大阪大學

メタマテリアルによる熱輻射の制御に向けて

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日本熱物性学会：研究会
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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.

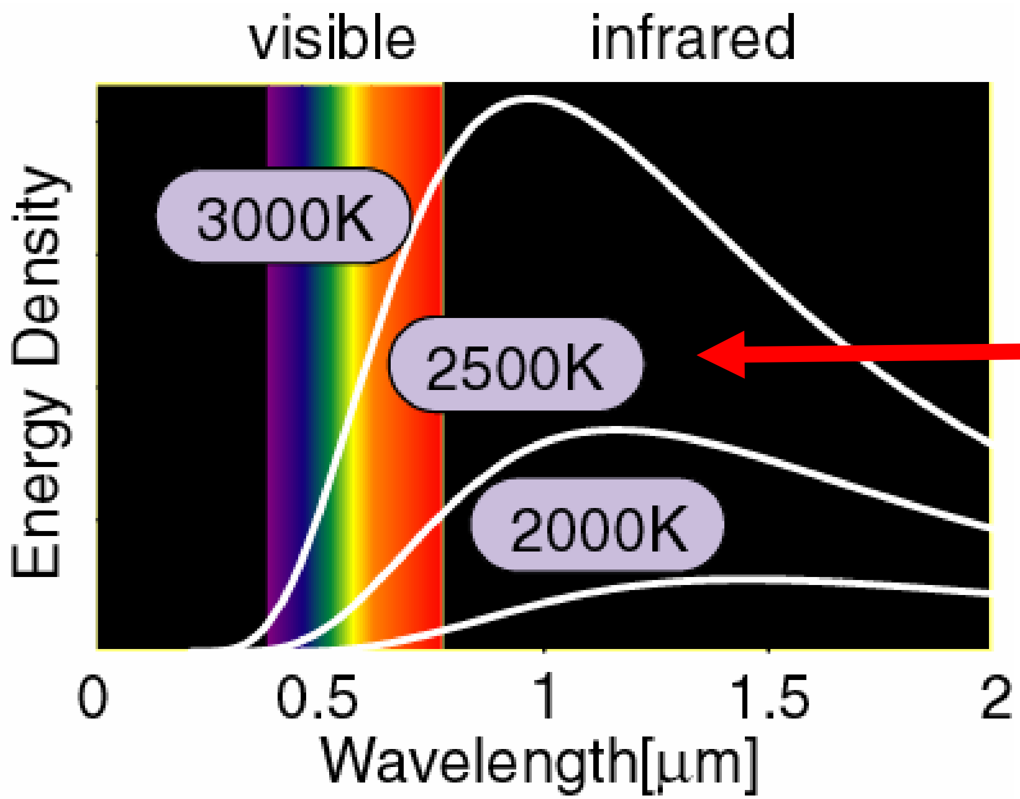
Swan lamp replica
Linear carbon filament
made from cotton

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



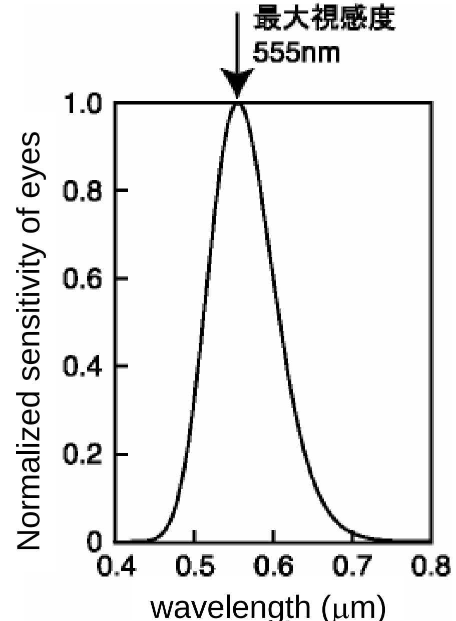
Planck's law

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

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

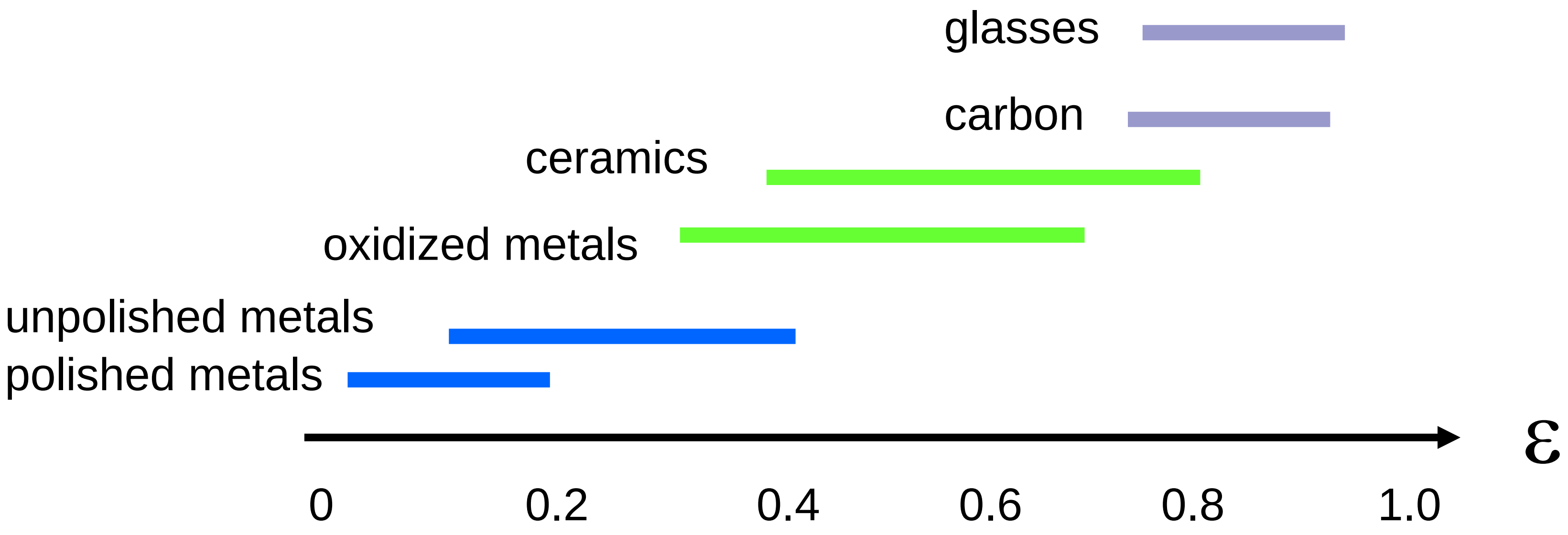
Efficiency of a lamp

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



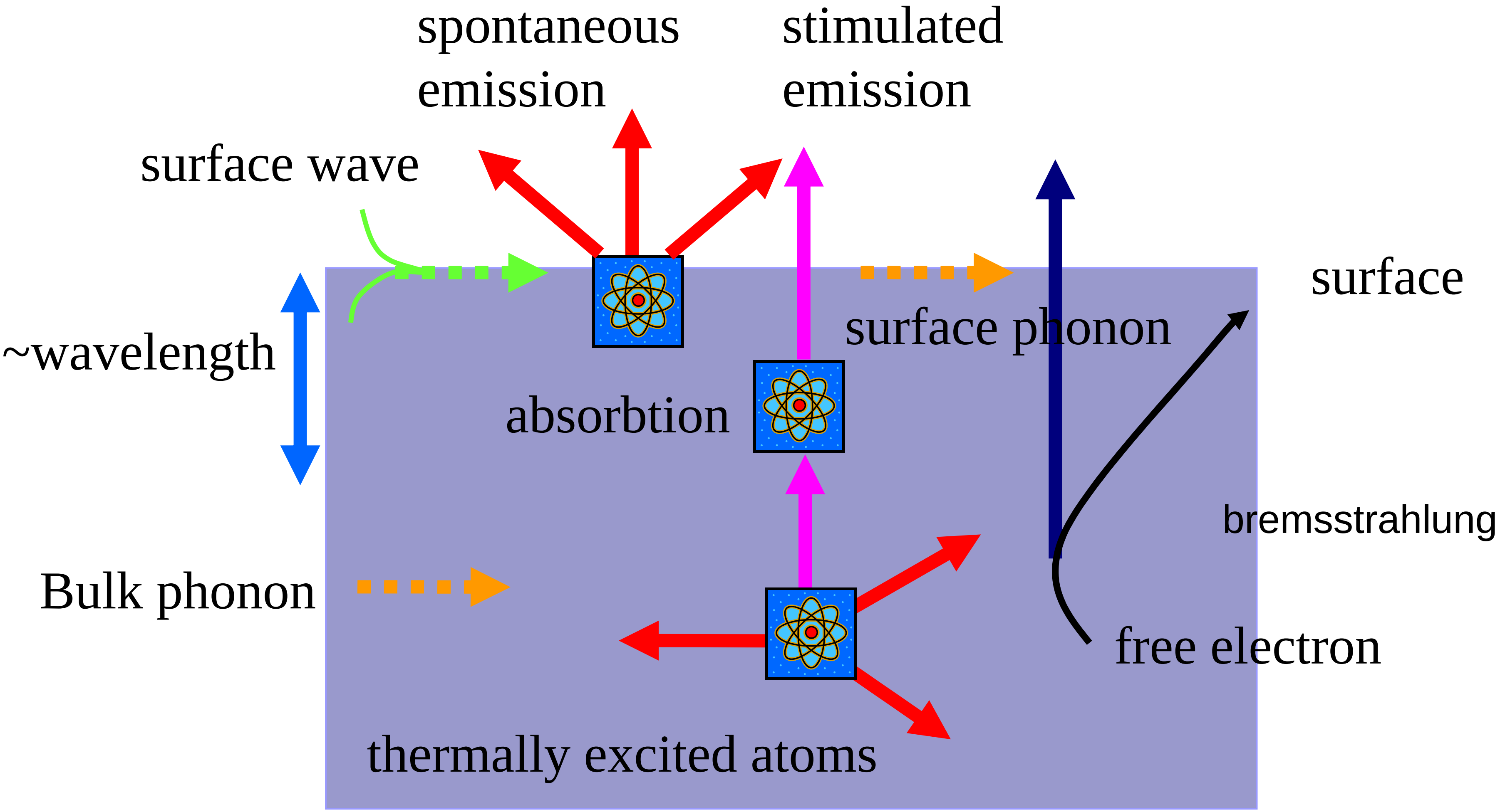
Emissivity of various materials

- blackbody $\varepsilon=1$
- Tungsten $\varepsilon=0.1\sim0.4$
- Typical ranges of emissivity



Y.A. Cengel: Introduction to Thermodynamics and heat transfer (McGraw-Hill, 1997)

Processes in thermal radiation



spontaneous emission

stimulated emission

surface wave

surface

~wavelength

surface phonon

absorbtion

bremsstrahlung

Bulk phonon

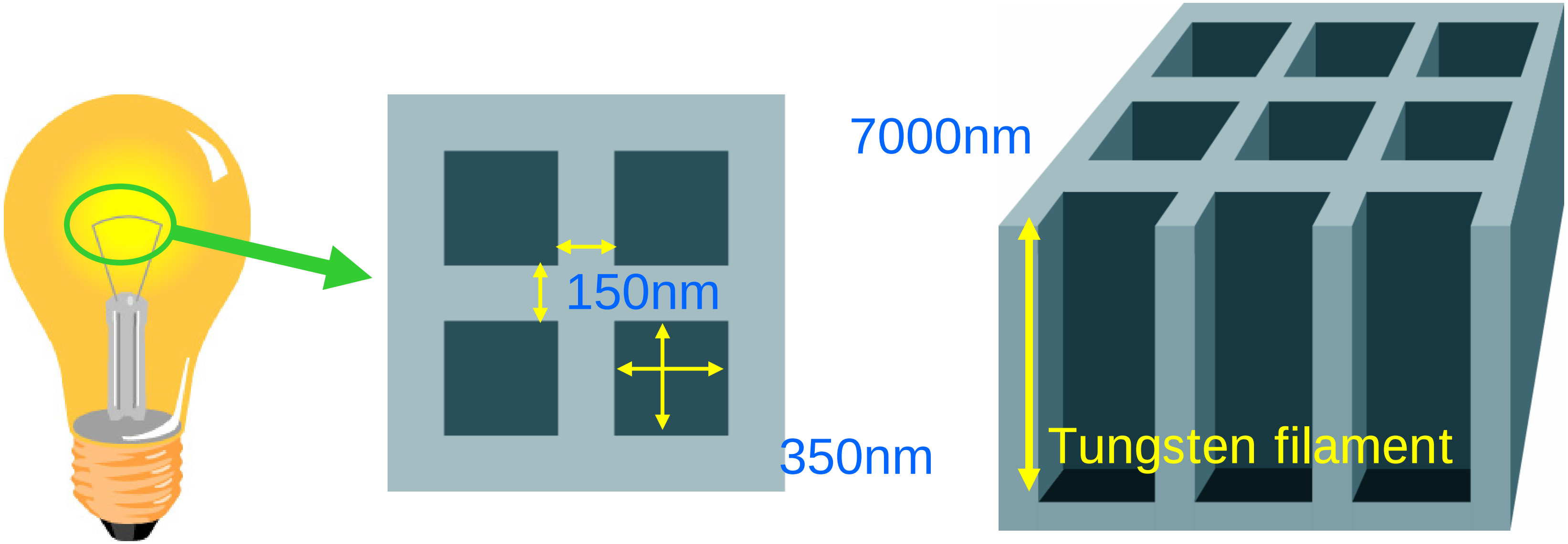
free electron

thermally excited atoms

Microstructures on surface → Control of thermal radiations

Micro-cavity Lamp

Analogy to microwave waveguide theory
Cutoff effect prohibits IR radiation



top view

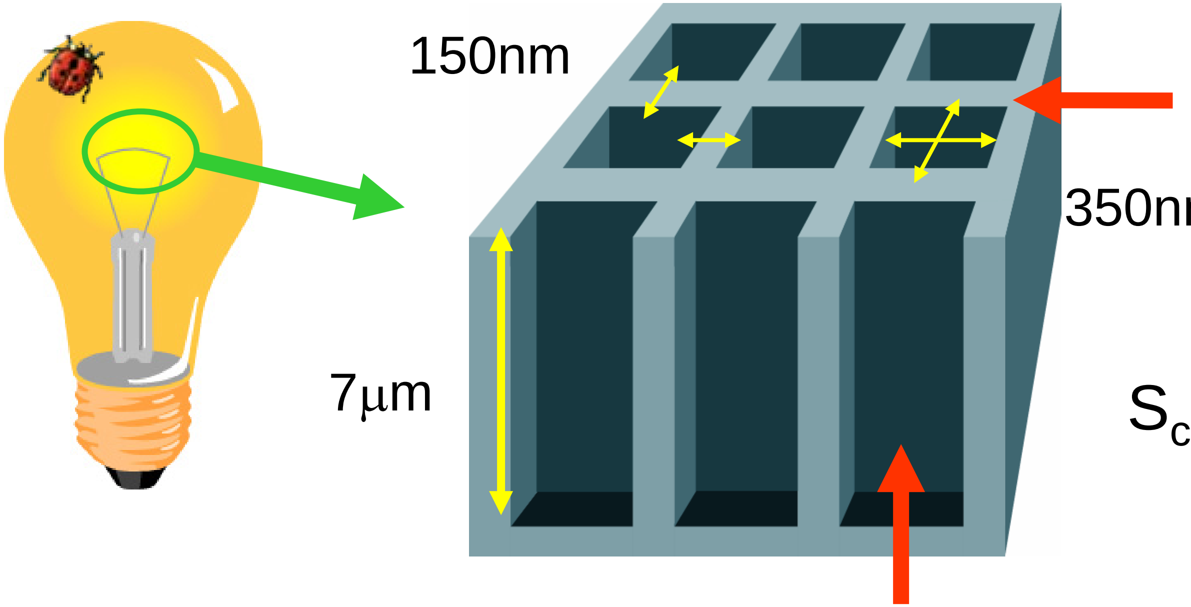
Cross sectional view

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

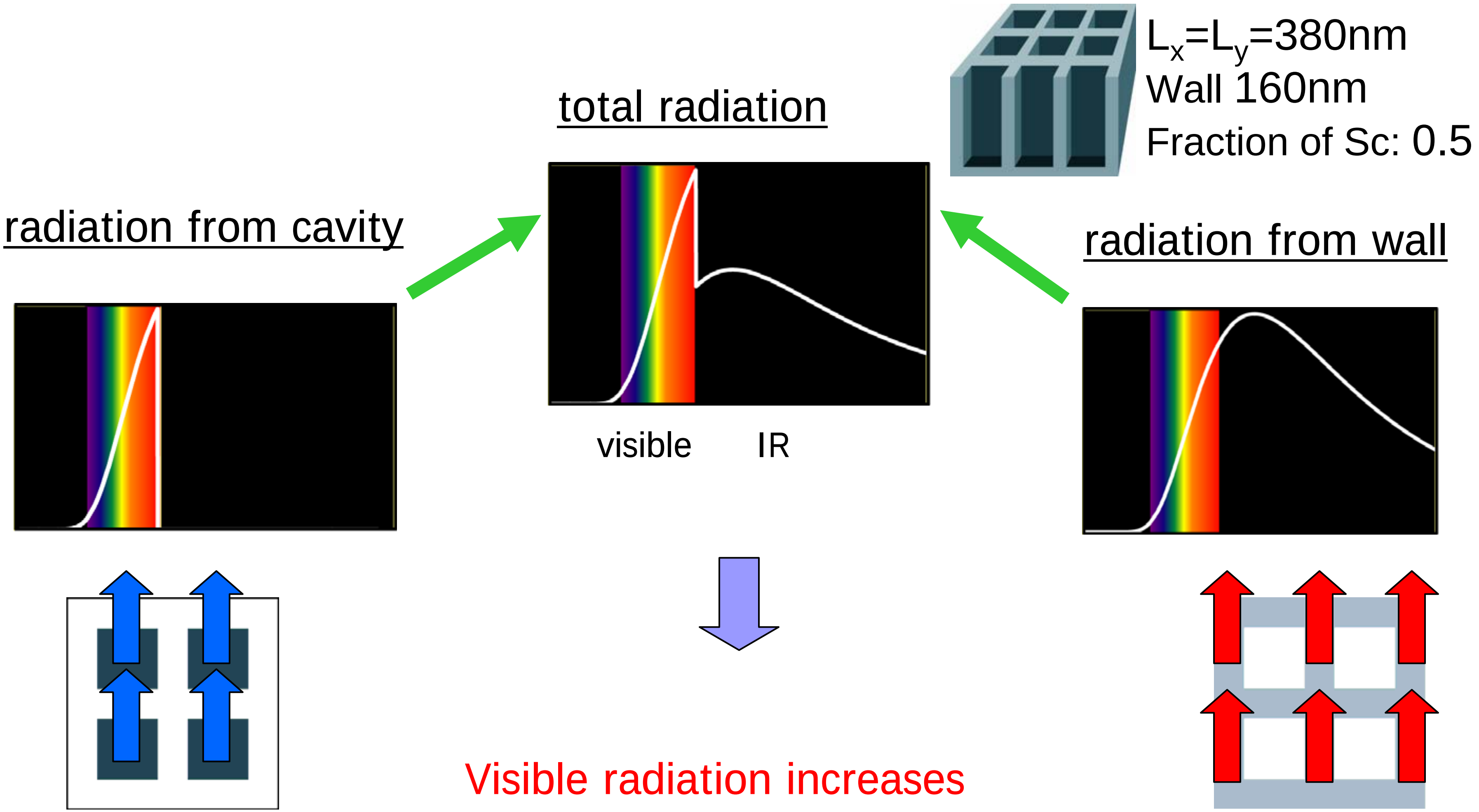
1) IR radiation is prohibited from microcavity due to cut-off
2) IR radiates only from the top wall
3) Radiation flux in top wall decreases to 20% to blackbody in cavity



$$S_c + S_w = 1$$

Radiation spectra of micro-cavity lamp

Energy flow: input power = radiative power



$L_x = L_y = 380$nm
Wall 160nm
Fraction of Sc: 0.5

total radiation

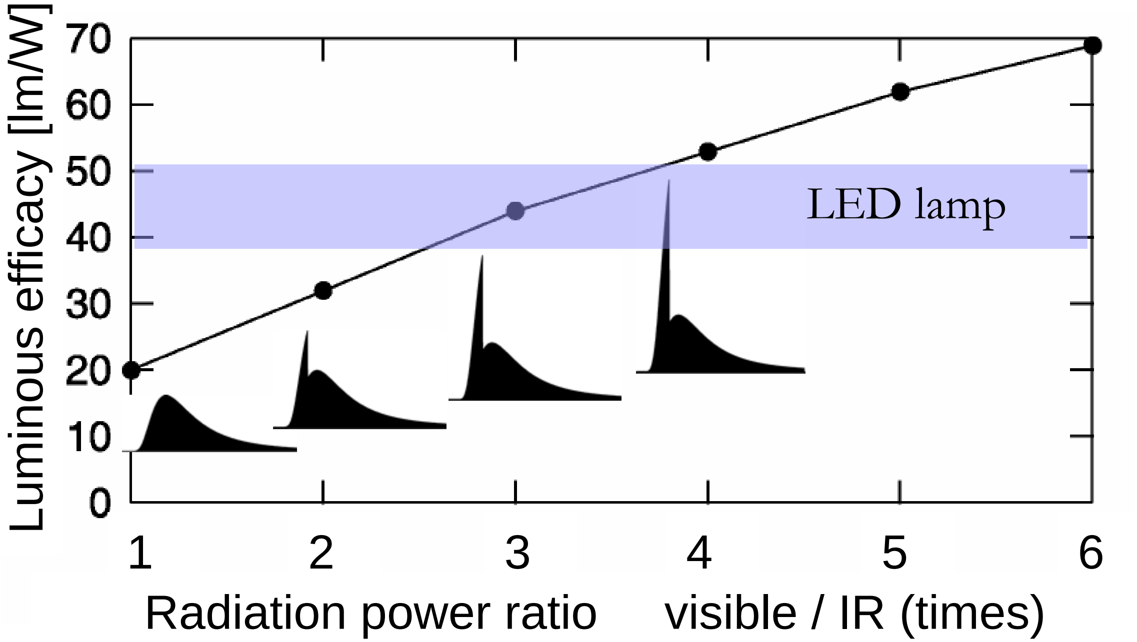
radiation from cavity

radiation from wall

visible IR

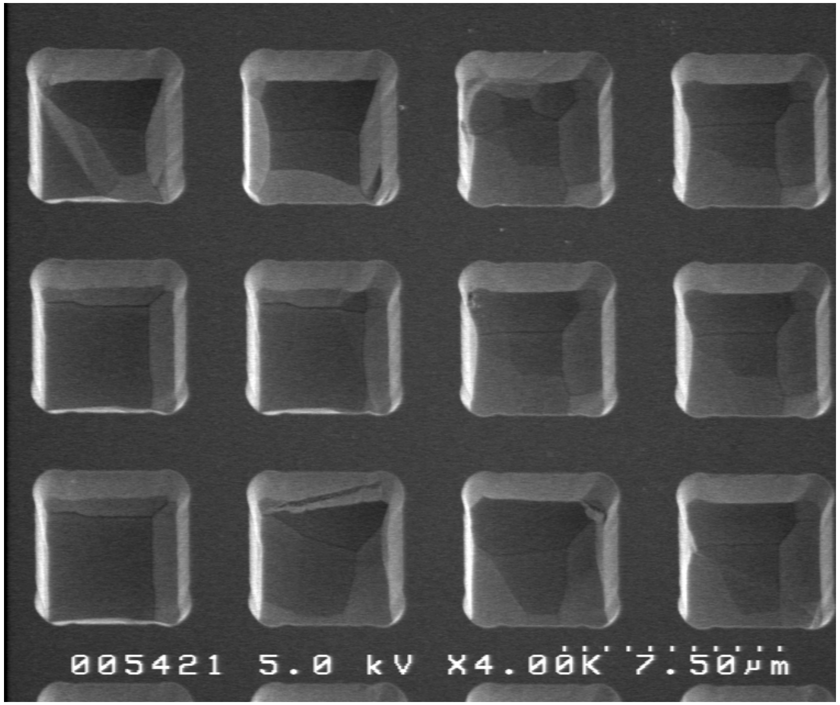
Visible radiation increases

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(45μm) 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.

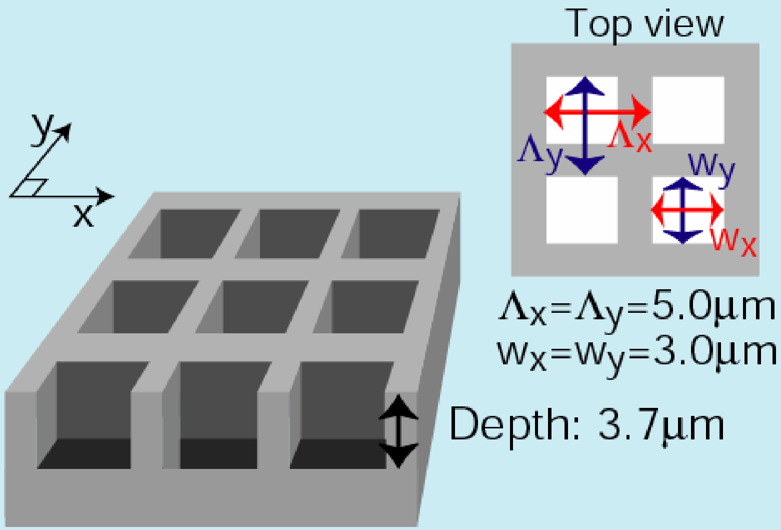
  1D grating on SiC
- Photonic crystals (PC)

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

Deep microcavity array

- Tungsten (W), Tantalum (Ta) substrate（t=0.5mm）
- W (T=3400°C), Ta (T=3000°C), doped Si
- cavity size: 3µm x 3µm x 3.7µm (36%)
- patterned area　3mm x 5mm

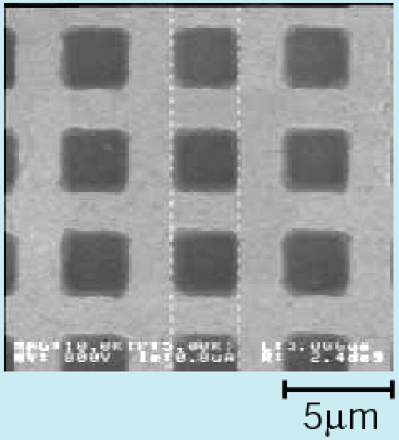
Periodic array of microcavities



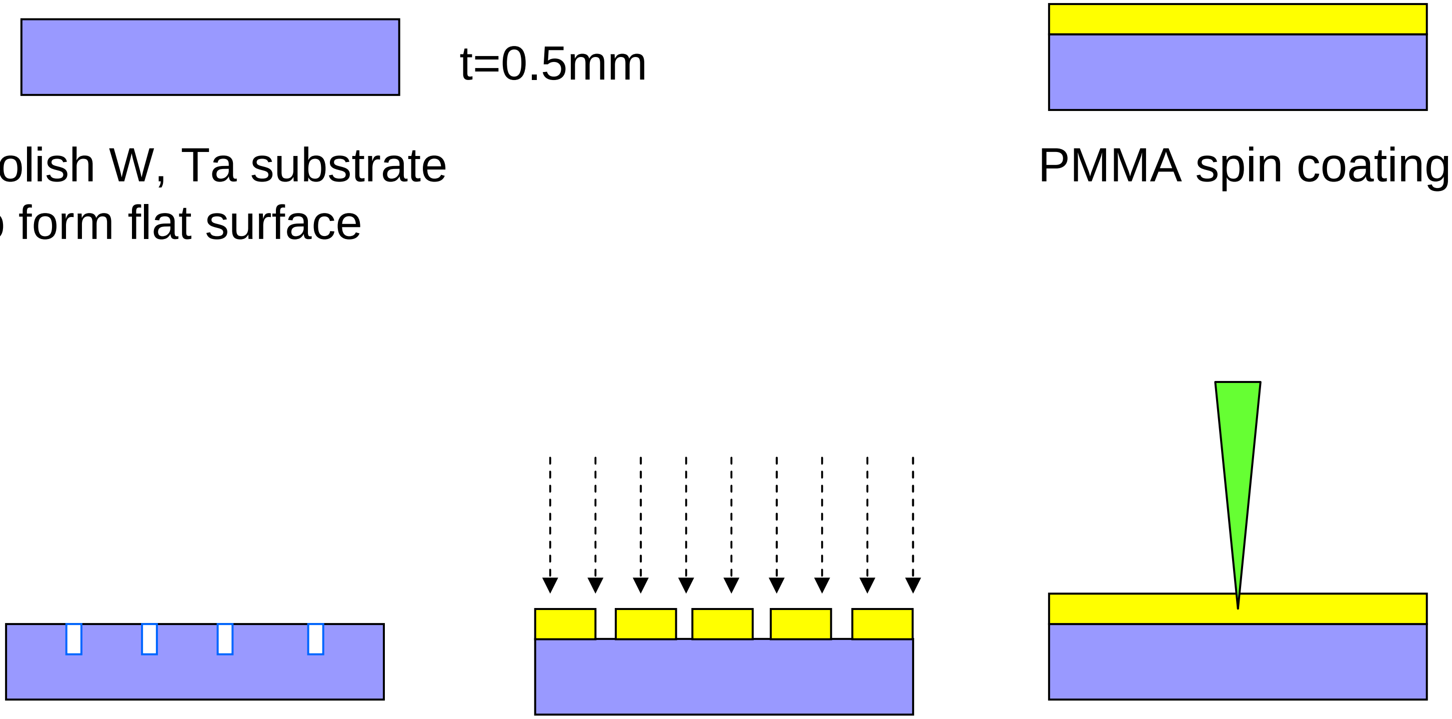
$\Lambda_x=\Lambda_y=5.0\mu m$
$w_x=w_y=3.0\mu m$

Depth: 3.7µm

SEM top image



Fabrication process



t=0.5mm

Polish W, Ta substrate
to form flat surface

PMMA spin coating

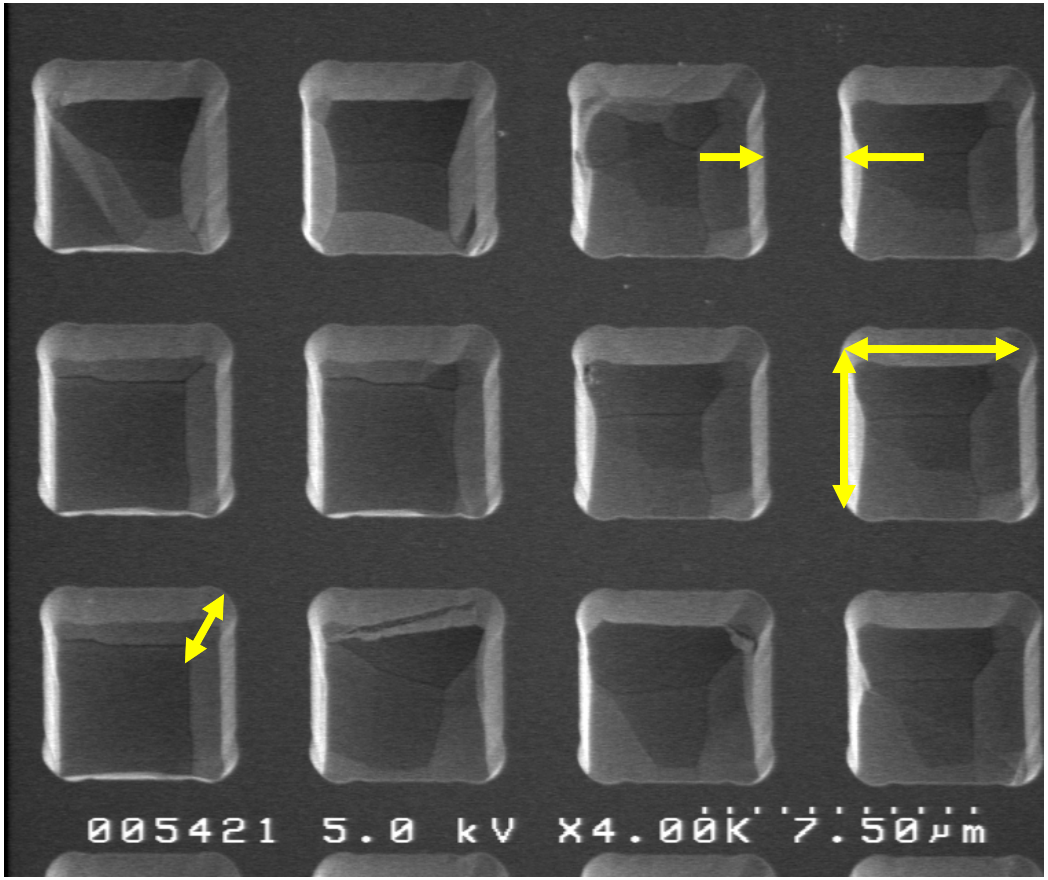
E-beam lithography
(5mm x 5mm area)

Dry etching

PMMA remove

W and Ta have large hardness (W:7.5, Ta:6.5, SiO_2: 7, diamond: 10).

Metallic microstructures



wall width
2.5μm

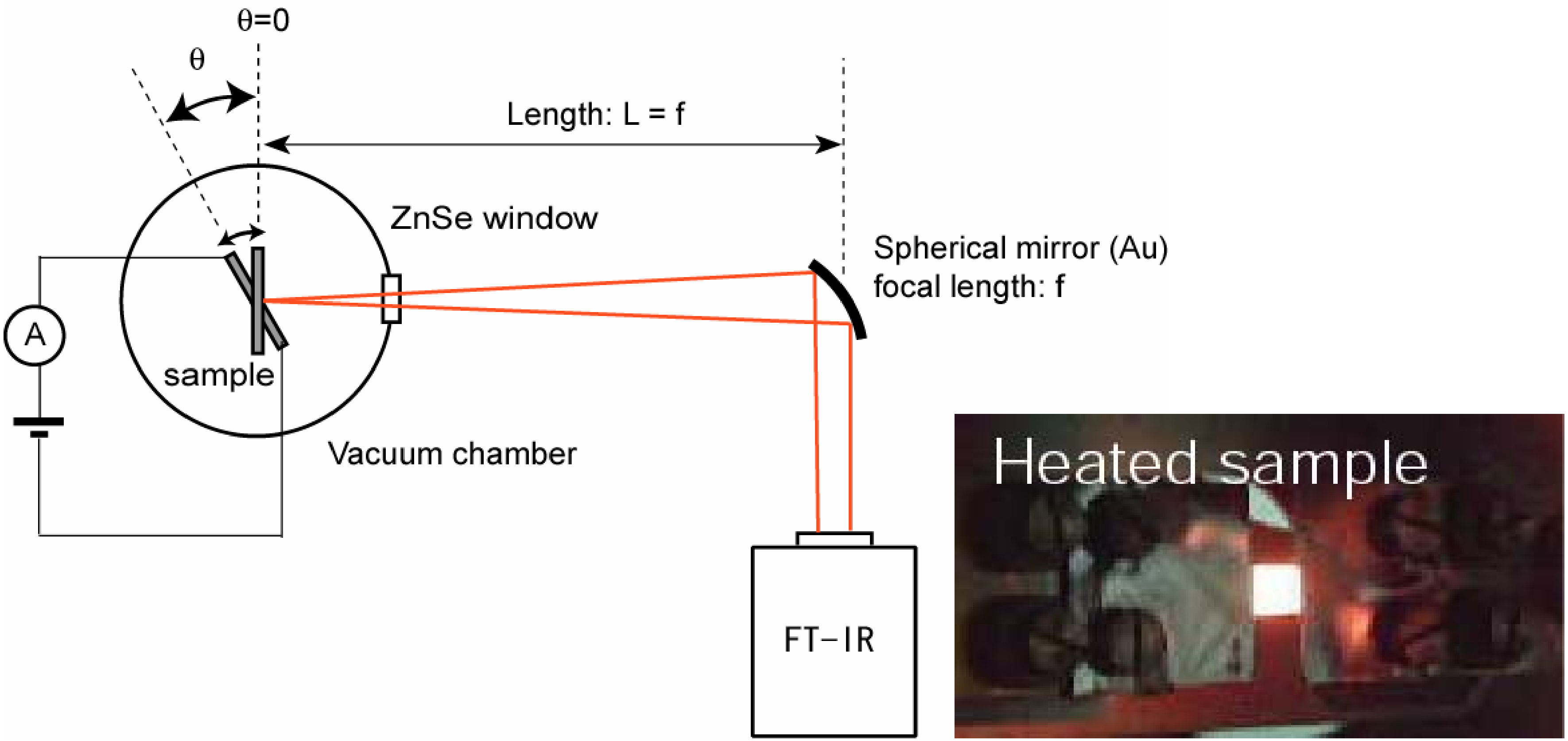
Cavity size
5.5μm x 5.5μm

periodicity
8.0μm

depth
3.2μm

(Example) Ta substrate

Experimental setup



■ heating → Electric current

■ temperature → 470-630℃

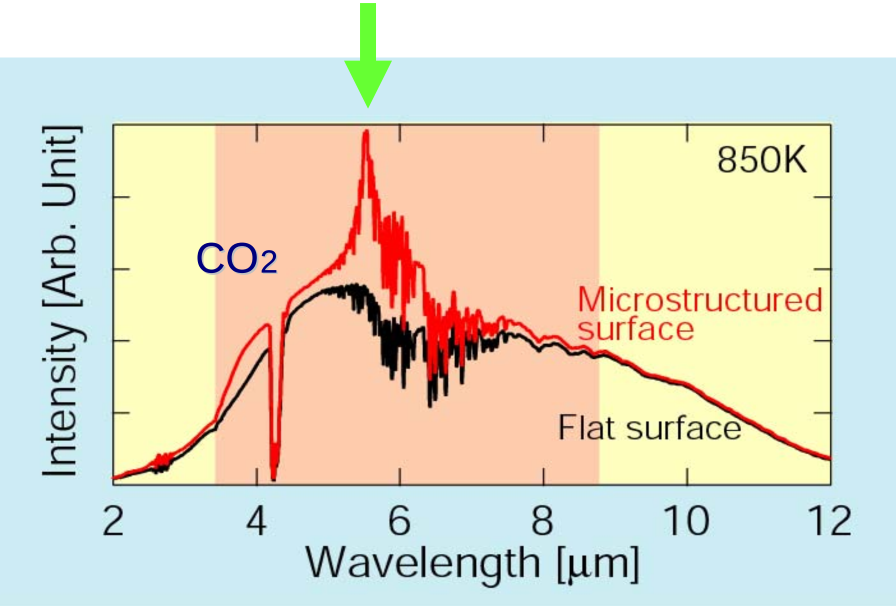
■ measurement → thermal radiation thermometer

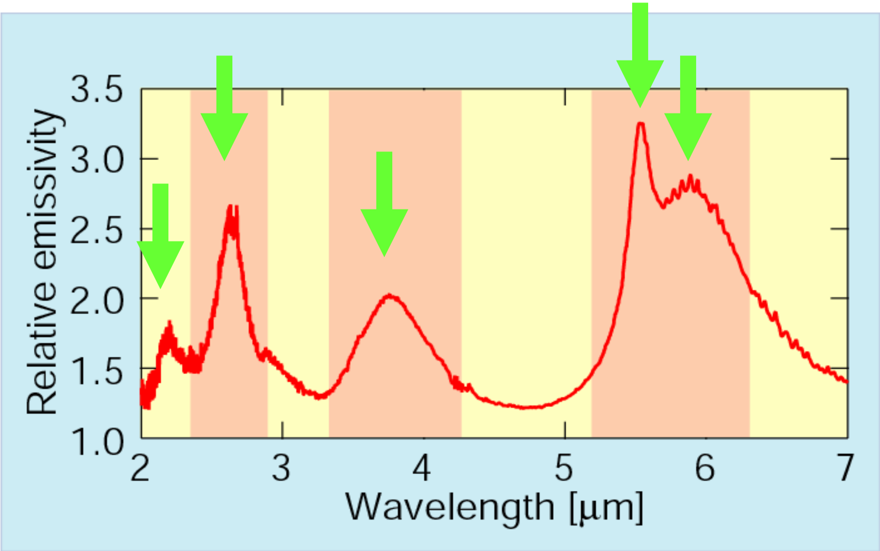
☐ concave mirror (Au)：f = 452 mm
☐ FT-IR （JASCO Inc.，FT-IR 660Plus）
☐ DLATGS detector
☐ DC current source
（KENWOOD Electronics， PS10-210）

Thermal radiation spectra

- flat and structured surfaces
- 3 times enhancement @5.6μm
- Many peaks in relative emissivity

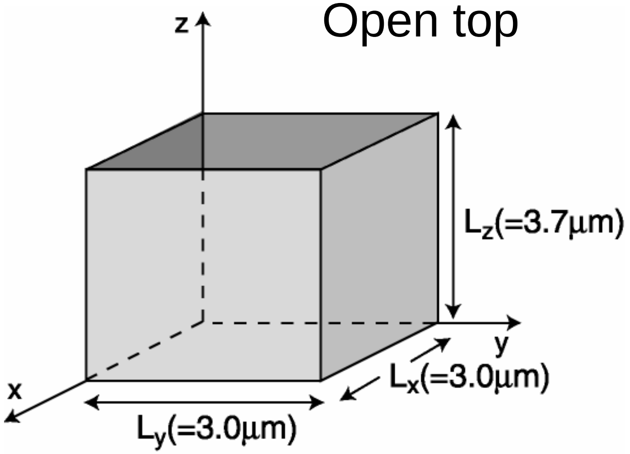
sample 1	
material	W
period	5.0μm
cavity	3.0μm
depth	3.7μm
cavity ratio	0.36





F. Kusunoki, J. Takahara and T. Kobayashi, "Narrow-Band Thermal radiation with Low Directivity by Resonant Modes inside Tungsten Microcavities", Japanese Journal of Appl. Phys., Vol.43, No.8A, (2004) 5253.

EM field in open cavity



Boundary condition for perfect conductor wall

Tangential components $E_t=0$ @ wall

Antinode @ open end of cavity

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

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

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

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

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

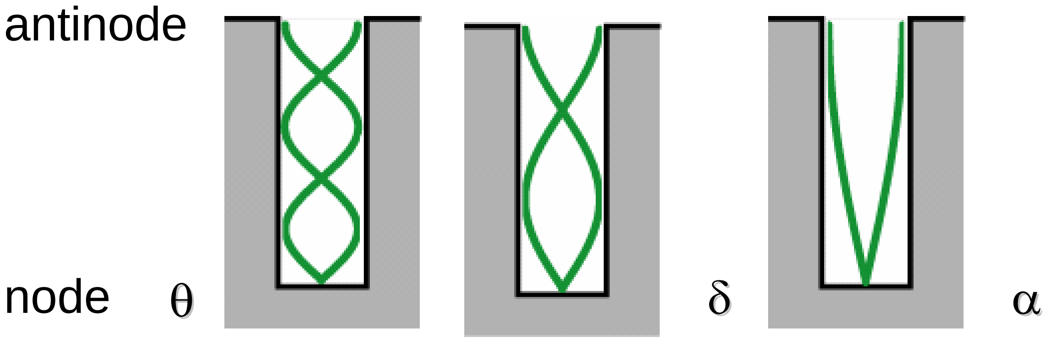
$$n_z=0,1,3,5,\ldots$$

Wavelength of eigenmode

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

Maruyama *et al.* APL, 79 (2001) 1393.

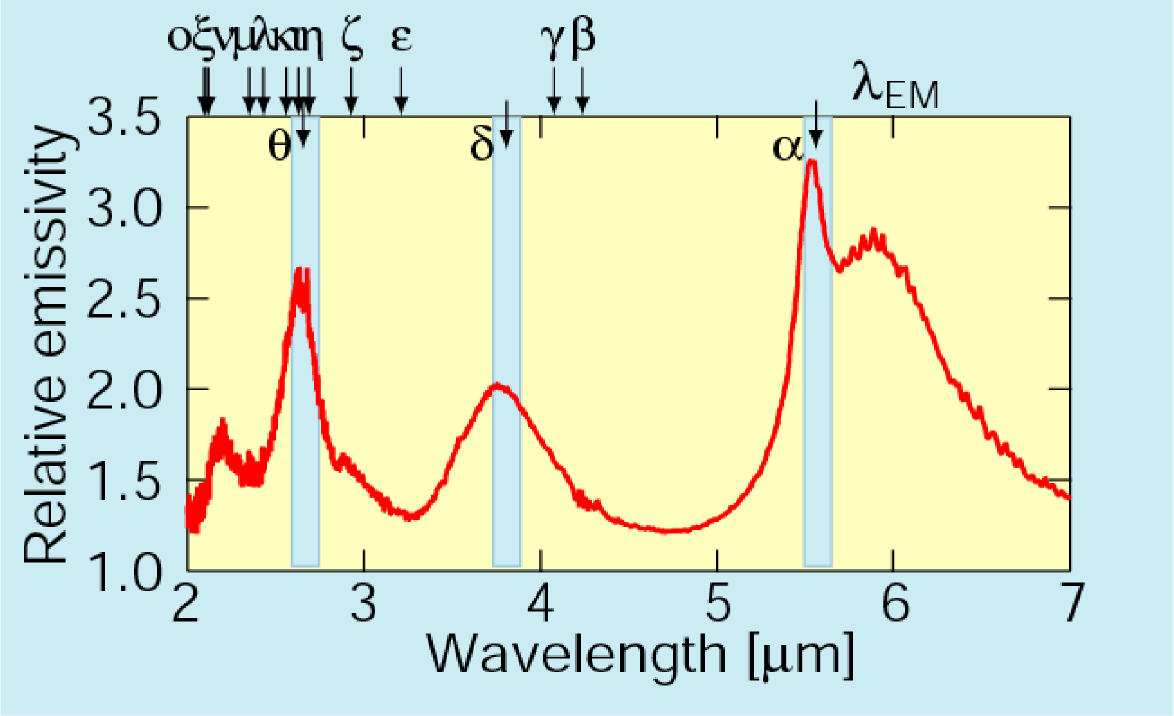
Single open cavity model



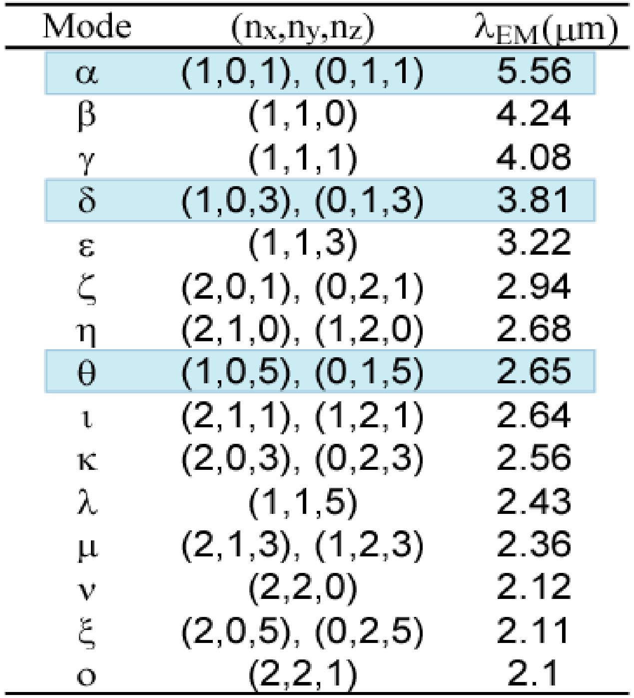
Boundary condition

perfect conductor wall

E(boundary) =0



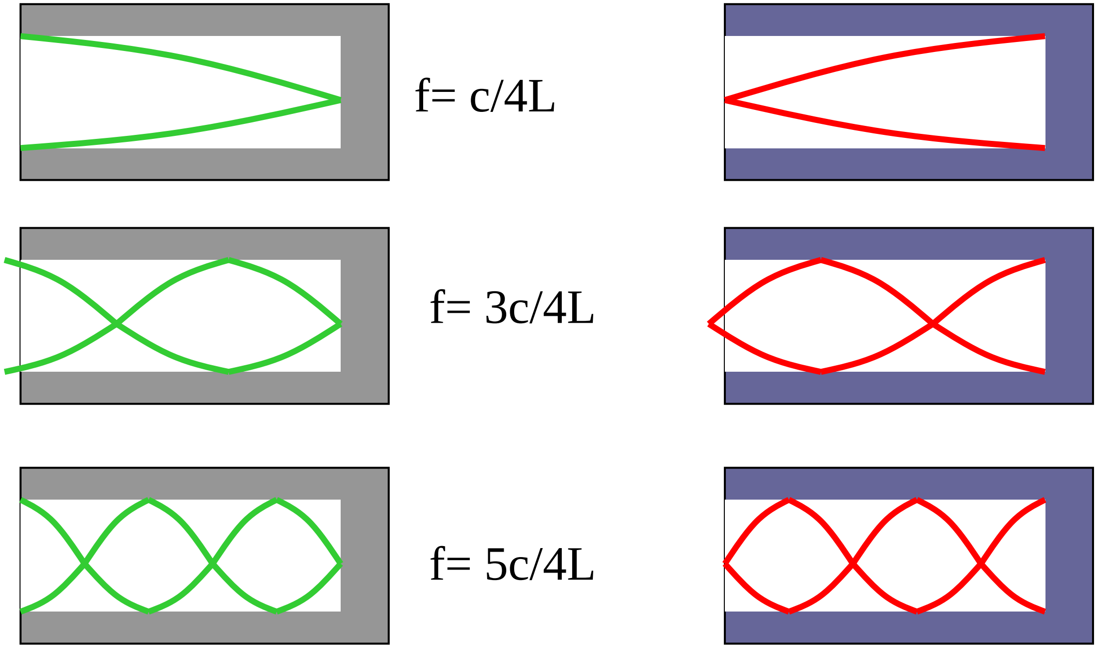
Theory (resonance)



Mode	(n_x,n_y,n_z)	$\lambda_{EM}(\mu m)$
α	(1,0,1), (0,1,1)	5.56
β	(1,1,0)	4.24
γ	(1,1,1)	4.08
δ	(1,0,3), (0,1,3)	3.81
ε	(1,1,3)	3.22
ζ	(2,0,1), (0,2,1)	2.94
η	(2,1,0), (1,2,0)	2.68
θ	(1,0,5), (0,1,5)	2.65
ι	(2,1,1), (1,2,1)	2.64
κ	(2,0,3), (0,2,3)	2.56
λ	(1,1,5)	2.43
μ	(2,1,3), (1,2,3)	2.36
ν	(2,2,0)	2.12
ξ	(2,0,5), (0,2,5)	2.11
ο	(2,2,1)	2.1

n_z=1,3,5… (Odd mode index)

Analogy ~Optical Woodwind Instruments



E-field in Optical cavity

Pressure in closed pipe

f= c/4L

f= v/4L

f= 3c/4L

f= 3v/4L

f= 5c/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 (3rd 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

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

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

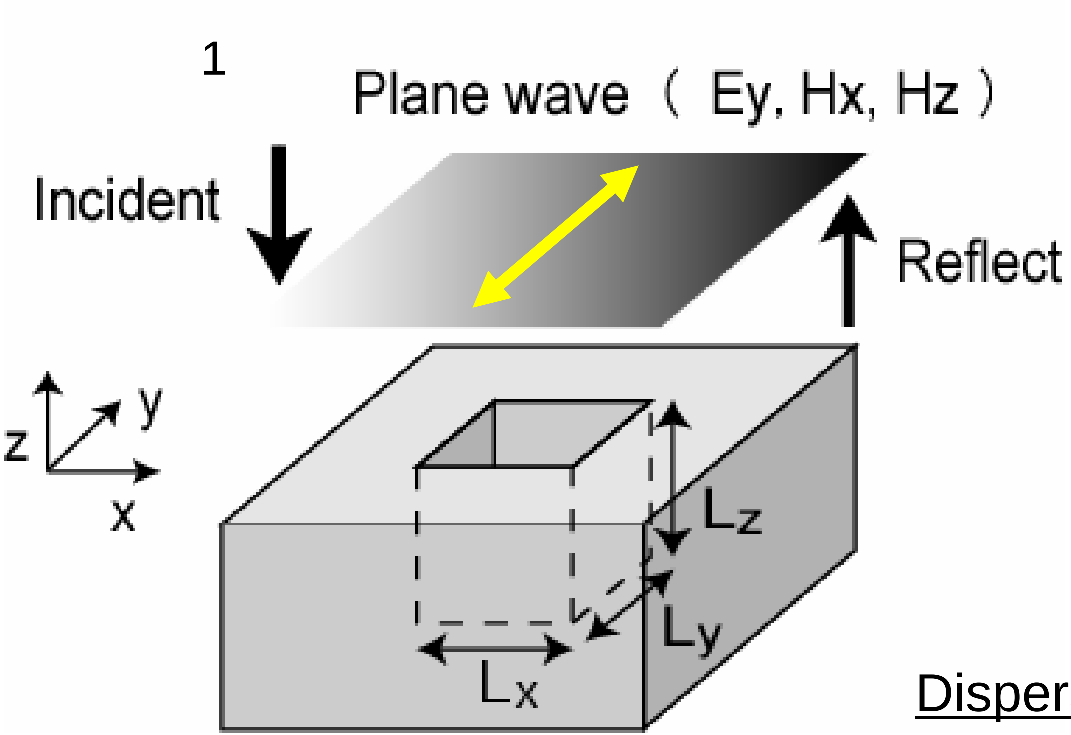
Maxwell equations
in FDTD algorithm

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

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

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

FDTD calculation model



Reflectance R

Pulse input

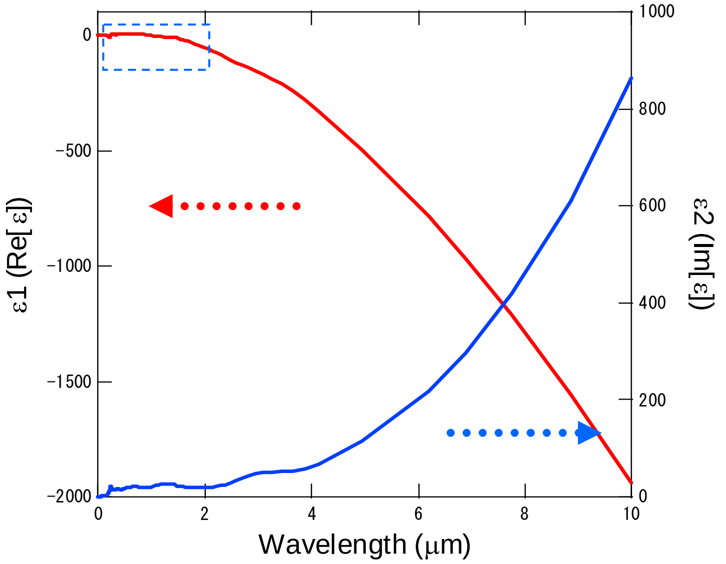
Time dependent field profile
Calculate spectral reflectance

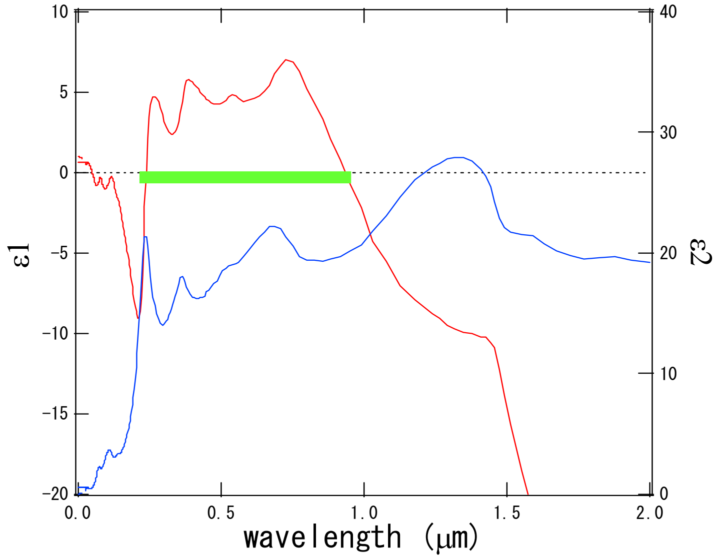
<u>Dispersion of metal</u>
Debye model
W, Ta negative dielectric（@IR）

<u>boundary condition</u>
1) PML (Perfectly Matched Layer: perfect absorber wall)
2) PBC (Periodic Boundary Condition)

Permittivity of Tungsten and Tantalum

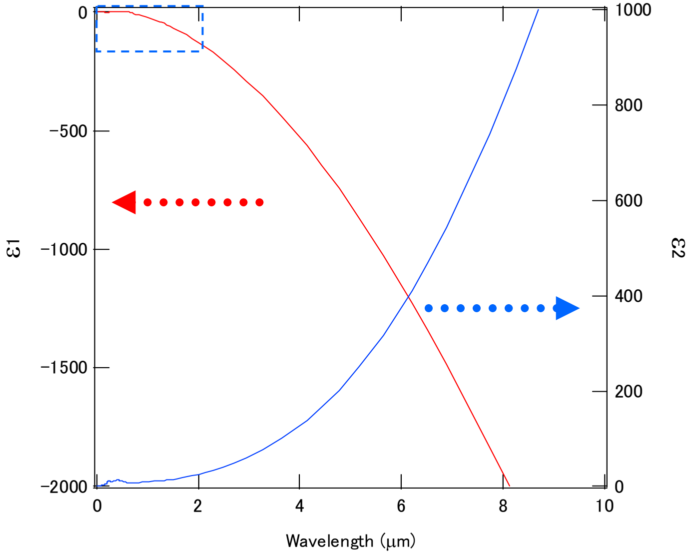
W

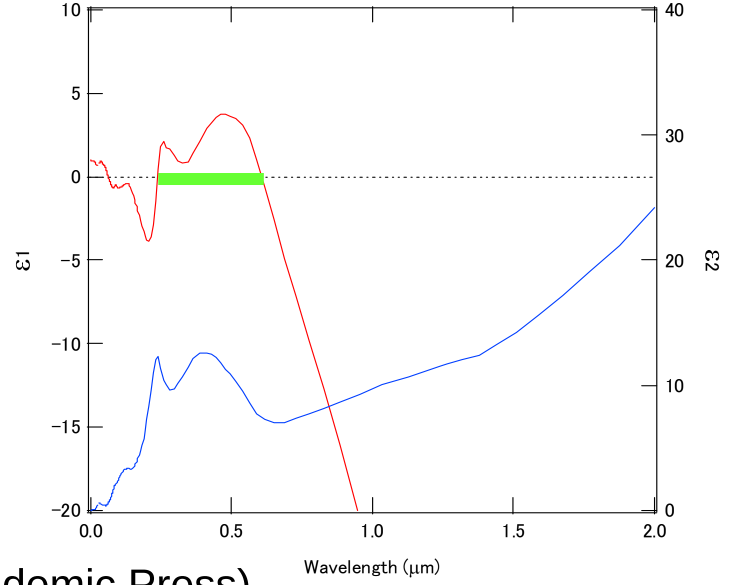




Negative dielectric

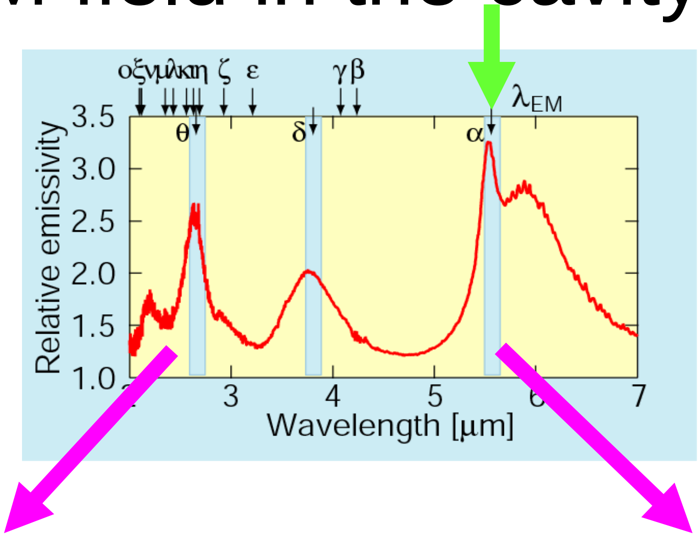
Ta



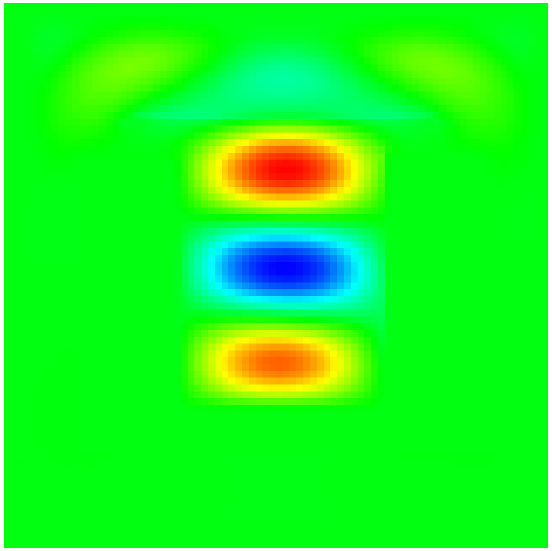


Palik: Handbook of Optical Constants of Solids (Academic Press)

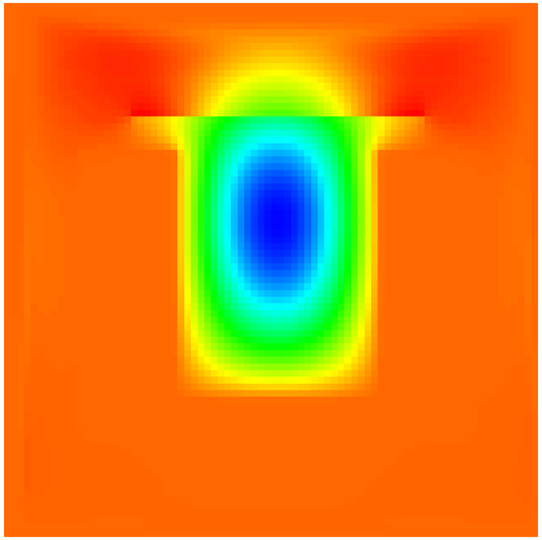
EM field in the cavity



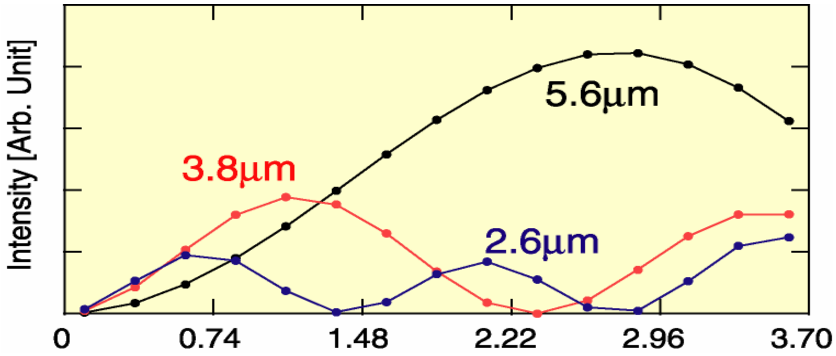
$\lambda = 2.6\mu m$



$\lambda = 5.6\mu m$

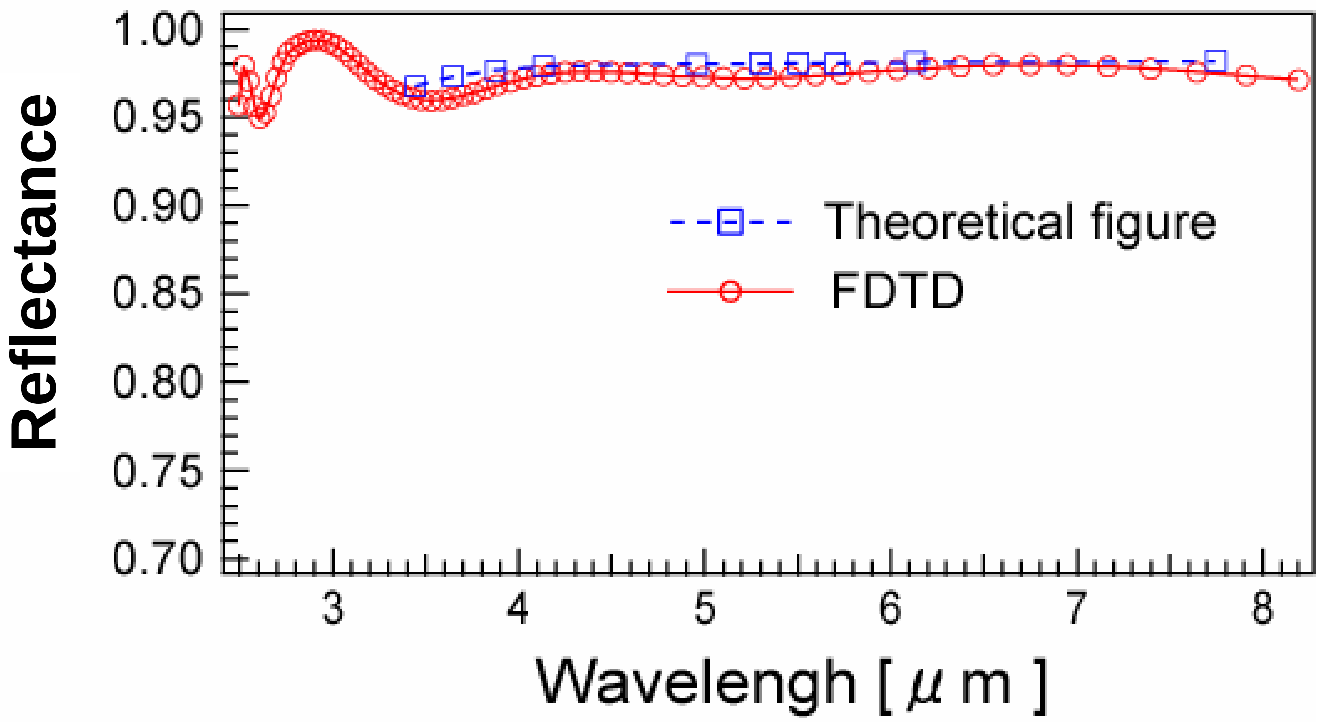


field inside the cavity



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)

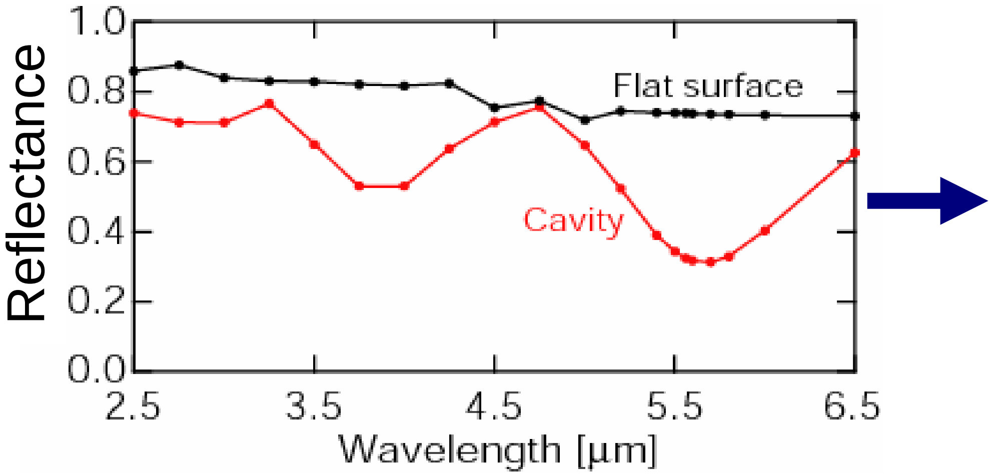
simulated results

- Calculation of reflectivity R from FDTD

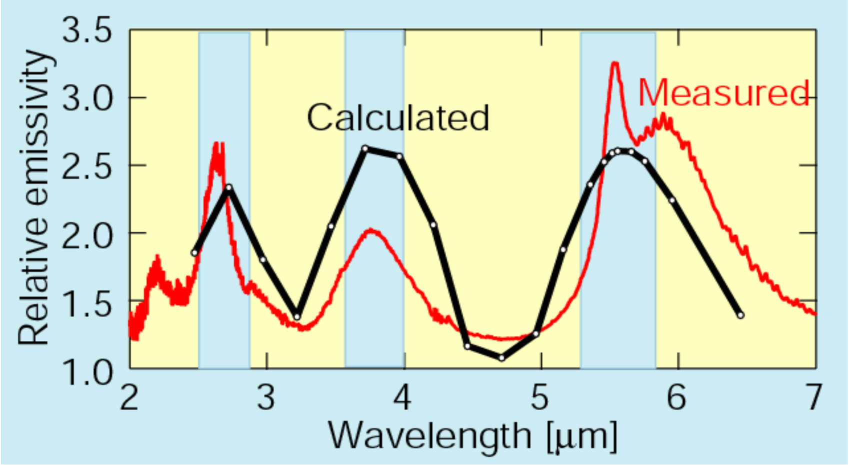
$$\alpha = 1 - R - T = 1 - R$$

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

reflectance



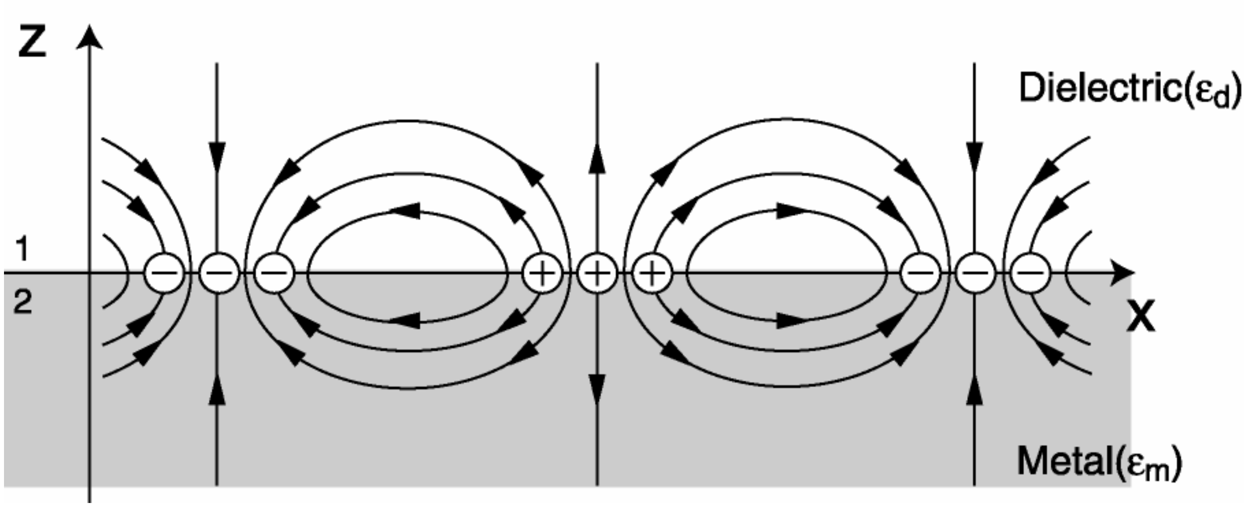
relative emmisivity



We can simulate thermal emission by FDTD calculations.

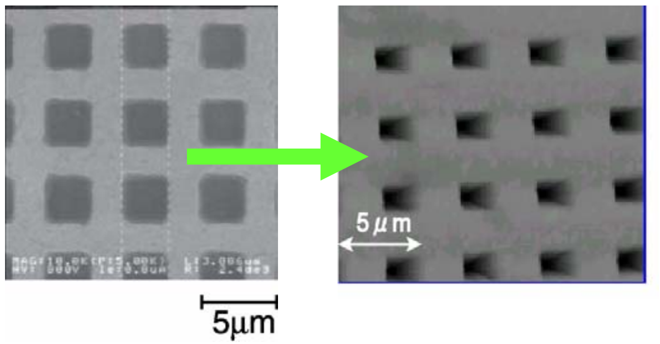
J. Takahara, F. Kusunoki and T. Kobayashi, "Resonant Thermal Radiation from Tungsten Surfaces With Rectangular Array of Square Holes", in IQEC '2005, JWH2-4, (2005).

擬似表面プラズモンと熱輻射

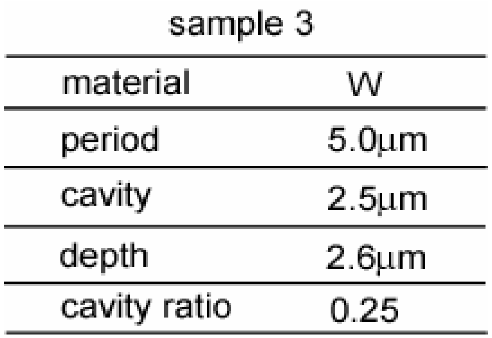


Thermal radiation spectra from small cavity

Smaller cavity

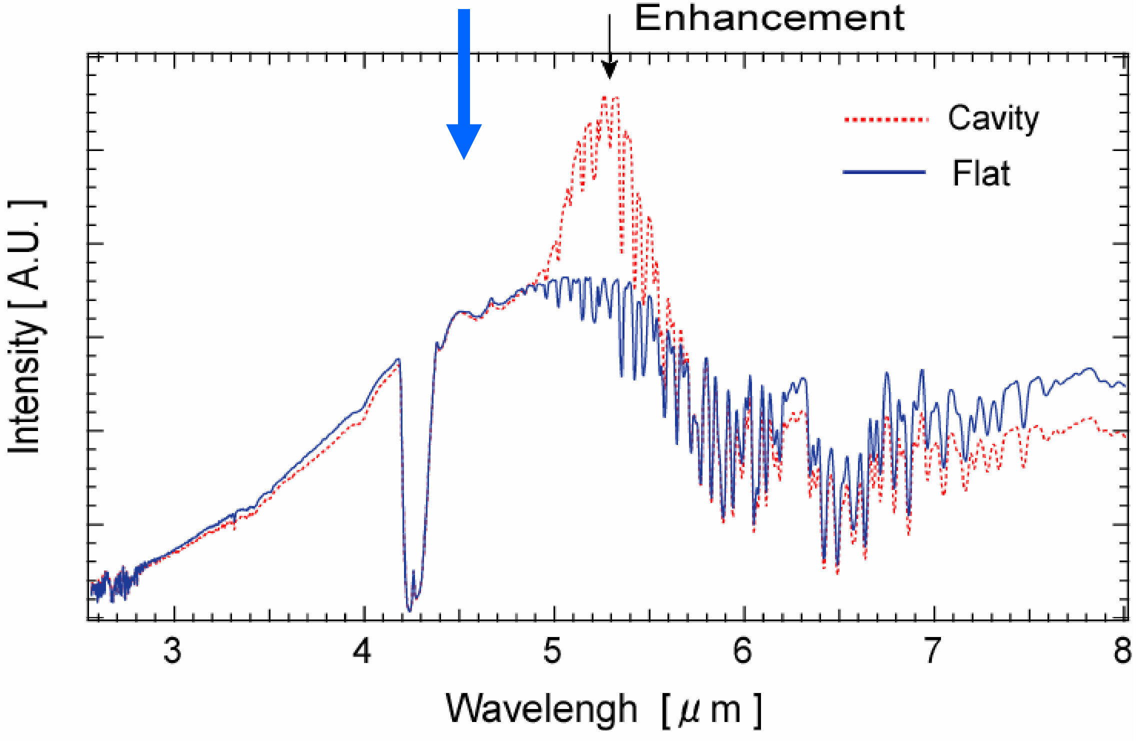


AFM image



sample 3	
material	W
period	5.0µm
cavity	2.5µm
depth	2.6µm
cavity ratio	0.25

Cavity mode

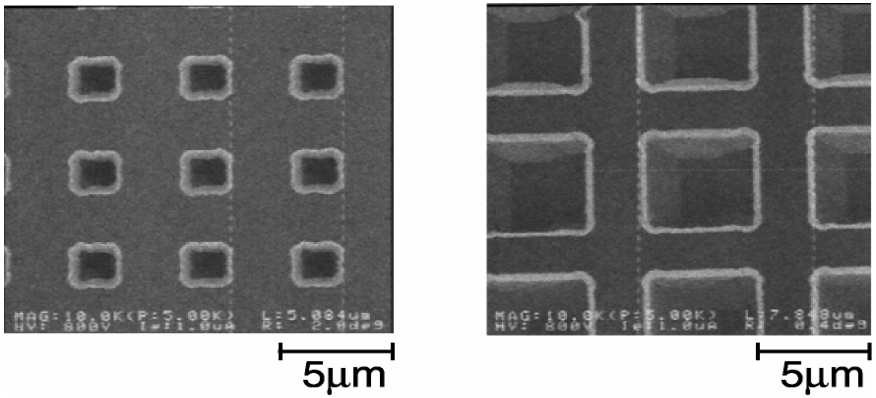


Difference

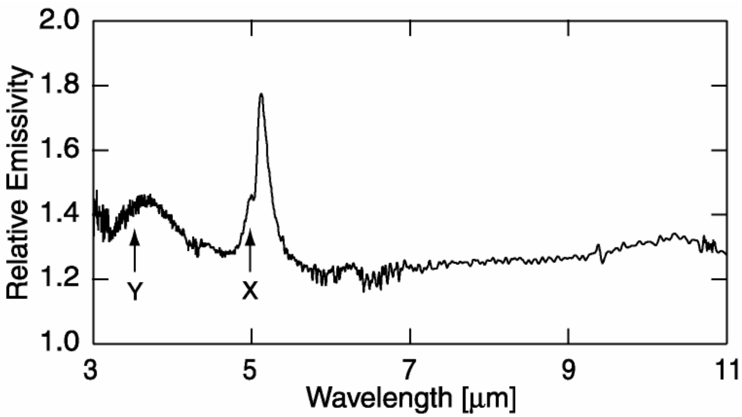
in cavity resonant mode → Surface Plasmon Polariton?

- 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変化

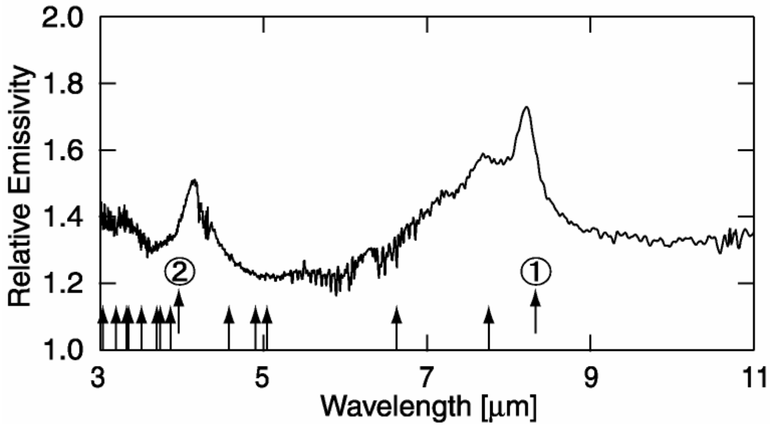
タングステン基板
表面のSEM像



SPP

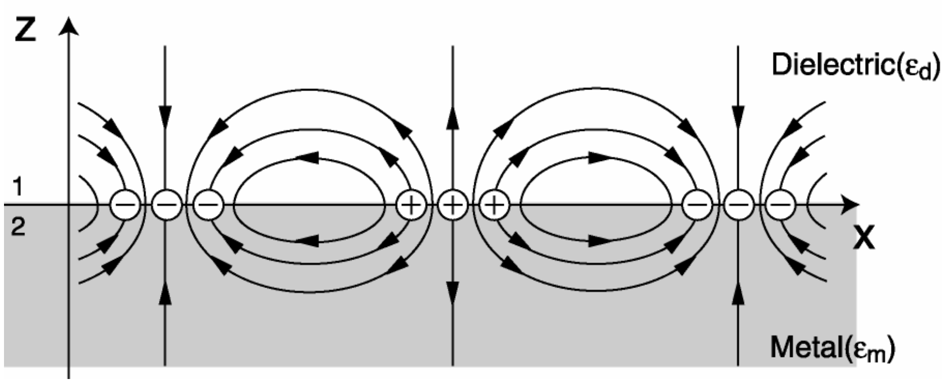


共振器



F.Kusunoki et al.: Electron. Lett. Vol.39, No.1 (2003) 23.

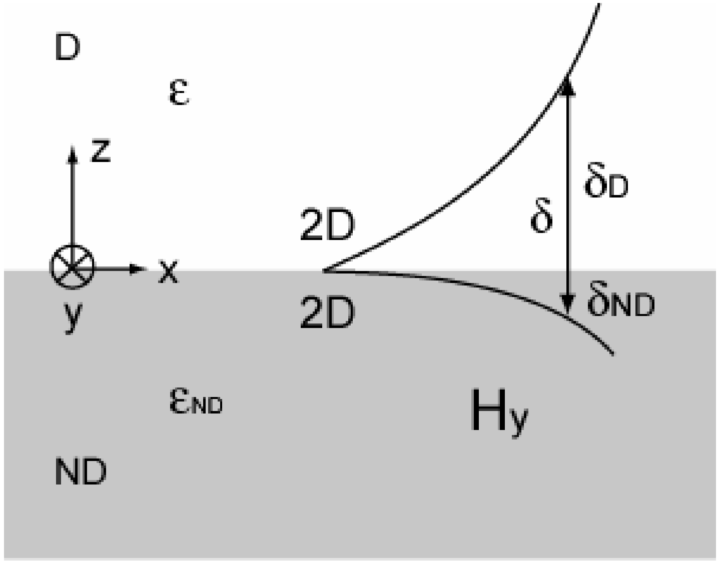
2D optical wave
~surface plasmon polariton (SPP)



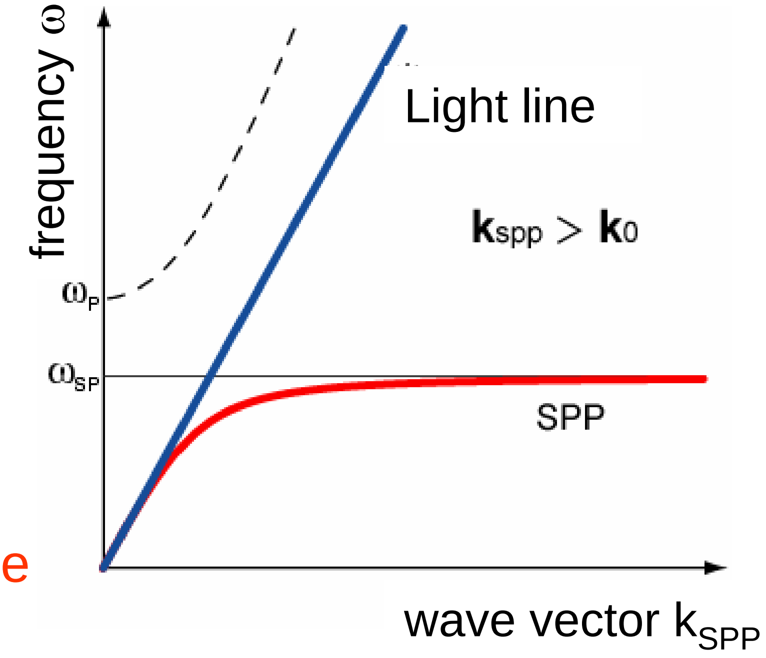
surface plasmon polariton (SPP)

$|\varepsilon_m| > \varepsilon > 0$

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



TM wave

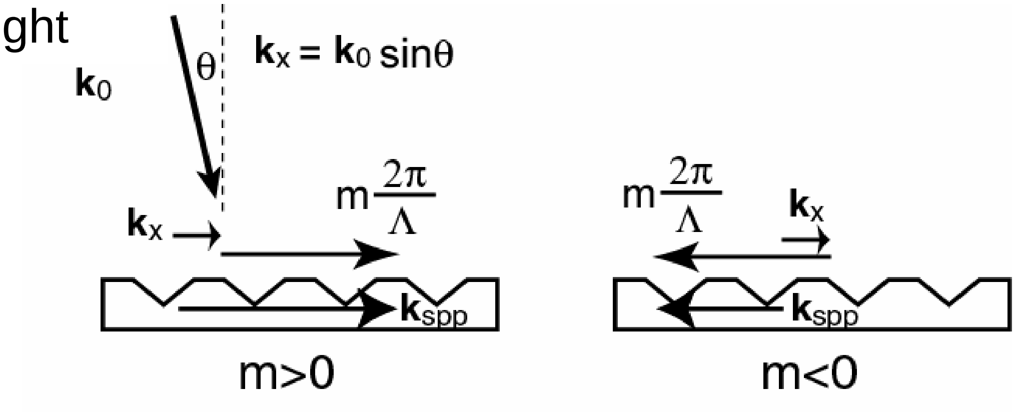


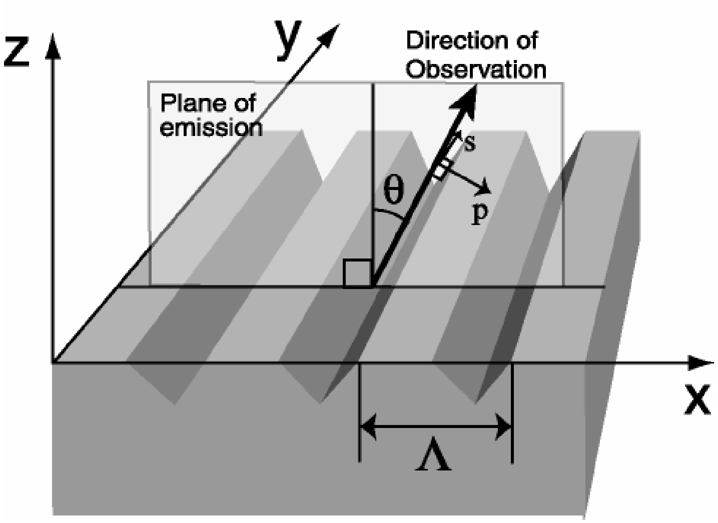
Coupling from SPP to radiation mode by 1D metallic grating

Coupling condition (1D)

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

Incident light





k_x: wavenumber, Λ:period, m: integer

Coupling wavelength

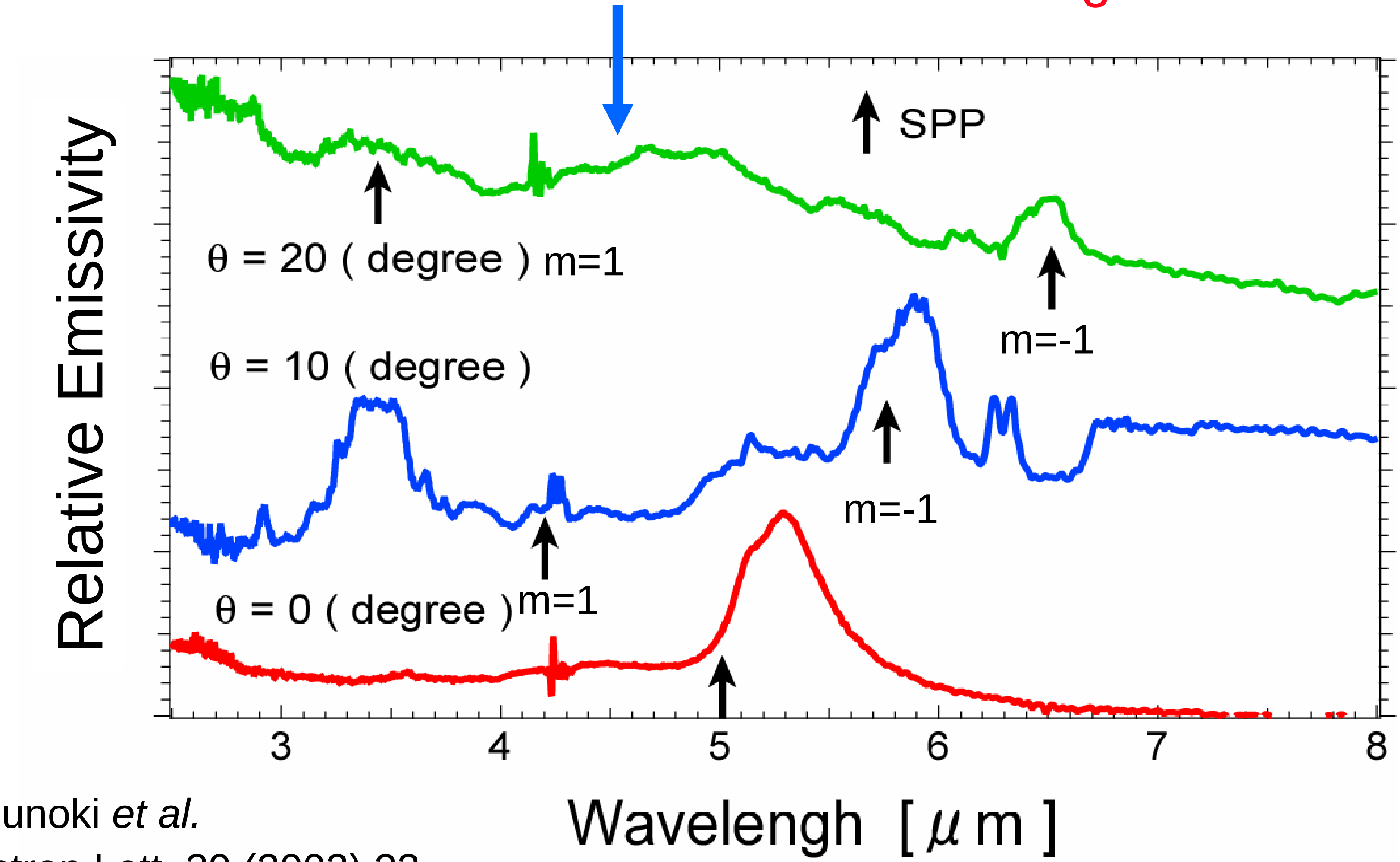
$$\lambda_{\mathrm{SPP}} = \frac{\Lambda}{|m|}\left(\sqrt{\frac{\varepsilon_{\mathrm{m}}}{1+\varepsilon_{\mathrm{m}}}} - \frac{m}{|m|}\sin\theta\right)$$

SPP resonance

difference in wavelength at θ=0

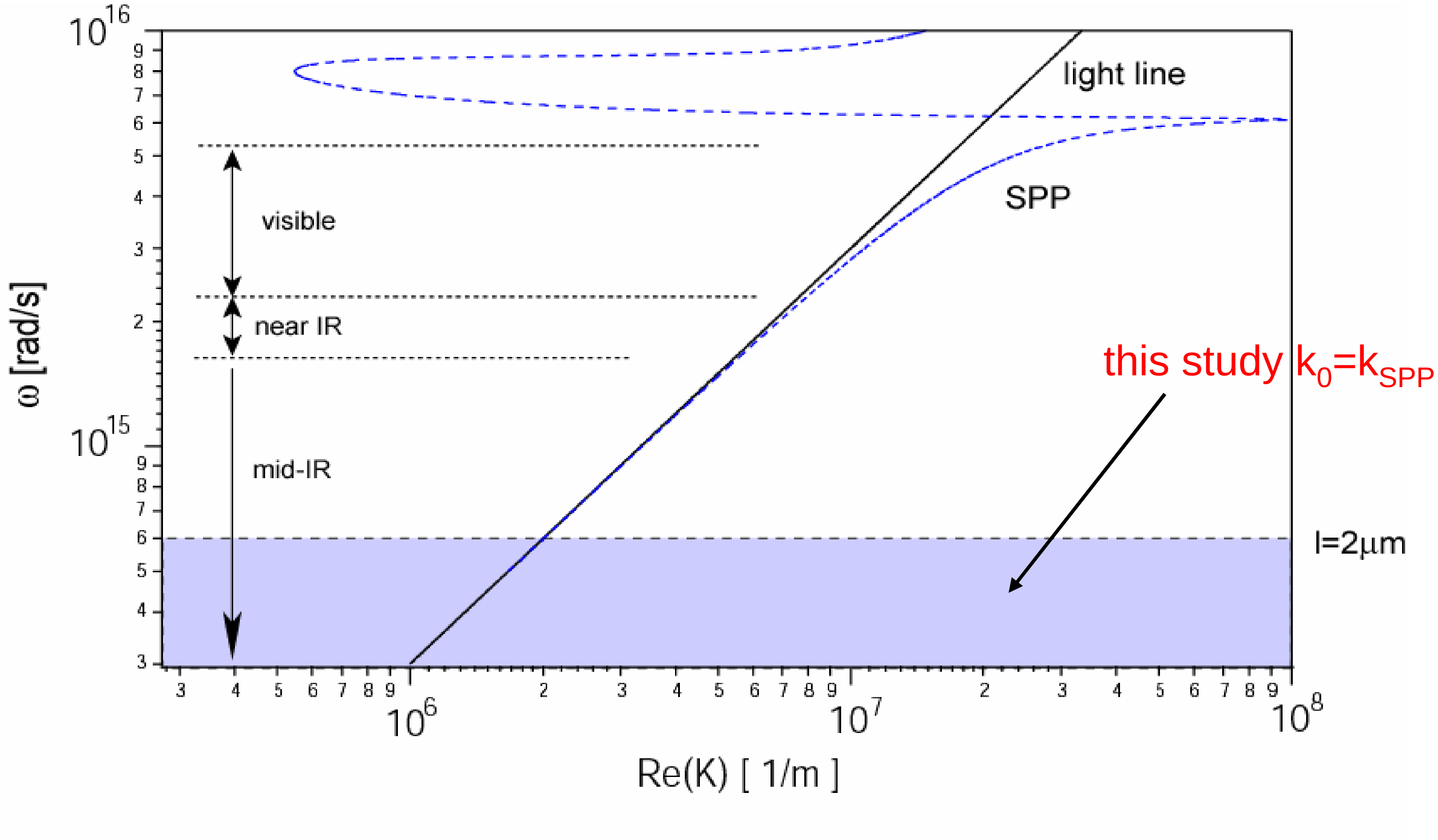
directivity

Cavity mode



Kusunoki *et al.*
Electron Lett. 39 (2003) 23.

Dispersion relation of SPP

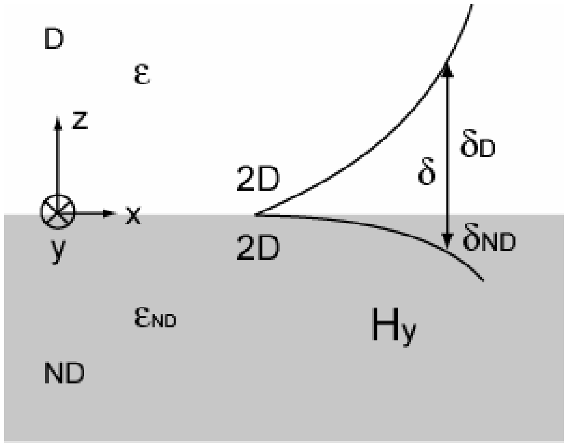


this study $k_0=k_{SPP}$

dispersion relation of SPP = light line?

Spoof surface plasmon in microstructured perfect conductor

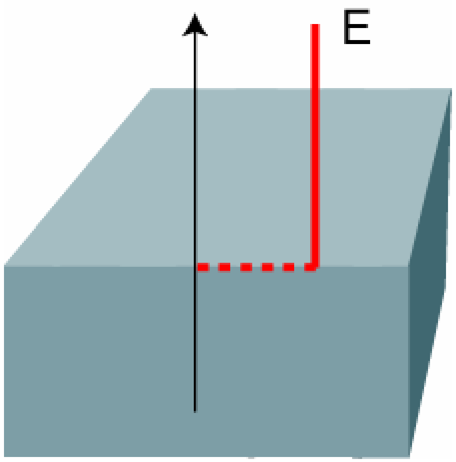
- SPP



Negative dielectric

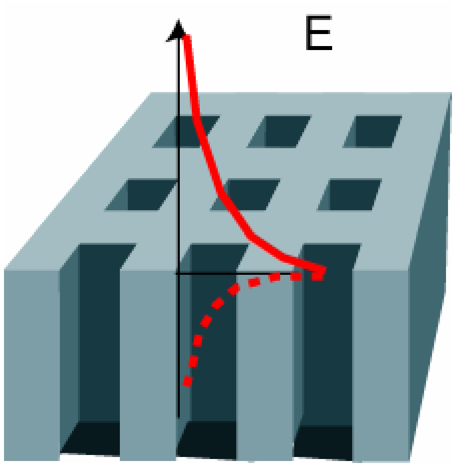
$$k_{SPP} \fallingdotseq k_0$$

- Spoof SPP



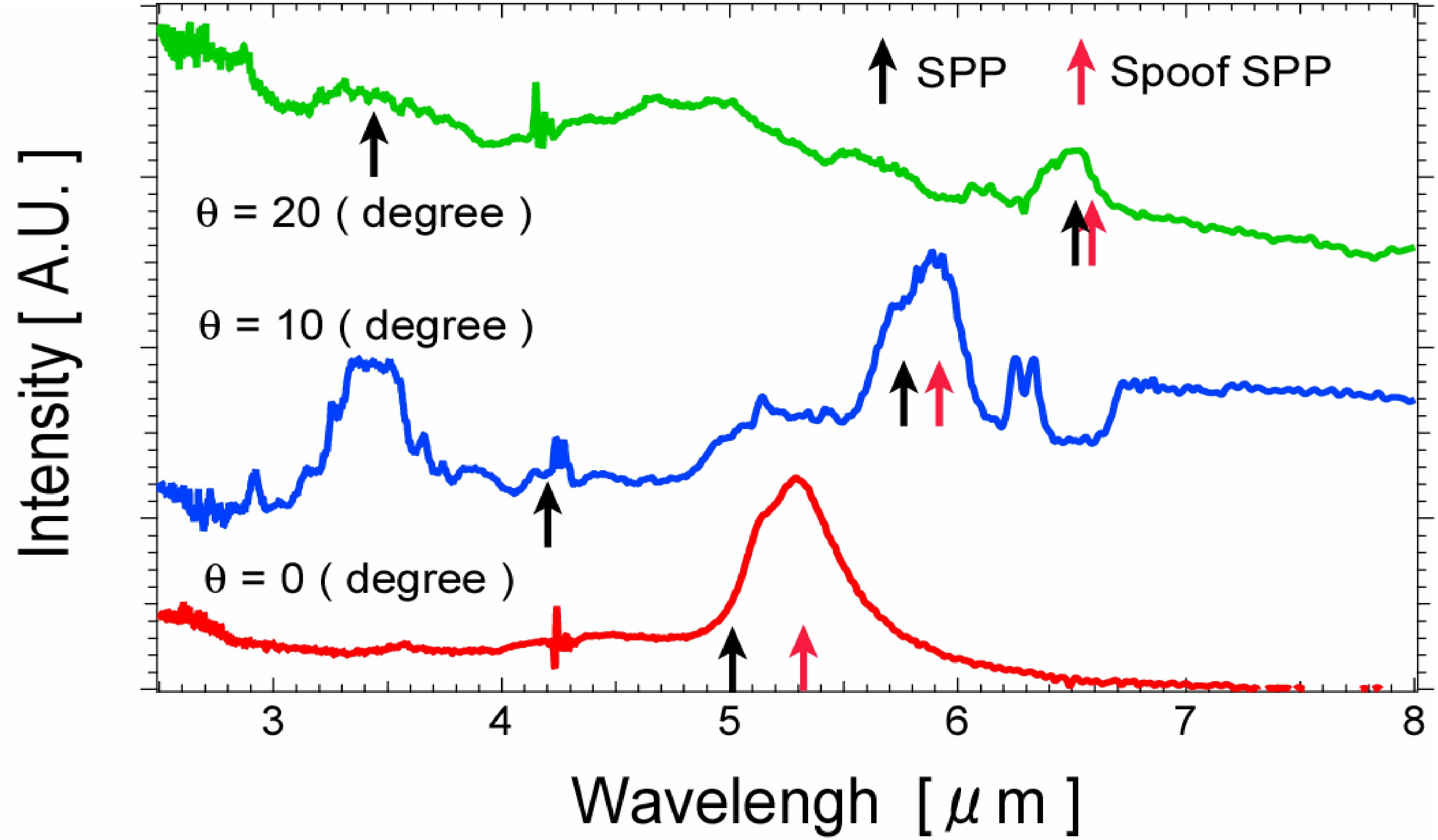
Perfect conductor

No surface wave



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

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

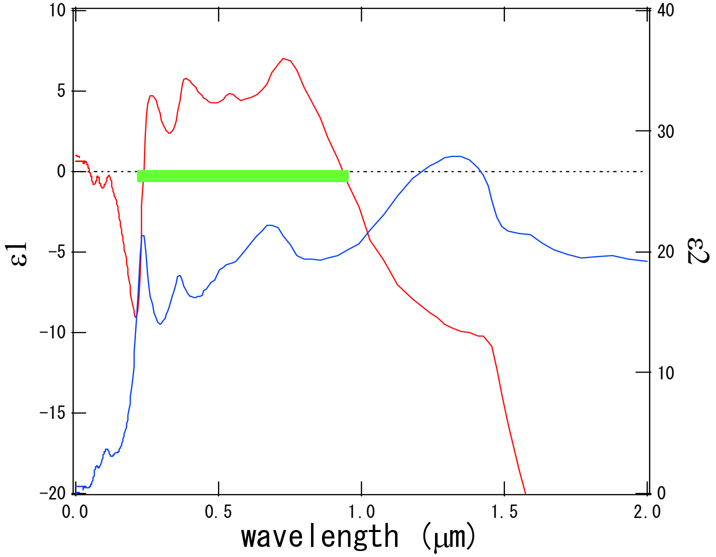
- 技術的課題
  ～タングステン微細構造の高温での耐久性

↓

１０００℃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℃
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

↓

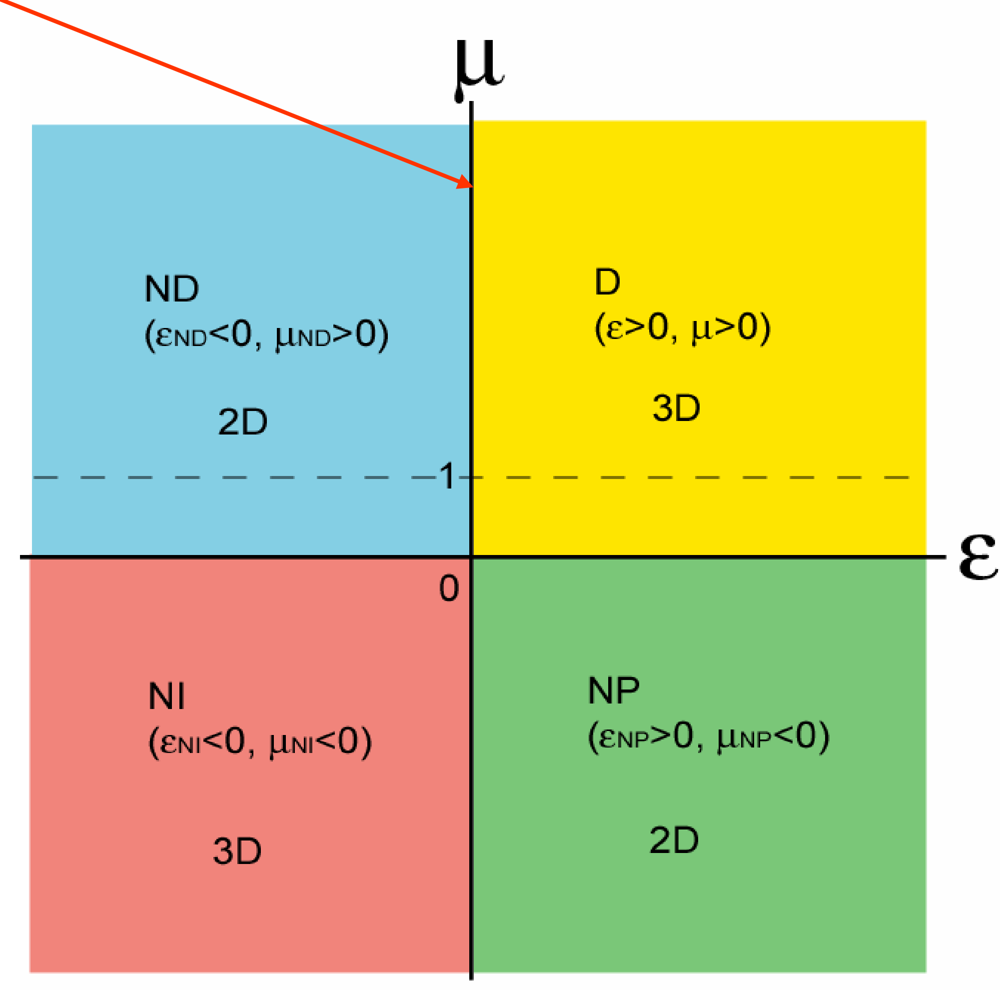
メタマテリアルによる熱輻射制御

SPP

ε-μ diagram

Negative Dielectric (ND)

Dielectric (D)



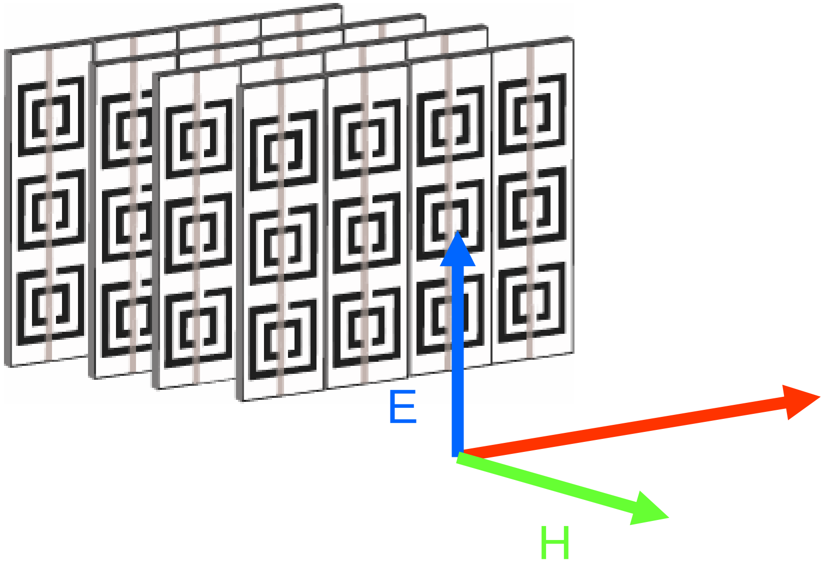
negative Index (NI) or left-handed materials (LHM)

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（Sprit 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 Commitee:

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 J·lich), **P. PITAEVSKII** (U. Trento and Kapitza Institute, Moscow), **S. REYNAUD** (École Normale Supérieure, Paris), **J. TAKAHARA** (U. Osaka), **Z. ZHANG** (Georgia Tech)

CENTRE NATIONAL
DE LA RECHERCHE
SCIENTIFIQUE

Lectures

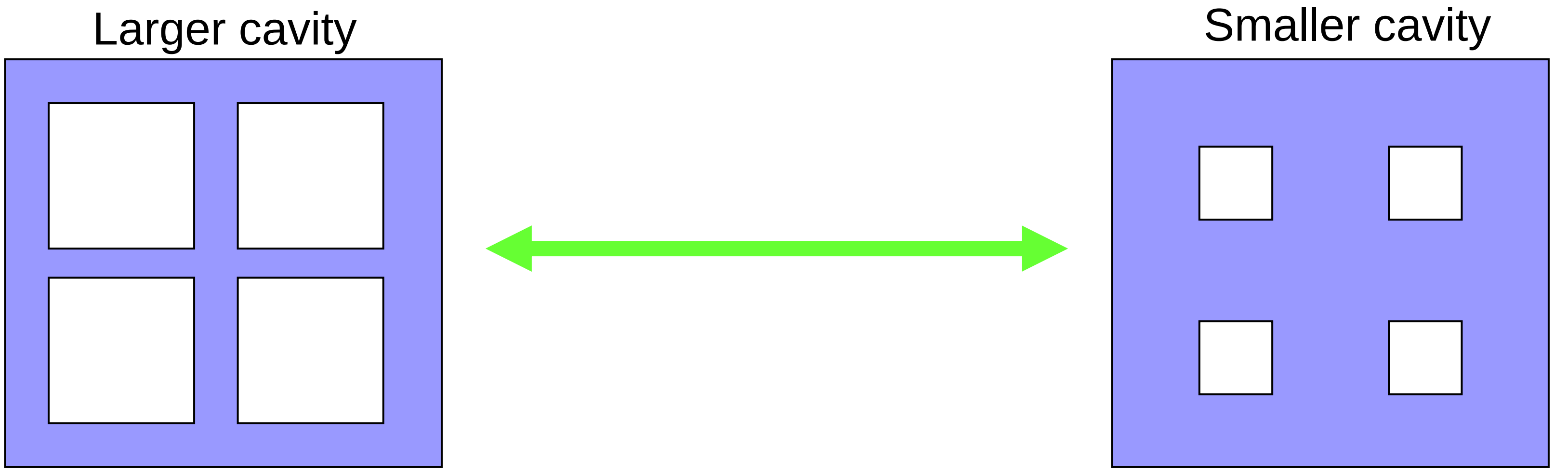
S. BARNETT (Strathclyde U.), Radiation pressure and momentum transfer in dielectrics
C. HENKEL (U. Potsdam), Introduction to fluctuational electrodynamics, surface polaritons and coherence
M. RUBI (U. Barcelona), Nanothermodynamics

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. DOROFEYEV (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



Larger cavity

Smaller cavity

Open cavity mode

FDTD simulation

Spoof surface plasmon

Thank you!