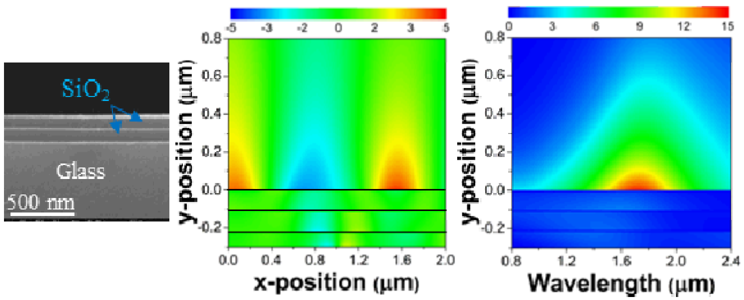
SAND2012-9965C

Near-infrared surface plasmon resonance (SPR) dispersion control with hyperbolic metamaterials



(Submitted to Nano Letters and under review)

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Nov. 14

ASME 2012 International Mechanical Engineering Congress & Exposition (IMECE), Houston, TX

❑ Historical Artifacts of Surface Plasmon Resonance

➢ The Lycurgus Cup (Rome, AD 4th)

The glass contains tiny amounts of gold and silver particles inducing SPR phenomena

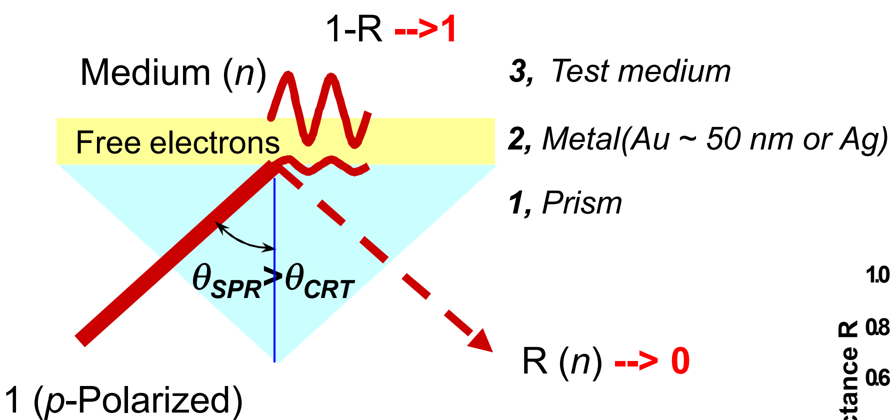
Without light

With light

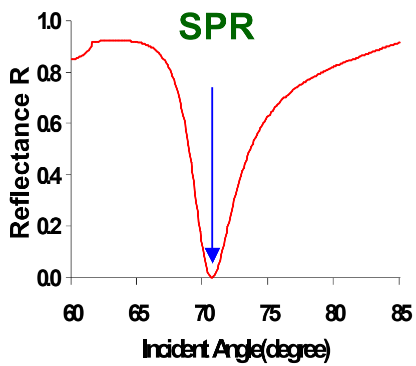
(Source: British Museum)

❑ Fundamentals of Surface Plasmon Resonance (SPR)

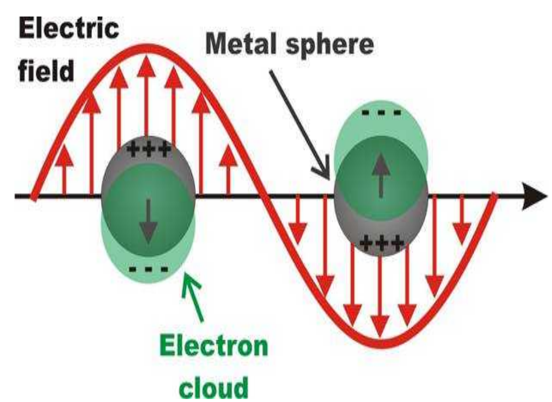
- SP is a collective oscillation of free electrons in the interface between metal and test medium
- SPR is phenomena that SP is excited by the evanescent wave preliminary generated in total internal reflection configuration
- SPR is known to be highly sensitive to the RI variation of test medium with sensitivity ~ *10^{-8}* in refractive index unit in noble metals (Au, Ag, Al, Cu)
- Classification: Planar (thin film) and localized (nanoparticles)



Planar SPR



* SPR Reflectance Curve



Localized SPR

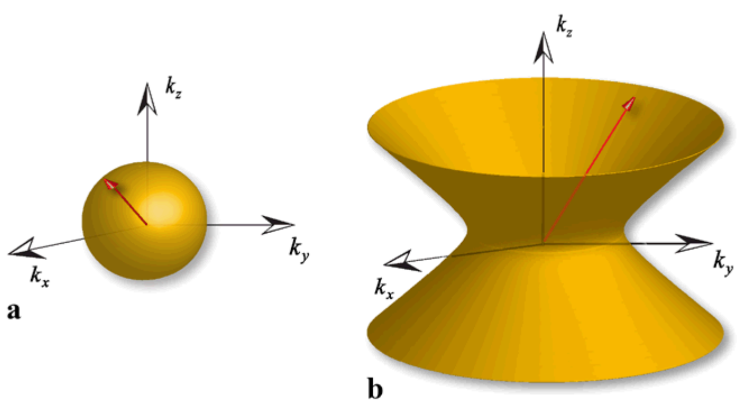
http://willets.cm.utexas.edu/LSPR.html

Metamaterials

- Artificial materials engineered to have properties that may not be found in nature
- Applications: subwavelength imaging, invisible cloak, sensing, enhanced emission, dispersion control, etc (electromagnetic, acoustic, and seismic metamaterials)

Hyperbolic Metamaterials

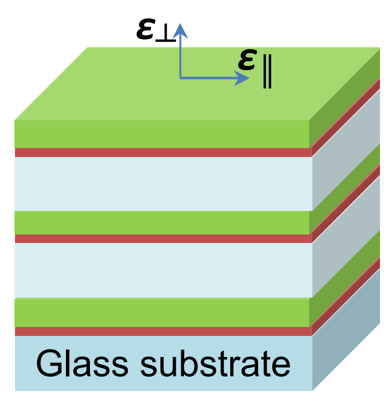
- Metamaterials which combine the properties of metal and dielectric, a recent development in nanophotonics
- Applications: super lens, enhanced spontaneous emission, and near-field thermophotovoltaics



Elliptic dispersion

Hyperbolic dispersion

[Jacob et al, APB, 2010]



$$\varepsilon_\parallel \varepsilon_\perp < 0$$

Outline

I. Research Motivation

II. Experimental Set-up & Characterization

III. Results

IV. Summary

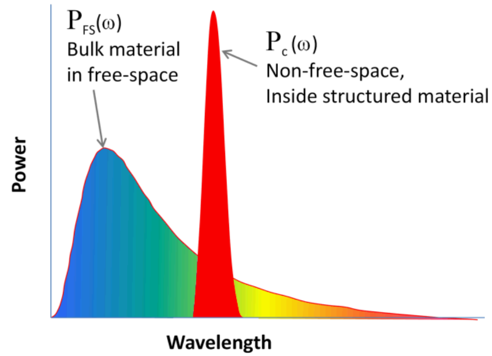
I. Research Motivation

Limited energy transfer rate lower than black-body radiation

* Spectral energy distribution

$$u(\omega) = \hbar\omega\rho(\omega)/(e^{\hbar\omega/kT} - 1)$$

* PDOS (ρ) is proportional to the inverse of group velocity, *dk/dw*



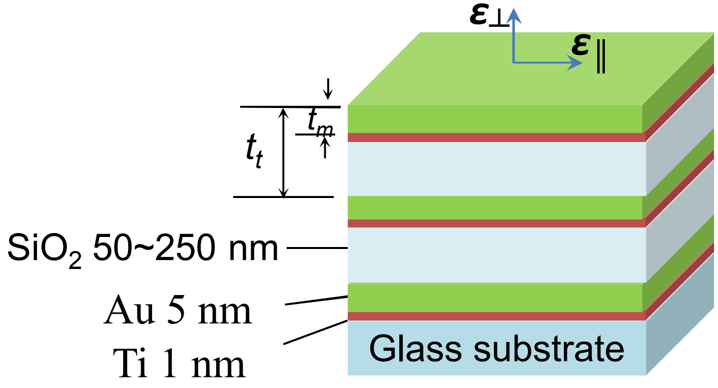
=> High photonic density of states (PDOS) by spectral tailoring and dispersion control

=> High controllable super-Plankian energy transfer

Near-IR SPR nanostructure for high dispersion control and PDOS with hyperbolic metamaterials

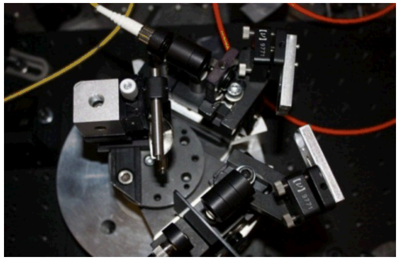
II. Experimental Set-up & Characterization

❑ Sample structure: Hyperbolic metamaterial (HMM)



❑ Ellipsometer measurement of dielectric function

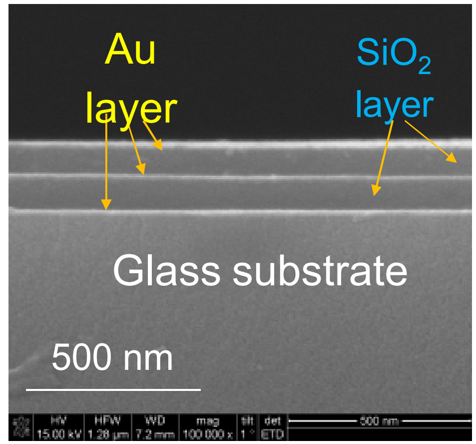
VVASE from J.A. Woolam



Custom-designed ATR set-up

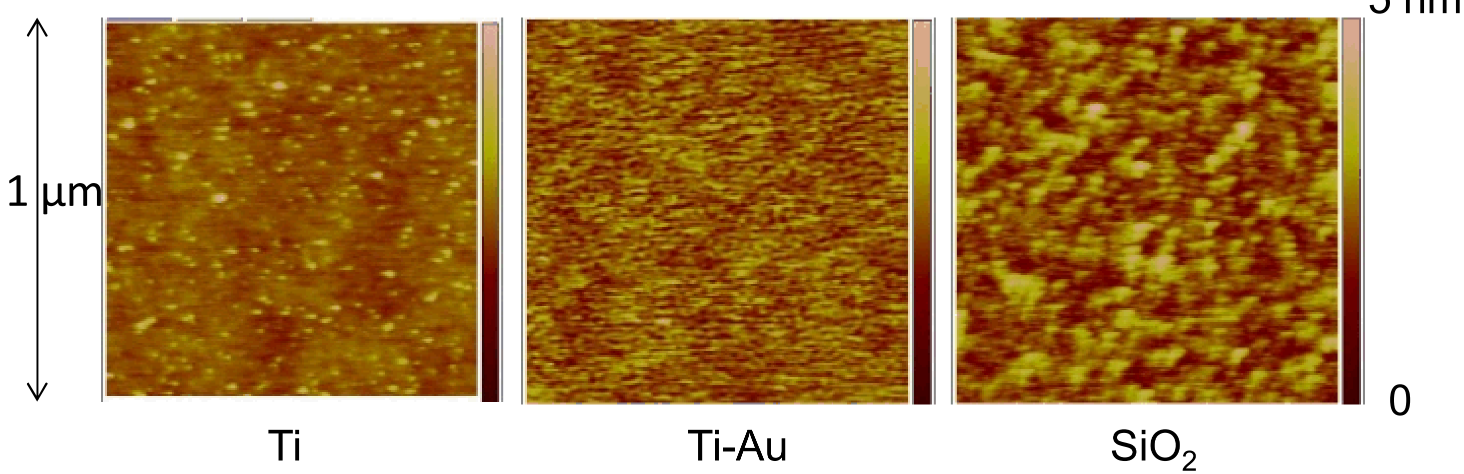
ATR Ellipsometry for SPP signatures

❑ Proof of high-quality film



SEM cross-section image

Roughness: ~ 0.2 nm ~ 0.2 nm ~ 0.4 nm

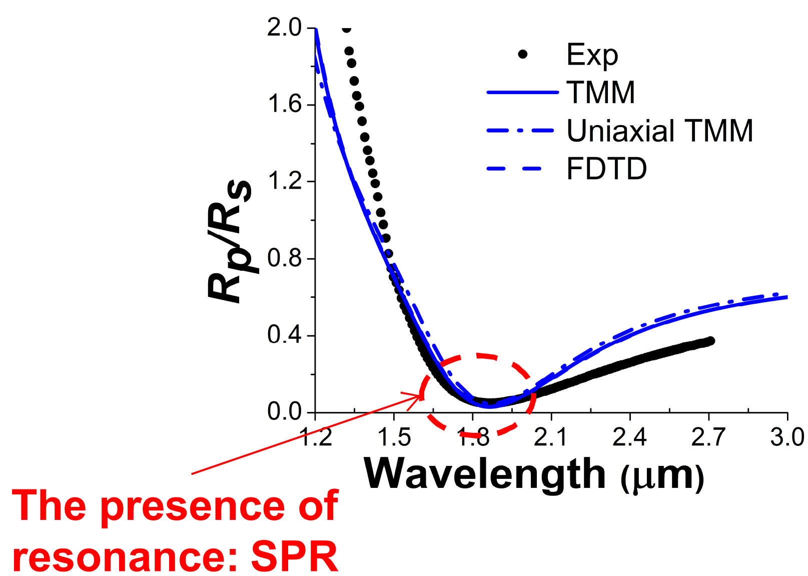


AFM Topological image

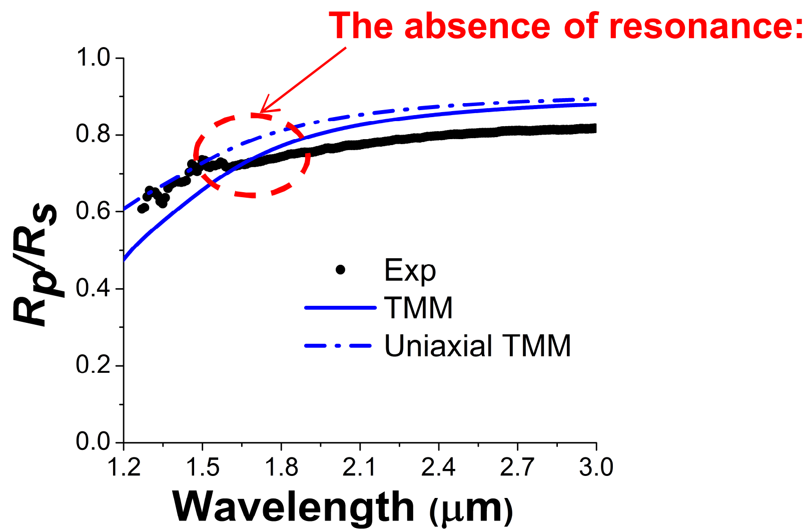
III. Results

❑ Signatures of Surface Plasmon Resonance (SPR)

➢ **Attenuated Total Reflection (ATR)**



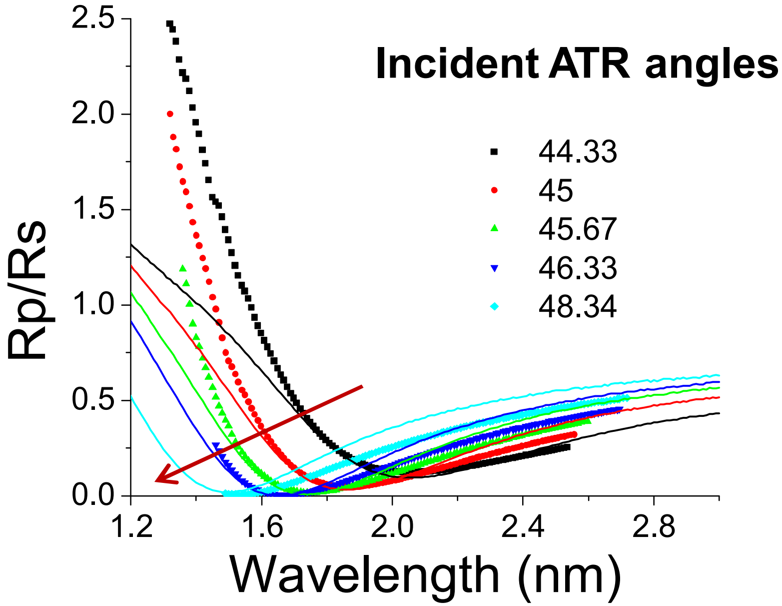
➢ **Non-ATR**



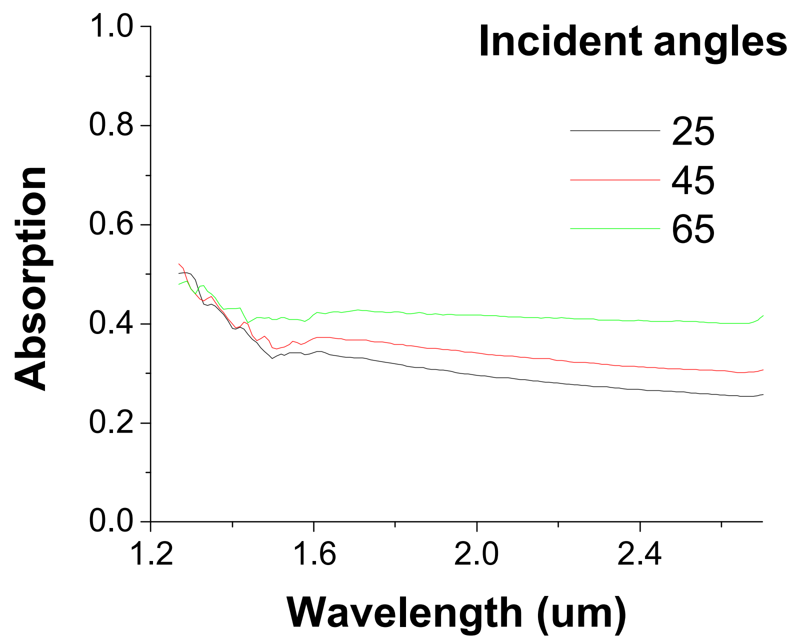
Notations;
Rp: Reflection in p-polarization
Rs: Reflection in s-polarization
TMM: Transfer matrix method
FDTD: Finite domain Time domain method

❑ Signatures of SPR (Cont.)

- ***Rp/Rs* blue-shift with ATR angles**



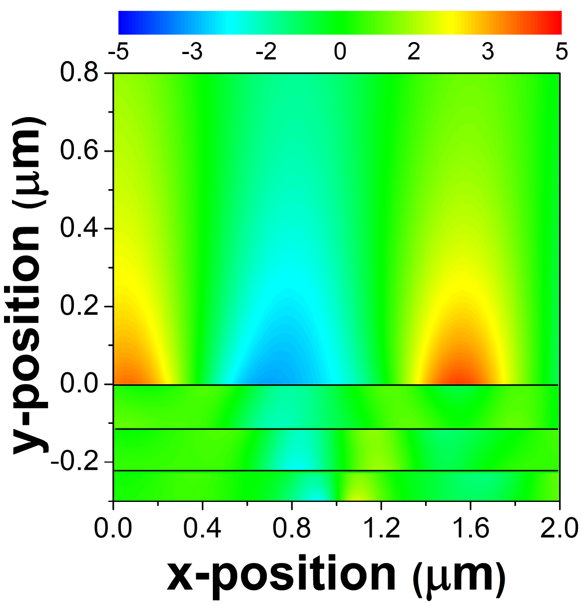
- **Absorption spectra**



No absorption feature in SPP resonance range

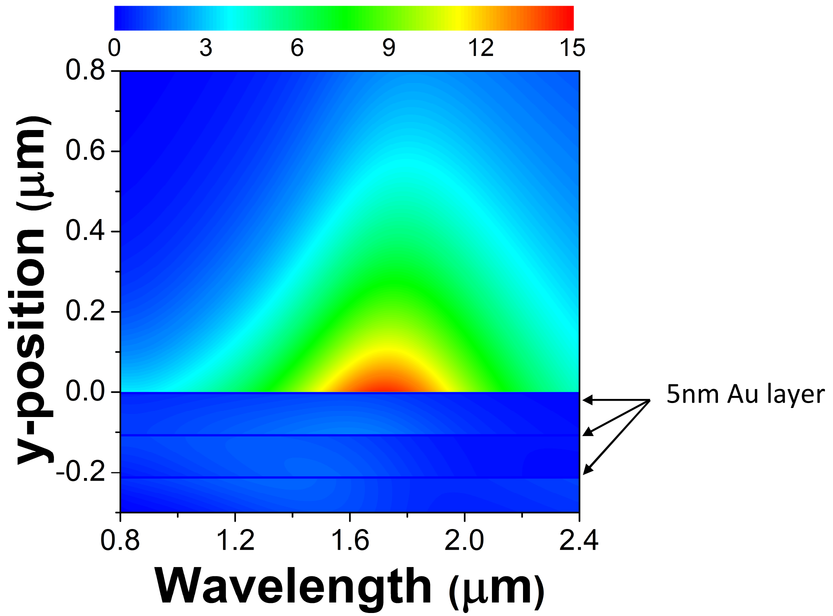
Signatures of SPR (Cont.)

- Electric field pattern of SPR on the surface



- The presence of SPR excitation oscillating along the surface

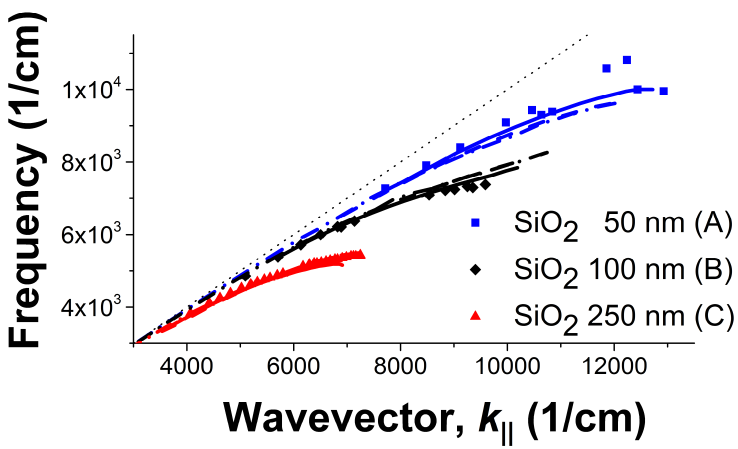
- Electric field enhancement



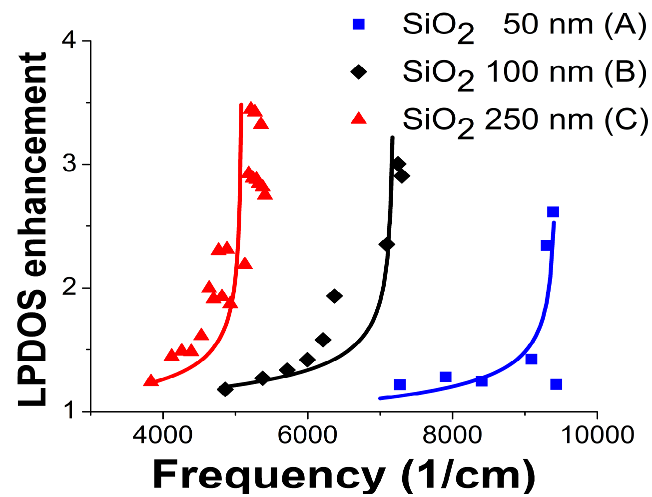
- Enhanced electric field by a factor of 14
- Intensity decay length : 0.2 (normalized to SPR wavelength)

SPR dispersion control & photonic density of states (PDOS)

- **SPR dispersion control**



- **Photonic density of states (PDOS)**



- **The short wavelength limit of SPR**

	λ_{exp}
Bulk Au	0.5
50 nm SiO_2	1.0
100nm SiO_2	1.4
250nm SiO_2	1.8

Unit: μm

PDOS: 3~4

Dispersion control : more than 3x

Compared with bulk Au

IV. Summary

- First time experimental demonstration of SPR in NIR with multi-layer hyperbolic metamaterials
- Experimental and high SPR frequency control from 1 to 1.8 μm
- Low degradation of PDOS with SPP frequency range and different filling factors & fairly good PDOS compared with pure metal => Significantly reduced loss
- High quality thin films are fabricated with the filling factor as low as 0.02 through easy-to fabricate process

⇒ **Highly dispersion-controllable and low-loss SPR nanostructure in near-infrared with multi-layer hyperbolic metamaterials**

⇒ **Further study for high PDOS is required**

Collaborators

Sandia National Lab

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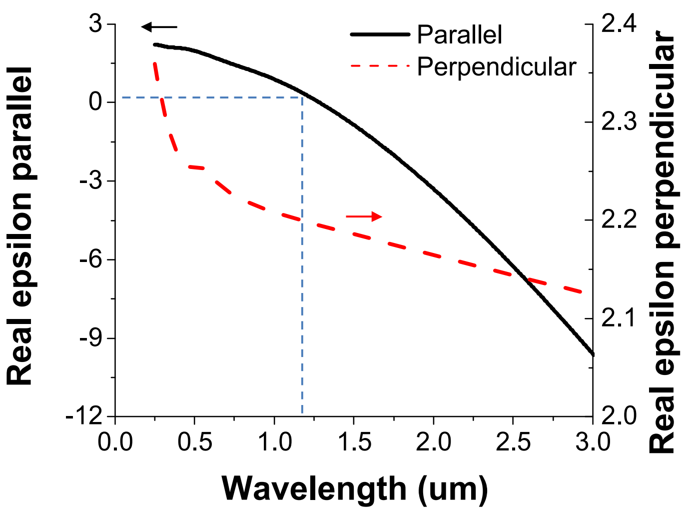
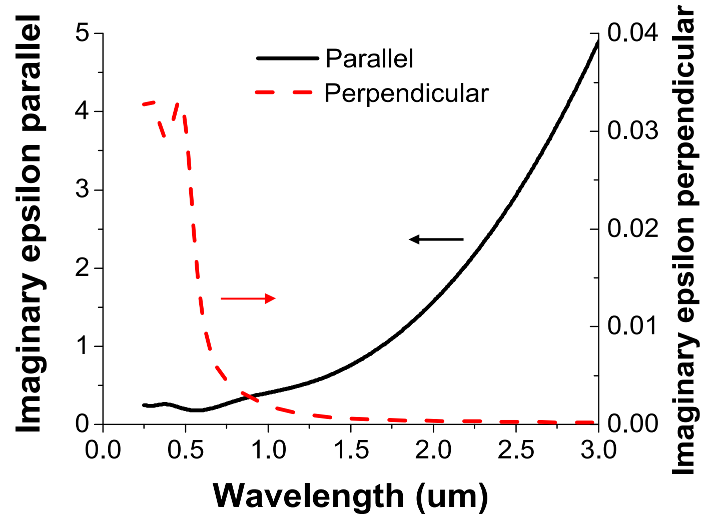
Acknowledgement
This work was supported U.S. Department of Energy (DOE), Office of Basic Energy Sciences, some measurements are performed in DOE The Center for Integrated Nanotechnologies at Sandia National Laboratories (SNL). SNL is a multiprogram laboratory operated by Sandia Corporation, a part of Lockheed-Martin Corporation, for the U.S. DOE under Contract No. DE-AC04-94AL85000.

❑ Dielectric functions of hyperbolic metamaterials (HMM)

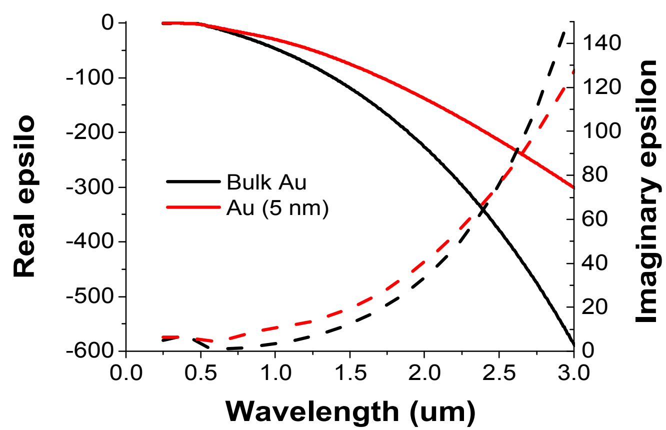
➢ **Parallel component, $\varepsilon_{\parallel}$**



➢ **Perpendicular component, $\varepsilon_{\perp}$**

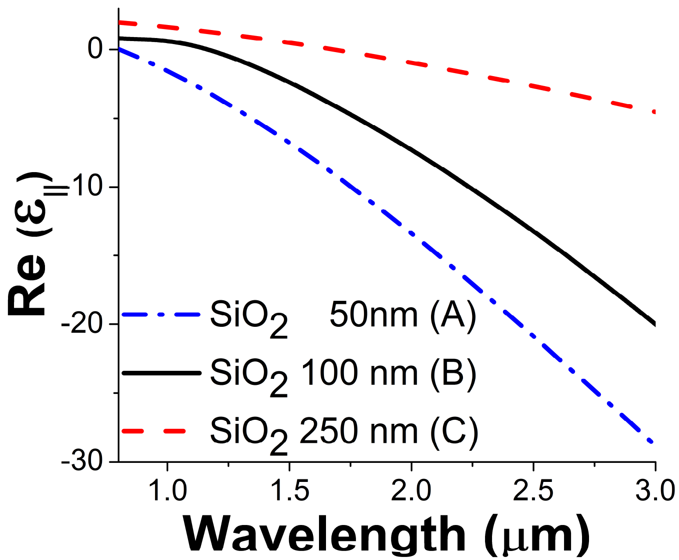


*** Thin Au (5 nm) v.s. thick Au**

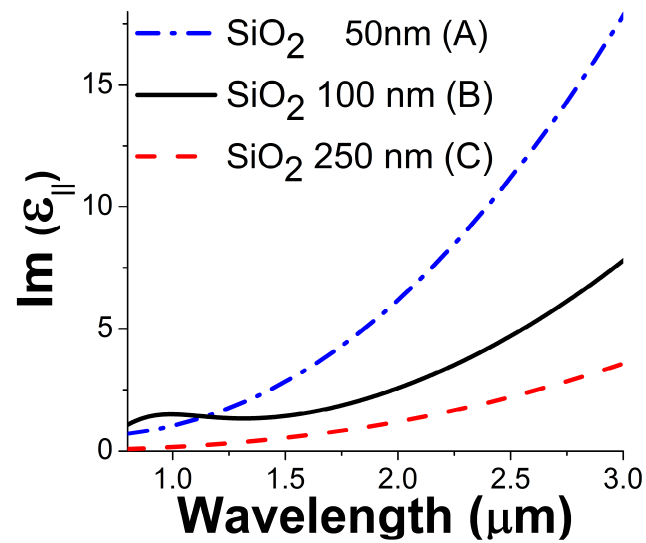


❑ Dielectric functions of hyperbolic metamaterials (HMM)

➢ **Real component of $\varepsilon_{\parallel}$**



➢ **Imaginary component of $\varepsilon_{\parallel}$**



- Hyperbolic dispersion equation

$$\frac{k_\perp^2}{\varepsilon_\parallel} + \frac{k_\parallel^2}{\varepsilon_\perp} = k_0^2 \qquad \varepsilon_\parallel = f\varepsilon_m + (1-f)\varepsilon_d \qquad 1/\varepsilon_\perp = f/\varepsilon_m + (1-f)/\varepsilon_d \qquad f = t_m / t_t$$

=> Type II hyperbolic metamaterials (HMM) with $\varepsilon_\parallel < 0$ & $\varepsilon_\perp > 0$

- SPP dispersion relation for multi-layer metallo-dielectric HMM

$$k_\parallel = k_o \sqrt{\varepsilon_1 \varepsilon_\perp (\varepsilon_1 - \varepsilon_\parallel)/(\varepsilon_1^2 - \varepsilon_\parallel \varepsilon_\perp)}$$