Applications of magnetic polaritons in micro/nanostructures for tailoring radiative properties

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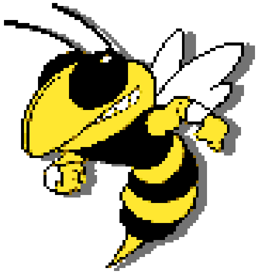
Presented at the Nanoscale Radiative Heat Transfer Physics School, Les Houches, France
May 12-17, 2013



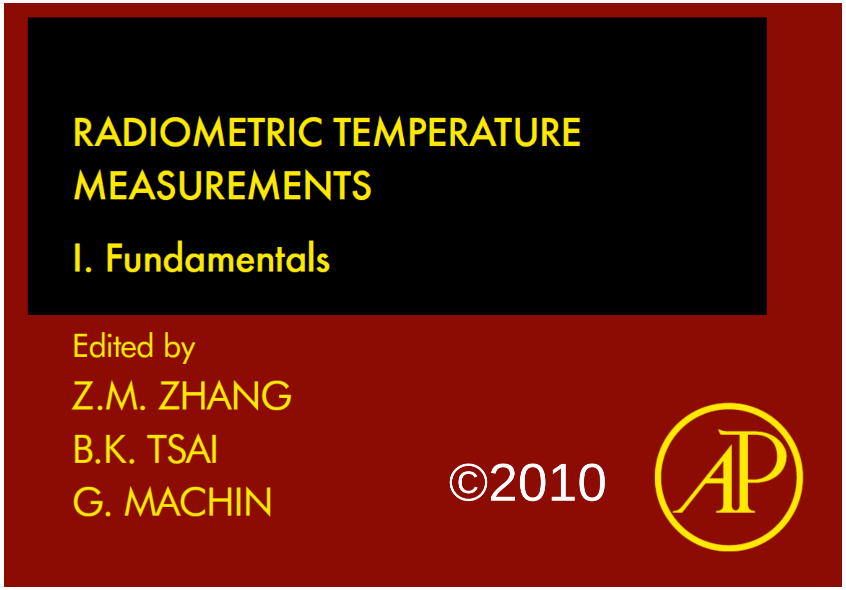
www.me.gatech.edu/~zzhang

Outline

- Introduction
- Negative Refractive Index & Metamaterials
- Magnetic (Plasmon) Polaritons (MPs)
- Tailoring Optical and Radiative Properties
- Summary and Acknowledgements

Applications of Thermal Radiation

- Solar energy harvesting
- Astronomy and space exploration
- Thermophotovoltaics
- Combustion systems
- Materials processing and manufacturing
- Cryogenics
- Metrology



RADIOMETRIC TEMPERATURE MEASUREMENTS

I. Fundamentals

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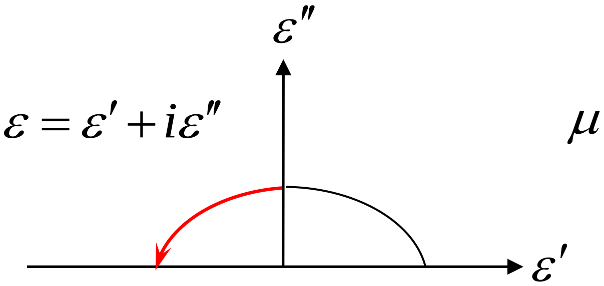
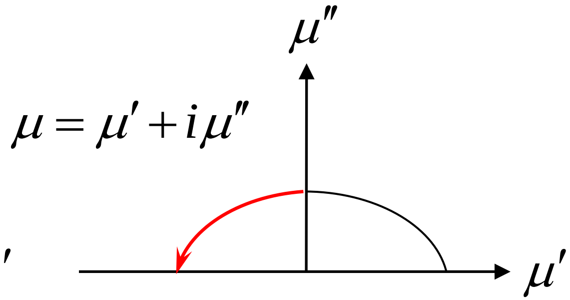
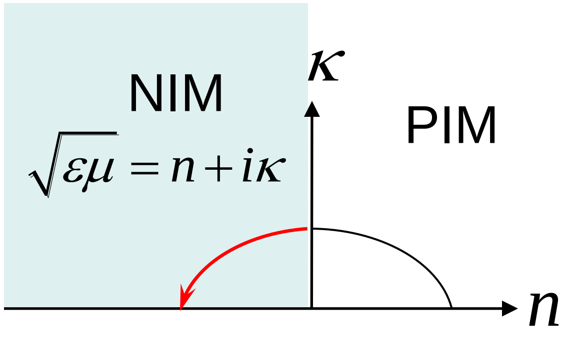
Negative Refractive Index (NIM)



Negative ε' exists in metal or polar materials



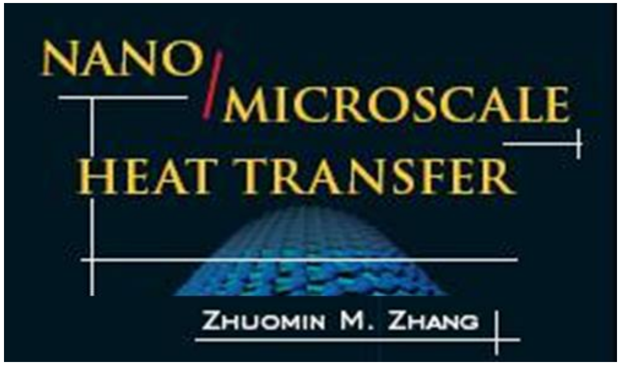
Negative μ' does not exist in natural materials at optical frequencies



Negative refraction → superlens

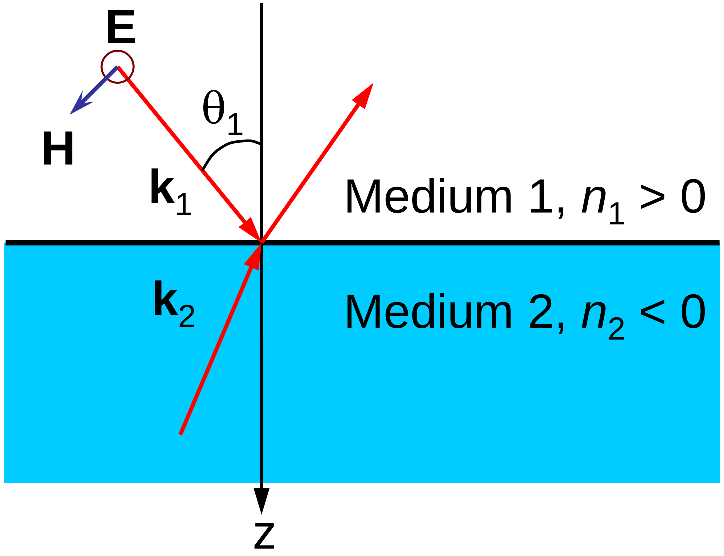
Passive materials (lossy or lossless): Imaginary part of permittivity, permeability or refractive index is always non-negative.

See, e.g., Zhang, Z.M., *Nano/Microscale Heat Transfer*, McGraw-Hill, New York, 2007.

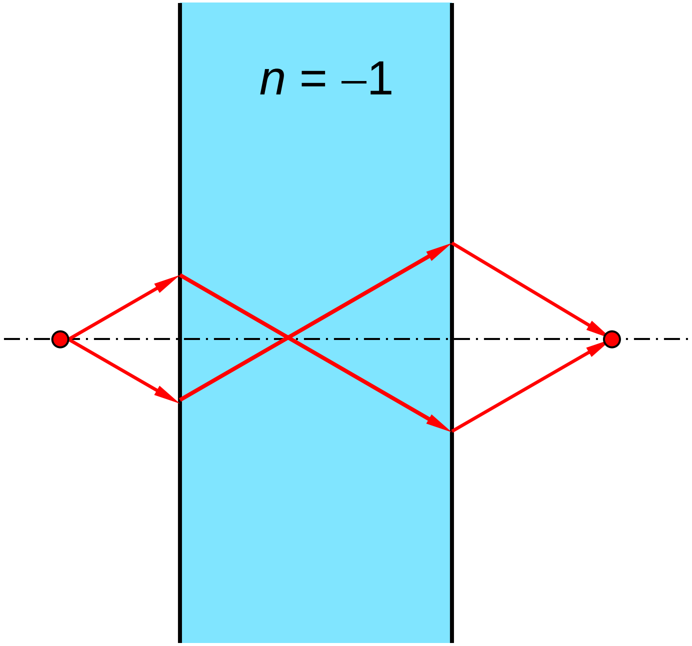


McGraw-Hill (2007)

Refraction from a PIM to a NIM



$$n = \begin{cases} \sqrt{\varepsilon\mu} & \text{if } \varepsilon > 0 \ \& \ \mu > 0 \\ -\sqrt{\varepsilon\mu} & \text{if } \varepsilon < 0 \ \& \ \mu < 0 \end{cases}$$



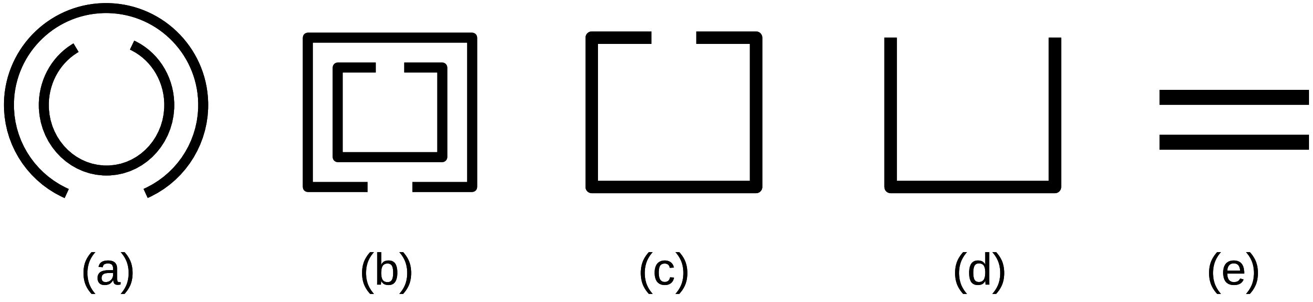
A NIM slab acts as a lens.

Veselago, *Sov. Phys. Usp.* 10, 509 (1968).

Diamagnetism or Magnetic Response

Magnetic materials seldom exist in natural materials at optical frequencies

Various structures can induce magnetic responses:



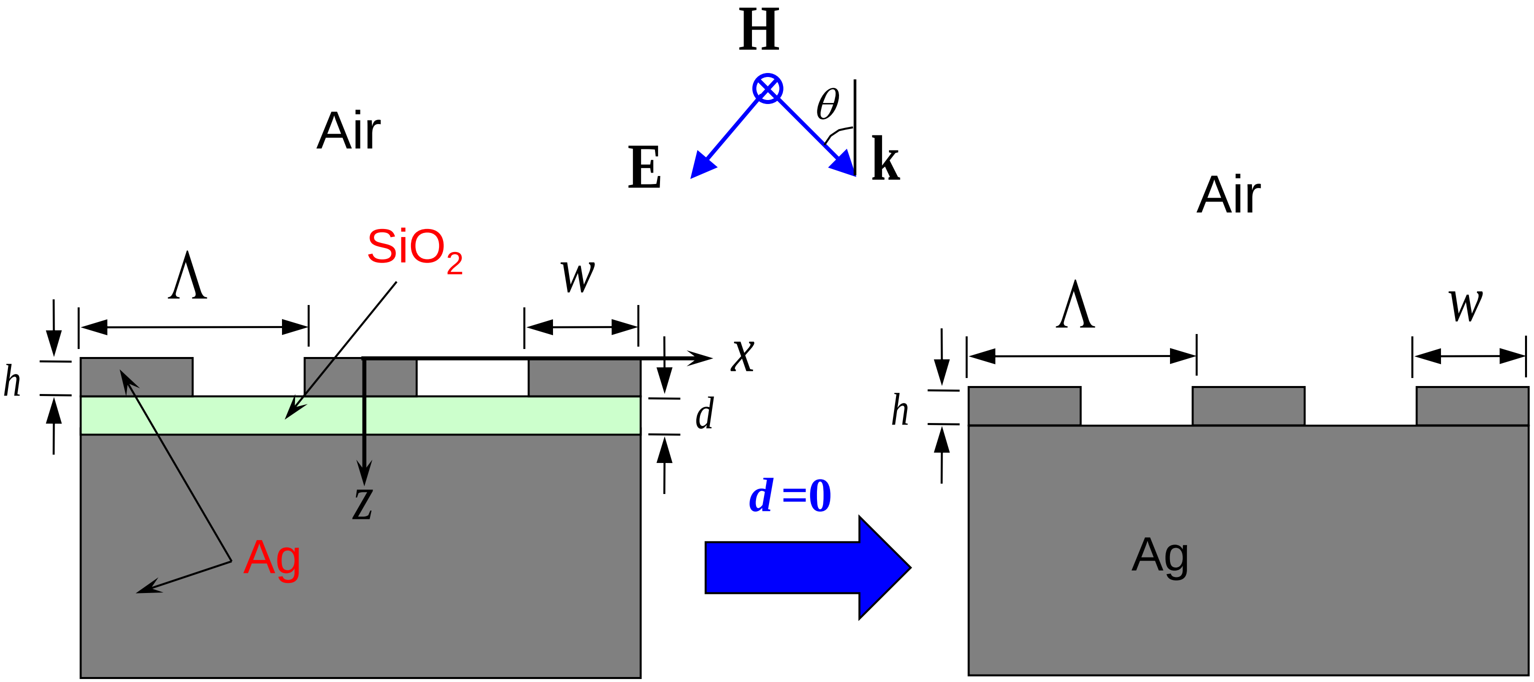
Negative magnetic permeability (relative to vacuum):

$$\mu(\omega) = 1 - \frac{F\omega^2}{\omega^2 - \omega_0^2 + i\gamma\omega}$$

Tailoring Optical and Radiative Properties

- Coherent Thermal Emission
- Unusual Transmission and IR Polarizers
- Phonon-Mediated MPs
- Thermophotovoltaic Emitters
- Measurements

Proposed Structure vs Simple Grating



Simple Grating

Parameters:

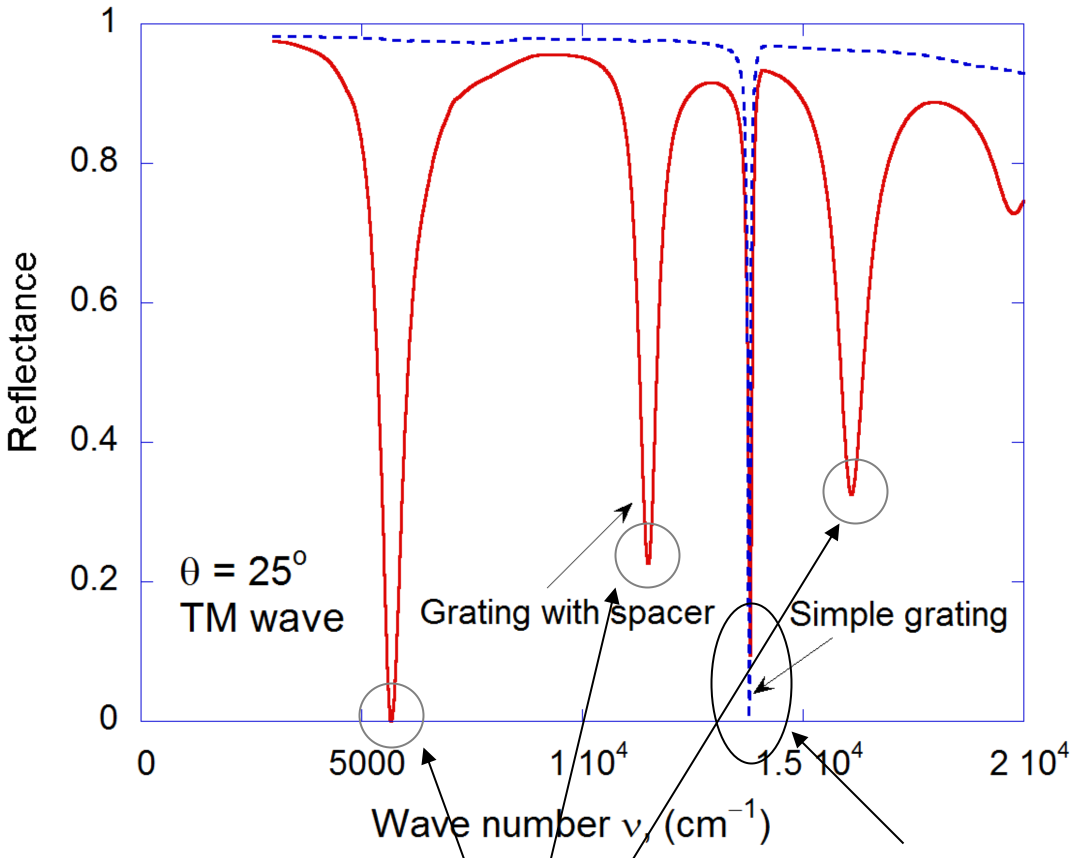
grating period Λ = 500 nm

metal strip width w = 250 nm

grating thickness h = 20 nm

spacer thickness d = 20 nm

Results



Magnetic polariton (MP)

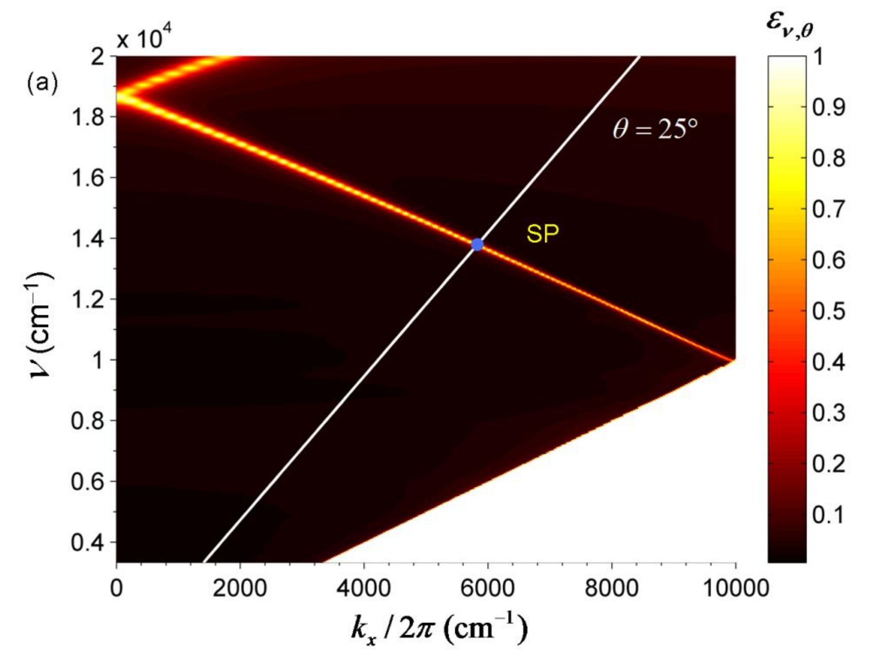
Surface plasmon polariton (SPP)

- Method:

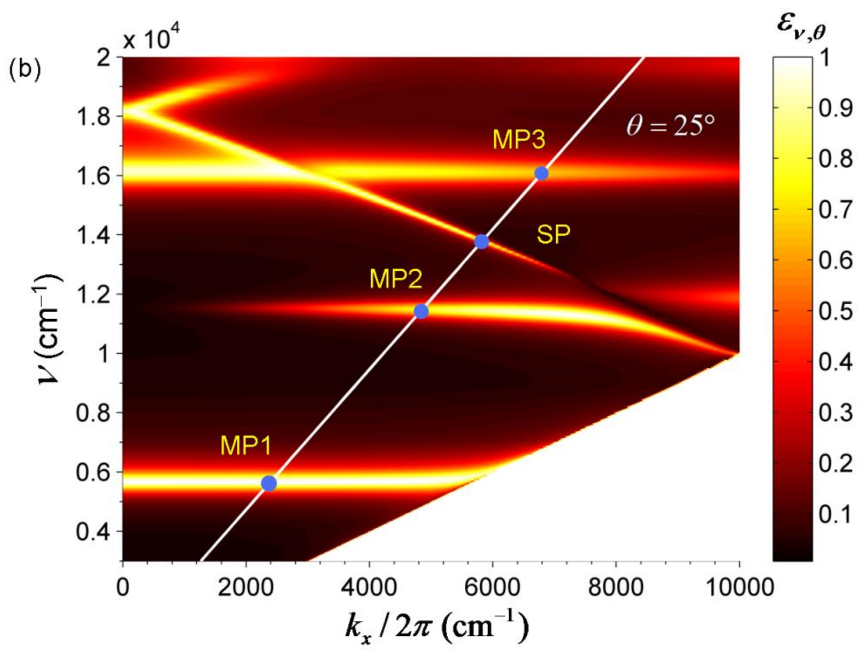
  Rigorous coupled-wave analysis (RCWA)

- The proposed structure has more reflectance dips comparing with the simple grating, which should result from surface magnetic polaritons.

Contour Plots of Emissivity



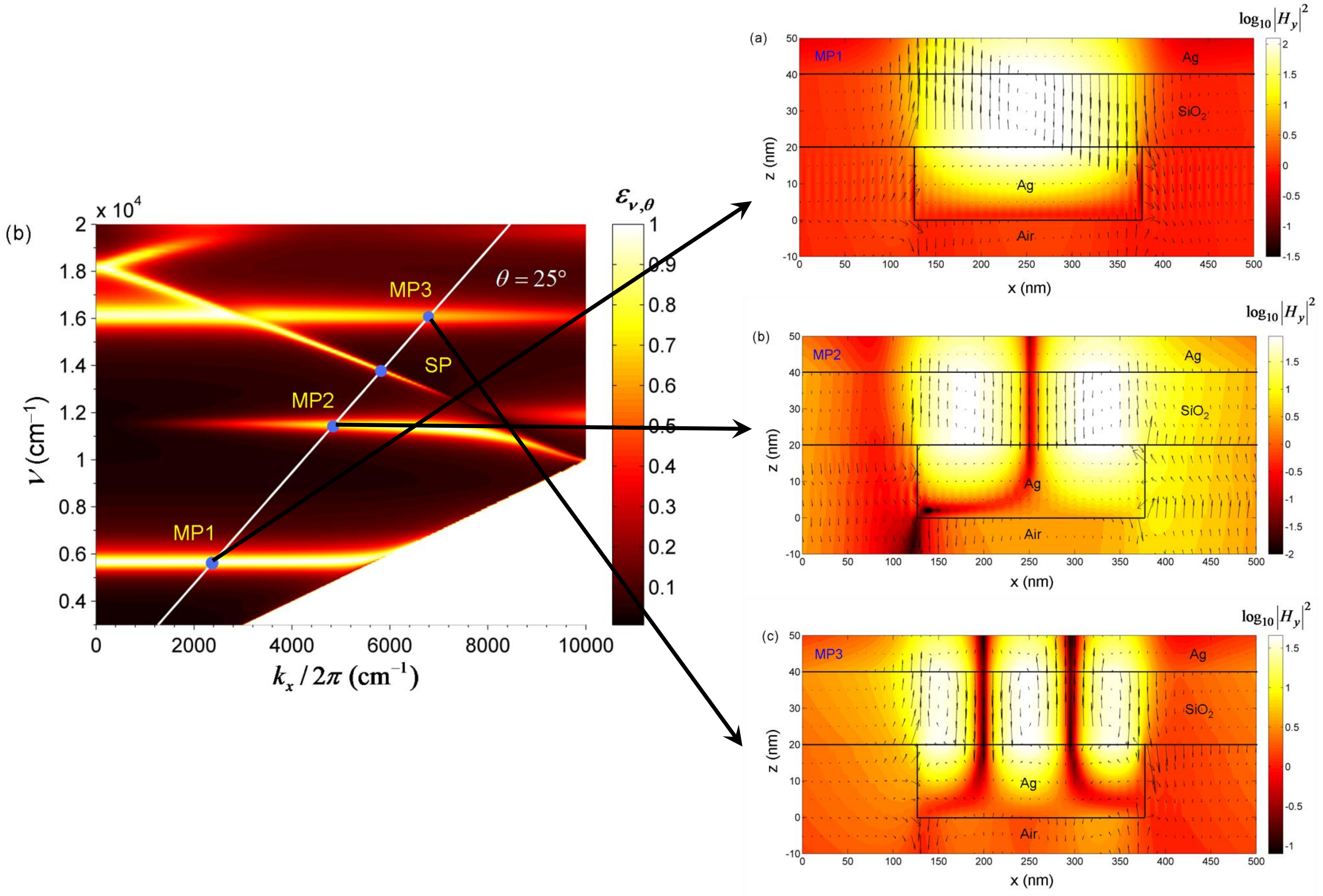
(a) Simple grating



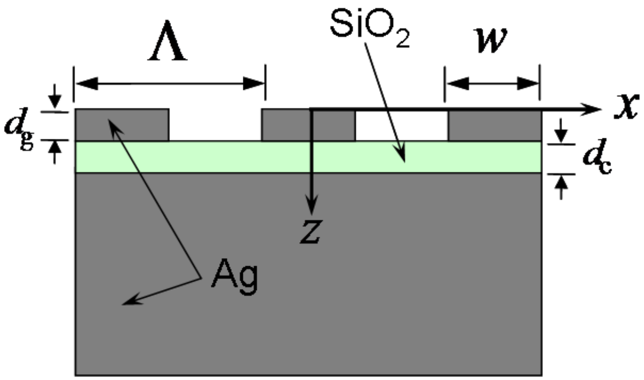
(b) Proposed structure

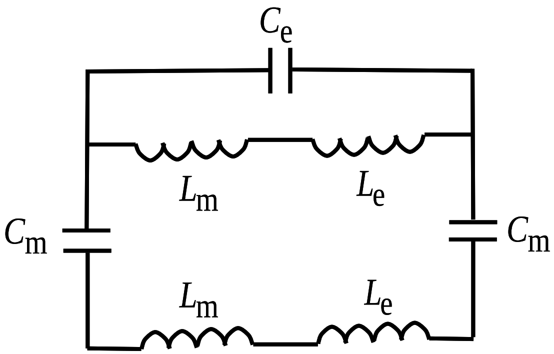
Lee, Wang, and Zhang, *Optics Express* **16**, 11328 (2008)

Multiple Modes of Resonance



Equivalent LC Circuit Model





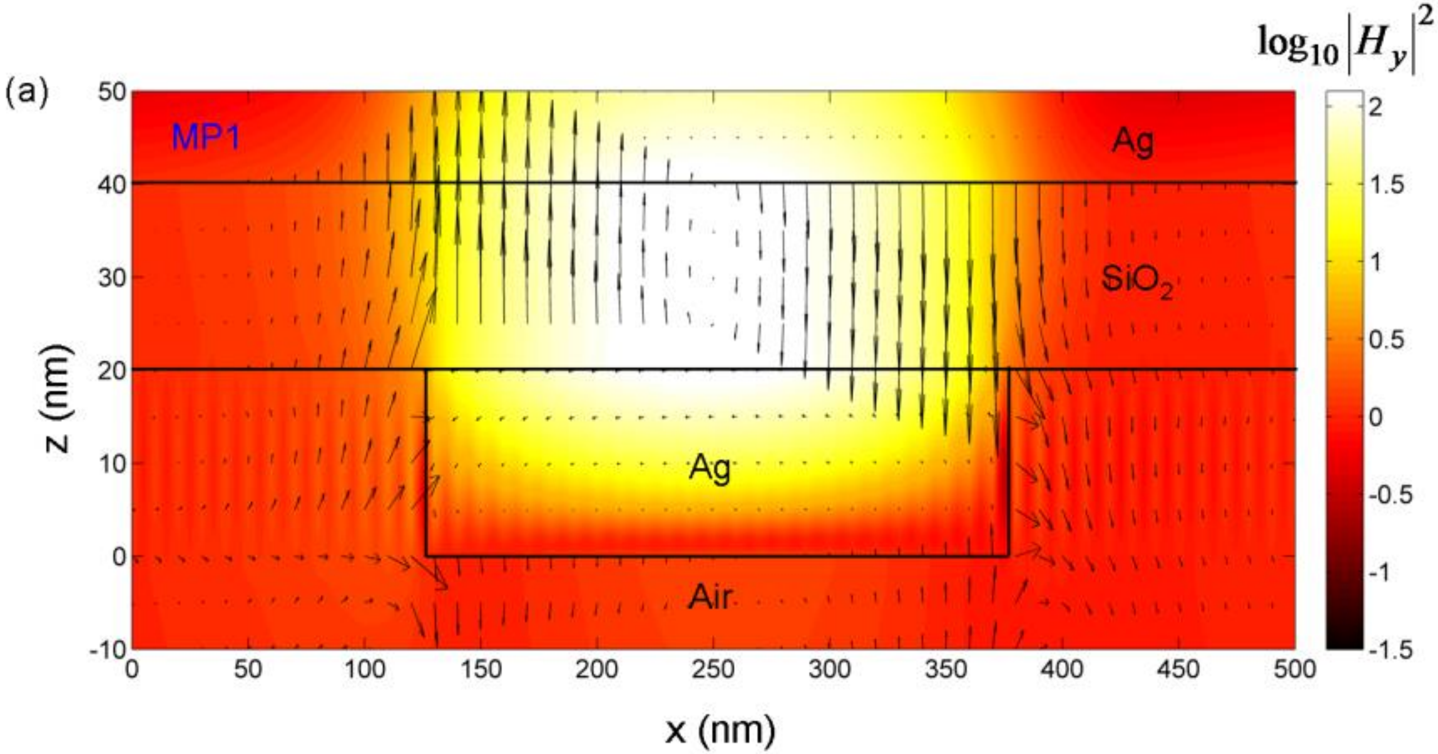
Resonance condition

$$Z_{\text{tot}} = \frac{i\omega\left(L_{\text{m}}+L_{\text{e}}\right)}{1-\omega^2 C_{\text{e}}\left(L_{\text{m}}+L_{\text{e}}\right)} - \frac{2i}{\omega C_{\text{m}}} + i\omega\left(L_{\text{m}}+L_{\text{e}}\right) \longrightarrow \omega_{\text{R}} = \left(\frac{C_{\text{m}}+C_{\text{e}}-\sqrt{C_{\text{m}}^2+C_{\text{e}}^2}}{(L_{\text{m}}+L_{\text{e}})C_{\text{m}}C_{\text{e}}}\right)^{1/2}$$

$$\text{where, } L_{\text{m}} = \frac{0.5\mu_0 dw}{l},\ L_{\text{e}} = \frac{w}{\gamma h l \omega_p^2 \varepsilon_0},\ C_{\text{m}} = \frac{0.222\varepsilon_{\text{d}}\varepsilon_0 wl}{d},\ \text{and } C_{\text{e}} = \frac{\pi\varepsilon_0 l}{\ln\left[(\Lambda - w)/h\right]}$$

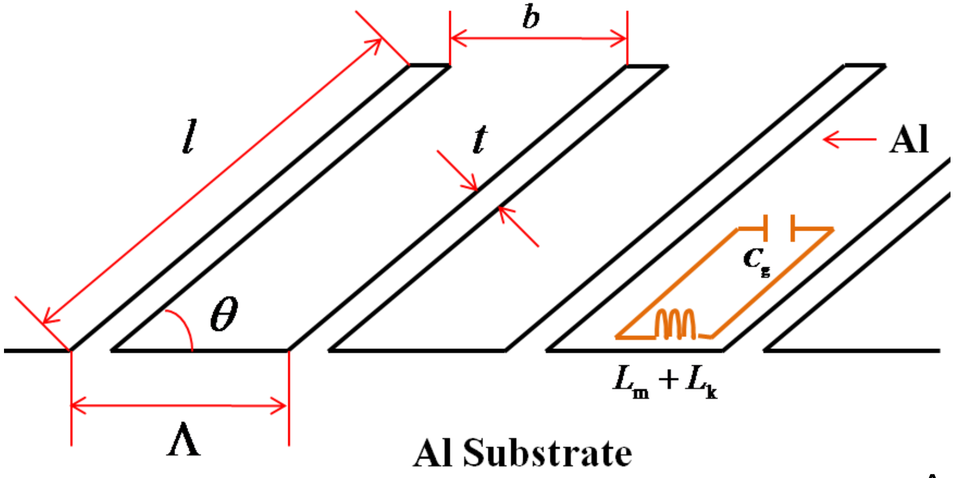
Lee, Wang, and Zhang, *Optics Express* **16**, 11328 (2008)

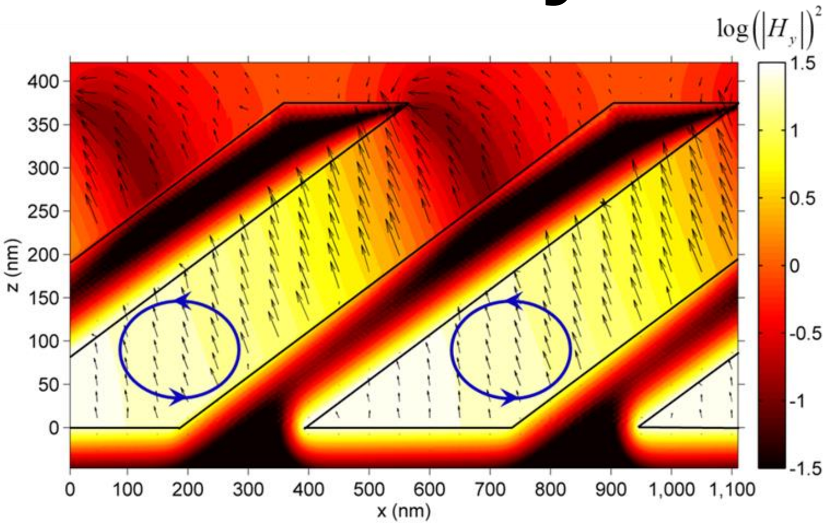
The coefficient in the C_m term

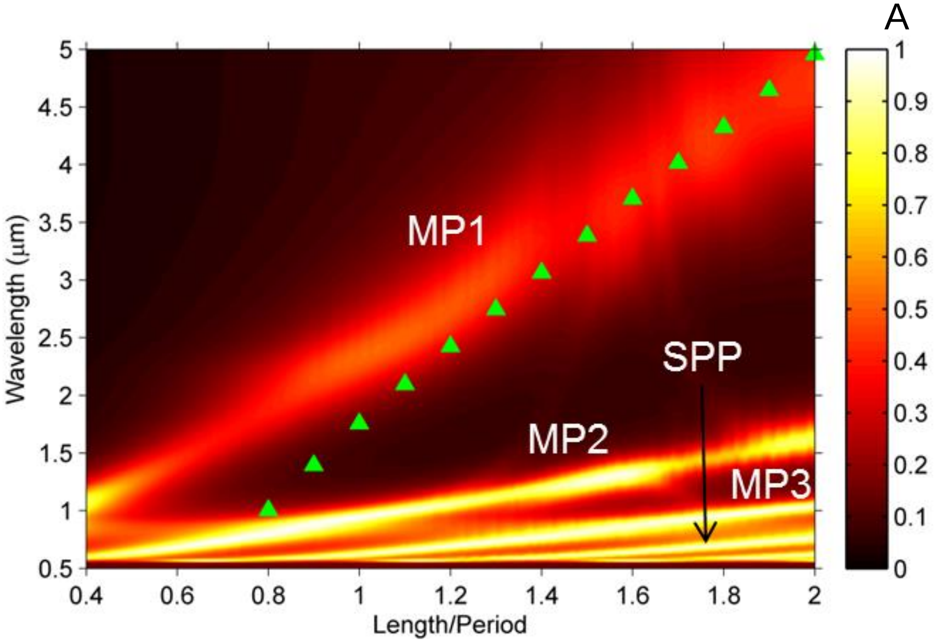


Parallel plate capacitance. The coefficient should be close to 0.25 in this case due to nonuniform charge distribution.

Inclined Aluminum Plate Arrays





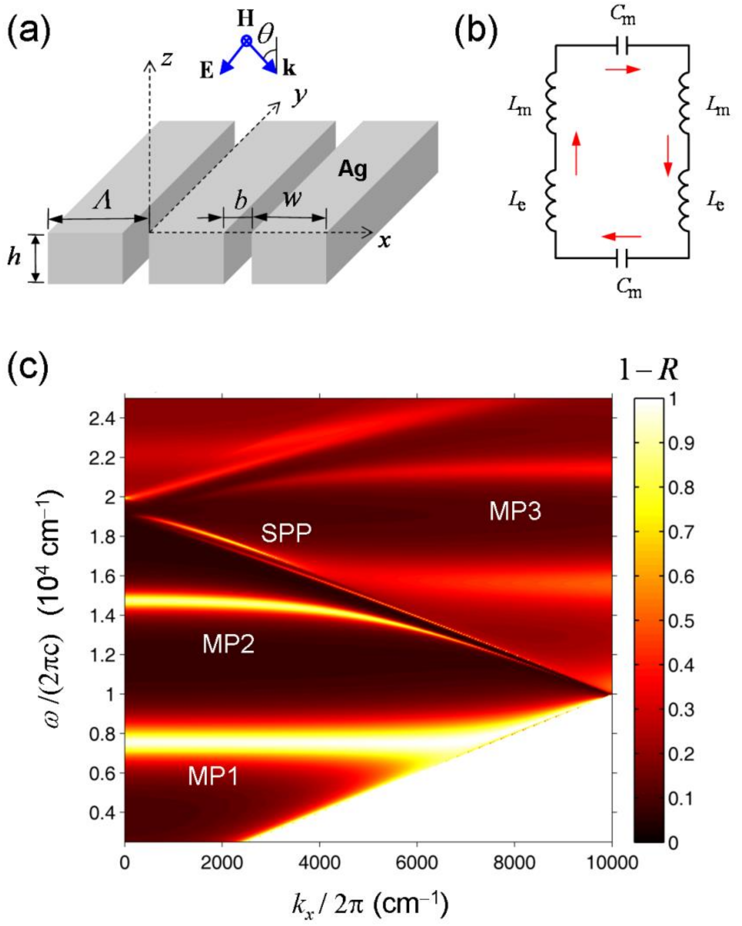


(Upper) Field distribution.

(Left) Absorptance contour and the triangle marks are from LC prediction.

For details, see Wang et al. *JQSRT* (2013 in press).

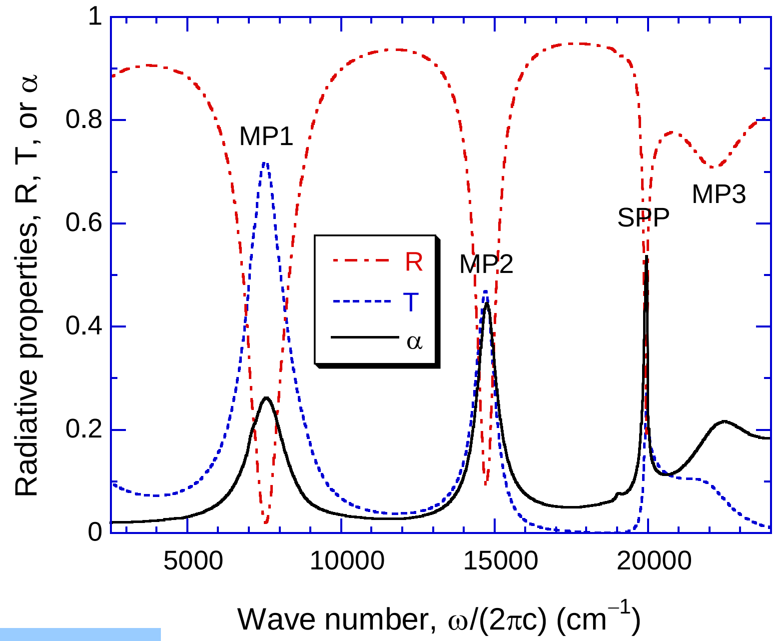
Resonance Transmission in Deep Gratings



$$Z_{\mathrm{tot}} = 2i\left[\omega(L_{\mathrm{m}} + L_{\mathrm{e}}) - (\omega C_{\mathrm{m}})^{-1}\right]$$

$$\omega_{\mathrm{R}} = \left[(L_{\mathrm{m}} + L_{\mathrm{e}})C_{\mathrm{m}}\right]^{-1/2}$$

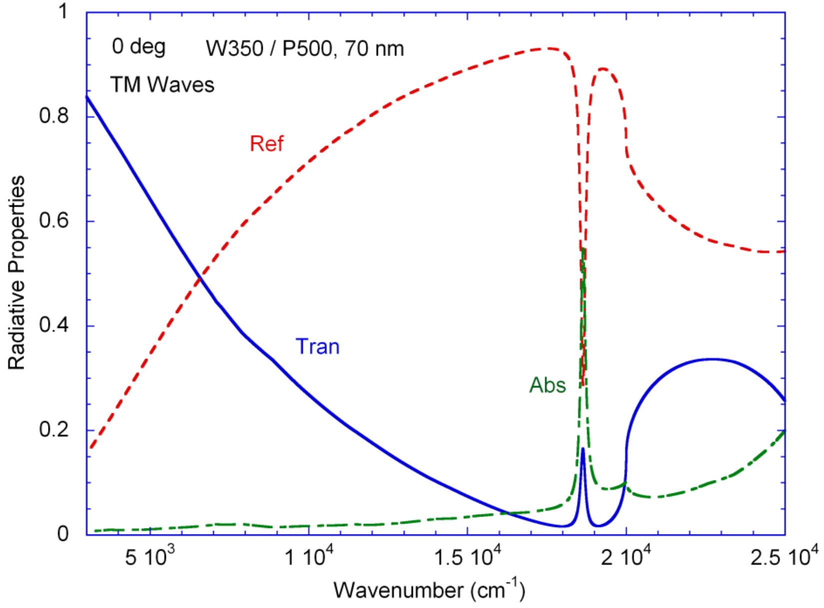
$$\alpha = 1 - R - T$$

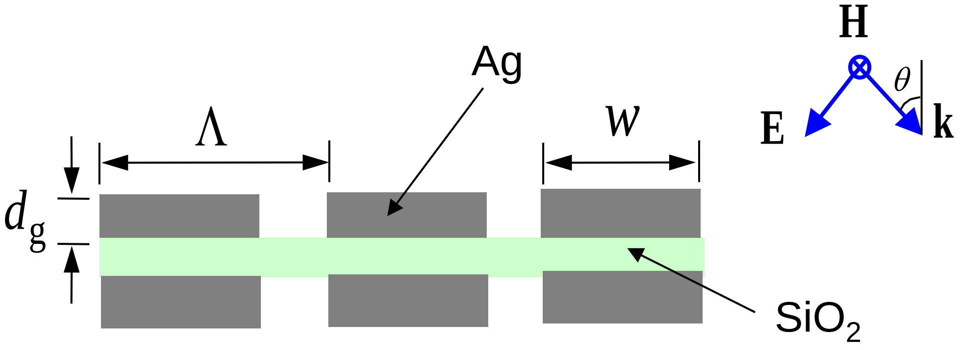


Wang and Zhang, *Appl. Phys. Lett.* (2009)

Tailoring Transmittance

1 layer nanoslit

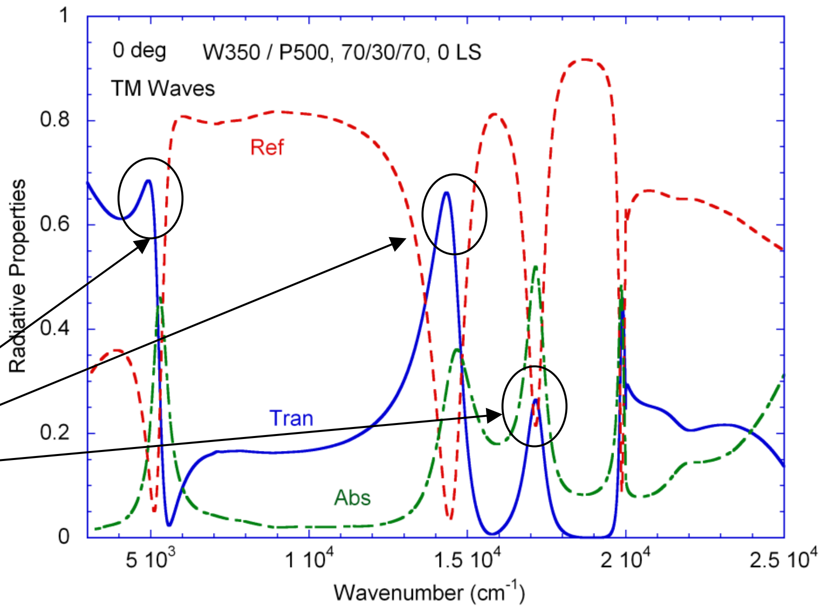




w = 350 nm

Λ = 500 nm

2 layer nanoslits

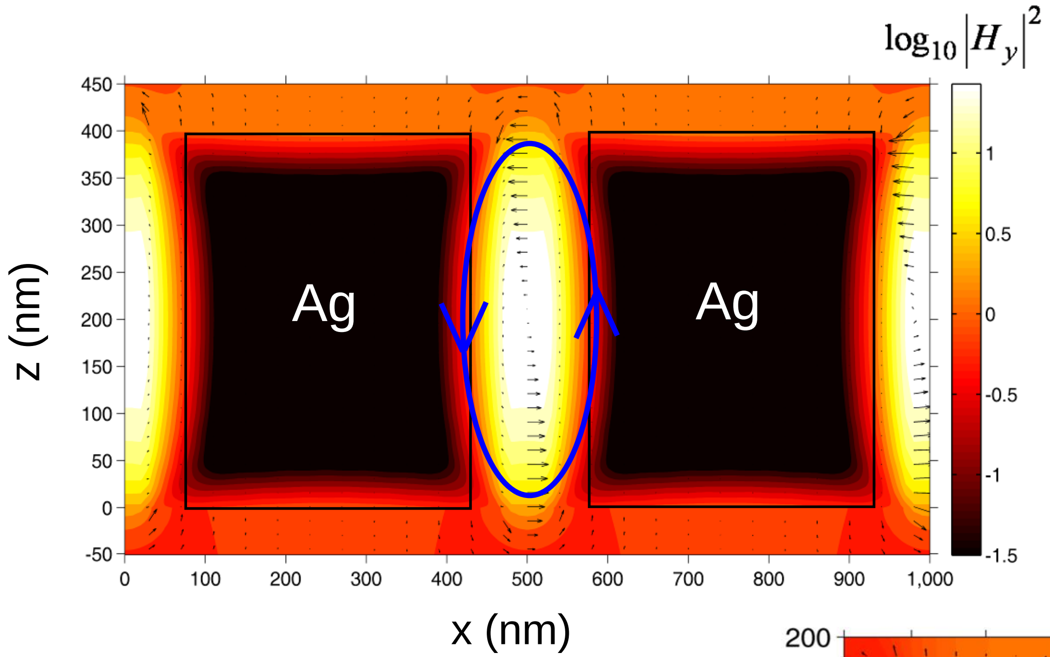


We show see next that these are due to the excitation of magnetic polaritons!

Transmission enhancement

Wang and Zhang, *JOSA_B* (2010)

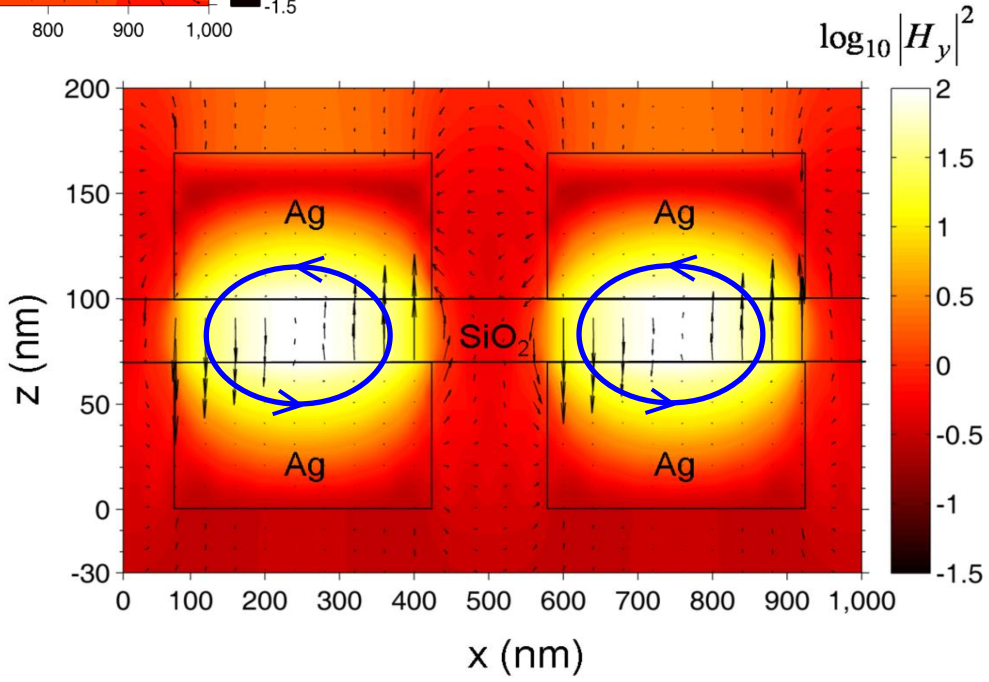
EM Field Distribution: MP1



Simple gratings

at normal incidence

Diamagnetic behavior!

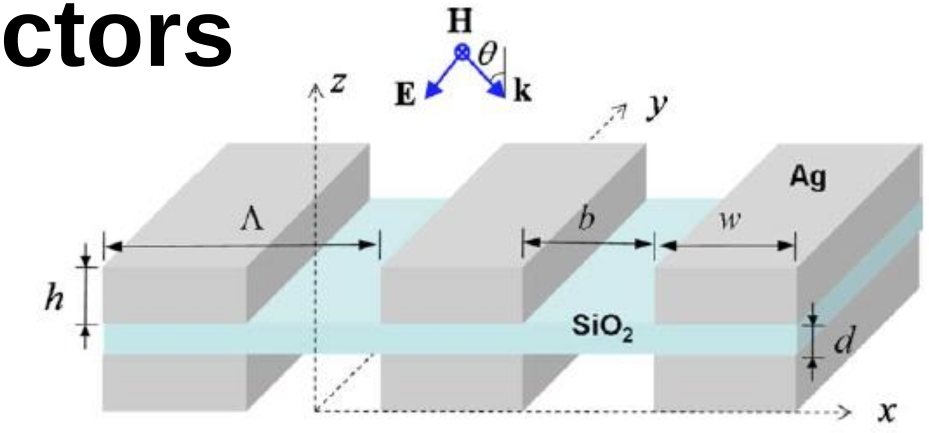


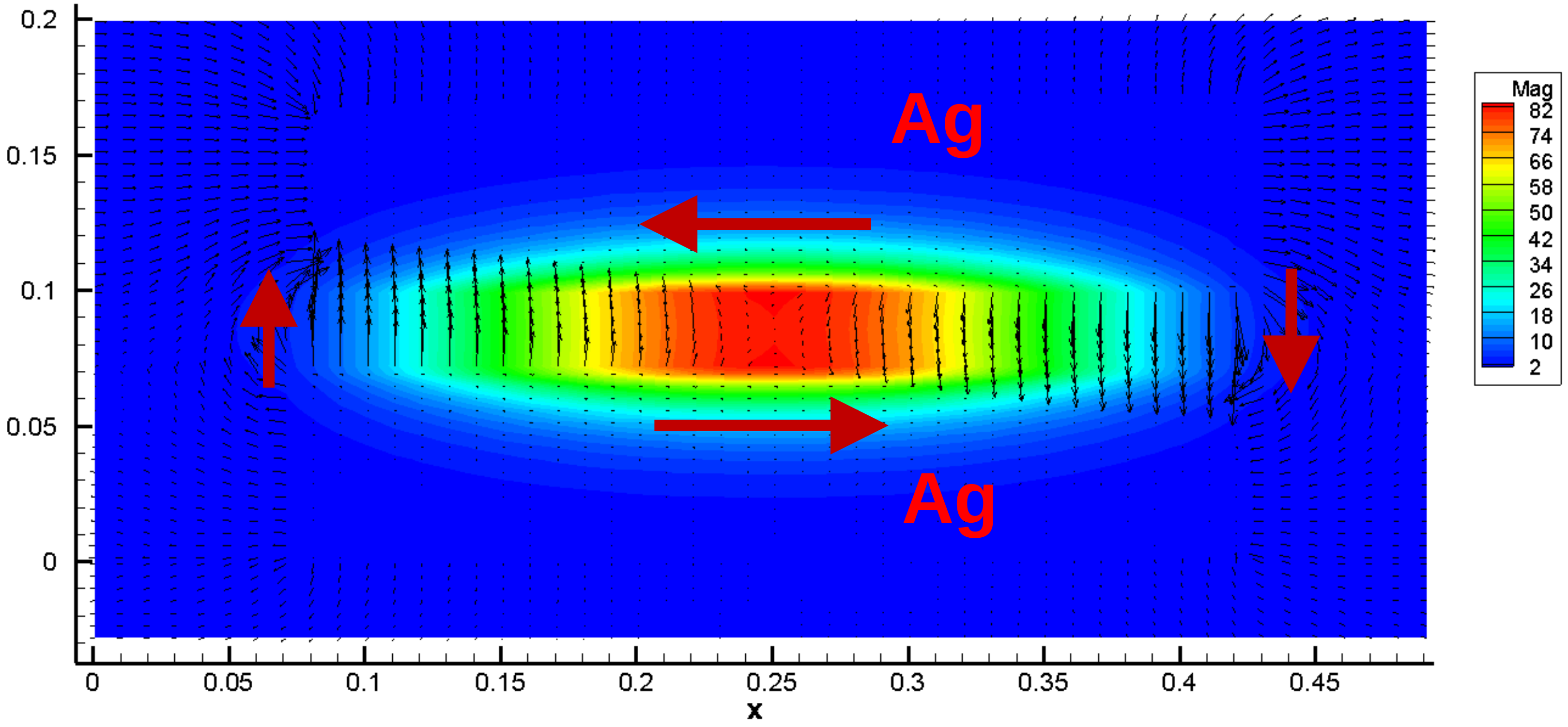
Double-layer slit array

at normal incidence

Electric Field Vectors

Λ = 500 nm, w = 350 nm,
d = 30 nm, h = 70 nm.
MP1 is @ 5120 cm^{-1}





Electric field vectors do not form a loop

Electric Field Vectors and Current Density Vectors

The complex conductivity can be expressed as :

$$\sigma = \sigma' + i\sigma'' = \omega\varepsilon_0(\varepsilon'' - i\varepsilon')$$

Full current density is :

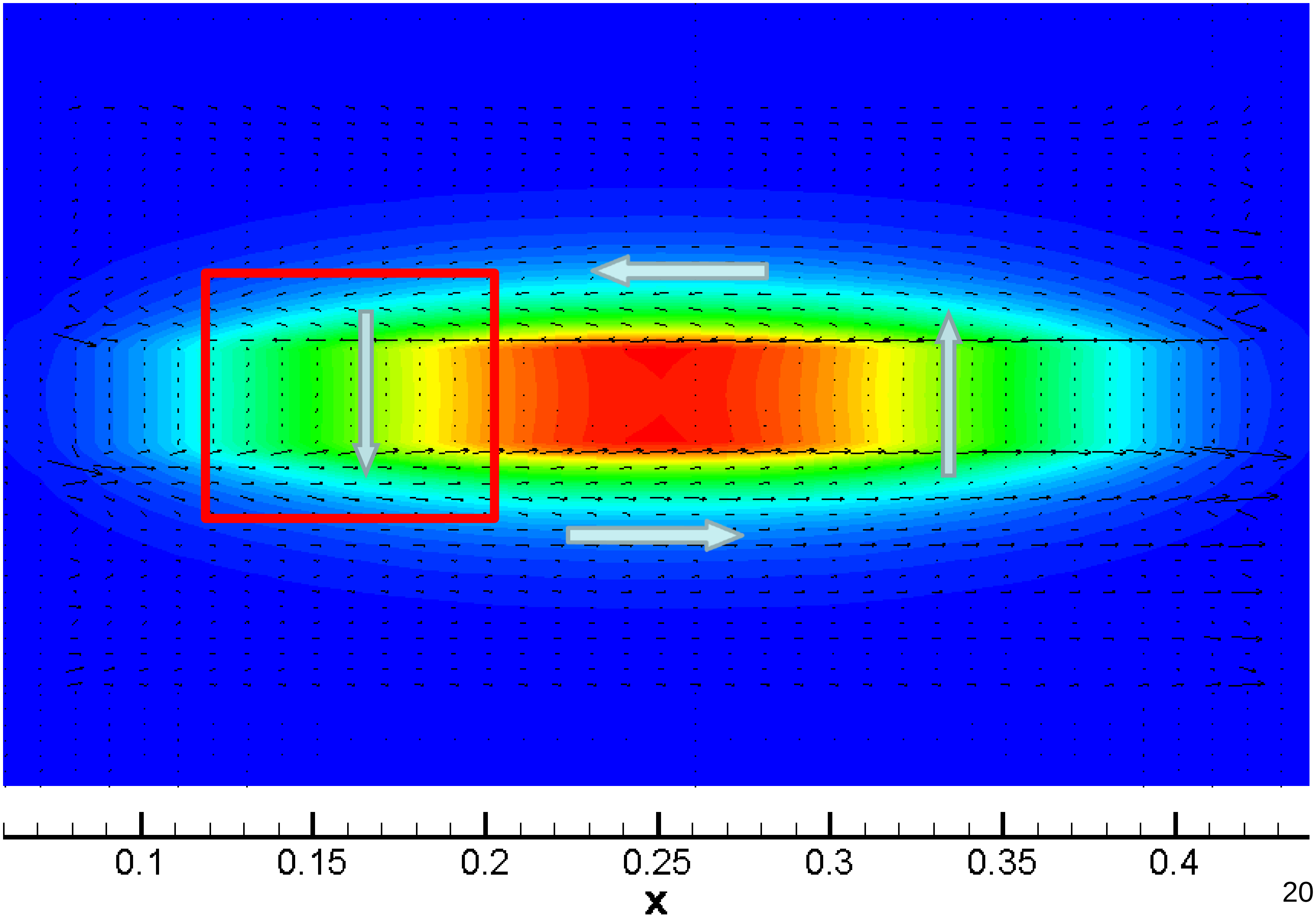
$$\mathbf{J} = \sigma\mathbf{E} = \mathbf{j}_0 + \frac{\partial \mathbf{D}}{\partial t}$$

Note that **J** includes both the conductive current density due to free charge and the displacement current density, which is

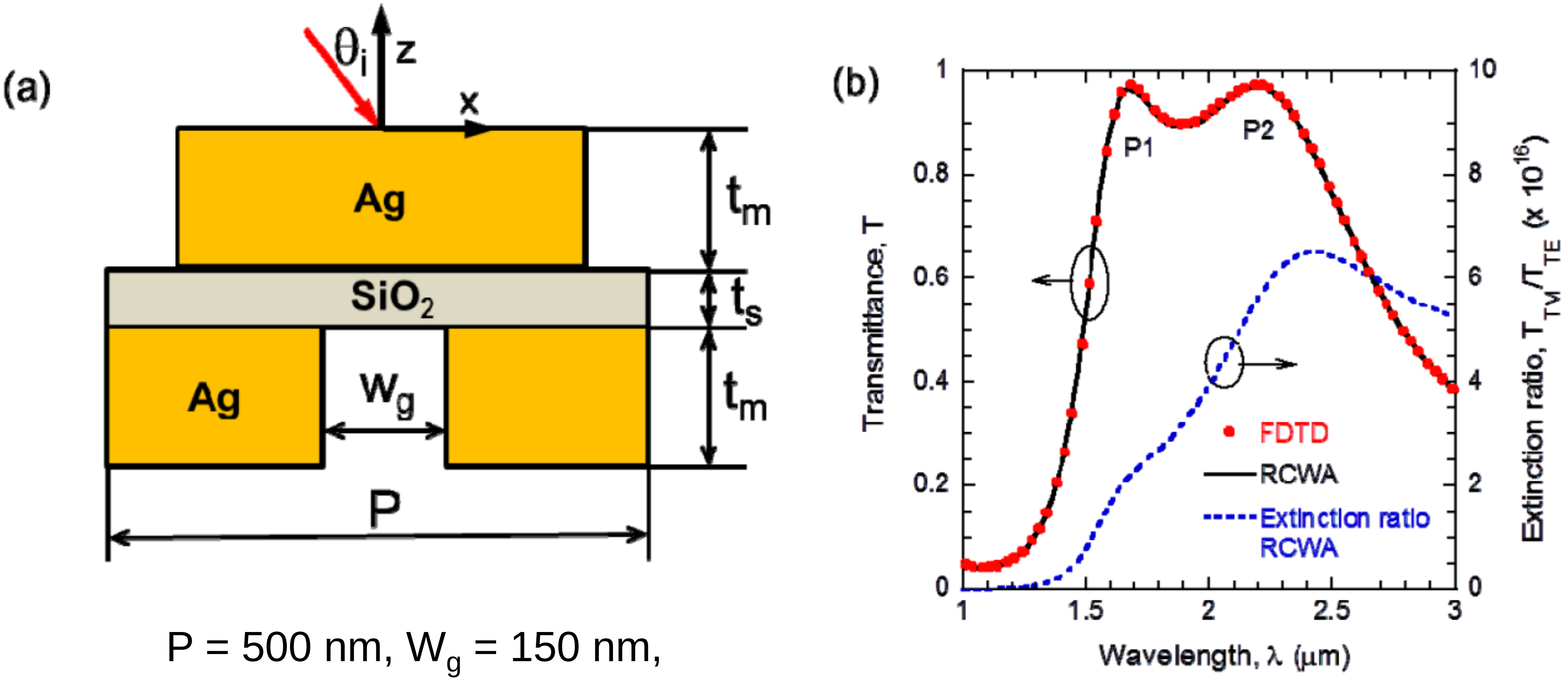
$$\mathbf{J}_{\mathrm{D}} = \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \frac{\partial \mathbf{P}}{\partial t}$$

$$\mathbf{J} = \sigma\mathbf{E} = \left(\sigma' + i\sigma''\right)\left(\mathbf{E}' + i\mathbf{E}''\right) = \sigma'\mathbf{E}' - \sigma''\mathbf{E}'' + imag(\mathbf{J})$$

Current Density Vectors Do Form a Loop



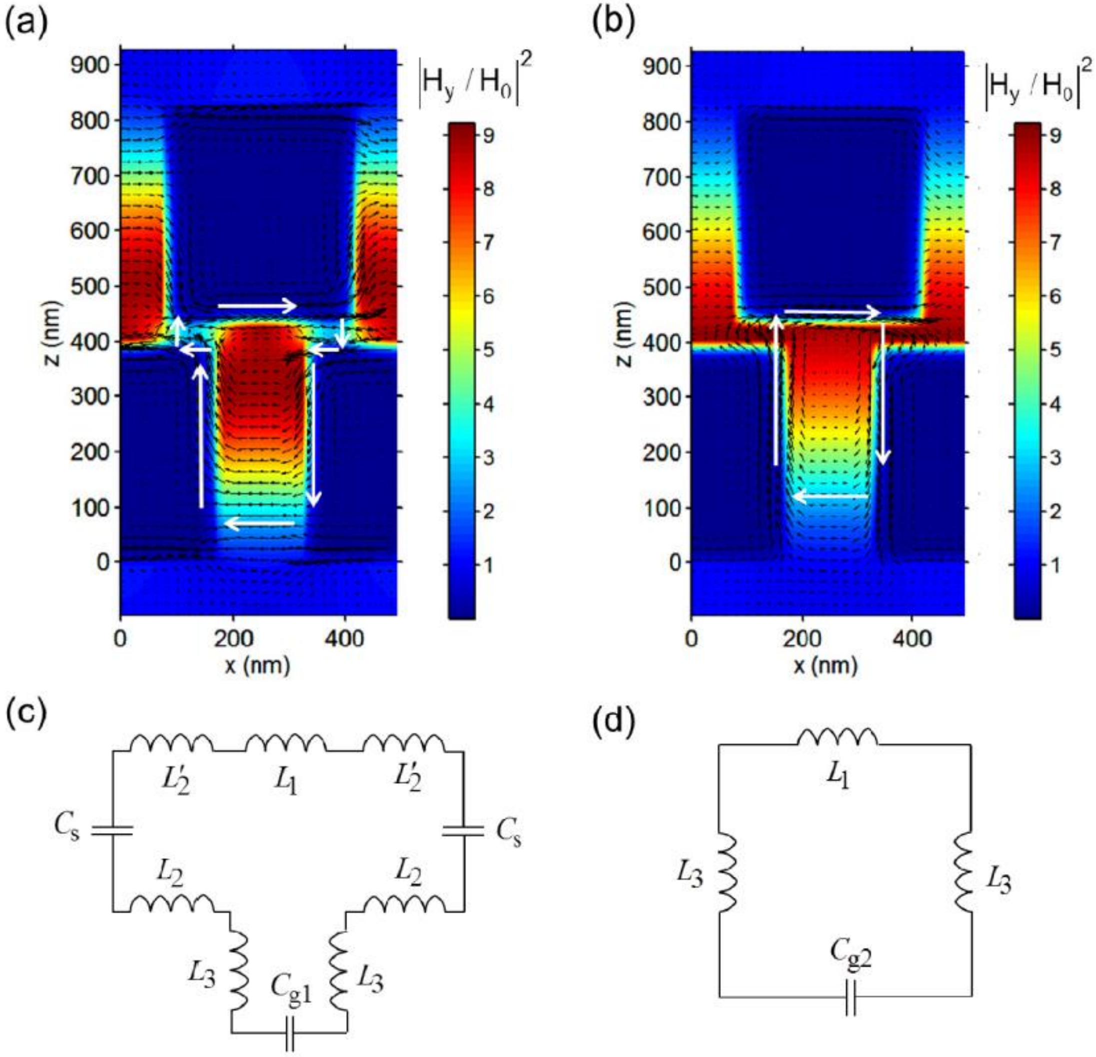
Near-IR Polarizer with Very High Extinction Ratio



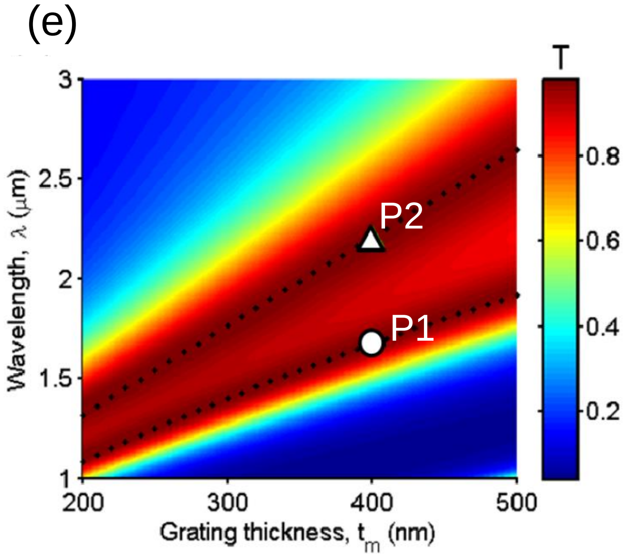
P = 500 nm, W_g = 150 nm,
t_m = 400 nm, and t_s = 30 nm

Liu, Zhao, and Zhang, *Optics Express* **21**, 10502 (2013)

Field Distributions and LC Models



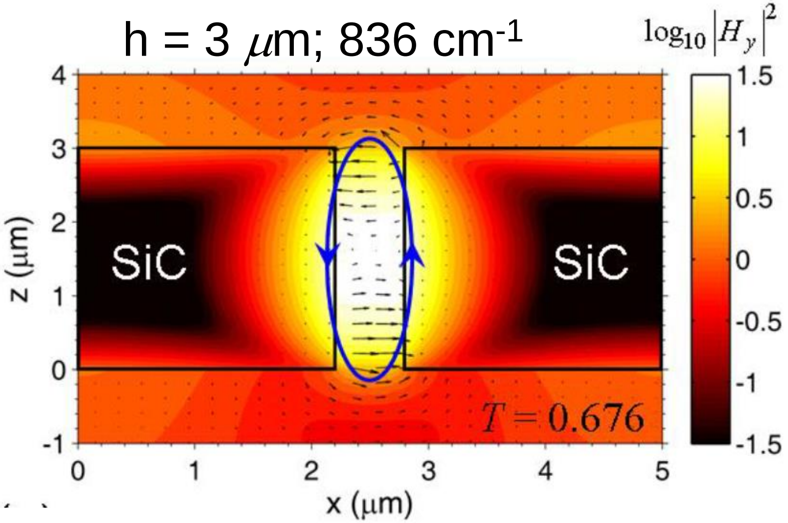
Simple LC models allow the prediction of resonance requencies for both P1 and P2 (below):

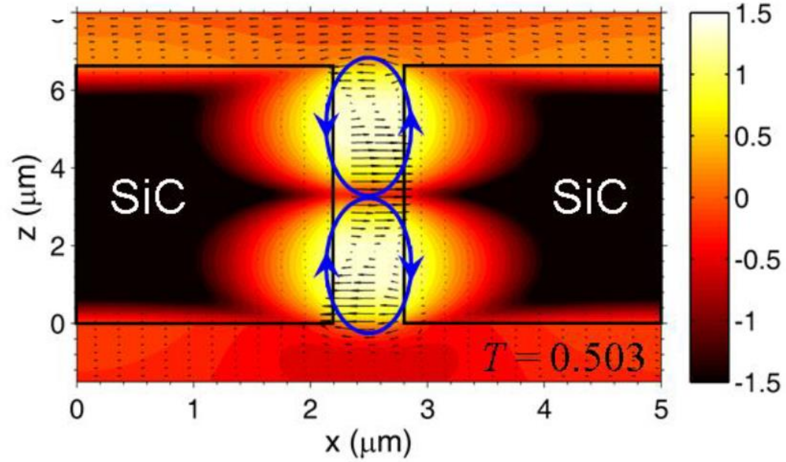


Liu, Zhao, and Zhang, *Optics Express* **21**, 10502 (2013)

Phonon-mediated MPs in SiC Slit Arrays

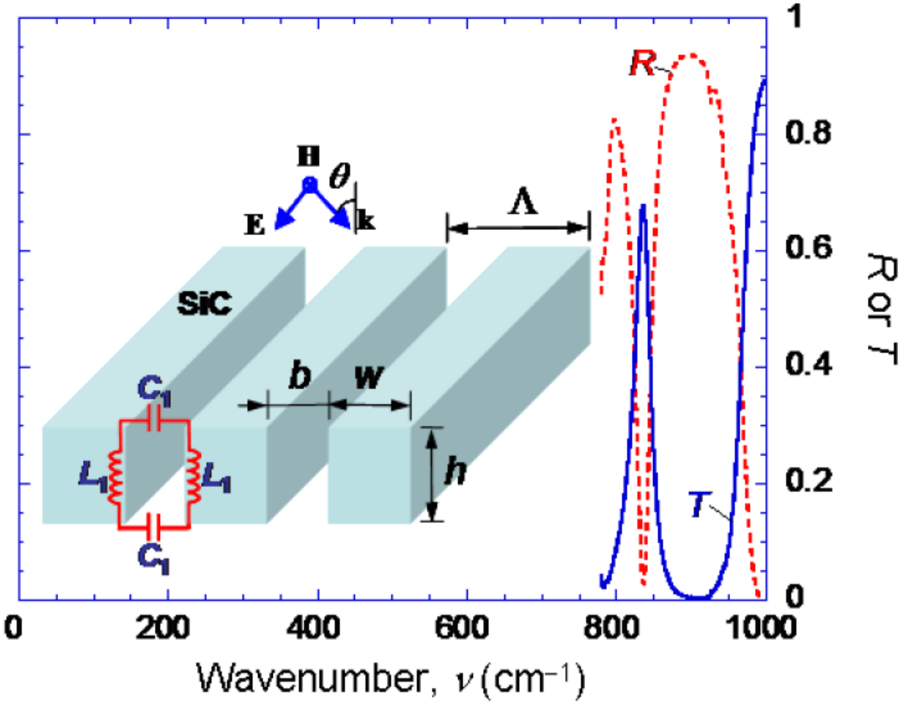
$h = 3\ \mu m$; 836 cm^{-1}





$h = 6.6\ \mu m$; 836 cm^{-1}

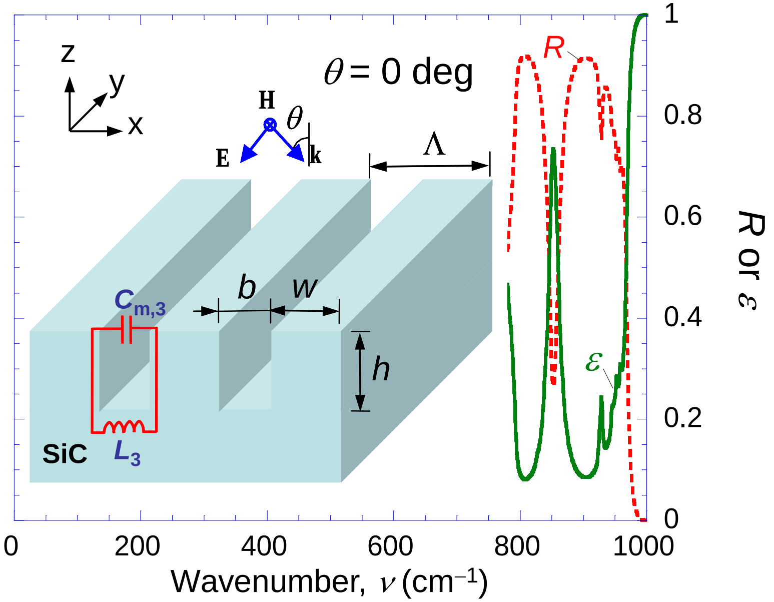
$\Lambda = 5\ \mu m$; $w = 4.5\ \mu m$; $h = 3\ \mu m$



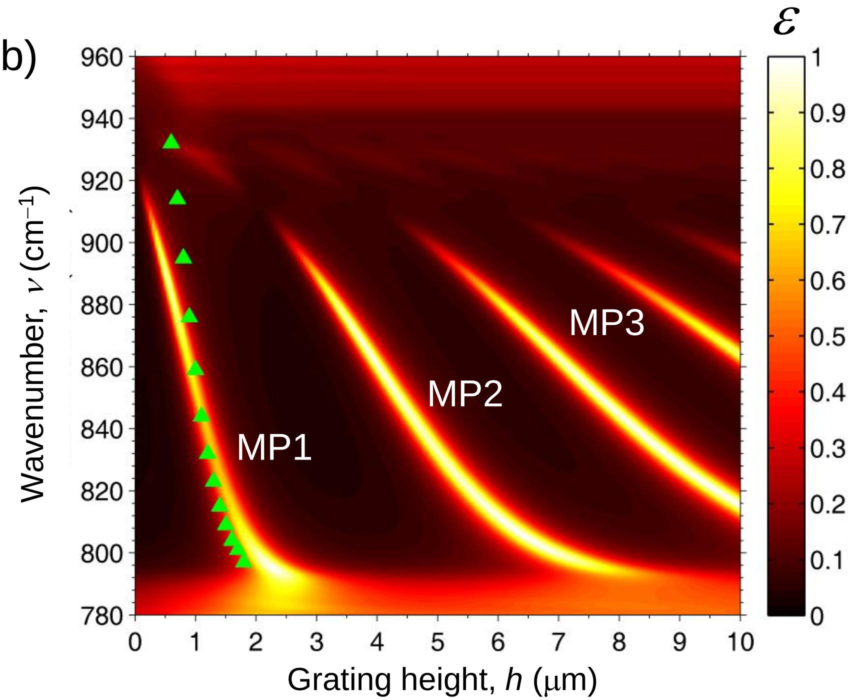
Wang and Zhang, *Opt. Express* **19**, A126 (2011)

Phonon-mediated MPs in SiC Gratings

(a) $\Lambda = 5\ \mu\text{m},\ w = 4.5\ \mu\text{m},\ h = 1\ \mu\text{m}$



(b)



***LC* model for MP1:**

$$L_{\mathrm{m,coil}} = \mu_0 hb/l,\quad \boxed{L_{\mathrm{k,ph}} = -(2h+b)/(\omega^2\varepsilon_0\varepsilon' l\delta),\ \text{where}\ \varepsilon_{\mathrm{SiC}} = \varepsilon' + i\varepsilon''}$$

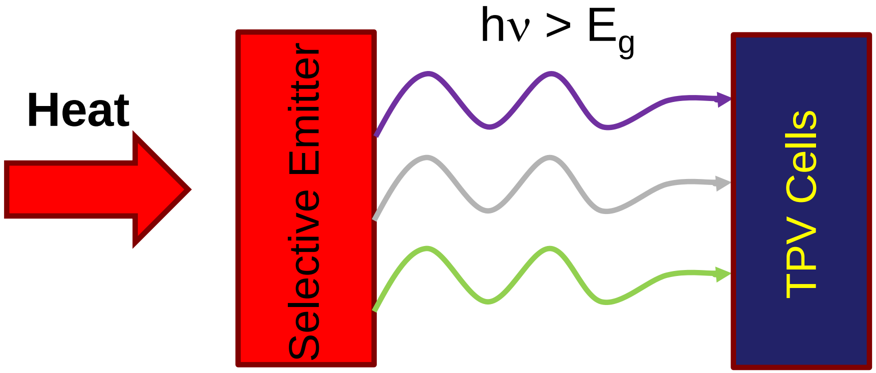
$$C_{\mathrm{m,3}} = c_2\varepsilon_0 hl/b,\ \text{where}\ c_2 = 0.55$$

Cannot use plasma frequency for L_k.

Total impedance: $$Z_{\mathrm{tot}} = i\omega\left(L_{\mathrm{m,coil}} + L_{\mathrm{k,ph}} - \frac{1}{\omega^2 C_{\mathrm{m,3}}}\right) = 0$$

Wang and Zhang, *Opt. Express* **19**, A126 (2011)

Thermophotovoltaic (TPV) System

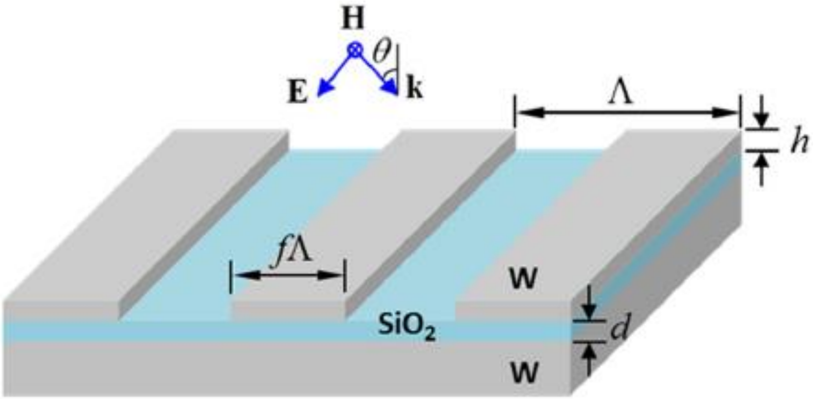


Only photons with energy higher than E_g of the TPV cells can be absorbed to generate electron-hole pairs.

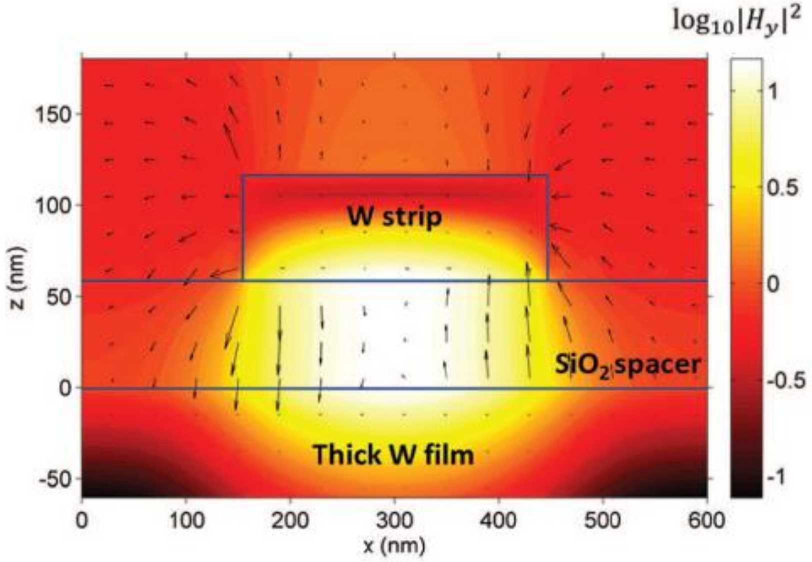
TPV Cell Material	Bandgap E_g (ev) / (μm)
GaSb	0.72 / 1.72
$In_xGa_{1-x}Sb$	0.17 - 0.72 / 7.29 – 1.72
$In_xGa_{1-x}As$	0.36 – 1.42 / 3.44 – 0.87
……	……

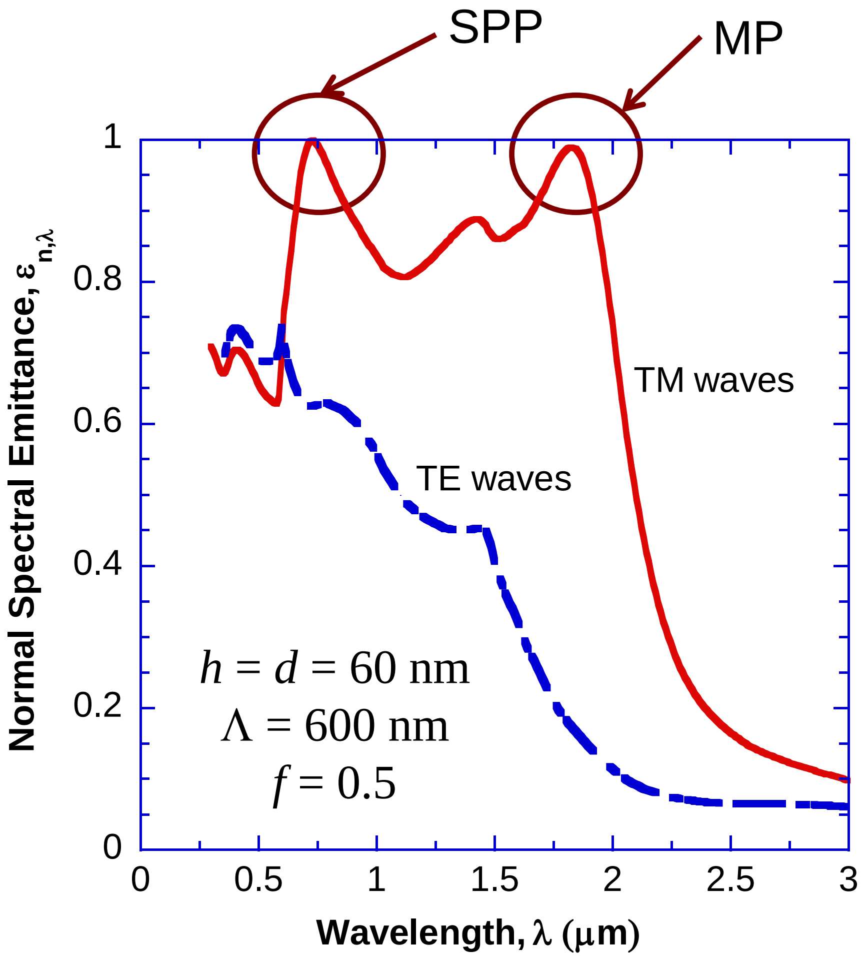
See for example, Basu et al., 2007, *Int. J. Energy Res.* **31**, pp. 689-716.

Microstructures as TPV Emitters



1D tungsten grating/film metameterial

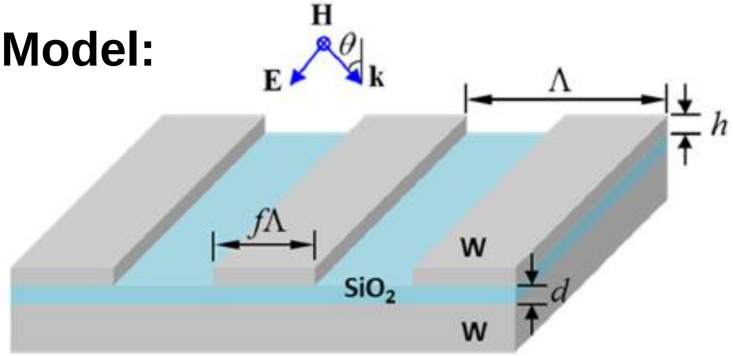


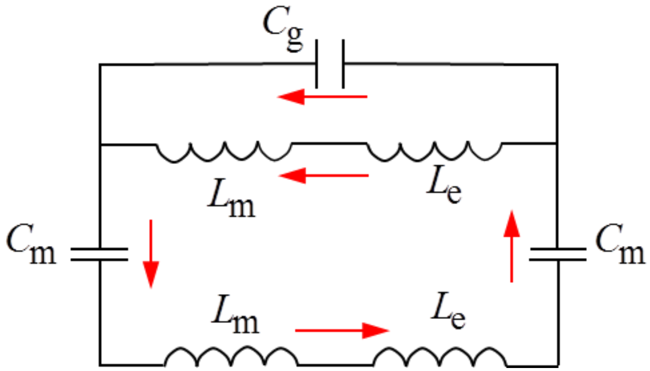


Wang and Zhang, 2012, *Appl. Phys. Lett.* **100,** p. 063902 .

LC Circuit Model and Current Density Loop for MP Resonance

LC Model:





$$Z_{tot}(\omega) = \frac{L_m + L_e}{1 - \omega^2 C_g (L_m + L_e)} - \frac{2}{\omega^2 C_m} + L_m + L_e = 0 \quad \Longrightarrow \quad \lambda_{MP} = 1.873\ \mu\text{m}$$

Current Density:

$$\sigma = \sigma' + i\sigma'' = \omega\varepsilon_0(\varepsilon'' - i\varepsilon') = -i\omega\varepsilon\varepsilon_0$$

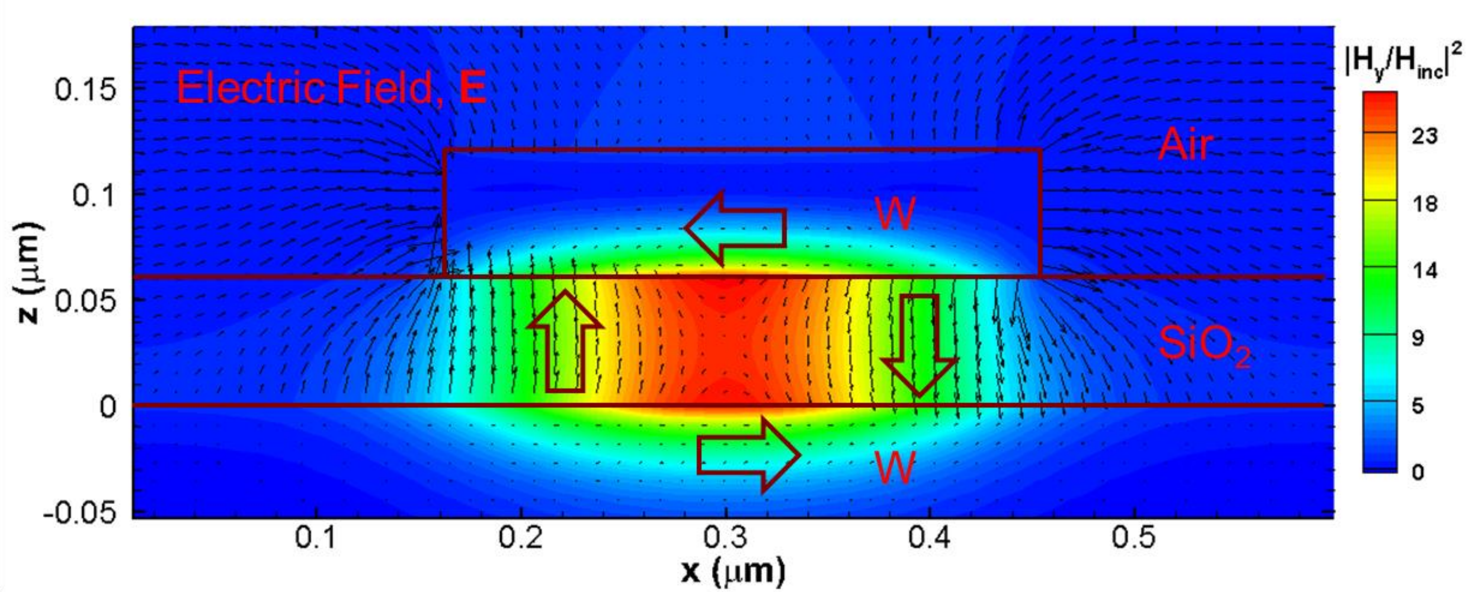
$$\mathbf{J} = \sigma\mathbf{E} = (\sigma' + i\sigma'')(\mathbf{E}' + i\mathbf{E}'') = \boxed{\sigma'\mathbf{E}'} - \boxed{\sigma''\mathbf{E}''} + imag(\mathbf{J})$$

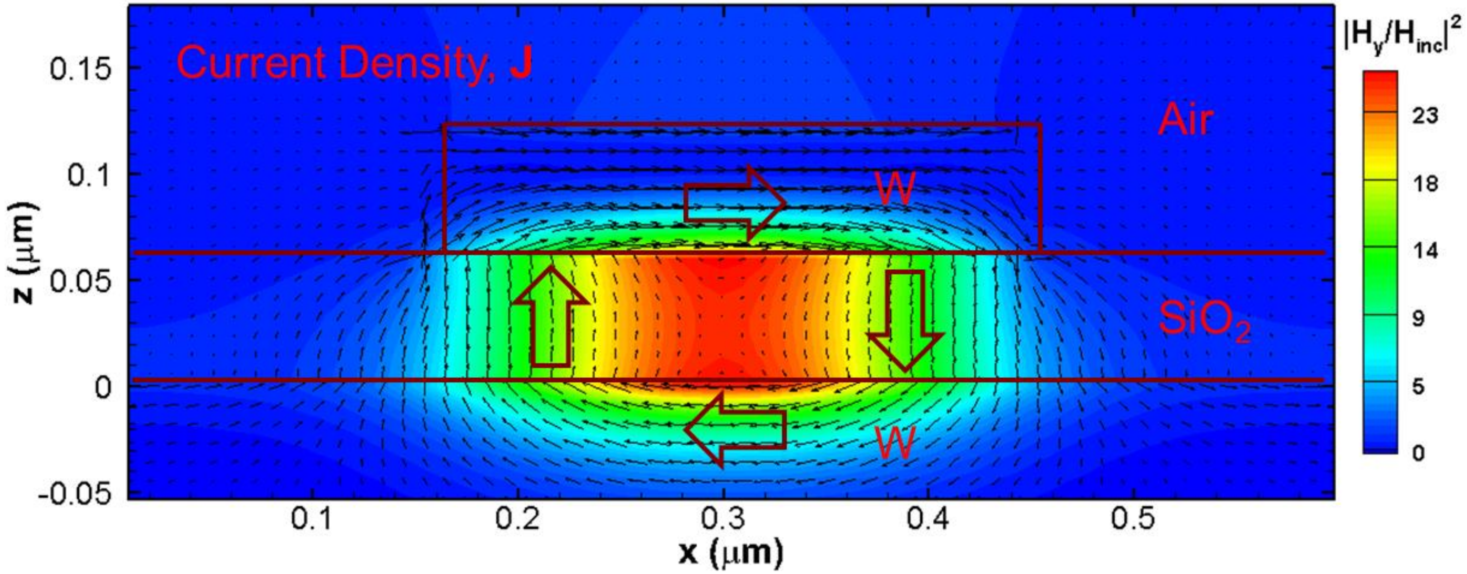
free current density

displacement current density

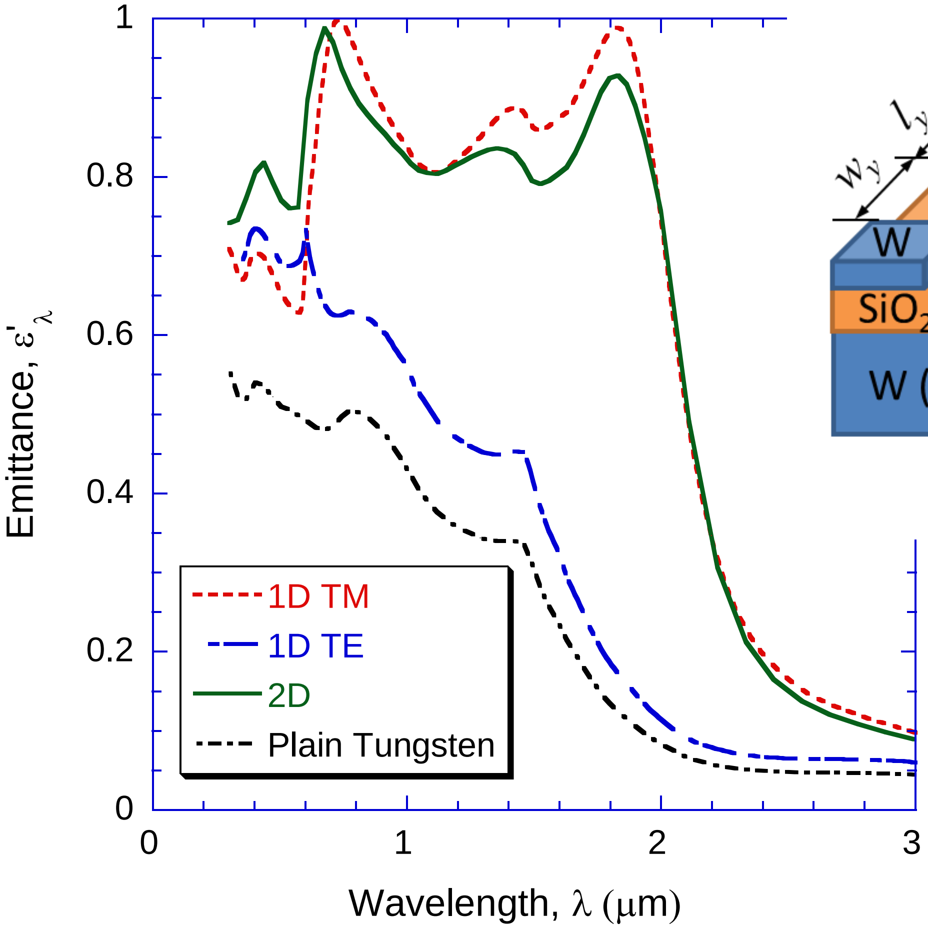
Field Distributions and Current Loop

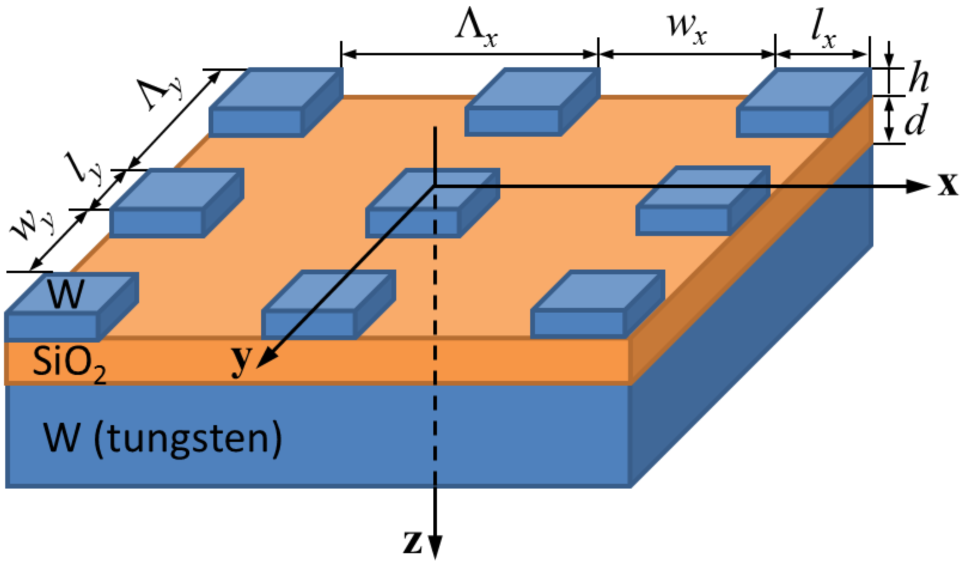
Inside W, E and J have different signs





Normal, Spectral Emittance

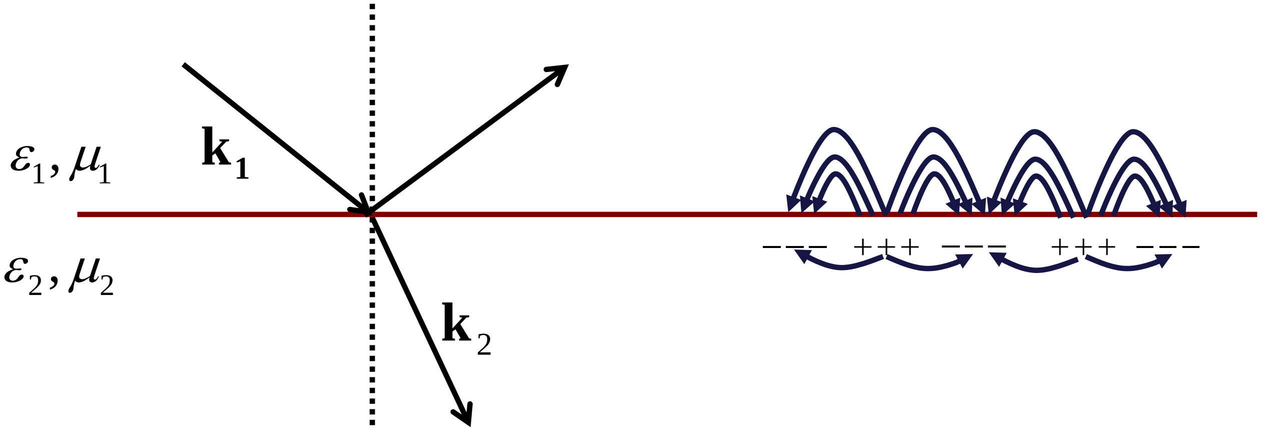


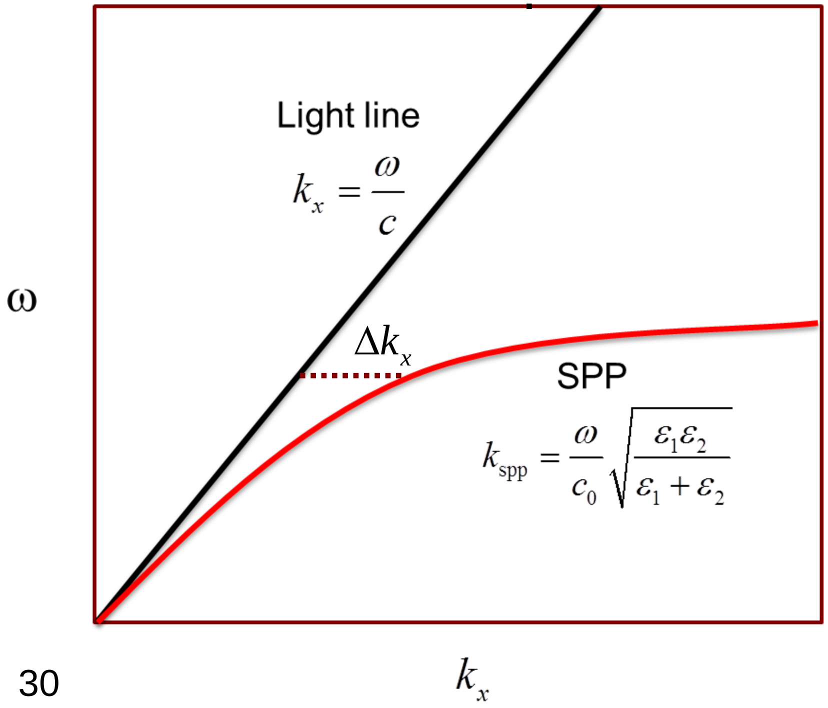


2D gratings will work well for both polarizations !

Zhao et al., submitted to *Int J Heat Mass Transfer* (2013)

Surface Plasmon Polaritons on Gratings





Wave vector of SPP:

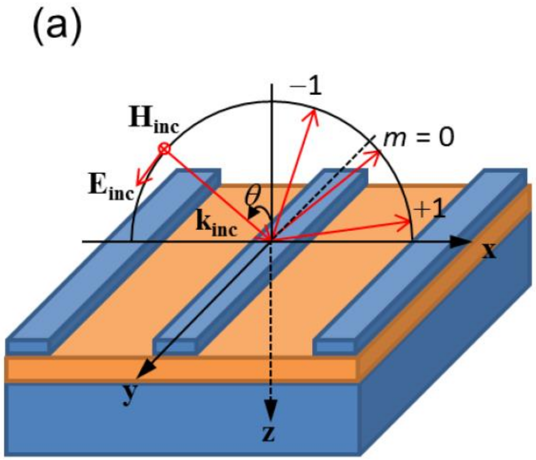
$$k_{\mathrm{spp}} = \frac{\omega}{c_0}\sqrt{\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}}$$

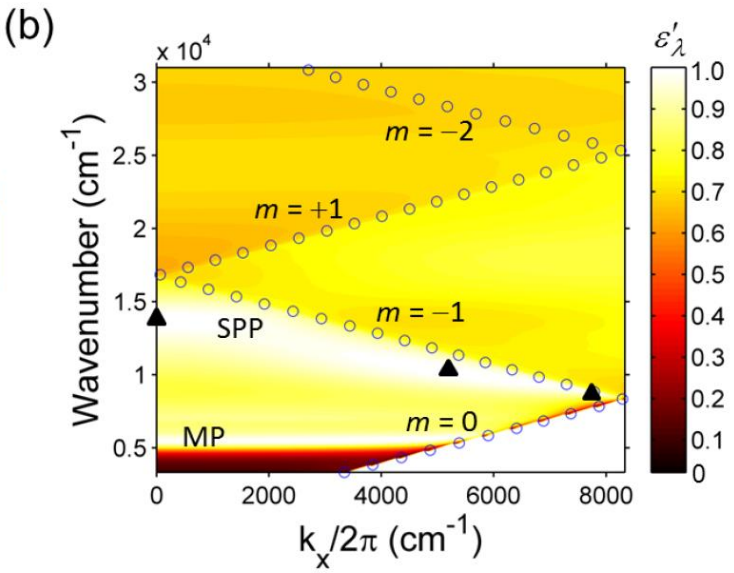
Conditions for the excitation of SPP with 2D gratings:

$$\mathbf{k}_{\mathrm{spp}} = \mathbf{k}_{\mathrm{inc},\|} + \frac{2\pi}{\Lambda_x} m\hat{\mathbf{x}} + \frac{2\pi}{\Lambda_y} n\hat{\mathbf{y}}$$

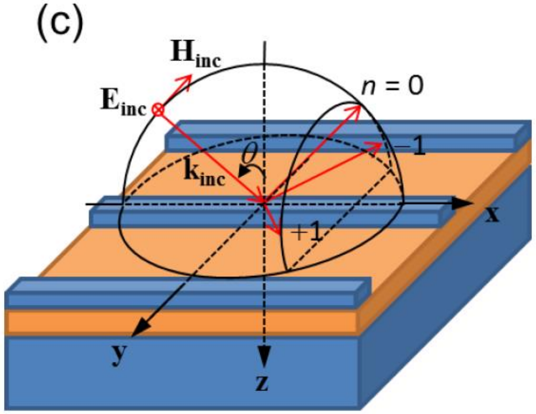
$$m, n \in [-M,\ M]$$

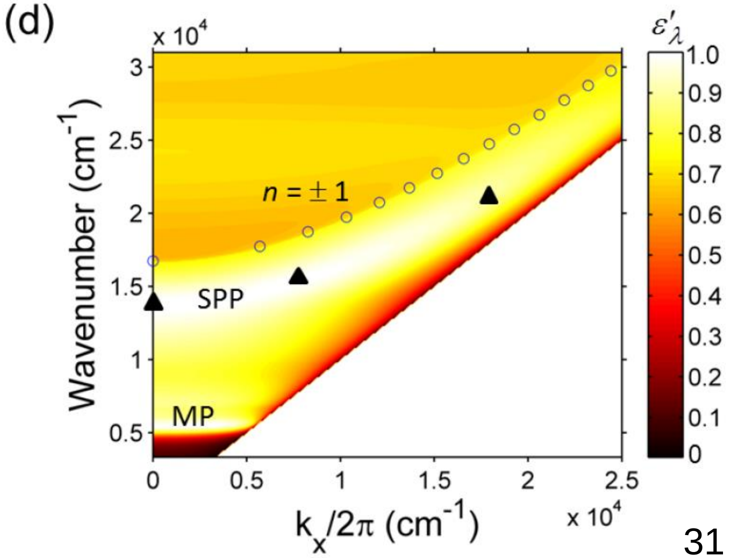
SPP for TM and TE Waves





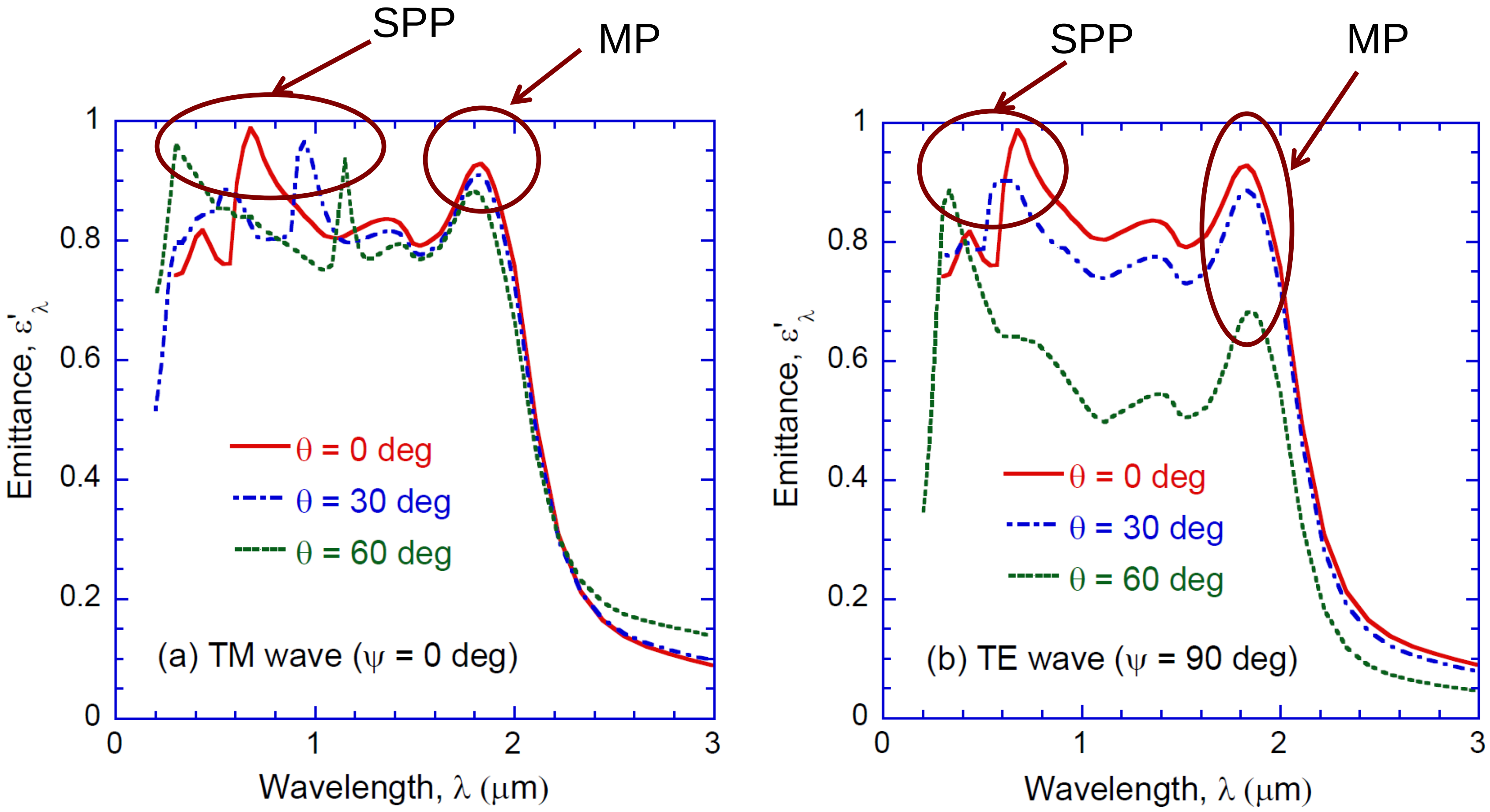
$$\left|k_{inc}\sin\theta+\frac{2\pi}{\Lambda_x}m\right|=k_x=\frac{\omega}{c_0}\sqrt{\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}}$$





$$\sqrt{(k_{\text{inc}}\sin\theta)^2+\left(\frac{2\pi}{\Lambda_y}n\right)^2}=k_x=\frac{\omega}{c_0}\sqrt{\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}}$$

Spectral Emittance of the 2D Grating



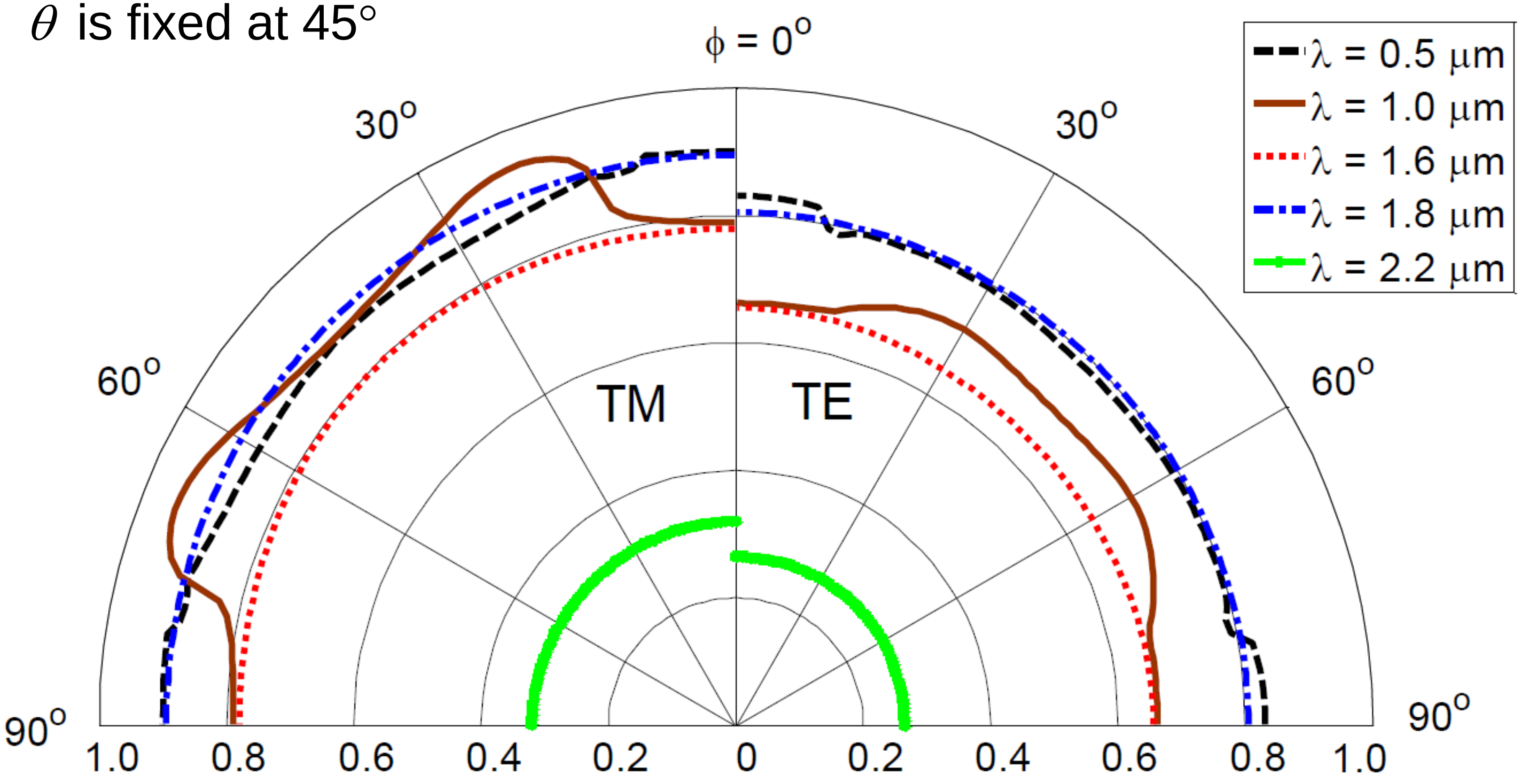
SPPs split and shift to both sides

SPPs shift to short wavelengths

MP frequencies are insensitive to the angle

Directional Emittance of the 2D Grating (Effect of Azimuthal Angle)

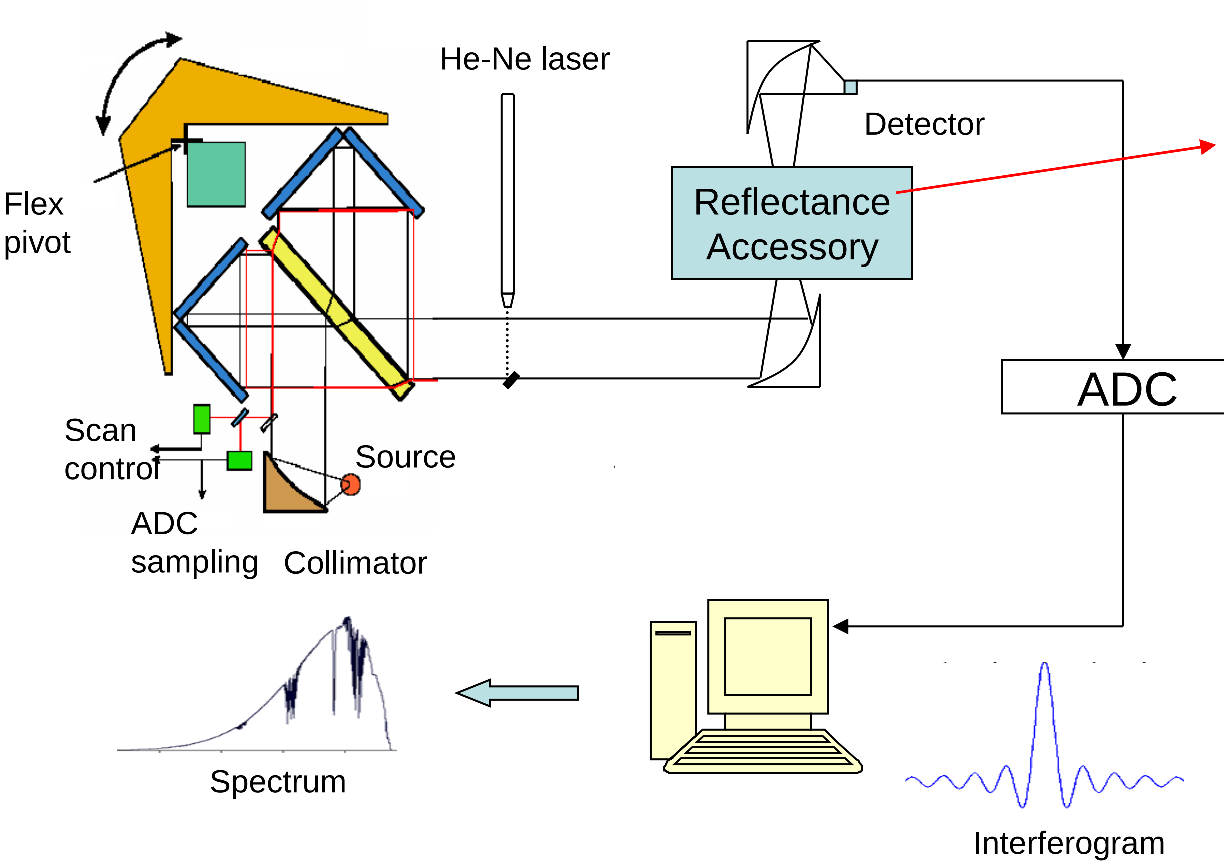
θ is fixed at 45°



Large emittance in the desired spectral region that is insensitive to polarization or direction.

FTIR Spectral Measurements

(1 – 20 μm wavelength range)



He-Ne laser

Detector

Flex pivot

Reflectance Accessory

Scan control

Source

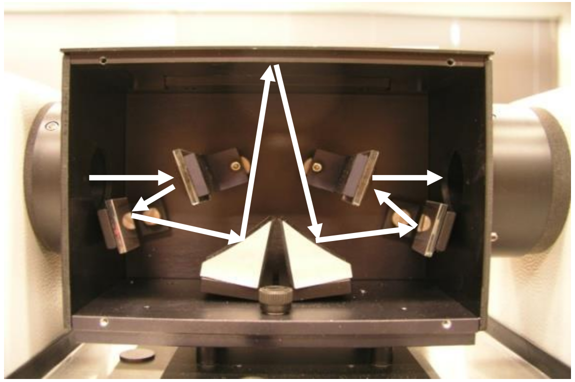
ADC sampling

Collimator

ADC

Spectrum

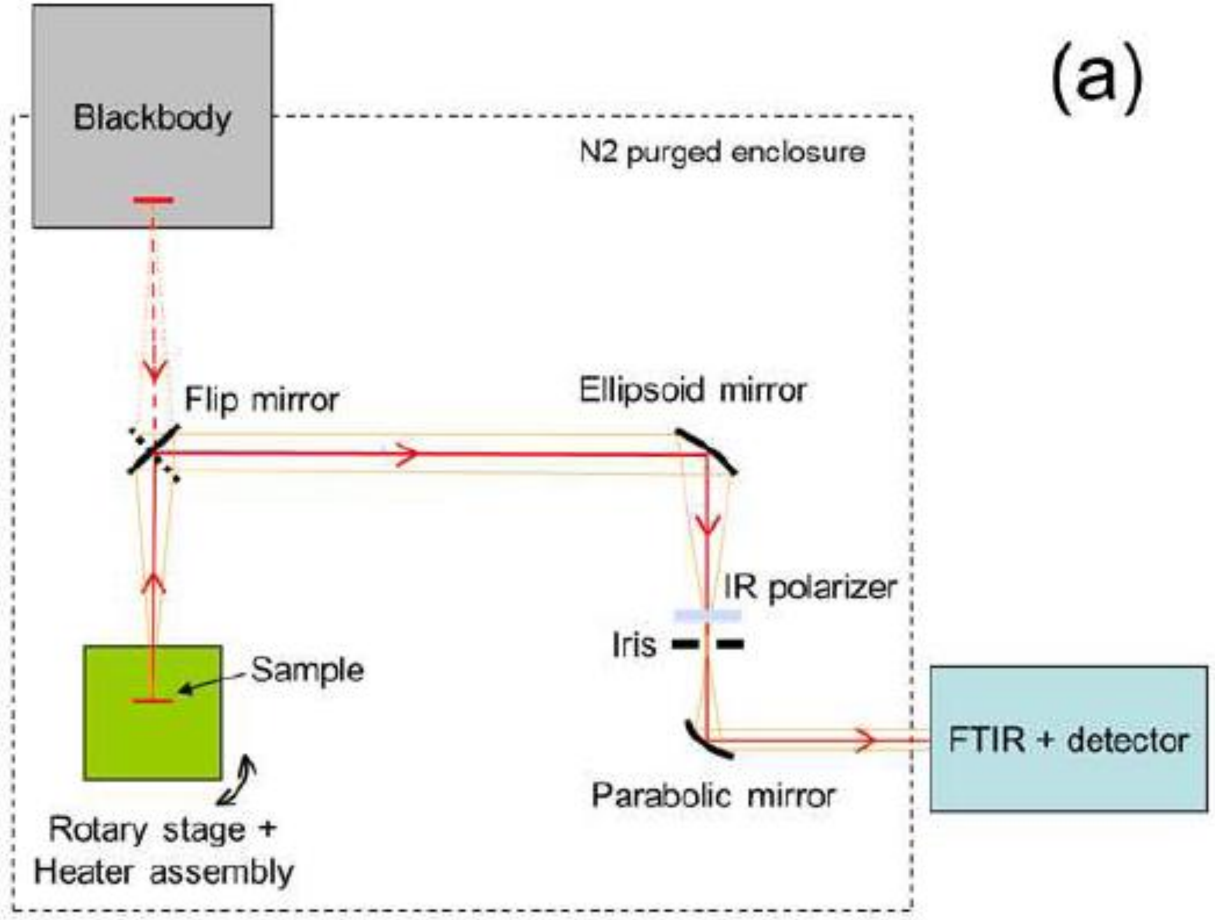
Interferogram



Specular reflectance accessory

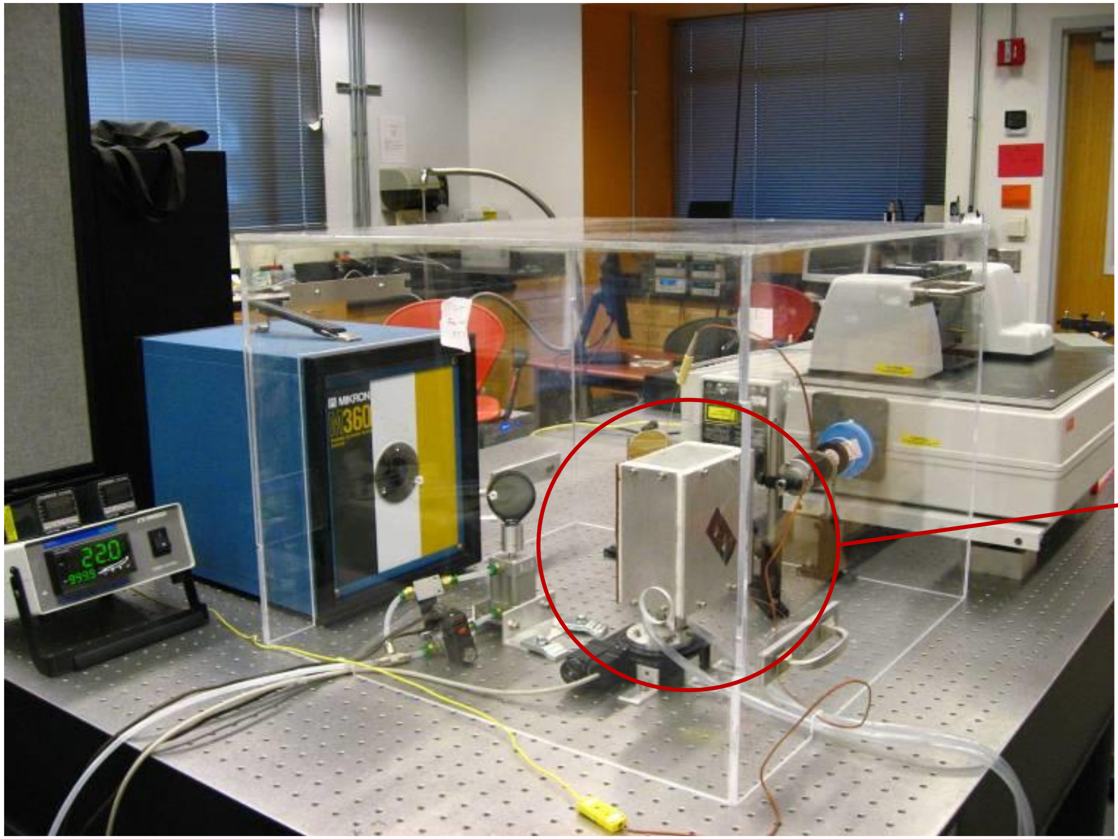
(near normal incidence)

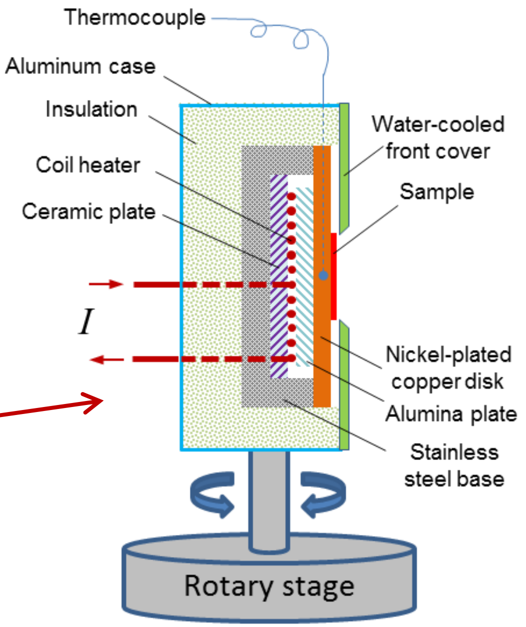
High-Temperature Emissometer



Wang et al., *J. Heat Transfer,* **134**, 072701 (2012).

Emissometry Setup





Heater Assembly

Specs:		
	Solid Angle: 8.35E–3 sr	PID control ΔT: ±1 K
	Rotation Resoln.: 0.01°	Detector: InSb (>500 K, 2 – 5.5 μm)
	Max. Temp: 1000 K	DTGS (>700 K, 0.7 – 20 μm)

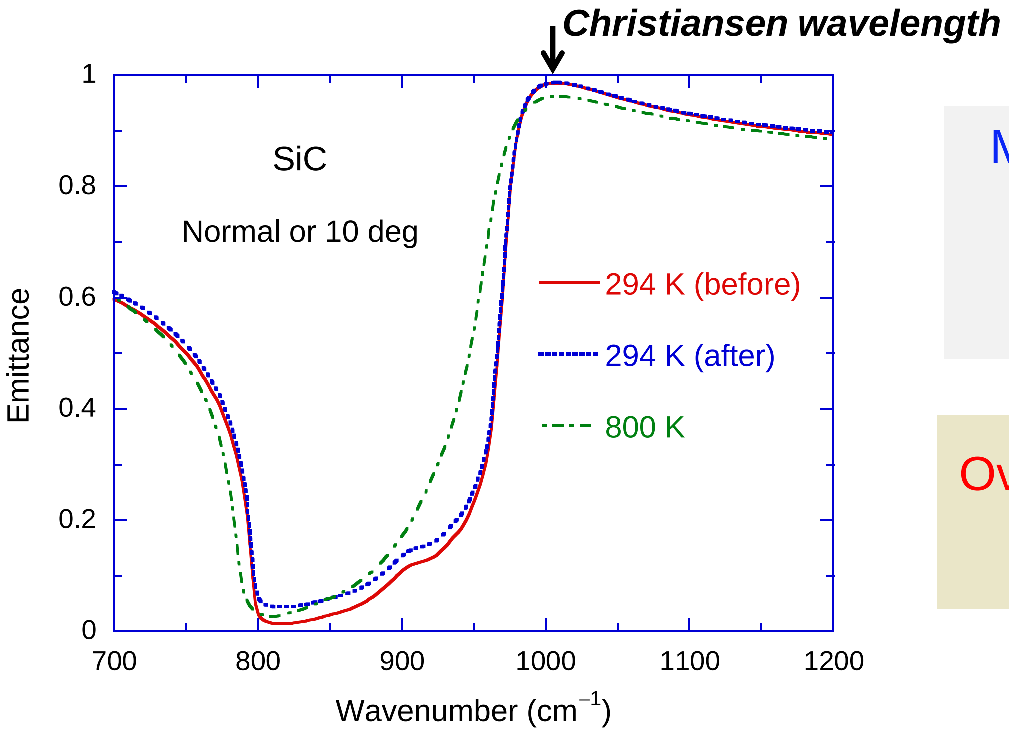
Emissometry Calibration

Spectral-directional emittance:

$$\varepsilon'_{\nu}(\nu,\theta)=\frac{S_{\mathrm{S}}(\nu,T_{\mathrm{S}})-S_{\mathrm{A}}(\nu,T_{\mathrm{A}})}{S_{\mathrm{B}}(\nu,T_{\mathrm{S}})-S_{\mathrm{A}}(\nu,T_{\mathrm{A}})}$$

Here, S_{S} is the signal from the sample surface at T_{S}
S_{B} is the signal from the Blackbody at T_{S}
S_{A} is the signal from the ambient at T_{A}

Sample: *n-doped* 6H-SiC wafer (resistivity of 0.02 to 0.1 Ω-cm)



Max. Emittance:

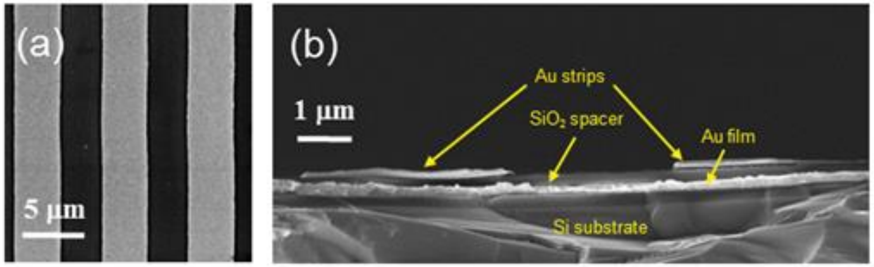
0.986 @ 300 K

0.962 @ 800K

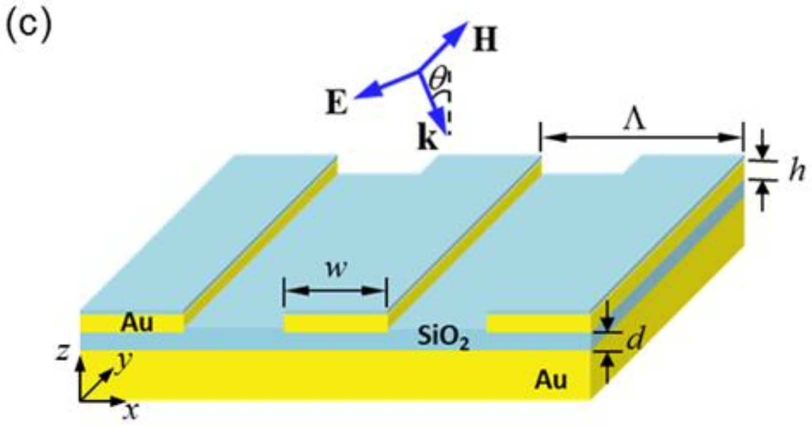
Overall uncertainty

< 0.03

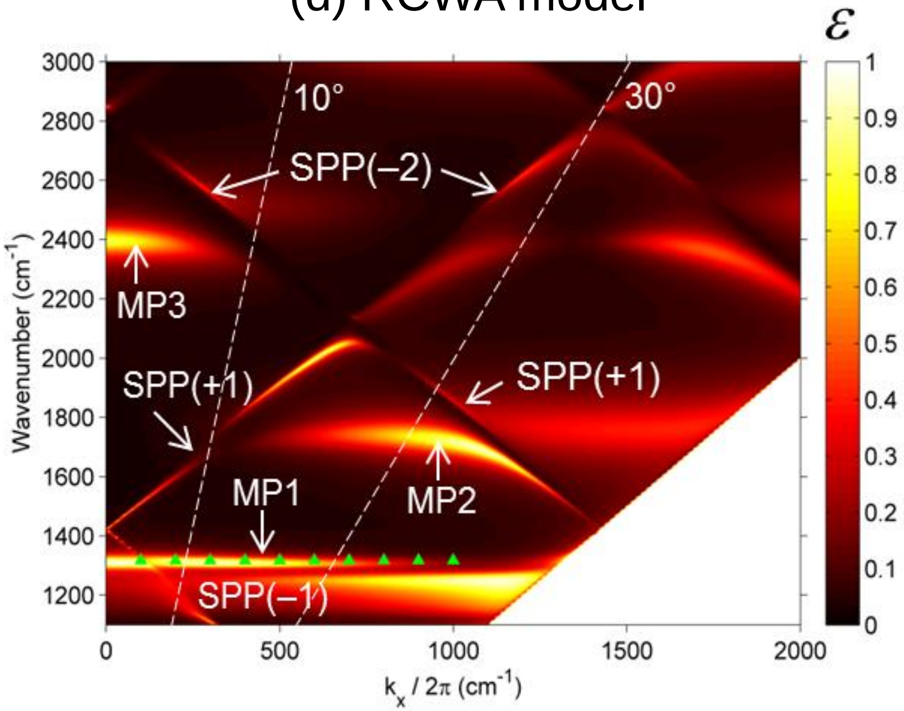
Au Grating-SiO$_2$ Spacer-Au Film



Fabricated sample with a period of 7 μm

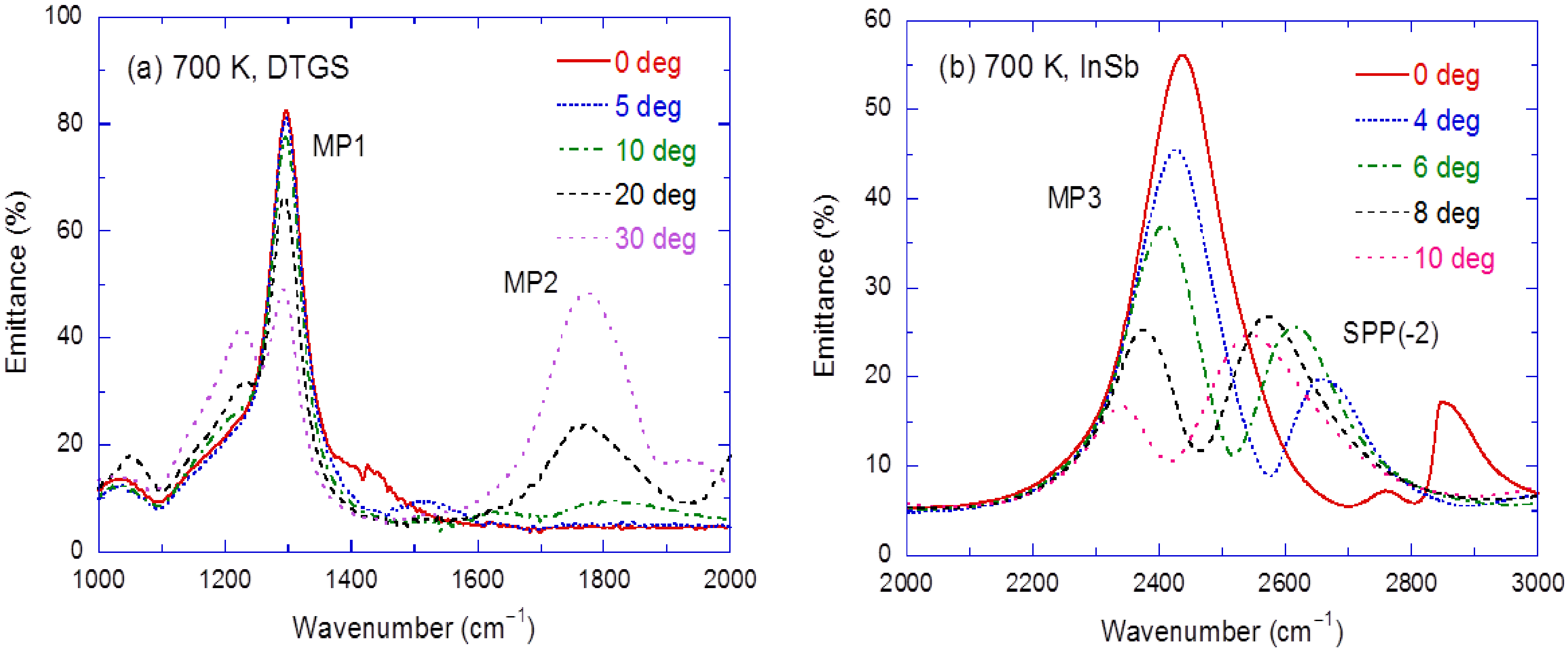


(d) RCWA model

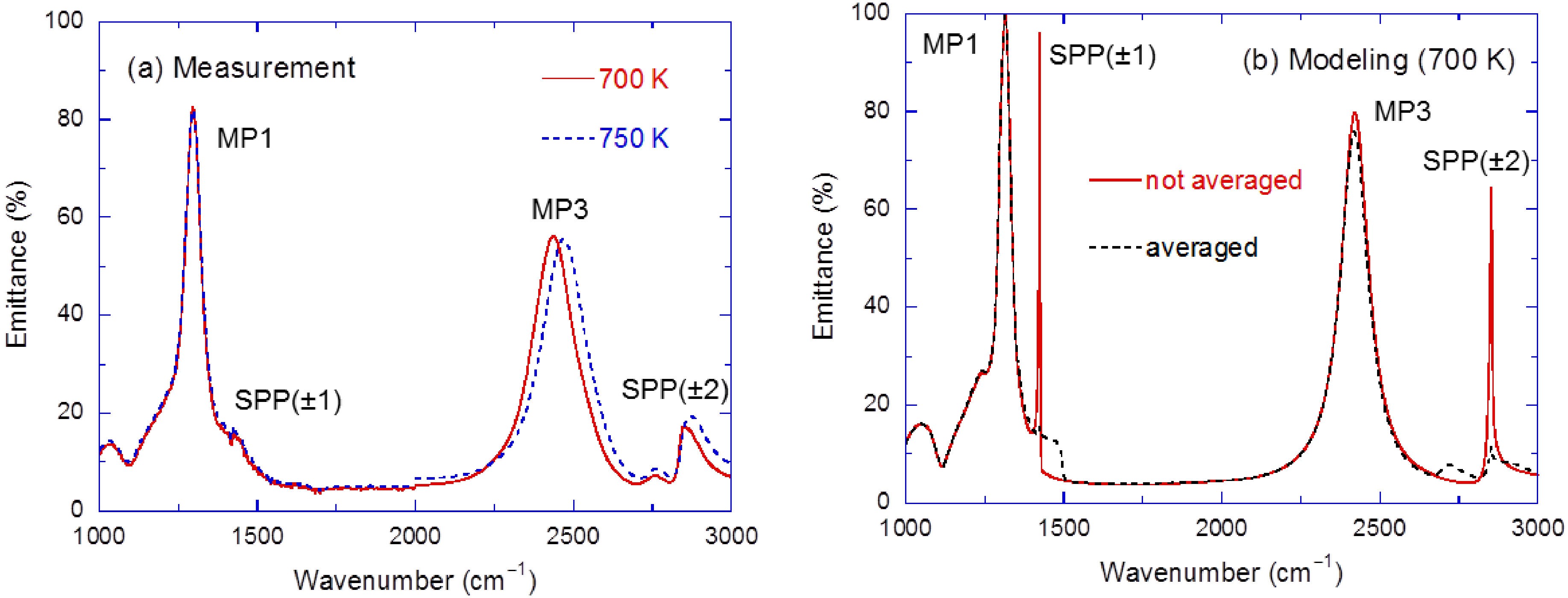


Wang and Zhang, *J. Heat Transfer* (to appear in MNHMT special issue, 2013)

Measured Emittance for TM Waves



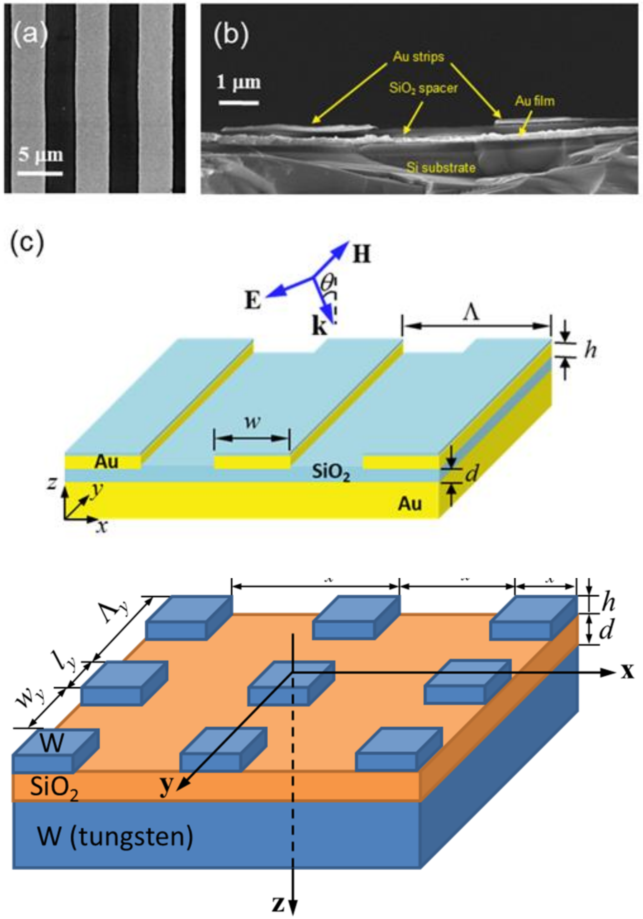
Comparison with Prediction
(normal emittance)



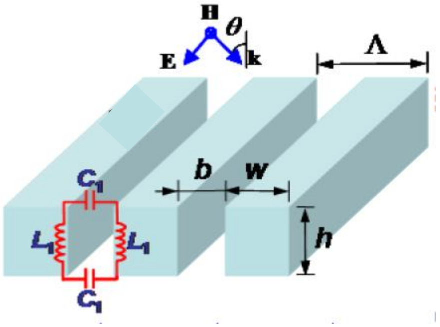
Wang and Zhang, *J. Heat Transfer* (to appear in MNHMT special issue, 2013)

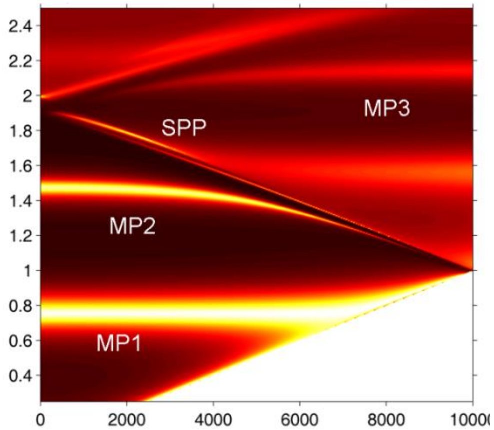
Summary

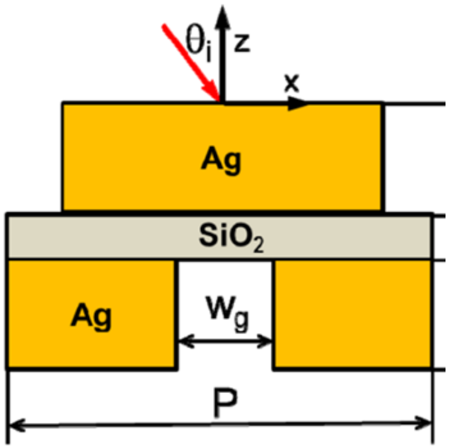
1. Coherent thermal emission and TPV applications with an experimental demonstration

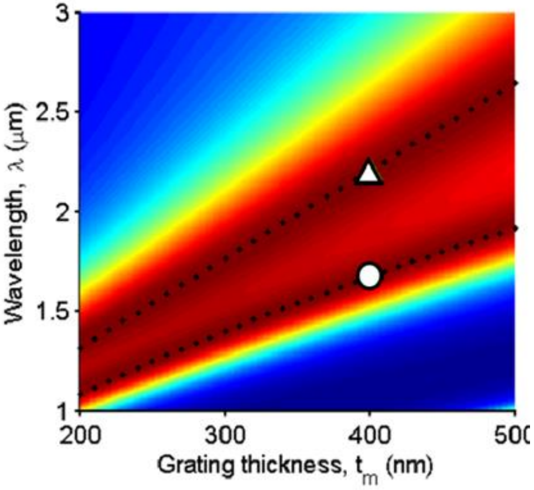


2. Unique transmission characteristics and a design of IR polarizers









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- Dr. Bong Jae Lee, Assis. Prof., KAIST, Korea
- Mr. Ahmad Haider (former M.S. student)
- Mr. Bo Zhao (current Ph.D. student)
- Mr. Xianglei Liu (current Ph.D. student)
- Dr. Yong Shuai (visiting scholar from HIT)

Sponsors

- **National Science Foundation (NSF)**
- **Department of Energy (DoE)**

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