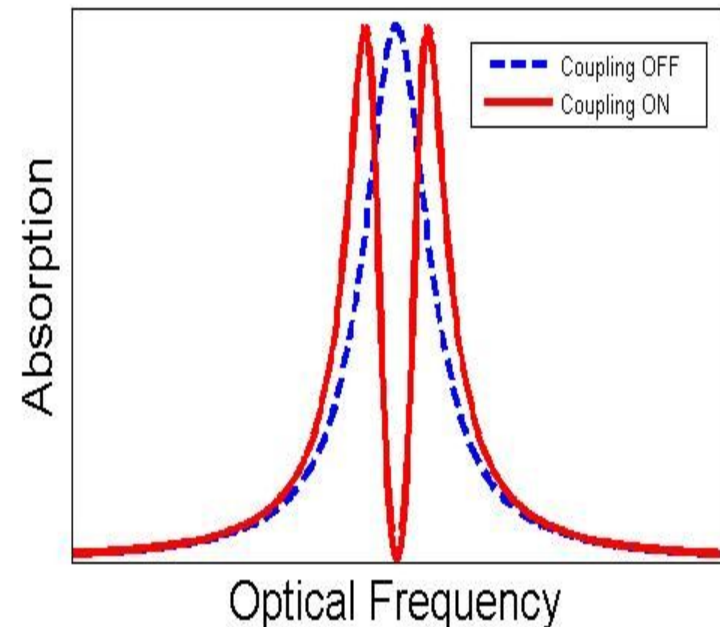
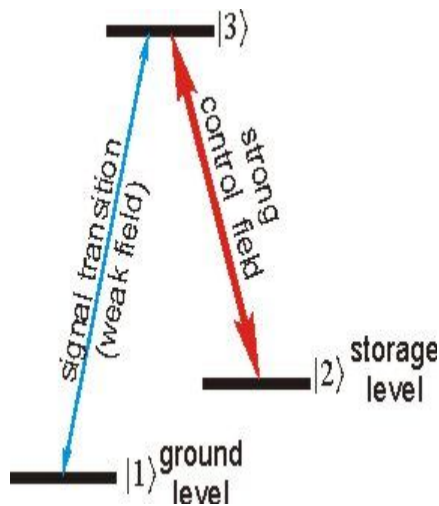


Some unusual subwavelength resonances and effects: EIT, Fano-resonance, Anapoles. Review

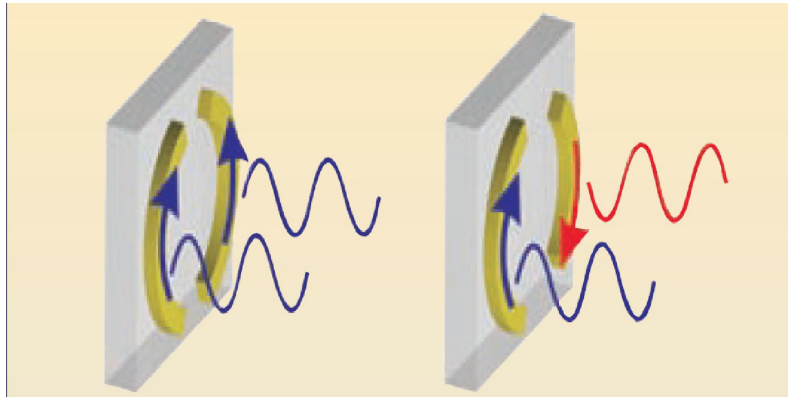
Electromagnetically Induced Transparency

Electromagnetically induced transparency - is a effect of a coherent optical nonlinearity which renders a medium transparent window over a narrow spectral range within an absorption line.

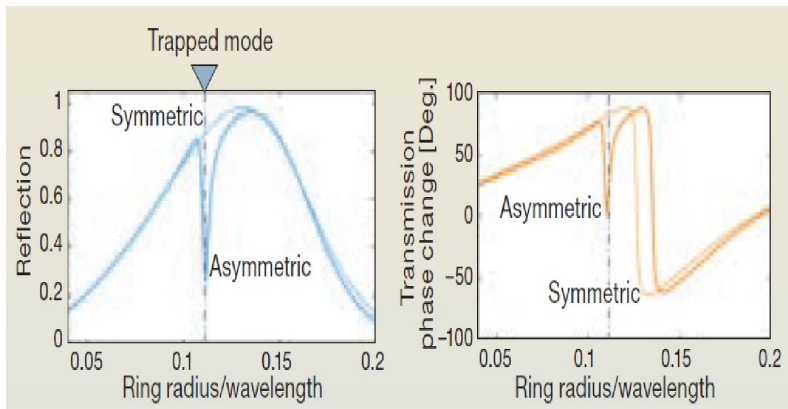


How to see EIT in metamaterials

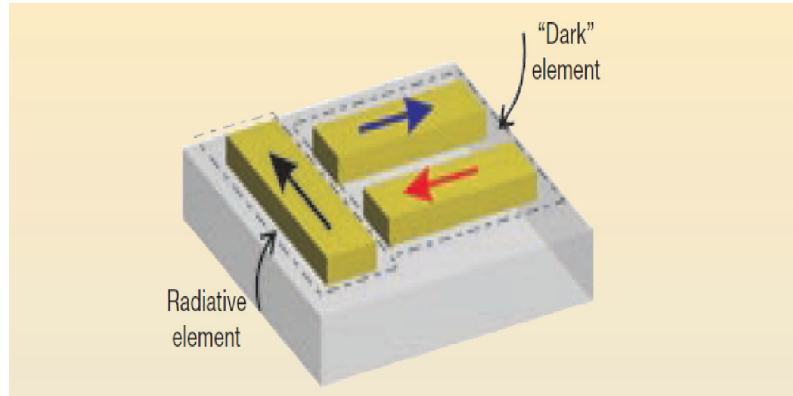
1. Split rings with asymmetry (Metamaterial Induced Transparency)



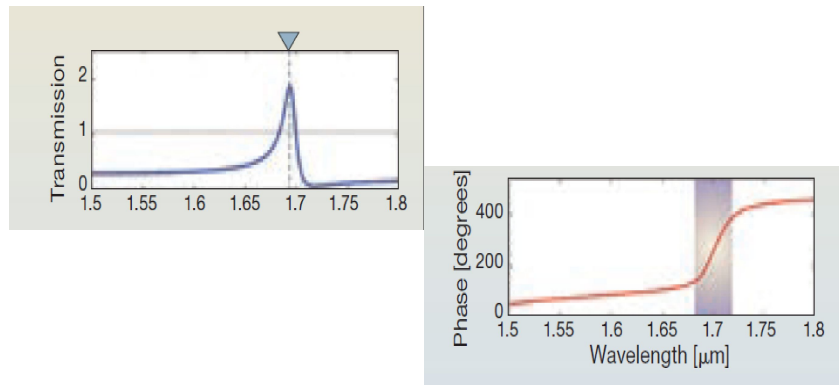
“Trapped mode” resonance



2. Plasmonic molecule with Fano-resonance (Plasmon Induced Transparency)



Bright/dark mode resonance



Metamaterial-Induced Transparency: Sharp Fano Resonances and Slow Light // Nikitas Papasimakis and Nikolay I. Zheludev // Optics and Photonics News Vol. 20, Issue 10, pp. 22-27 (2009),
Plasmon-Induced Transparency in Metamaterials // Shuang Zhang, Dentcho A. Genov, Yuan Wang, Ming Liu, and Xiang Zhang // PRL 101, 047401 (2008)
Sharp Trapped-Mode Resonances in Planar Metamaterials with a Broken Structural Symmetry // V. A. Fedotov, M. Rose, S. L. Prosvirnin, N. Papasimakis and N. I. Zheludev // PRL 99, 147401 (2007)

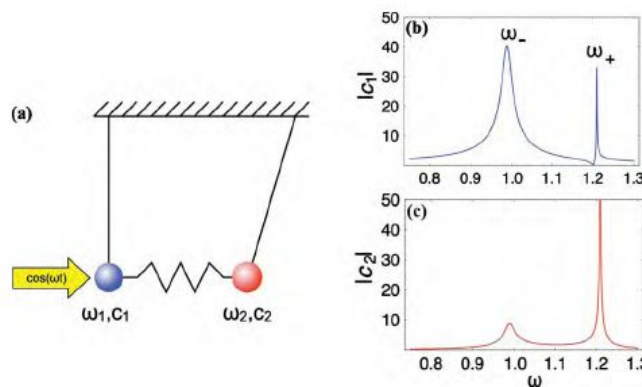
Fano- resonance



Fano resonance is a type of resonant scattering phenomenon that gives rise to an asymmetric line-shape. Interference between a background and a resonant scattering process produces the asymmetric line-shape.

$$I \propto \frac{(F\gamma + \omega - \omega_0)^2}{(\omega - \omega_0)^2 + \gamma^2}$$

$$Q_{\text{sca}} = \frac{2}{q^2} \sum_{\lambda=1}^{\infty} (2\lambda + 1) \left\{ |a_{\lambda}|^2 + |b_{\lambda}|^2 \right\}$$

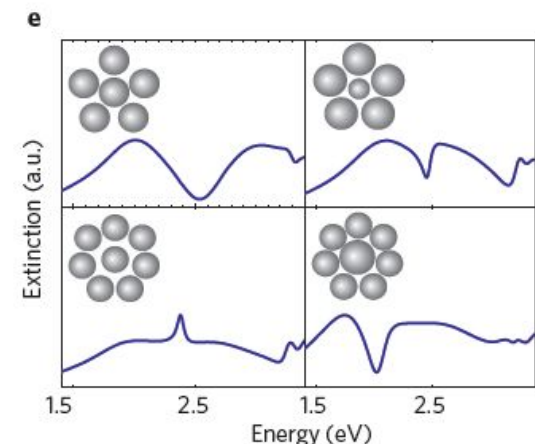


Fano- resonance

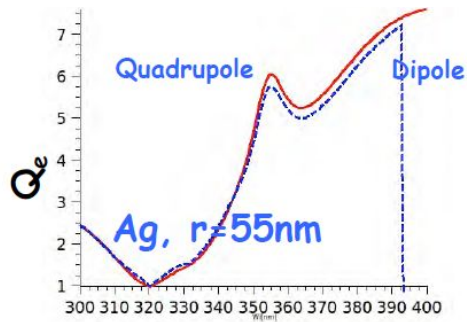


- The Fano resonance in metamaterials associated with mutual excitation of at least two scattering channels - modes occurring in the inclusions of metamaterials. This is possible due to the collective excitation of **dark mode**, which interferes with a resonances **bright mode**. As a result of such interference, it occurs **asymmetrical peak** of the transmission of electromagnetic waves through the layer of the metamaterial. Usually, **bright mode** has a strong connection with the incident plane wave. In contrast, **dark mode** weakly coupled with the incident plane wave and can not be directly excited it. Thus, in the vicinity of the resonance frequency, constructive and destructive interference between these modes are occurred, which manifests itself as acute asymmetrical peak Fano-resonance in the scattering metamolecules

$$Q_{\text{sca}} = \frac{2}{q^2} \sum_{\lambda=1}^{\infty} (2\lambda + 1) \left\{ |a_{\lambda}|^2 + |b_{\lambda}|^2 \right\}$$

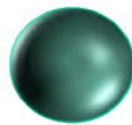


Fano- resonance in the metallic nano-sphere



BROAD mode (Lowest-order, E-Dipole)
DARK mode (Higher-order, EM Multipole)

$$Q_{sca} = \frac{2}{q^2} \sum_n (2n+1) \left[|a_n|^2 + |b_n|^2 \right]$$



Plasma frequency

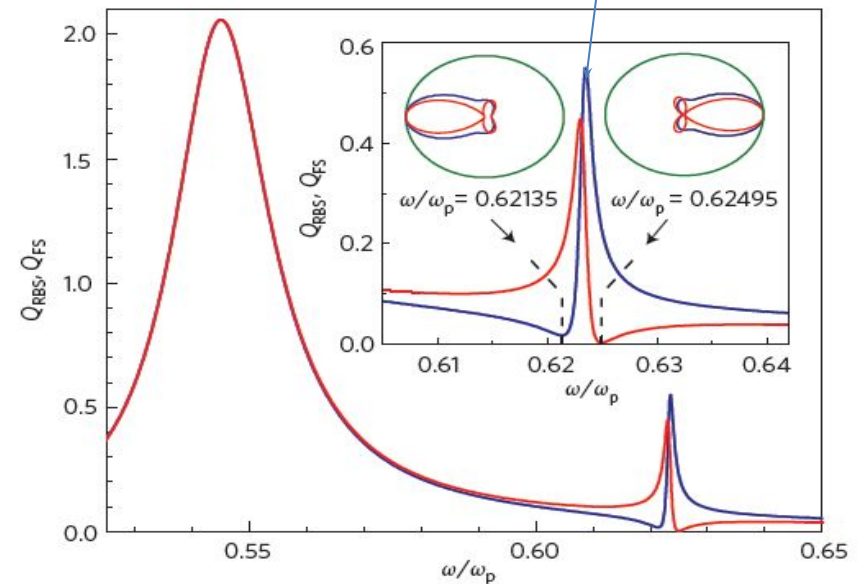


Figure 2 | Mie scattering against a solid metallic sphere. Radar back

Fano- resonance

- A narrow spectral line
- Frequency scanning
- High Q-factor
- Strong field localization
- Sensing

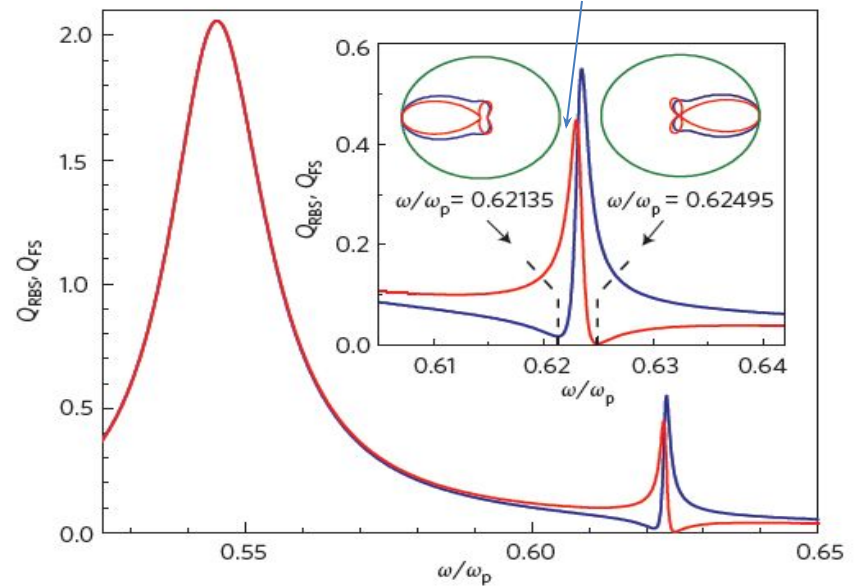
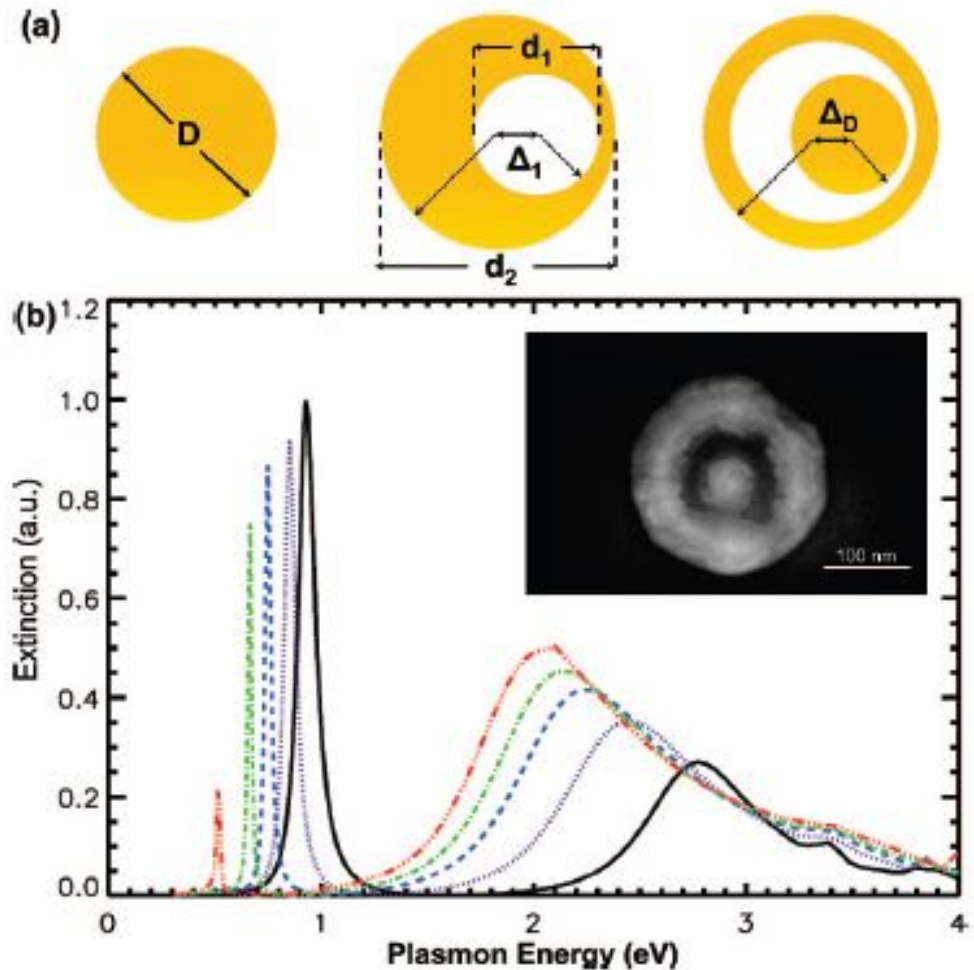
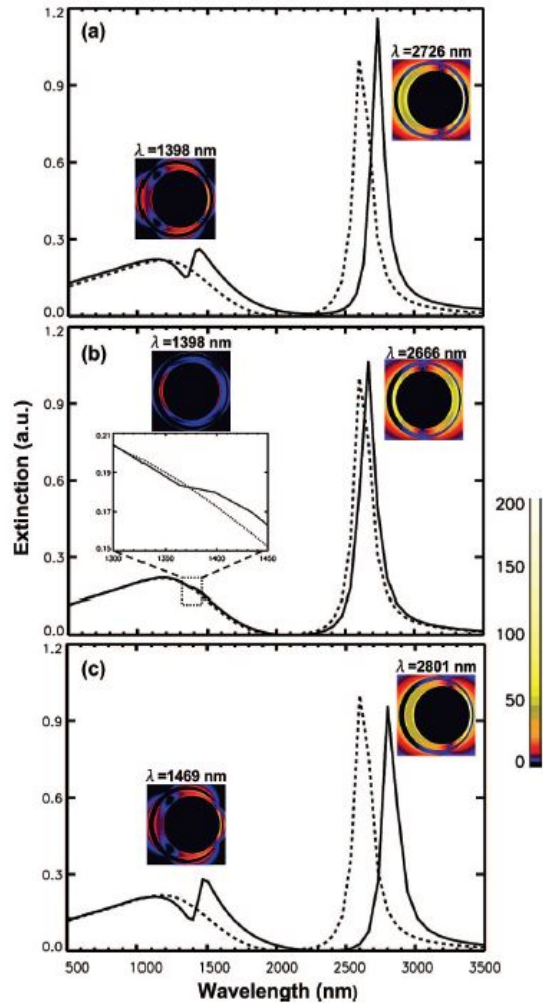


Figure 2 | Mie scattering against a solid metallic sphere. Radar back

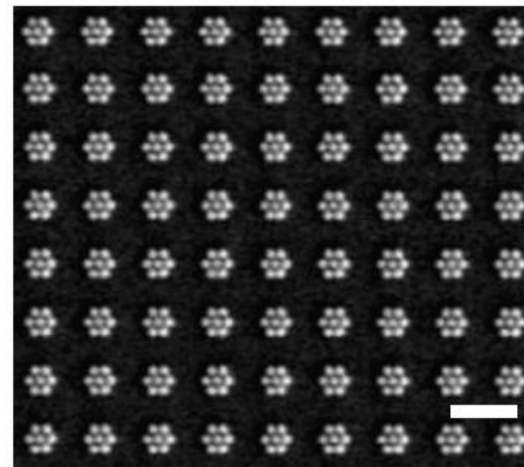
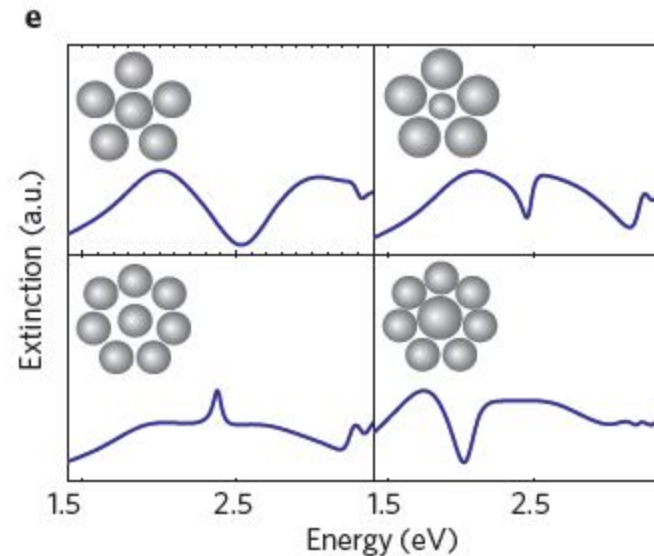
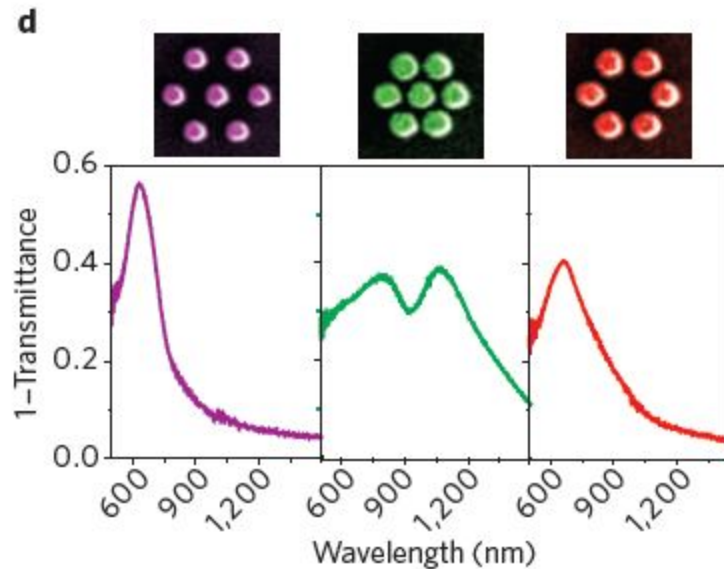
Fano- resonance. Other types of the particles.

System of the nano-disks



Fano- resonance. Other types of the particles.

Nano-clusters of Ag, Au



2. Vortex/whirlpool resonances in nano-particles

Vortex resonance- occurs in plasmonic particles and accompanied by **vortex** distribution of the Poynting vector close to the nano-particle and penetrated the fields inside particle. Strong retardation, absorption.

Vortex/whirlpool resonances in nano-sphere.

Extinction's coefficients

$$c_n^{TM} = - \frac{\epsilon j_n(ka)[(k_0a)j_n(k_0a)]' - \epsilon_0[(ka)j_n(ka)]'j_n(k_0a)}{\epsilon j_n(ka)[(k_0a)h_n(k_0a)]' - \epsilon_0[(ka)j_n(ka)]'h_n(k_0a)},$$

$$c_n^{TE} = - \frac{j_n(ka)[(k_0a)j_n(k_0a)]' - [(ka)j_n(ka)]'j_n(k_0a)}{j_n(ka)[(k_0a)h_n(k_0a)]' - [(ka)j_n(ka)]'h_n(k_0a)},$$

где $k = \omega \sqrt{\epsilon \mu_0}$
 $k_0 = \omega \sqrt{\epsilon_0 \mu_0}$

The strong field conditions:

$c \ll 1$ - weak scattering, strong concentration of the field inside particle

Vortex/whirlpool resonances in nano-sphere.

Extinction's coefficients

The strong field localization conditions

$$\epsilon j_n(ka)[(k_0a)y_n(k_0a)]' = \epsilon_0[(ka)j_n(ka)]'y_n(k_0a) \quad (\text{TM}),$$

$$j_n(ka)[(k_0a)y_n(k_0a)]' = [(ka)j_n(ka)]'y_n(k_0a) \quad (\text{TE}),$$

Y- Neiman function

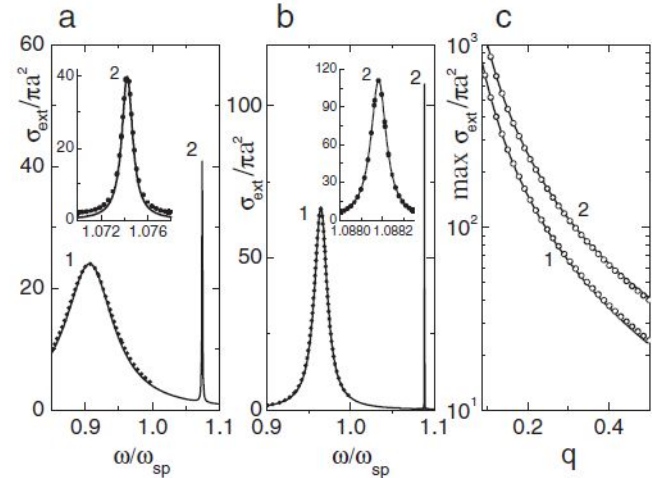
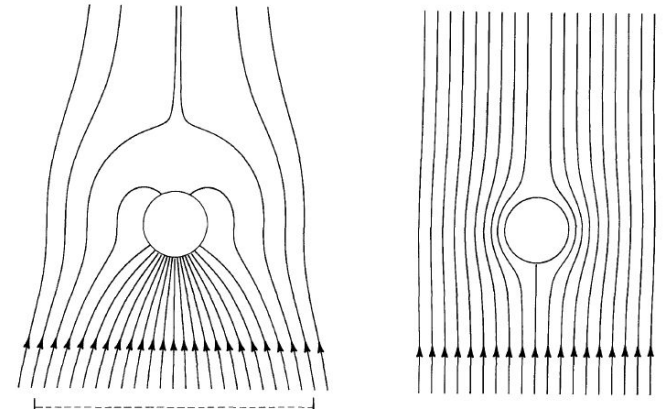
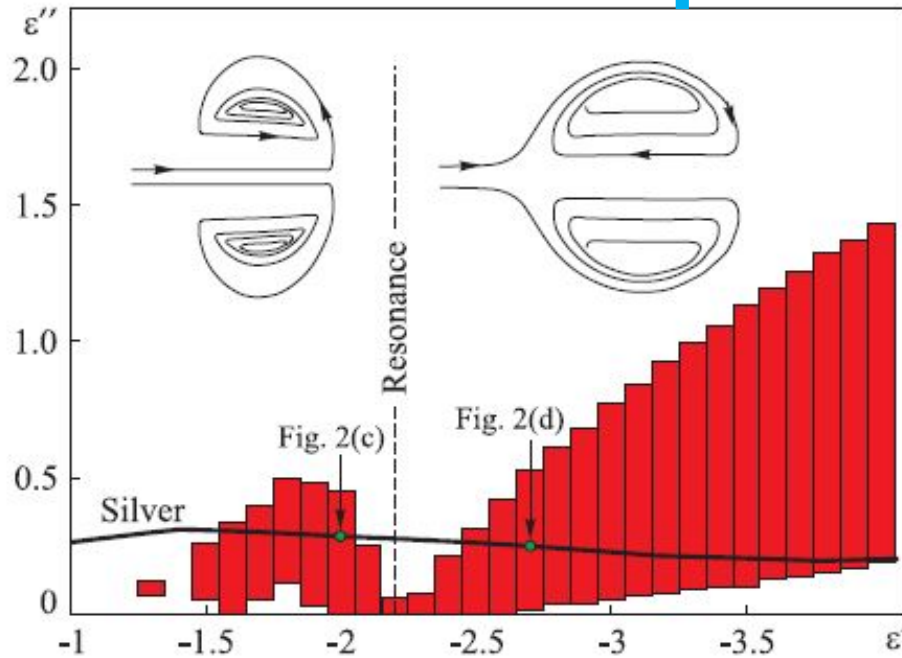
$$\text{Im}[\epsilon/\epsilon_0] \ll (k_0a)^{2n+1} \frac{n+1}{n^2[(2n-1)!!]^2}.$$

How can a particle absorb more than the light incident on it?

Craig F. Bohren

Department of Meteorology, Pennsylvania State University, University Park, Pennsylvania 16802

Perfect absorption



Vortex/whirlpool resonances in nano-sphere.

Examples. Poynting Vector

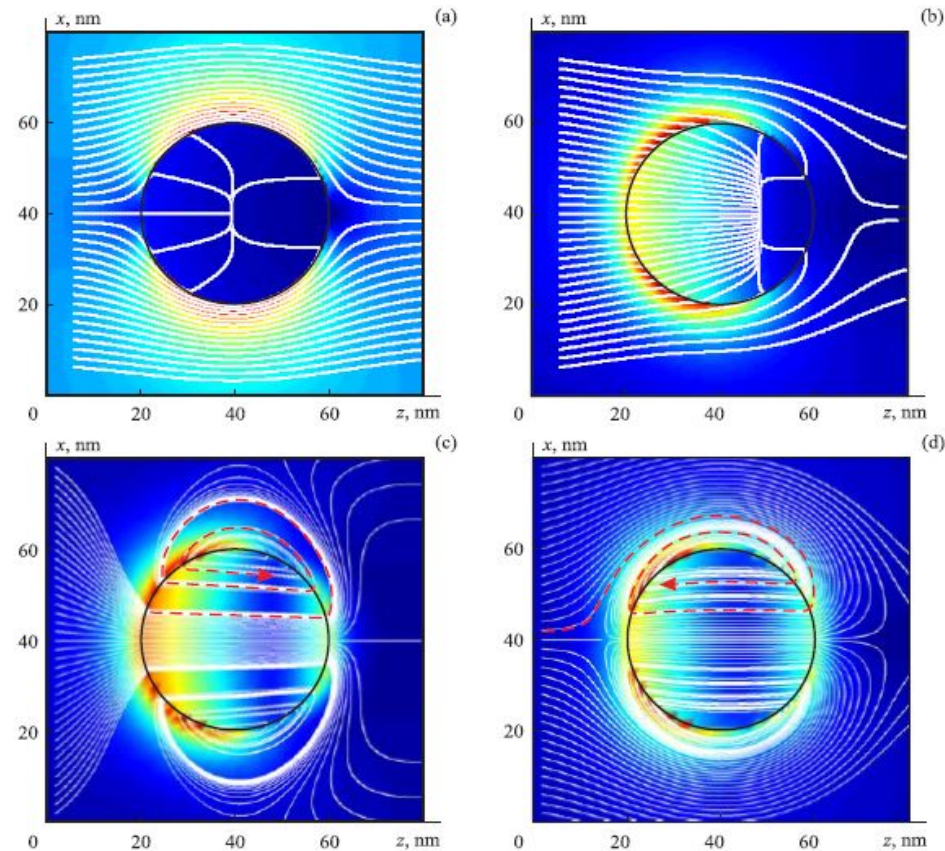
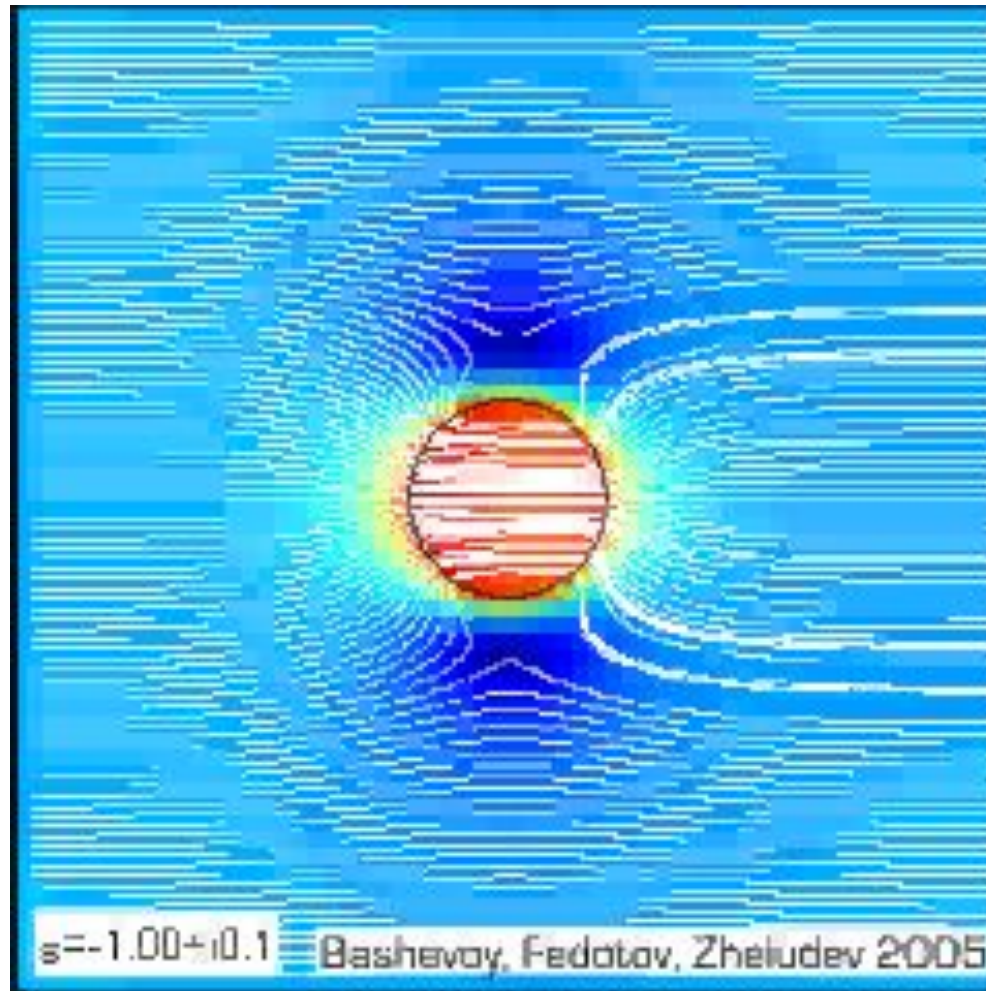


Fig. 2. [Movie 2.5 MB, 10.5 MB version] Mie Theory: powerflow distribution around a spherical nanoparticle with a radius of approximately 20 nm ($\lambda/r = 20$) in the plane containing the directions of propagation (from left to right) and polarization of the incident light. The colors indicate the absolute value of the Poynting vector, the white lines show the direction of powerflow. (a) $\epsilon = -2.0 + i10.0$, $\lambda = 400$ nm; (b) $\epsilon = -2.0 + i1.0$, $\lambda = 400$ nm; (c) $\epsilon = -2.0 + i0.28$ — the dielectric coefficient of silver at $\lambda = 354$ nm. Red dashed lines indicate outward vortex structure; (d) $\epsilon = -2.71 + i0.25$ — the dielectric coefficient of silver at $\lambda = 367$ nm. Red dashed lines indicate inward vortex structure [15].

Vortex/whirlpool resonances in nano-sphere.

Examples. Poynting Vector



Vortex/whirlpool resonances. Example of nano- ellipsoid . Poynting Vector

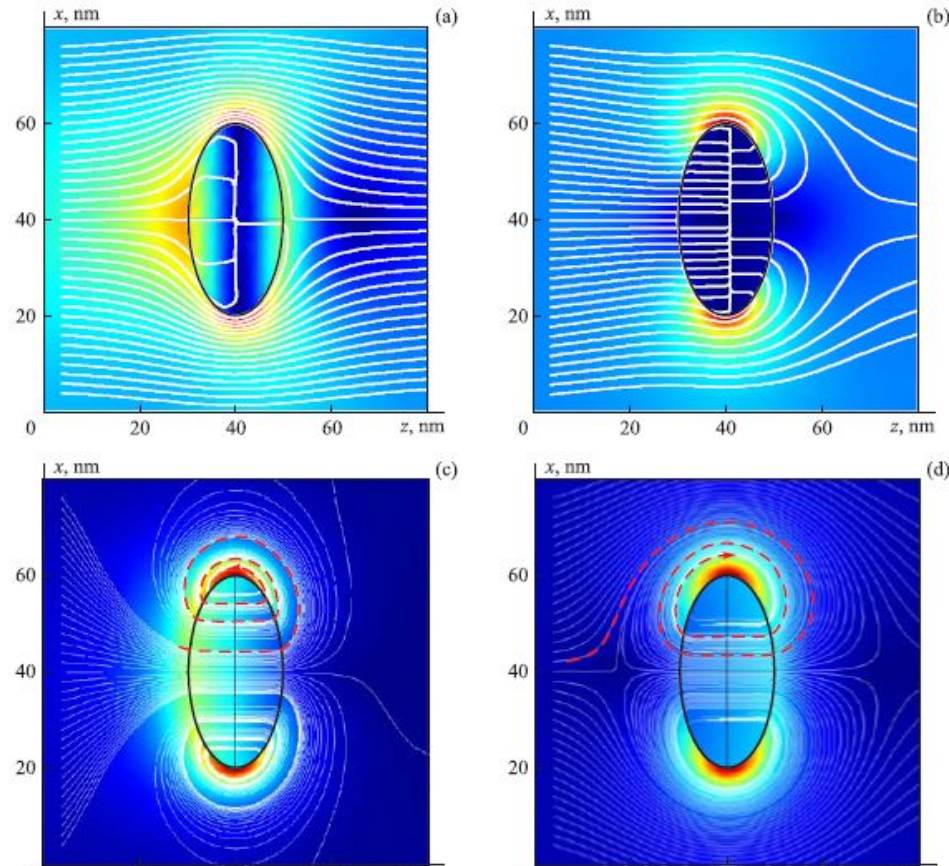


Fig. 3. 3D finite element modelling: powerflow distribution around an oblate spheroidal nanoparticle (with a semi-major axial radius of approximately 20 nm ($\lambda/r = 20$) and an aspect ratio of 2) in the plane containing the directions of propagation (from left to right) and polarization of the incident light. The colors indicate the absolute value of the Poynting vector, the white lines show the direction of powerflow. (a) $\epsilon = -3.52 + i10.0$, $\lambda = 400$ nm; (b) $\epsilon = -3.52 + i1.0$, $\lambda = 400$ nm; (c) $\epsilon = -3.37 + i0.2$ — the dielectric coefficient of silver at $\lambda = 380$ nm. Red dashed lines indicate outward vortex structure; (d) $\epsilon = -4.0 + i0.2$ — the dielectric coefficient of silver at $\lambda = 392$ nm. Red dashed lines indicate inward vortex structure [15].

Vortex/whirlpool resonances. Example of Yin and yang Symbol

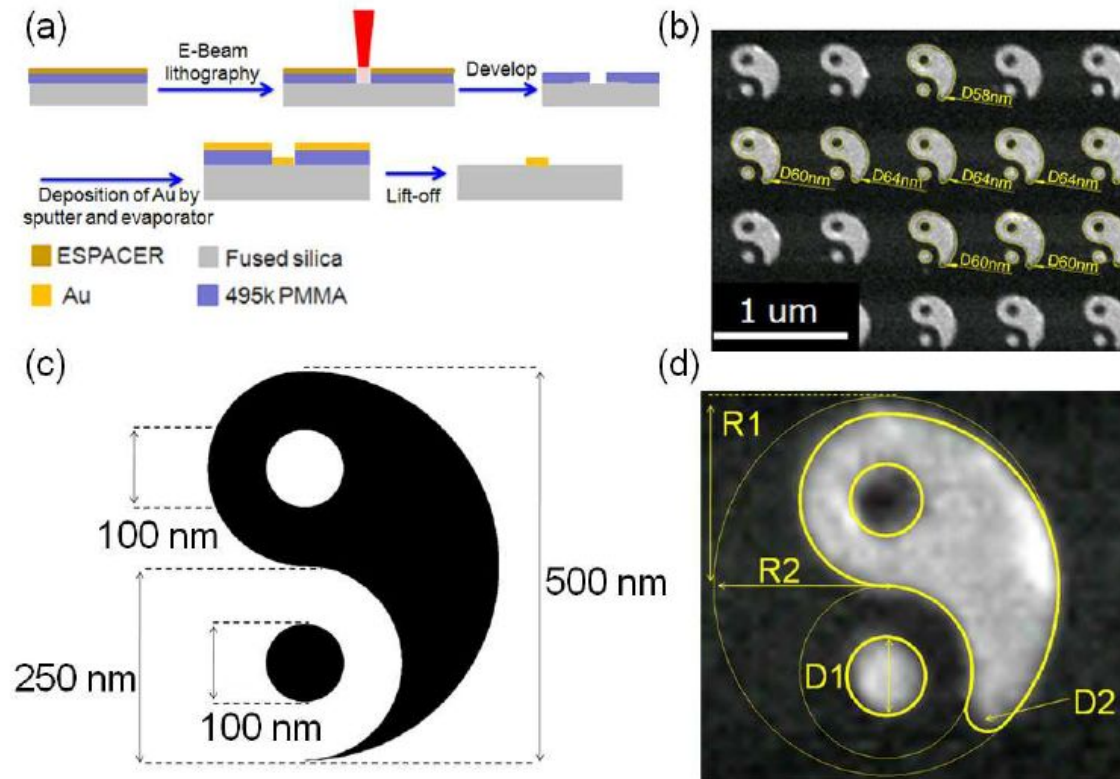
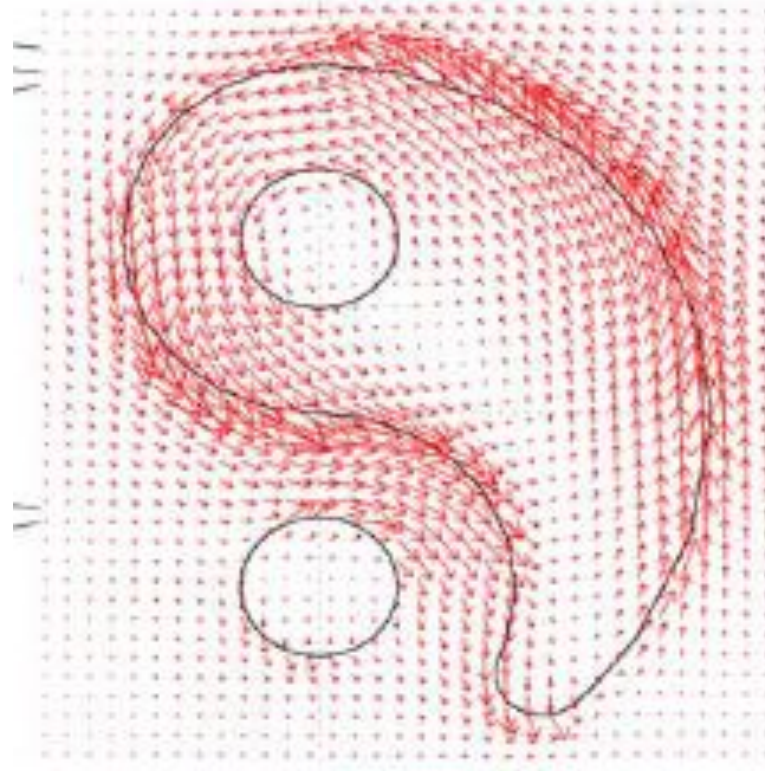
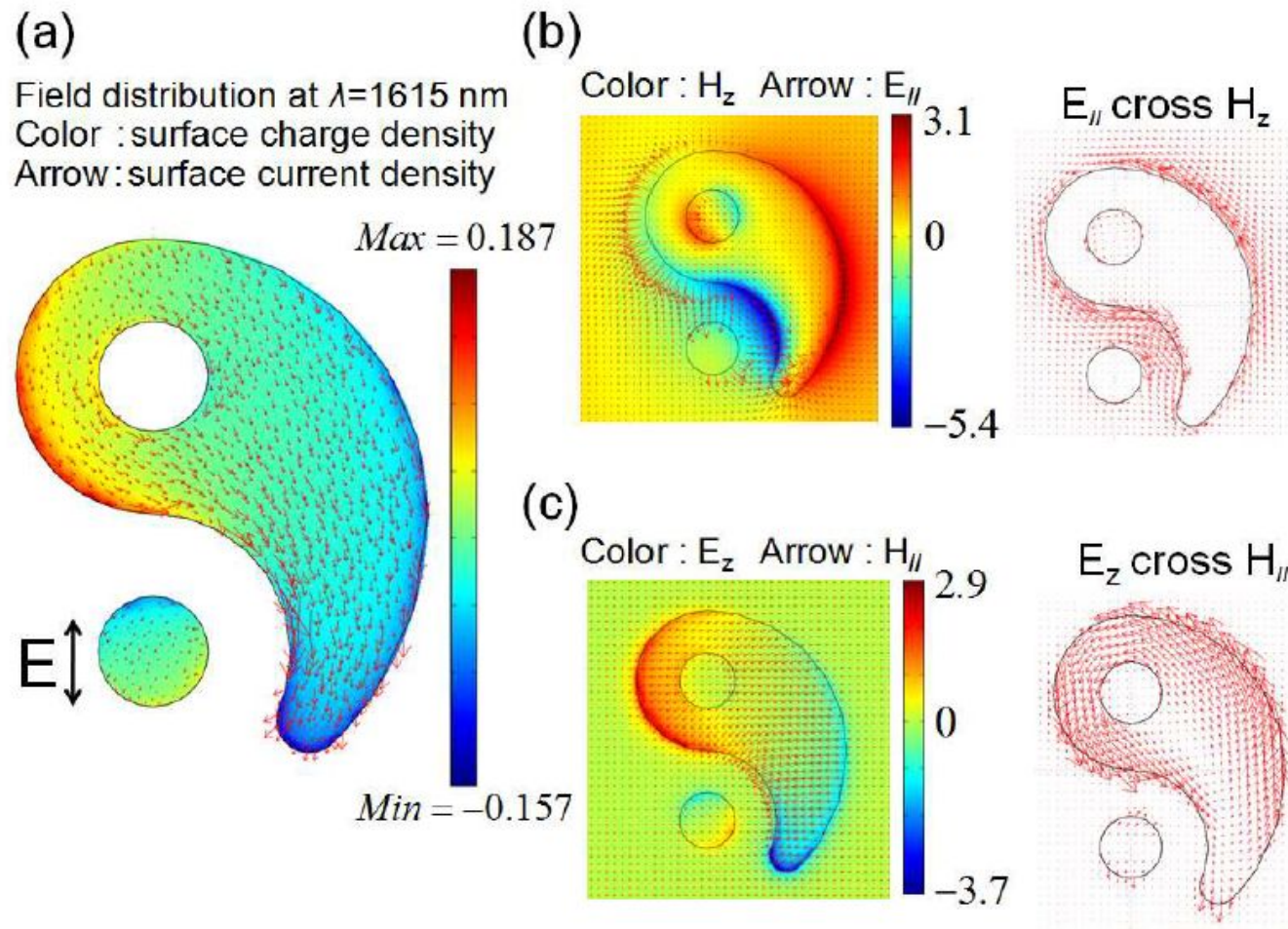


Fig. 1. (a) Schematic diagram showing the process of e-beam lithography. Our samples were fabricated without any adhesion layer (such as Ti or Cr) between the gold film and the glass substrate. A 3 nm film of gold was sputter-deposited on the developed resist layer, followed by the thermal evaporation of another 27 nm of gold. (b) SEM image of a small region from the fabricated sample, showing diameter of tails. (c) The ideal Taiji mark designed for the studies reported in this paper. (d) Magnified view of a single cell in the SEM image of frame (b), showing the fitting curves of a fabricated Taiji mark ($R_1 = 275$ nm, $R_2 = 250$ nm, $D_1 = 100$ nm, diameter of the tangent circle $D_2 = 60$ nm).

Vortex/whirlpool resonances. Example of Yin and Yang Symbol. Vector Poynting

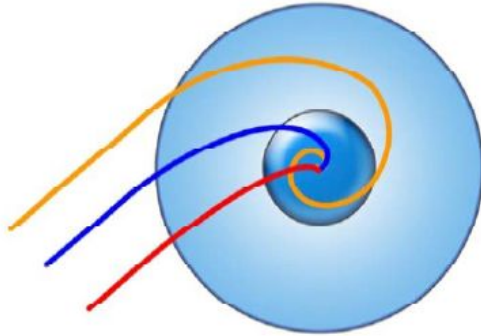


Vortex/whirlpool resonances. Example of Yin and yang Symbol. Fields distributions

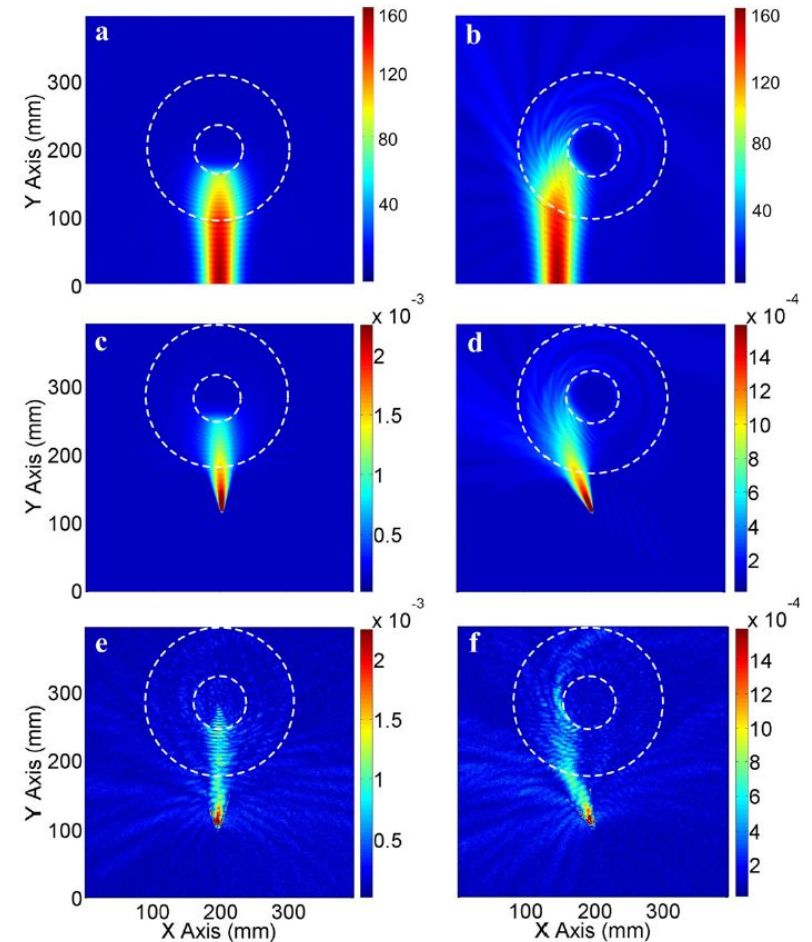


Vortex/whirlpool resonances. Example of a model of a Black hole. Vector Poynting

a



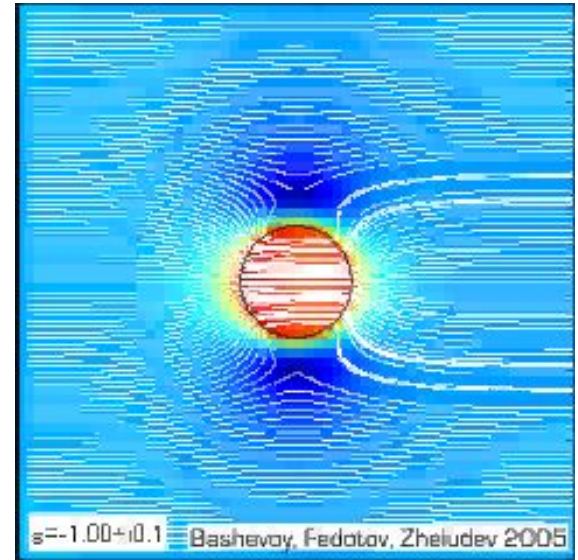
b



Vortex/whirlpool resonances

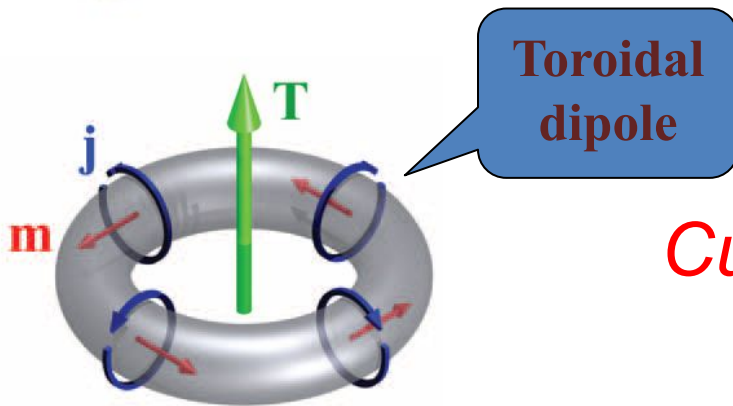
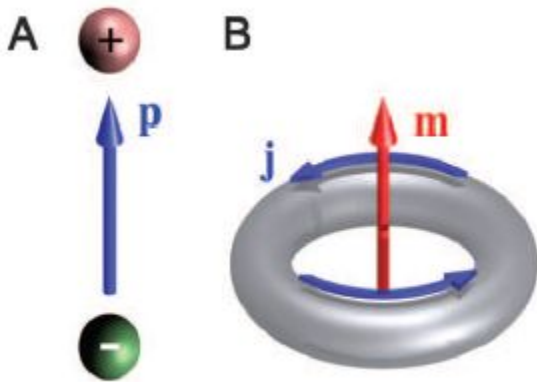
Applications:

- Strong field localization
- As element of delay line
- High Q-factor resonator
- Element of the nano-antennas?



3. Toroidal Dipole in Metamaterials

What is toroidal dipole



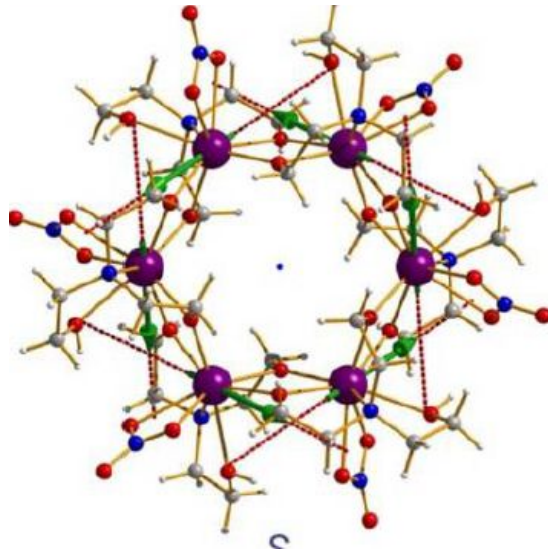
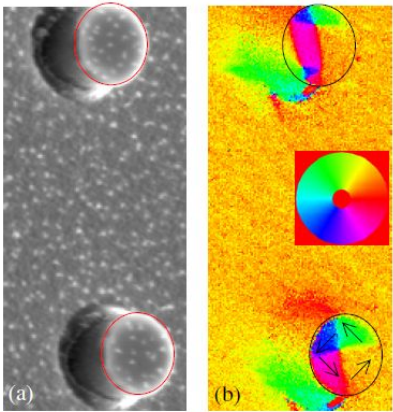
Curl $\mathbf{B}$

Unusual electromagnetic phenomena

- **Extremely High Q-factor**
- **Optical activity & circular dichroism**
- **Negative refraction and backward waves**
- **Generation of waves with gauge irreducible vector potentials with no EM fields**
- **Aharonov-Bohm Effect**
- **The Radiation pattern of $\mathbf{P}=\mathbf{T}$**
- **Quantum Effects in metamaterials due to manipulation with Vector Potentials**

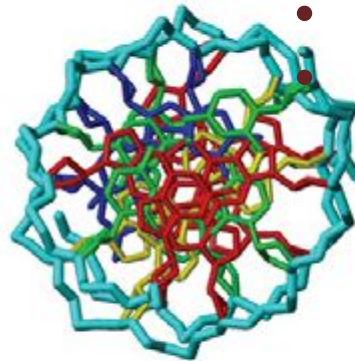
T. Kaelberer *et al*, *Science* 330, 1510 (2010)
B. Zel'dovich, *Sov. Phys. JETP*, 6,1184 (1958)

Toroidal dipole in nature

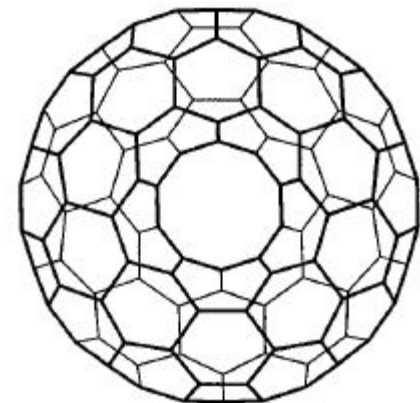


Why toroidal dipole?

- Correct characterization of toroidal objects
- Interaction with electromagnetic fields
- Sensitive sensors of toroidal objects
- Fundamental interest
- Quantum effects like Aharonom-Bohm effect

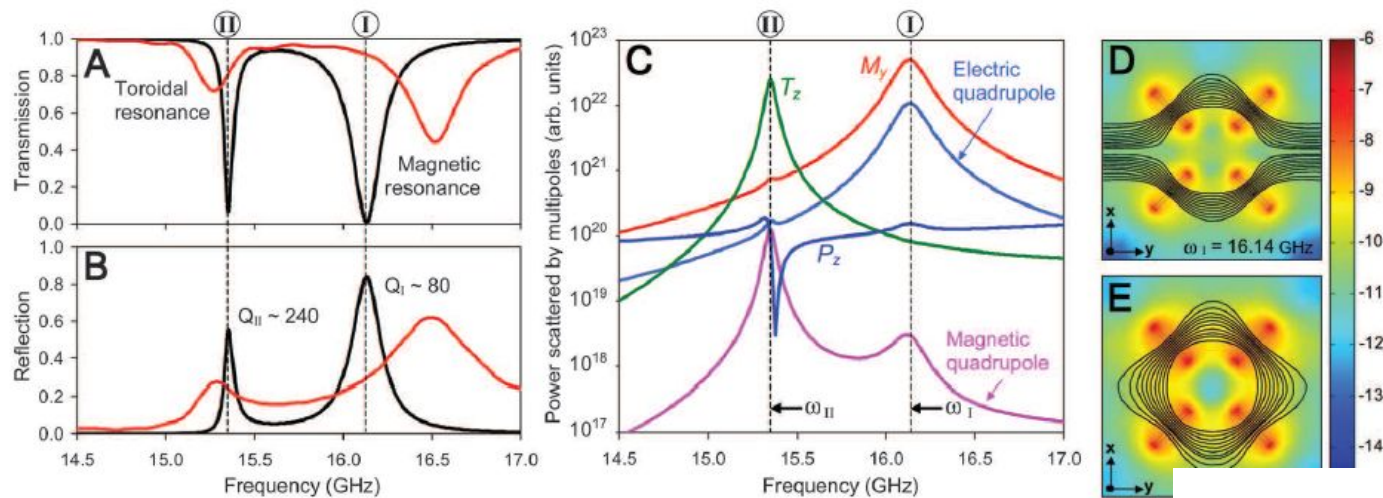
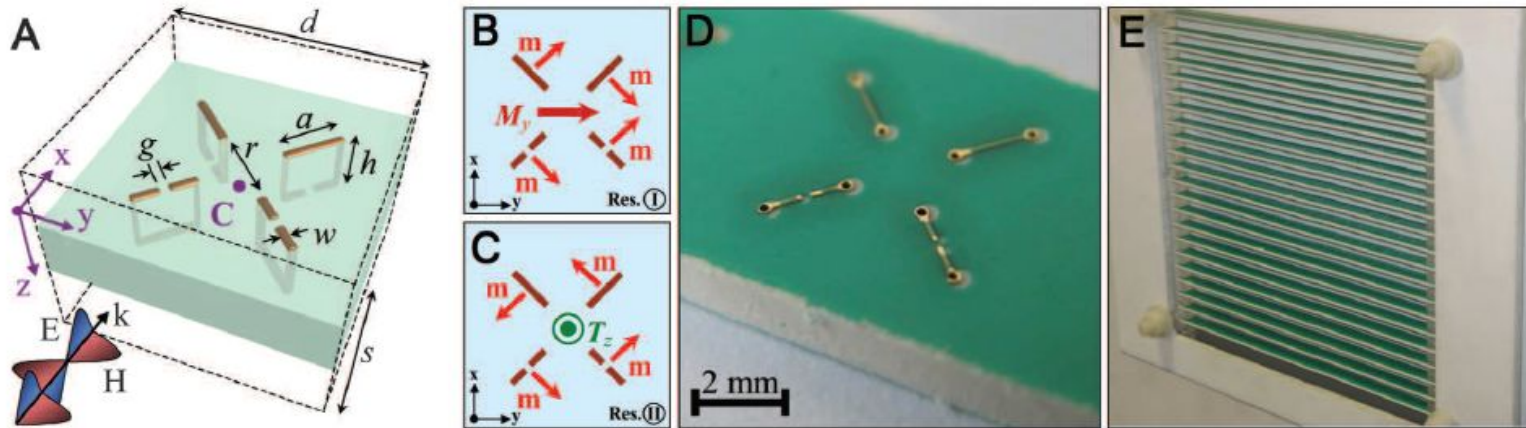


B-DNA



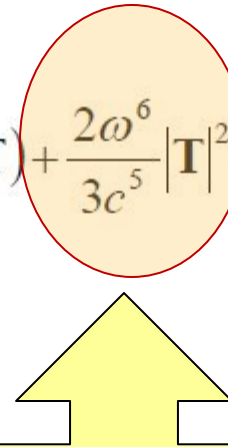
Y. B. Zel'dovich, 1958
Naumov I, et al., 2004
M. Kläui et al., 2003
Y. F. Popov et al., 1998
Y. V. Kopaev et al., 2009
L. Ungur et al., 2012
A. Ceulemans et al., 1998
A. Karsisiotis et al., 2013

First demonstration of toroidal response by metamaterials



Toroidal response in multipoles expansion. Radiating power of multipoles.

$$I = \frac{2\omega^4}{3c^3} |\mathbf{P}|^2 + \frac{2\omega^4}{3c^3} |\mathbf{M}|^2 + \frac{4\omega^5}{3c^4} (\mathbf{P} \cdot \mathbf{T}) + \frac{2\omega^6}{3c^5} |\mathbf{T}|^2 + \frac{\omega^6}{5c^5} Q_{\alpha\beta} Q_{\alpha\beta} + \frac{\omega^6}{20c^5} M_{\alpha\beta} M_{\alpha\beta} + \frac{2\omega^6}{15c^5} (\mathbf{M} \cdot \langle \mathbf{R}_M^2 \rangle) + o\left(\frac{1}{c^5}\right)$$



We need to consider this term in order to correctly describe the characteristics of toroidal objects.

P- Electric

M- Magnetic

T- toroidal

Q- Electric

M – Magnetic quadrupole moment

j- current density

T. Kaelberer *et al*, *Science* (2010)

E. E. Radescu and G. Vaman, *PRE* (2002)

$$\mathbf{P} = \frac{1}{i\omega} \int \mathbf{j} d^3r$$

$$\mathbf{j}) d^3r$$

$$\mathbf{j}) \mathbf{r} - 2r^2 \mathbf{j}] d^3r$$

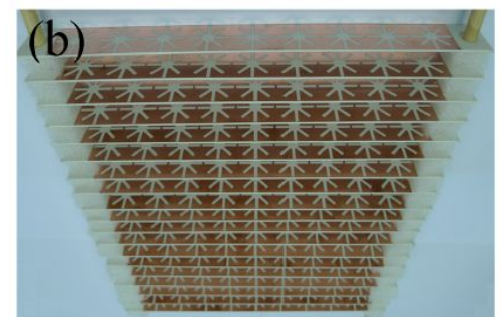
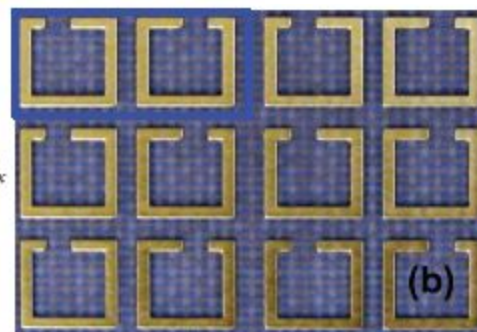
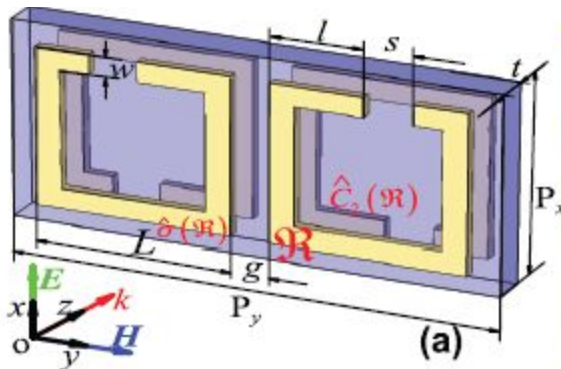
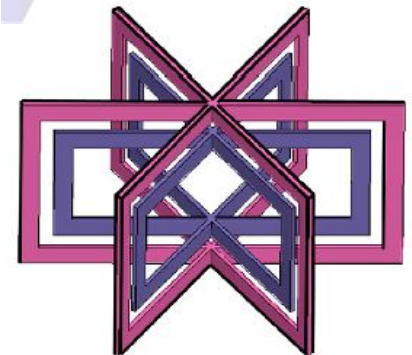
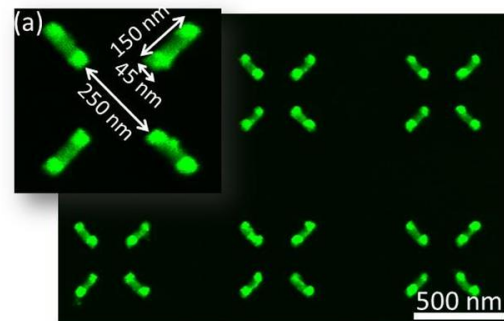
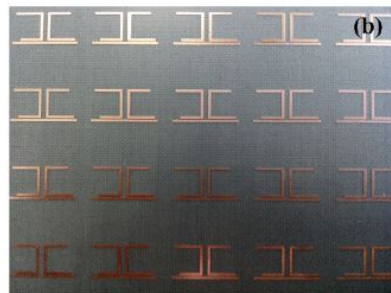
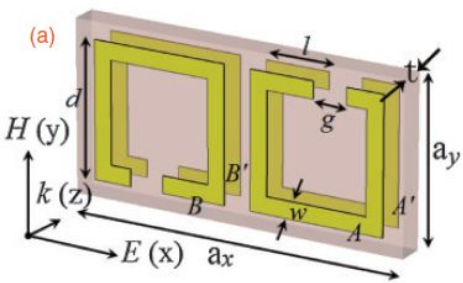
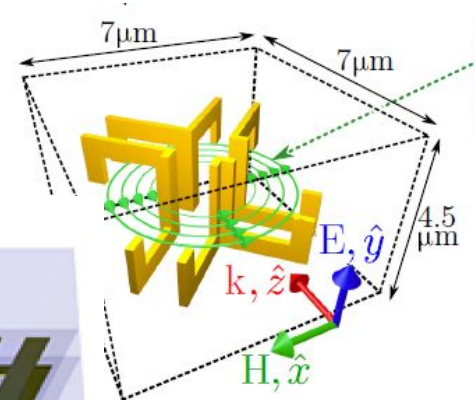
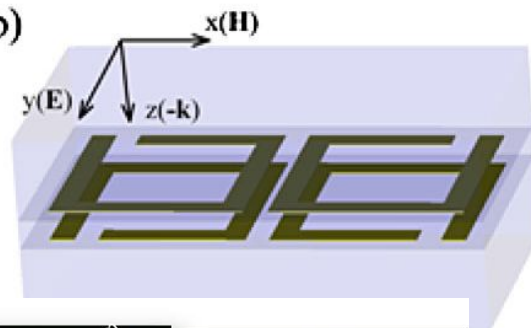
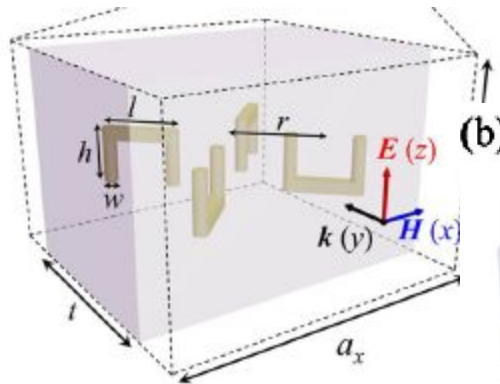
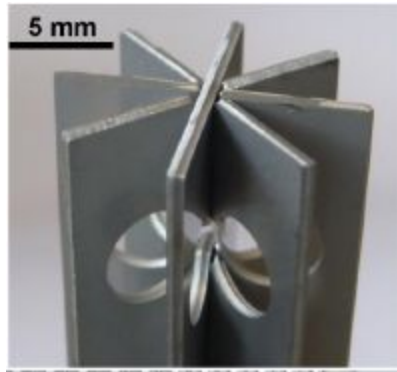
$$10c^5 \mathbf{j} \cdot \mathbf{r}$$

$$Q_{\alpha\beta} = \frac{1}{i\omega} \int \left[r_\alpha j_\beta + r_\beta j_\alpha - \frac{2}{3} (\mathbf{r} \cdot \mathbf{j}) \right] d^3r$$

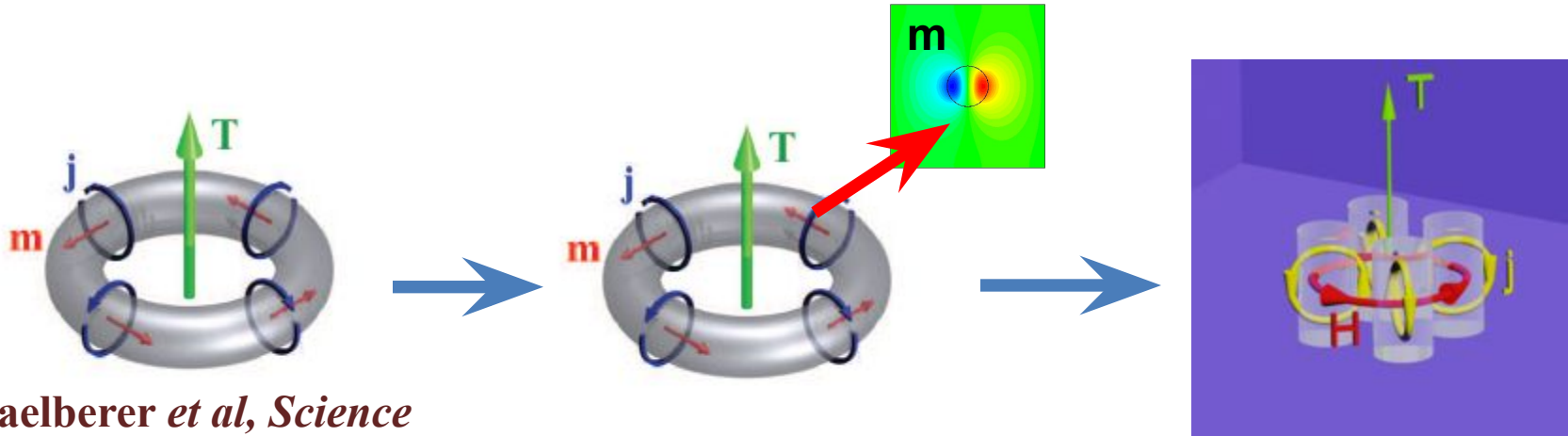
$$M_{\alpha\beta} = \frac{1}{3c} \int [(\mathbf{r} \times \mathbf{j})_\alpha r_\beta + (\mathbf{r} \times \mathbf{j})_\beta r_\alpha] d^3r$$

Family of the toroidal metamolecules.

Complicated design?

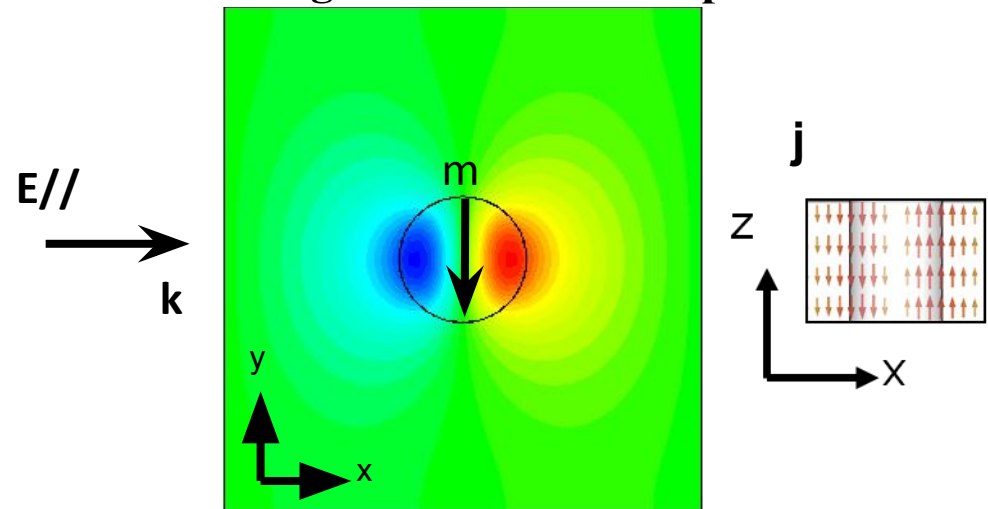


2. Toroidal response in dielectric metamaterials- without Joule losses



T. Kaelberer *et al*, *Science*
330, 1510 (2010)

Magnetic moments due to Mie- resonance
in high-index dielectric particles



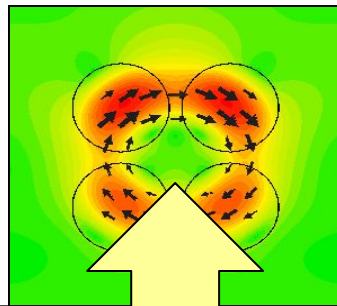
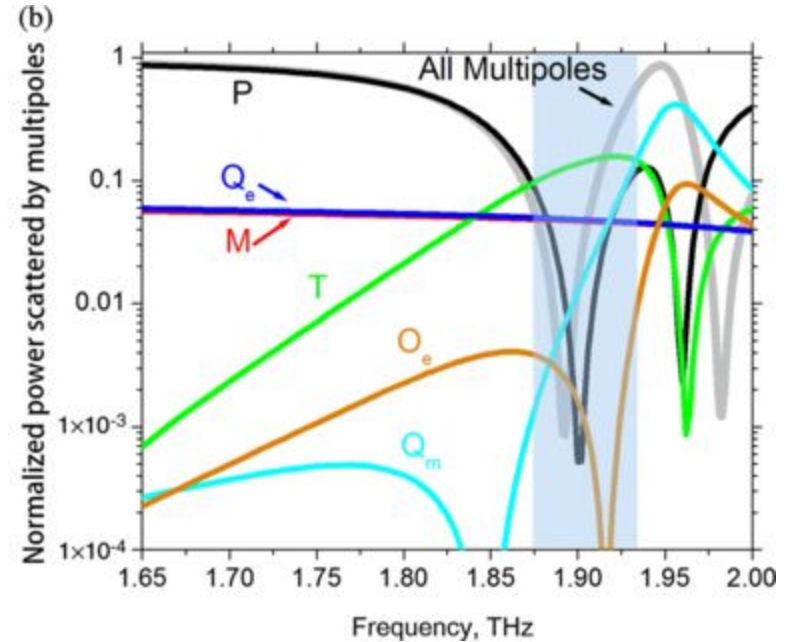
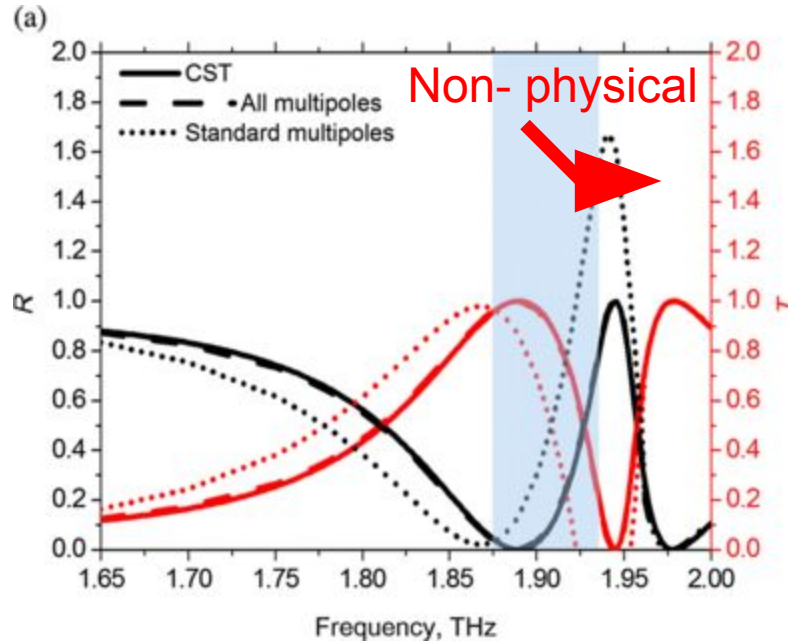
High index dielectrics :

In microwave- BSTO ceramics

S. O'Brien and J. B. Pendry, 2002

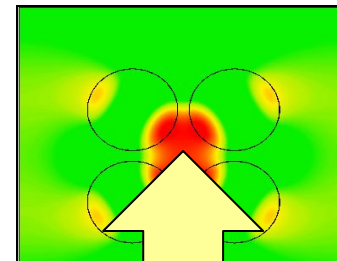
L. Peng and al., 2007

LiTaO₃ cluster: Reflection and Transmission; Radiated power of multipoles



Closed magnetic field- Toroidal response.

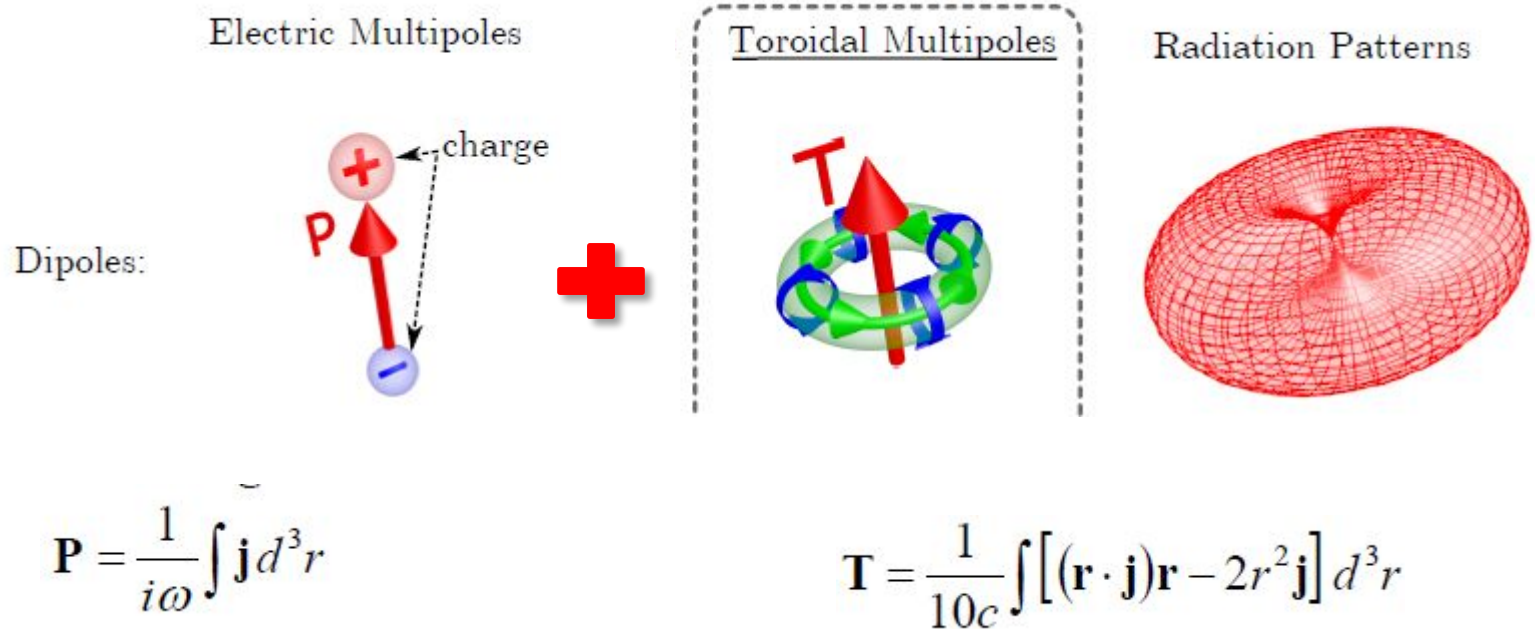
No fields between cylinders



Strong localization of E- field between cylinders- Excitation of Nonlinearities

$$0 \quad 8.22 \times 10^6 \frac{V}{m}$$

Non-Trivial Excitation: $\mathbf{P} = i\mathbf{k}T$ and analog of Electromagnetically induced transparency



Interference of $\mathbf{P}$ and $\mathbf{T}$ gives EIT and symmetrical Peak of transmission

Non-Trivial non-radiating toroidal source

For Electric dipole

$$\begin{aligned}\varphi_P &= \frac{(\mathbf{r} \cdot \mathbf{P})D(\omega, r)}{cr} \frac{\exp(-ikr + i\omega t)}{r}, & \mathbf{A}_P &= ik \mathbf{P} \frac{\exp(-ikr + i\omega t)}{r} \\ \mathbf{E}_P &= \left[\frac{(\mathbf{r} \cdot \mathbf{P})F(\omega, r)}{c^2 r^2} \mathbf{r} - \frac{G(\omega, r)}{c^2} \mathbf{P} \right] \frac{\exp(-ikr + i\omega t)}{r} \\ \mathbf{H}_P &= -\frac{ikD(\omega, r)}{cr} [\mathbf{r} \times \mathbf{P}] \frac{\exp(-ikr + i\omega t)}{r}\end{aligned}$$

For Toroidal dipole

$$\begin{aligned}\varphi_T &= 0, & \mathbf{A}_T &= \left[\frac{(\mathbf{r} \cdot \mathbf{T})F(\omega, r)}{c^2 r^2} \mathbf{r} - \frac{G(\omega, r)}{c^2} \mathbf{T} \right] \frac{\exp(-ikr + i\omega t)}{r} \\ \mathbf{E}_T &= \left[\frac{ikG(\omega, r)}{c^2} \mathbf{T} - \frac{ik(\mathbf{r} \cdot \mathbf{T})F(\omega, r)}{c^2 r^2} \mathbf{r} \right] \frac{\exp(-ikr + i\omega t)}{r} \\ \mathbf{H}_T &= -\frac{k^2 D(\omega, r)}{cr} [\mathbf{r} \times \mathbf{T}] \frac{\exp(-ikr + i\omega t)}{r}\end{aligned}$$

Non-Trivial Excitation: $\mathbf{P} = i\mathbf{k}\mathbf{T}$

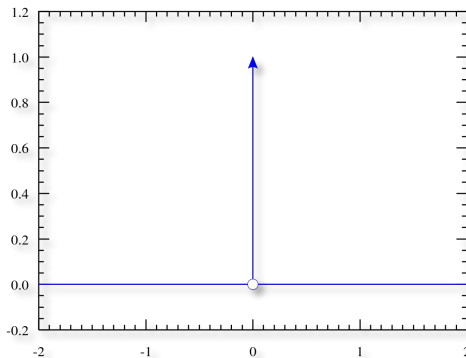
$$\begin{aligned}\mathbf{A}_{tot} &= \mathbf{A}_P + \mathbf{A}_T = \left[\frac{(\mathbf{r} \cdot \mathbf{T})F(\omega, r)}{c^2 r^2} \mathbf{r} - \frac{G(\omega, r)}{c^2} \mathbf{T} + i\mathbf{k}\mathbf{P} \right] \frac{\exp(-ikr + i\omega t)}{r} \\ \mathbf{E}_{tot} &= \mathbf{E}_P + \mathbf{E}_T = \left[\frac{(\mathbf{r} \cdot (\mathbf{P} - i\mathbf{k}\mathbf{T}))F(\omega, r)}{c^2 r^2} \mathbf{r} - \frac{G(\omega, r)}{c^2 r} (\mathbf{P} - i\mathbf{k}\mathbf{T}) \right] \frac{\exp(-ikr + i\omega t)}{r} \\ \mathbf{H}_{tot} &= \mathbf{H}_P + \mathbf{H}_T = -\frac{ikD(\omega, r)}{cr} [\mathbf{r} \times (\mathbf{P} - i\mathbf{k}\mathbf{T})] \frac{\exp(-ikr + i\omega t)}{r}\end{aligned}$$

$$\mathbf{P} = i\mathbf{k}\mathbf{T}$$

E and H vanish in FAR-field zone

Поля точечного анаполя, ближняя зона: $P=i\mathbf{k}T$

δ - функция



$$P=i\mathbf{k}T$$

E и H исчезают везде, кроме $r=0$:

$$\begin{aligned}E_{tot}(r=0) &= -i\mathbf{k}T\delta(r)\exp(i\omega t) \\ H_{tot}(r=0) &= -i\mathbf{k} \operatorname{rot}(\mathbf{T})\delta(r)\exp(i\omega t) \\ \varphi_{tot}(r=0) &= \varphi_p + \varphi_T = 0 \\ A_{tot}(r=0) &= T4\pi\delta(r)\exp(i\omega t)\end{aligned}$$

Бесконечная добротность?

$$Q=\omega_0 W/P$$

ARTICLE

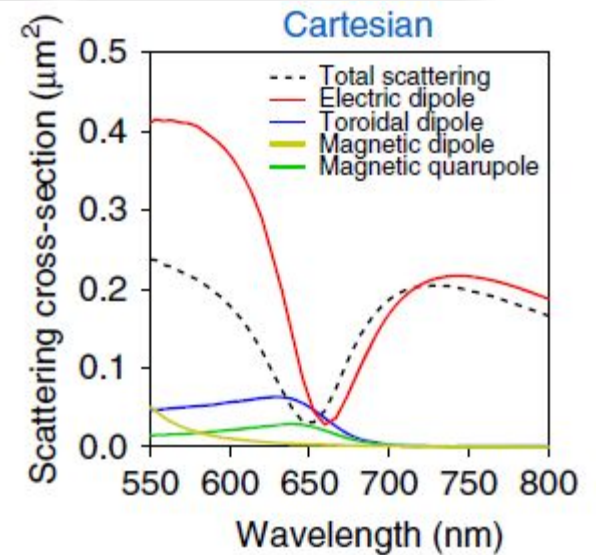
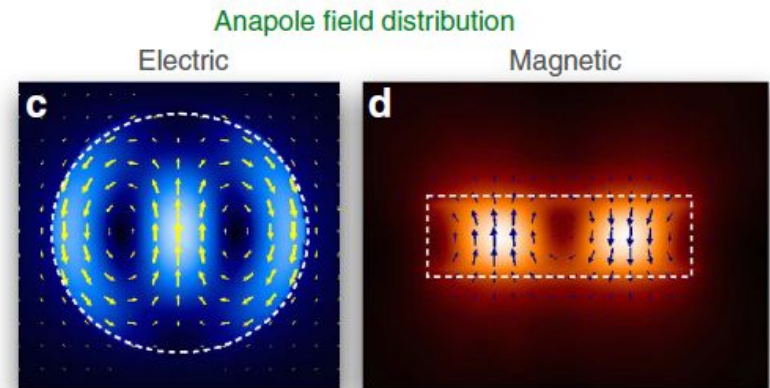
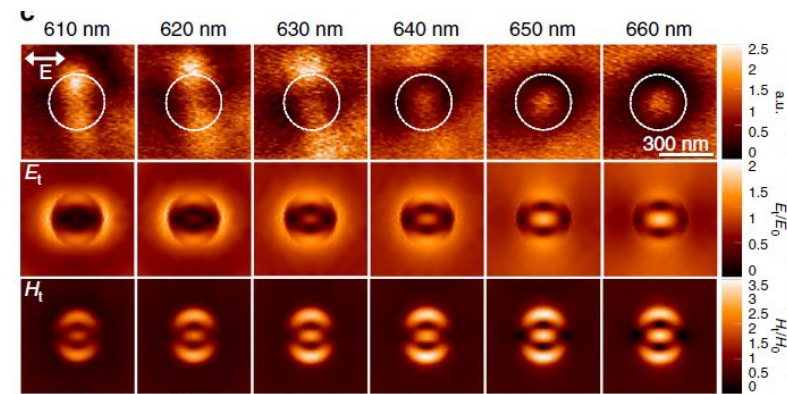
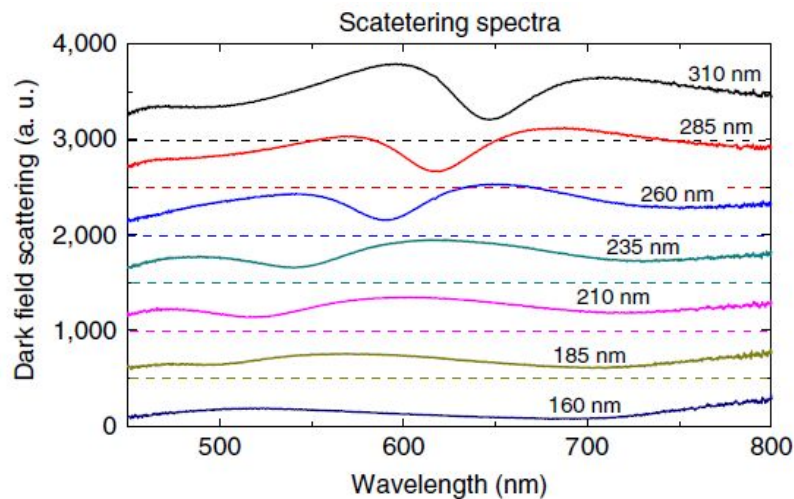
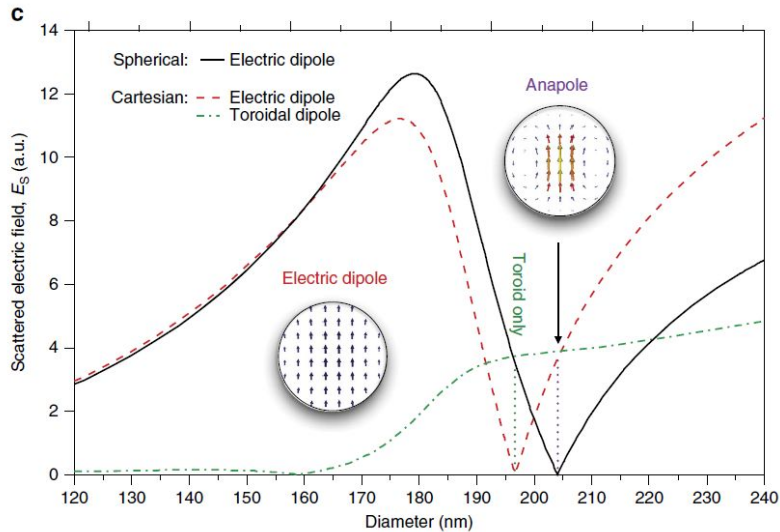
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Nonradiating anapole modes in dielectric nanoparticles

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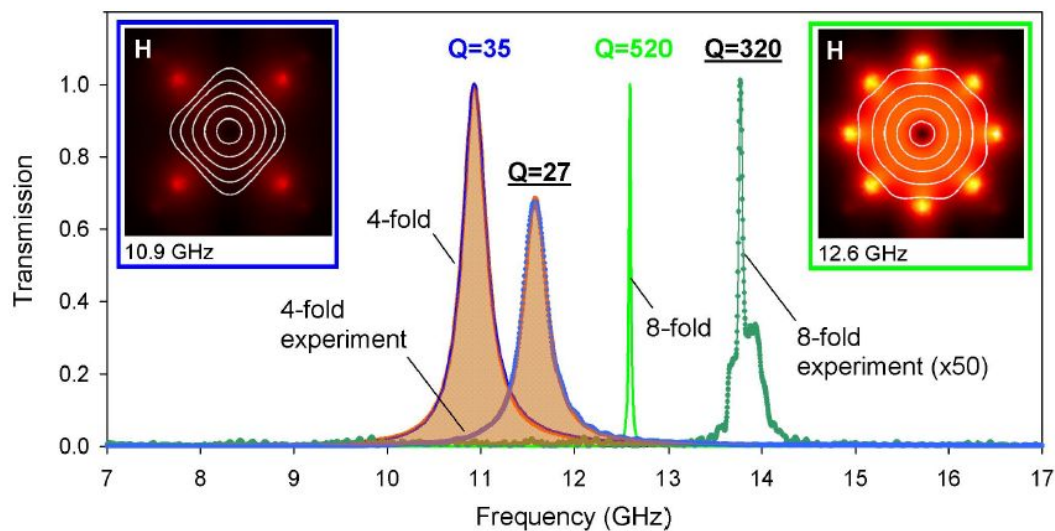
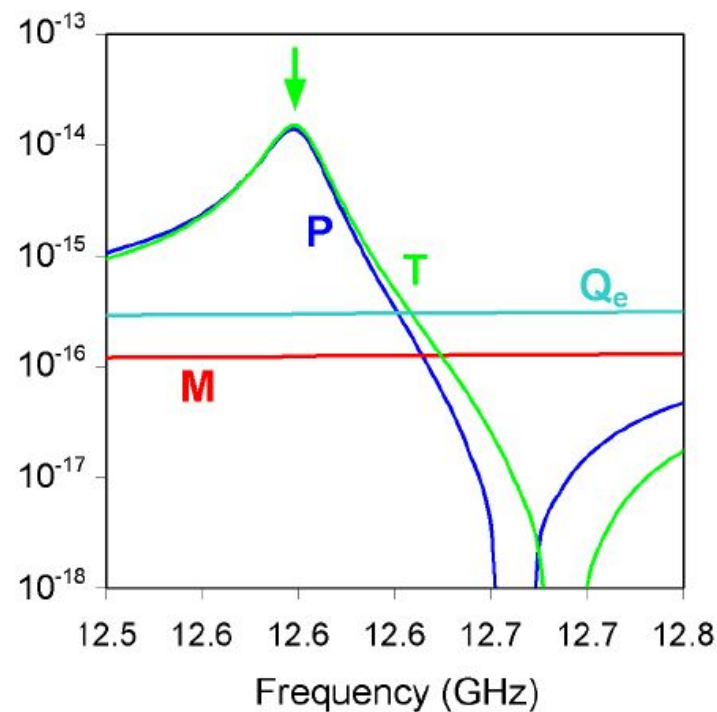
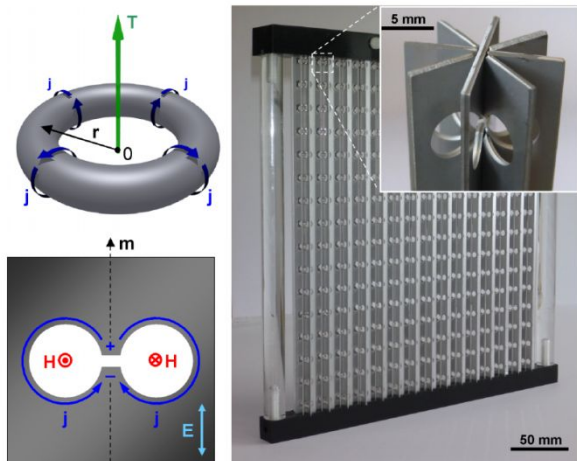


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Resonant Transparency and Non-Trivial Non-Radiating Excitations in Toroidal Metamaterials

SUBJECT AREAS:
ELECTRICAL AND
ELECTRONIC
ENGINEERING
METAMATERIALS

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Conclusions

Fano – resonance assymmetric peak

Vortices in nano-particles give possibilities for absorption and localization

Toroidal response in metamaterials is a very promising candidate for optoelectronics

**Thank you
and
questions?**