Unidirectional and Wavelength Selective Photonic Spherical Nanoantennas

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Outline

Introduction

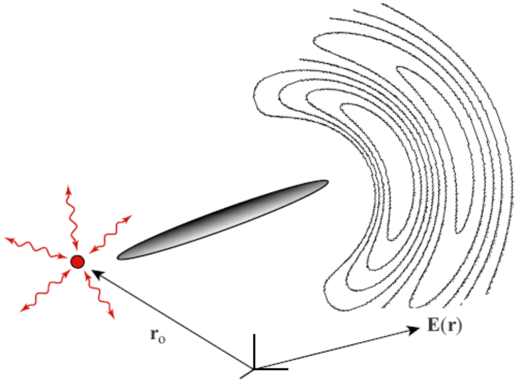
T-matrix method

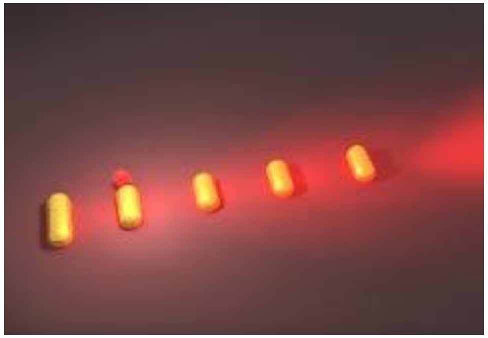
Theoretical results

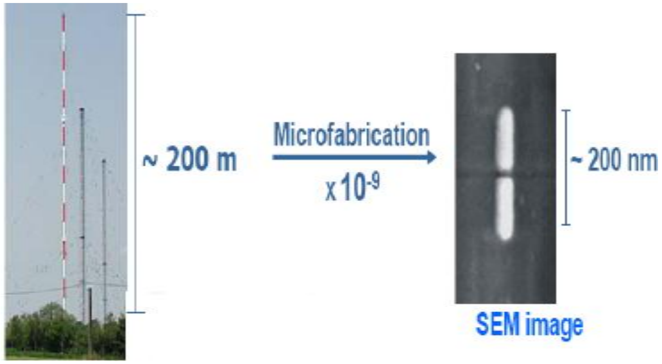
Summary

Introduction

Nanoantenna (NA), to some extent, is a direct analogue and extended technology of the radio wave and microwave antenna. They play a fundamental role in the nanotechnology due to their capabilities to confine and enhance the light through converting the localized to propagating electromagnetic fields, and vice versa. Developing a directional NAs to redirect the emission from an ensemble of atoms or molecules with random dipole orientations is particularly important to photon detection and sensing, spectroscopy and microscopy, and spontaneous emission manipulation. Although various plasmonic NAs have been reported in the literature to realize the directional functionality, they suffer from a fundamental limit due to intrinsic metallic loss. Photonic NAs could reduce the ohmic loss and maintain other useful functionalities of plasmonic NAs.







A Hertzian dipole source

A Hertzian dipole source in free space can be described as

$$\mathbf{J} = \hat{\mathbf{n}} I l \delta(\mathbf{r} - \tilde{\mathbf{r}})$$

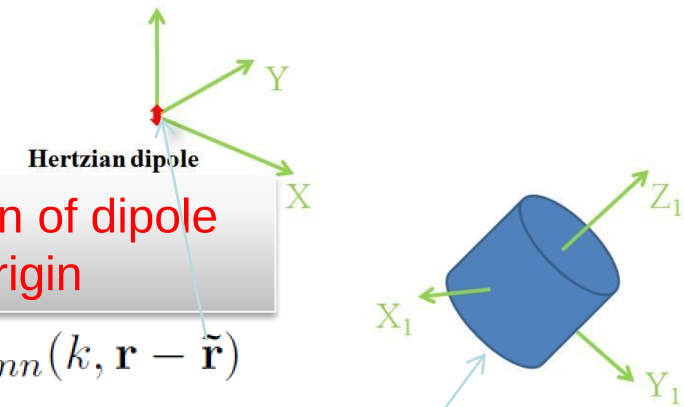
- $\hat{\mathbf{n}}$: Direction of the Hertzian dipole
- Il: Current moment
- δ: Delta function
- $\tilde{\mathbf{r}}$: Position vector of the dipole source

T-matrix method for a particle (1)

- The incident field can be written as

$$\begin{aligned}\mathbf{E}^{inc}(\mathbf{r}) &= \sum_{m,n} \overline{\mathbf{\Psi}}^{t}_{mn}(k, \mathbf{r}-\tilde{\mathbf{r}}) \cdot \mathbf{b}_{mn} \\ &= -\omega\mu k I l \sum_{m,n} \frac{1}{n(n+1)} \left[\Re g\mathbf{M}^{*}_{mn}(k,\mathbf{0}) \cdot \hat{\mathbf{n}}\mathbf{M}_{mn}(k, \mathbf{r}-\tilde{\mathbf{r}}) \right. \\ &\quad \left. + \Re g\mathbf{N}^{*}_{mn}(k,\mathbf{0}) \cdot \hat{\mathbf{n}}\mathbf{N}_{mn}(k, \mathbf{r}-\tilde{\mathbf{r}})\right],\end{aligned}$$

Take the position of dipole source as the origin



- The incident field can be rewritten as

$$\begin{aligned}\mathbf{E}^{inc}(\mathbf{r}) &= \sum_{m,n} \Re g\overline{\mathbf{\Psi}}^{t}_{mn}(k, \mathbf{r}-\mathbf{r}_0) \cdot \mathbf{a}^{inc}_{mn} \\ &= \sum_{m,n} a^{inc(M)}_{mn} \Re g\mathbf{M}_{mn}(k, \mathbf{r}-\mathbf{r}_0) + a^{inc(N)}_{mn} \Re g\mathbf{N}_{mn}(k, \mathbf{r}-\mathbf{r}_0) \\ &= -\omega\mu k I l \sum_{m,n} \frac{1}{n(n+1)} \left[\mathbf{M}^{*}_{mn}(k, \tilde{\mathbf{r}}-\mathbf{r}_0) \cdot \hat{\mathbf{n}}\Re g\mathbf{M}_{mn}(k, \mathbf{r}-\mathbf{r}_0) \right. \\ &\quad \left. + \mathbf{N}^{*}_{mn}(k, \tilde{\mathbf{r}}-\mathbf{r}_0) \cdot \hat{\mathbf{n}}\Re g\mathbf{N}_{mn}(k, \mathbf{r}-\mathbf{r}_0)\right],\end{aligned}$$

Take the position of particle as the origin

Addition theorem

(outgoing → incoming)

T-matrix method for a particle (2)

- The scattered field

$$\mathbf{E}^{sca}(\mathbf{r}) = \sum_{m,n} a_{mn}^{sca(M)} \mathbf{M}_{mn}(k, \mathbf{r} - \mathbf{r}_0) + a_{mn}^{sca(N)} \mathbf{N}_{mn}(k, \mathbf{r} - \mathbf{r}_0)$$

With the continuity of tangential part of electrical field and magnetic field on the particle surface

$$\mathbf{a}^{sca} = \overline{\mathbf{T}} \cdot \mathbf{a}^{inc}$$

Scattered field coefficient

T-matrix

incident field coefficient

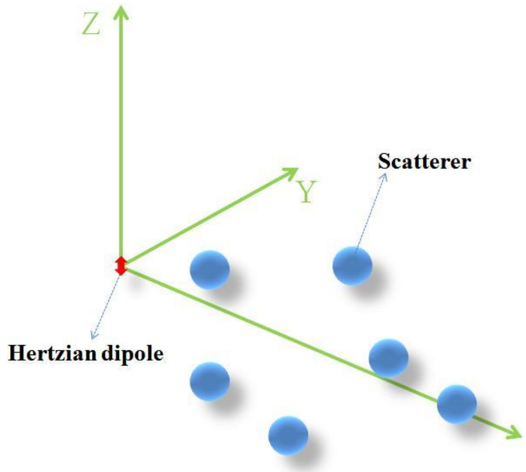
T-matrix method for multiple particles (1)

For P_n particles, the total scattered field is

$$\mathbf{E}^{sca}(\mathbf{r}) = \sum_{i=1}^{P_n} \mathbf{E}_i^{sca}(\mathbf{r})$$

- The scattered field of the i-th particle

$$\mathbf{E}_i^{sca}(\mathbf{r}) = \sum_{m,n} \overline{\mathbf{\Psi}}_{mn}^{t}(k, \mathbf{r} - \mathbf{r}_i) \cdot \mathbf{a}_{mn}^{i}$$



T-matrix method for multiple particles (2)

For the i-th particle, the total incident field

$$\mathbf{E}_i^{inc}(\mathbf{r}) = \mathbf{E}^{inc}(\mathbf{r}) + \sum_{j\neq i} \mathbf{E}_j^{sca}(\mathbf{r})$$

$$= \sum_{m,n} \overline{\mathbf{\Psi}}^t_{mn}(k, \mathbf{r} - \tilde{\mathbf{r}}) \cdot \mathbf{b}_{mn} + \sum_{j\neq i} \sum_{m,n} \overline{\mathbf{\Psi}}^t_{mn}(k, \mathbf{r} - \mathbf{r}_j) \cdot \mathbf{a}^j_{mn}$$

From the Hertzian dipole source

From all the other particles

- The total incident field can be rewritten as

$$\begin{aligned}\mathbf{E}_i^{inc}(\mathbf{r}) &= \sum_{m,n} \Re g \overline{\mathbf{\Psi}}^t_{mn}(k, \mathbf{r} - \mathbf{r}_i) \sum_{m',n'} \overline{\boldsymbol{\alpha}}_{mn,m'n'}(\mathbf{r}_i - \tilde{\mathbf{r}}) \cdot \mathbf{b}_{m'n'} \\ &+ \sum_{j\neq i} \sum_{m,n} \Re g \overline{\mathbf{\Psi}}^t_{mn}(k, \mathbf{r} - \mathbf{r}_i) \sum_{m',n'} \overline{\boldsymbol{\alpha}}_{mn,m'n'}(\mathbf{r}_i - \mathbf{r}_j) \cdot \mathbf{a}^j_{m'n'} \\ &= \sum_{m,n} \Re g \overline{\mathbf{\Psi}}^t_{mn}(k, \mathbf{r} - \mathbf{r}_i) \Bigg[\sum_{m',n'} \overline{\boldsymbol{\alpha}}_{mn,m'n'}(\mathbf{r}_i - \tilde{\mathbf{r}}) \cdot \mathbf{b}_{m'n'} \\ &+ \sum_{j\neq i} \sum_{m',n'} \overline{\boldsymbol{\alpha}}_{mn,m'n'}(\mathbf{r}_i - \mathbf{r}_j) \cdot \mathbf{a}^j_{m'n'} \Bigg]\end{aligned}$$

Addition theorem

T-matrix method for multiple particles (3)

- The coefficient vector of the total incident field for the i-th particle

$$\mathbf{h}^{i}_{mn} = \left[\sum_{m',n'} \overline{\boldsymbol{\alpha}}_{mn,m'n'}(\mathbf{r}_i - \tilde{\mathbf{r}}) \cdot \mathbf{b}_{m'n'} + \sum_{j \neq i} \sum_{m',n'} \overline{\boldsymbol{\alpha}}_{mn,m'n'}(\mathbf{r}_i - \mathbf{r}_j) \cdot \mathbf{a}^{j}_{m'n'} \right]$$

- T-matrix for the i-th particle

$$\mathbf{a}^{i} = \overline{\mathbf{T}}^{i} \cdot \mathbf{h}^{i}, \quad i = 1, \ldots, P_n$$

T-matrix method is a rigorous, fast and efficient tool for describing the optical response of spherical nanoparticles.

Theoretical results (1)

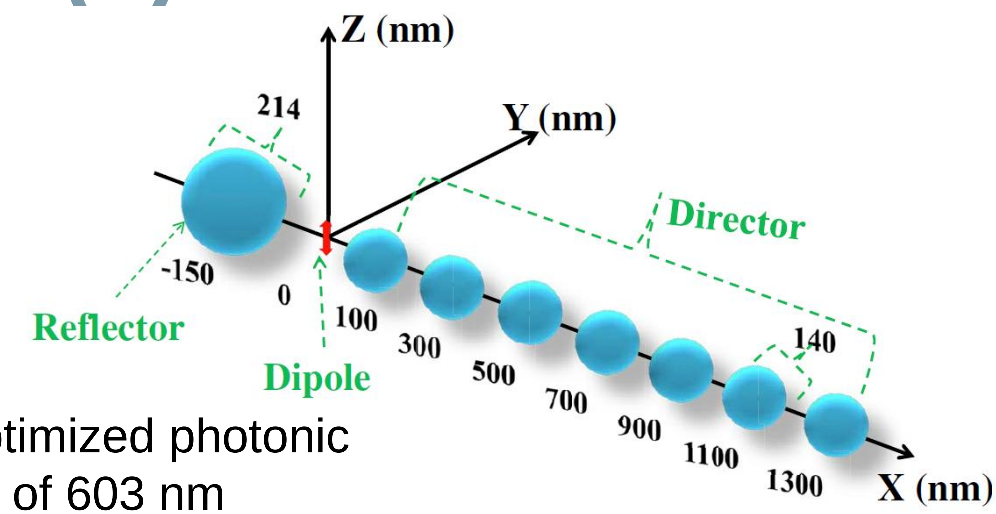


Fig. 1. The schematic design for an optimized photonic spherical NA at a selected wavelength of 603 nm

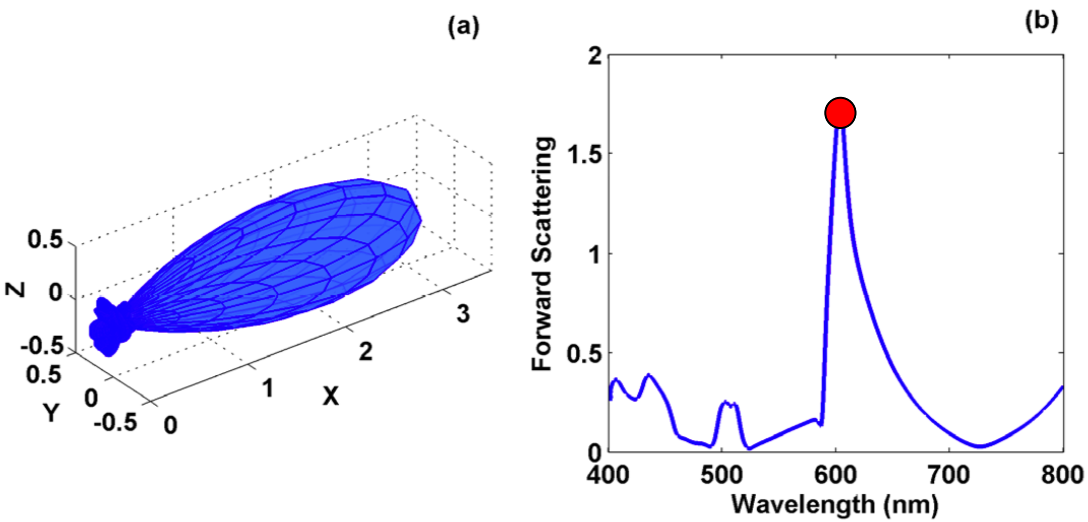


Fig. 2. (a) The radiation pattern of the optimized photonic NA at a selected wavelength of 603 nm; (b) The forward scattering intensity (along the *x* direction) of the photonic NA as a function of the wavelength.

Y.G. Liu, W.C.H. Choy, W.E.I. Sha, and W.C. Chew, Opt. Lett., 37(11), 2112-2114, 2012.

Theoretical results (2)

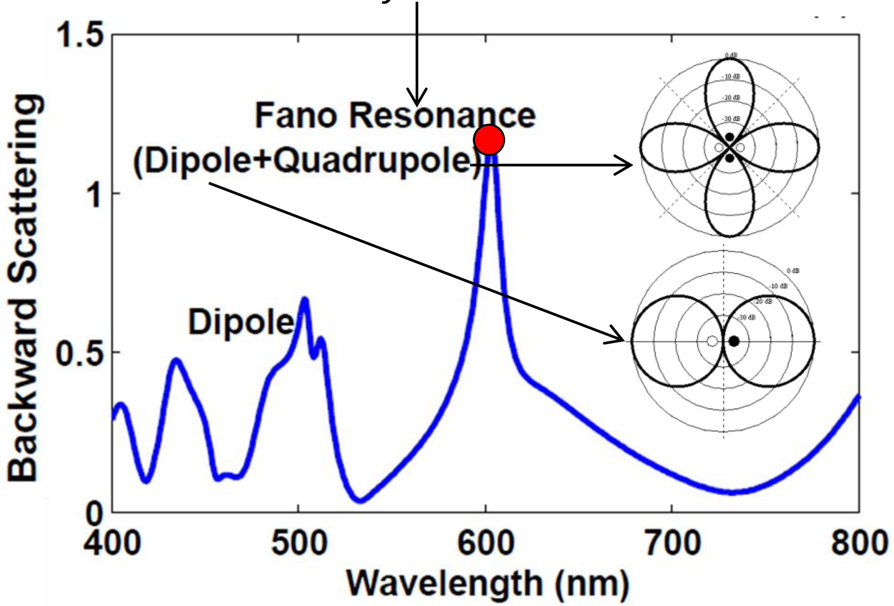


Fig. 3. The backward scattering intensity of a silicon nanosphere (with the radius of 107 nm) as a function of the wavelength

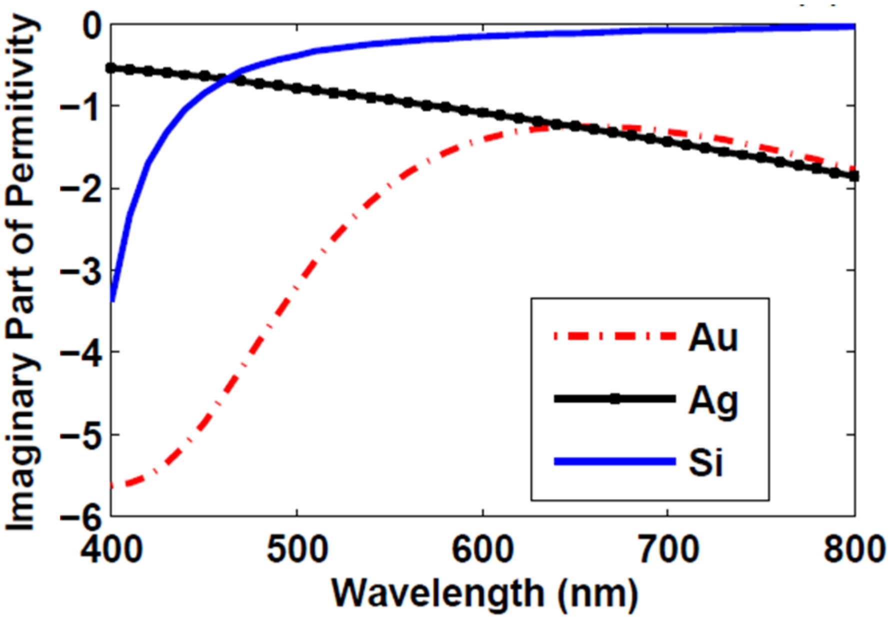


Fig. 4. The imaginary parts of the relative permittivities of the gold, silver, and silicon

narrow and sharp Fano-resonance is required to resolve and match the vibrational modes of the target molecule!

Theoretical results (3)

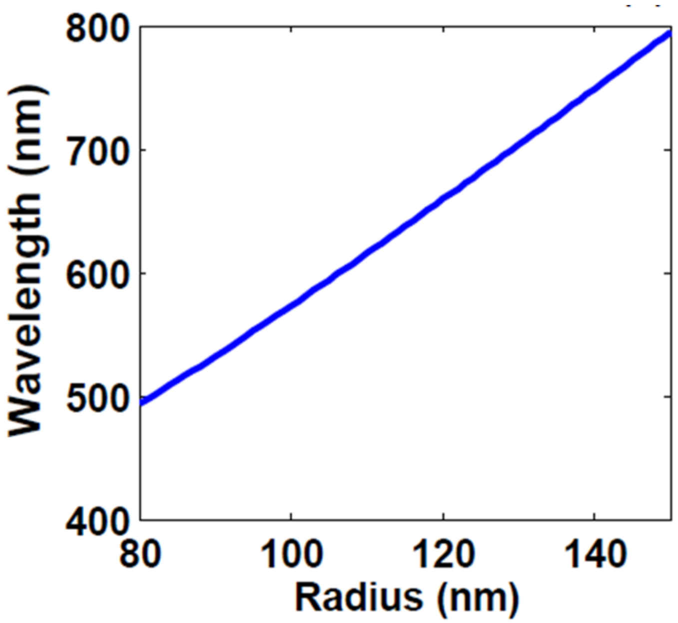


Fig. 5. The tunable Fano resonance by varying the sphere radius

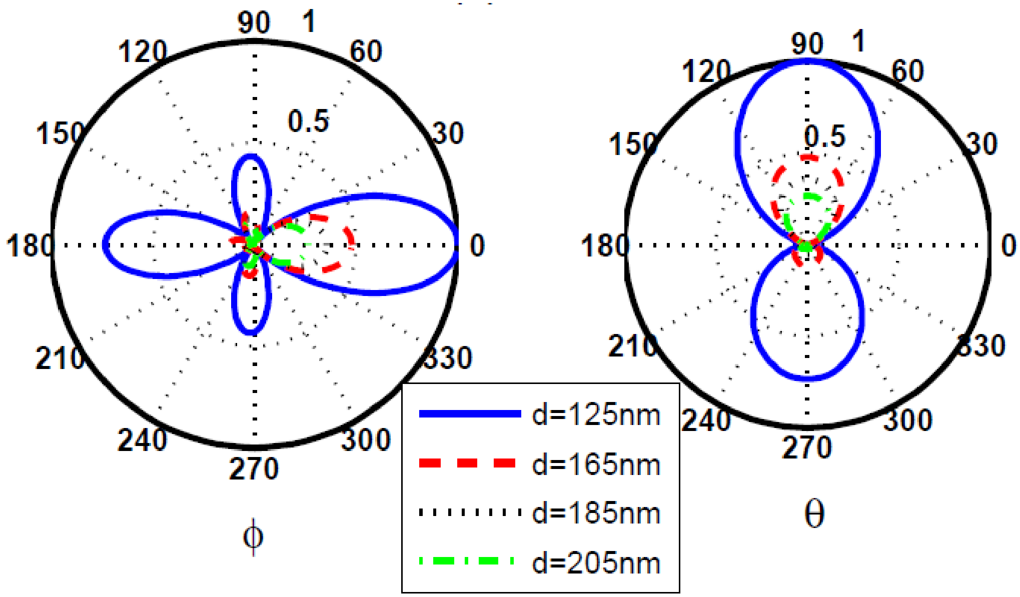


Fig. 6. The radiation patterns at the *xoy* plane after modifying the separation *d* between the dipole emitter and the center of the sphere; The radiation patterns at the *zox* plane.

Theoretical results (4)

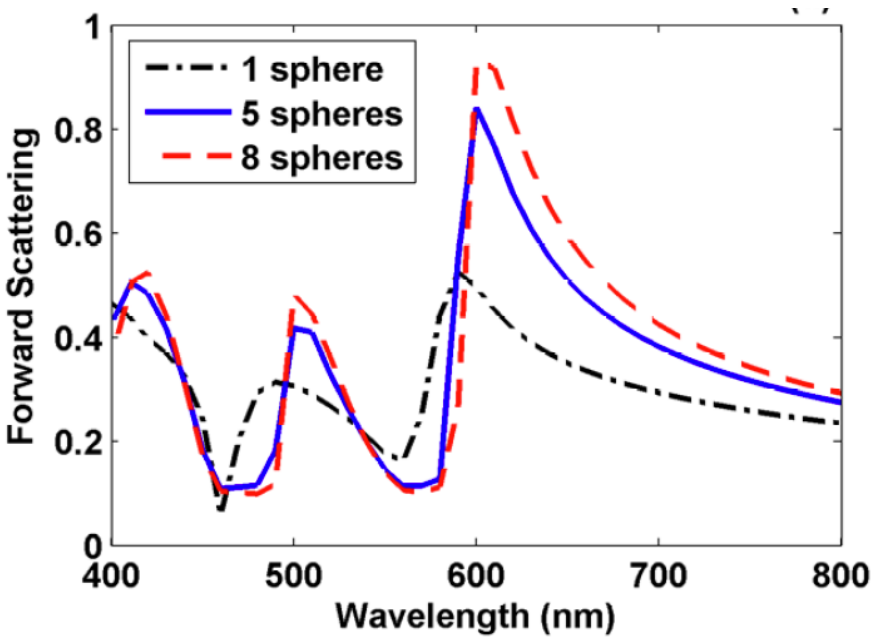


Fig. 7. The forward scattering intensity for three directors comprising 1, 5 and 8 silicon nanospheres, respectively. The radius of each sphere is 70 nm

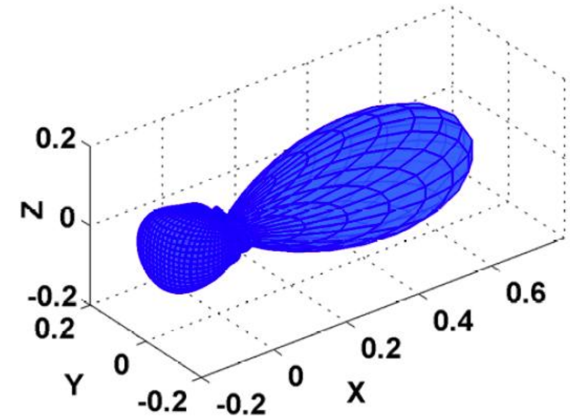


Fig. 8. The radiation pattern of the director working at the dipole resonance peak (603 nm)

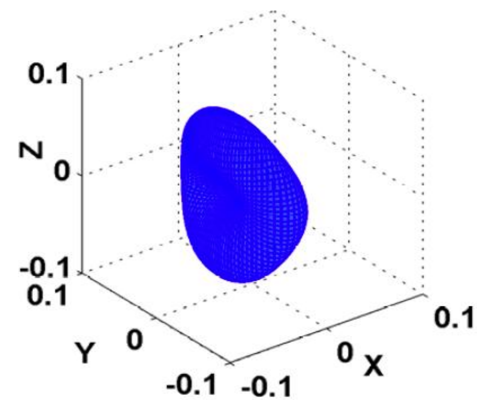


Fig. 9. The radiation pattern of the director at off-resonance (565 nm)

Theoretical results (5)

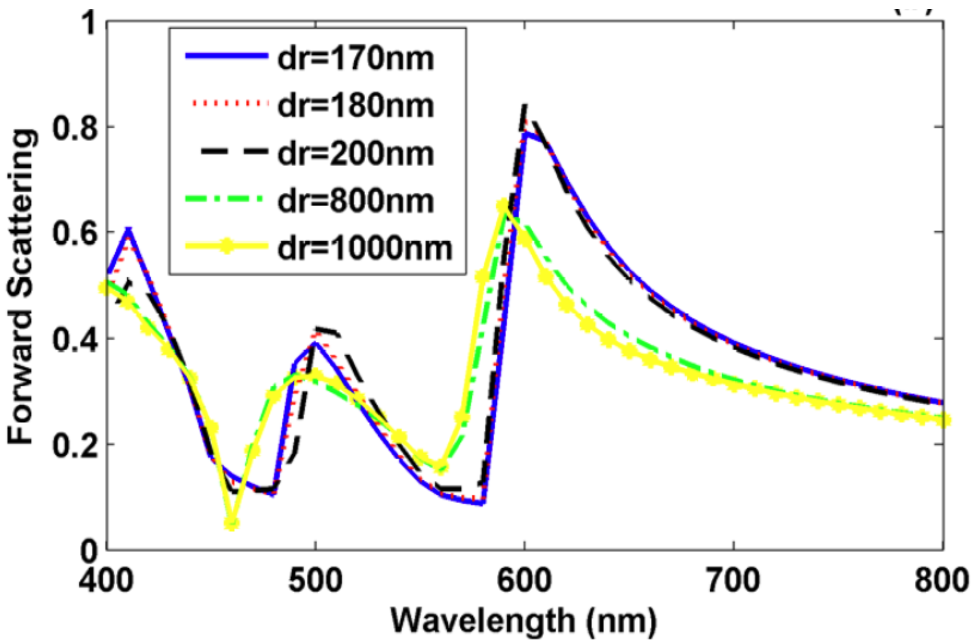


Fig. 10. The forward scattering intensity for the director (involving 5 silicon nanospheres) as a function of the periodicity of the sphere chain

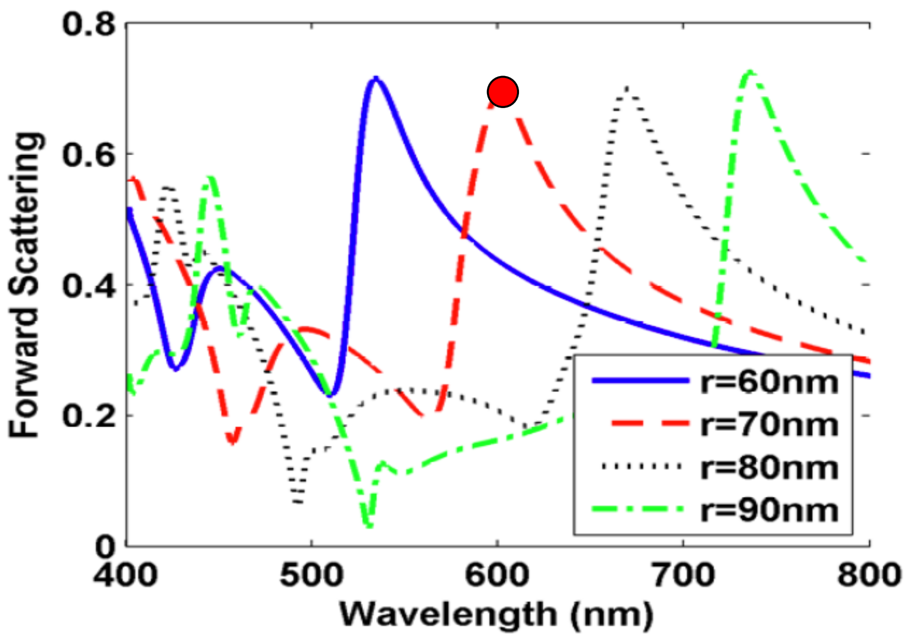


Fig. 11. The forward scattering intensity of the director as a function of the sphere radius

Summary

A. We design a directional and selective photonic NA composed of a single sphere reflector and a sphere chain director.

B. The high directionality originates both from the backward reflection by the Fano resonance and from the forward direction by the dipole resonance.

C. The seamless wavelength selectability is realized by matching the operating wavelength of the reflector with that of the director via tuning the geometrical configurations.

D. The smaller loss of photonic elements, compared with the metallic ones, can induce stronger directionality.

Thanks for your attention!