# Microstructures based on particles and their novel optical properties

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# Outlines

I. *Electromagnetic wave multiple scattering theory* **for arrays of spherical particles**

II. **The use of particles in construction of** ***complete band gap photonic crystals***

III. **The use of colloidal crystals in construction of** ***quasi-3D plasmonic crystals***

IV. *Light tunneling through* **2D ordered dense array of metal nanoshells**

V. **Summary**

## 1. Electromagnetic wave (EM) multiple scattering theory (MST)

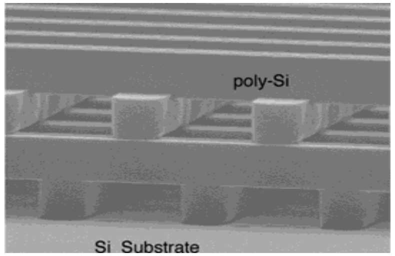
- ✓ Development of an analog of KKR method for electron in solid, for photons propagating in arrays of spherical particles;
- ✓ Construction of the software programs;
- ✓ Various implementations of the theory.

W.Y. Zhang et al., PRL, 84, 2853 (2000);
Z.L. Wang et al., PRB 64, 113108 (2001);
Z.L. Wang et al., PRE 67, 016612 (2003);
H. Chen et al., J. Phys.: Condens. Matter 16, 741 (2004);

*Typical Approaches for PC in visible/near IR*

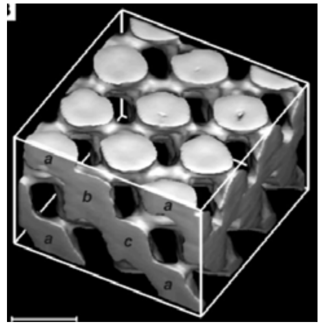
***via microfabrication***

S. –Y. Lin, *Nature* 394, (1998) 251;
S. Noda et al., *Science* 289, (2000) 604




***via holographic lithography***

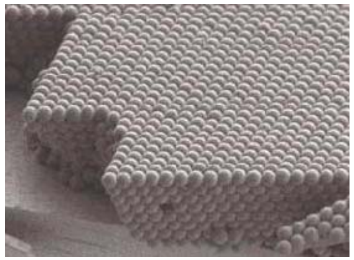
M. Campbell *et al*., *Nature* 404 (2000) 53.



***via self-assembly***

A. Blanco et al., *Nature* 405 (2000) 437.

Y. A. Vlasov et al., *Nature* 414 (2001) 289.



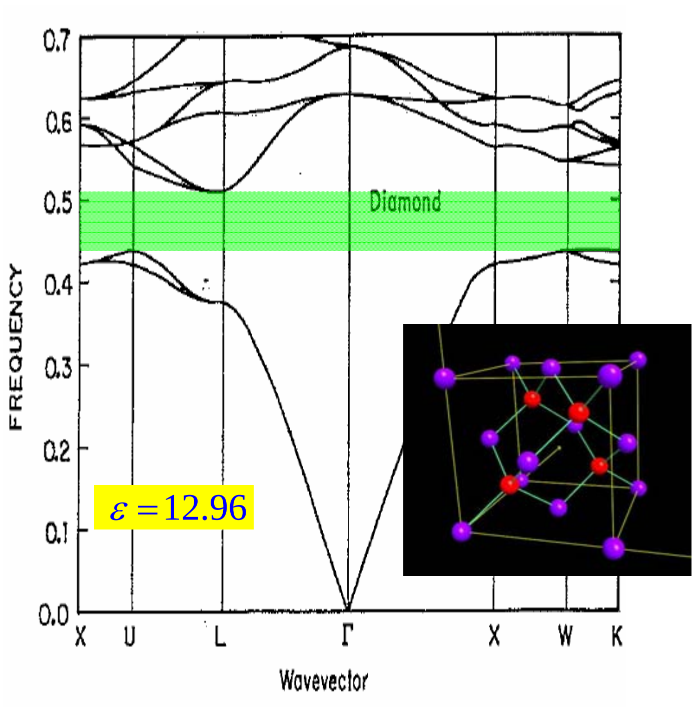
## *The features of EM MST*

- Applicable to photonic crystals composed of dielectric *spheres*, either in *simple* lattices, or in *complex* lattice, i.e., diamaond lattice;
- Much *improvement in precision* as compared to plane-wave-expansion method;
- Applicable to photonic crystals consisting of core/shell *composite spheres*;
- Applicable to spheres with dielectric *dispersion or absorption* without CPU time increase.
- **Disadvantage:** not applicable to crystals with point or line defects

## *Specific implementations of EM MST：*

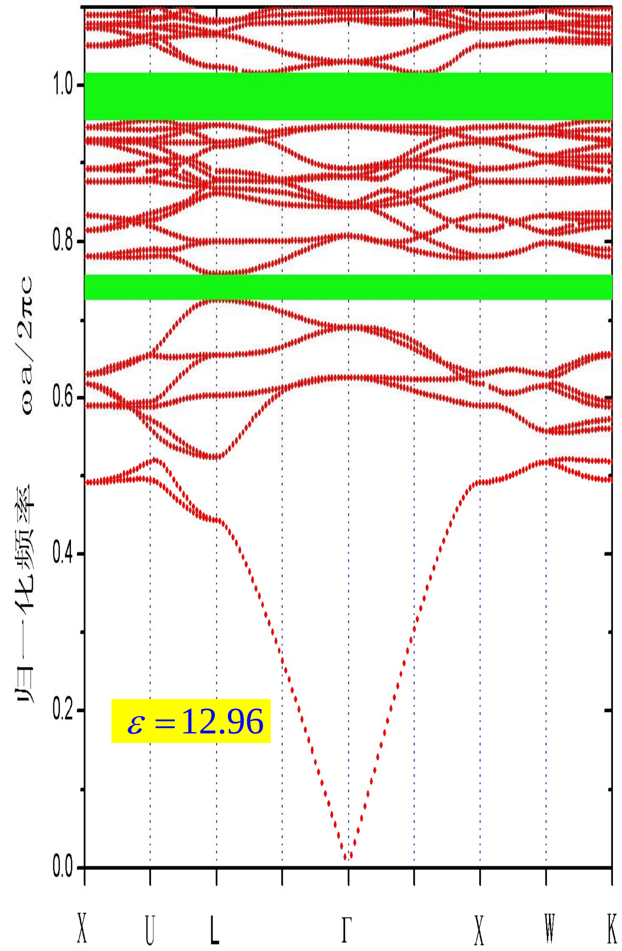
- We clarified the photonic band structure of diamond photonic crystals composed of dielectric spheres;
- In contrast to the well known prediction made in *PRL* 65 (1990) 3152 by Ho et al., **the 2nd-3rd** band gap is found to be no larger than 2%**；**
- We designed two kinds photonic crystals, both with a complete band gap.

# Photonic band structure of diamond photonic crystal of dielectric spheres, calculated using different methods




Based on plane-wave expansion

Ho et al., Phys. Rev. Lett. 65 (1990) 3152




Based on **EM MST**

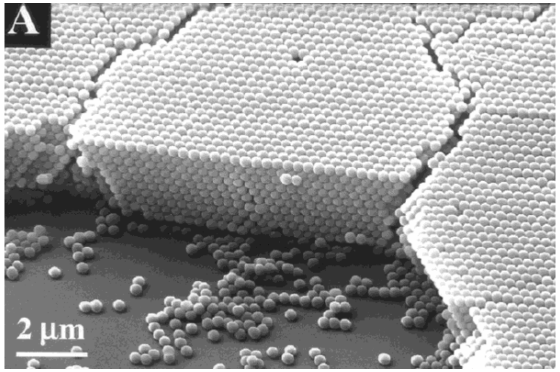
## Design of photonic crystals with complete band gap

*The band structure of a photonic crystal is related to crystal symmetry, and are also closely related to the optical properties of the building blocks of the crystals.*

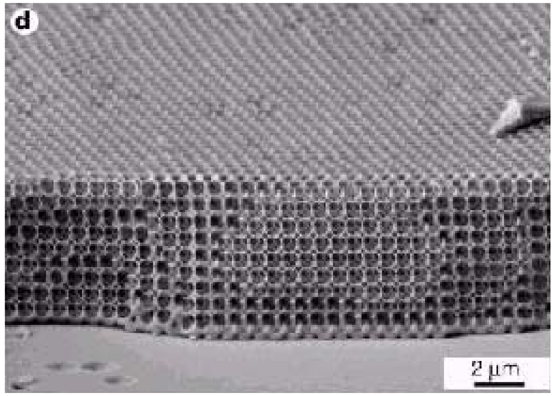
**A) photonic crystals made of hollow dielectric spheres in a diamond lattice;**

**B) photonic crystals made of metal-coated spheres in a face-centered-cubic lattice**

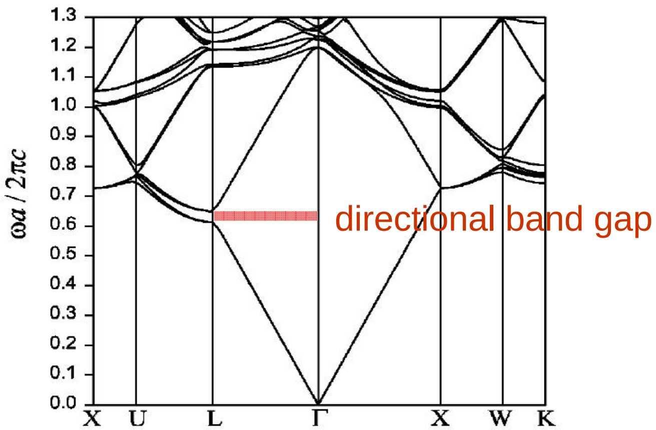
## Background: Towards 3D photonic crystals in the visible



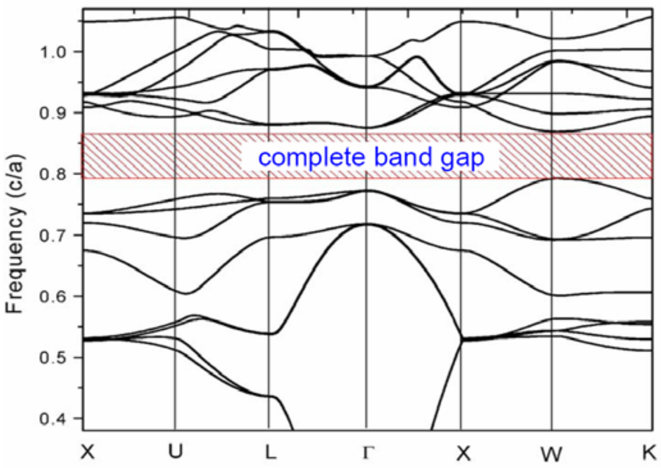

(SEM of silica opal)

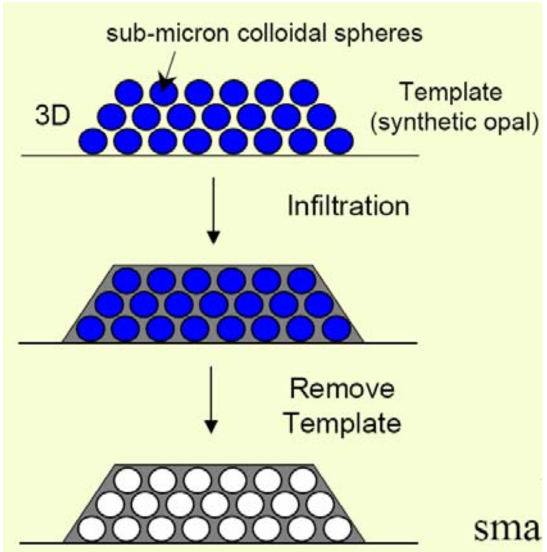


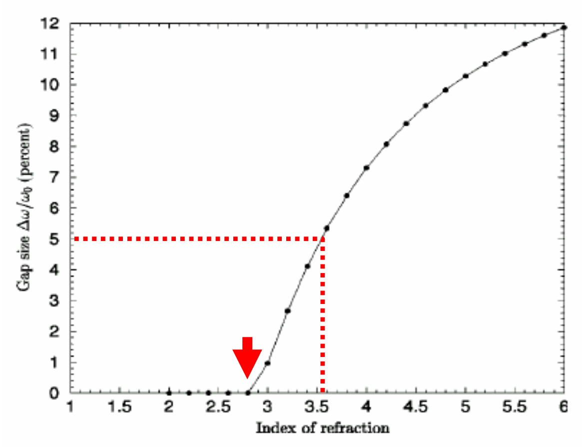

(SEM of silicon inverse opal)

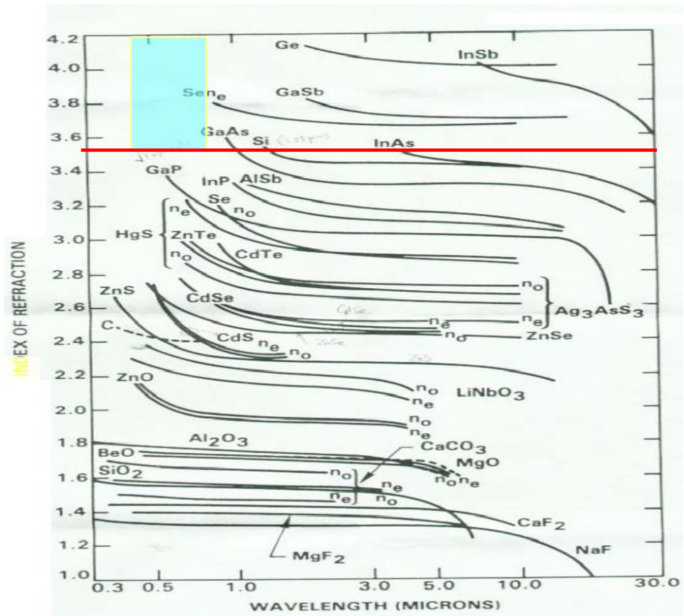



(Photonic band structure)





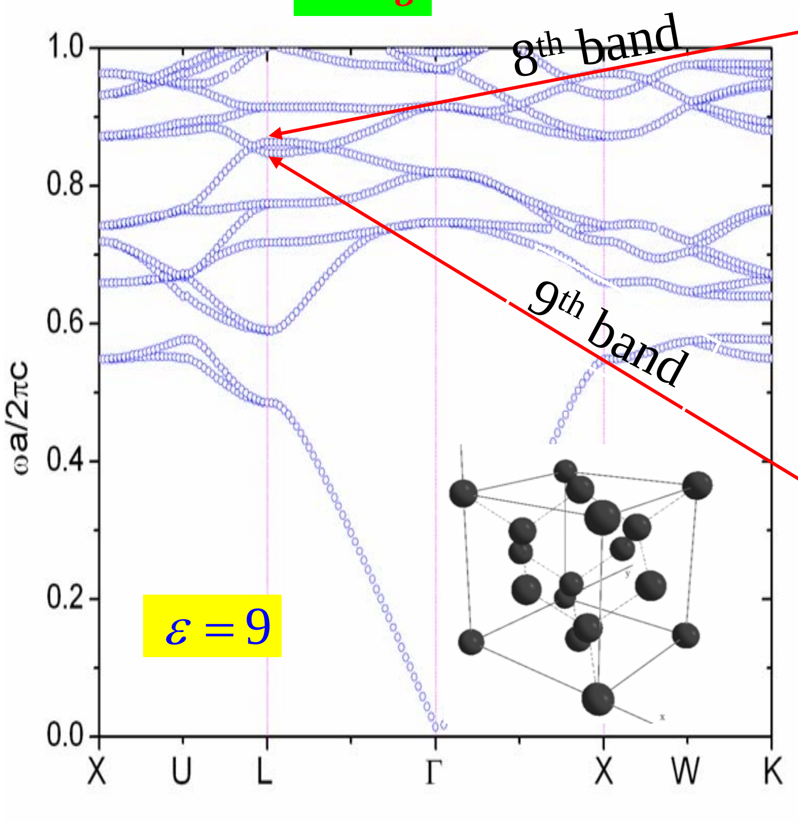



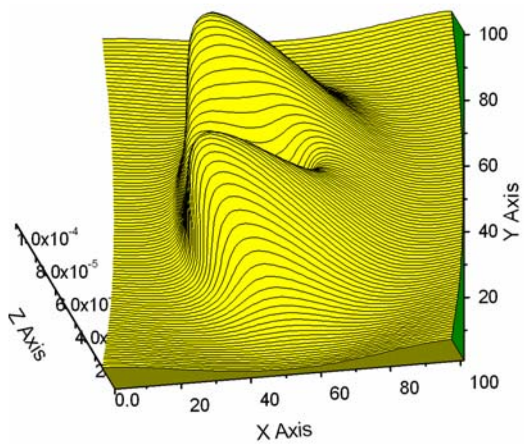



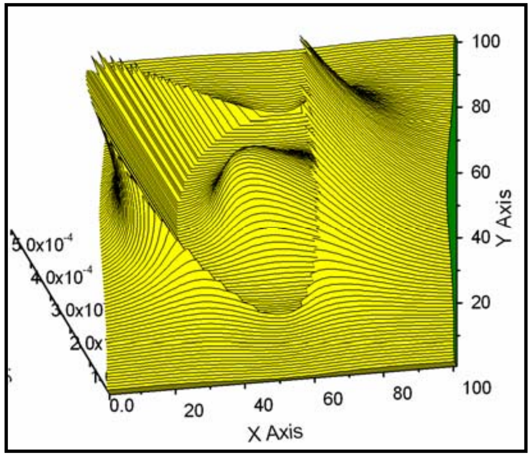

B.T. Holland *et al.*, *Science*, 281 (1998) 538
A.A. Zakhidov *et al.*, *Science*, 282 (1998) 897
S.A. Johnson *et al.*, *Science*, 283 (1998) 963
A. Blanco *et al.*, *Nature*, 405 (2000) 437.
Y.A. Vlasov *et al.*, *Nature*, 414 (2001) 289.
R.F. Service, *Science*, 295 (2002) 2399.
P. Lodahl et al., *Nature* 430 (2004) 654.

## Solution A: Photonic crystals made of hollow dielectric spheres in a diamond lattice

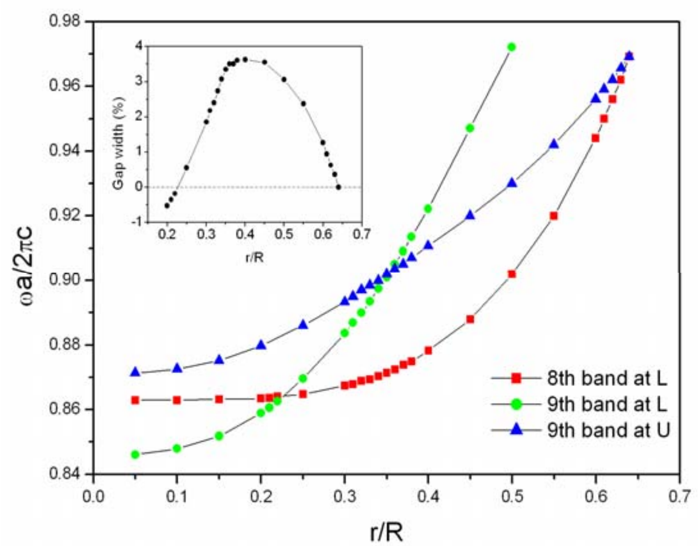
$$U \propto \frac{1}{\varepsilon}$$



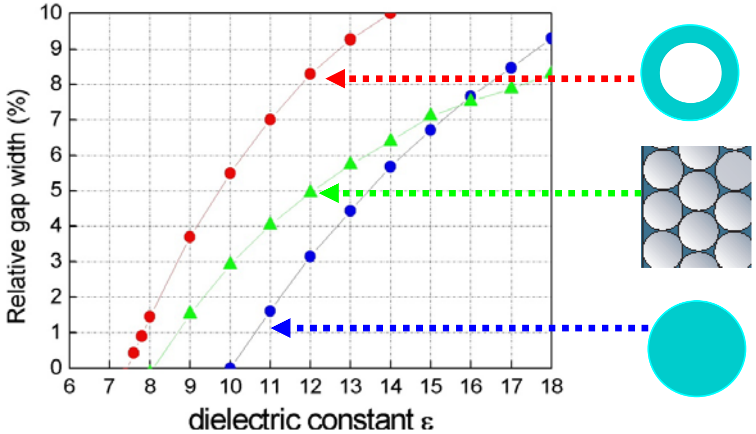



**Opening a true gap in diamond photonic crystals using hollow dielectric spheres**




**Comparison of the gap size in different structures**

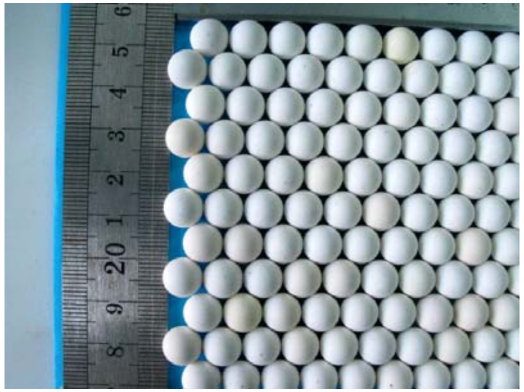


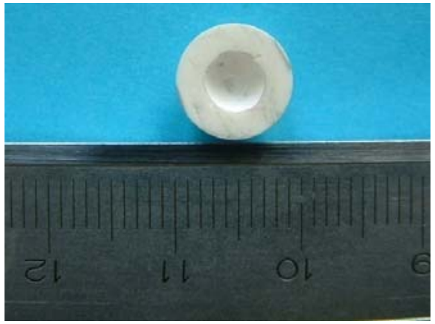

Diamond PC made of solid dielectric spheres

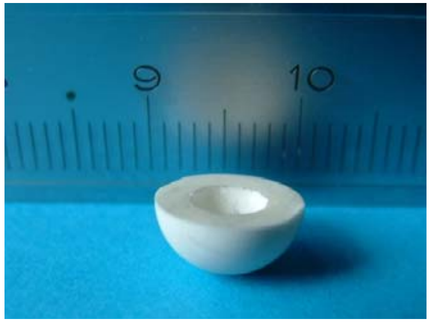
Inverted opal PC

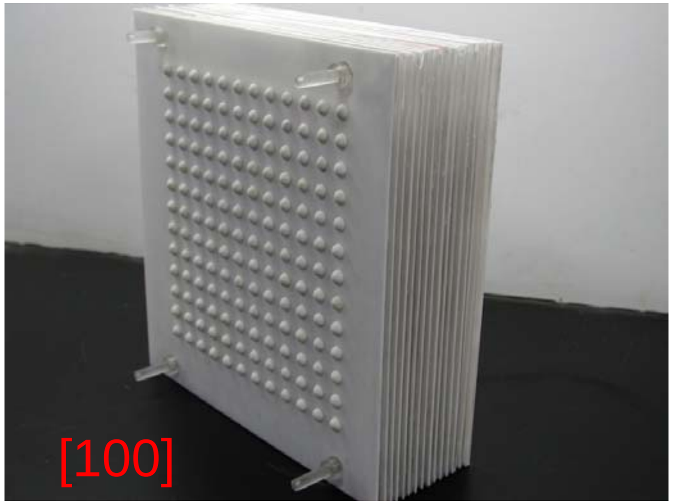
Diamond PC made of solid dielectric spheres

# True gap diamond lattice photonic crystals composed of hollow dielectric spheres

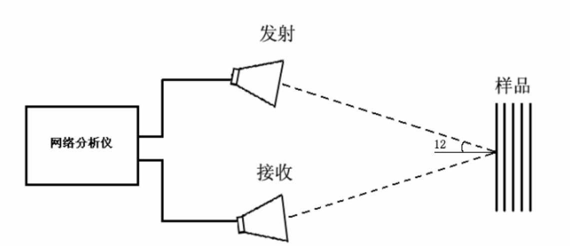


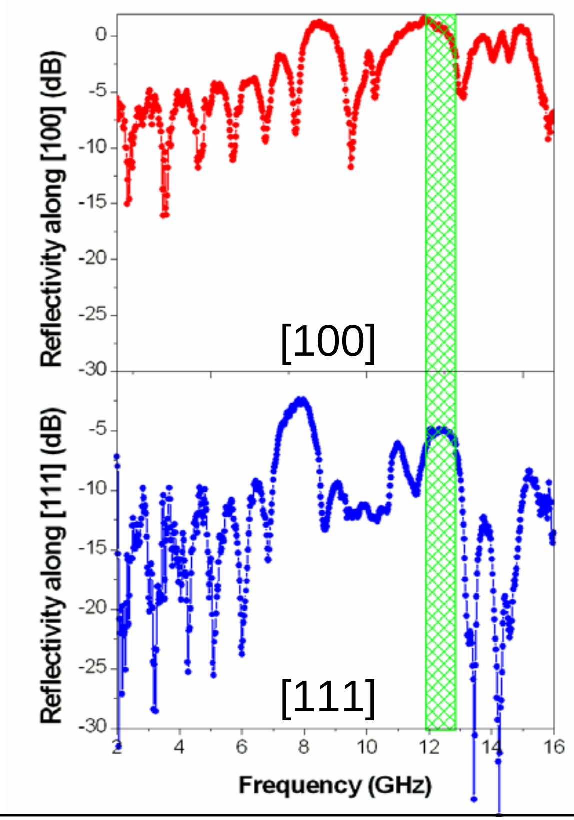






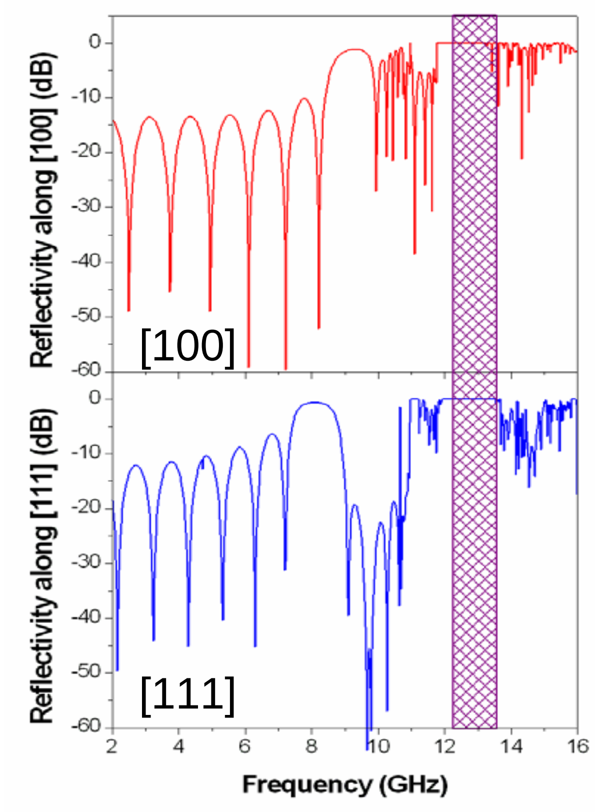

## Experiment



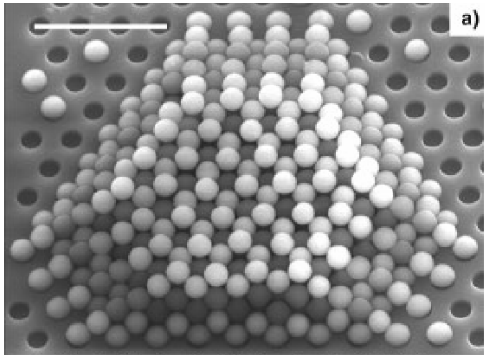




## Calculations

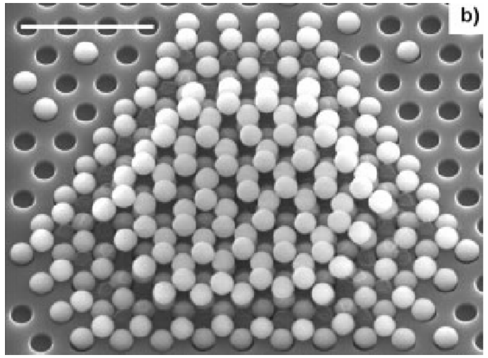
Assuming that hollow dielectric spheres are arranged in air in a diamond lattice.



# *Silica beads in diamond lattice*

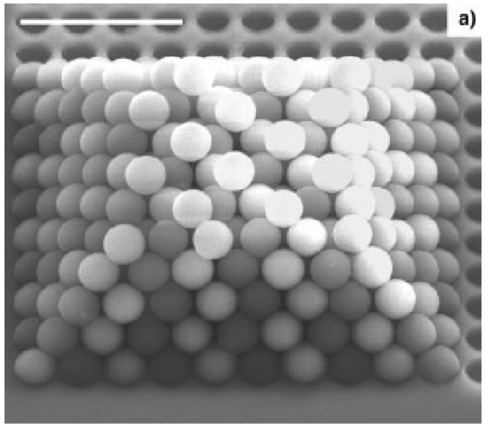



(PS + silica spheres)

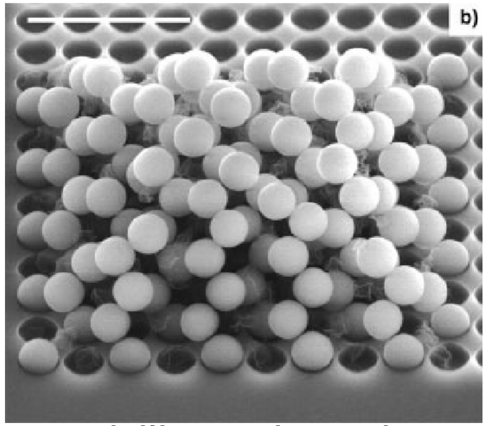



(silica spheres)

[111]




(PS + silica spheres)

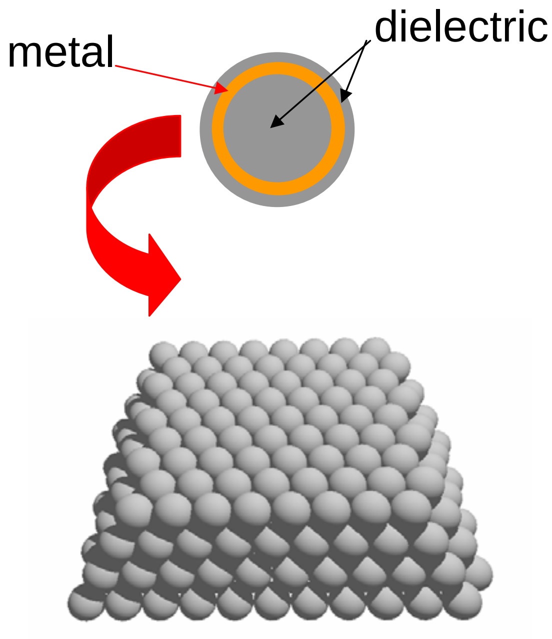


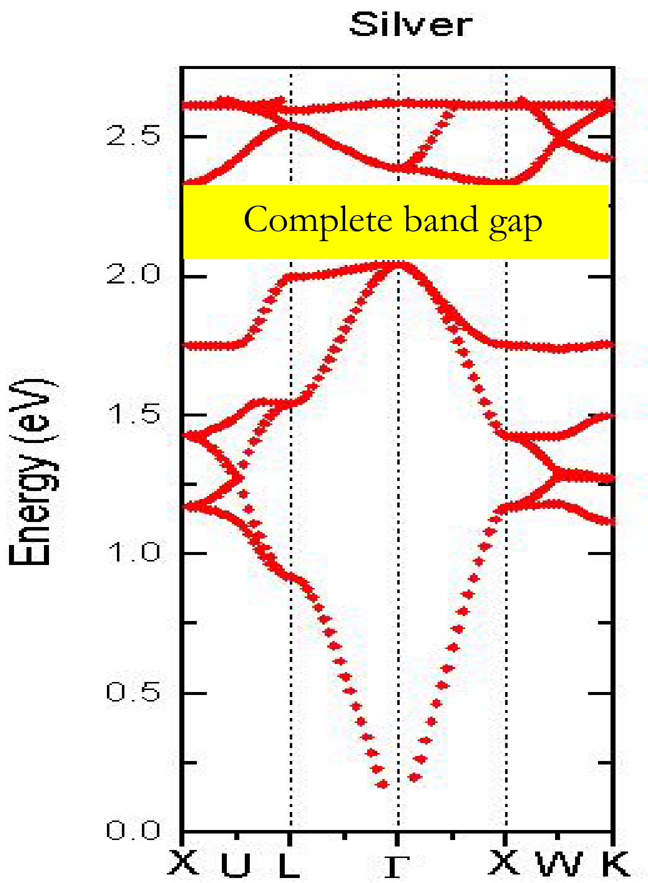

(silica spheres)

[100]

*F.G.S. et al. Adv. Mater. 14(2002), 1144*

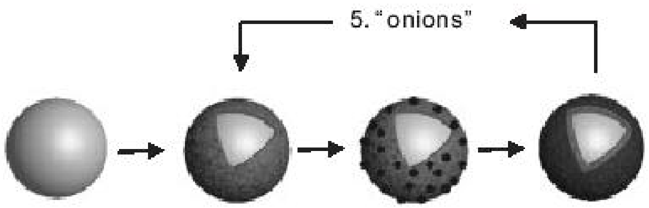
## Solution B: photonic crystals made of metal-coated spheres in a face-centered-cubic lattice



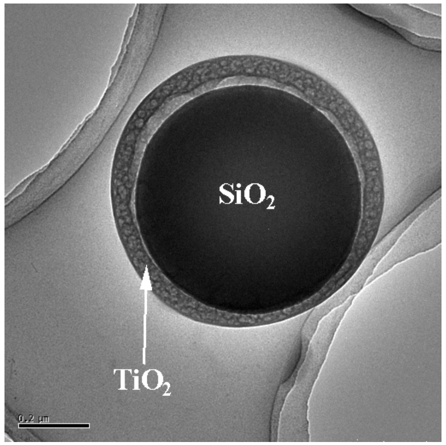




Z. L. Wang, et al., **Phys. Rev. B 64**, 113108 (2001); W. Y. Zhang, et al., **Phys. Rev. Lett. 84**, 2853 (2000).

## *Growth of onion-structure particles via coating on supporting spheres*

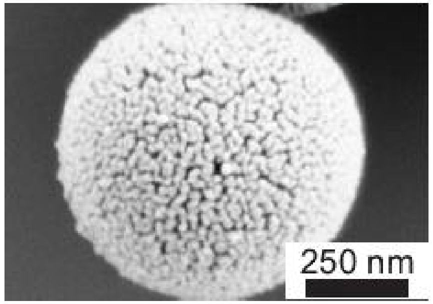



Dielectric/Dielectric

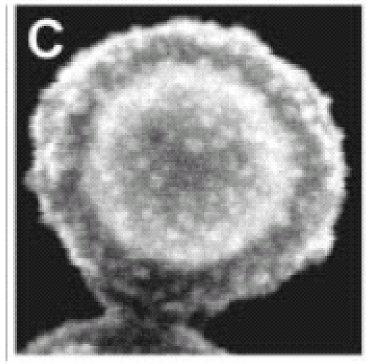



Results from our group

Dielectric/Metallic

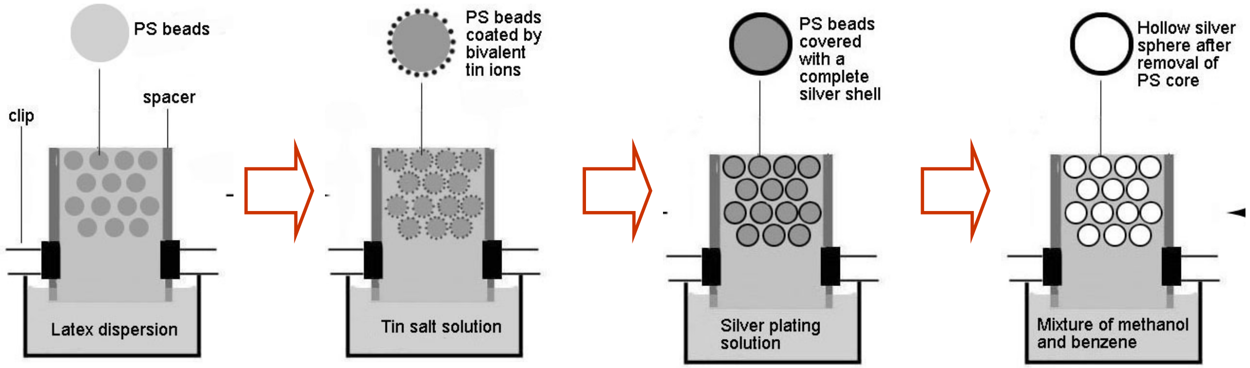


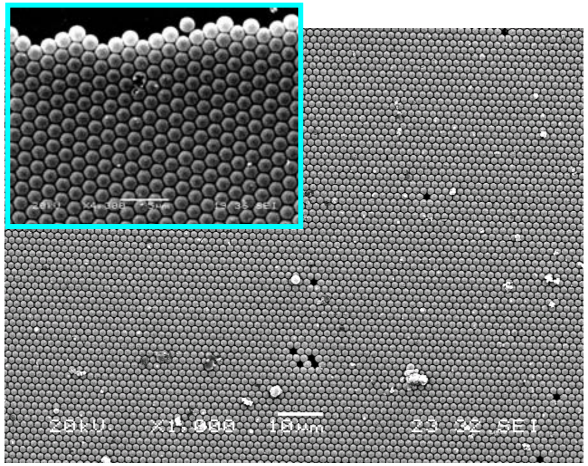

G. Kaltenpoth et al., ***Adv. Mater.* *15*** (2003) 1113.

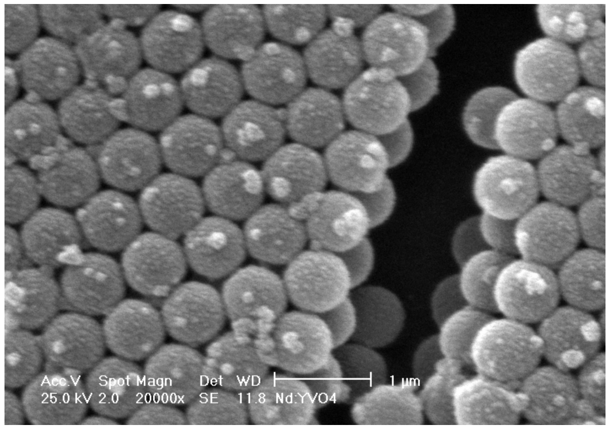



E. Prodan,et al. ***Science 302*** (2003) 419

# Ordered arrays of silver hollow spheres via colloidal crystal templating



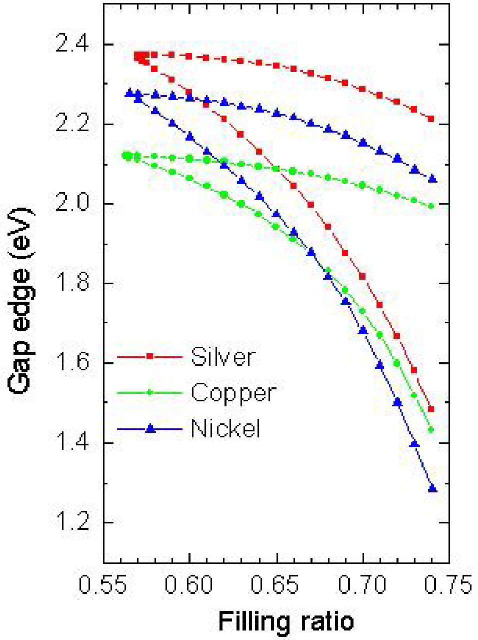



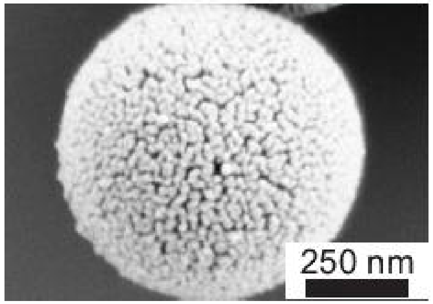



Z. Chen et al., ***Adv. Mater.*** **16**, 417 (2004)

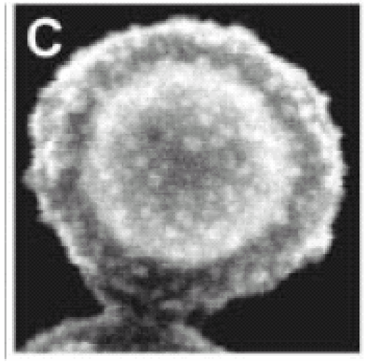
## ***Questions to be solved:***

- How to obtain a **non-close-packing of metallic nanoshell** array, with controllable separations?
- How to deal with challenges in growth of the metallic nanoshells, such as **rough surface, low coverage, and fragibility**?



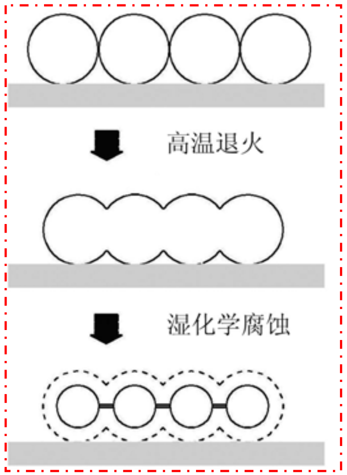




G. Kaltenpoth et al., ***Adv. Mater.* *15*** (2003) 1113.

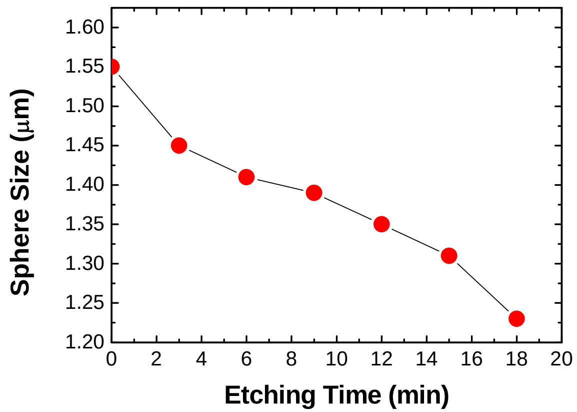


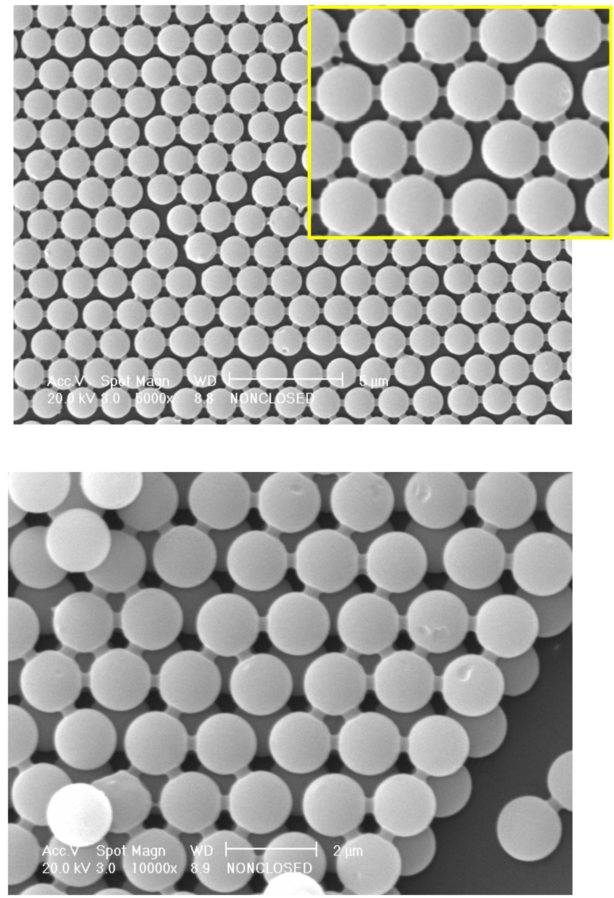

E. Prodan,et al. ***Science 302*** (2003) 419

## Step one: Non-closely packed colloidal crystals



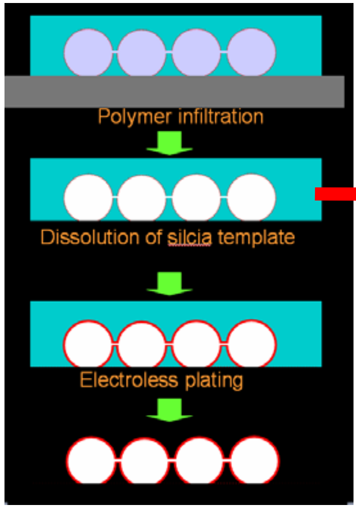

Schematic



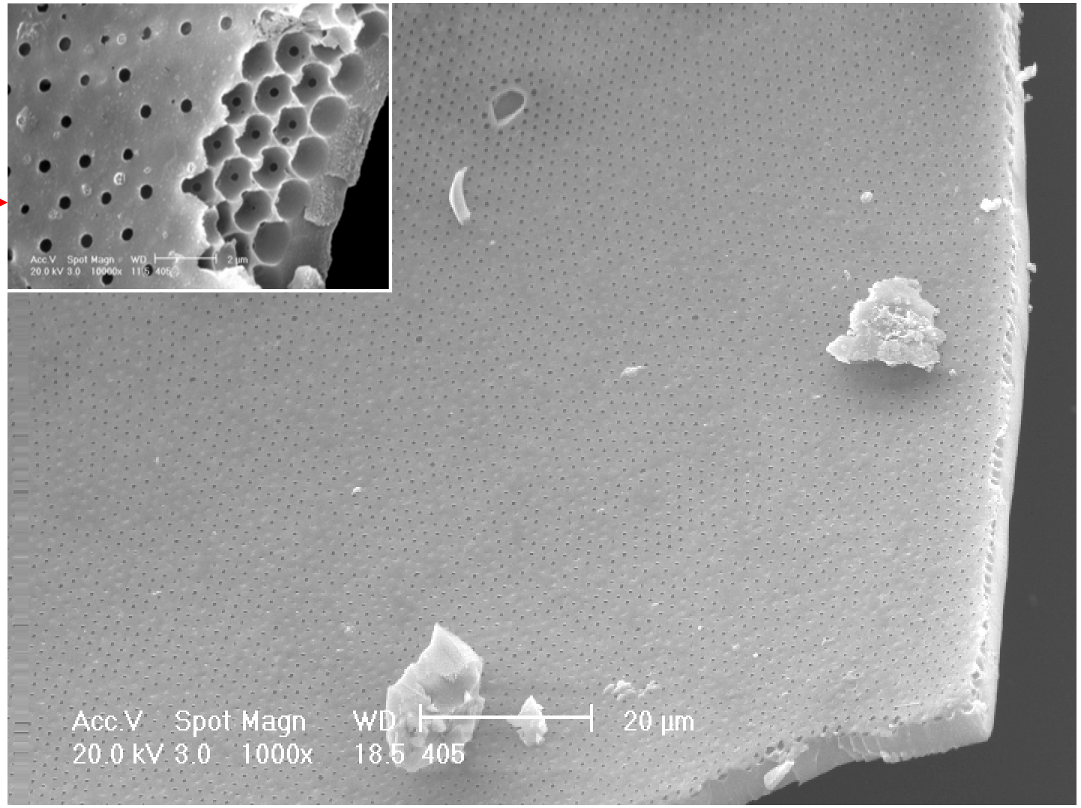




SEM images of a non-close-packing of silica colloidal crystals

## Step two and three: Gold nanoshells interconnected with gold nanotubes by double templating

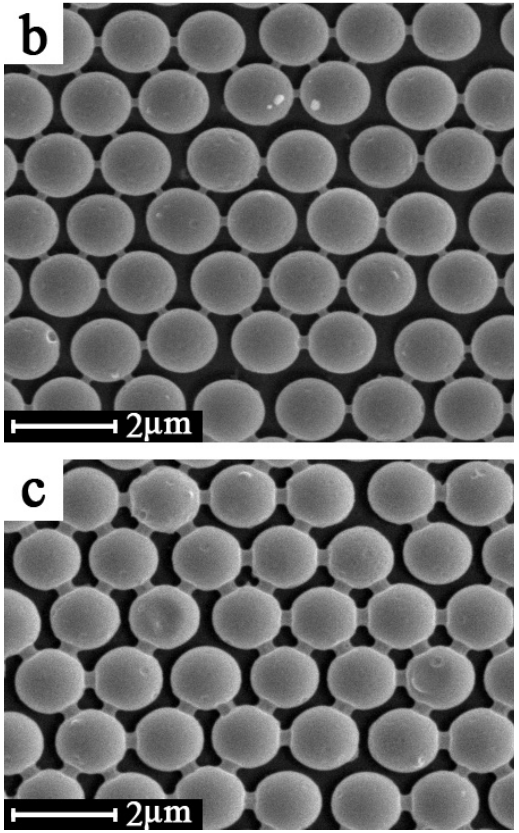


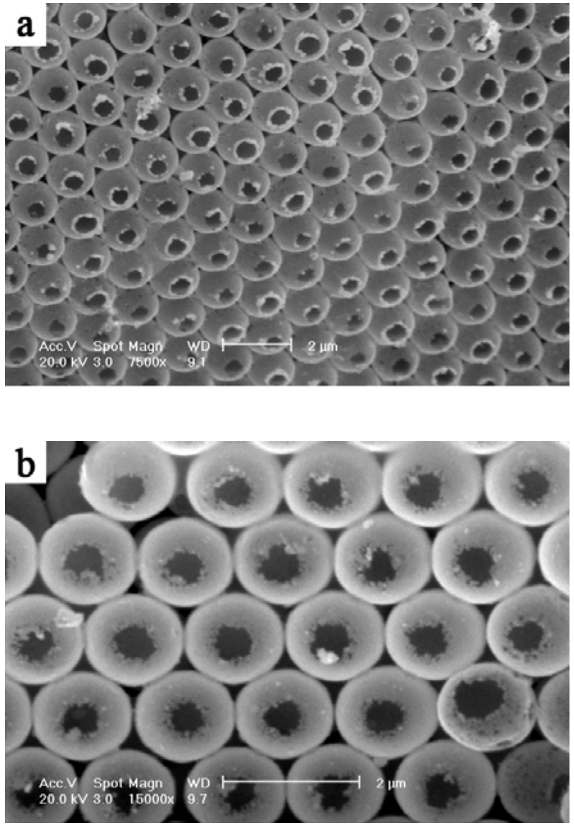

Schematic




SEM images of an inverse polymer opal

# Au nanoshells interconnected with Au nanotubes via electroless plating in inverse polyer opal

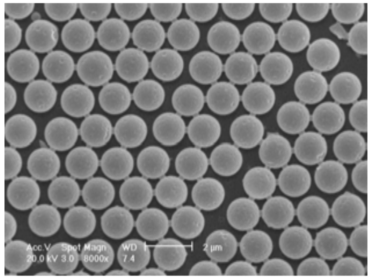


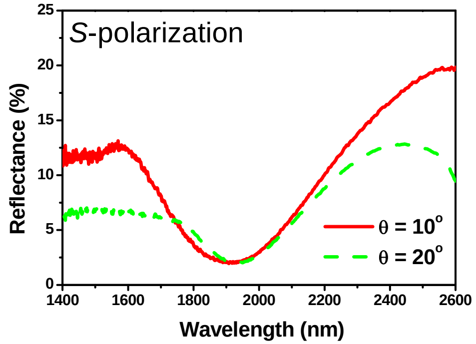



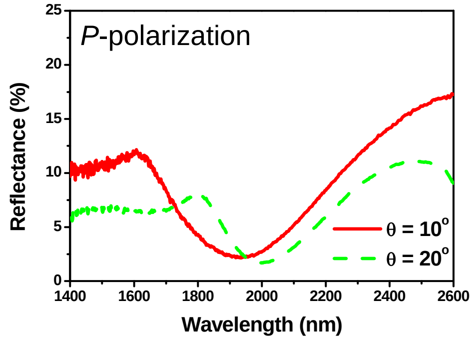

SEM images of a non-close-packing gold nanoshells

W. Dong et al., ***Adv. Mater.*** **18**, 755 (2006).

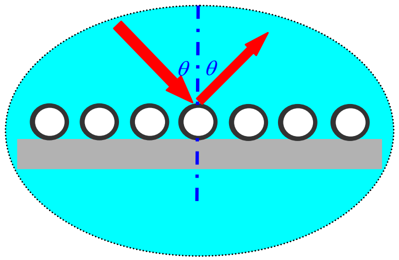
# The specular optical reflection of a monolayer gold nanoshells

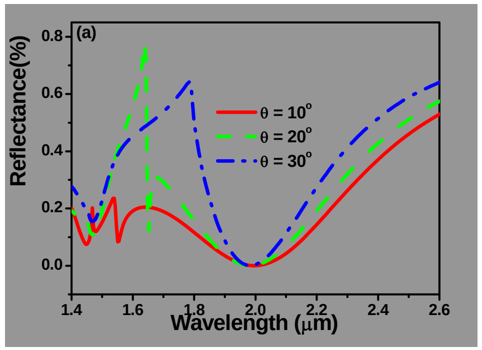


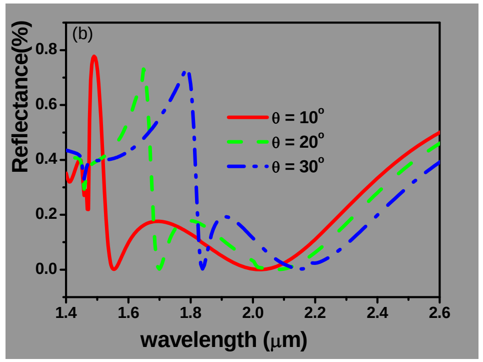



（experimental）



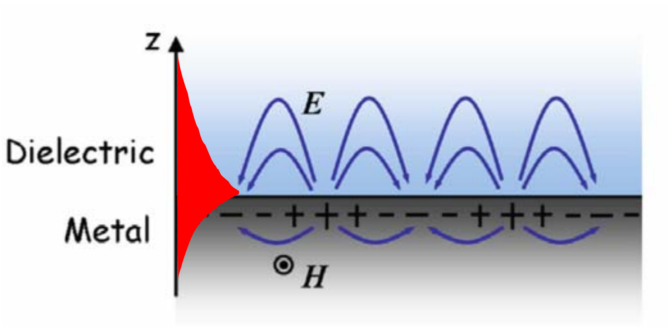



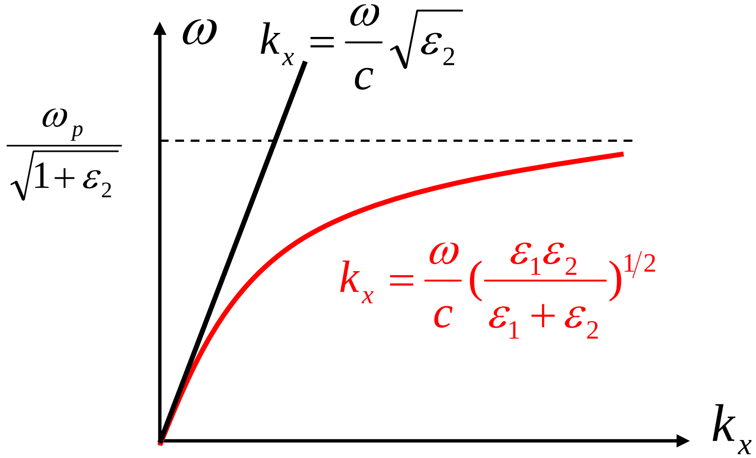




（calculations）

## 3. The use of colloidal crystals in construction of *quasi-3D plasmonic crystals*

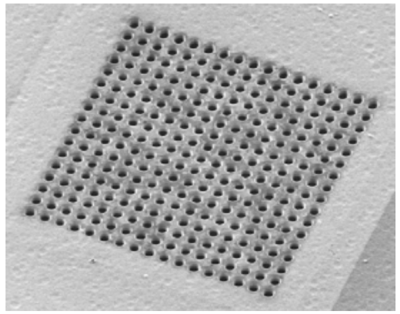
## surface plasmon plariton



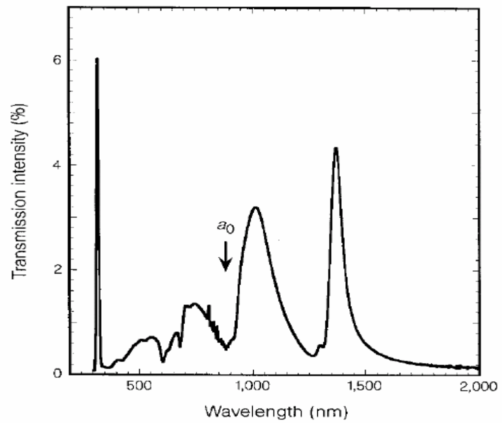




(SPP dispersion relation)

## *Planar plasmonic crystals with enhanced transmittance*

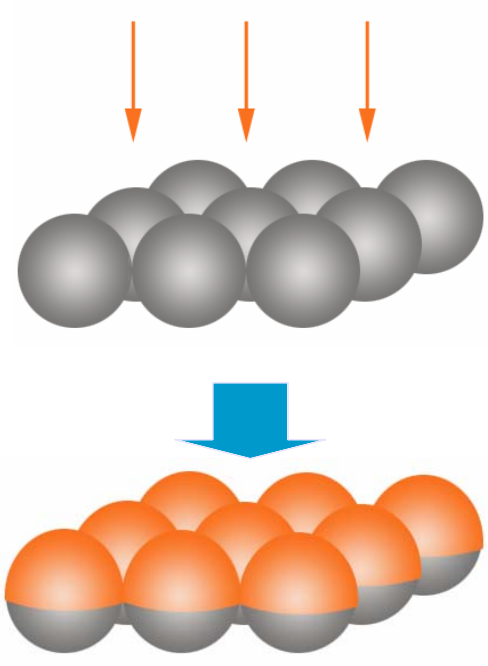


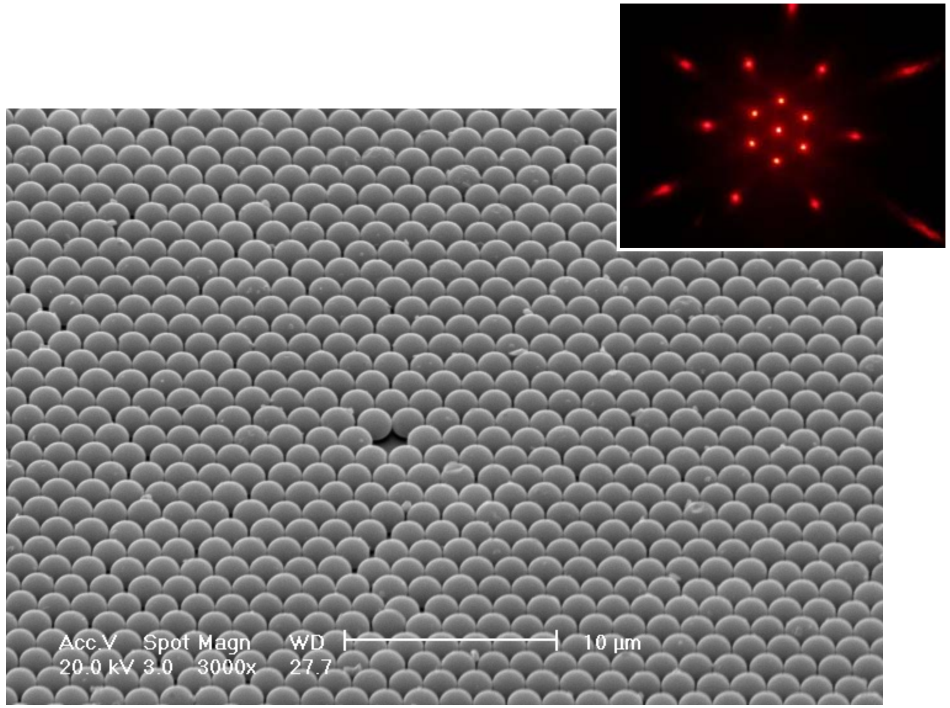
(Ag film perforated with a 2D hole array)




T. W. Ebbesen *et al.*, *Nature* 391, 667 (1998)

# Preparation of quasi-3D plasmonic crystals

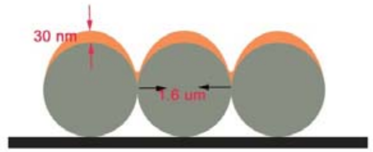


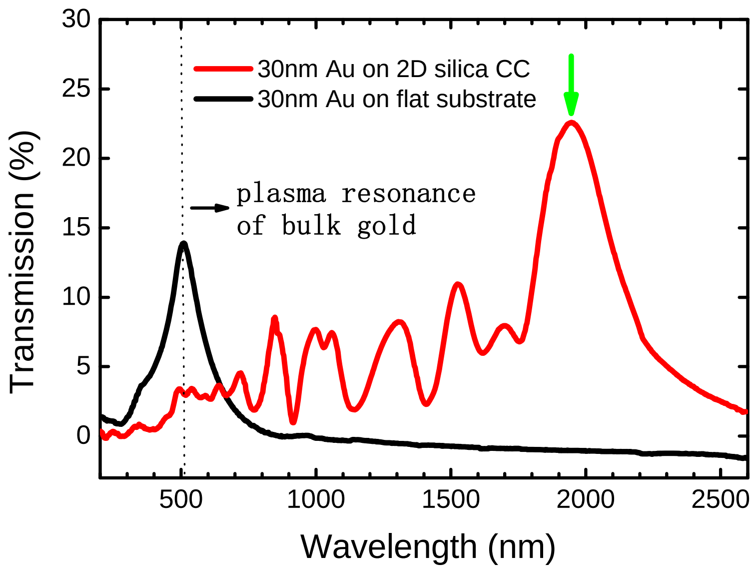


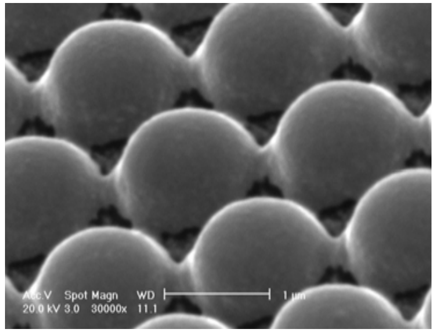

(2D colloidal crystal covered with a thin gold layer)

P. Zhan et al., ***Adv. Mater*. 18** (2006) 1612.

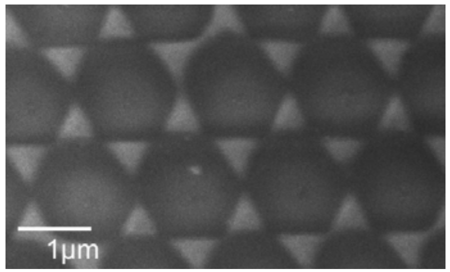
# Anomalous light transmission



ordered array of inter-connected metal half-nano-shells



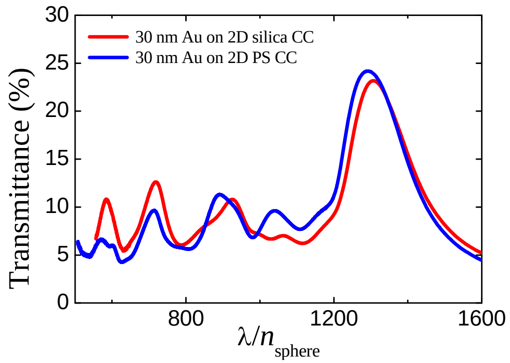

ordered array of nano-triangles deposited through 2D colloidal crystal  pores onto a substrate

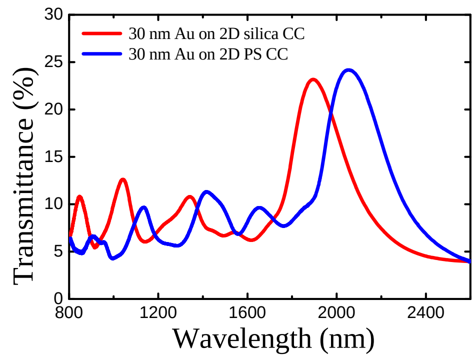
# Scalable optical properties

(silica spheres: *d=1.58 μm, n= 1.45;*
polystyrene spheres: *d=1.59 μm, n=1.59*)

Relation I:

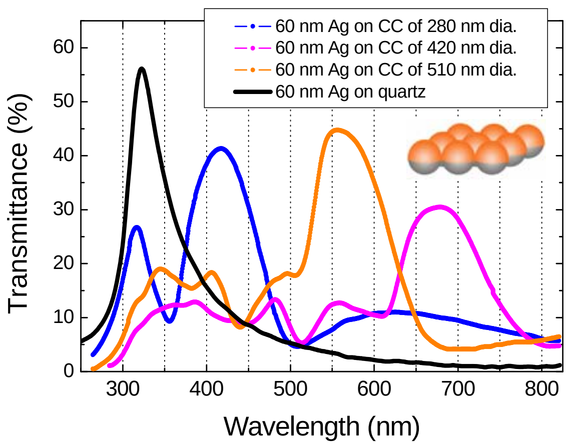
$$\frac{\lambda_{r1}}{n_1} = \frac{\lambda_{r2}}{n_2}$$

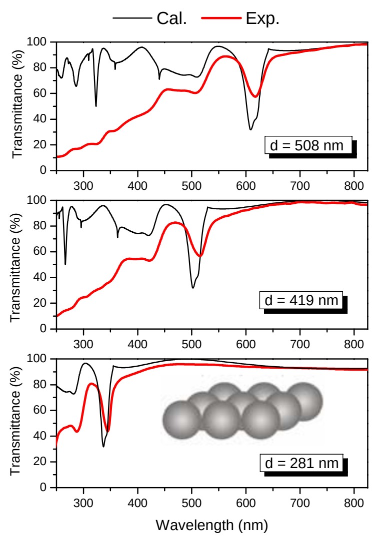


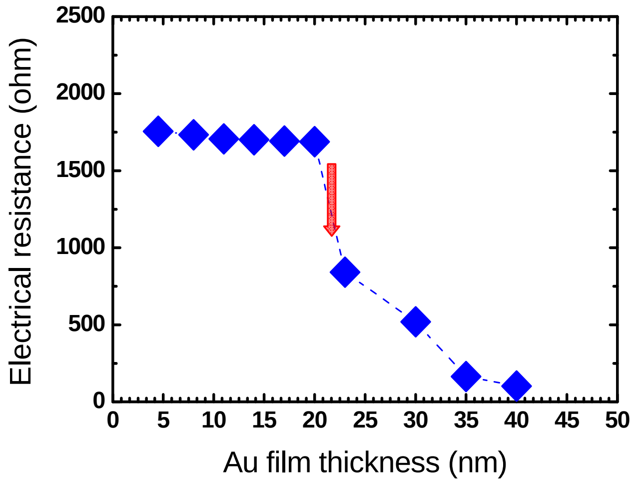

Relation II:

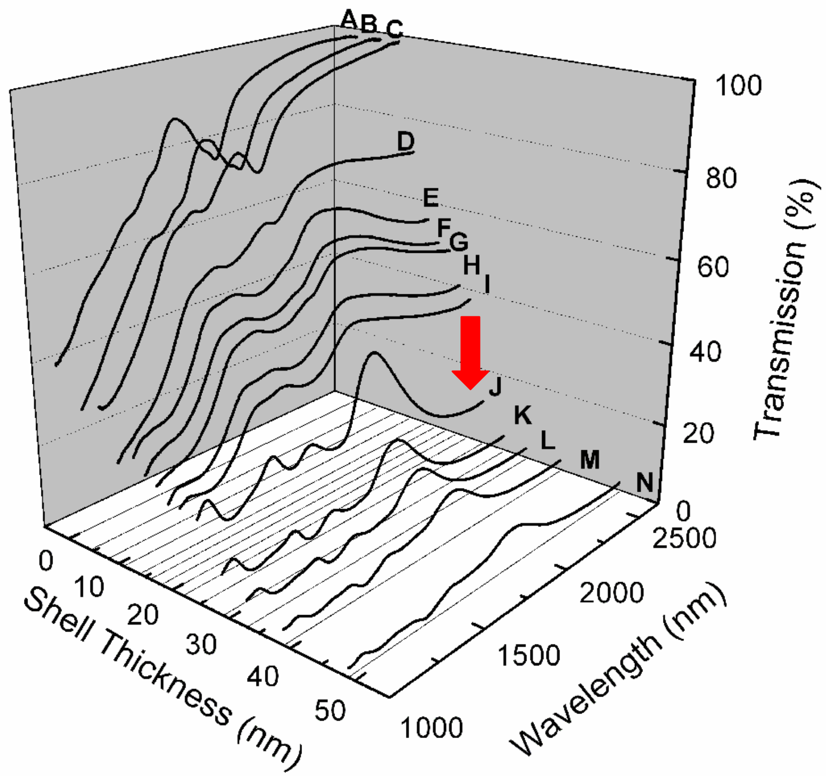
$$\frac{\lambda_{r1}}{d_1} = \frac{\lambda_{r2}}{d_2}$$

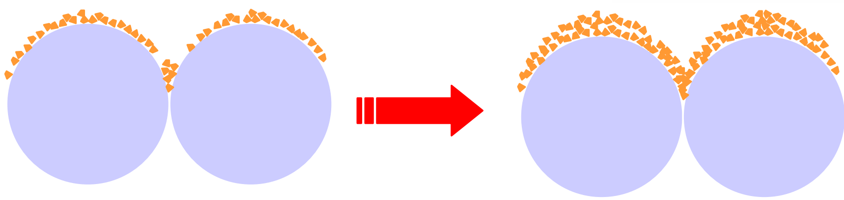


# Critical dependence on metal film thickness

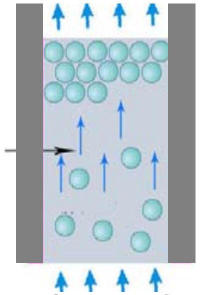


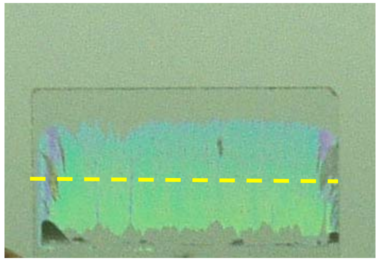



**Assumption: a transition between the excitation of localized SPs and SPP.**

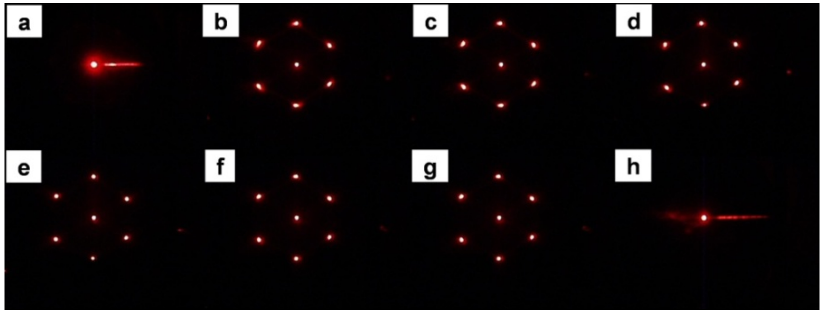
## *Large single domain of the template produced via self-assembly under capillary forces in micro-channels*



schematic

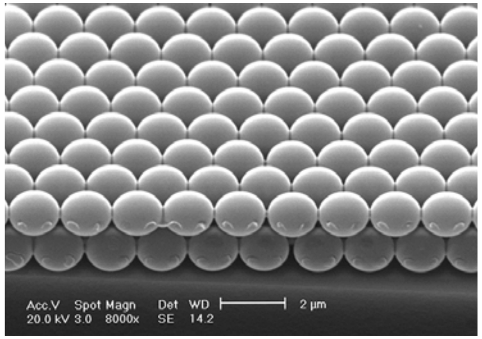


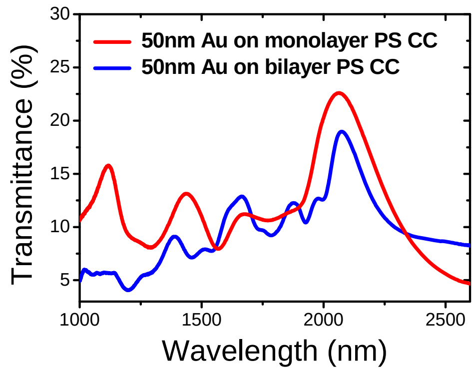
Optical image of a 2D colloidal crystal

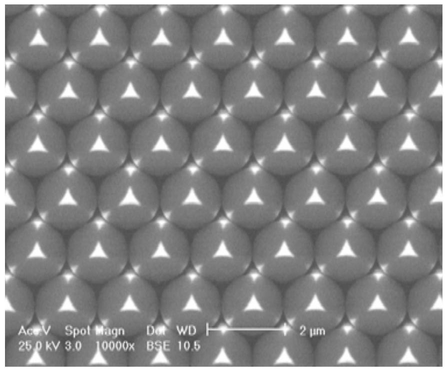



Diffraction pattern probed across the sample in steps of 5 mm (spot size 1 mm)

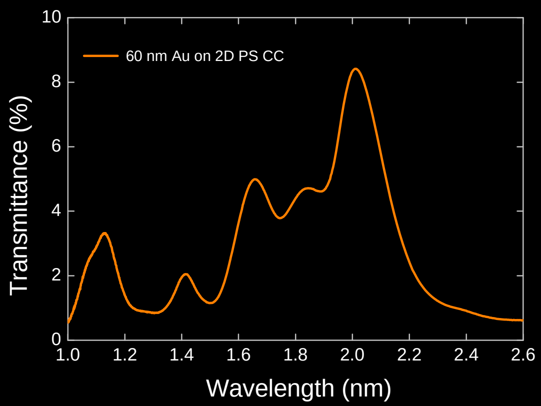
## *Insensitive to the number of colloidal crystal layers*

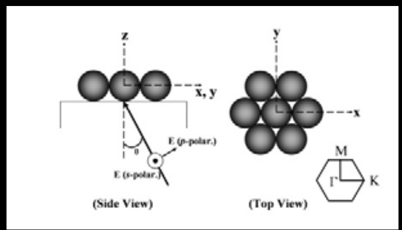


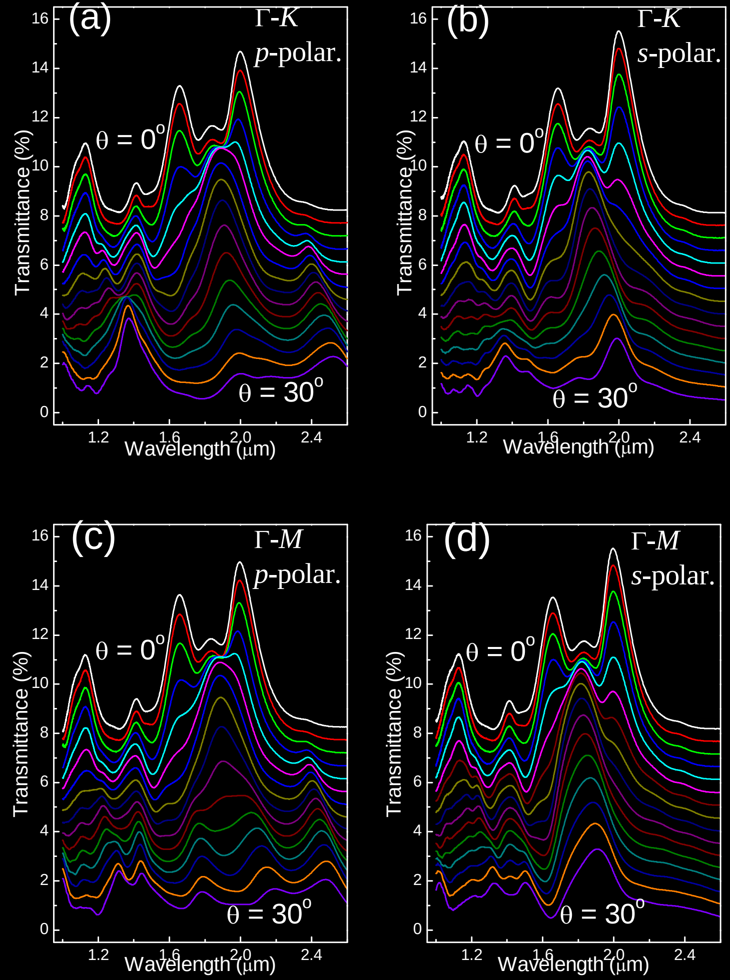



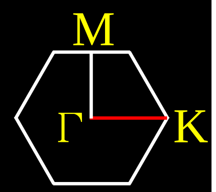



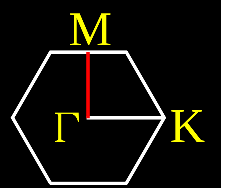
# Transmission resonance dispersion



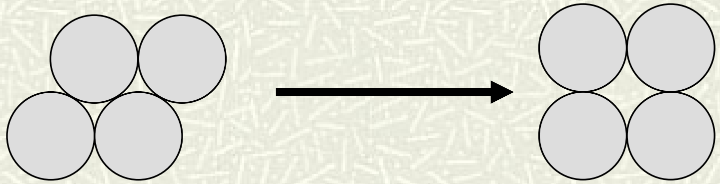



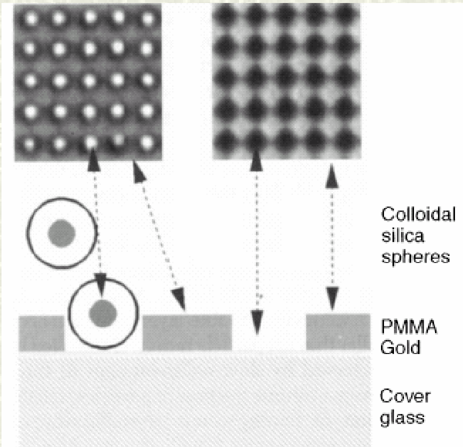

J. Sun et al., ***Adv. Mater.*** (to be submitted).

# 2D square lattice colloidal crystals



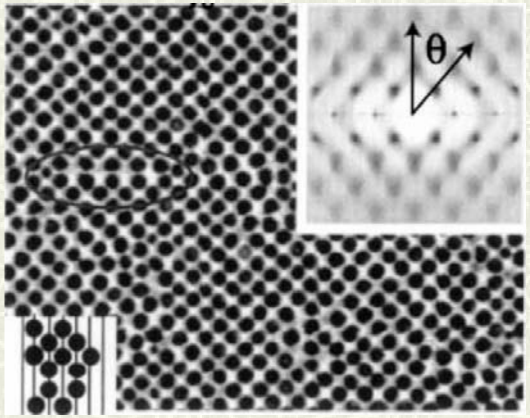
Questions to be solved:
short-range order, high density of defects

(colloidal epitaxy)



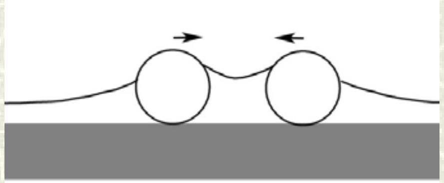

A. van Blaaderen et al., ***Nature*** **385**, 321 (1997)

(self-assembly on 1D patterns)

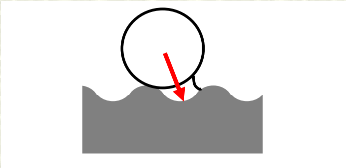



K. Lin et al., ***Phys. Rev. Lett.*** **85**, 1770 (2000).

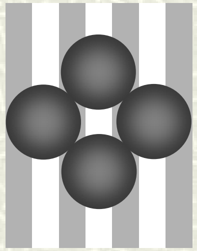
In our experiments, the action of capillary forces is first introduced. Conditions:



(on planar substrate)



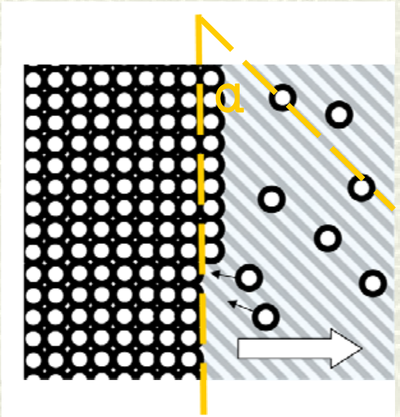
(on patterned substrate)



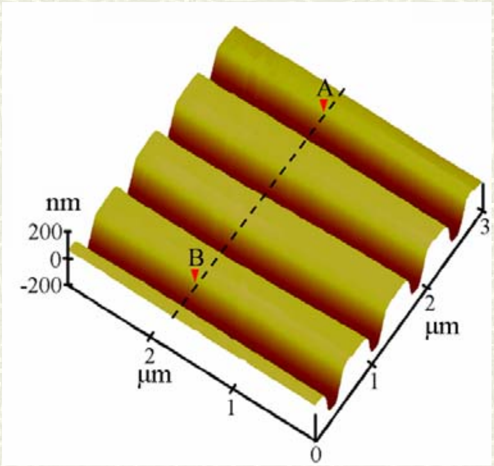
D = 1020 nm

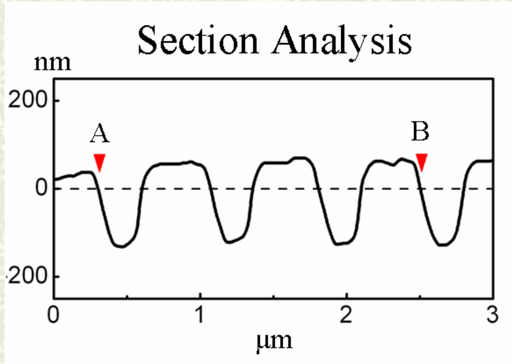
p = 730 nm

$$\boxed{D/p = 1.4 \approx \sqrt{2}}$$




(schematic)

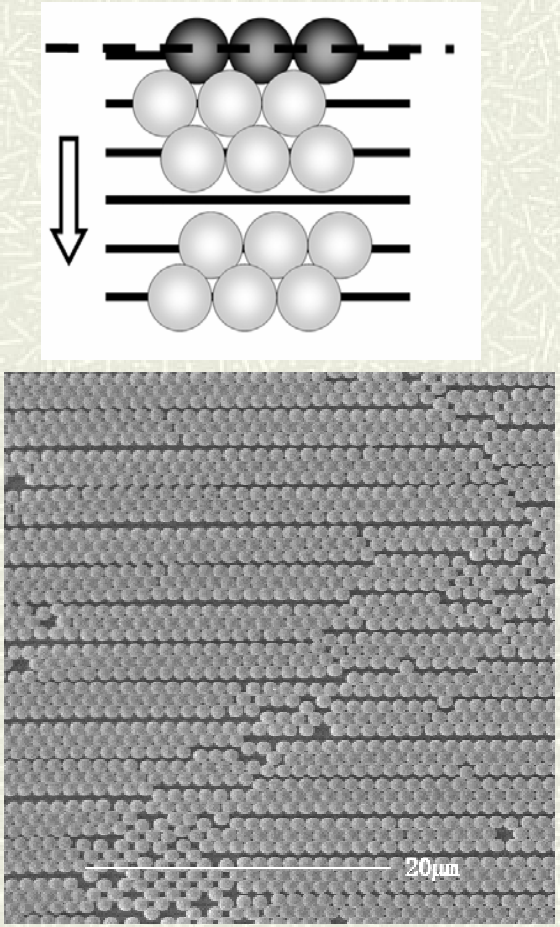


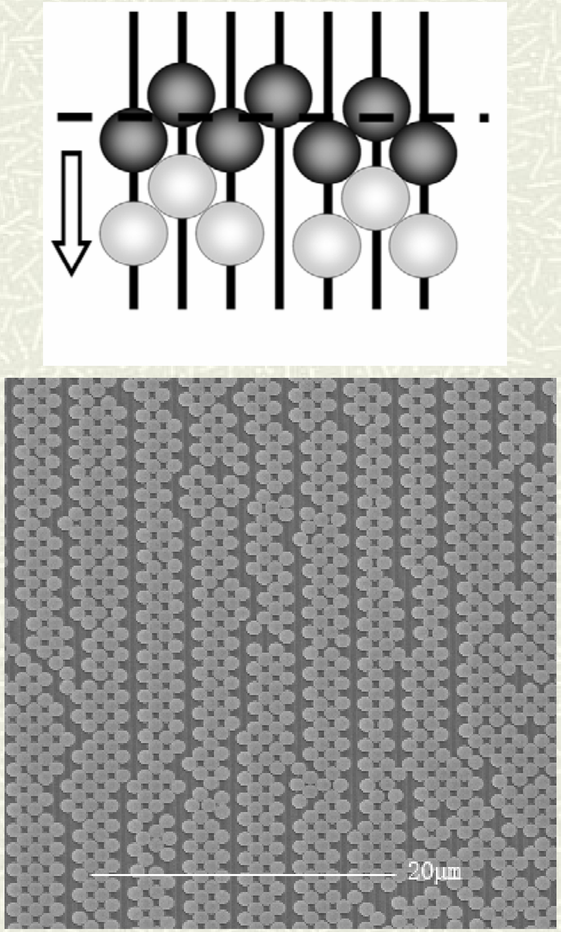

AFM of 1D grooves on polycarbonate

See J. Sun et al., ***Adv. Mater.*** 20, 123 (2008).

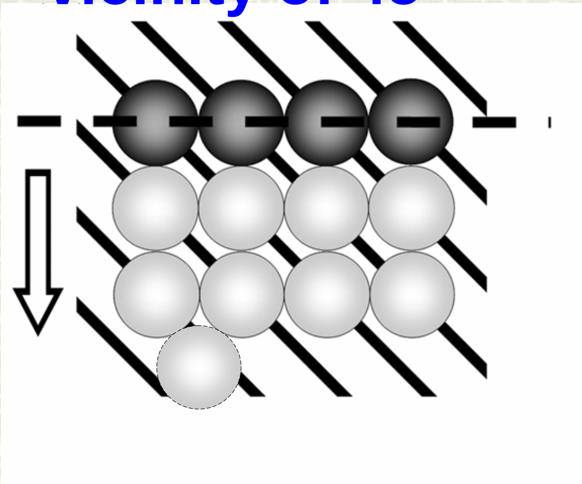
## (a) For $\alpha = 0°$

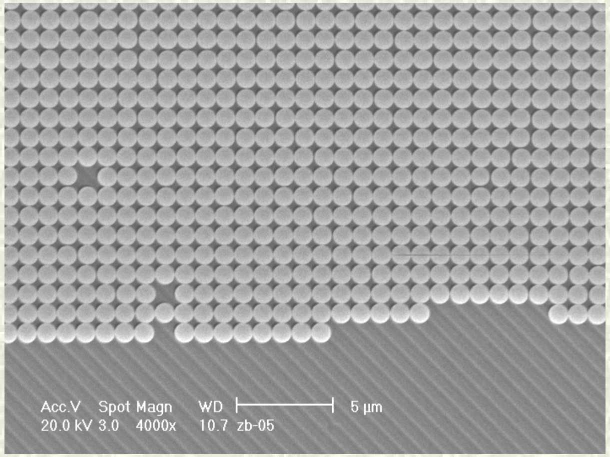


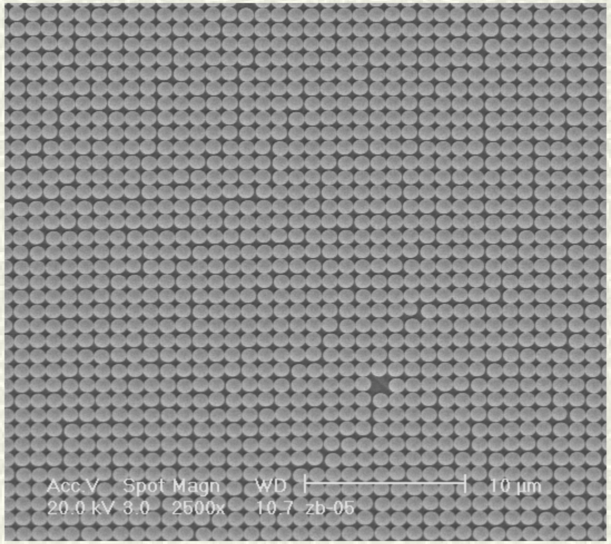

## (b) For $\alpha = 90°$



## Only for α controlled in the vicinity of 45°






By controlling the angle *a* in the vicinity of 45°, a highly ordered 2D square-lattice colloidal crystal with a minimum density of defects can be self-organized.

*One of the possible applications*

**Quasi-3D plasmonic crystal sensors with an enhanced sensitivity**

Y. Y. Li et al., to be published.

## 4. Light tunneling through 2D ordered array of metal nanoshells

C. J. Tang et al., to be submitted.

## Basic optical properties and applications of metal films with hole or slit arrays

- ***Ultrafast response***

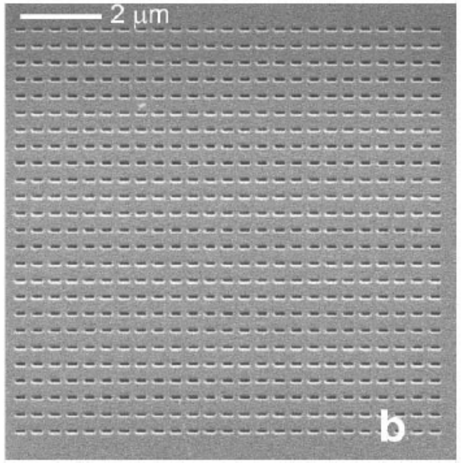
  M. Tong et al., *PRL* 100, 056808 (2008)
- ***Strong modification of nonlinear optical response***

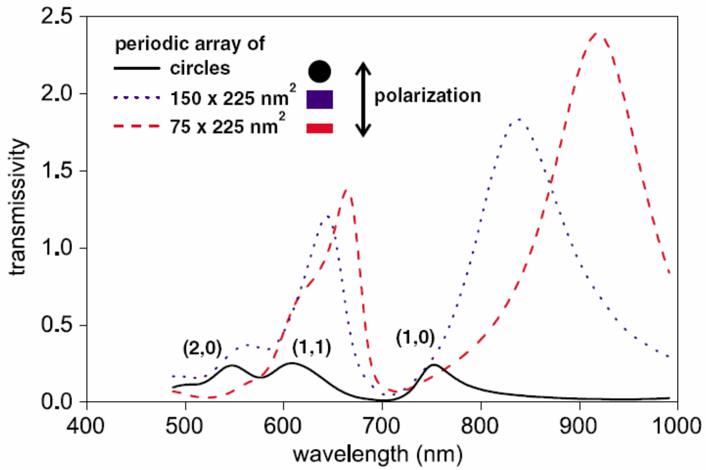
  J. A. H. van Nieuwstadt et al., *PRL* 97, 146102 (2006)
- ***Interplane coupling***

  X. Fang et al., *PRL* 99, 066805 (2007)
- ***Sensing, data storage, light beam collimation, and extraction from LEDs***

  **………**
- *Question about the mechanism associated with enhanced transmittance*

## *Strong influence of hole shape on extraordinary transmission (experiment)*



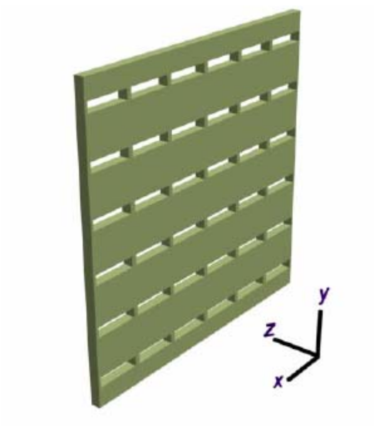



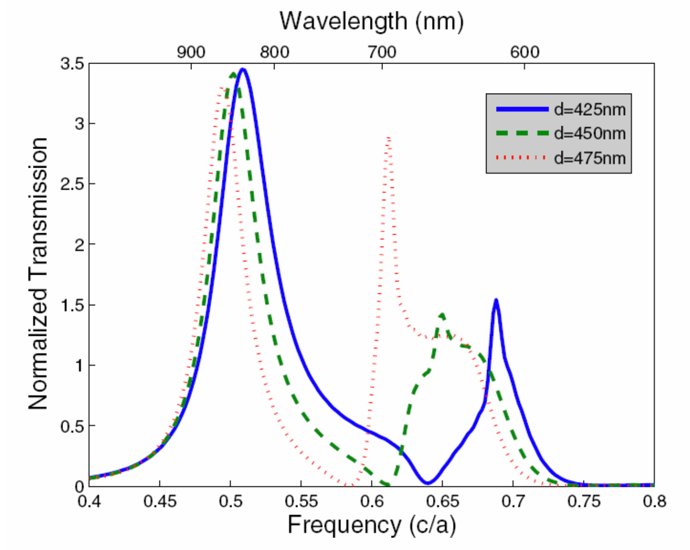

K.J.K. Koerkamp et al., ***PRL*** 92, 183901 (2004).

(U. Twente, The Netherlands)

## ***Different resonances involved (theory):***

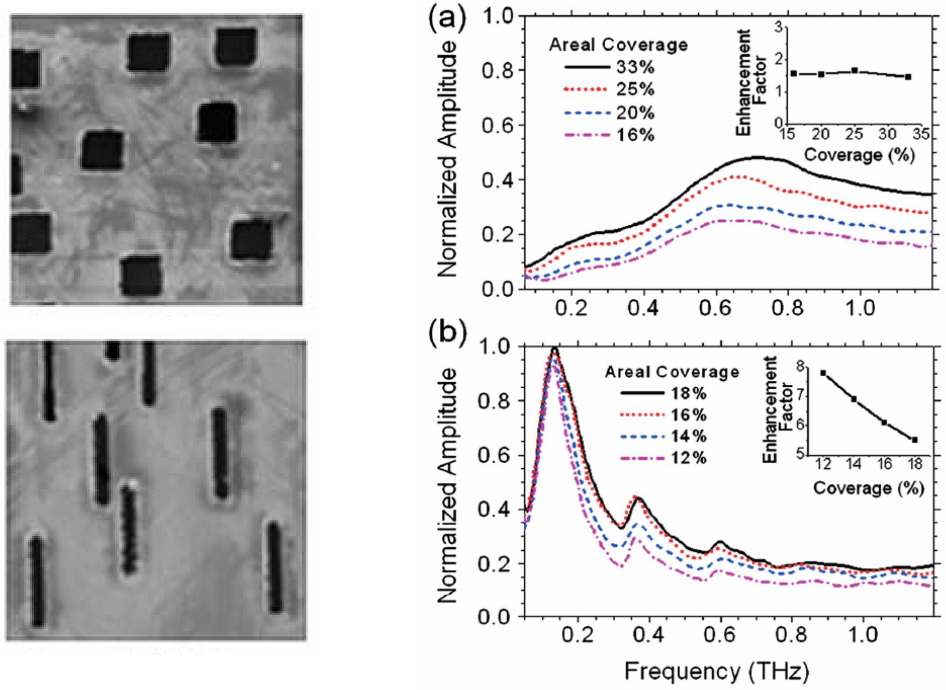
Min Qiu et al., PRL **96, 233901 (2006)**




- surface plasmon resonances due to the periodicity.
- waveguide resonances in the nanohole with *a low-quality-factor resonator*

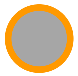
## *Terahertz electromagnetic wave transparency*




**terahertz transparency can be realized through the shape resonance only**, *when the hole shape is strongly asymmetric.*

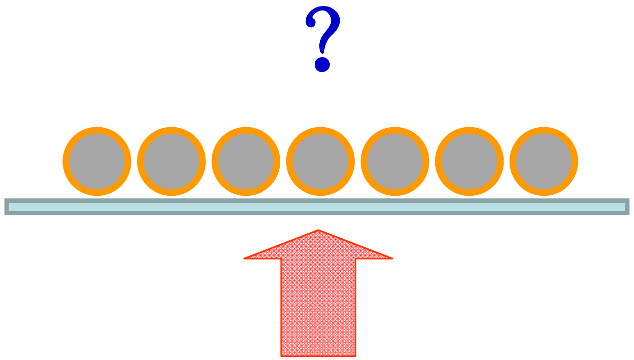
J.W. Lee et al., PRL **99, 137401 (2007)**

- **For a single metallic nanoshells supporting:**



  - ✓ Sphere surface mode
  - ✓ Cavity mode

- How about light transmission through a dense array of metallic nanoshells?



# 5. Summary

- We developed an efficient MST for EM wave in structures composed of ordered array of spheres
- We designed two types of photonic crystals with true gap using spheres as building blocks.
- We revealed the enhanced optical transmission and other properties of quasi-3D plasmonic crystals.
- We predicted various tunneling channels for light through 2D dense array of metallic

## Collaborators

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Fudan University

Prof. G. Sun

The Institute of Physics, CAS

Prof. X. Y. Jiang

Institute of Microsystem and Information Technology, CAS

Prof. W.Y. Zhang, Prof. S.N. Zhu, Prof. Y.Y. Zhu, Prof. N.B. Ming

Nanjing University

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- Key Program of NSFC

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