



# メタマテリアルによる熱輻射 の制御に向けて

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# 背景と目的

## ～高効率白熱電球へむけて



# From carbon to tungsten filament



Tungsten  
double coil filament  
100W

\*Carbon filament  
made from cotton  
30W

\*Single wire carbon  
filament made  
from bamboo in Kyoto  
30W

1878  
J.W. Swan  
Carbon filament  
lamp

1879.10  
T.A. Edison  
Carbon filament  
lamp

1880.11  
Bamboo filament  
lamp

\*Commercially available incandescent lamps with carbon filament for use of antique lamps.

# Historic incandescent lamp replicas in my lab.



Swan lamp replica

Linear carbon filament  
made from cotton



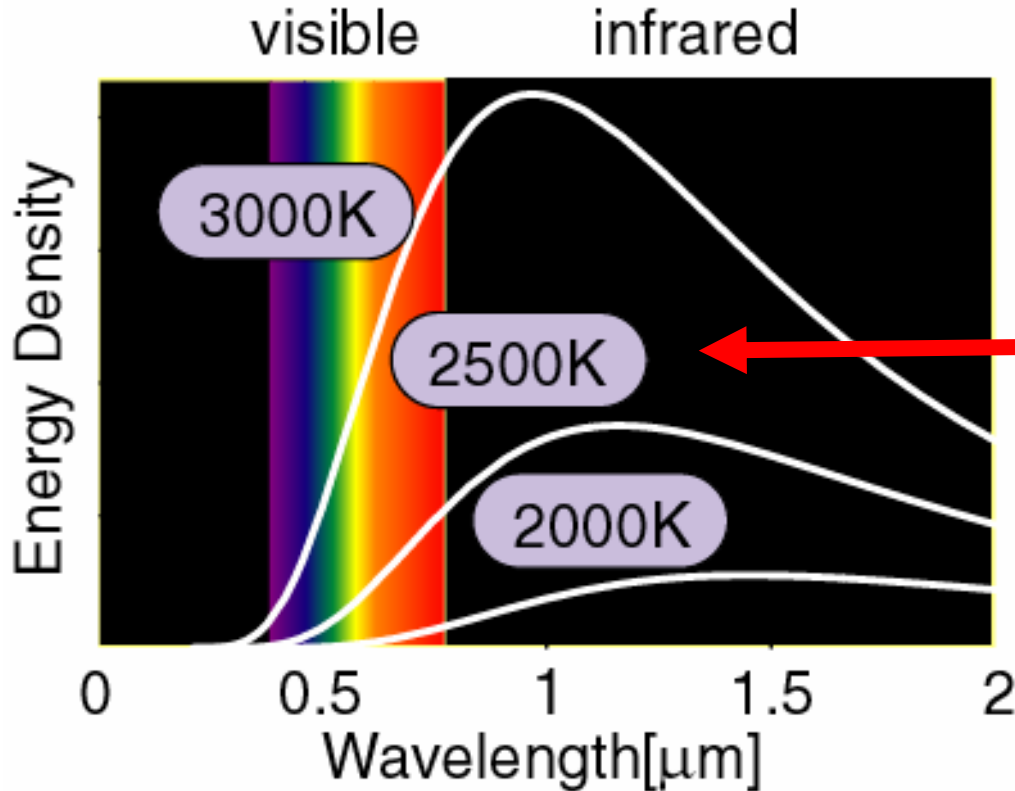
Edison lamp replica

Carbon filament made from real  
bamboo in Yawata city, Kyoto

# Luminous efficacy of various light sources

type	supplementation	Luminous efficacy (lm/W)
Incandescent lamp	100W-95W、2856K	16
Halogen lamp	With hotmirror, for home	19
Halogen lamp	With hotmirror, for studio	28
Fluorescent lamp (bulb)		58
Fluorescent lamp	White light 6500K	96
Metal haloid lamp		80~140
Low pressure Na lamp	180W	180
High pressure Na lamp	400W	125~140
LED	Toshiba in 2007	18-50

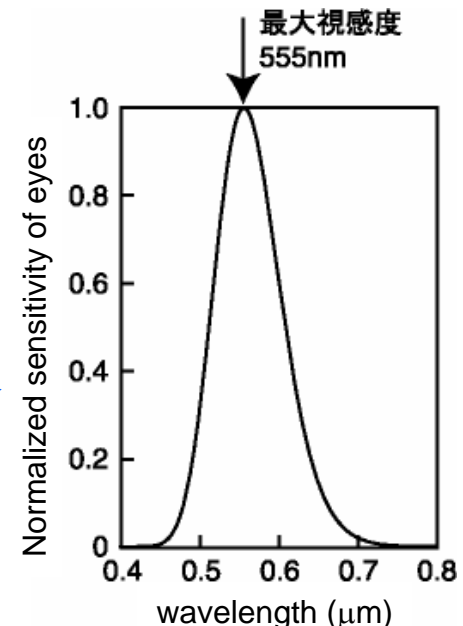
# Low energy efficiency of incandescent lamp



Planck's law

$$I(\nu) = \frac{2h\nu^3}{c^2} \frac{1}{\exp(h\nu/kT) - 1}$$

90% of total radiation energy is infrared (IR)!

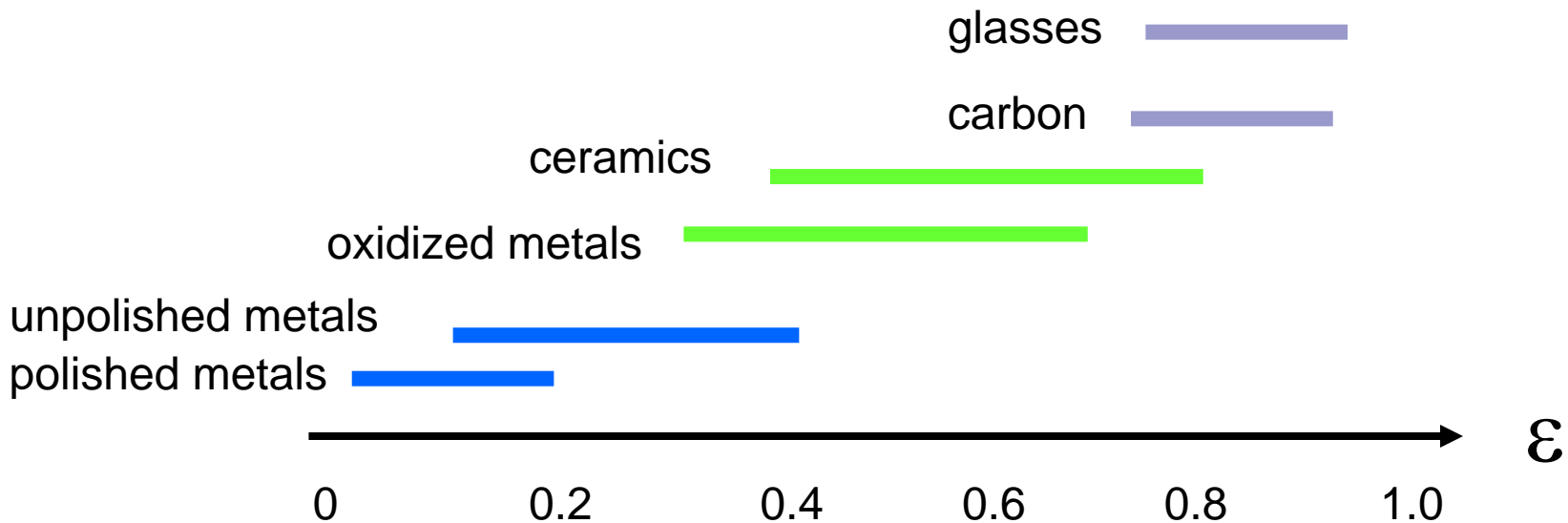


Efficiency of a lamp

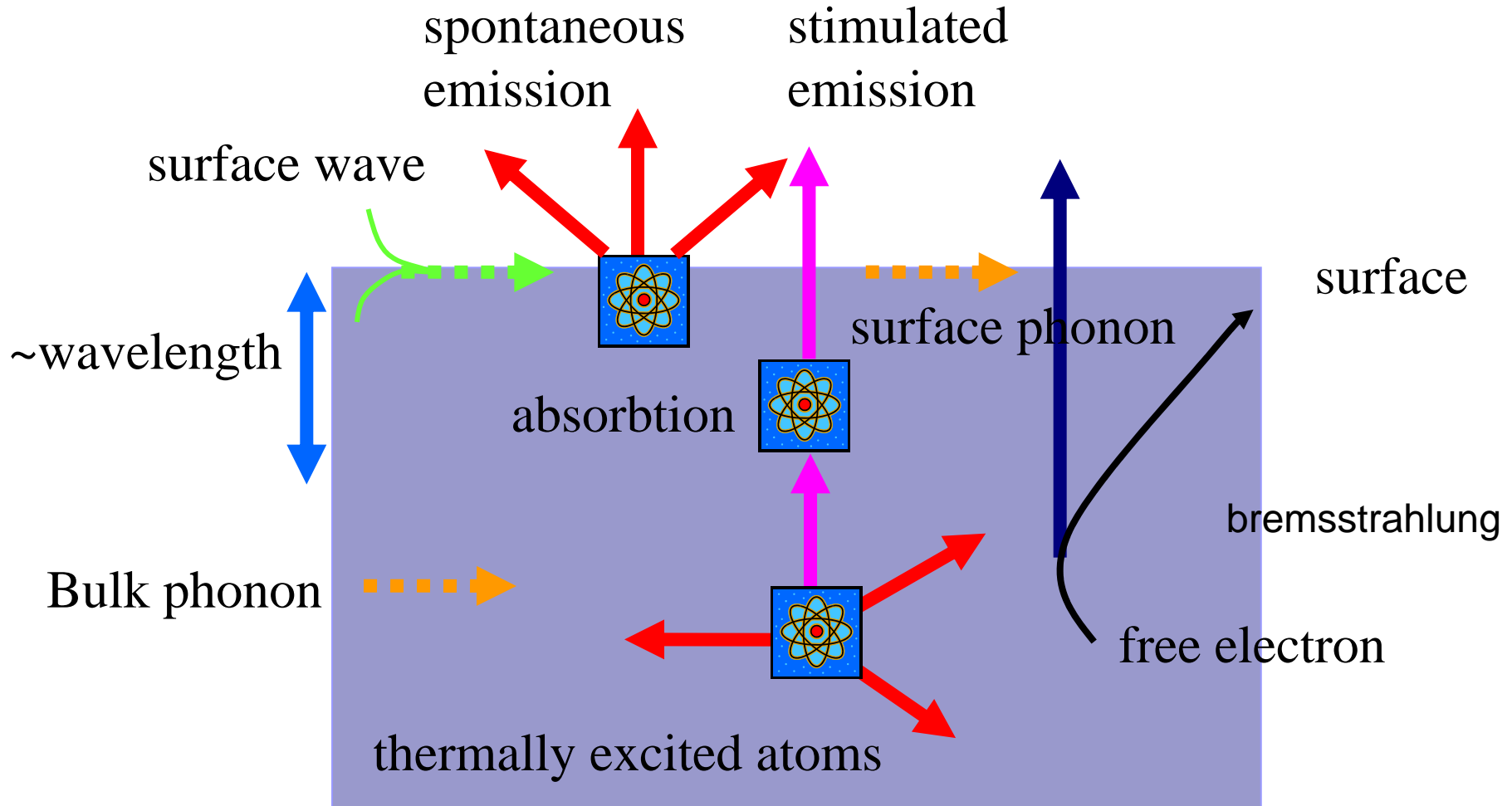
$$\text{Luminous efficacy (lm/W)} = \frac{\text{Luminous flux}}{\text{Input power}}$$

# Emissivity of various materials

- blackbody  $\varepsilon=1$
- Tungsten  $\varepsilon=0.1\sim 0.4$
- Typical ranges of emissivity



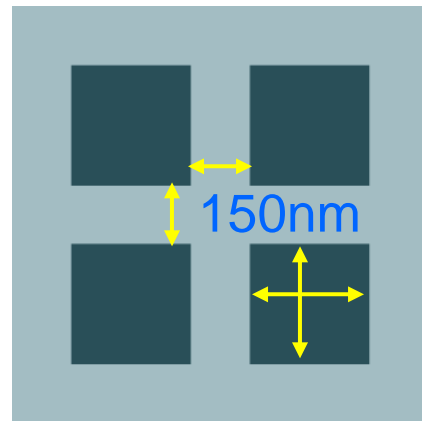
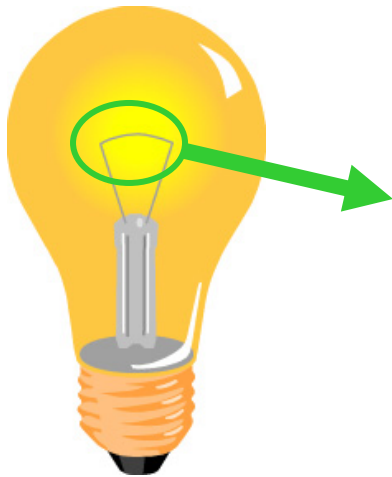
# Processes in thermal radiation



Microstructures on surface → Control of thermal radiations

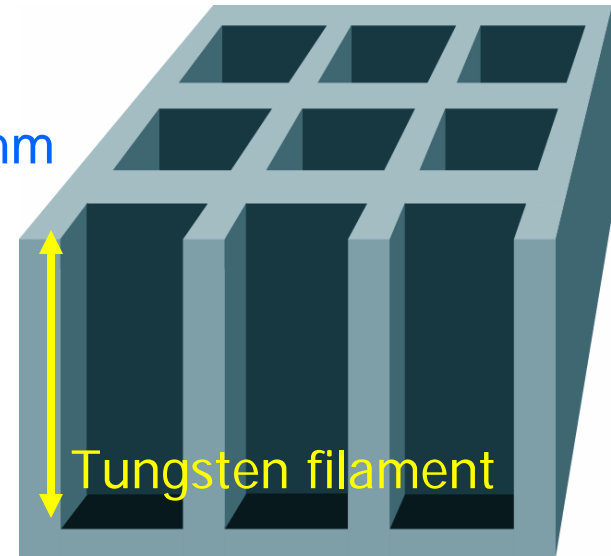
# Micro-cavity Lamp

Analogy to microwave waveguide theory  
Cutoff effect prohibits IR radiation



top view

7000nm




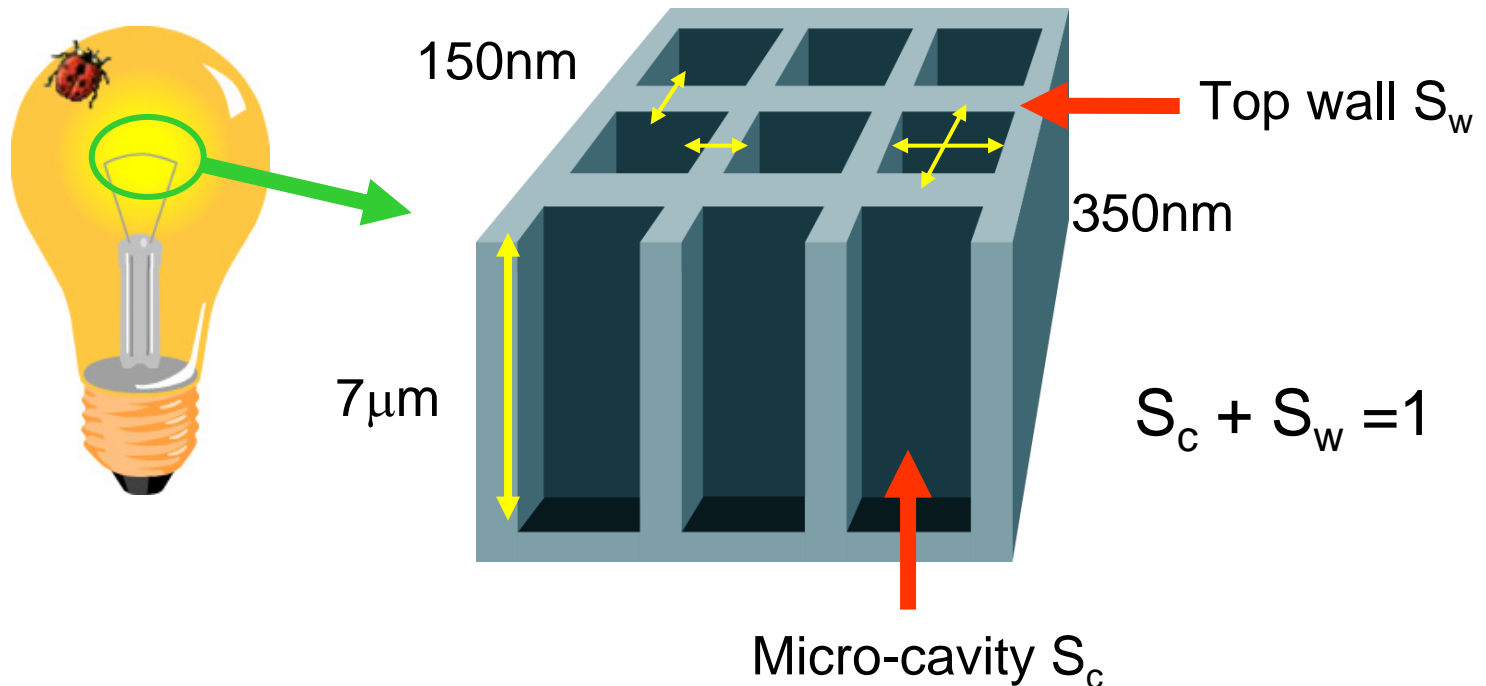
Cross sectional view

J.F. Waymouth, J. Light & Vis. Env. 13, 2 (1989) 51.  
U.S.Patent No.5079473(1992).

# Principles of micro-cavity lamp

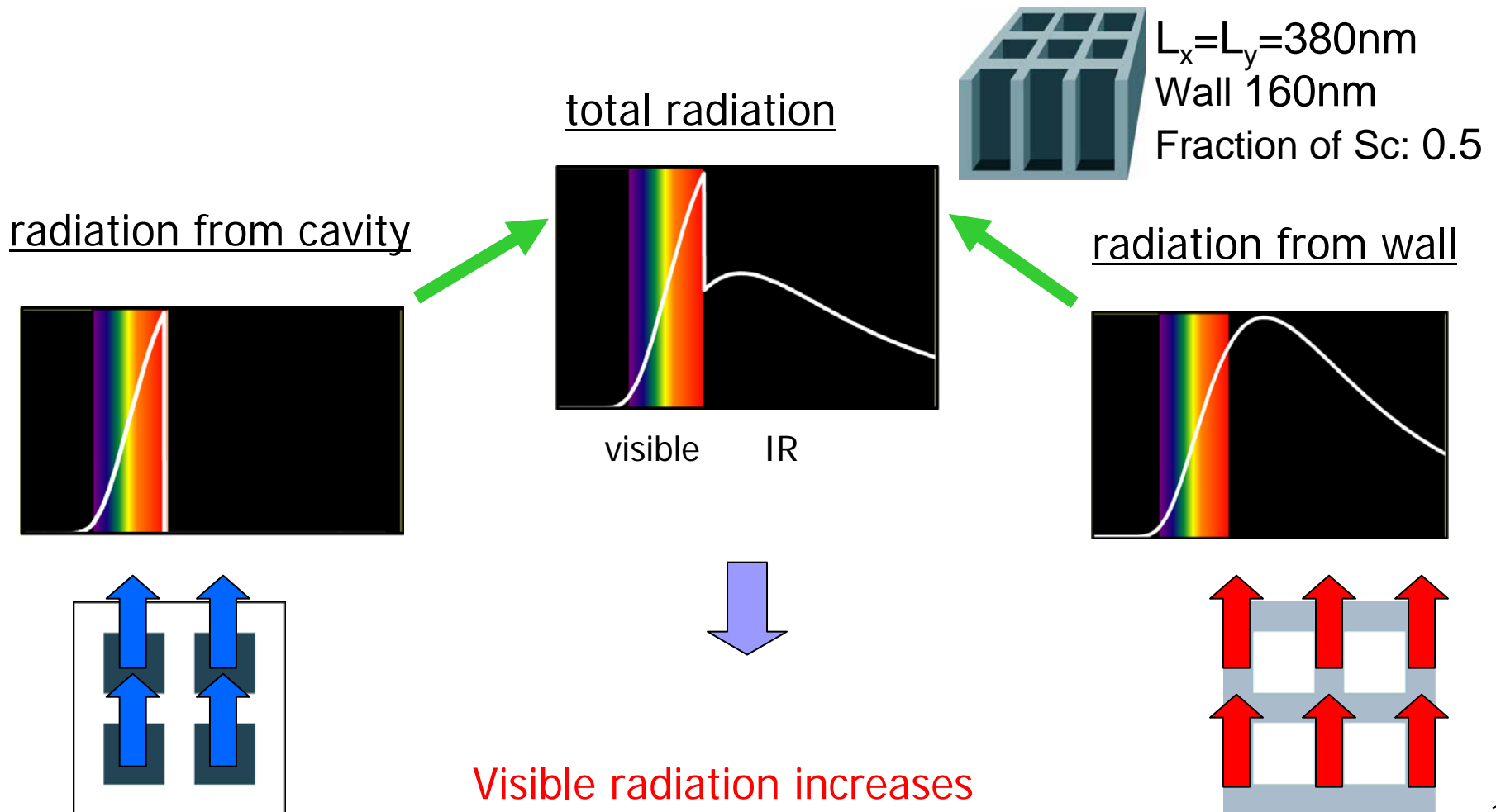
Waymouth's assumptions

- 
- 1) IR radiation is prohibited from microcavity due to cut-off
  - 2) IR radiates only from the top wall
  - 3) Radiation flux in top wall decreases to 20% to blackbody in cavity

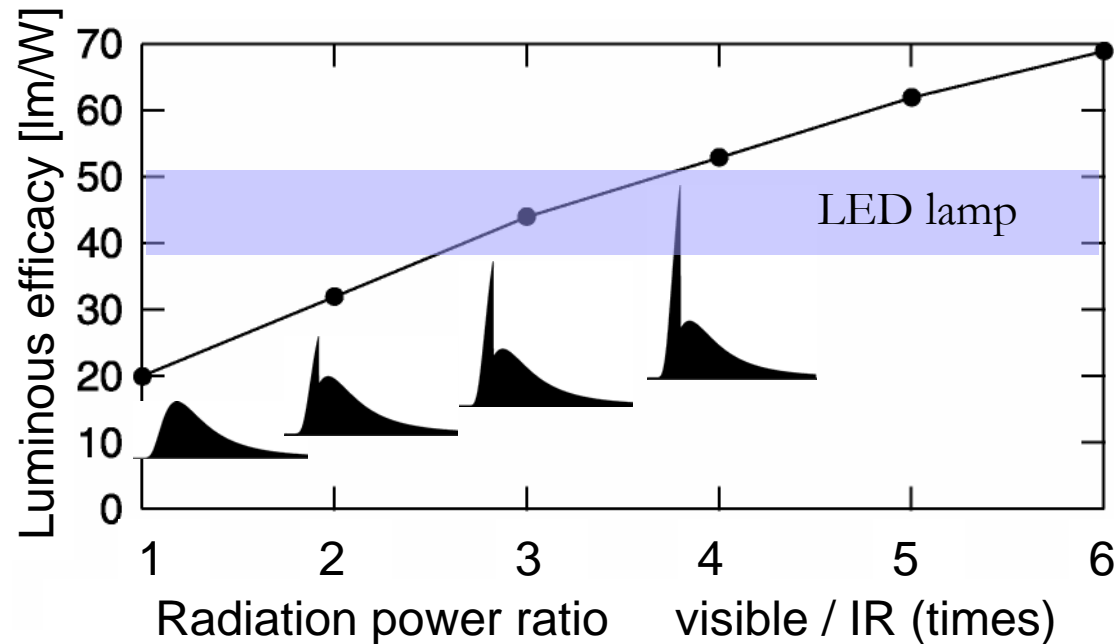


# Radiation spectra of micro-cavity lamp

Energy flow: input power = radiative power

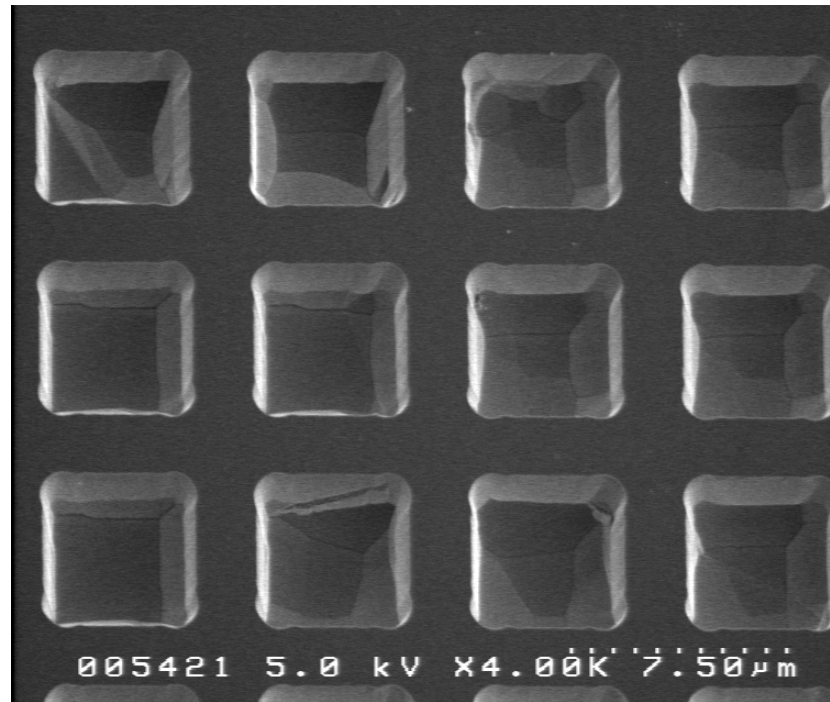


# Improvement of luminous efficacy by thermal spectral control



Luminous efficacy can be improved close to fluorescence lamps.

# マイクロキャビティアレイ における熱輻射



# History of thermal radiation control by microstructured surface

- **Deep 1D grating**

P.J. Hesketh *et al.* Nature, 324 (1986) 549.  
deep(45 $\mu$ m) grating on doped Si

- **Proposal of micro-cavity lamp**

J. F. Waymouth (1989)

Experiments in GE and Matsushita Electric (1992-1994)

- **Applications to TPV cell**

Maruyama APL 79 (2001) 1393.

- **Radiation control by surface phonon polariton**

Spatial coherence: J.J.Greffet *et al.* Nature, 416 (2002) 61.  
1D grating on SiC

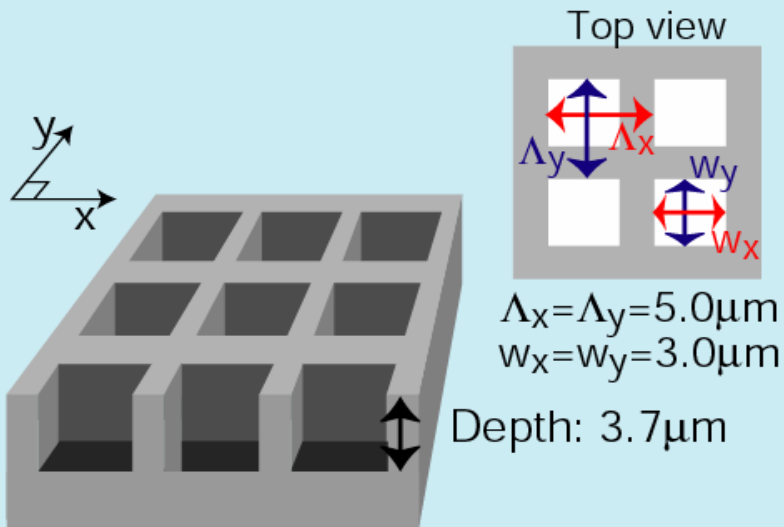
- **Photonic crystals (PC)**

Tungsten rod pile PC: J.G. Fleming, Nature, 417 (2002) 52.

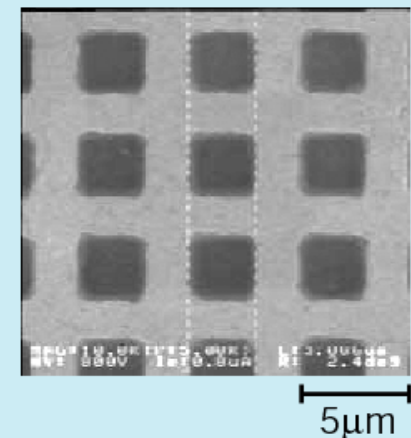
# Deep microcavity array

- Tungsten (W), Tantalum (Ta) substrate ( $t=0.5\text{mm}$ )
- W ( $T=3400^\circ\text{C}$ ), Ta ( $T=3000^\circ\text{C}$ ), doped Si
- cavity size:  $3\mu\text{m} \times 3\mu\text{m} \times 3.7\mu\text{m}$  (36%)
- patterned area  $3\text{mm} \times 5\text{mm}$

## Periodic array of microcavities



## SEM top image

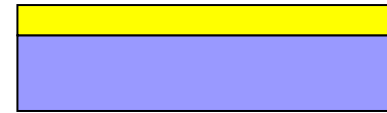


# Fabrication process

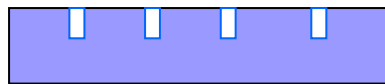


$t=0.5\text{mm}$

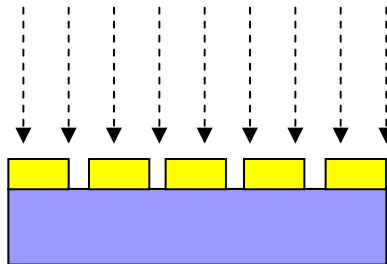
Polish W, Ta substrate  
to form flat surface



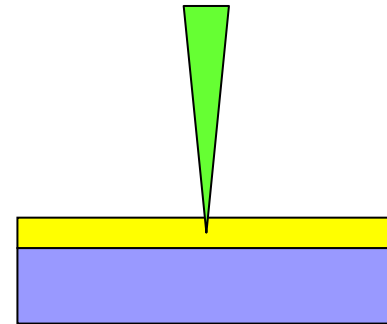
PMMA spin coating



PMMA remove



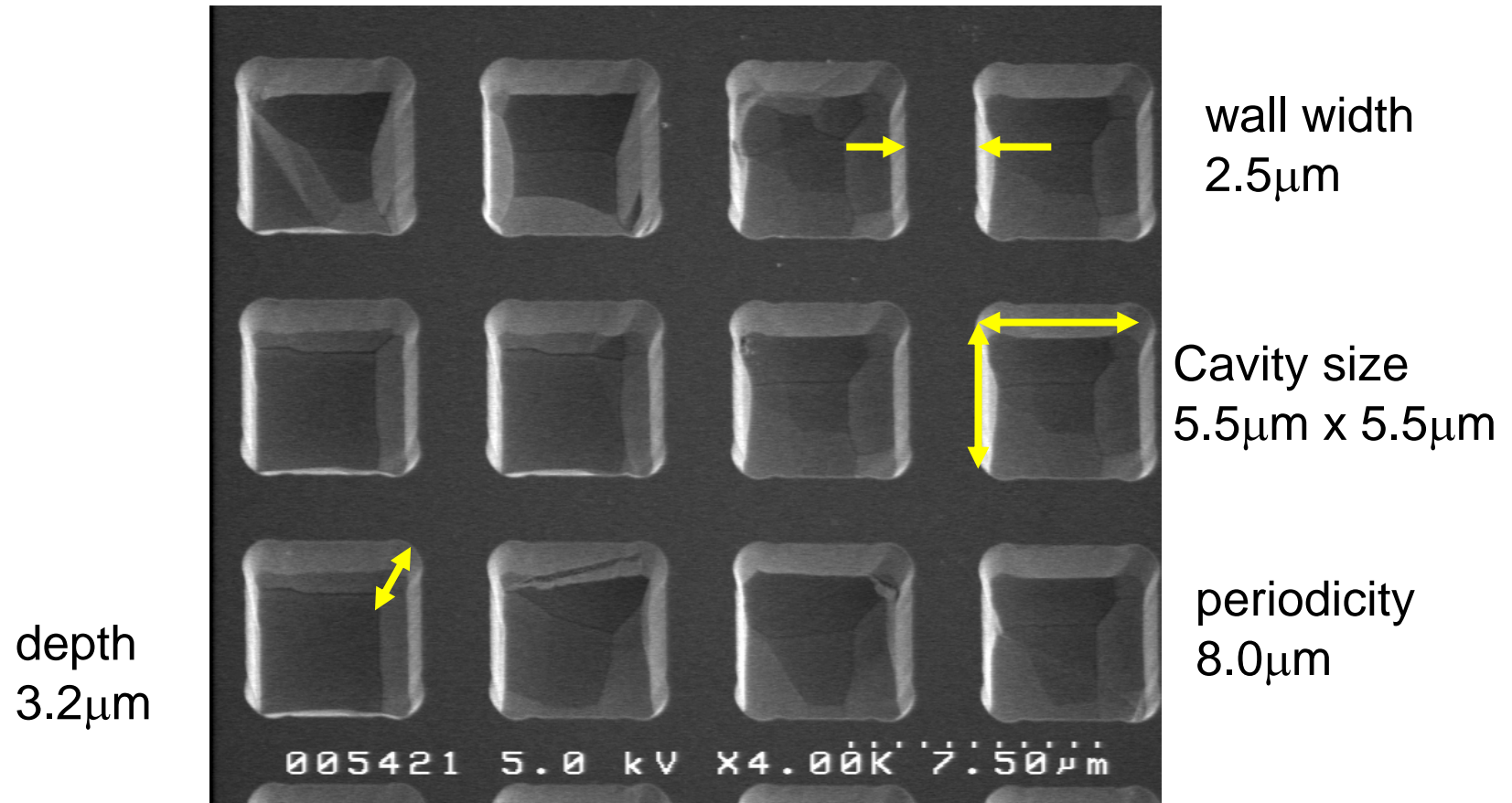
Dry etching



E-beam lithography  
(5mm x 5mm area)

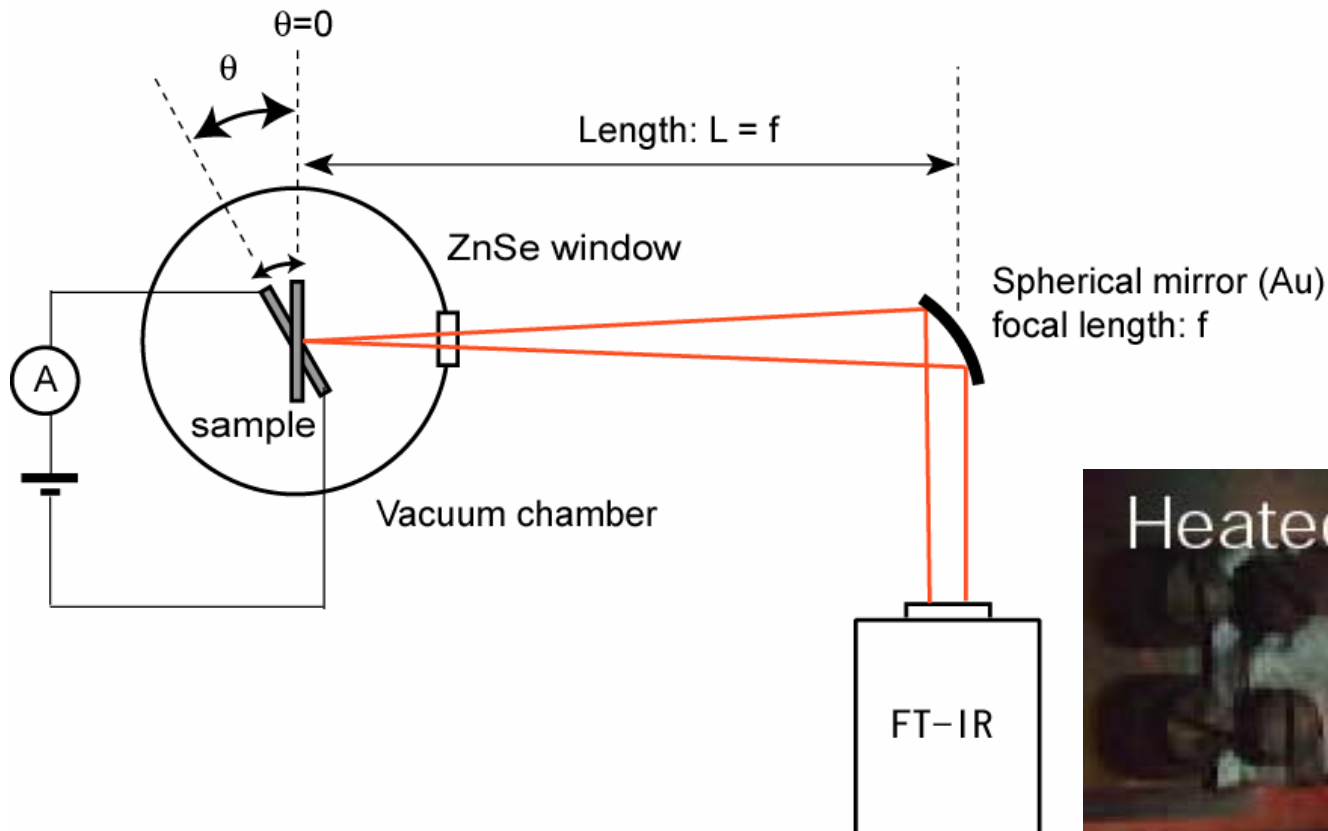
W and Ta have large hardness (W:7.5, Ta:6.5, SiO<sub>2</sub>: 7, diamond: 10).

# Metallic microstructures



(Example) Ta substrate

# Experimental setup



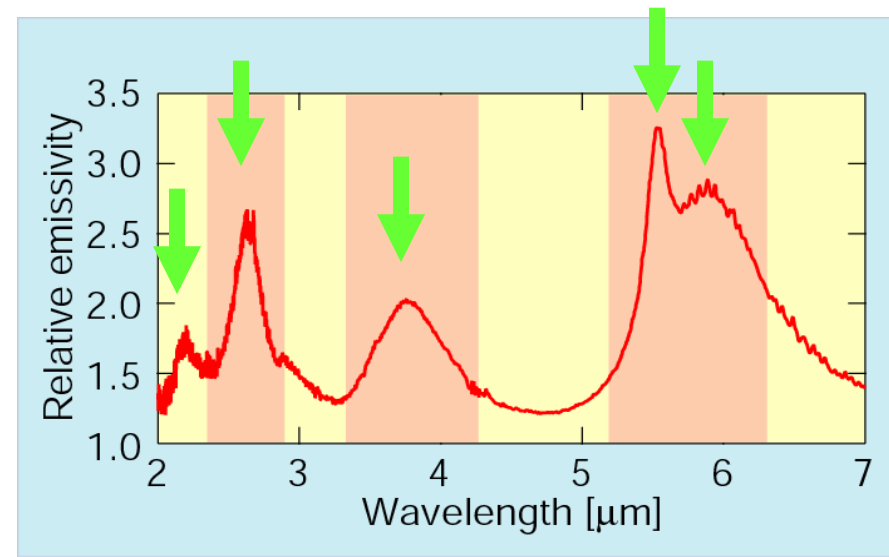
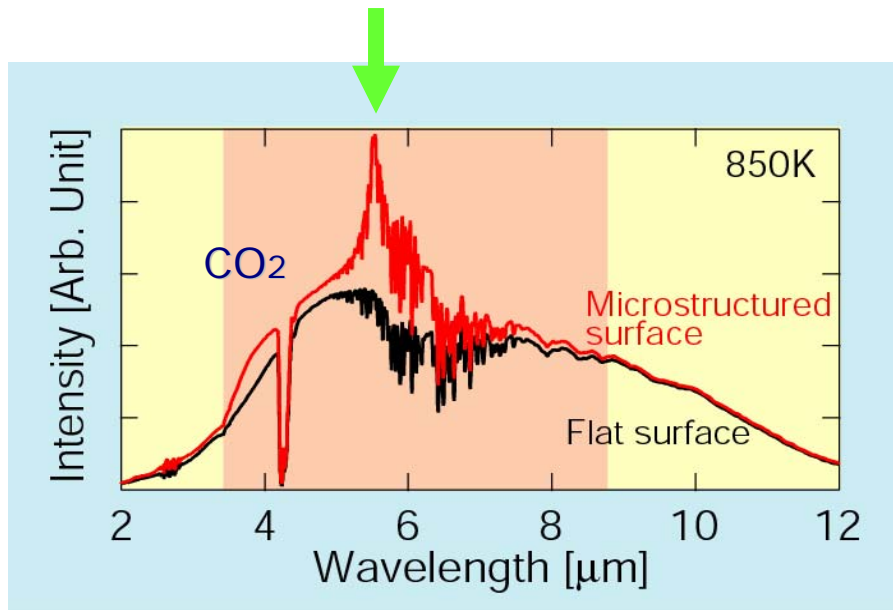
- heating → Electric current
- temperature → 470-630°C
- measurement → thermal radiation thermometer

- concave mirror (Au):  $f = 452$  mm
- FT-IR ( JASCO Inc., FT-IR 660Plus )
- DLATGS detector
- DC current source  
( KENWOOD Electronics, PS10-210 )<sub>19</sub>

# Thermal radiation spectra

- flat and structured surfaces
- 3 times enhancement @ $5.6\mu\text{m}$
- Many peaks in relative emissivity

sample 1	
material	W
period	$5.0\mu\text{m}$
cavity	$3.0\mu\text{m}$
depth	$3.7\mu\text{m}$
cavity ratio	0.36

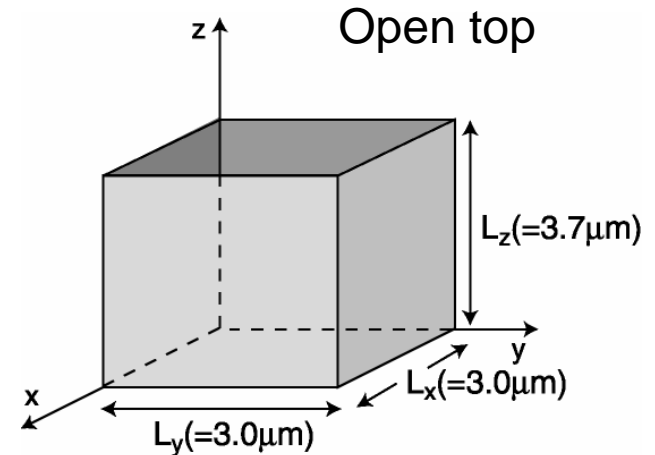


# EM field in open cavity

Boundary condition for perfect conductor wall

Tangential components  $E_t=0$  @ wall

Antinode @ open end of cavity



$$E_x(r, t) = E_x(t) \cos(k_x x) \sin(k_y y) \sin(k_z z)$$

$$E_y(r, t) = E_y(t) \sin(k_x x) \cos(k_y y) \sin(k_z z)$$

$$E_z(r, t) = E_z(t) \sin(k_x x) \sin(k_y y) \cos(k_z z)$$

$$k_x = n_x \pi / L_x, k_y = n_y \pi / L_y, k_z = n_z \pi / 2L_z$$

$$n_x, n_y = 0, 1, 2, 3, \dots$$

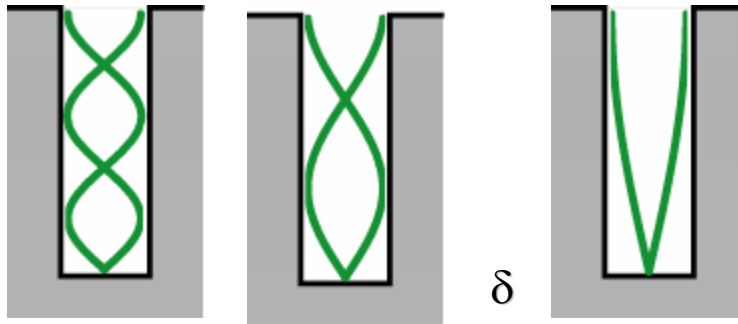
$$n_z = 0, 1, 3, 5, \dots$$

Wavelength of eigenmode

$$\lambda_{\text{cavity}}(n_x, n_y, n_z) = \frac{2}{\sqrt{\left(\frac{n_x}{L_x}\right)^2 + \left(\frac{n_y}{L_y}\right)^2 + \left(\frac{n_z}{2L_z}\right)^2}}$$

# Single open cavity model

antinode



Boundary condition  
perfect conductor wall  
 $E(\text{boundary}) = 0$

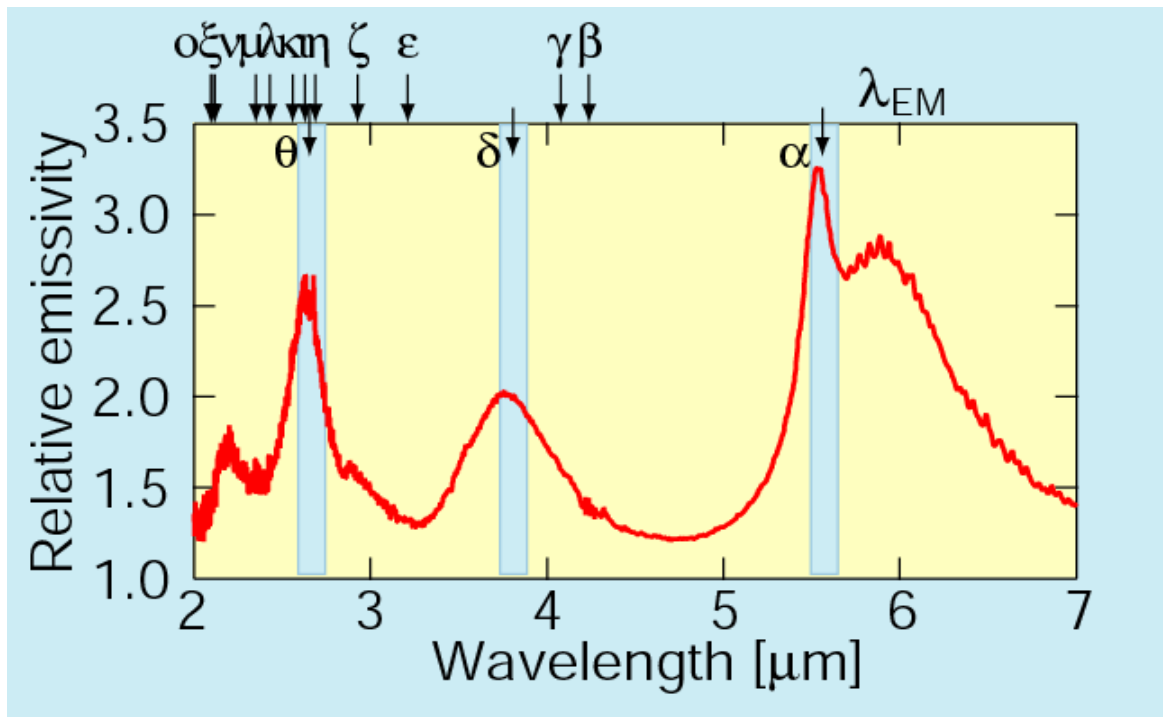
node

$\theta$

$\delta$

$\alpha$

Theory (resonance)

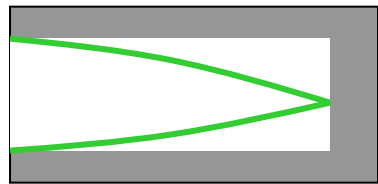


Mode	$(n_x, n_y, n_z)$	$\lambda_{EM}(\mu\text{m})$
$\alpha$	(1,0,1), (0,1,1)	5.56
$\beta$	(1,1,0)	4.24
$\gamma$	(1,1,1)	4.08
$\delta$	(1,0,3), (0,1,3)	3.81
$\epsilon$	(1,1,3)	3.22
$\zeta$	(2,0,1), (0,2,1)	2.94
$\eta$	(2,1,0), (1,2,0)	2.68
$\theta$	(1,0,5), (0,1,5)	2.65
$\iota$	(2,1,1), (1,2,1)	2.64
$\kappa$	(2,0,3), (0,2,3)	2.56
$\lambda$	(1,1,5)	2.43
$\mu$	(2,1,3), (1,2,3)	2.36
$\nu$	(2,2,0)	2.12
$\xi$	(2,0,5), (0,2,5)	2.11
$\omicron$	(2,2,1)	2.1

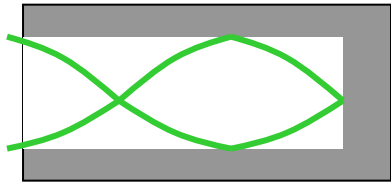
$n_z=1,3,5\dots$  (Odd mode index)

# Analogy ~Optical Woodwind Instruments

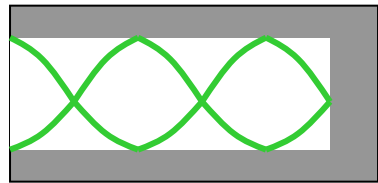
E-field in Optical cavity



$$f = c/4L$$

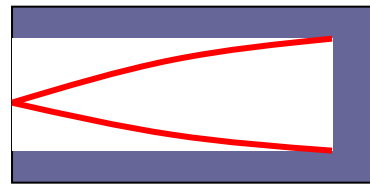


$$f = 3c/4L$$

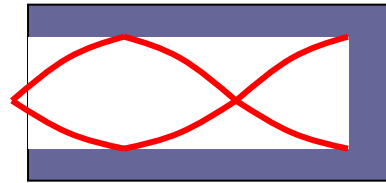


$$f = 5c/4L$$

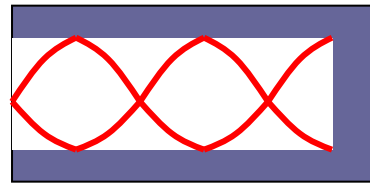
Pressure in closed pipe



$$f = v/4L$$



$$f = 3v/4L$$



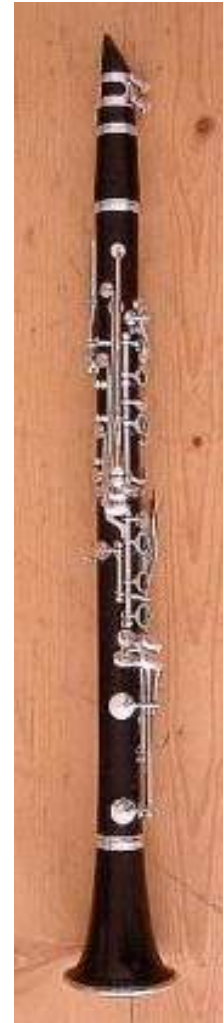
$$f = 5v/4L$$

open  
end

L

odd-number  
harmonics

closed  
end



clarinet

T.D. Rossing, F.R. Moore and P.W. Wheeler,  
The Science of Sound (3<sup>rd</sup> ed.), (Addison Wesley, 2002).

# Numerical simulation ~FDTD method

- Finite Difference Time Domain (FDTD) method
- RSoft Design Group, Inc. *FullWAVE*
- Popular in antenna design, plasmonics, nanophotonics

Maxwell equations

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{J}$$

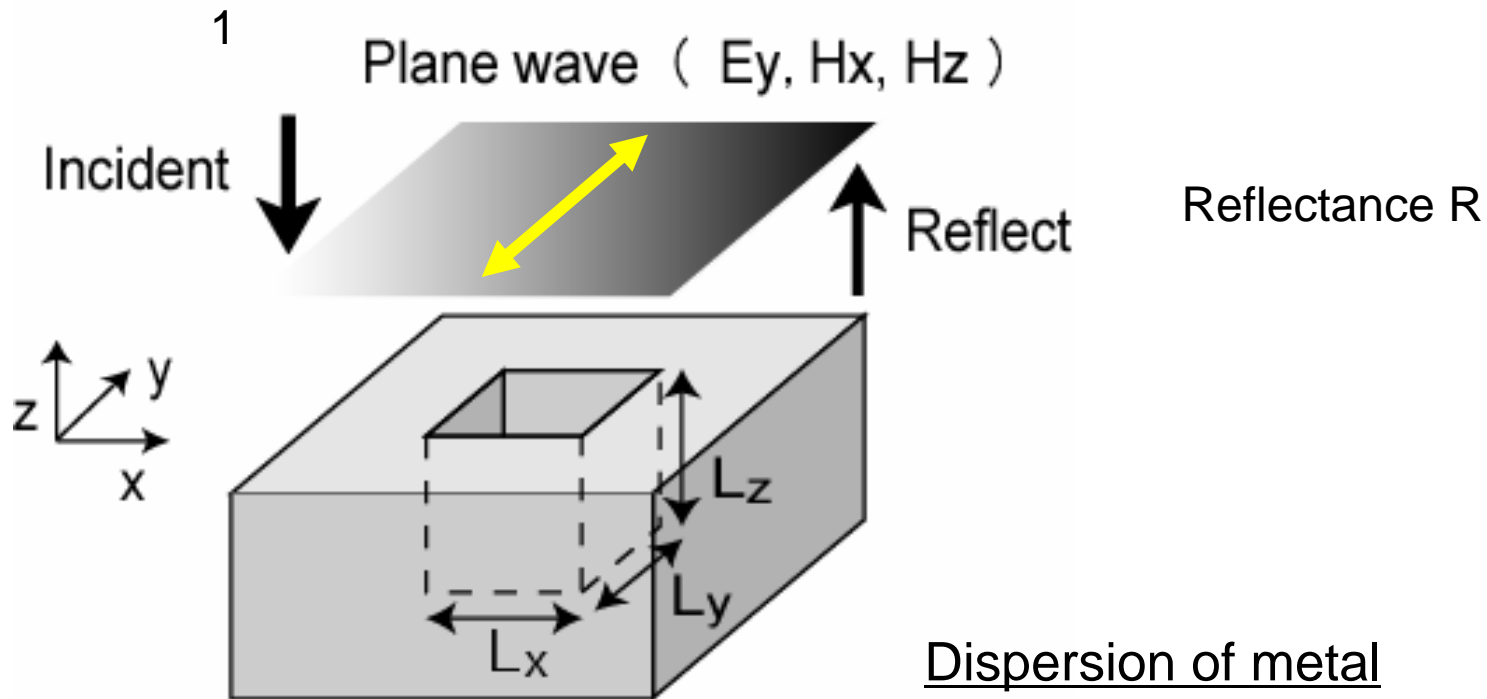
Maxwell equations  
in FDTD algorithm

$$\frac{\partial \vec{H}}{\partial t} = -\frac{1}{\mu} \nabla \times \vec{E}$$

$$\frac{\partial \vec{E}}{\partial t} = \frac{1}{\epsilon} \nabla \times \vec{H} - \frac{\sigma}{\epsilon} \vec{E}$$

Time evolution of  $E$  and  $H$   
in Yee's mesh in space

# FDTD calculation model



Pulse input



Time dependent field profile  
Calculate spectral reflectance

Dispersion of metal

Debye model

$\omega_p, \tau$  negative dielectric (@IR)

boundary condition

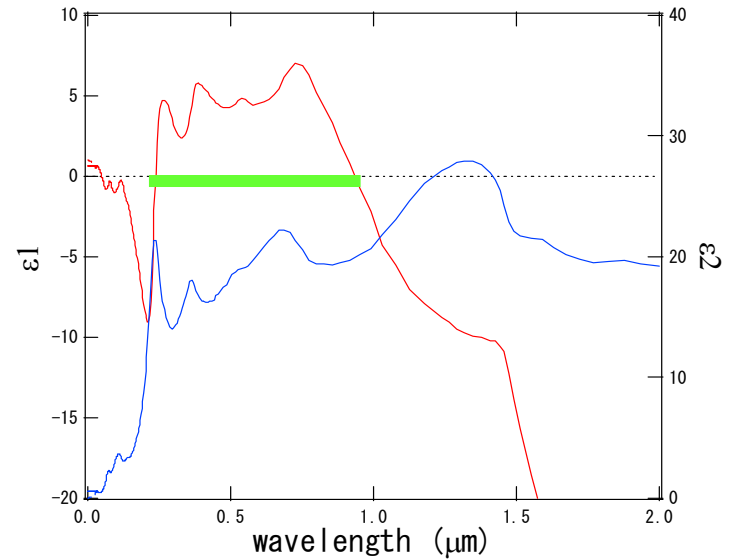
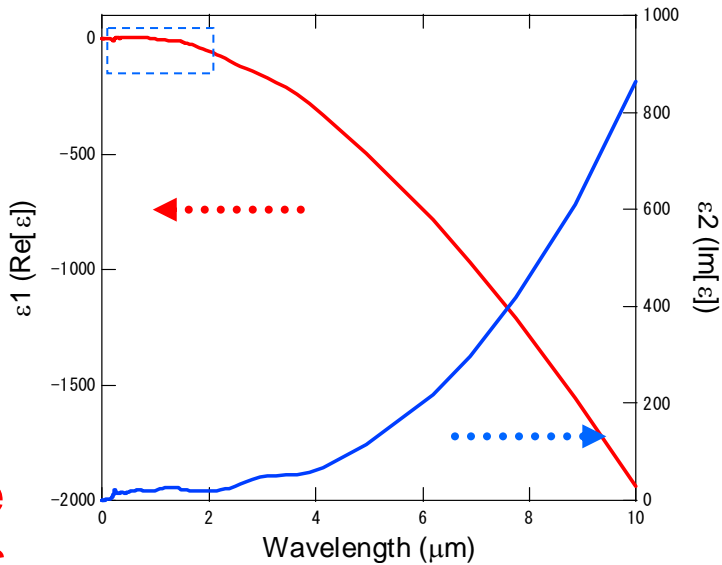
1) PML (Perfectly Matched Layer:  
perfect absorber wall)

2) PBC (Periodic Boundary Condition)

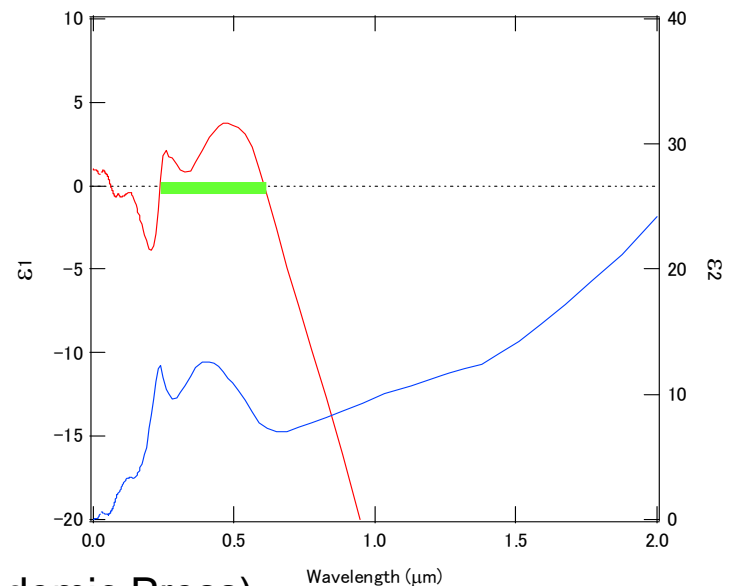
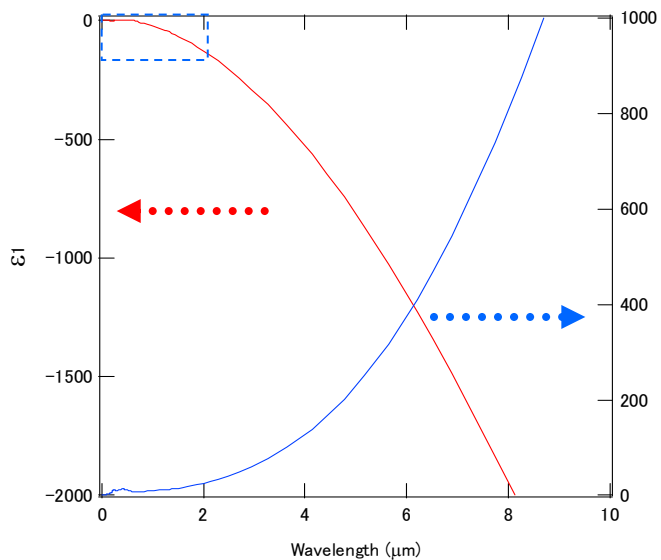
# Permittivity of Tungsten and Tantalum

W

Negative dielectric

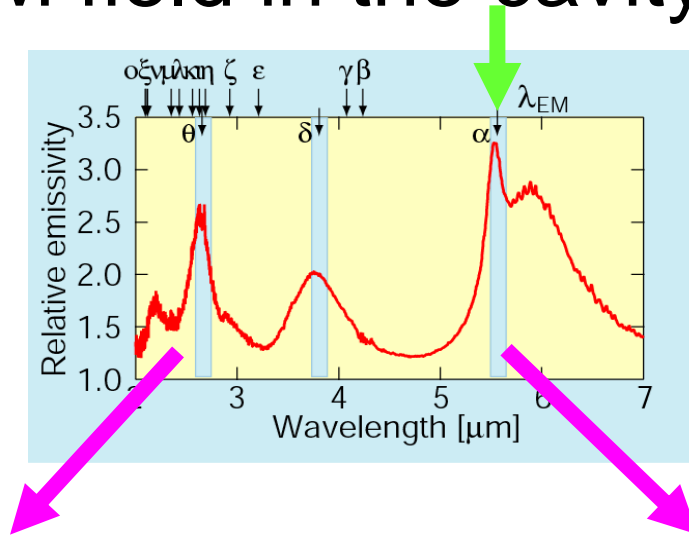
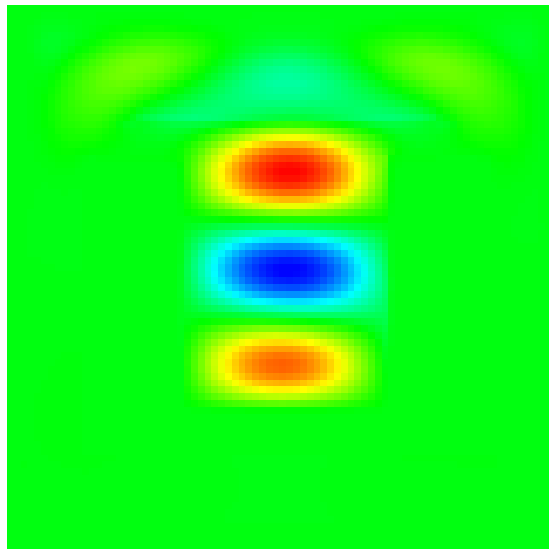


Ta

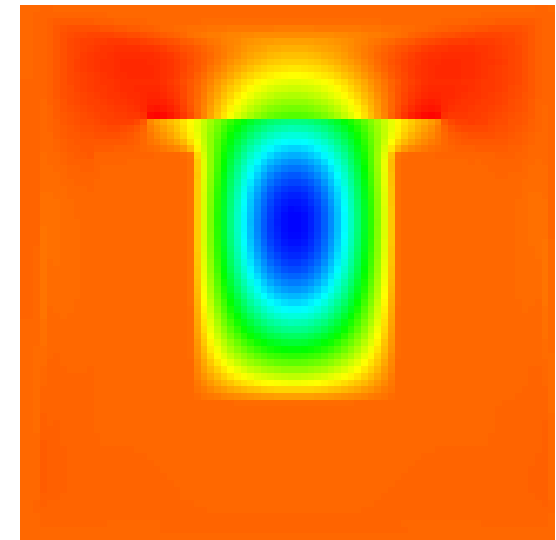


# EM field in the cavity

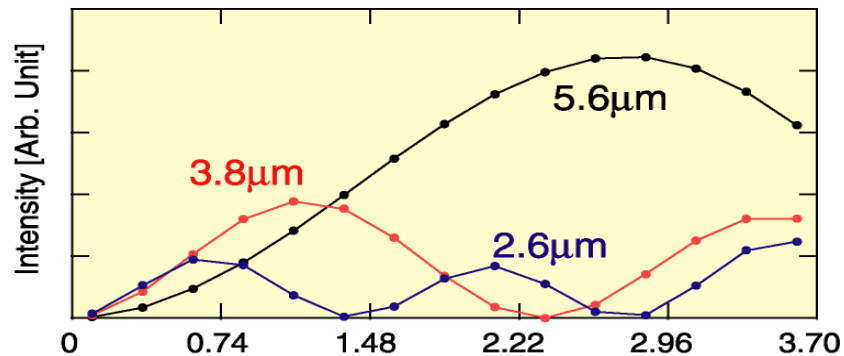
$\lambda = 2.6 \mu\text{m}$



$\lambda = 5.6 \mu\text{m}$

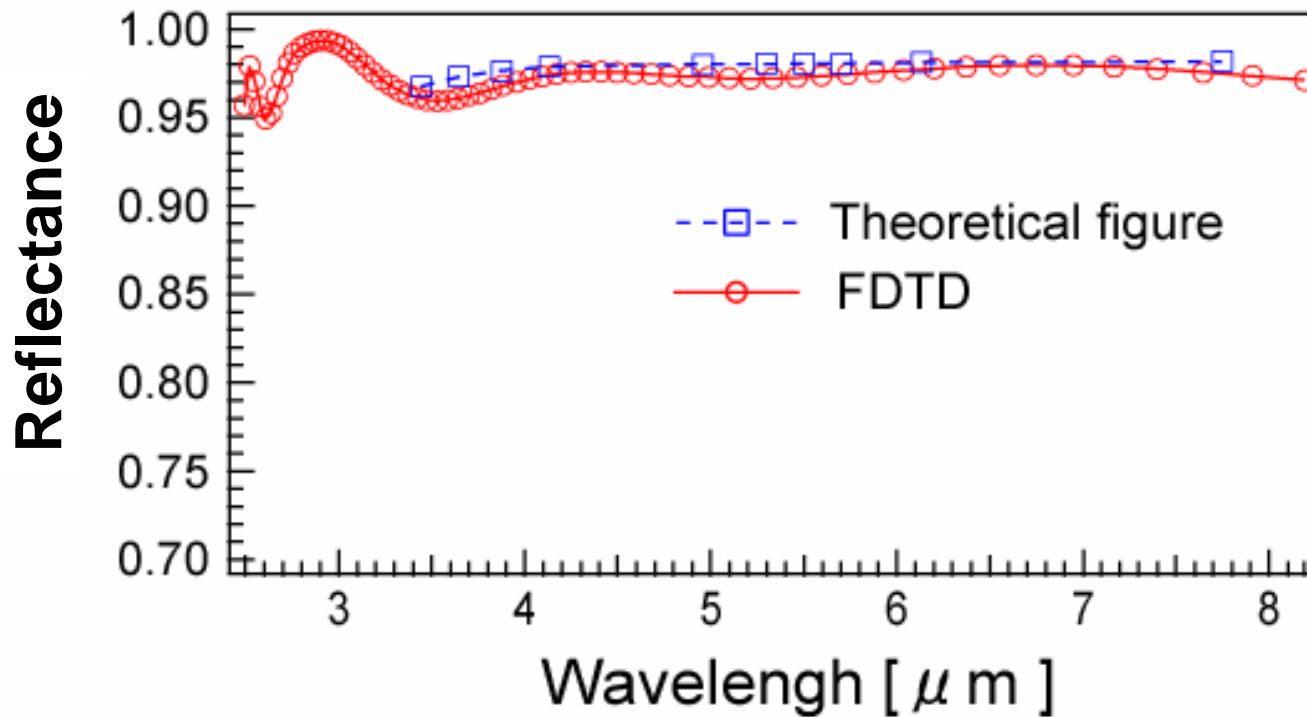


field inside the cavity



The open cavity model is confirmed !

# Reflectance of plane metal surface



Theoretical values are taken from  
Palik: Handbook of Optical Constants of Solids (Academic Press)

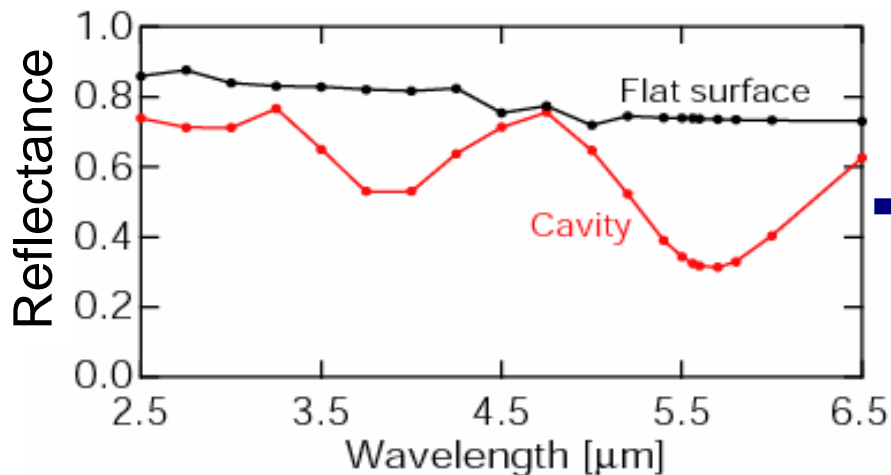
# simulated results

- Calculation of reflectivity R from FDTD

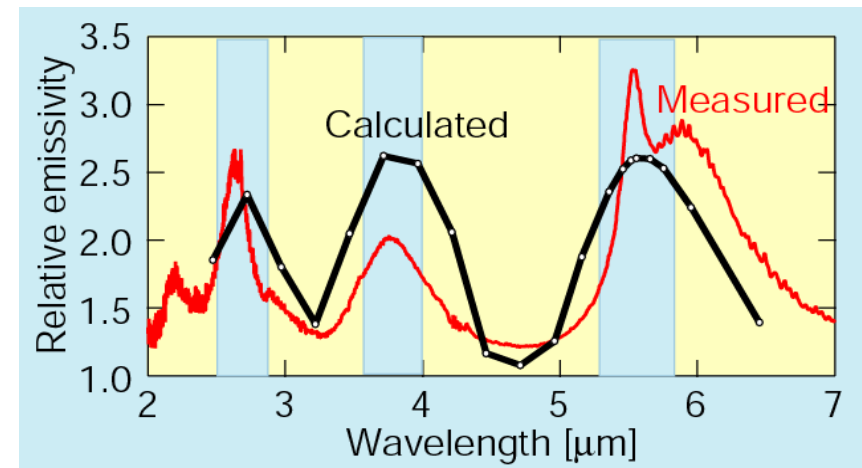
$$\alpha = 1 - R - T = 1 - R$$

- Kirchhoff's law (absorption=emissivity)  $\alpha = \varepsilon$

reflectance



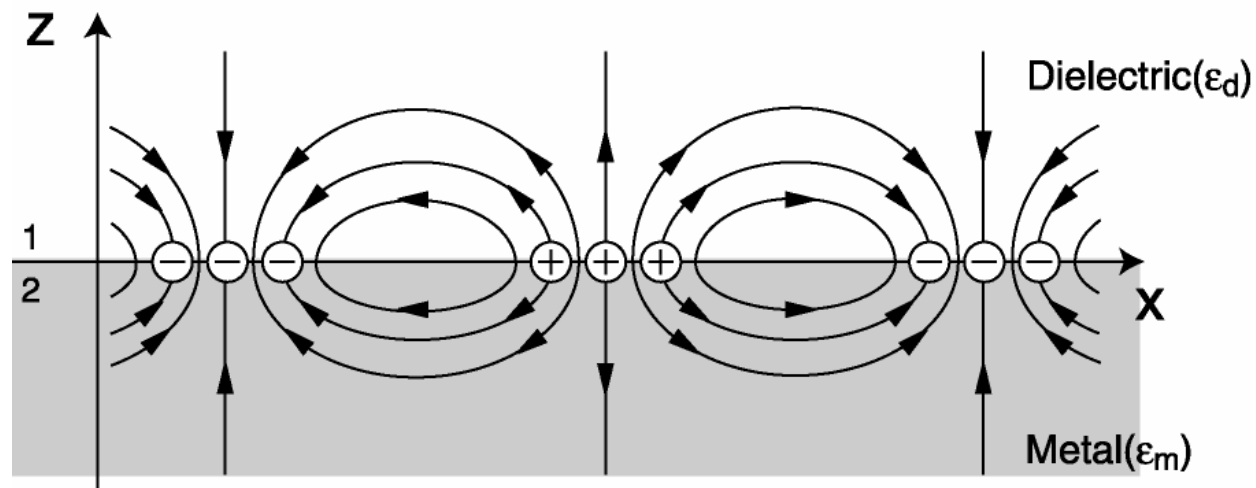
relative emmissivity



We can simulate thermal emission by FDTD calculations.

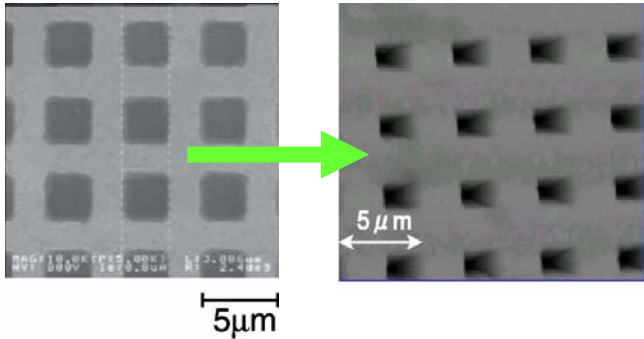
J. Takahara, F. Kusunoki and T. Kobayashi, "Resonant Thermal Radiation from Tungsten Surfaces With Rectangular Array of Square Holes", in IQEC '2005, JWH2-4, (2005).

# 擬似表面プラズモンと熱輻射



# Thermal radiation spectra from small cavity

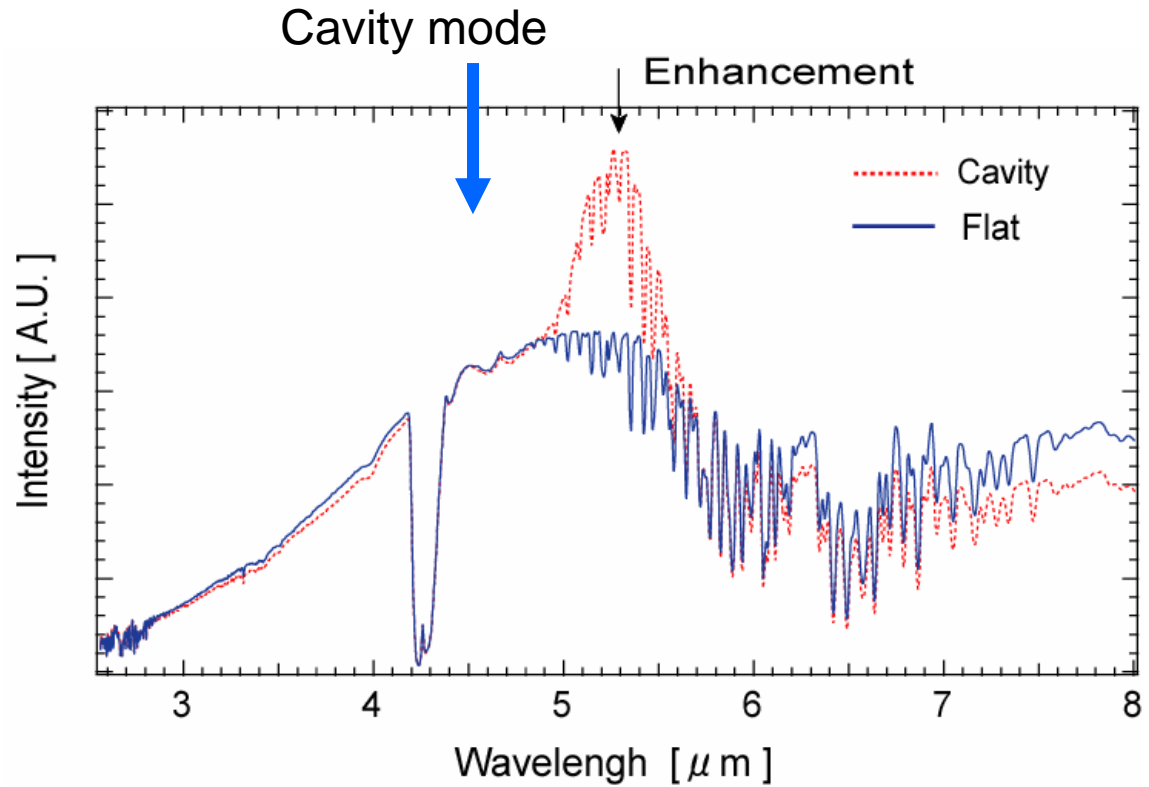
Smaller cavity



AFM image

sample 3

material	W
period	5.0 $\mu\text{m}$
cavity	2.5 $\mu\text{m}$
depth	2.6 $\mu\text{m}$
cavity ratio	0.25



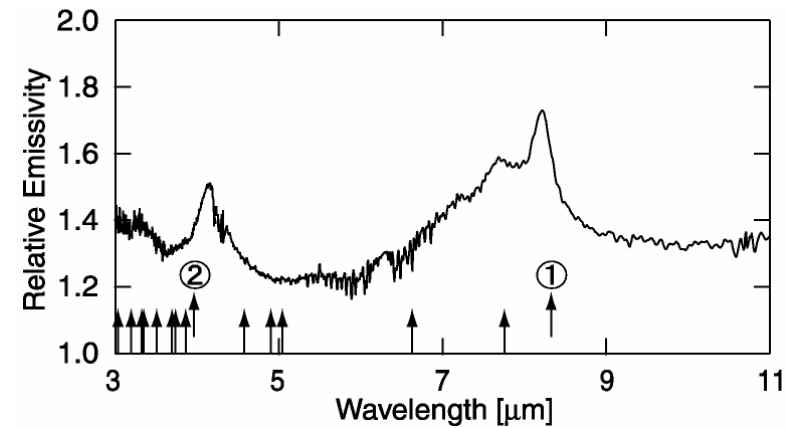
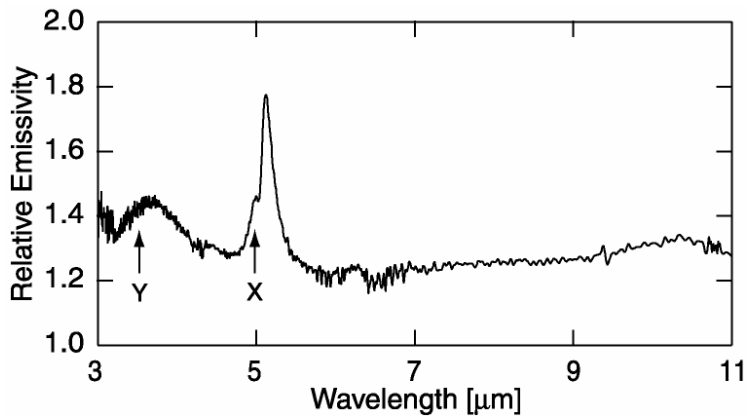
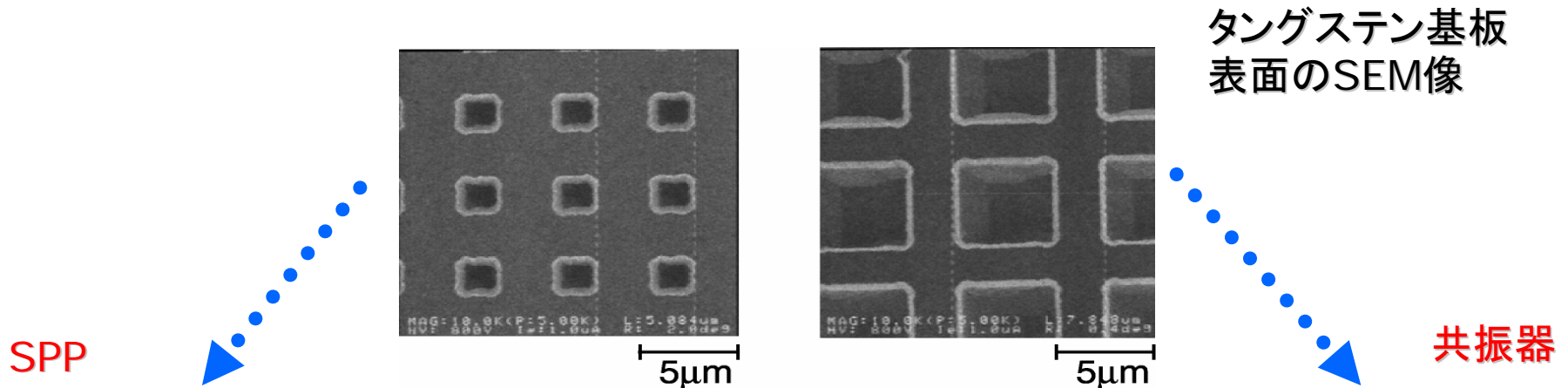
Difference

in cavity resonant mode

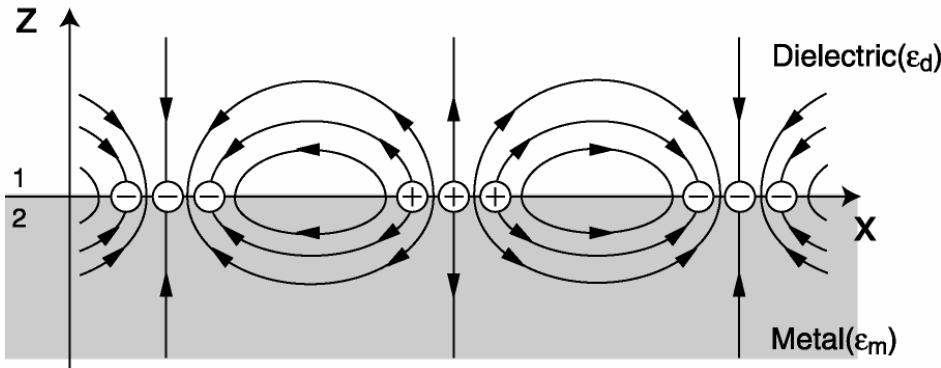


Surface Plasmon Polariton?

- 表面微細周期構造によって熱輻射が変化
- 開口部の割合により輻射スペクトルに質的变化



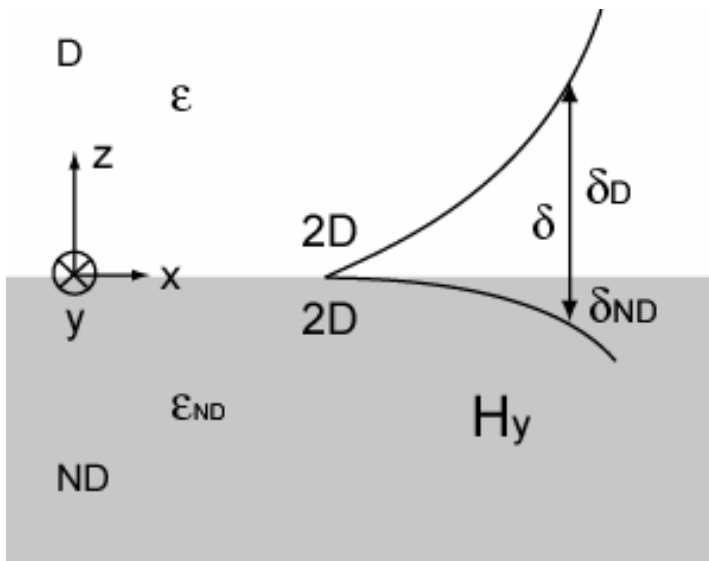
# 2D optical wave ~surface plasmon polariton (SPP)



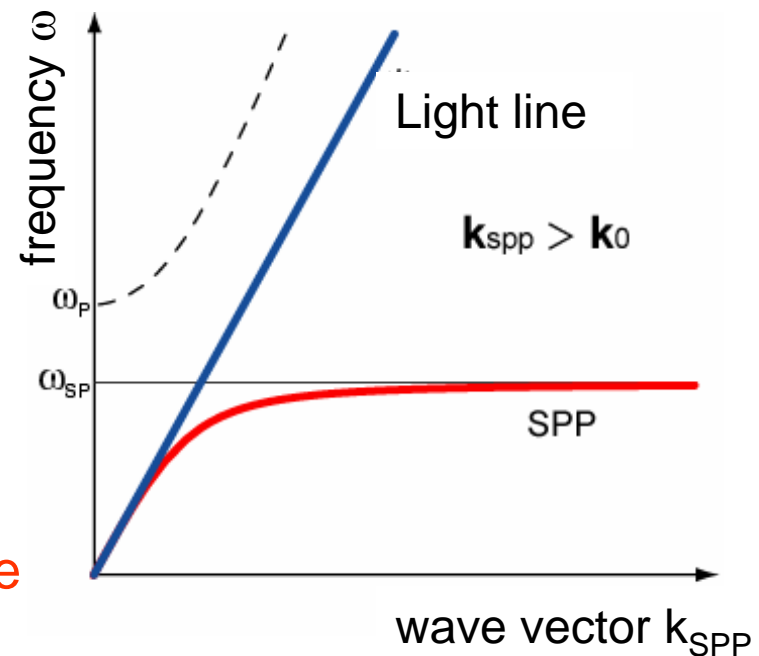
surface plasmon polariton (SPP)

$$|\epsilon_m| > \epsilon > 0$$

$$k_{\text{SPP}} = \frac{\omega}{c} \sqrt{\frac{\epsilon \epsilon_{\text{ND}}}{\epsilon + \epsilon_{\text{ND}}}} = k_0 \sqrt{\frac{\epsilon \epsilon_{\text{ND}}}{\epsilon + \epsilon_{\text{ND}}}}$$



TM wave

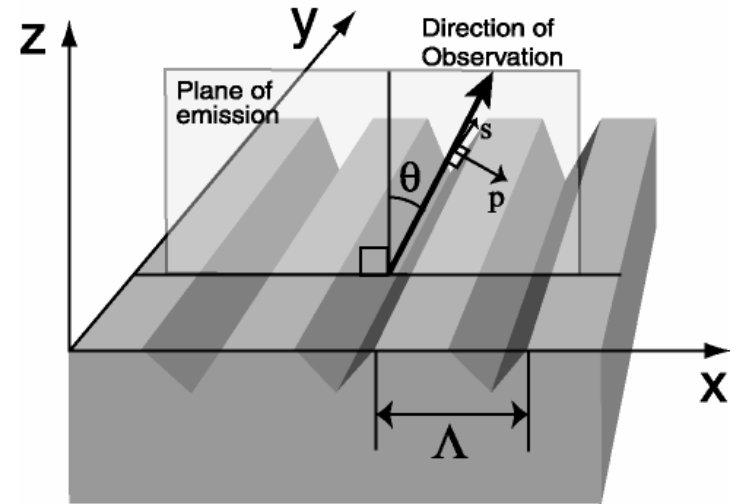
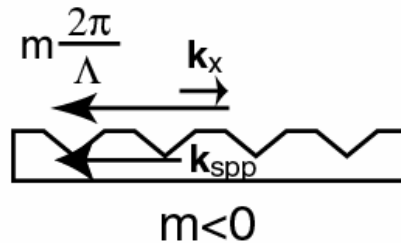
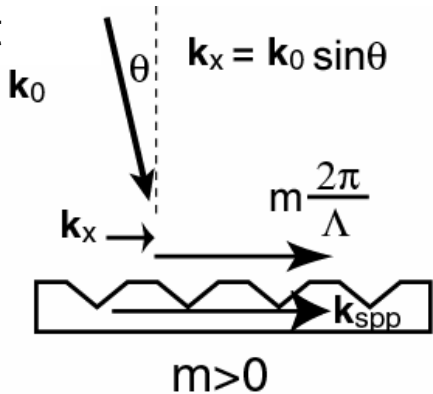


# Coupling from SPP to radiation mode by 1D metallic grating

Coupling condition (1D)

$$\mathbf{k}_{\text{SPP}} = \mathbf{k}_{xy} + m\mathbf{K}$$

Incident light



$k_x$ : wavenumber,  $\Lambda$ : period,  $m$ : integer

Coupling wavelength

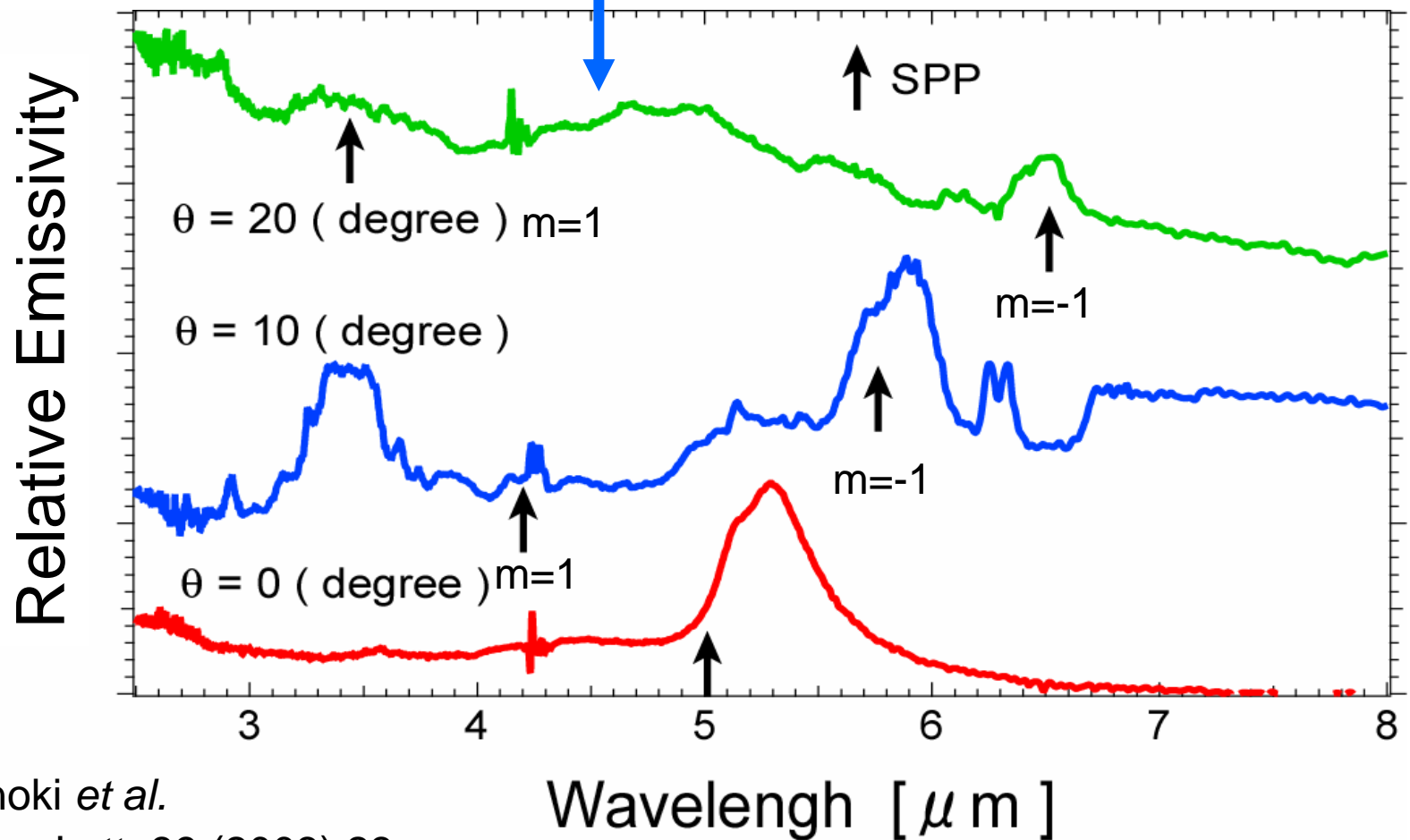
$$\lambda_{\text{SPP}} = \frac{\Lambda}{|m|} \left( \sqrt{\frac{\epsilon_m}{1 + \epsilon_m}} - \frac{m}{|m|} \sin \theta \right)$$

directivity

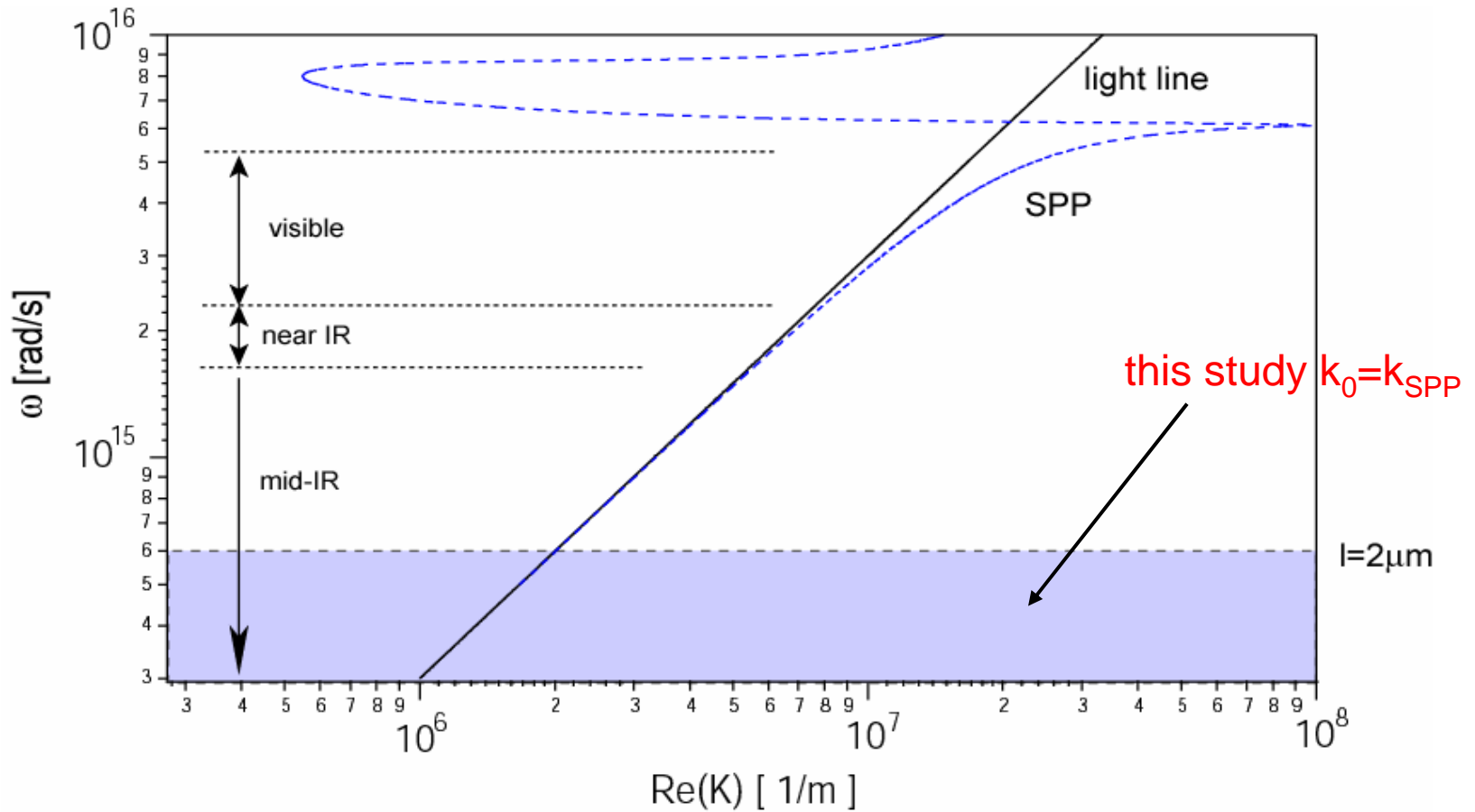
Cavity mode

SPP resonance

difference in wavelength at  $\theta=0$



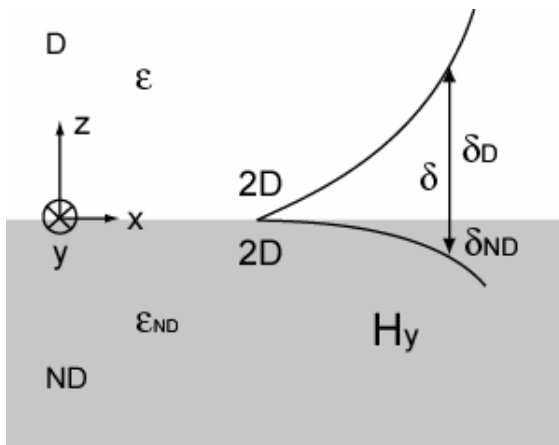
# Dispersion relation of SPP



dispersion relation of SPP = light line?

# Spoof surface plasmon in microstructured perfect conductor

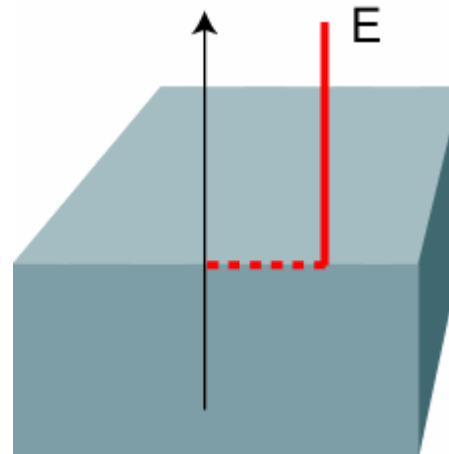
## ■ SPP



Negative dielectric

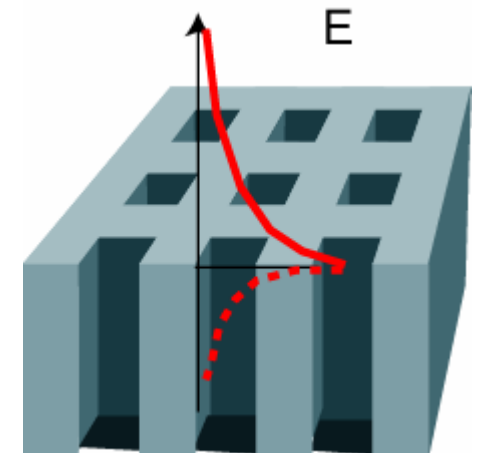
$$k_{\text{SPP}} \doteq k_0$$

## ■ Spoof SPP



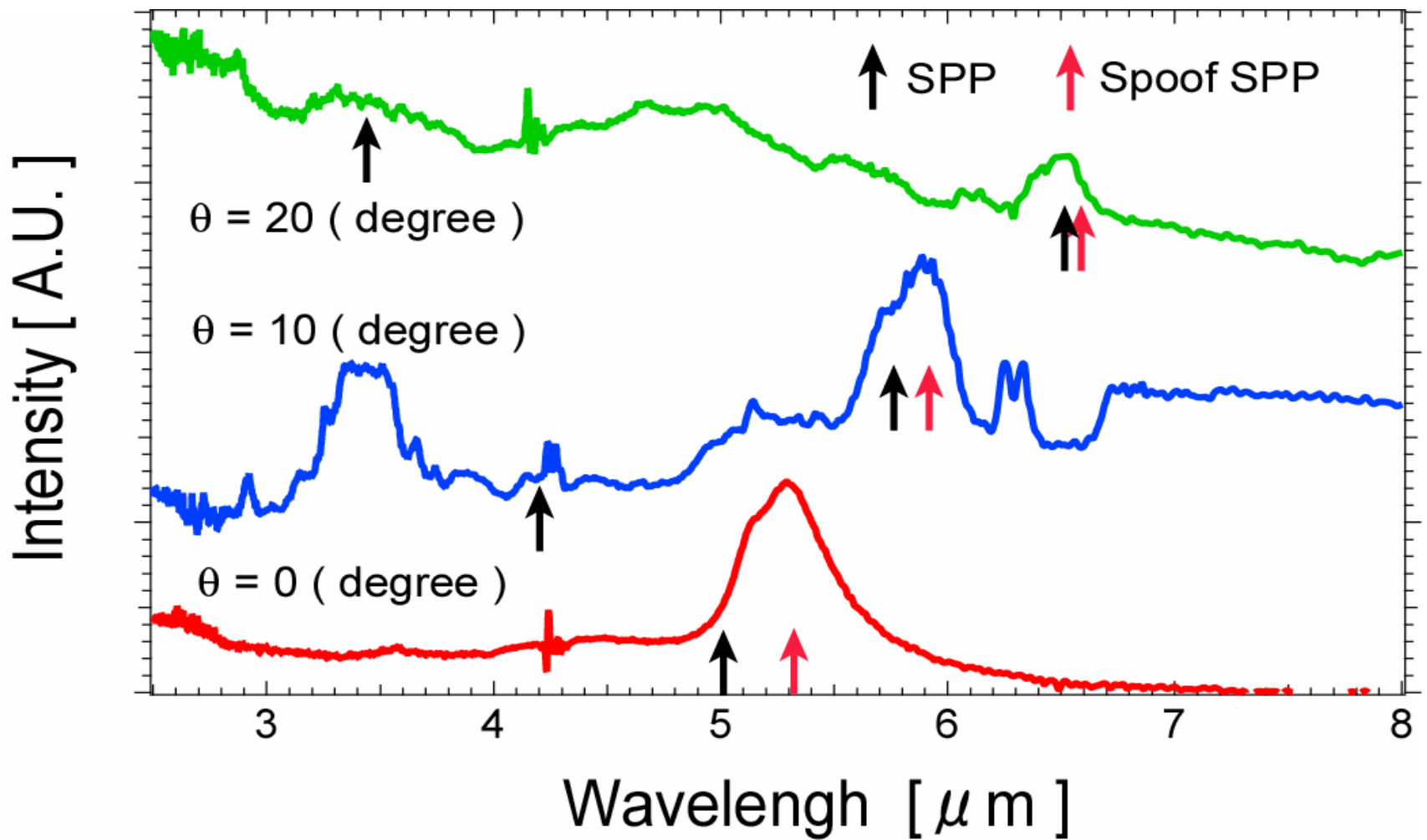
Perfect conductor

No surface wave




Perfect conductor  
with periodic hole  
( $a \ll \lambda_0$ )

J.B. Pendry *et. al.*, Science 305 (2004) 847.



good agreement with spoof SP theory



# 今後の展望と応用

## ～メタマテリアルによる熱輻射制御

# 技術的展望

- 技術的課題

～タングステン微細構造の高温での耐久性



1000°C以下での応用分野

# Difficulty of Micro-cavity lamp

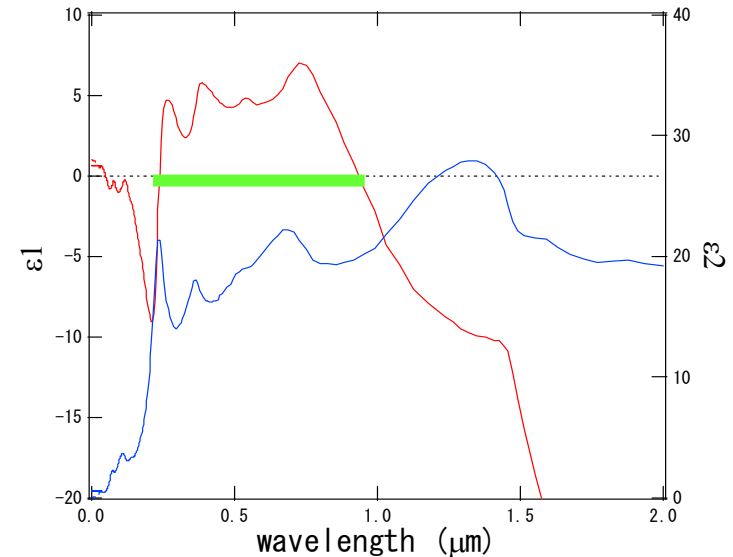
- 1) Damage by dry etching process
- 2) Local T is higher than macro T
- 3) Melting point modification in microstructure



- 1) Microstructure melting
- 2) W, Ta are not negative dielectric at visible range



Micro-cavity lamp is difficult to realize at current technology.



## Practical application

$T < 1000^{\circ}\text{C}$   
IR radiation control  
IR emitter

# 科学的展望

- 将来展望  
～メタマテリアルと擬似表面プラズモン



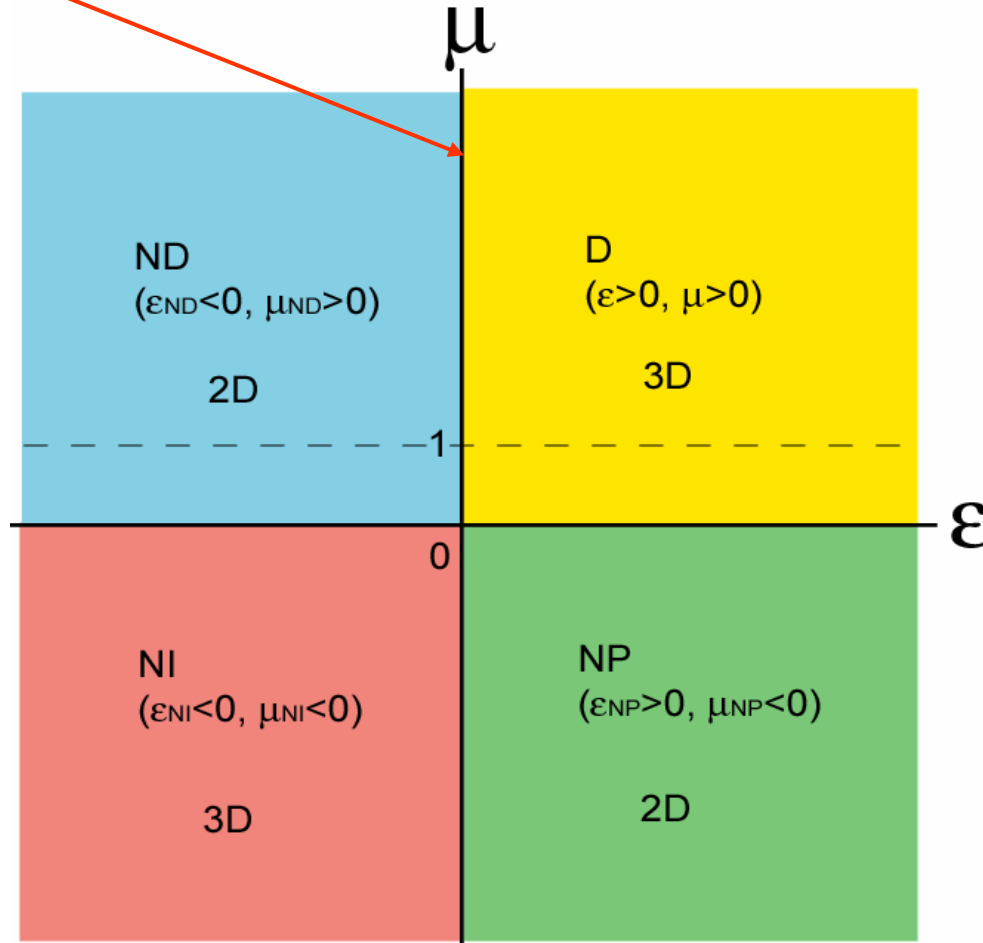
メタマテリアルによる熱輻射制御

SPP

# $\epsilon$ - $\mu$ diagram

Negative Dielectric (ND)

negative Index (NI) or left-handed materials (LHM)



Dielectric (D)

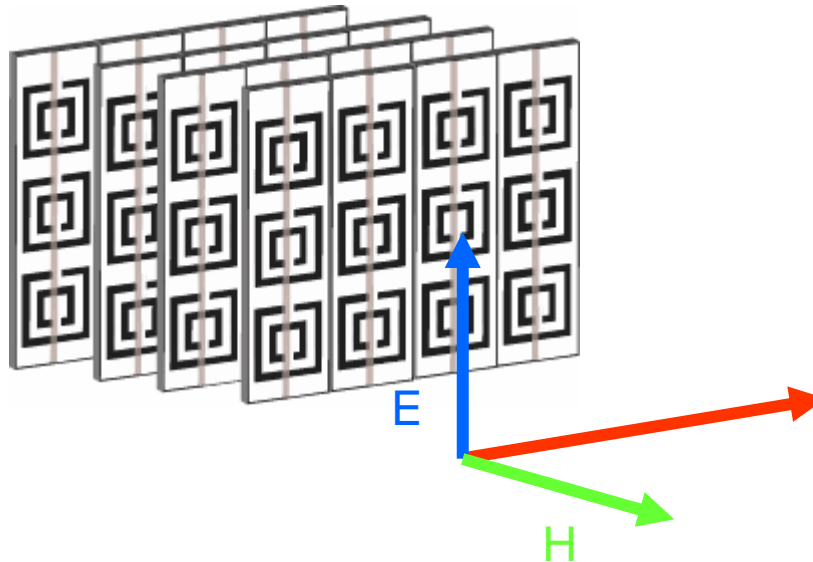


Negative Permeability (NP)

V. Veselago (1968).

# 負屈折率媒質の実現

- TEMモードに対する負屈折率媒質 (NIM)



SRR (Split Ring Resonator)

TW (Thin Wire)

D.R. Smith *et. al.*, PRL 84,  
4148 (2000).

SRRとTWを用いたメタマテリアルによりNIMが実現

## Centre de Physique 2007 / *Physics center 2007*

### THERMAL RADIATION AT THE NANOSCALE: FORCES, HEAT TRANSFER, COHERENCE (TRN 07)

May 21-25, 2007, Les Houches, France

**Organizers:** Jean-Jacques Greffet (École Centrale Paris) and Daniel Bloch (Université Paris 13)

#### **Scientific Committee:**

**G. BARTON** (Sussex U.), **G. CHEN** (MIT), **I. DOROFEYEV** (RAS, Nizhny Novgorod), **C. HENKEL** (U. Potsdam), **M. HOLTHAUS** (U. Oldenburg), **K. KARRAI** (LMU, Munich), **J. OBRECHT** (JILA, Boulder), **B.N.J. PERSSON** (IFF Forschungszentrum Jülich), **P. PITAEVSKII** (U. Trento and Kapitza Institute, Moscow), **S. REYNAUD** (École Normale Supérieure, Paris), **J. TAKAHARA** (U. Osaka), **Z. ZHANG** (Georgia Tech)

## Lectures

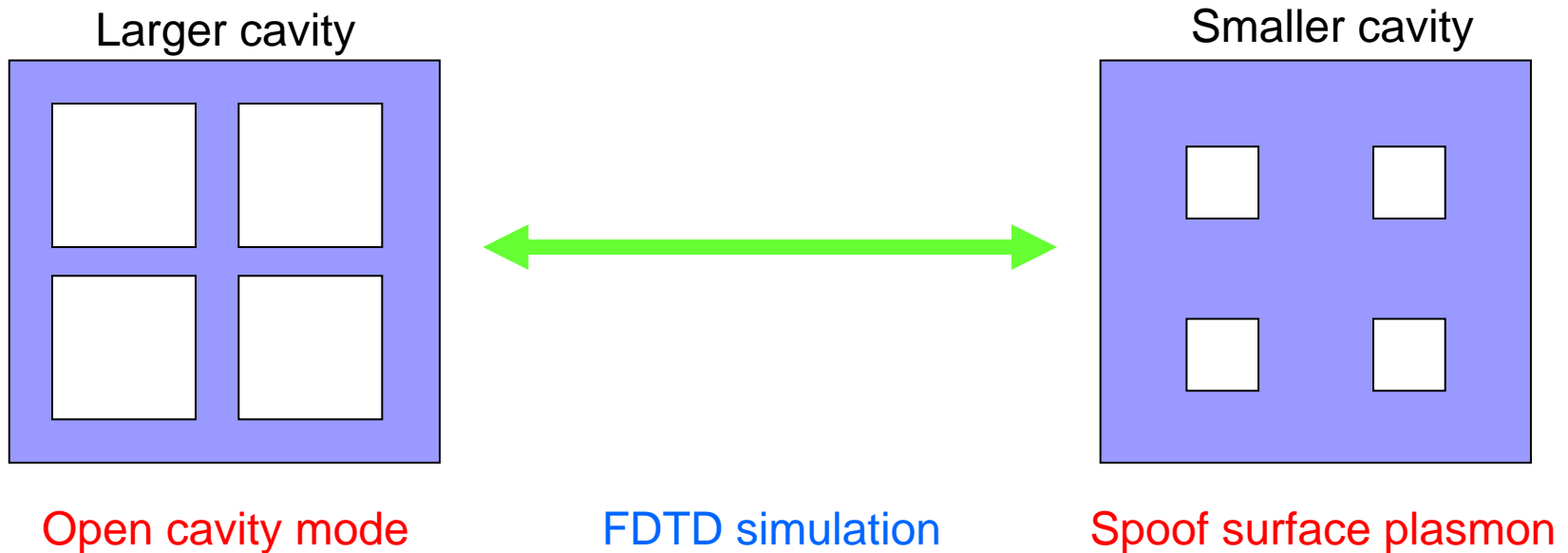
- S. BARNETT (Strathclyde U.), Radiation pressure and momentum transfer in dielectrics
- C. HENKEL (U. Potsdam), Introduction to fluctuational electrodynamics, surface polaritons and coherence
- M. RUBI (U. Barcelona), Nanothermodynamics

## Seminars

- M. ANTEZZA (U. Trento), Interaction between atoms and thermal radiation
- D. BLOCH (U. Paris 13), Towards temperature effects in atom-surface van der Waals interaction
- G. CHEN (MIT), Heat transfer at nanoscale
- I. DOROFYEV (RAS, Nizhny Novgorod), Energy and momentum transfer between microparticles and solids
- J-J. GREFFET (École Centrale Paris), Coherent thermal emission
- K. JOULAIN (ENSMA Poitiers), Radiative heat transfer in the near field
- A. KITTEL (U. Oldenburg), Experimental study of the radiative heat transfer in the near field
- K. KARRAI (U. Munich), Friction forces measurements in the near field
- S. REYNAUD (ENS Paris), Casimir forces, a (re)view
- U. MOHIDEEN (UC Riverside), Measurements on Casimir forces
- K. MILTON (U. Oklahoma), Dependence of Casimir force on temperature
- J. OBRECHT (JILA, Boulder), Recent experiments on temperature dependence of Casimir-Polder force
- A. I. VOLOKITIN (Samara Tech. State U.), Radiative friction forces, a review of the theoretical models
- J. TAKAHARA (Osaka U.), Modification of light emission by microstructured surfaces
- E. VINOGRADOV (RAS), Vibrational polaritons in semiconductor films and surfaces
- Y. DE WILDE (ESPCI Paris), Experimental measurements of thermal fields in the near field

# まとめ

- マイクロキャビティアレイの熱輻射
- 単一キャビティの共鳴モードによる輻射増大
- キャビティアレイの擬似表面プラズモンにともなう共鳴増大
- メタマテリアルによる熱輻射の制御の概念





Thank you!