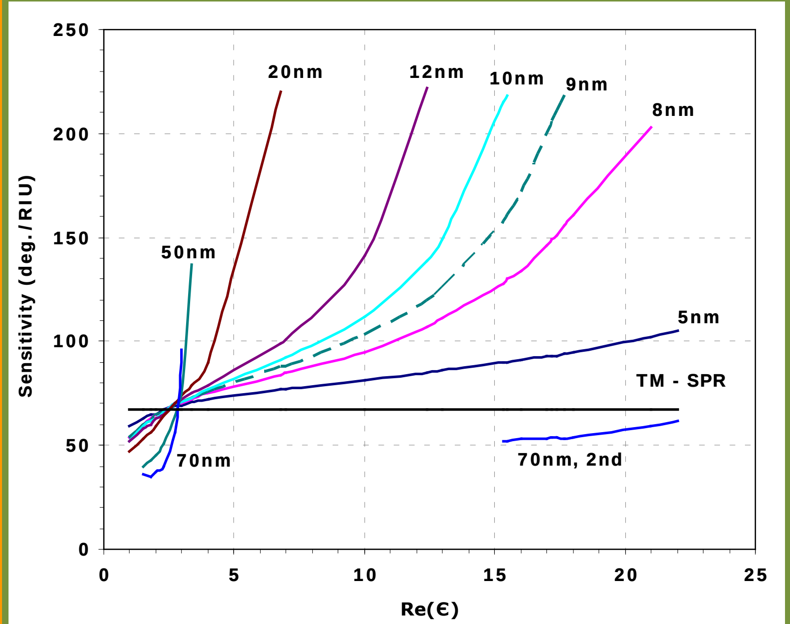


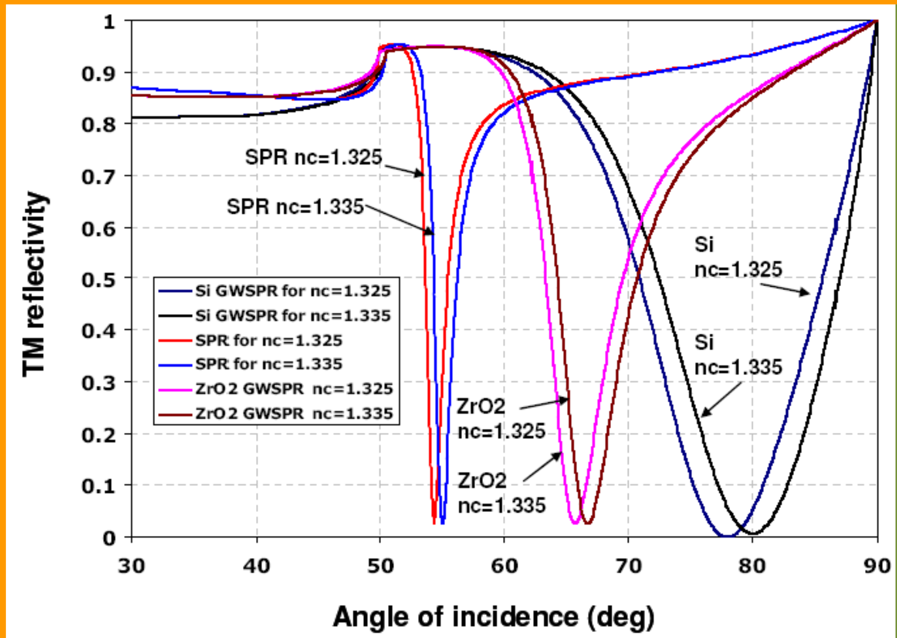


Amit Lahav, Mark Auslender and **I. Abdulhalim**, Sensitivity enhancement of guided wave surface plasmon resonance sensors, Opt.Lett. 33, 2539-2541 (2008).

1st case: Adding top nano-dielectric Layer







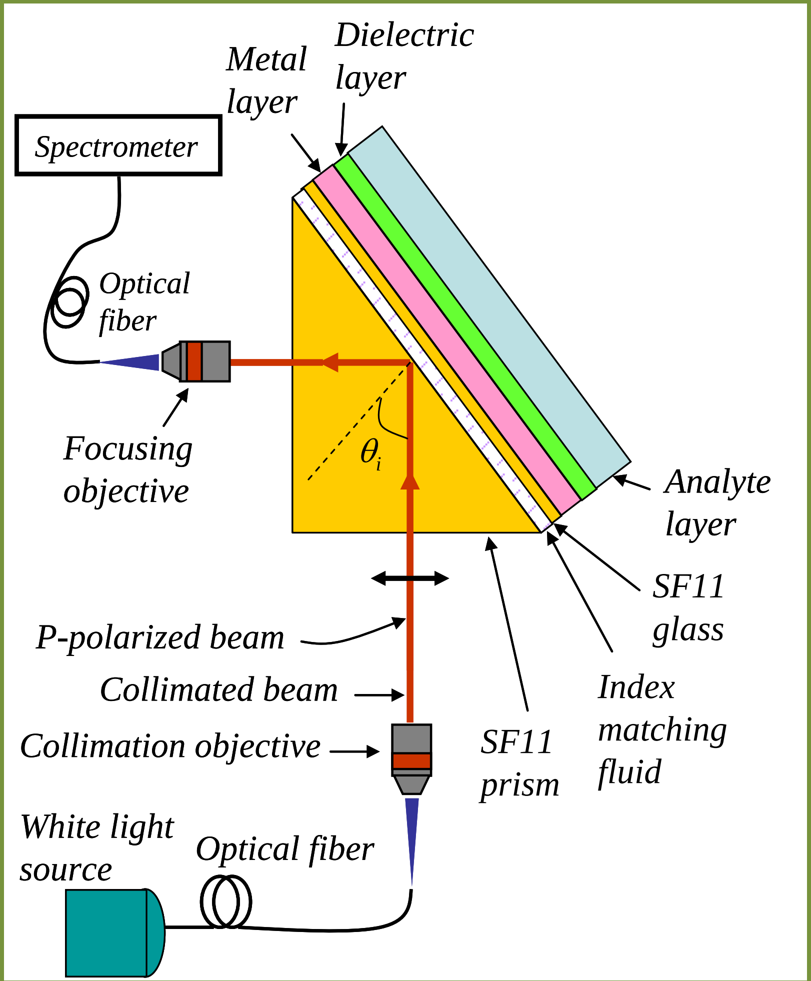
Amit Lahav, Mark Auslender and I. Abdulhalim, Sensitivity enhancement of guided wave surface plasmon resonance sensors, Opt.Lett. 33, 2539-2541 (2008).

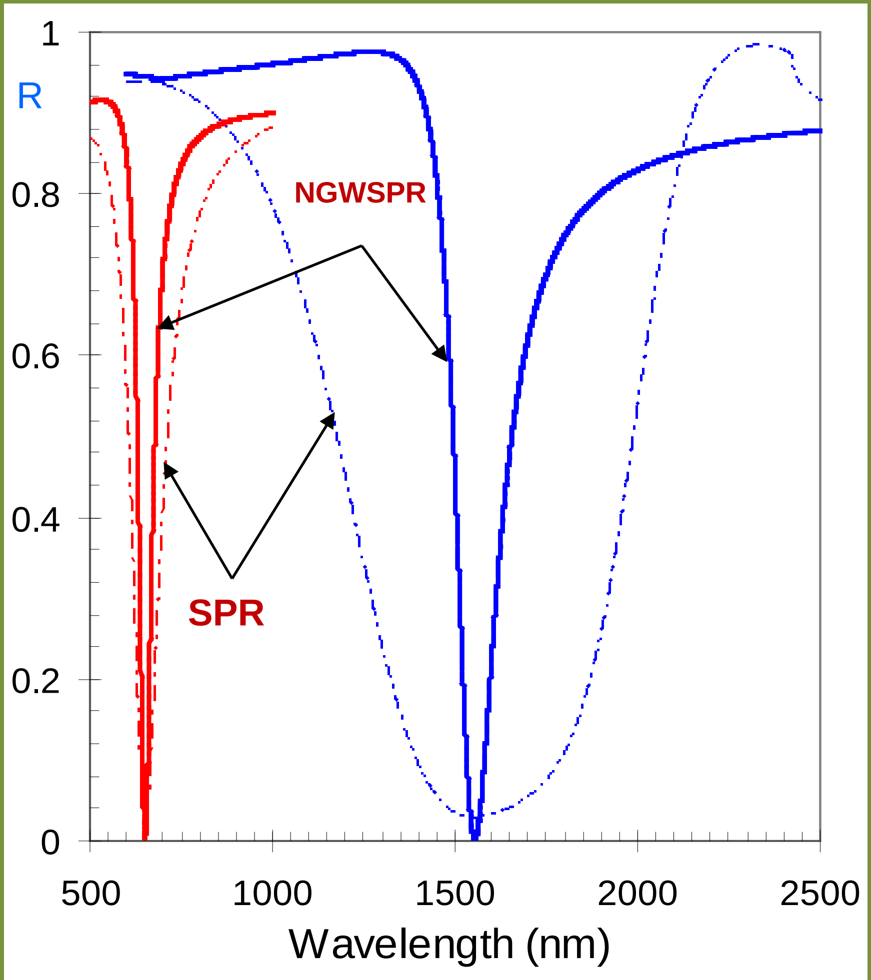
Amit Lahav, Atef Shalabney, I. Abdulhalim, Surface plasmon resonance sensor with enhanced sensitivity using nano-top dielectric layer, Journal of Nano-photonics 3, 031501 (2009 .

Sabine Szunerits, Atef Shalabney, Rabah Boukherroub and I. Abdulhalim, Dielectric coated plasmonic interfaces: their interest for sensitive sensing of analyte-ligand interactions, Anal.Chem. 31, 15-28 (2012).

Improving the FoM with top Nanofilm

NGWSPR- spectral interrogation- dip narrowing



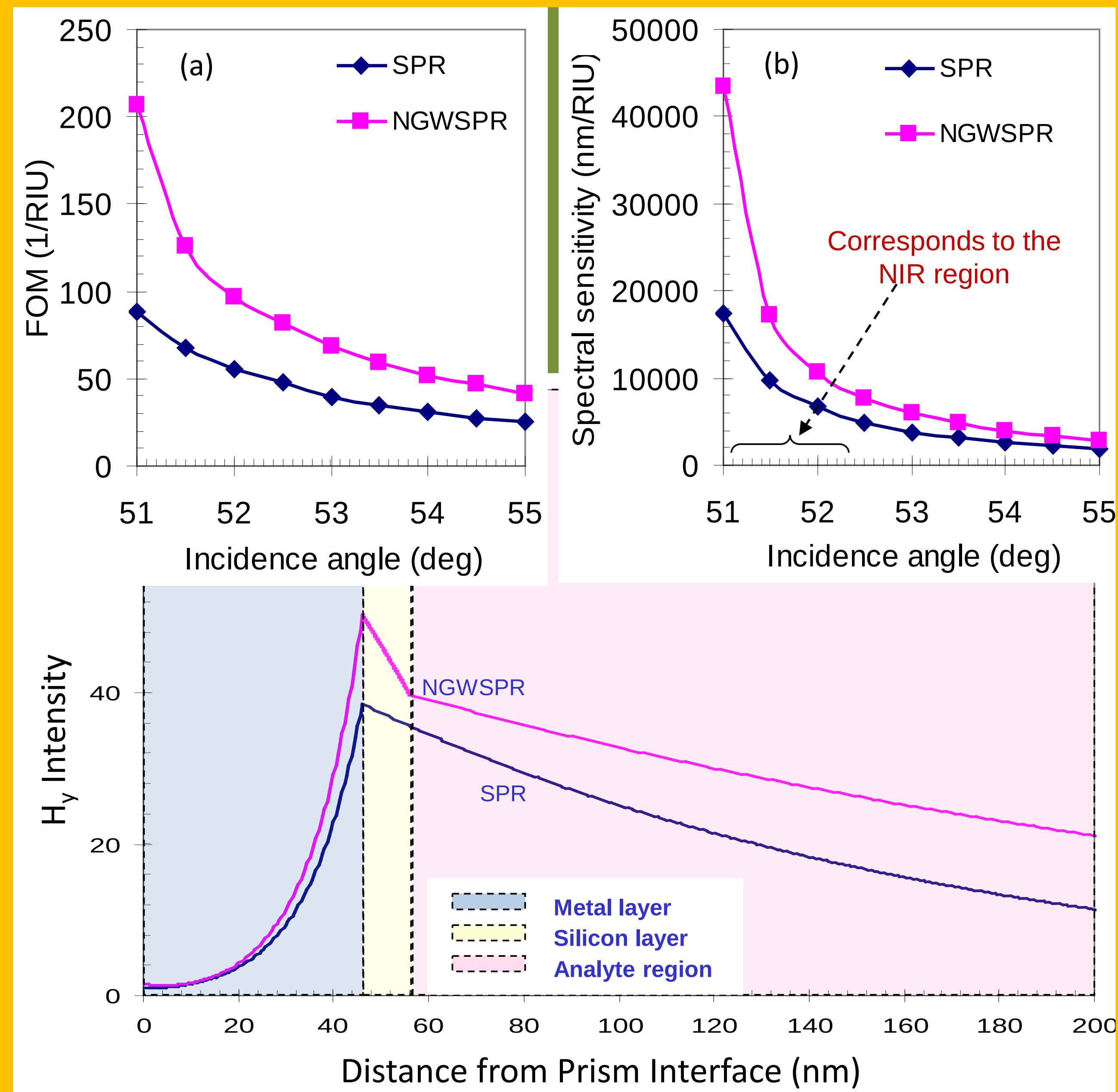


The incident angle is adjusted for both SPR and NGWSPR to determine the wavelength location

A. Shalabney and I. Abdulhalim, Optics Letters, 37(7), (2012)

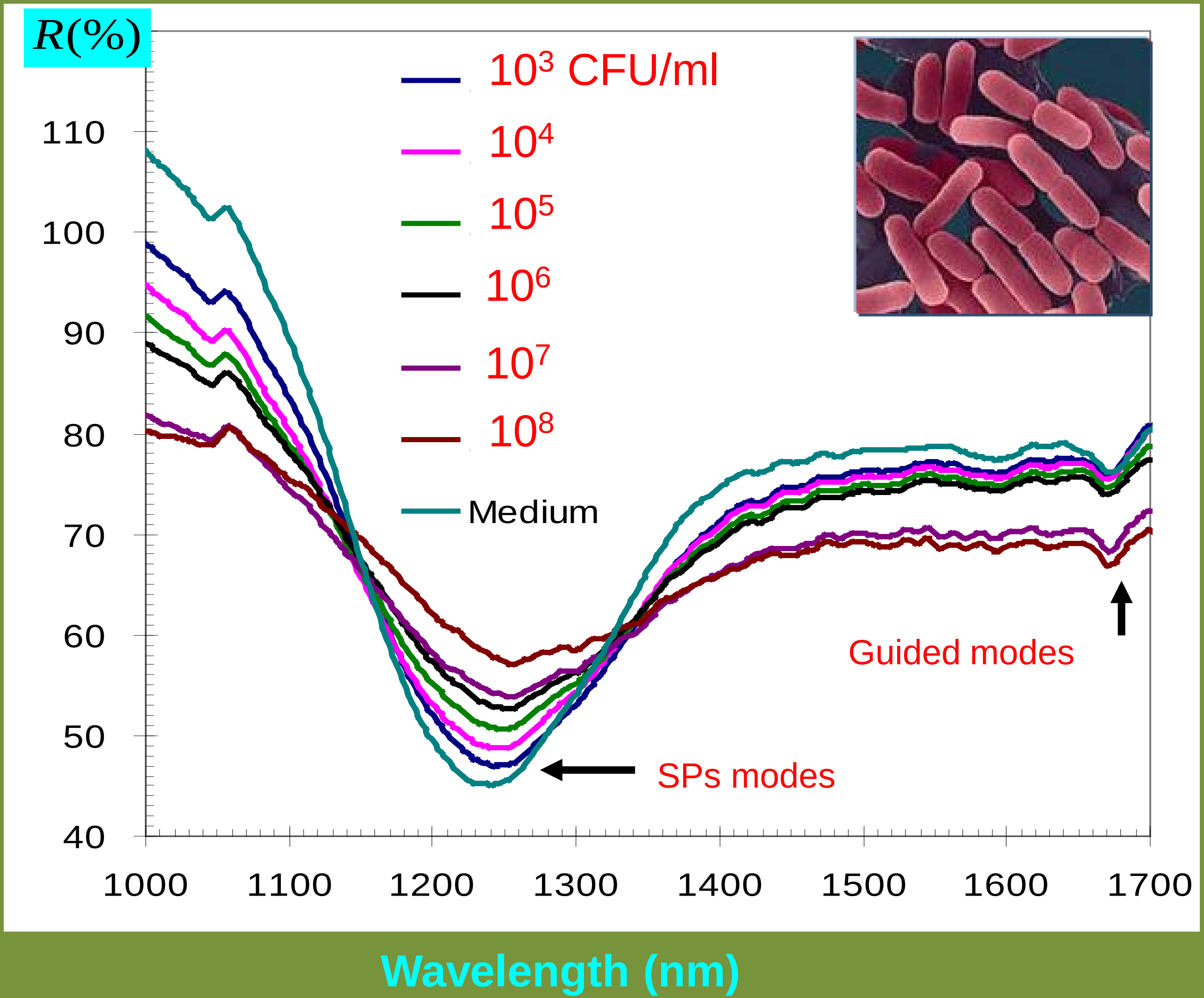
Improving the S-FoM with top Nanofilm

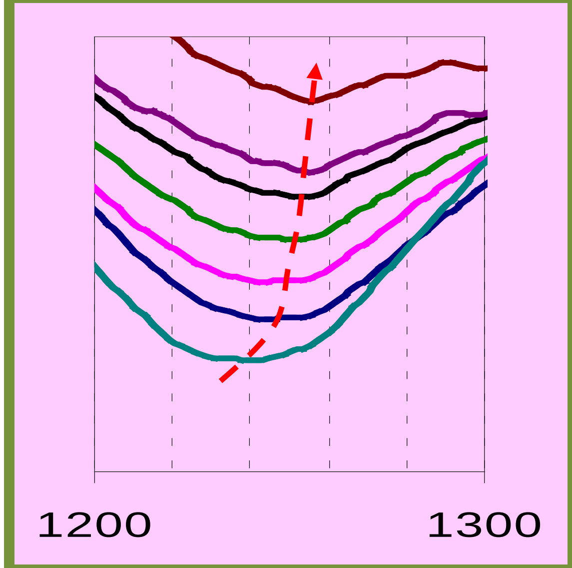
- Same incidence angle
- Larger EM fields
- Larger sensitivity
- Larger penetration depth
- Larger FOM



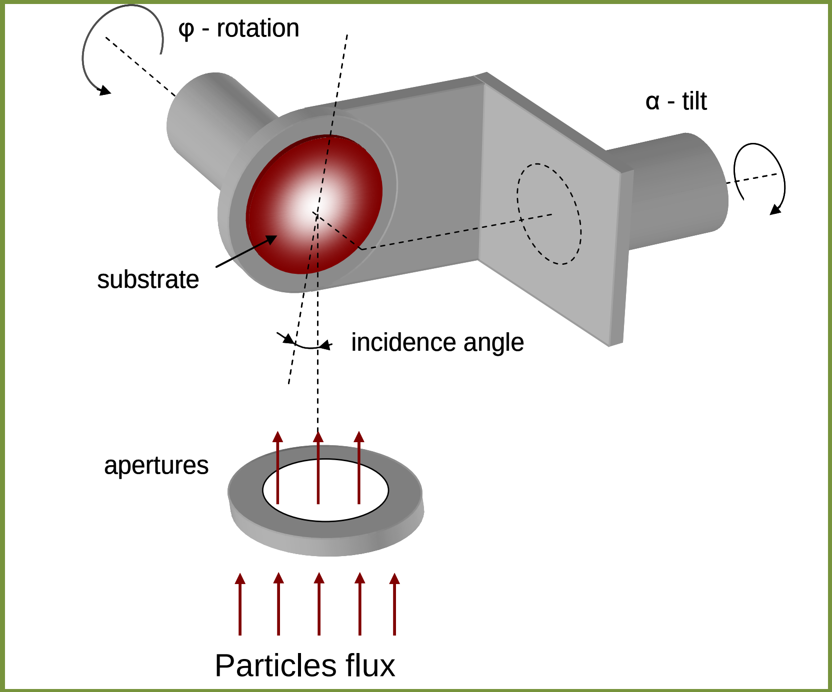
A. Shalabney and I. Abdulhalim, Optics Letters, 37(7), (2012)

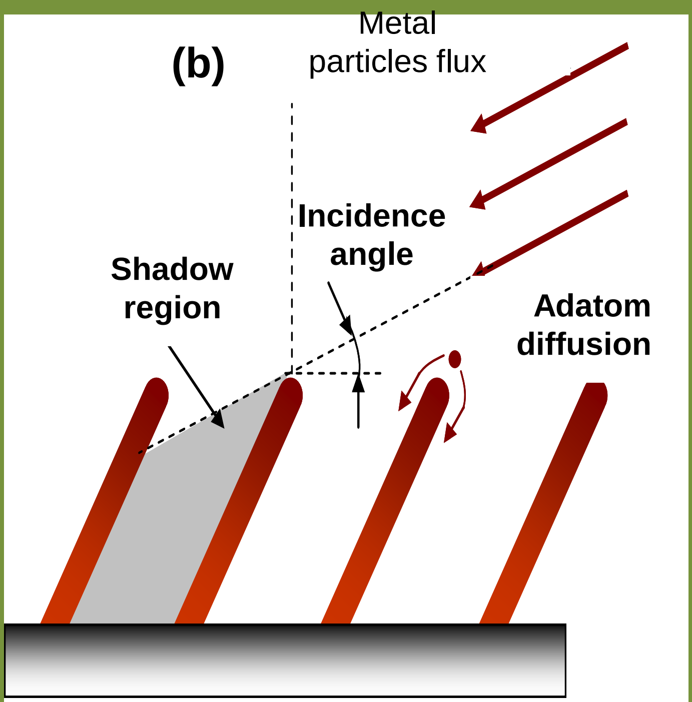
It Enables Detecting Bacteria with NIR



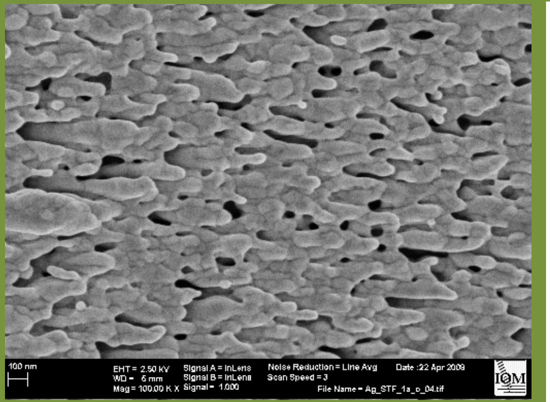


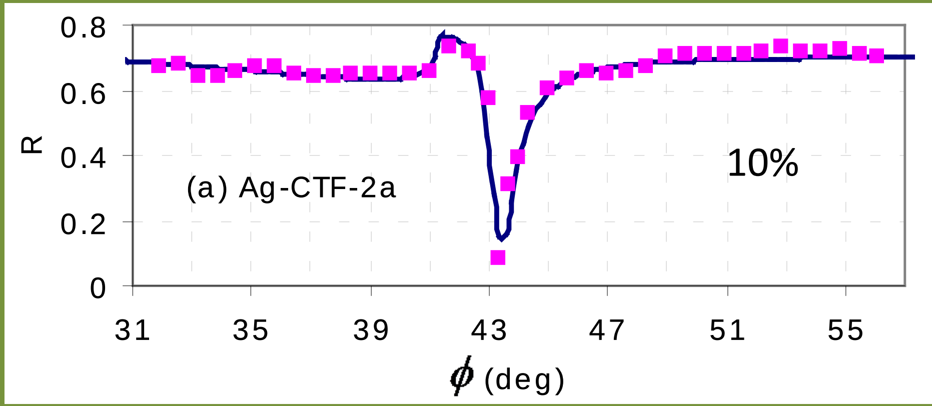
2nd Case: Porosity Effect - nSTFs

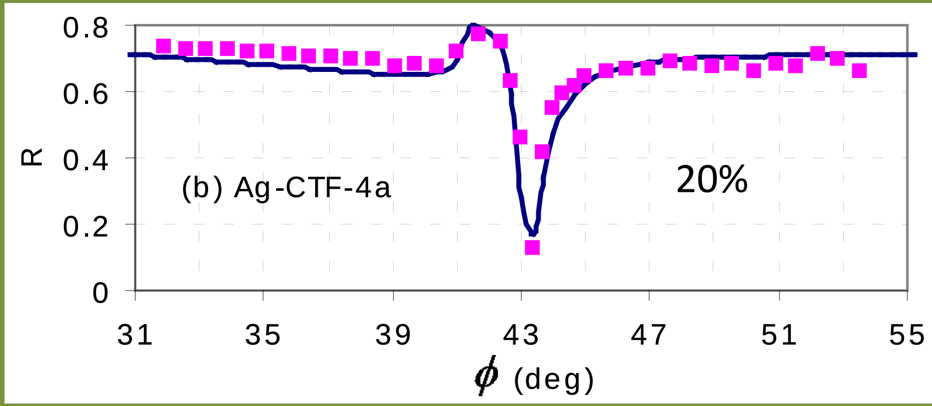


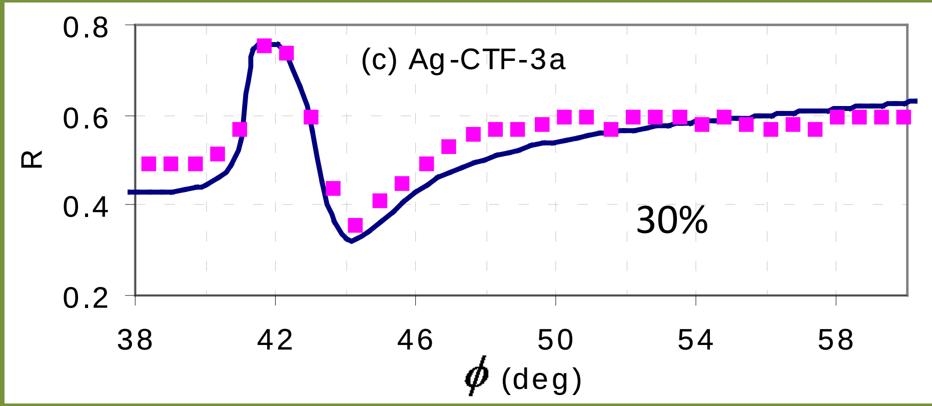


SPR at Different Porosities





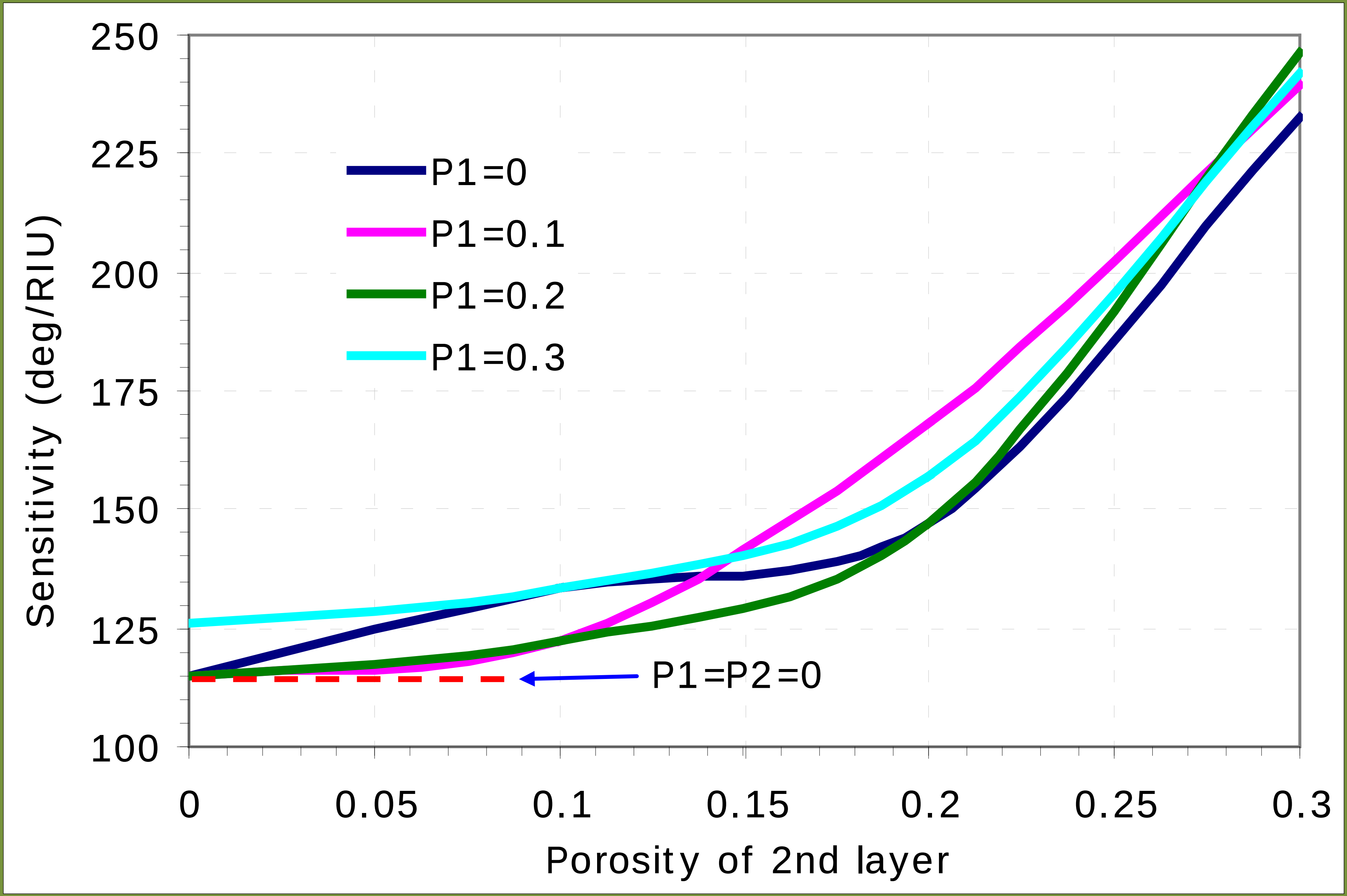




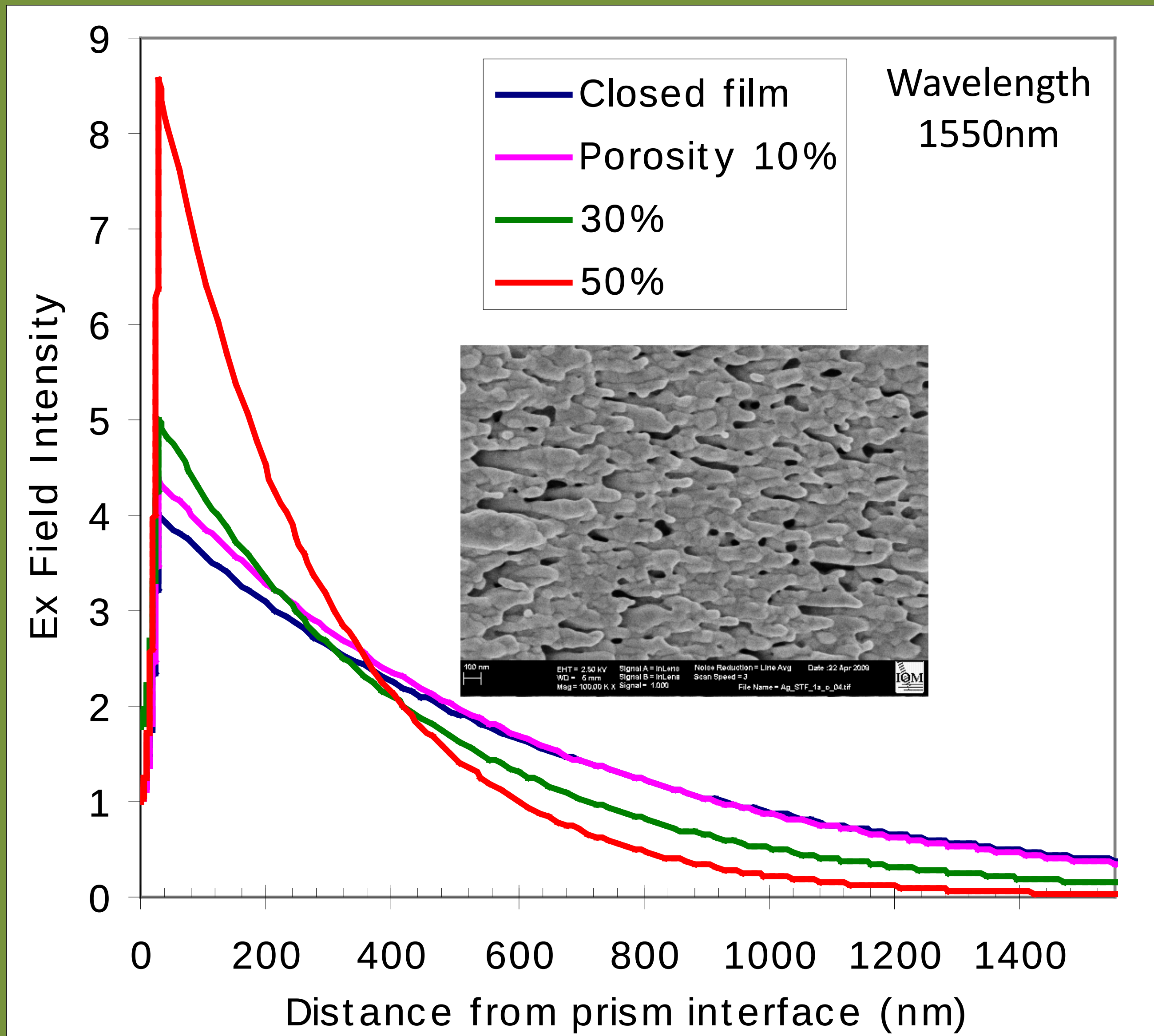
Increasing film porosity

A. Shalabney, A. Lakhtakia, I. Abdulhalim, A. Lahav, Christian Patzig, I. Hazek, A. Karabchevky, Bernd Rauschenbach, F. Zhang, J. Xu, Surface plasmon resonance from metallic columnar thin films, Photon Nanostruct: Fundam Appl. 7, 176-185 (2009)

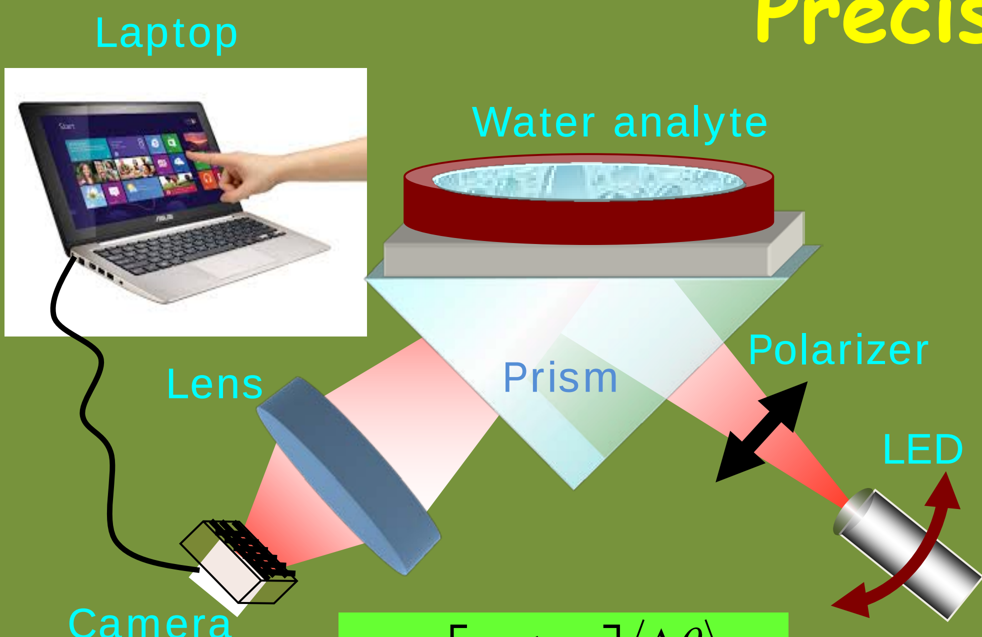
Sensitivity Increases with Porosity



Field Enhancement with Porosity

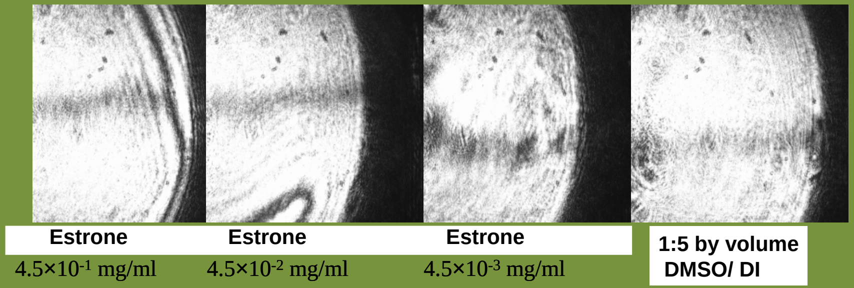


System Simplification and Improved Precision

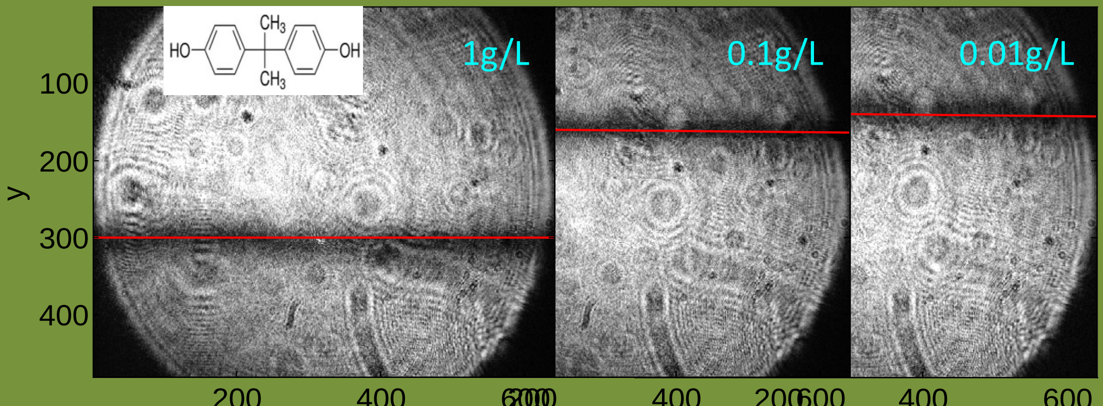


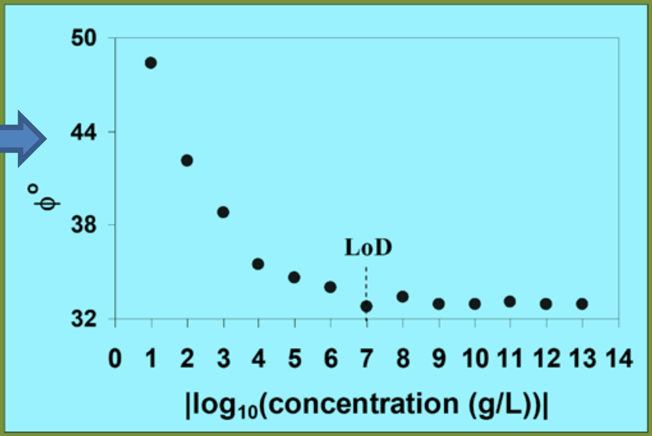
$$DL = \left[\frac{1}{\sqrt{N-1}}\right]\frac{\langle\Delta\theta\rangle_{\min}}{S_\theta}$$

Estron Detection in Water



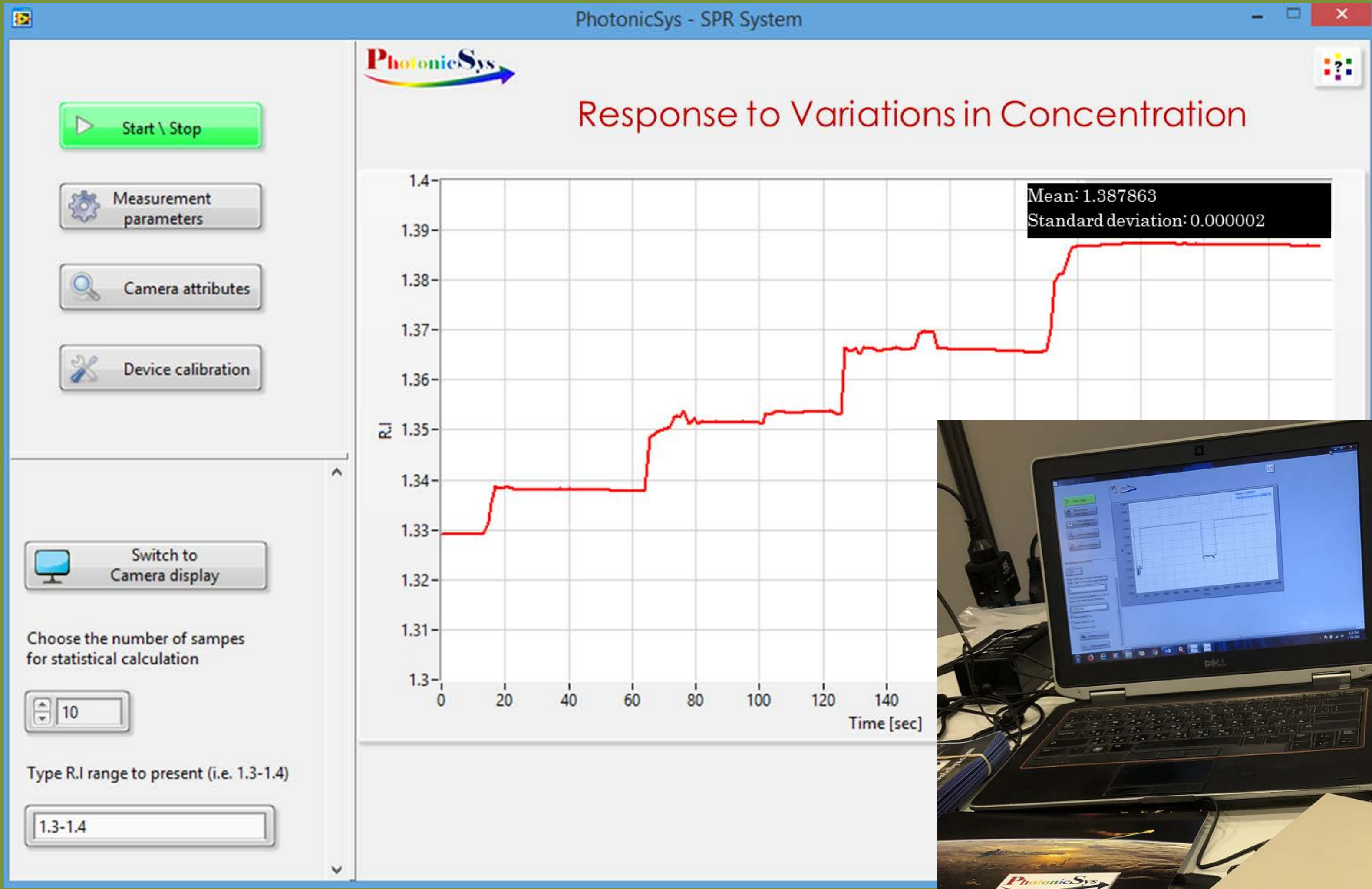
BPA Detection in Water

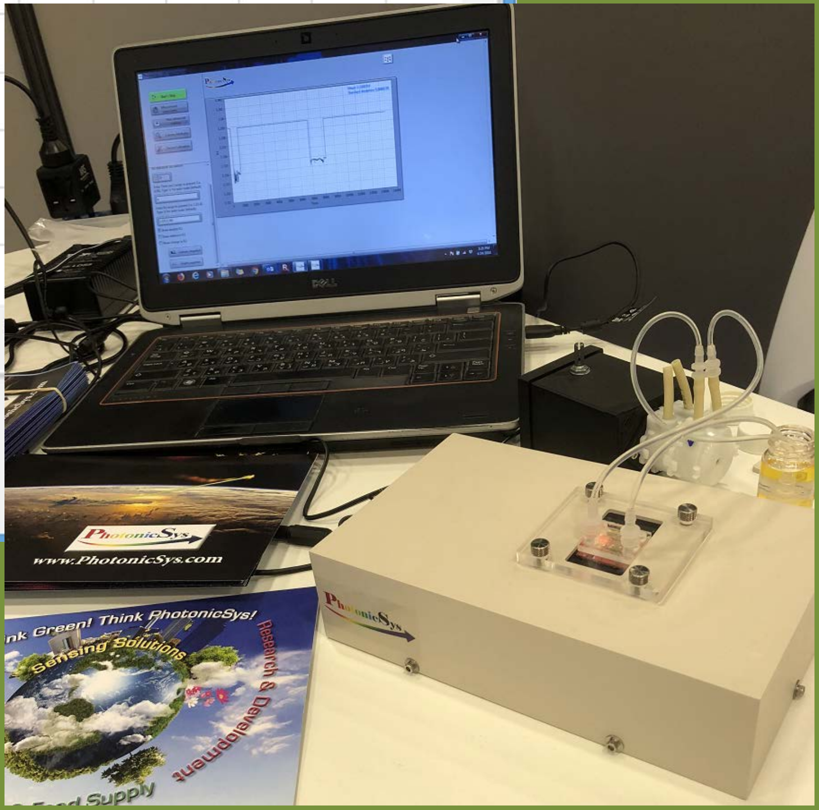




Karabchevsky et.al., 2009, 2010, 2011

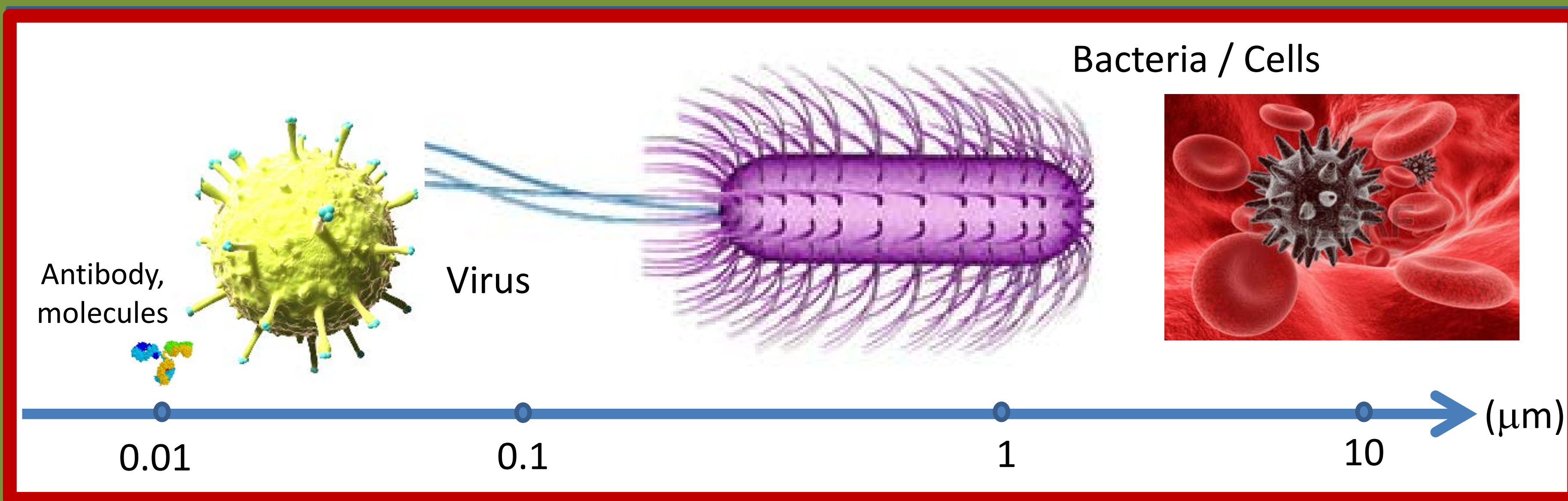
System Miniaturization



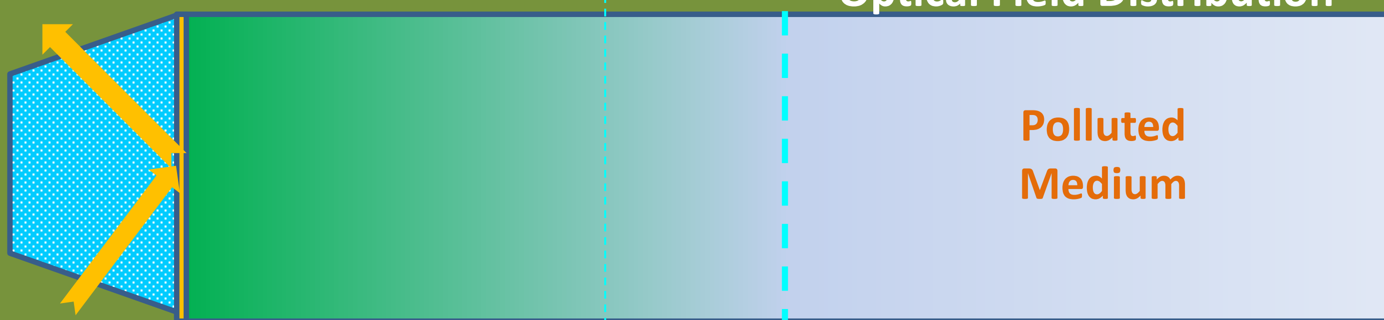


With permission from: www.photonicsys.com

The Field Penetration Depth Importance

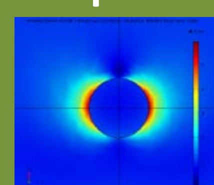


Optical Field Distribution

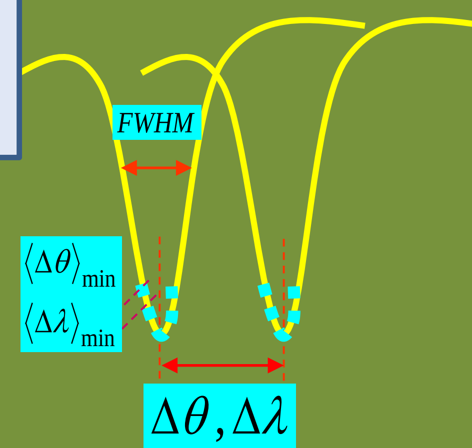


Penetration depth for visible light ~300nm!
Good for specific sensing!

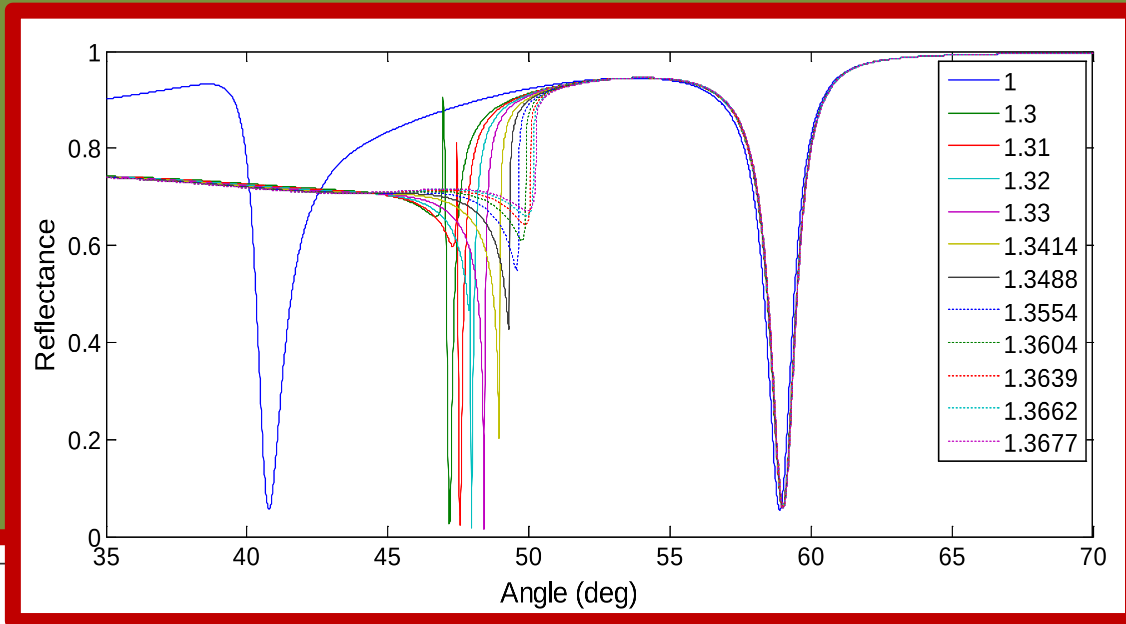
Near Nps ~10nm

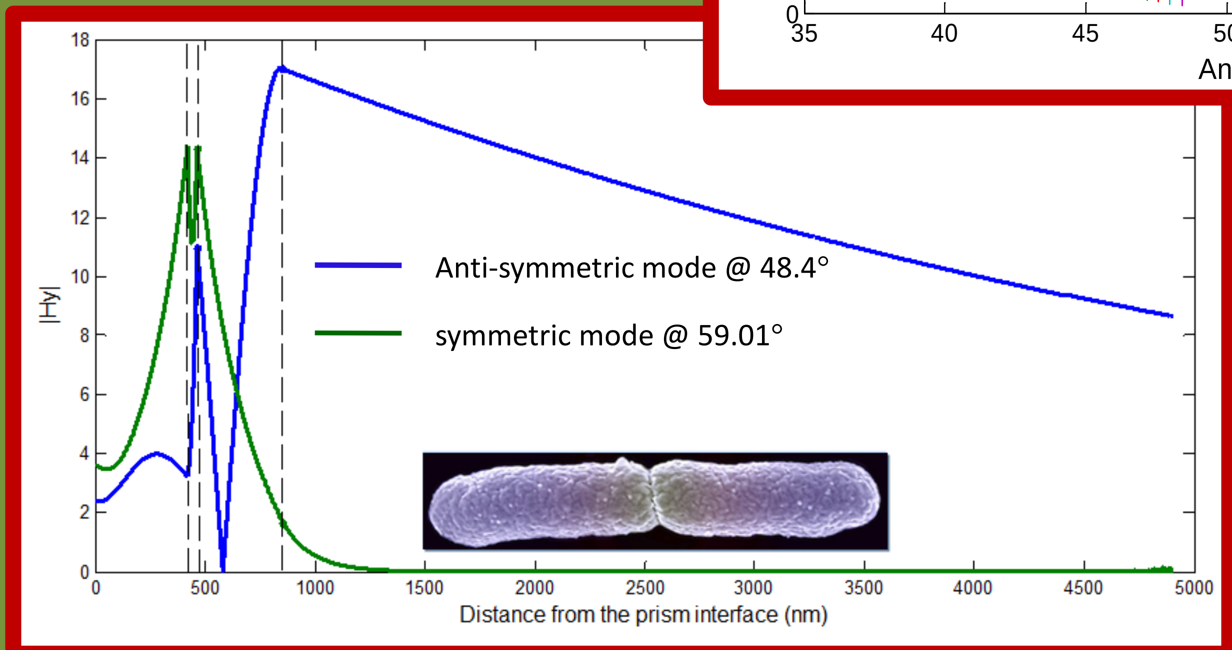


Detection Limit



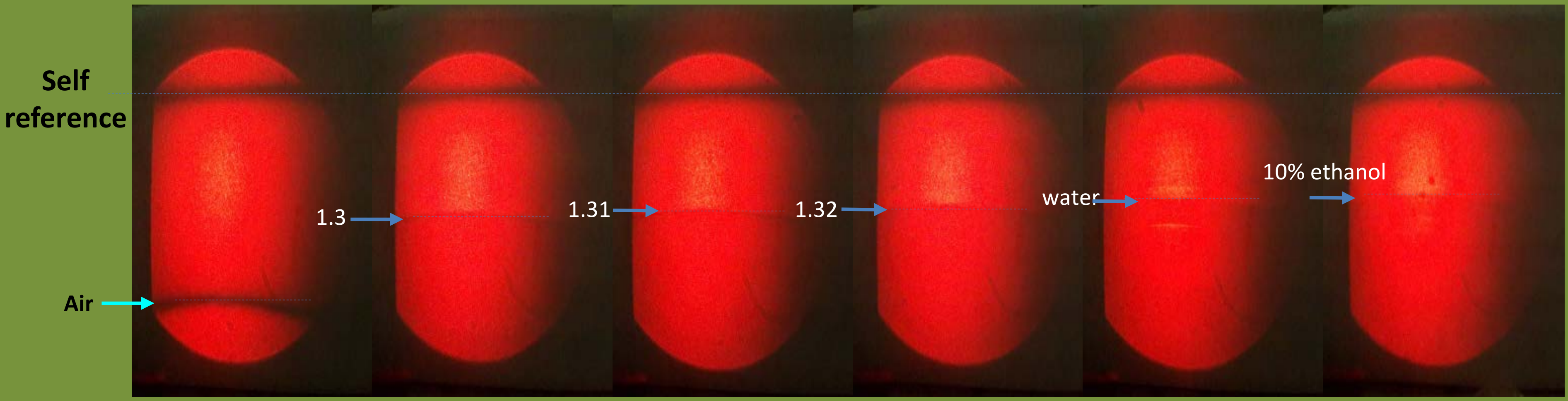
Ultra-high Penetration Depth Self Referenced GW-SPR Sensor



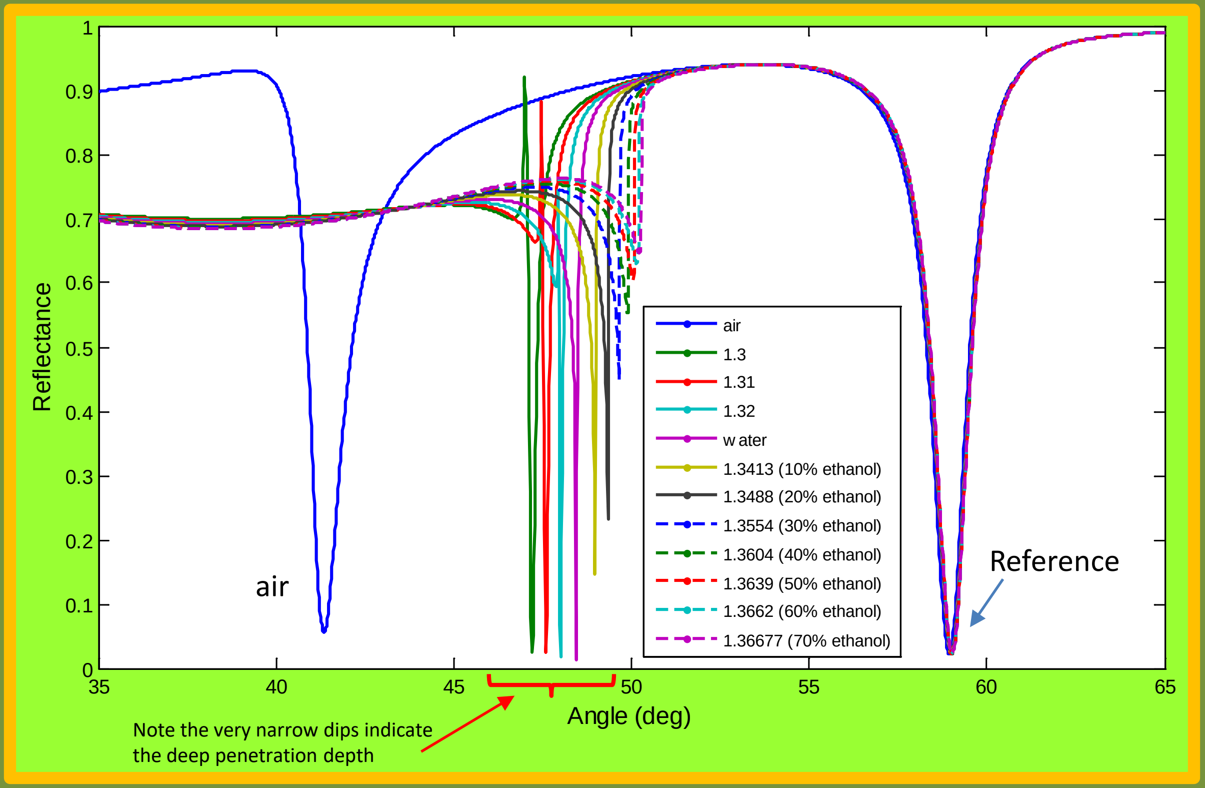


Sivan Issacs and Ibrahim Abdulhalim, Appl.Phys.Lett. 106, 193701-4 (2015).

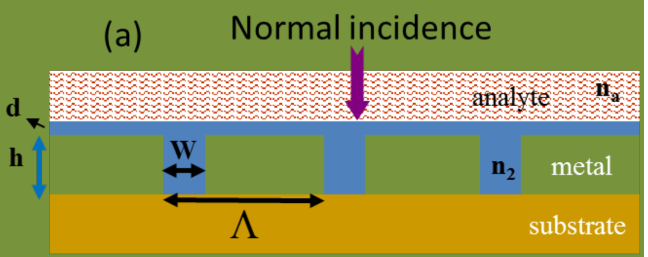
Experimental Confirmation

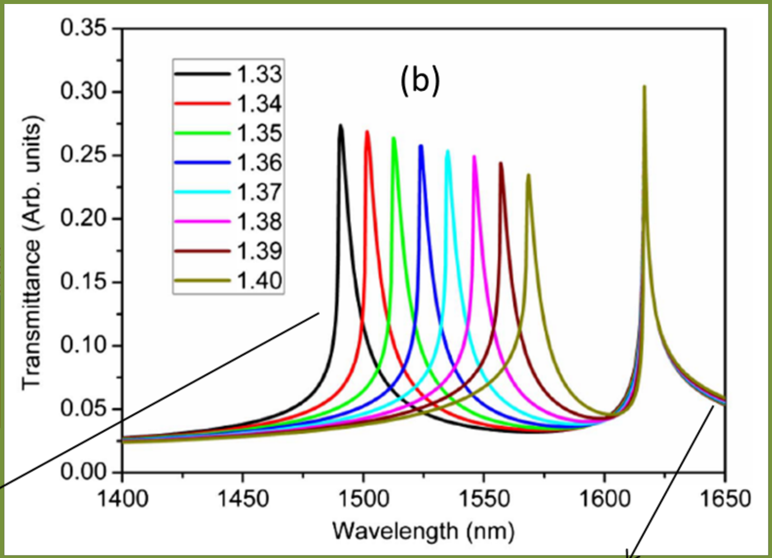


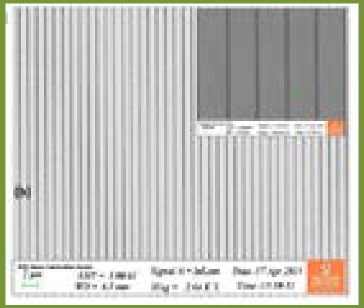
Sivan Issacs et.al., Long range surface plasmon resonance with ultrahigh penetration depth for self-referenced sensing and ultralow detection limit using diverging beam approach, Appl.Phys.Lett. 106, 193701-4 (2015).

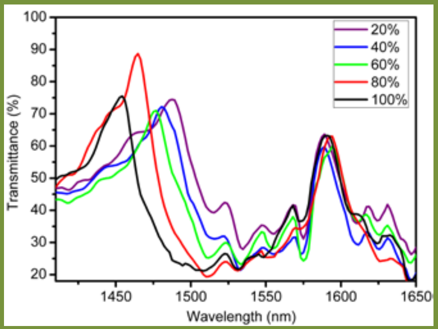


Self Referenced SPR with Grating Coupling



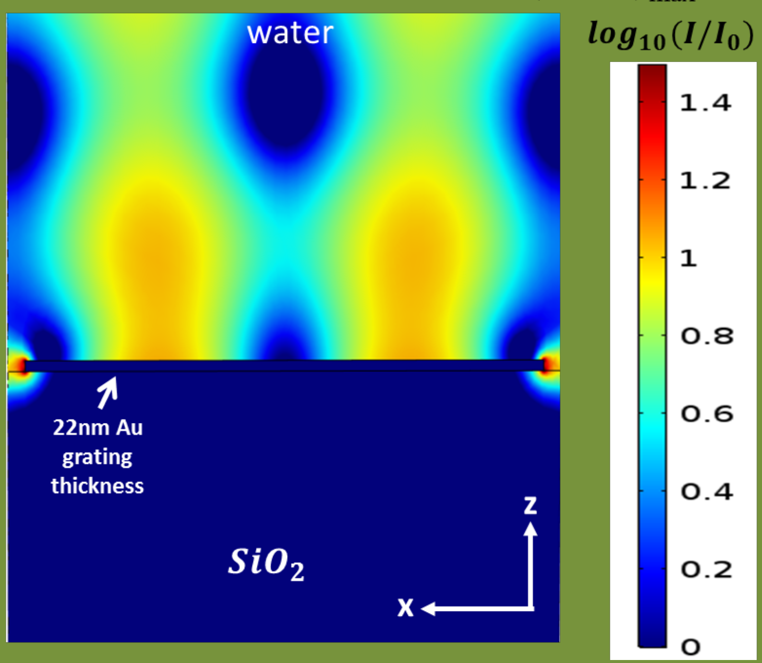


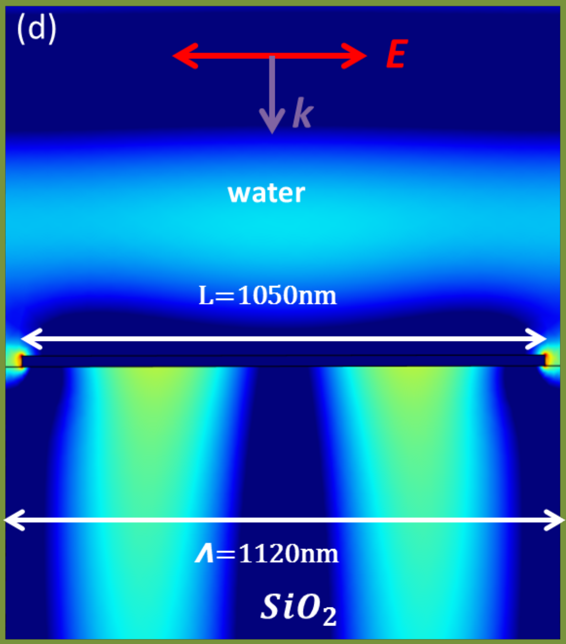




(c)

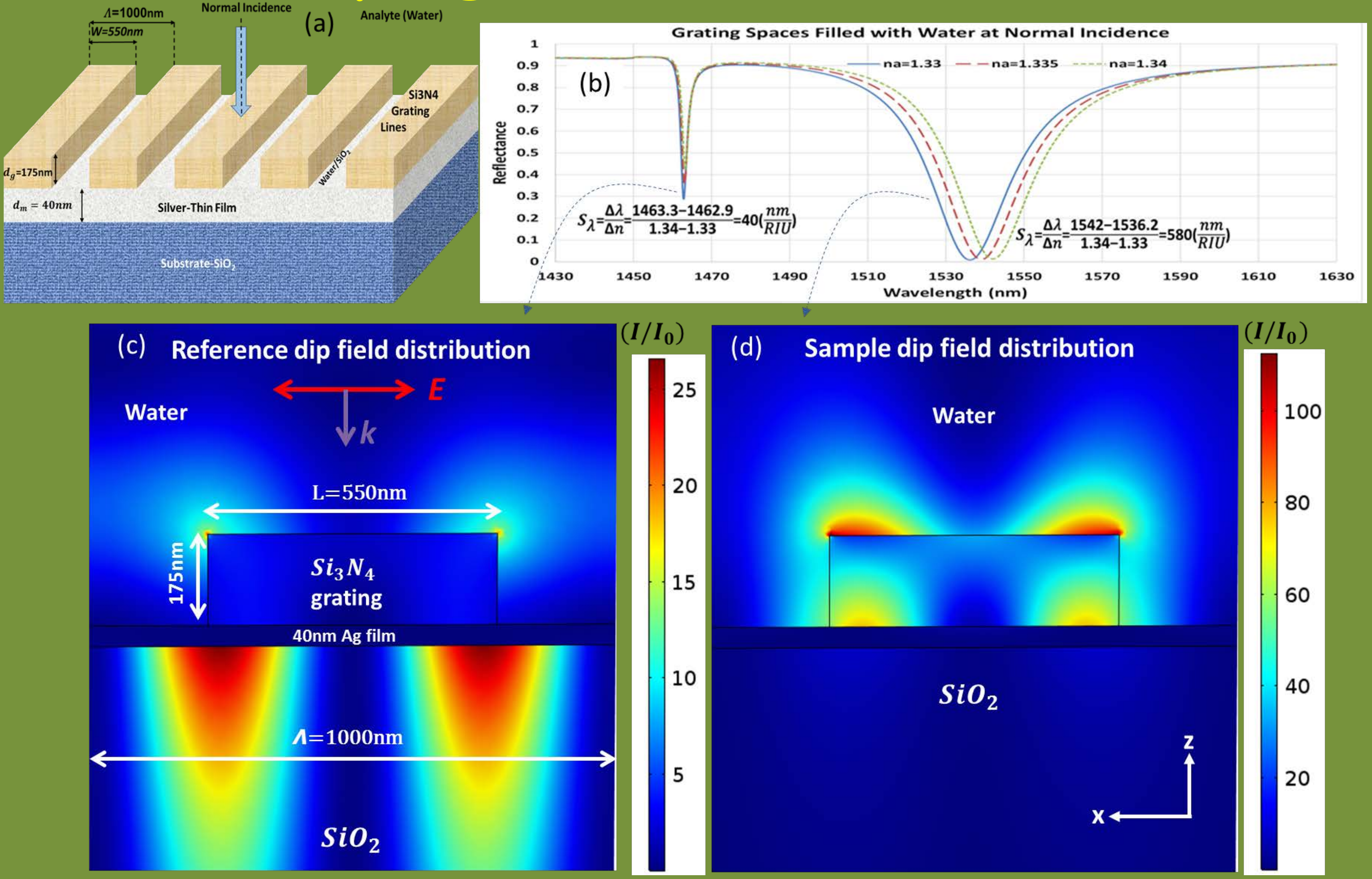
Sample dip field distribution $\left(I/I_0\right)_{max} \approx 10^3$ **Reference dip field distribution**





- Sachin K. Srivastava and Ibrahim Abdulhalim, *Opt. Lett.* 40, 2425-28 (2015).
- Olga Krasnykov et.al., Opt.Commu. 284, 1435-1438 (2011).
- Alina Karabchevsky, et.al., Journal of Plasmonics, 4, 281-292 (2009).

Self Referenced SPR Thin Dielectric Grating Coupling on Thin Metal Film



M. Abutoama et.al., Optics Express 23, 28667-82 (2015) and IEEE J. Selected Topics in Quantum Electronics, 23, 4600309 (2017).

Summary and Future Trends

- SPR biosensors have a large growing market
- Field of interest are environmental sensing and health

- SPR Physics/optics allows for many different modes with variety of improvements in the performance. All originates from the EM field distribution/enhancement
- SPR systems can be miniaturized made portable and cheap.

- For the future specific sensing should be developed more through binding layers development