Optical Antennas versus Microwave Antennas
——A Personal Review

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1. Function

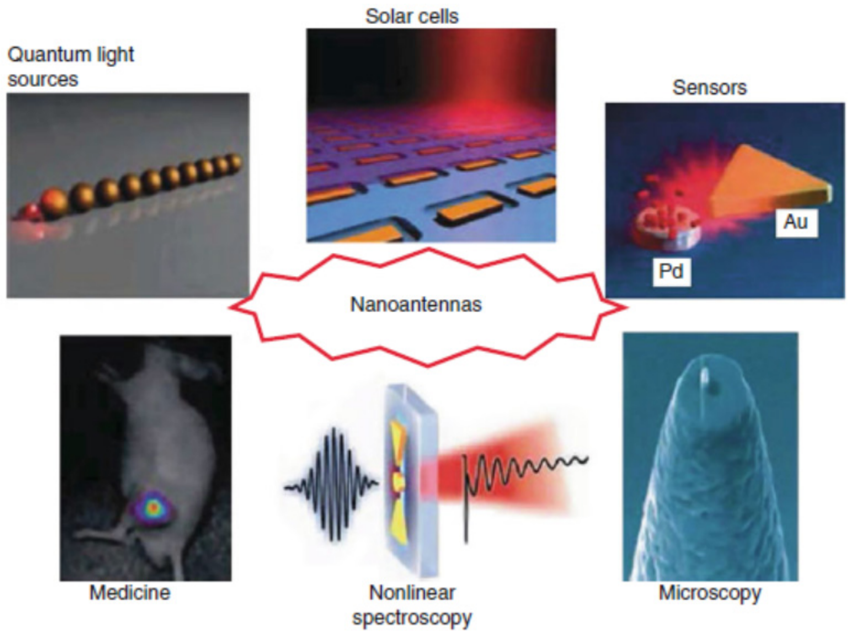
Microwave

Microwave or radio wave antennas are electrical devices which convert electric power into radio waves, and vice versa.

radio broadcasting, television, communication, radar, cell phone, etc

Optical

Optical antennas convert freely propagating optical radiation into localized electromagnetic energy, and vice versa.



photodetection, solar energy, light emission, sensing, microscopy, and spectroscopy

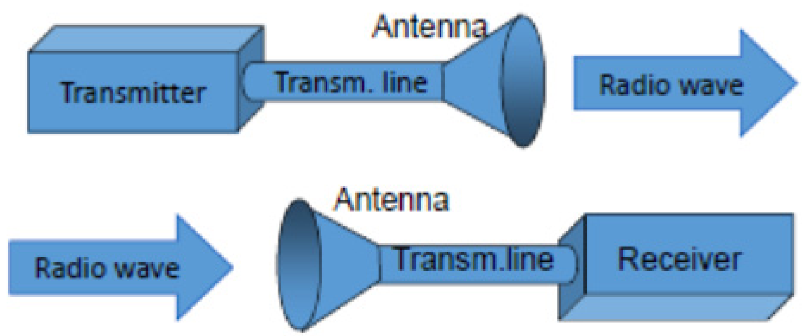
2. Basic Elements

Microwave

Transmitter:
current (voltage) source

Receiver:
electrical load

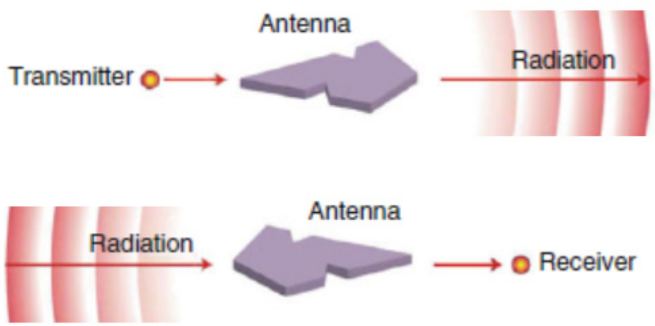
Resonant Transducer:
half-wavelength limit
scaling law



Optical

Transmitter/Receiver:
quantum dots
atoms
molecules
ions

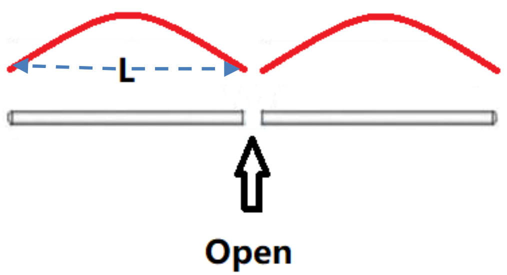
Resonant Transducer:
<u>break</u> half-wavelength limit
<u>break</u> scaling law



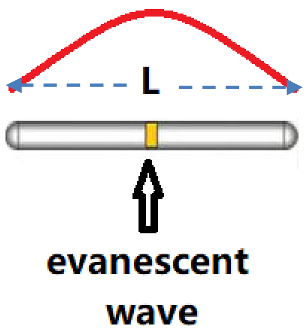
Antennas satisfy <u>reciprocity theorem</u>. $\int_V \mathbf{E}_1 \cdot \mathbf{J}_2 dV = \int_V \mathbf{E}_2 \cdot \mathbf{J}_1 dV$

3. Computational Models

Microwave	*Optical*
far-field radiation	near-field concentration
perfect electric conductor low loss dielectric	highly dispersive and lossy materials
propagation wave interaction	evanescent/surface wave couplings
linear, single-physics, classical	nonlinear, multiphysics, and quantum effects



L~λ/2



L<<λ/2

4. Directivity and Gain (1)

Microwave

$$\boxed{D = \frac{U}{U_0} = \frac{4\pi U}{P_{\text{rad}}}}$$

Directivity

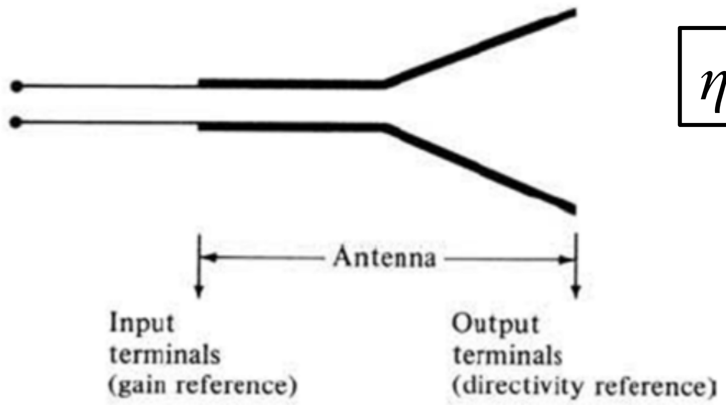
U = radiation intensity (W/unit solid angle)

U_0 = radiation intensity of isotropic source (W/unit solid angle)

P_{rad} = total radiated power (W)

$$\boxed{\text{Gain} = 4\pi \frac{\text{radiation intensity}}{\text{total input (accepted) power}} = 4\pi \frac{U(\theta, \phi)}{P_{in}} \quad \text{(dimensionless)}}$$

Gain



$$\boxed{\eta = P_{\text{rad}}/(P_{\text{rad}} + P_{\text{ohmic}})}$$

Radiation efficiency

$$\boxed{\text{Gain} = \eta D}$$

4. Directivity and Gain (2)

Optical (Consistency)

$$\boxed{D = \frac{U}{U_0} = \frac{4\pi U}{P_{\text{rad}}}}$$ Directivity

$$\boxed{\text{Gain}=\eta D}$$ Gain

Optical (Difference)

$$\boxed{\eta_{in}=P^0_{\text{rad}}/(P^0_{\text{rad}}+P^0_{l})}$$ Internal efficiency

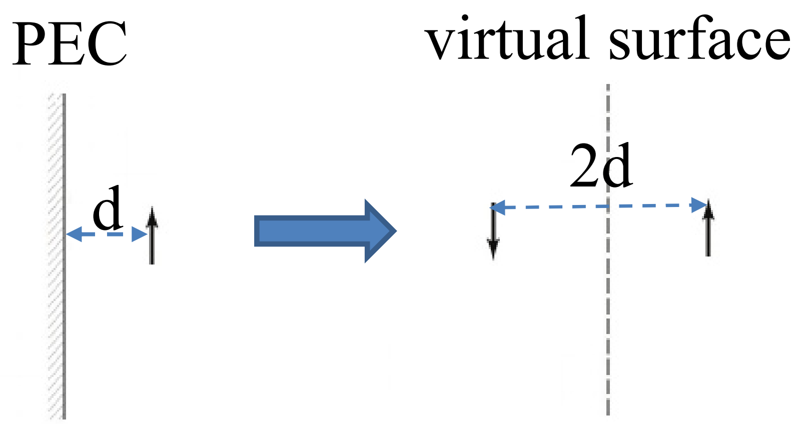
P^0_{rad} : power radiated by the emitter in the absence of the optical antenna
P^0_{l} : internal losses

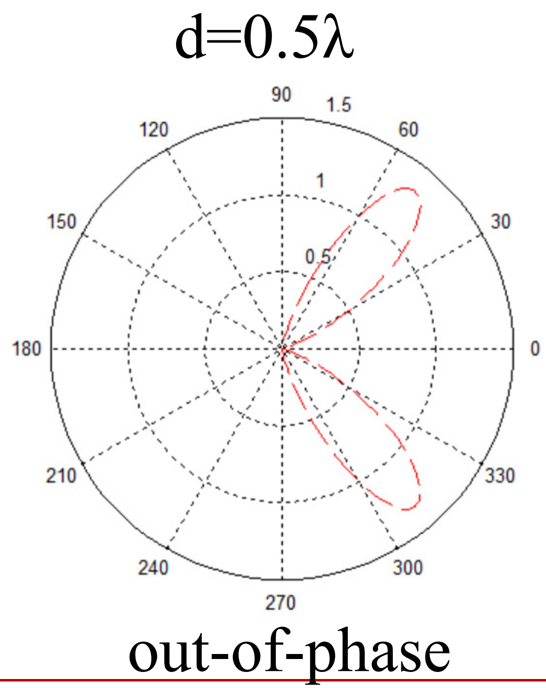
$$\boxed{\eta=P_{\text{rad}}/(P_{\text{rad}}+P_{\text{ohmic}}+P^0_{l})}$$ Radiation efficiency

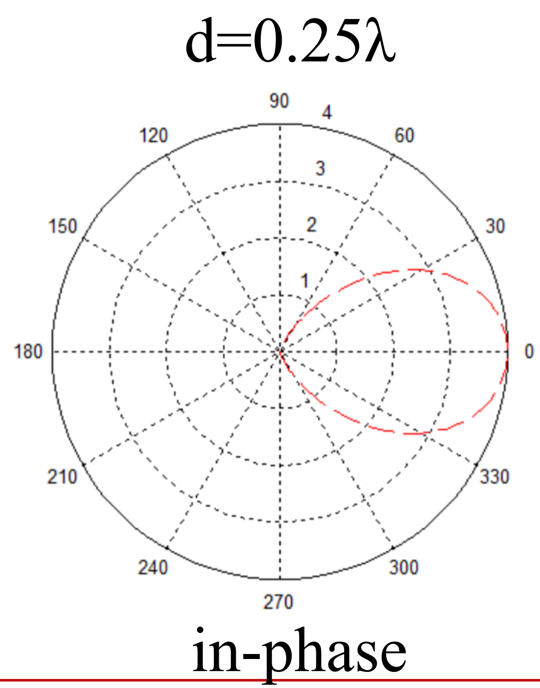
optical antennas could significantly improve the radiation efficiency of a poor emitter!

5. Unidirectional Antennas: Yagi-Uda Antennas (1)

<u>image theory</u> and antenna array synthesis

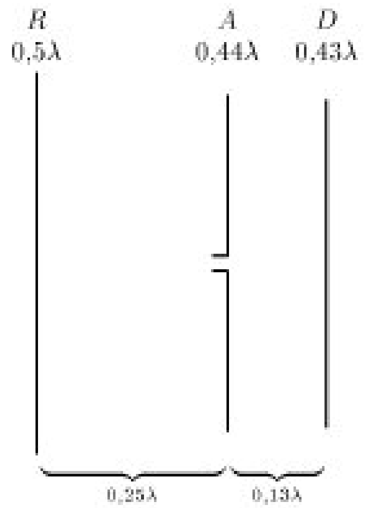




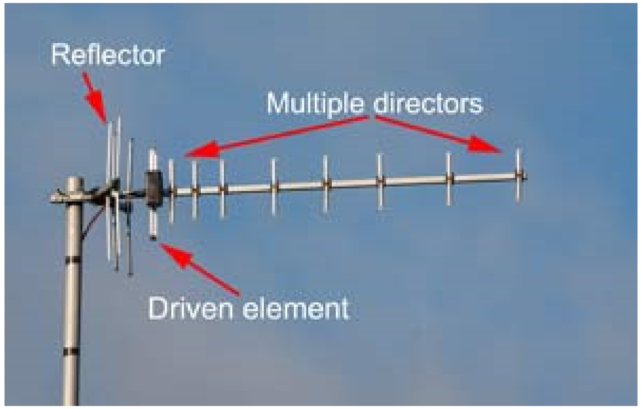


5. Unidirectional Antennas: Yagi-Uda Antennas (2)

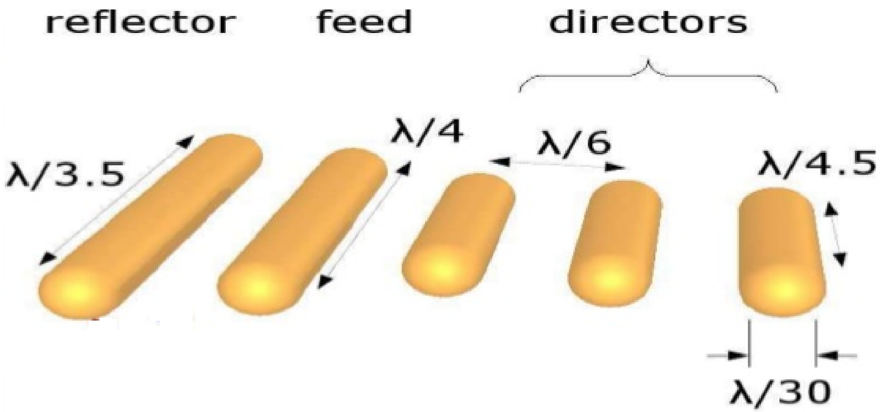
Microwave



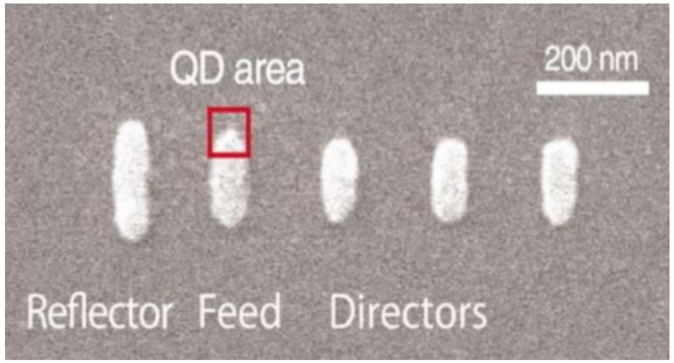
R: reflector; A: driven element (feed); D:director



Optical



Science 329:930, 2010.



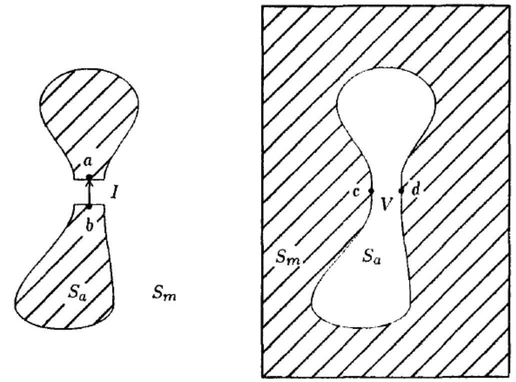
The distance between feed and reflector is smaller than 0.25λ.

6. Broadband V.S. Wavelength Selectivity (1)

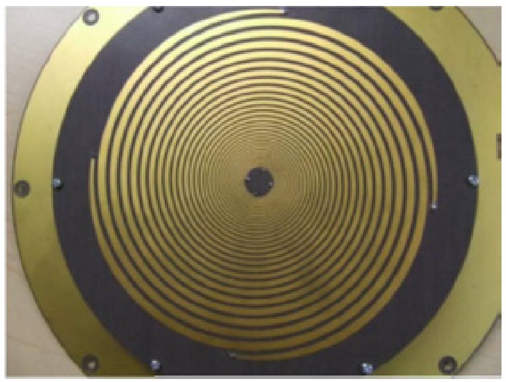
Babinet principle and broadband antennas

Input impedances of metal antenna and complementary aperture antenna satisfy

$$Z_m Z_a = \frac{\eta^2}{4}$$



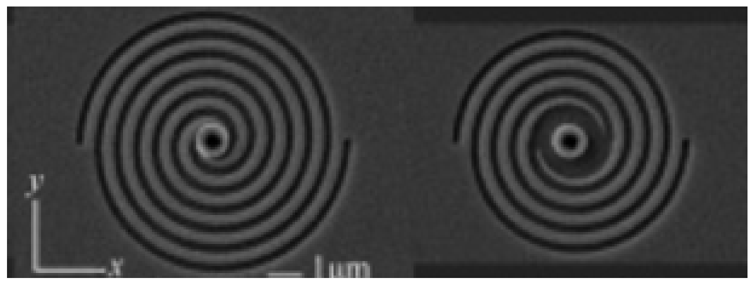
For self-complementary antenna, its input impedance is frequency of independent and thus the self-complementary antenna is a kind of broadband antennas.



microwave

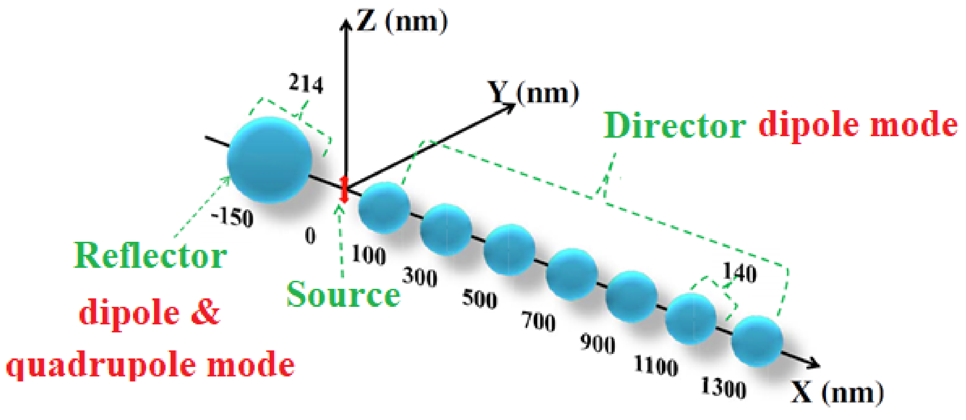
Planar Spiral

Opt. Express, 20(2): 1308, 2012

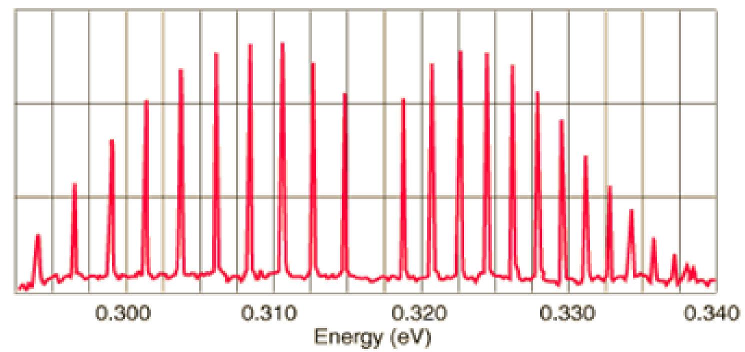


optical

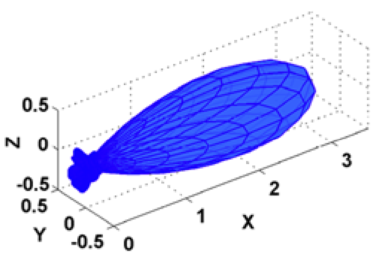
wavelength selectivity by dielectric Yagi-Uda antenna and Fano resonance



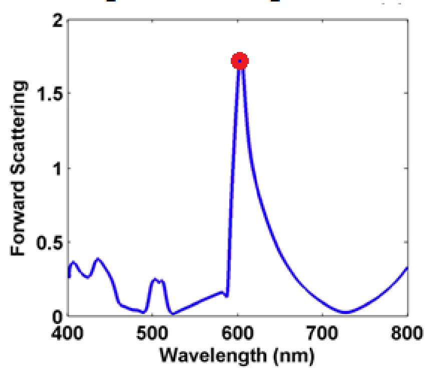
resolved vibration spectra

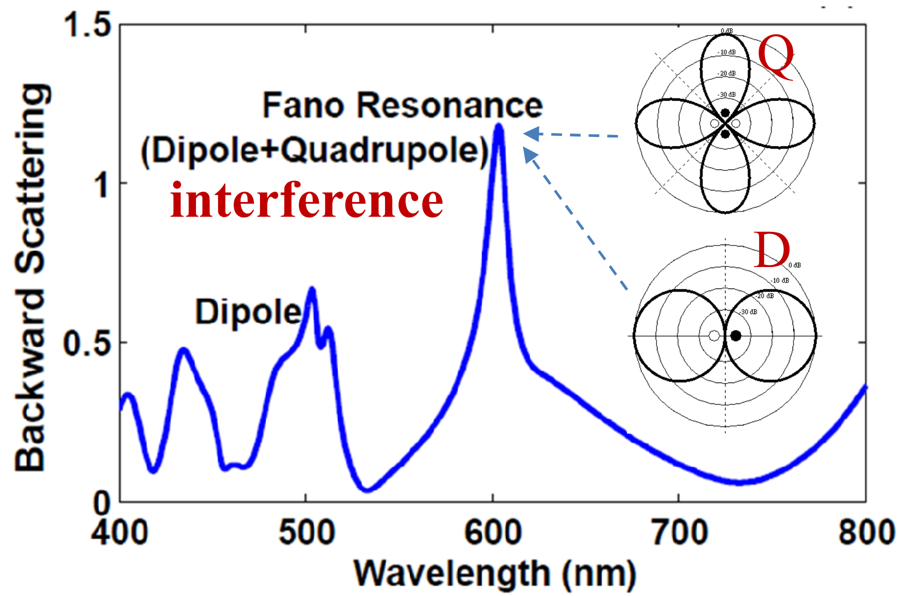


radiation pattern



spectral response





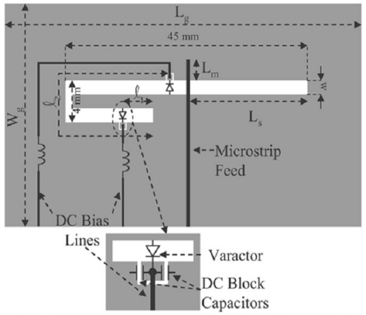
Opt. Lett., 37(11), 2112-2114, 2012.

7. Active Antennas: Electrical V.S. Optical Tunable

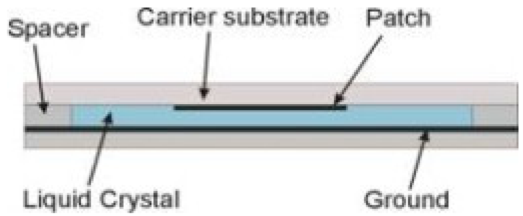
Microwave

phased array

plasma



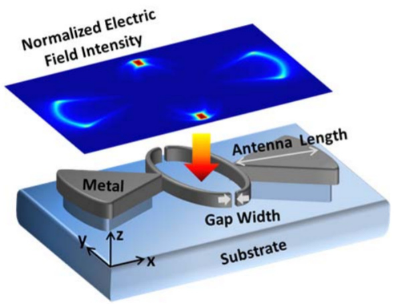
varactor diode



liquid crystals

Optical

Opt. Lett. 37:3258, 2012

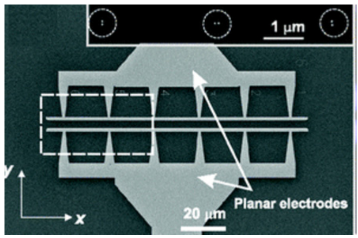


optical force

Phys. Rev. B 82:235405, 2010

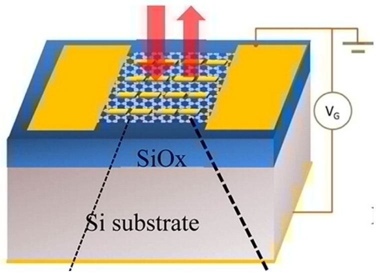
nonlinear effect

Nano. Lett. 9:3914, 2009



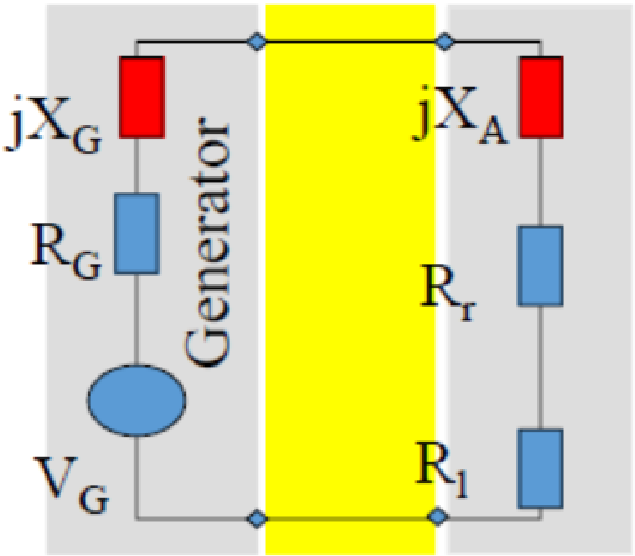
liquid crystals

Nano. Lett. 13:1257, 2013



graphene

impedance matching for *microwave antennas*



Maximum Power Condition

$$R_A = R_r + R_l = R_G,\ X_A = -X_G$$

$$P_G = P_A = \frac{V_G^2}{4R_G},\ P_r = P_A \frac{R_r}{(R_r + R_l)}$$

The transmitter with the transmission line is represented by an (Thevenin) equivalent generator (with V_G, R_G and X_G)

The antenna is represented by its **input impedance** (which is frequency-dependent and is influenced by objects nearby) as seen from the generator

jX_A represents energy stored in electric (E_e) and magnetic (E_m) near-field components; if $|E_e| = |E_m|$ then $X_A = 0$ (antenna resonance)

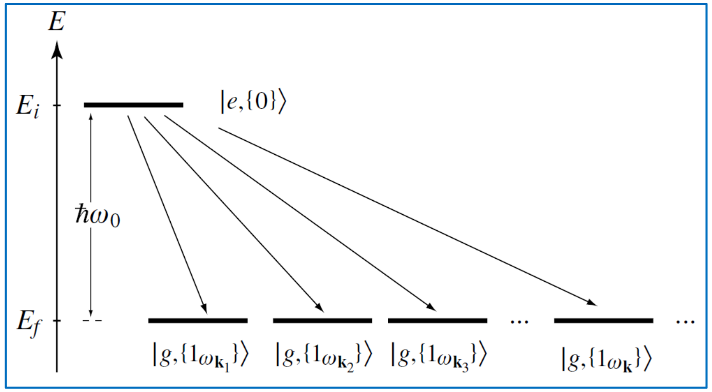
R_r represents energy radiated into space (far-field components)

R_l represents energy lost, i.e. transformed into heat in the antenna structure

8. Input Impedance V.S. Local Density of States (2)

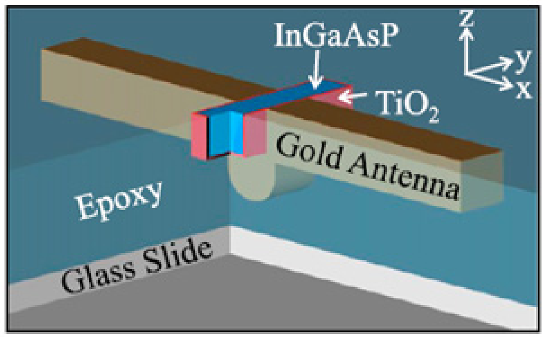
local density of states for *optical antennas*

To let quantum emitters efficiently radiate EM waves, photon local density of states (LDOS) should be enhanced. The LDOS counts the number of EM modes at the emitter point. Each EM mode can be taken as a decay channel. The more decay channels there are, the easier it is for an excited atom to emit photons via returning to its ground state.

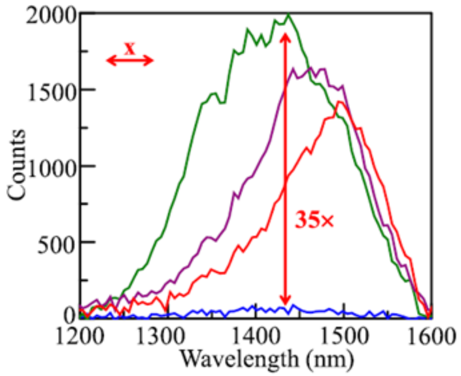


In isotropic, inhomogeneous, and nonmagnetic medium, the LDOS is represented by the dyadic Green's function in inhomogeneous environment

$$\rho(\mathbf{r}_0,\omega_0) = \frac{2\omega_0}{\pi c^2}\mathrm{Tr}\{\mathfrak{Im}[\overline{\mathbf{G}}^e(\mathbf{r}_0,\mathbf{r}_0;\omega_0)]\}$$



PNAS, 112 (6), 1704, 2015



Optical antennas could significantly boost LDOS due to the localized near-field enhancement by plasmonic effects. Blue: without antenna; Others: with antenna of different arm lengths

9. Linear V.S. Nonlinear and Quantum Regimes (1)

1. Classical linear Maxwell equation or wave equation will be solved to model the EM response from *microwave antennas.*

2. Coupled wave equations with nonlinear sources will be solved to model the EM response from *nonlinear optical antennas*, where radiated waves and incident waves have different frequencies. The coupled wave equations for second-harmonic generation is given by

$$\nabla^2 \mathbf{E}^{(\omega)} + k(\omega)^2 \mathbf{E}^{(\omega)} = -\frac{\omega^2}{\varepsilon_0 c^2} \mathbf{P}^{(\omega),NL} - \frac{i\omega}{\varepsilon_0 c^2} \mathbf{J}^{(\omega)}_{pump}$$ fundamental field

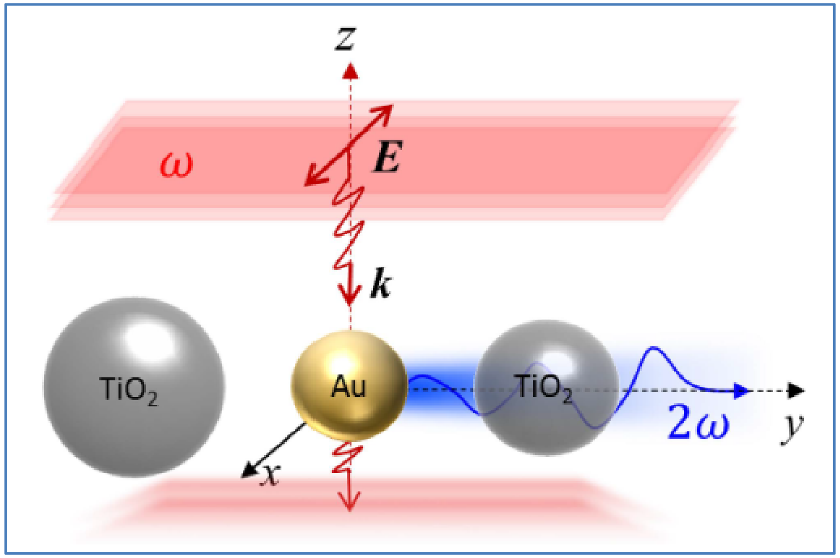
$$\nabla^2 \mathbf{E}^{(2\omega)} + k(2\omega)^2 \mathbf{E}^{(2\omega)} = -\frac{(2\omega)^2}{\varepsilon_0 c^2} \mathbf{P}^{(2\omega),NL}$$ second harmonic field

$\mathbf{P}^{(\omega),NL}$ nonlinear source for downconversion process

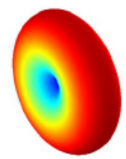
$\mathbf{P}^{(2\omega),NL}$ nonlinear source for upconversion process

9. Linear V.S. Nonlinear and Quantum Regimes (2)

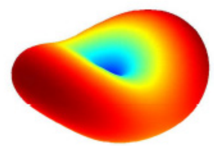
nonlinear optical antennas: Yagi-Uda case

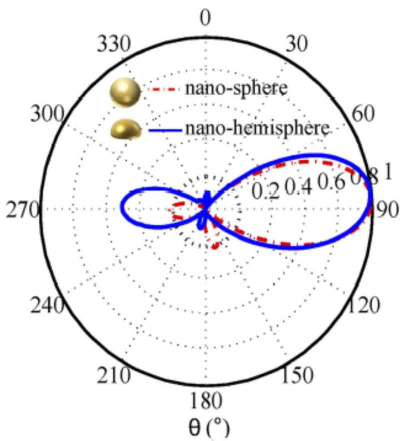


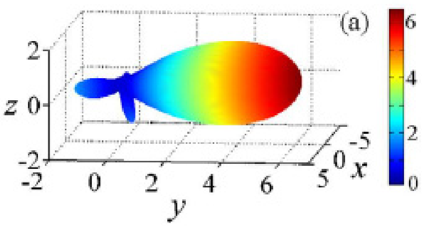
fundamental

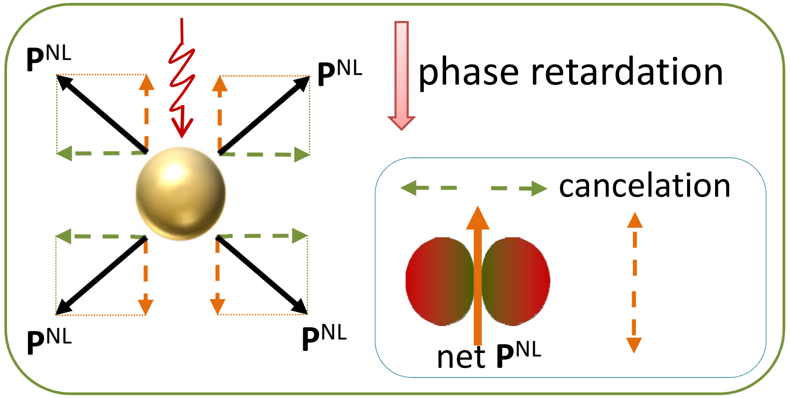


second-harmonic









Sci. Rep., 6: 18872, 2016

second harmonic radiation obeys a selection rule that the radiation is strictly zero along the incident *z* direction if the scatterer is centrosymmetric at the *xoy* plane.

9. Linear V.S. Nonlinear and Quantum Regimes (3)

Quantum World

- At quantum regime, when the object size is tiny small (typically smaller than 10 nm) so that "homogenized" permittivity and permeability of Maxwell equation is invalid or meaningless.

- If the field intensity is strong or the number of photons is large, semi-classical Maxwell-Schrödinger system is required to describe the light-particle interaction, where Maxwell equation is still classical.

- If the field intensity is very weak and the number of photons is quite small (vacuum fluctuation, single photon source, etc), Maxwell equation should be quantized and classical Maxwell equation breaks down.

strong field condition $$\boxed{|\mathbf{E}| \gg \frac{\sqrt{\hbar c}}{(c\Delta_t)^2}}$$

9. Linear V.S. Nonlinear and Quantum Regimes (4)

Semi-classical Framework — Maxwell-Schrödinger equations

Hamiltonian

$$H^s(\mathbf{A},\mathbf{Y},\psi,\psi^*) = H^{em}(\mathbf{A},\mathbf{Y}) + H^q(\psi,\psi^*,\mathbf{A})$$

$$H^{em}(\mathbf{A},\mathbf{Y}) = \int_v \left(\frac{1}{2\epsilon_0}|\mathbf{Y}|^2 + \frac{1}{2\mu_0}|\nabla\times\mathbf{A}|^2\right) d\mathbf{r}$$

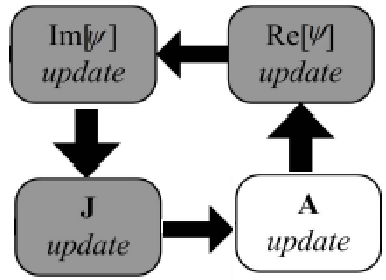
$$H^q(\psi,\psi^*,\mathbf{A}) = \int_v \left[\psi^*\frac{(\hat{\mathbf{p}}-q\mathbf{A})^2}{2m}\psi + \psi^* V\psi\right] d\mathbf{r}$$

Generalized coordinate and momentum

$$\mathbf{q} = (\mathbf{A},\psi_r) \qquad \mathbf{p} = (\mathbf{Y},\psi_i)$$

$$\frac{\partial\mathbf{p}}{\partial t} = -\frac{\partial H^s}{\partial\mathbf{q}}$$

$$\frac{\partial\mathbf{q}}{\partial t} = \frac{\partial H^s}{\partial\mathbf{p}}$$



Maxwell equation

$$\frac{\partial\mathbf{A}}{\partial t} = \frac{\partial H^s}{\partial\mathbf{Y}} = \frac{\mathbf{Y}}{\epsilon_0}$$

$$\frac{\partial\mathbf{Y}}{\partial t} = -\frac{\partial H^s}{\partial\mathbf{A}} = -\frac{\nabla\times\nabla\times\mathbf{A}}{\mu_0} + \mathbf{J}$$

Schrödinger equation

$$\frac{\partial\psi}{\partial t} = \frac{1}{i\hbar}\frac{\partial H^s}{\partial\psi^*} = \frac{1}{i\hbar}\left[\frac{(\hat{\mathbf{p}}-q\mathbf{A})^2}{2m} + V\right]\psi$$

$$\frac{\partial\psi^*}{\partial t} = \frac{-1}{i\hbar}\frac{\partial H^s}{\partial\psi} = -\frac{1}{i\hbar}\left[\frac{(\hat{\mathbf{p}}+q\mathbf{A})^2}{2m} + V\right]\psi^*$$

$$\mathbf{J} = \frac{q}{2m}\left[\psi^*(\hat{\mathbf{p}}-q\mathbf{A})\psi + \psi(-\hat{\mathbf{p}}-q\mathbf{A})\psi^*\right]$$

Quantum current

Comp. Phys. Commun., 215: 63-70, 2017.

9. Linear V.S. Nonlinear and Quantum Regimes (5)

Quantized Maxwell equation in dispersive and lossy media by Lorentz model

Maxwell equation in time-domain

$$\dot{\hat{\mathbf{H}}} = -\nabla \times \hat{\mathbf{E}}$$

$$\dot{\hat{\mathbf{E}}} = \nabla \times \hat{\mathbf{H}} - \dot{\hat{\mathbf{P}}}$$

$$\dot{\hat{\mathbf{\Pi}}} = -\omega_0 \hat{\mathbf{P}} - \eta \hat{\mathbf{\Pi}} + \hat{\mathbf{F}}_I + \frac{\omega_p^2}{\omega_0} \hat{\mathbf{E}}$$

$$\dot{\hat{\mathbf{P}}} = \omega_0 \hat{\mathbf{\Pi}} - \eta \hat{\mathbf{P}} + \hat{\mathbf{F}}_R$$

$$\left\langle \left[\hat{\mathbf{F}}_R, \hat{\mathbf{F}}_I \right] \right\rangle = i2\eta \frac{\omega_p^2 \hbar}{\omega_0} \delta(t - t') \hat{\bar{\mathbf{I}}}$$

Wave equation in frequency domain

$$\nabla \times \nabla \times \hat{\mathbf{E}}(\mathbf{r}, \omega) - \omega^2 \epsilon(\mathbf{r}, \omega) \hat{\mathbf{E}}(\mathbf{r}, \omega) = i\omega \hat{\mathbf{j}}_n(\mathbf{r}, \omega)$$

$$\hat{\mathbf{j}}_n(\mathbf{r}, \omega) = \frac{-i\omega\omega_0 \hat{\mathbf{F}}_I(\mathbf{r}) - i\omega \left[\eta(\mathbf{r}) - i\omega\right] \hat{\mathbf{F}}_R(\mathbf{r})}{\left[\eta(\mathbf{r}) - i\omega\right]^2 + \omega_0^2}$$

$$\epsilon(\mathbf{r}, \omega) = 1 + \frac{\omega_p^2}{\left[\eta(\mathbf{r}) - i\omega\right]^2 + \omega_0^2}$$

$$\left\langle \left[\hat{\mathbf{j}}_n(\mathbf{r}, \omega), \hat{\mathbf{j}}_n^\dagger(\mathbf{r}, \omega') \right] \right\rangle = \frac{\hbar\omega}{\pi} \sigma(\mathbf{r}, \omega) \delta(\omega - \omega')$$

arXiv:1704.02448

Fluctuation-dissipation theorem

Conclusion

1. Electromagnetic theories still show great capabilities to design both microwave and optical antennas.

2. Due to dispersive and lossy materials at optical frequencies, the design of optical antennas could borrow the ideas from that of microwave antennas but needs to be optimized by rigorous full-wave simulation. The consideration of evanescent or surface wave coupling is essential to the optimized design.

3. A new principle should be explored for a new application of optical antennas, such as vibration spectra detection by wavelength selectivity through Fano resonance concept.

4. Some figures of merit of optical antennas should be modified or regenerated, such as radiation efficiency and local density of states.

5. Manipulation of nonlinear and quantum effects of optical antennas is a new emerging research area.

THANKS FOR YOUR ATTENTION!