Spontaneous Emission Rate is Enhanced by an Optical Antenna

Croucher Advanced Study Institute:
New Materials and New Concepts for Controlling Light and Waves

Hong Kong, Thursday Oct. 4, 2012

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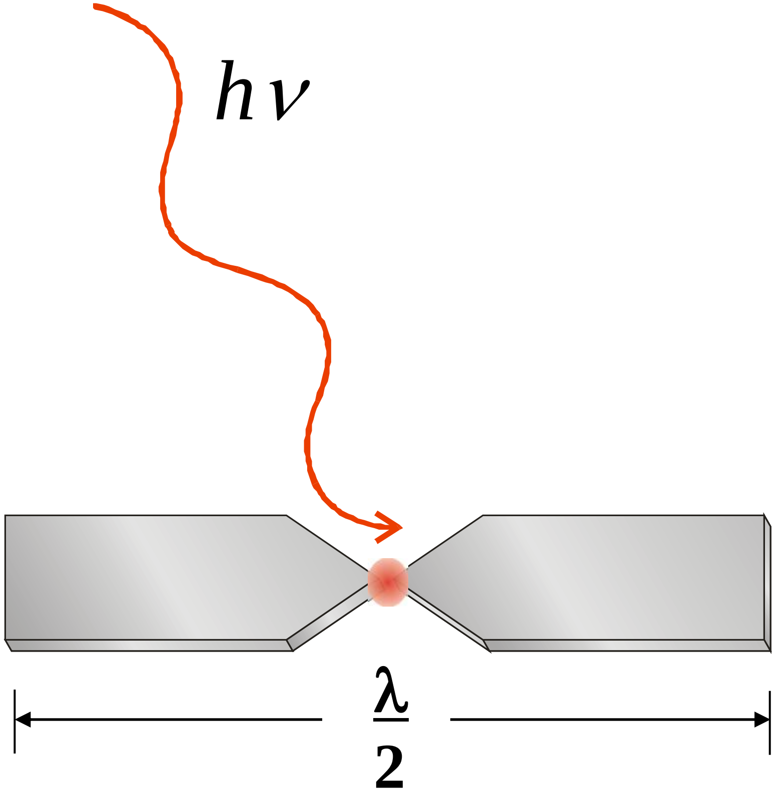
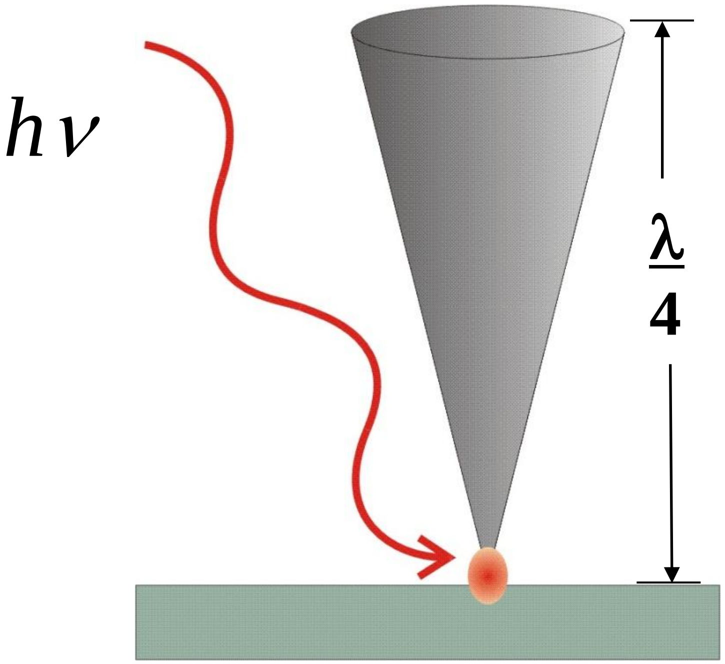
Antennas are part of Plasmonics & Metal-Optics:

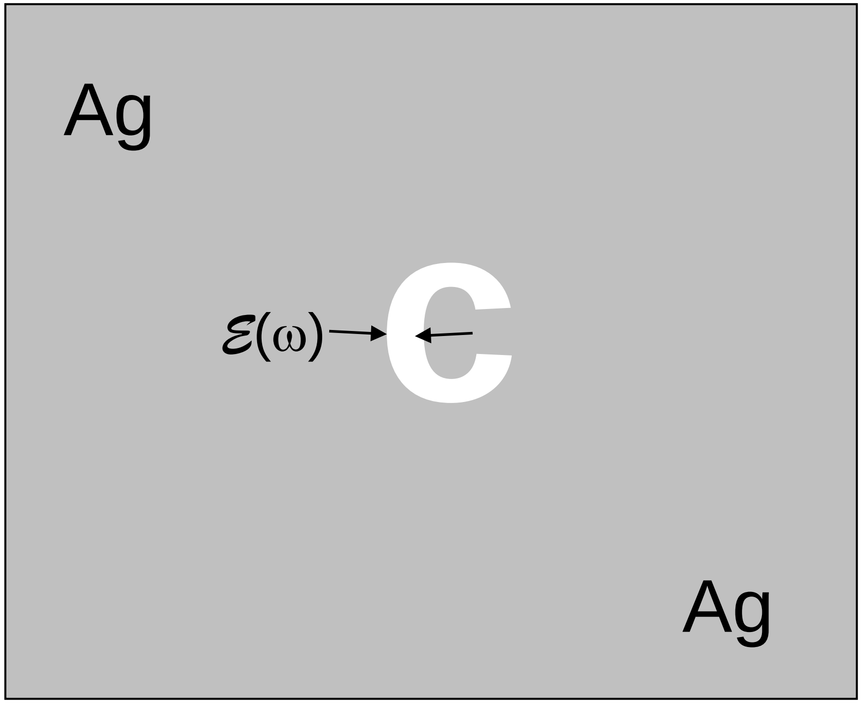


Bow-Tie Antenna
half-wave dipole

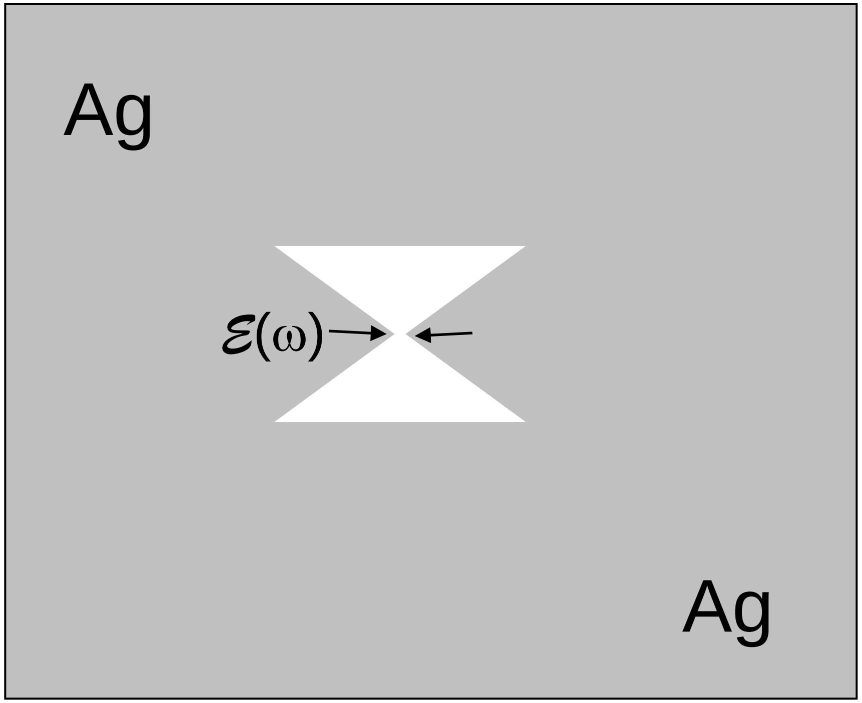


Optical STM
quarter-wave monopole

Slot antennas, Babinet's Principle:

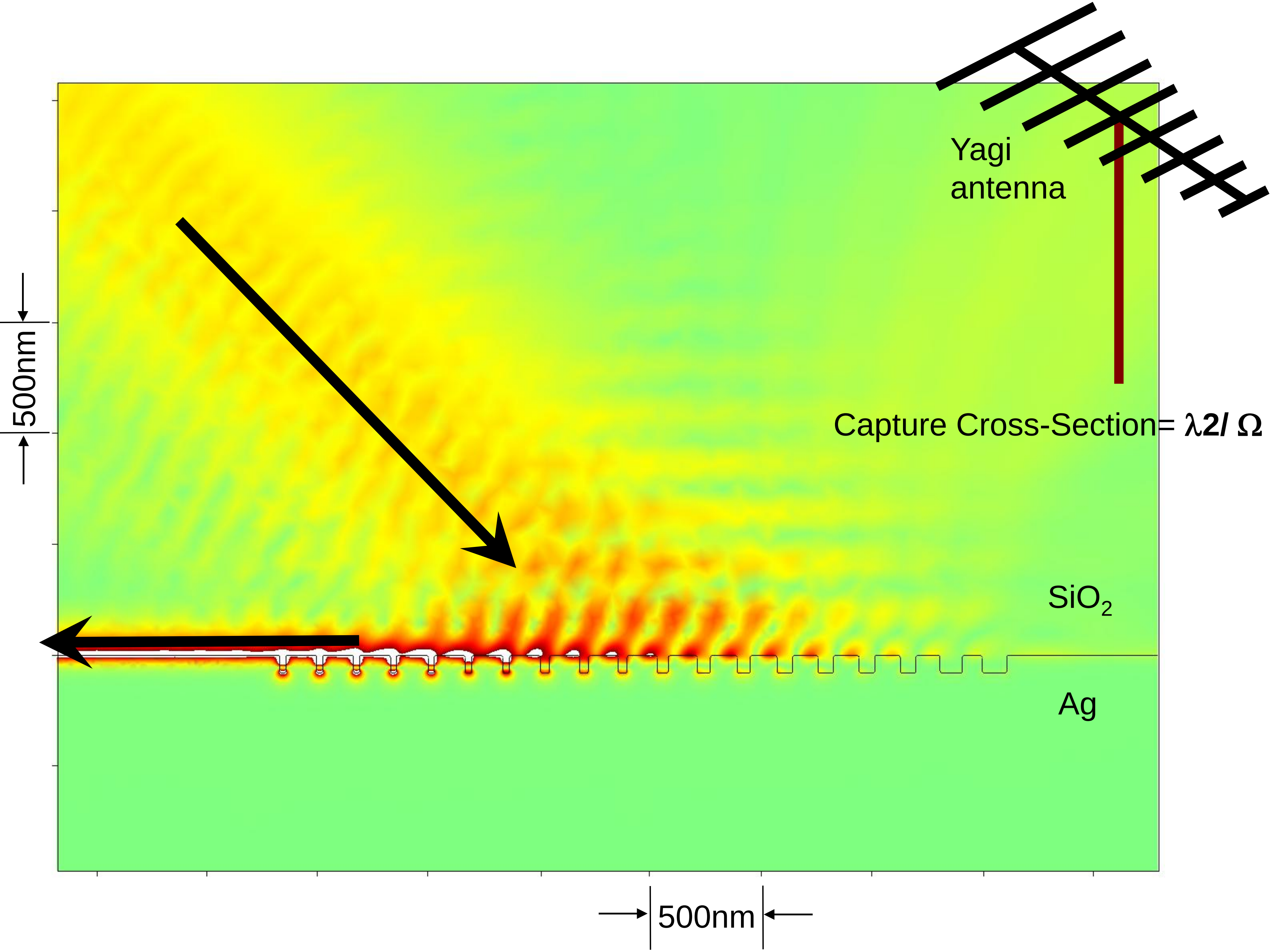


The Complementary C-slot antenna



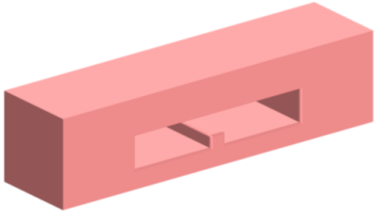
Bow-Tie Slot antenna

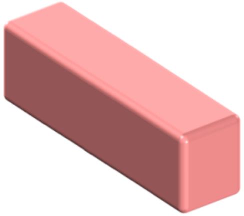
This type will have less Ohmic resistance,
based simply on have more metal.

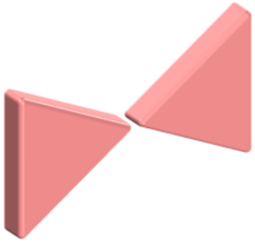


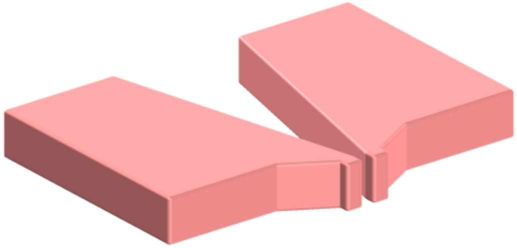
Capture Cross-Section= **λ2/ Ω**

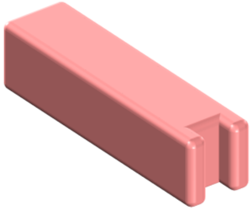
The Optical Antenna Zoo

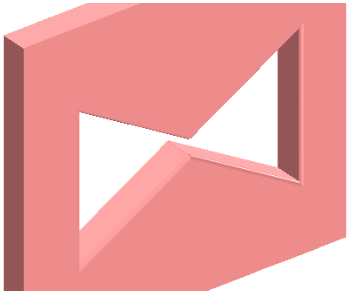

Ridge Waveguide

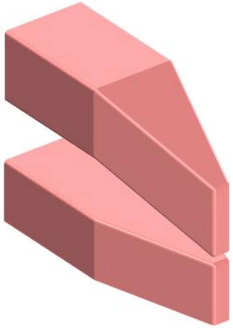

Pin Antenna

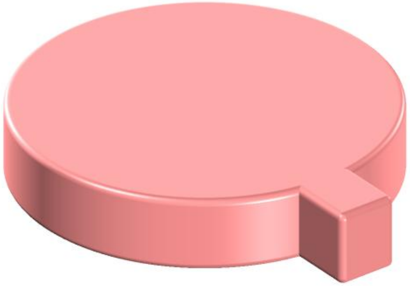

Bowtie Antenna

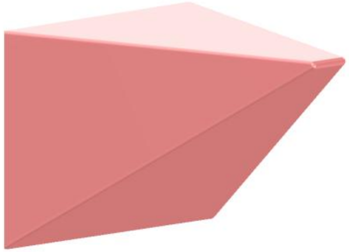

2D Tapered Waveguide


Recessed Pin Antenna

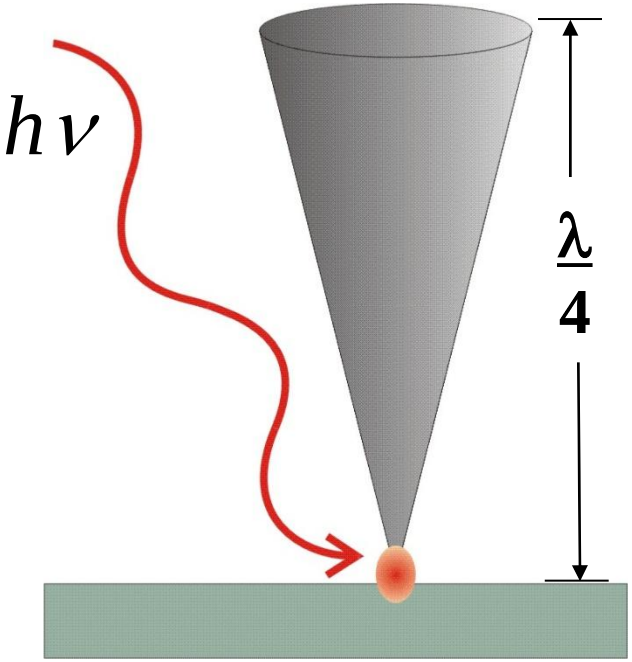

Comp-Bowtie Antenna

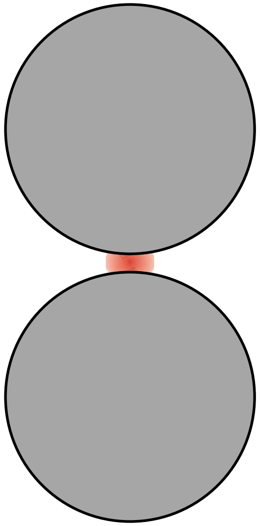

3D Tapered Waveguide


Patch Antenna


Blade Waveguide

Concentrating Electromagnetic Energy:



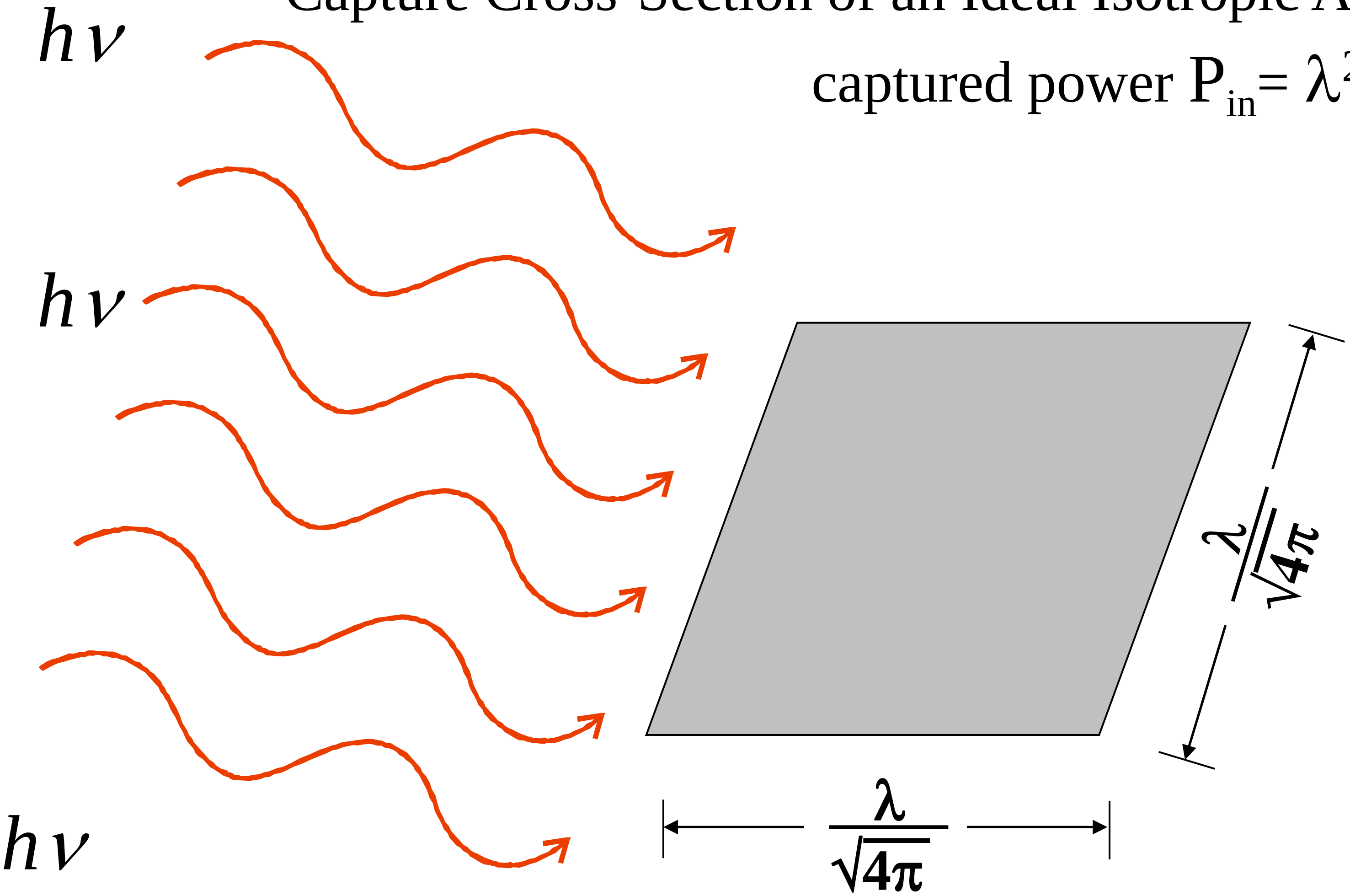


double
cylinder
antenna

Optical Scanning Tunneling Microscope
quarter-wave monopole antenna
Super-resolution depends upon tip dimensions <<λ.

Capture Cross-Section of an Ideal Isotropic Antenna = $\lambda^2/4\pi$

captured power $P_{in} = \lambda^2/4\pi \times$ Intensity



For a highly directional antenna, Capture Cross-Section = $\lambda^2/\,\Omega$

where Ω is the acceptance solid-angle.

λ = Vacuum Wavelength

The Concept of Antenna Radiation Resistance

Radiated Power is proportional to {charge×acceleration}^{2}: $\left(\frac{1}{6\pi\varepsilon_o c^3}\right)\left\{Nq\frac{dv}{dt}\right\}^2$

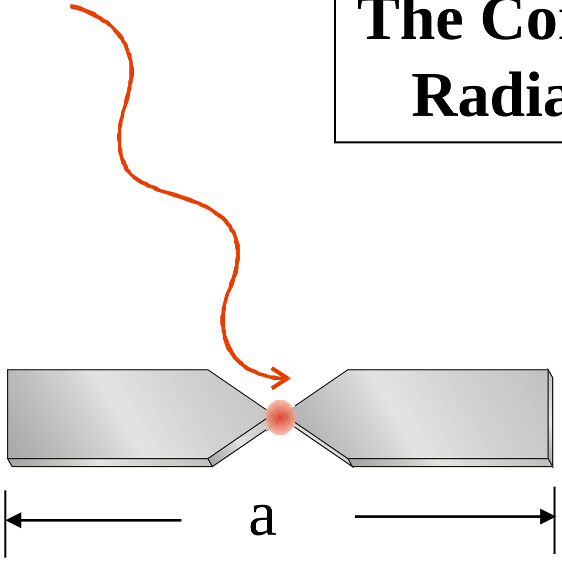
$$\left(\frac{1}{6\pi\varepsilon_o c^3}\right)\{\omega\, Nqv\}^2$$

$$= \left(\frac{\omega^2}{6\pi\varepsilon_o c^3}\right)\times\left\{a\,\underbrace{\frac{N}{a}qv}\right\}^2$$

$$= \underbrace{\left(\frac{\omega^2}{6\pi\varepsilon_o c^3}\right)\times a^2}\times I^2$$

$$= \underbrace{R_{radiation}}\times I^2$$

depends on
geometry,
frequency,
etc.



By time reversal, the captured power:

$$\text{Intensity} \times \lambda^2/4\pi = P_{in} = I^2 \times R_{radiation}$$

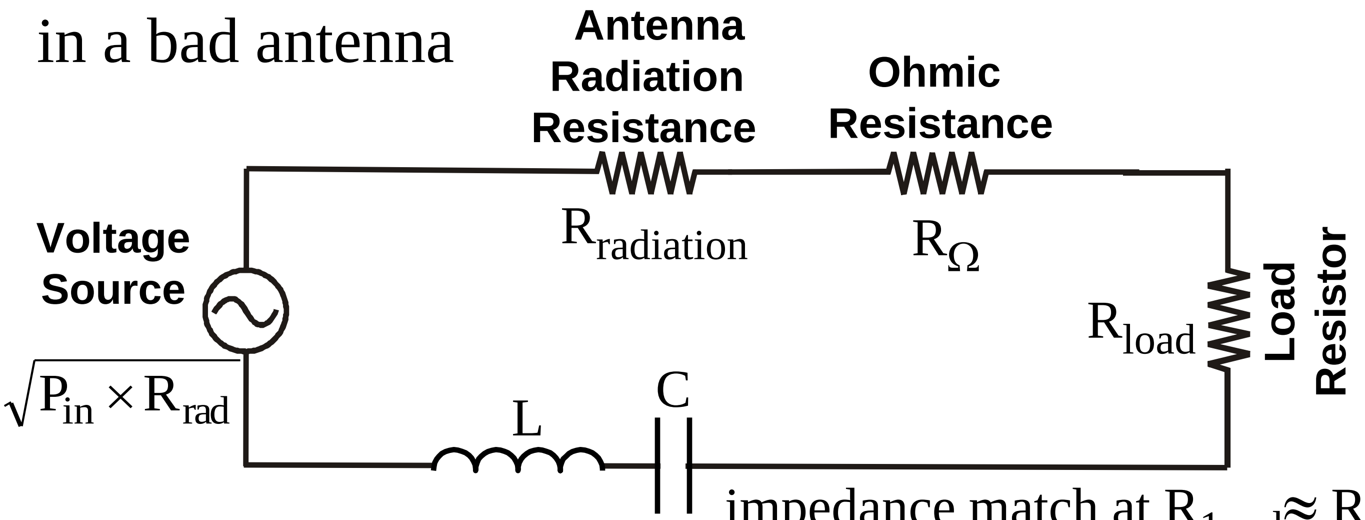
$$\text{Intensity} \times \lambda^2/4\pi = P_{in} = \frac{V^2}{R_{radiation}}$$

$R_{radiation} \approx 50\Omega \approx 377\Omega/2\pi$
in a very good antenna

$R_{radiation} \approx (a/\lambda)^2 \times 377\Omega \approx 1\Omega$
in a bad antenna

$377\Omega = \sqrt{\mu_o/\varepsilon_o}$ in MKS units

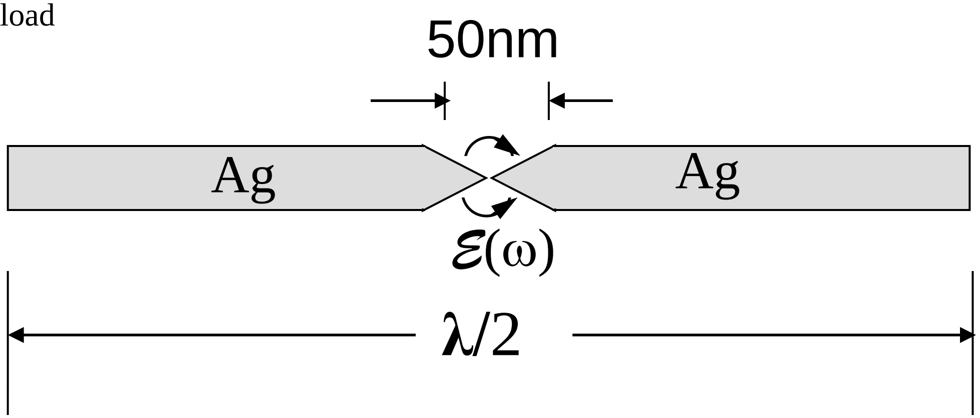
$377\Omega = 4\pi/c$ in CGS units



$V_{in} = 2\sqrt{P_{in} \times R_{rad}}$

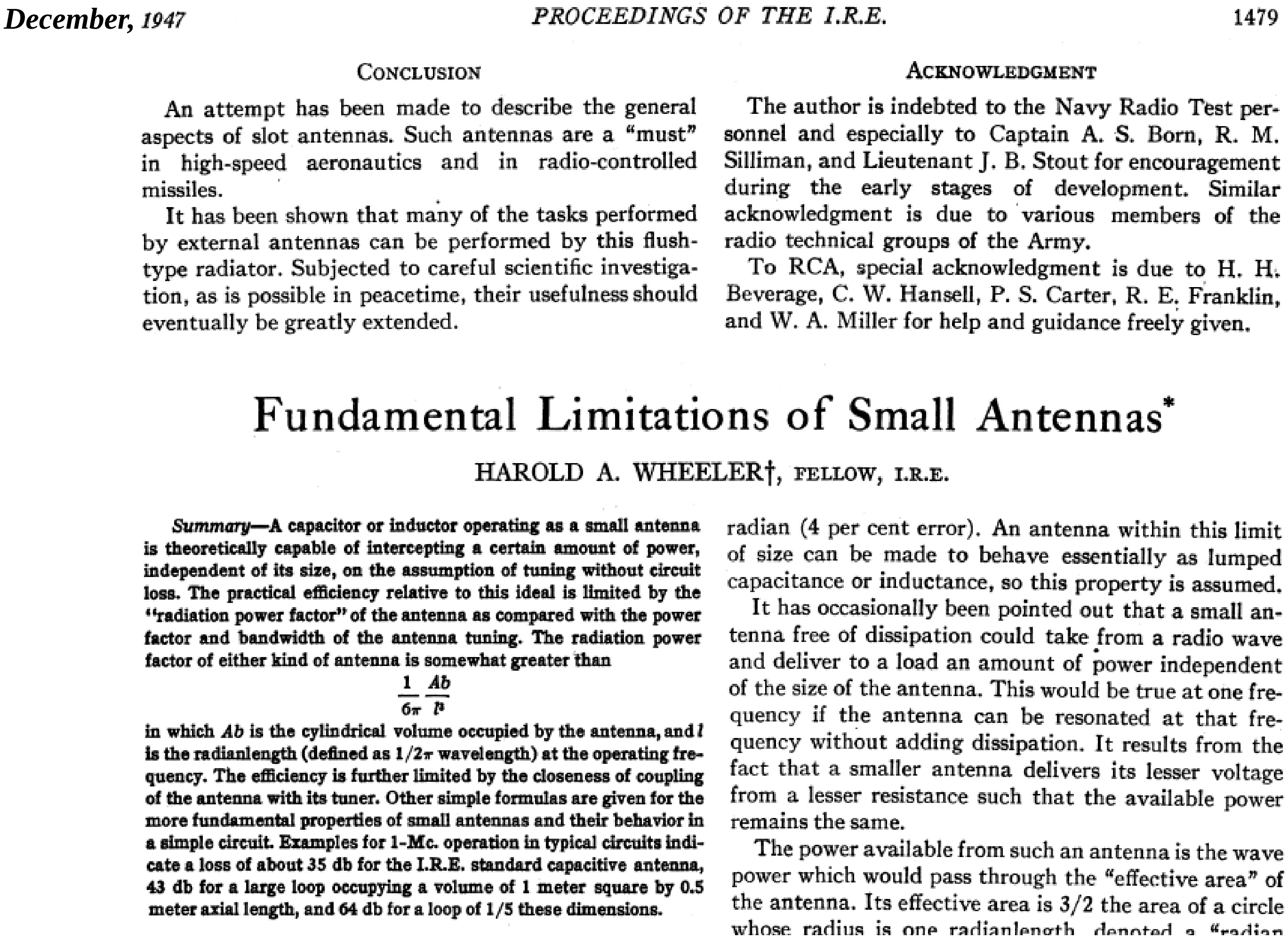
allows for correct power into R_{load}

impedance match at $R_{load} \approx R_{rad} + R_\Omega$



$$\text{Antenna Efficiency} = \frac{R_{radiation}}{R_{radiation} + R_\Omega} \approx \frac{R_{radiation}}{R_\Omega} < 1$$

Wheeler's Limit: (1947)



December, 1947 PROCEEDINGS OF THE I.R.E. 1479

CONCLUSION

An attempt has been made to describe the general aspects of slot antennas. Such antennas are a "must" in high-speed aeronautics and in radio-controlled missiles.

It has been shown that many of the tasks performed by external antennas can be performed by this flush-type radiator. Subjected to careful scientific investigation, as is possible in peacetime, their usefulness should eventually be greatly extended.

ACKNOWLEDGMENT

The author is indebted to the Navy Radio Test personnel and especially to Captain A. S. Born, R. M. Silliman, and Lieutenant J. B. Stout for encouragement during the early stages of development. Similar acknowledgment is due to various members of the radio technical groups of the Army.

To RCA, special acknowledgment is due to H. H. Beverage, C. W. Hansell, P. S. Carter, R. E. Franklin, and W. A. Miller for help and guidance freely given.

Fundamental Limitations of Small Antennas*

HAROLD A. WHEELER†, FELLOW, I.R.E.

***Summary*—A capacitor or inductor operating as a small antenna is theoretically capable of intercepting a certain amount of power, independent of its size, on the assumption of tuning without circuit loss. The practical efficiency relative to this ideal is limited by the "radiation power factor" of the antenna as compared with the power factor and bandwidth of the antenna tuning. The radiation power factor of either kind of antenna is somewhat greater than**

$$\frac{1}{6\pi}\frac{Ab}{l^3}$$

in which Ab is the cylindrical volume occupied by the antenna, and l is the radianlength (defined as $1/2\pi$ wavelength) at the operating frequency. The efficiency is further limited by the closeness of coupling of the antenna with its tuner. Other simple formulas are given for the more fundamental properties of small antennas and their behavior in a simple circuit. Examples for 1-Mc. operation in typical circuits indicate a loss of about 35 db for the I.R.E. standard capacitive antenna, 43 db for a large loop occupying a volume of 1 meter square by 0.5 meter axial length, and 64 db for a loop of 1/5 these dimensions.

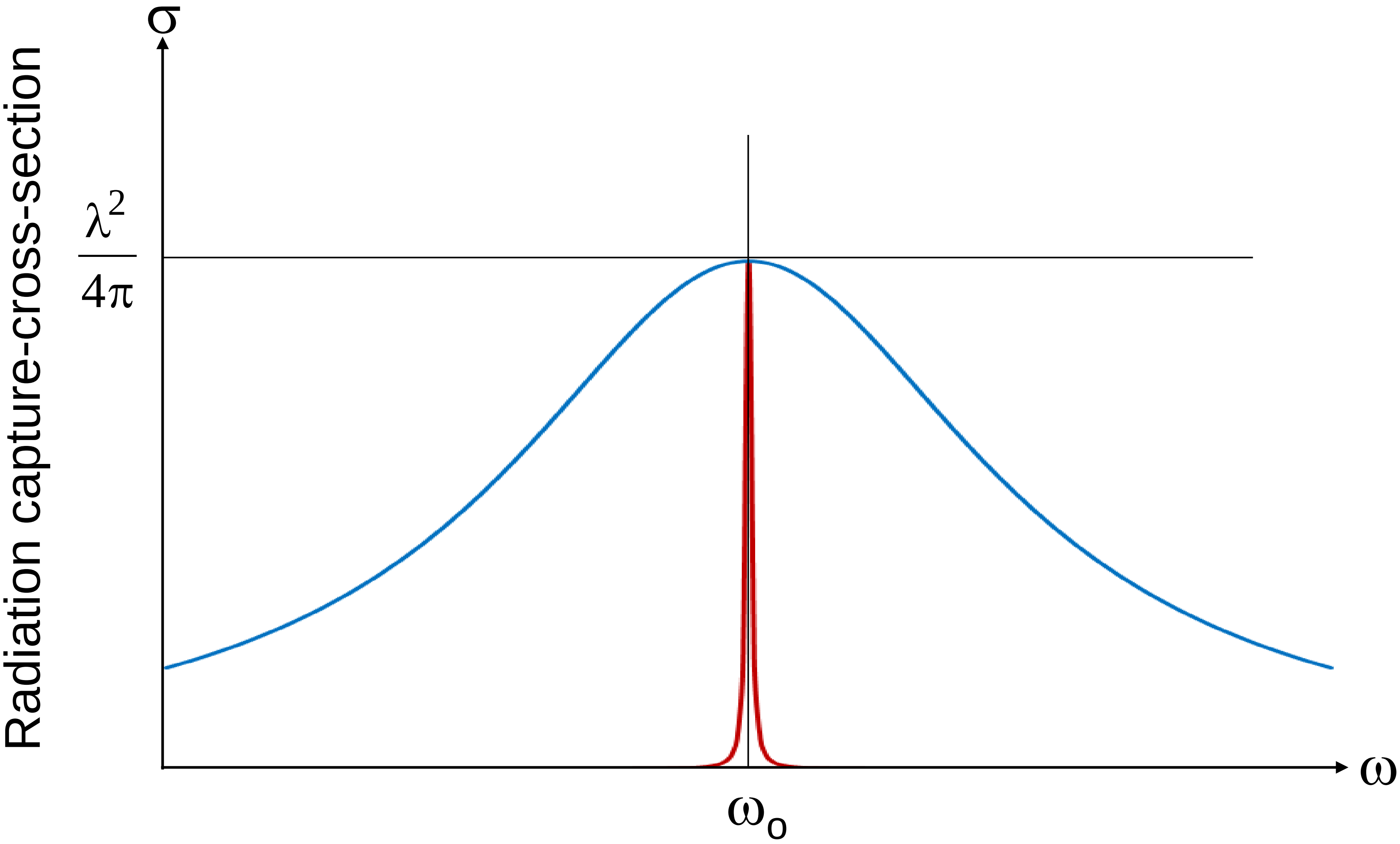
radian (4 per cent error). An antenna within this limit of size can be made to behave essentially as lumped capacitance or inductance, so this property is assumed.

It has occasionally been pointed out that a small antenna free of dissipation could take from a radio wave and deliver to a load an amount of power independent of the size of the antenna. This would be true at one frequency if the antenna can be resonated at that frequency without adding dissipation. It results from the fact that a smaller antenna delivers its lesser voltage from a lesser resistance such that the available power remains the same.

The power available from such an antenna is the wave power which would pass through the "effective area" of the antenna. Its effective area is 3/2 the area of a circle whose radius is one radianlength, denoted a "radian

The most important electromagnetic equation that does NOT appear in Jackson:

$$Q_{rad} \approx \frac{3}{4\pi^2}\left(\frac{\lambda^3}{a^3}\right)$$



1. Every piece of metal is an LC resonator—
2. Every LC resonator is an antenna, penalty is bandwidth.

NEWS / MEDIA

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Ethertronics Ships 500 Millionth Embedded Antenna

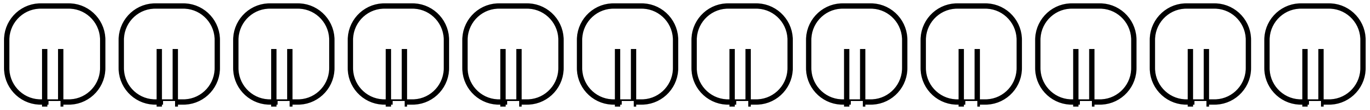
+ Samsung Galaxy 3S

Technology Company Gains Momentum as Demand for its Innovative Antenna Solutions Grows

SAN DIEGO, Calif. - January 17, 2012- Ethertronics, a leading technology company enabling innovative antenna and RF system solutions to deliver the best connected experience, today announced it shipped its 500 millionth antenna in the fourth quarter of 2011, further underscoring the company's position as a market leader in the industry.

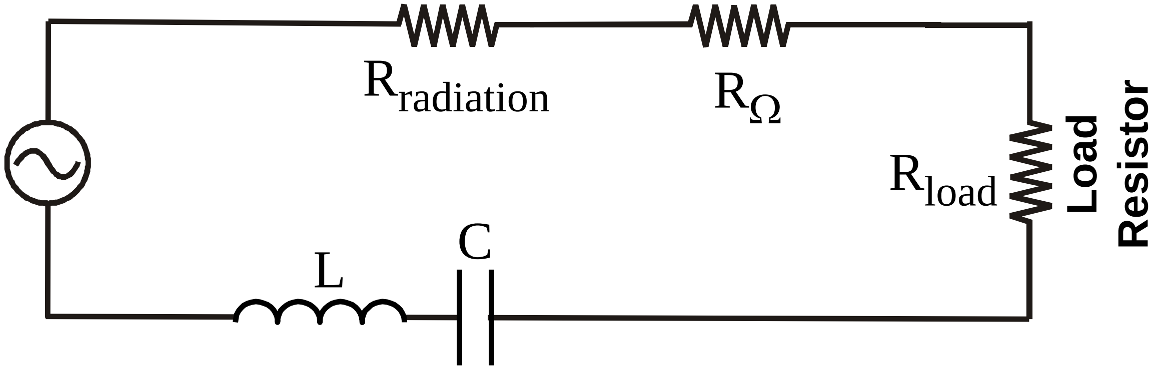
1. There are creative insights from the Meta-Material viewpoint.

There are many amazing new properties in meta-materials.



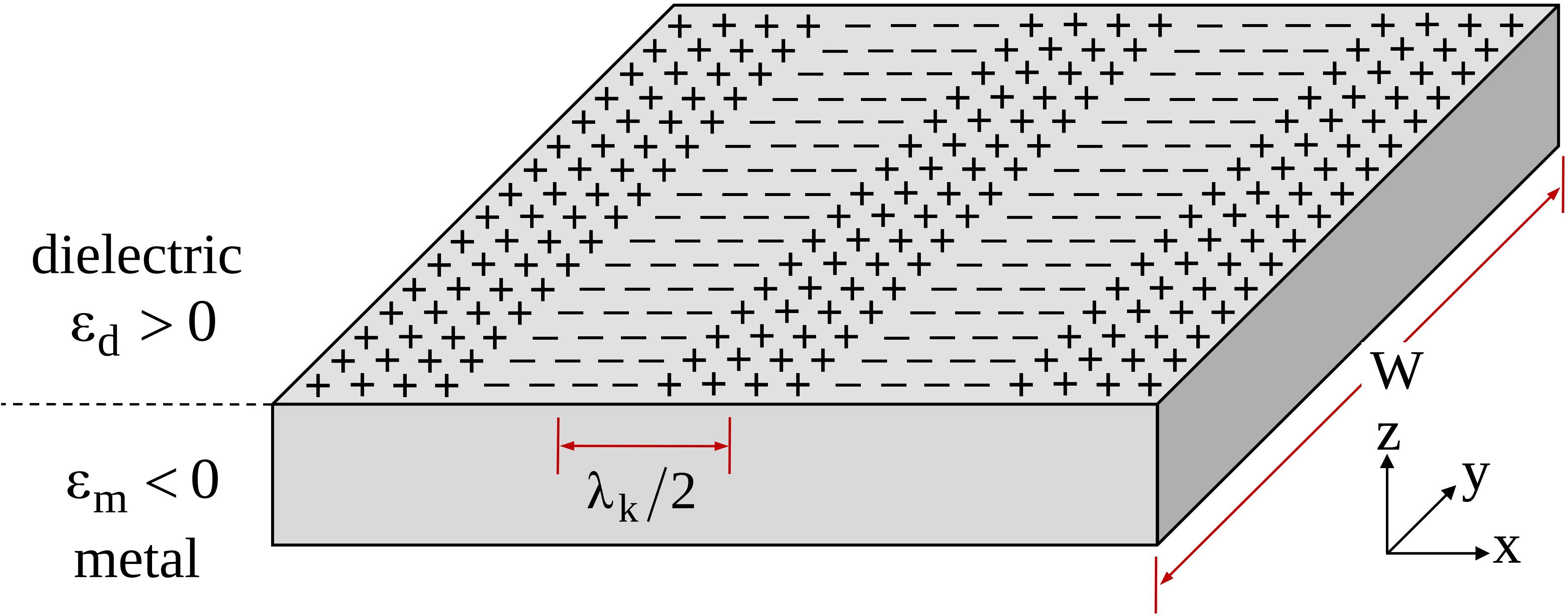
2. There are creative insights from the Circuit viewpoint.

There are many amazing new properties in optical circuits.



The circuit viewpoint is more general, since it doesn't
require repeating units, and
is every bit as amazing.

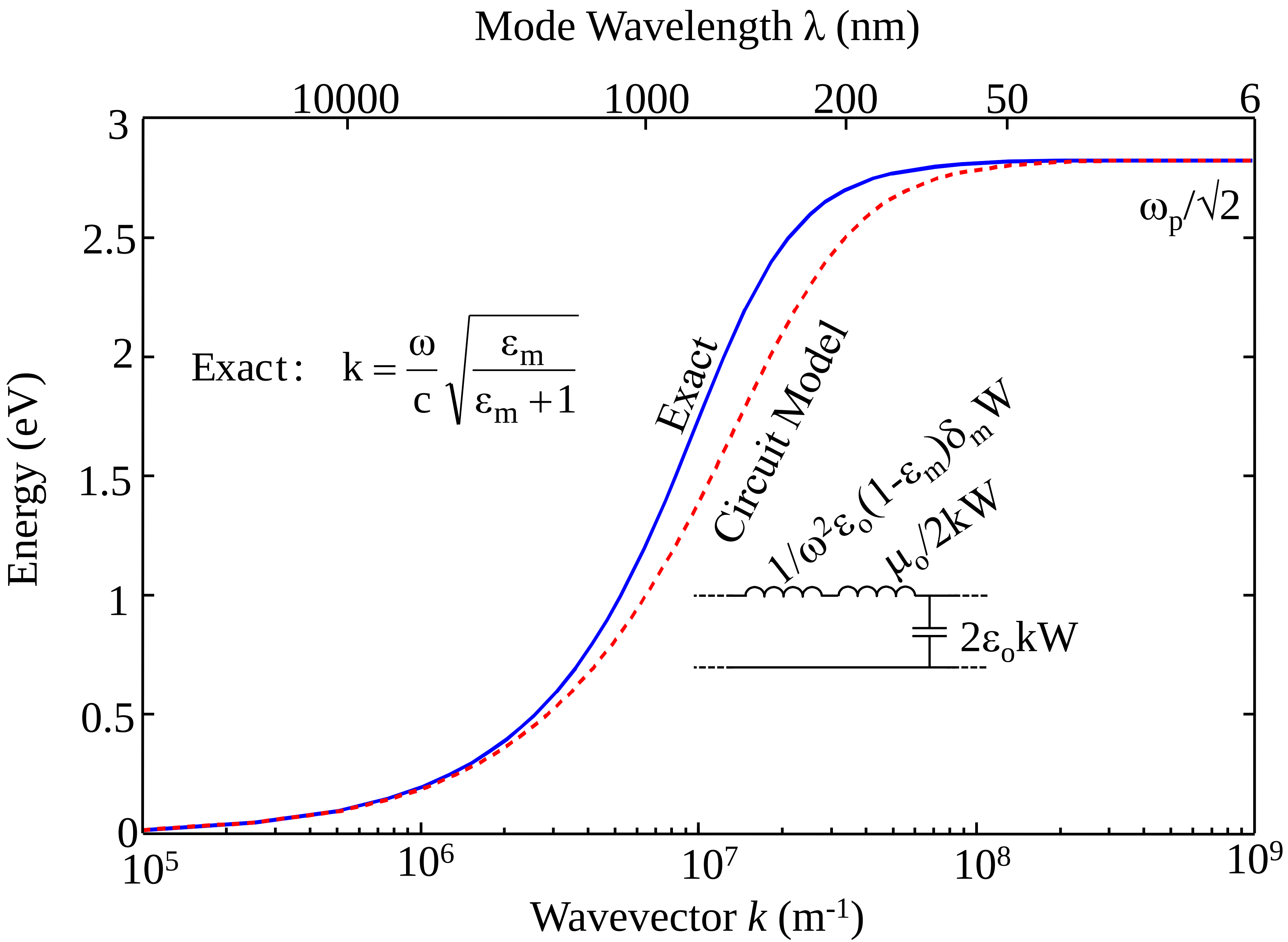
Proposal: unified name should be "Metal Optics".

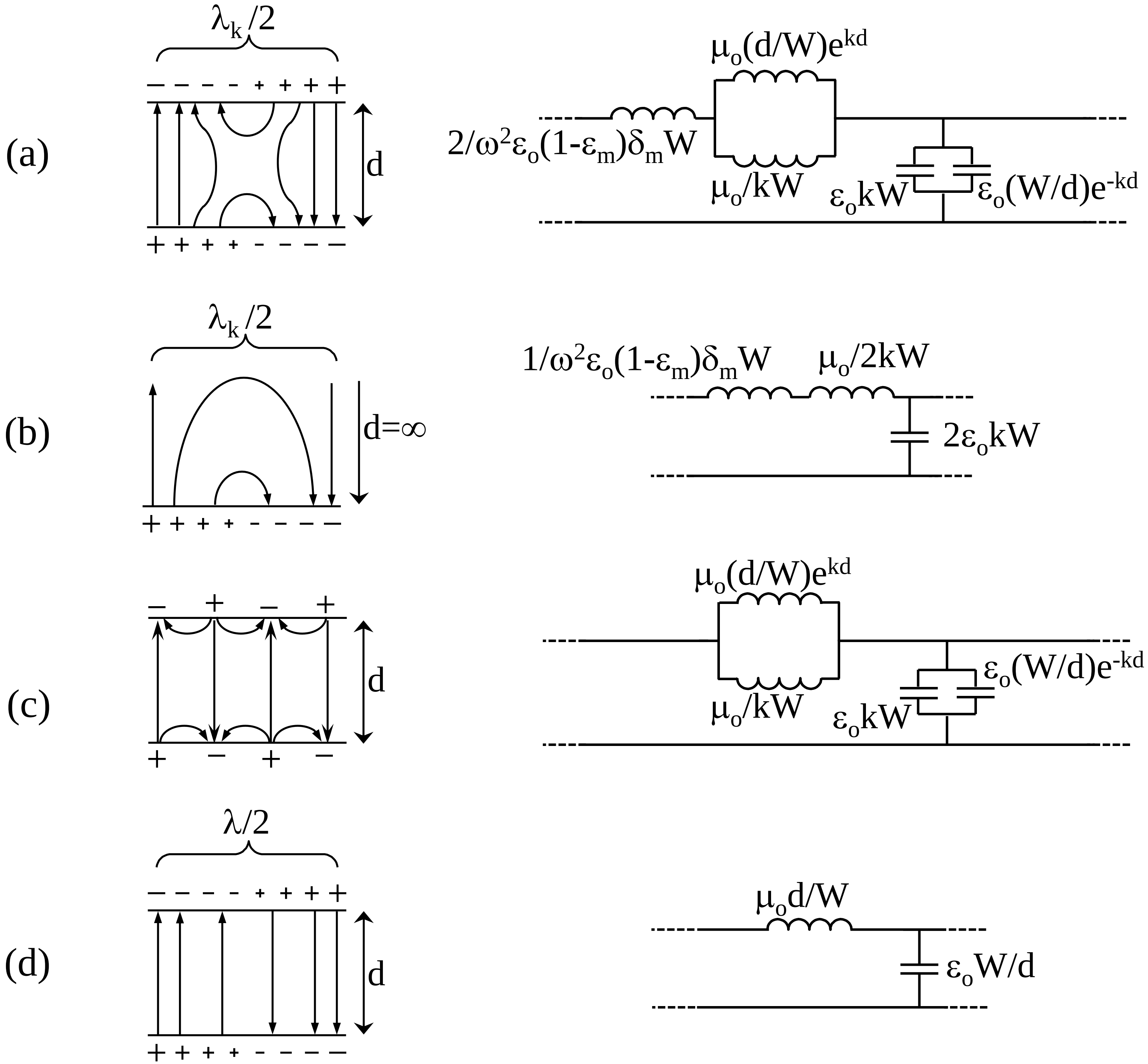


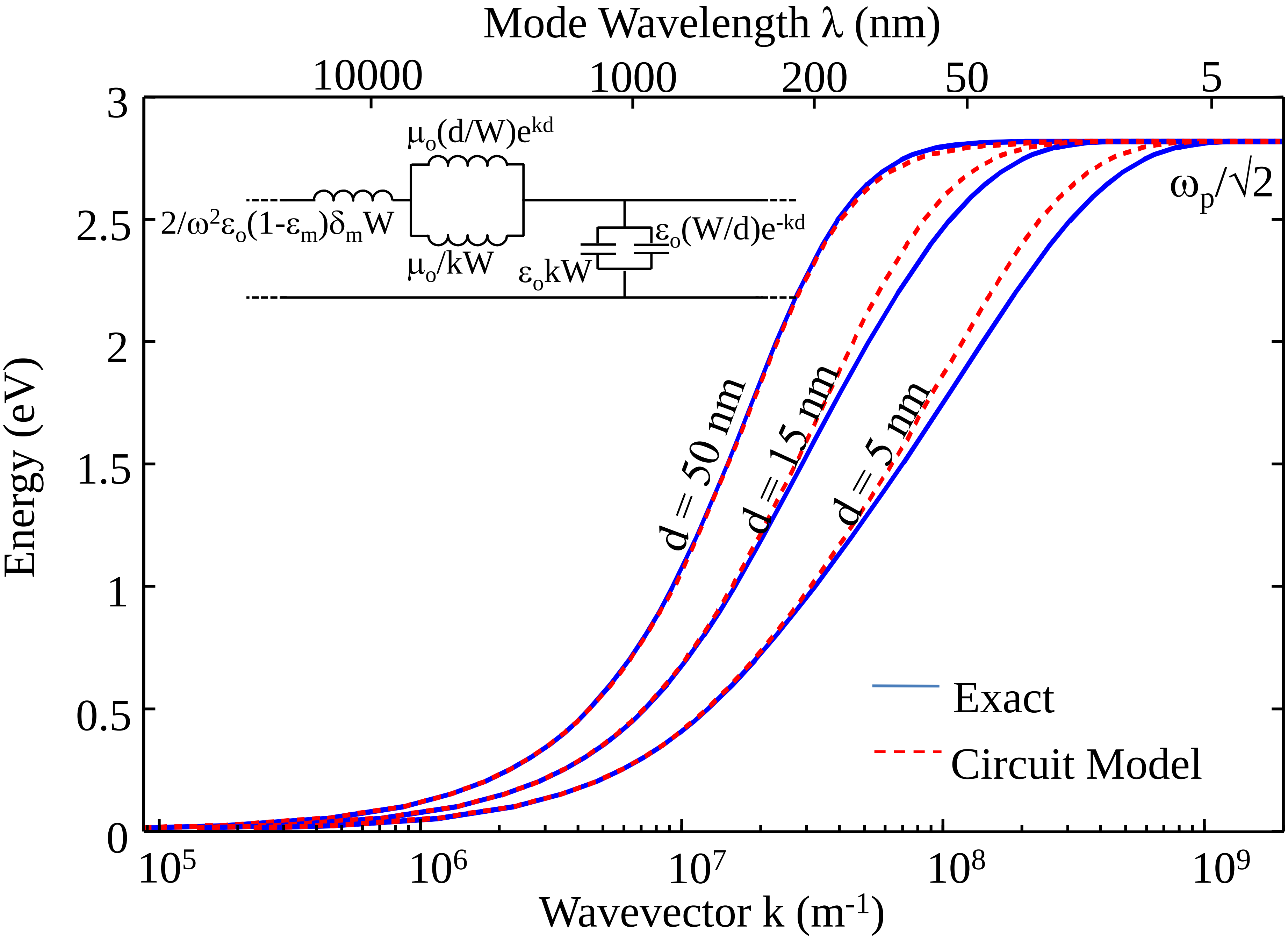
$$L'_k = \frac{1}{\varepsilon_o \omega_p^2} \cdot \frac{1}{W\,\delta_m}$$

After much electrostatic calculation: $C' = 2\varepsilon_o kW$

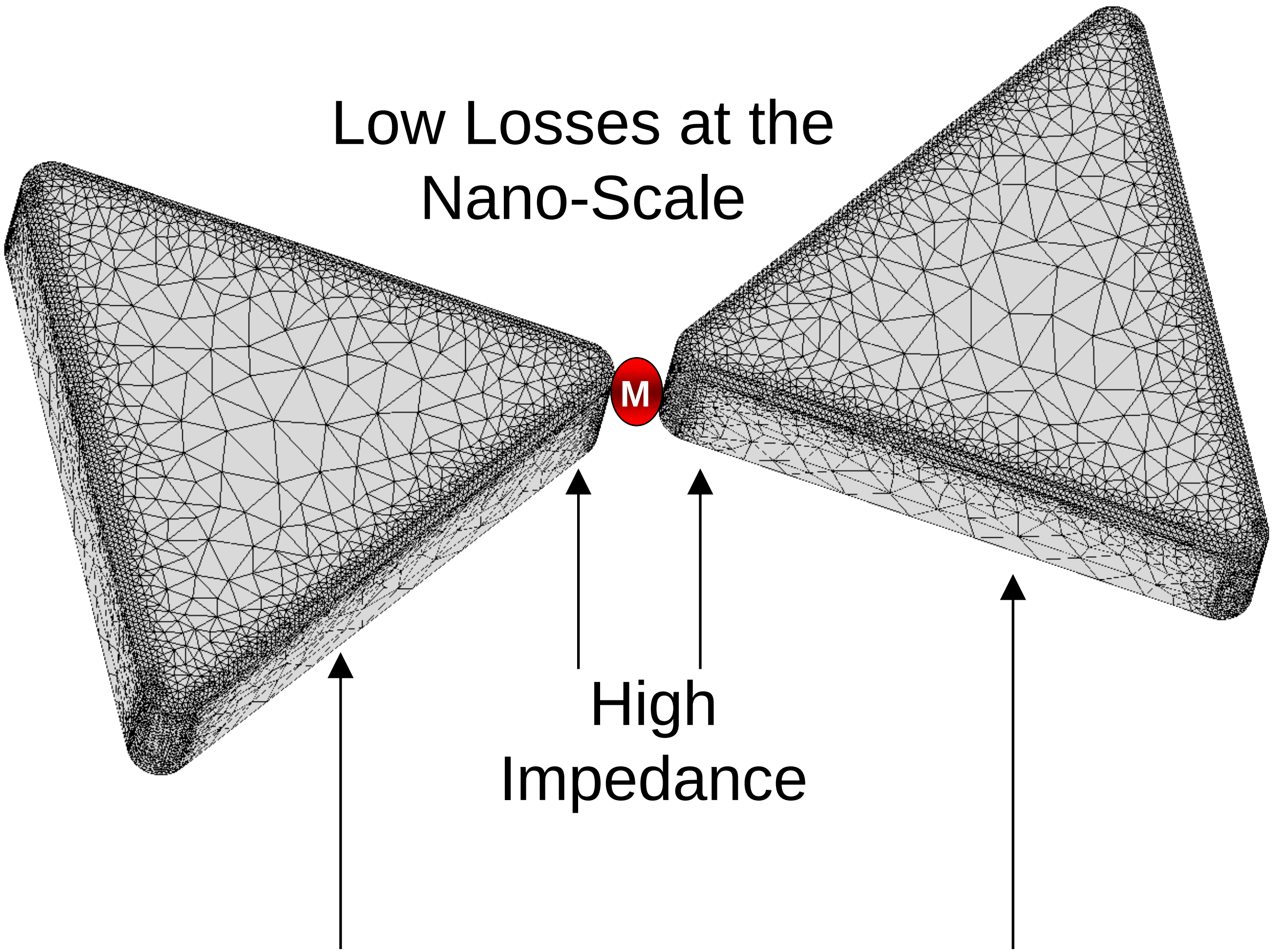
After much magnetostatic calculation: $L'_F = \mu_o/2kW$


Mode Wavelength λ (nm)
10000
1000
200
50
6
3
2.5
2
1.5
1
0.5
0
Energy (eV)
$\omega_p/\sqrt{2}$
Exact: $k = \frac{\omega}{c}\sqrt{\frac{\varepsilon_m}{\varepsilon_m + 1}}$
Exact
Circuit Model
$1/\omega^2\varepsilon_o(1-\varepsilon_m)\delta_m W$
$\mu_o/2kW$
$2\varepsilon_o kW$
10^5
10^6
10^7
10^8
10^9
Wavevector k (m^{-1})


(a)
λk/2
– – – - + + + +
+ + + + - – – –
d
μo(d/W)e^kd
2/ω²εo(1-εm)δmW
μo/kW
εokW
εo(W/d)e^-kd
(b)
λk/2
d=∞
+ + + + - – – –
1/ω²εo(1-εm)δmW
μo/2kW
2εokW
(c)
– + – +
+ – + –
d
μo(d/W)e^kd
μo/kW
εokW
εo(W/d)e^-kd
(d)
λ/2
– – – - + + + +
+ + + + - – – –
d
μod/W
εoW/d


Mode Wavelength λ (nm)
10000
1000
200
50
5
3
2.5
2
1.5
1
0.5
0
Energy (eV)
$\mu_o(d/W)e^{kd}$
$2/\omega^2\varepsilon_o(1-\varepsilon_m)\delta_m W$
μ_o/kW
$\varepsilon_o kW$
$\varepsilon_o(W/d)e^{-kd}$
$\omega_p/\sqrt{2}$
d = 50 nm
d = 15 nm
d = 5 nm
Exact
Circuit Model
10^5
10^6
10^7
10^8
10^9
Wavevector k (m^{-1})

Plasmonic Effect on Antennas:

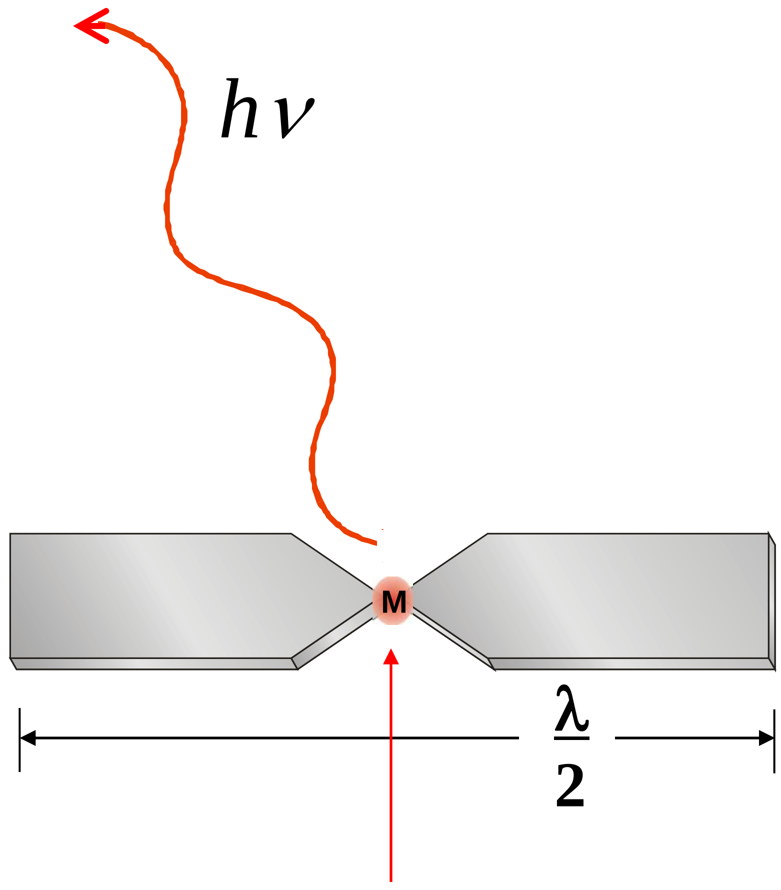


Low Losses at the Nano-Scale

High Impedance

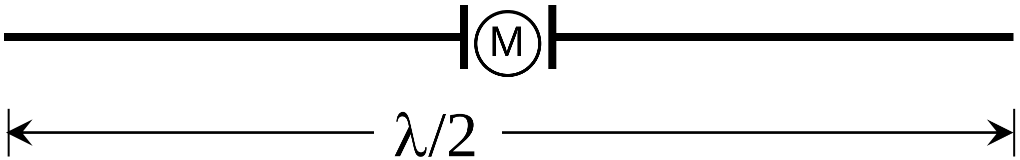
Normal Impedance <377Ω

Spontaneous Emission Enhancement, molecules attached to optical antennas



molecule or quantum dot

Power Radiated by a molecule in an antenna:



$$P = I^2 R$$

$$P = (q\omega/2\pi)^2 R$$

Ⓜ ≡ molecule

$$\frac{1}{\tau_{sp}} \equiv \frac{P}{\hbar\omega} = \frac{(q\omega)^2}{(2\pi)^2\hbar\omega} \times \sqrt{\frac{\mu_o}{\varepsilon_o}}$$

What is the fastest speed of spontaneous emission?

$$\frac{1}{\omega\tau_{sp}} = \frac{P}{\hbar\omega^2} = \frac{(q\omega)^2}{(2\pi)^2\hbar\omega^2} \times \sqrt{\frac{\mu_o}{\varepsilon_o}}\sqrt{\frac{\varepsilon_o}{\varepsilon_o}}$$

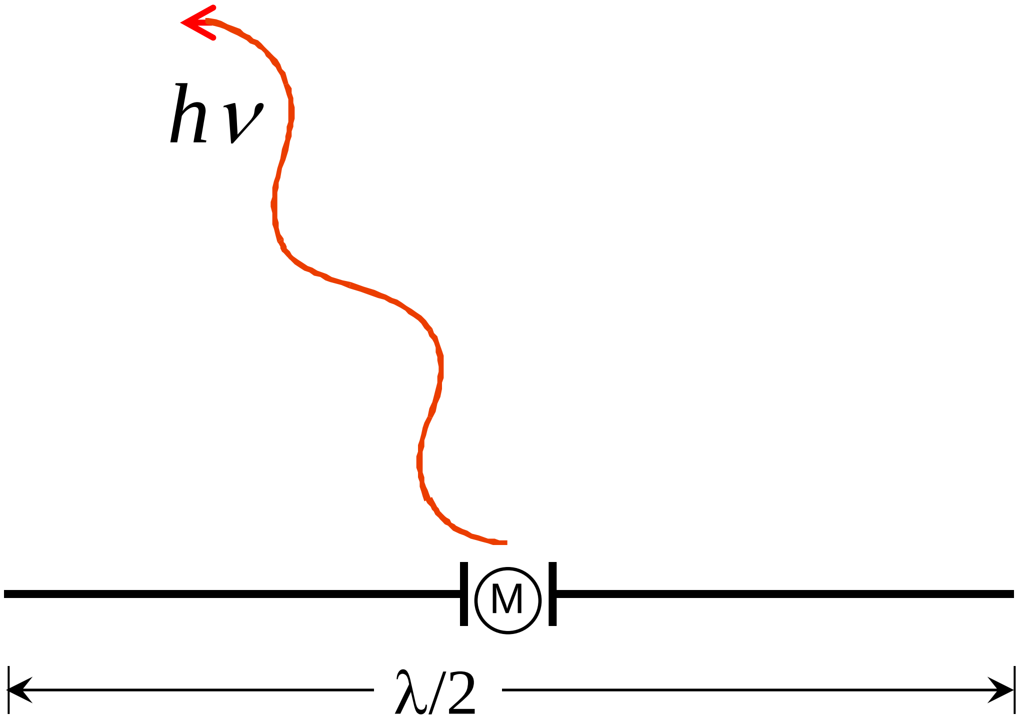
$$\frac{1}{\omega\tau_{sp}} = \frac{q^2}{(2\pi)^2\hbar} \times \frac{\sqrt{\mu_o\varepsilon_o}}{\varepsilon_o}$$

$$\alpha \equiv \frac{q^2}{4\pi\varepsilon_o\hbar c} \equiv \frac{1}{137}$$

Fine Structure Constant

$$\frac{1}{\omega\tau_{sp}} = \frac{q^2}{4\pi^2\varepsilon_o\hbar c} = \frac{1}{\pi}\left\{\frac{q^2}{4\pi\varepsilon_o\hbar c}\right\}$$

$$\frac{1}{\omega\tau_{sp}} = \frac{\alpha}{\pi} = \frac{1}{\pi} \times \frac{1}{137}$$



$$\frac{1}{\tau_{\mathrm{sp}}} = \frac{2}{137} \times \nu$$

With the aid of an antenna
spontaneous emission can be really fast!

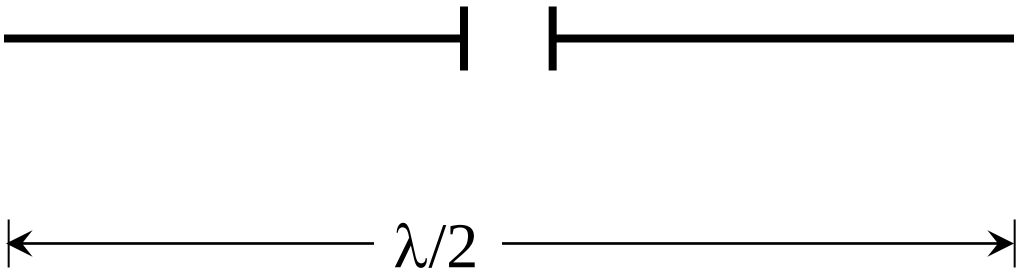
Spontaneous Emission
can be faster
than Stimulated Emission!

Spontaneous Emission rates
can compete with the radiation frequency, ω_o , itself!

How can Spontaneous Emission possibly be Faster than Stimulated Emission?

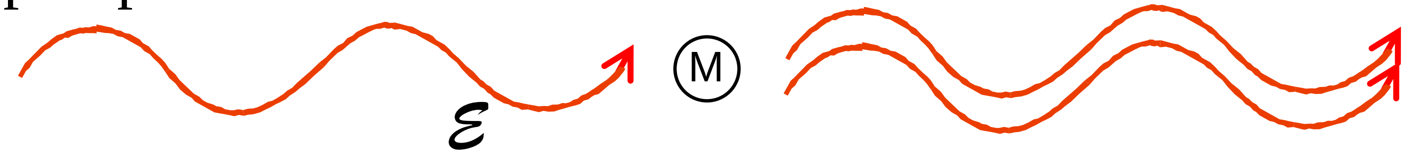
spontaneous emission:

zero point electric field: $\mathcal{E}_o$



stimulated emission:

Real pump electric field



Data-Communications	Modulation Speed:
Light Emitting Diode	200Mb/s
Edge Emitting laser	50Gb/s
VCSEL laser	25Gb/s

while maintaining good efficiency and reliability

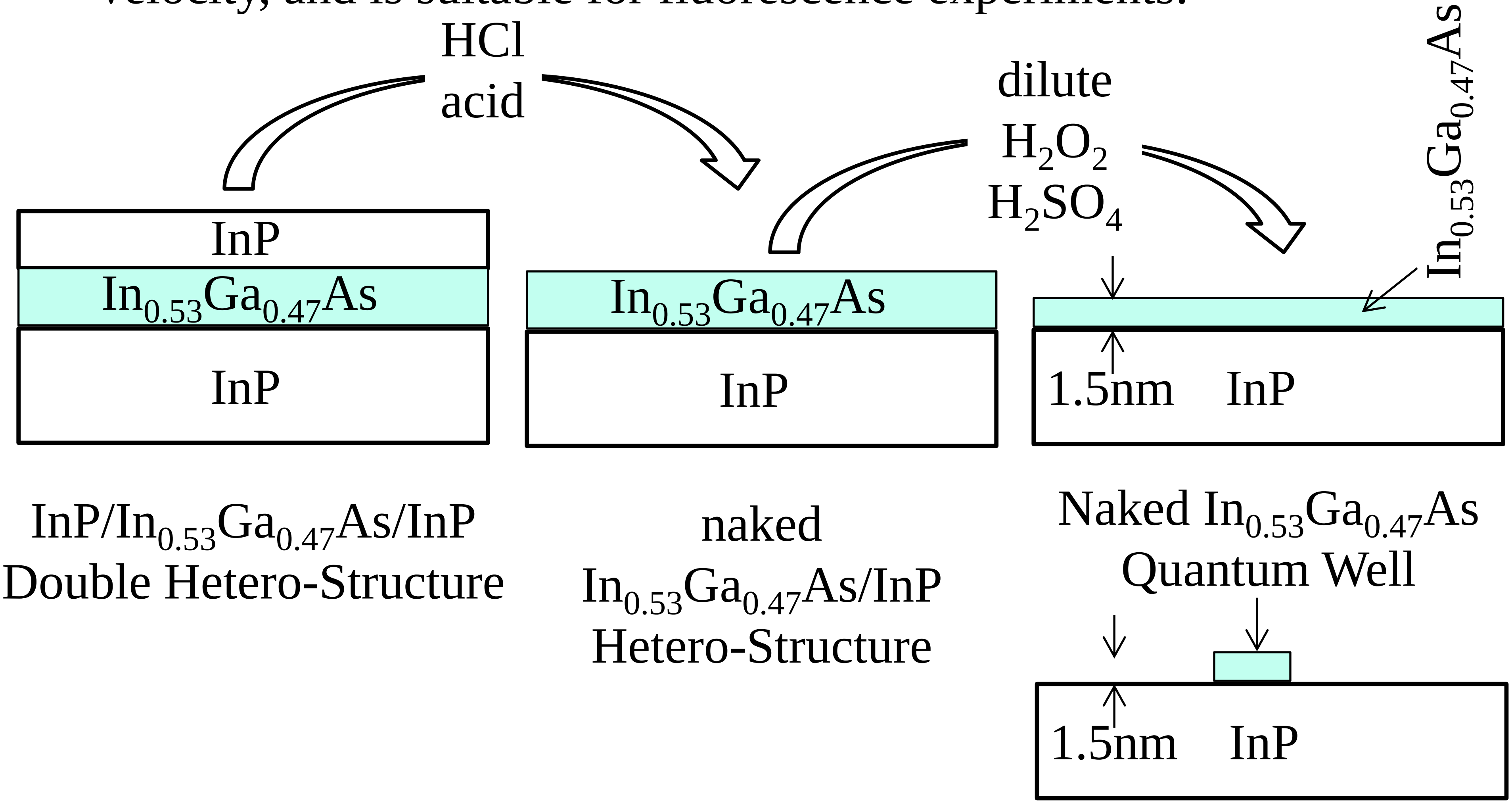
A 200X speed up of Spontaneous Emission
would make the LED
faster than the Laser!

Applications:

1. Direct modulation speed of nano-LED's for interconnects will be >100Gbits/sec

2. Many substances that do not fluoresce, will radiate efficiently when placed near an antenna structure. This has implications for bio-sensors, etc.

Bare $In_{0.53}Ga_{0.47}As$ has a low surface recombination velocity, and is suitable for fluorescence experiments:



HCl acid

dilute H_2O_2 H_2SO_4

InP

$In_{0.53}Ga_{0.47}As$

InP

$In_{0.53}Ga_{0.47}As$

InP

$In_{0.53}Ga_{0.47}As$

1.5nm InP

InP/$In_{0.53}Ga_{0.47}As$/InP
Double Hetero-Structure

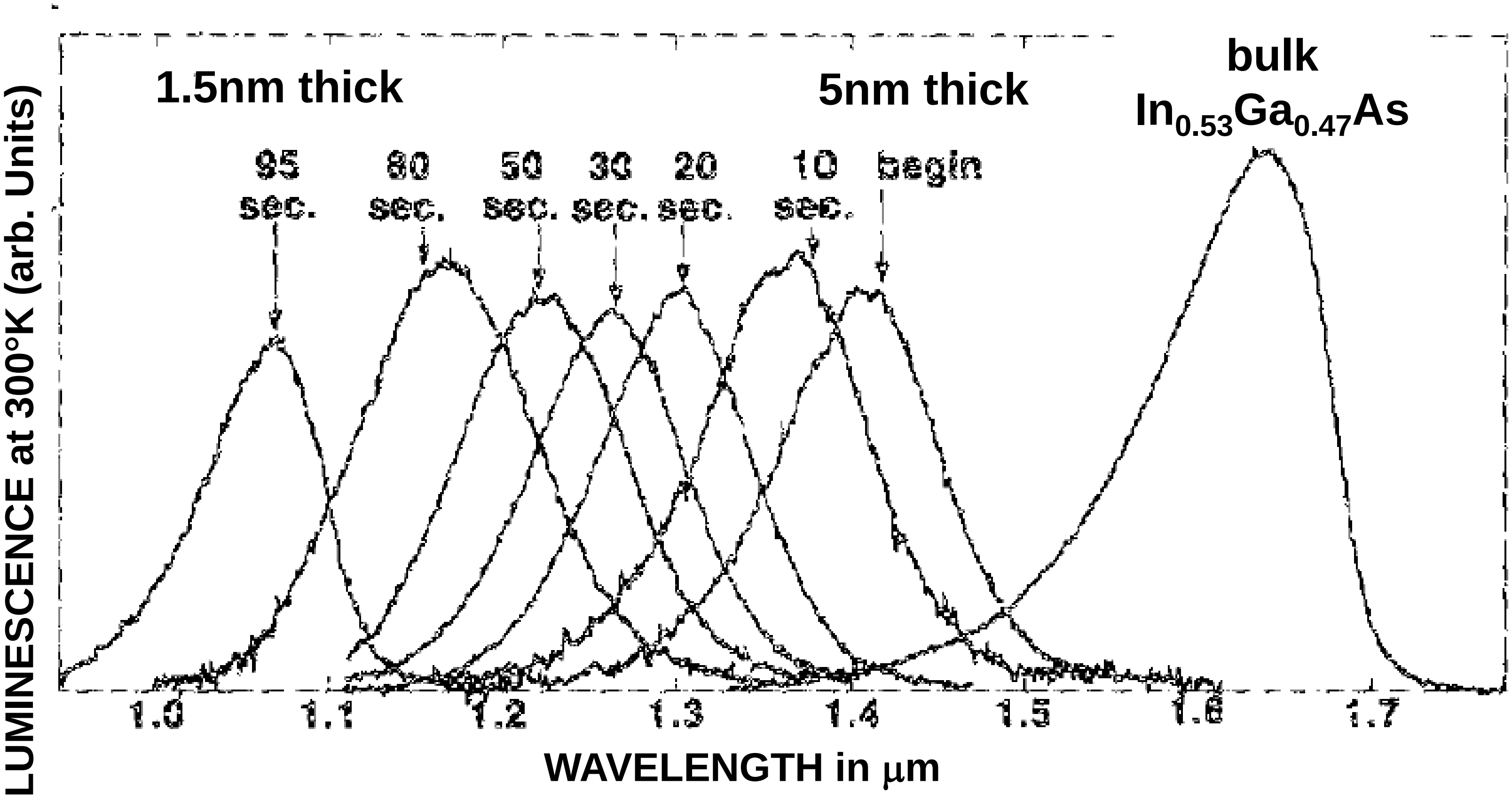
naked
$In_{0.53}Ga_{0.47}As$/InP
Hetero-Structure

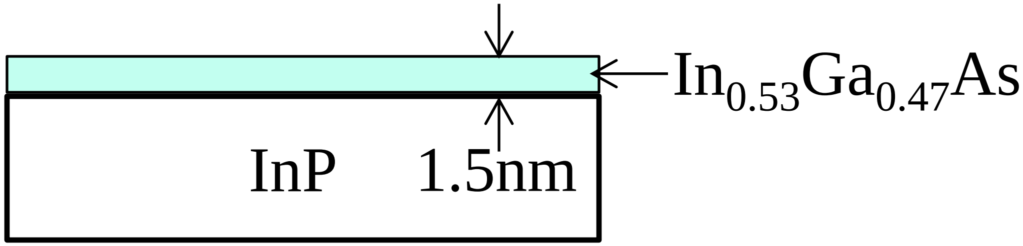
Naked $In_{0.53}Ga_{0.47}As$
Quantum Well

1.5nm InP

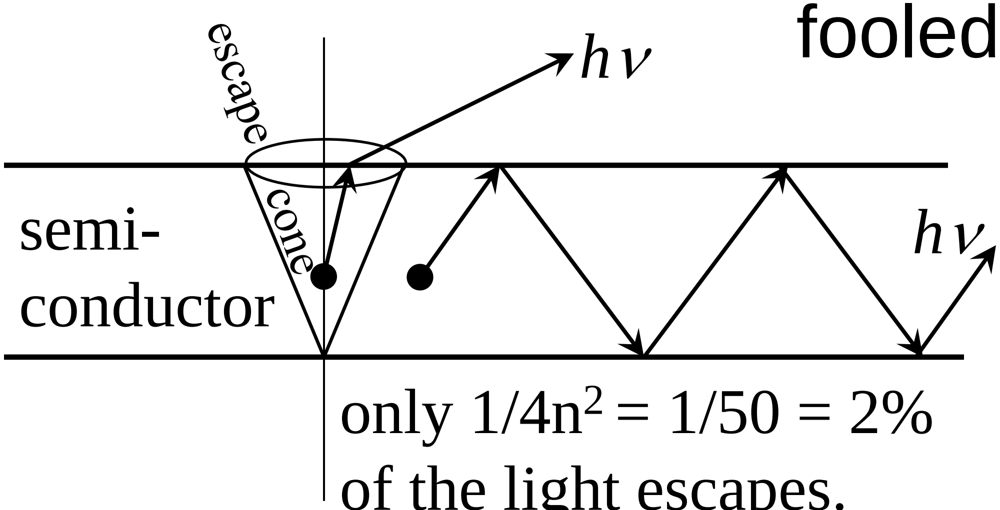
Nearly Ideal Electronic Surfaces on Naked $In_{0.53}Ga_{0.47}As$ Quantum Wells
E. Yablonovitch, H.M. Cox, and T.J. Gmitter, APL 52, 1002 (1988)

Naked $In_{0.53}Ga_{0.47}As$ Quantum Well Photo-Luminescence





It is important to remove the substrate, to not be fooled by Light Extraction:

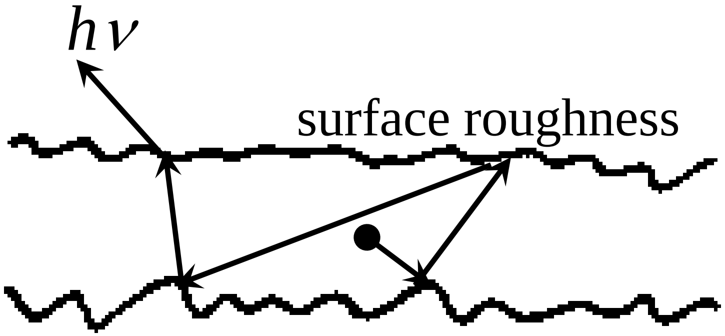


only $1/4n^2 = 1/50 = 2\%$ of the light escapes.

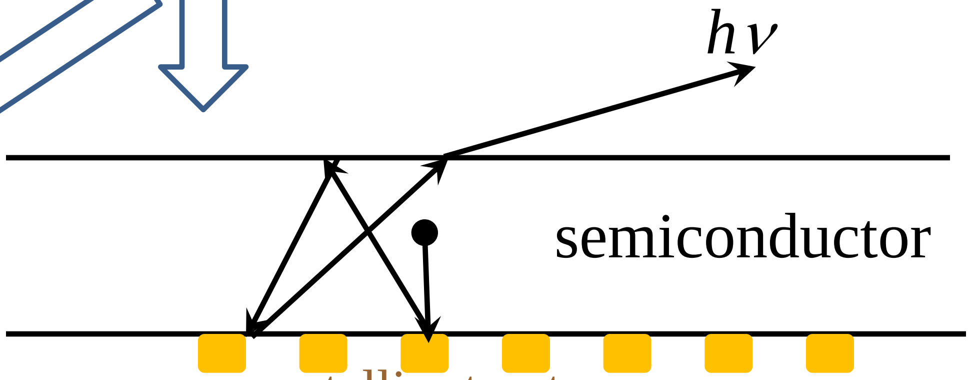
As a result of superior light extraction, light emitting diodes now have >50% external efficiency.

Not Spontaneous Emission Enhancement,
just superior light extraction.

New Light Emitting Diodes:

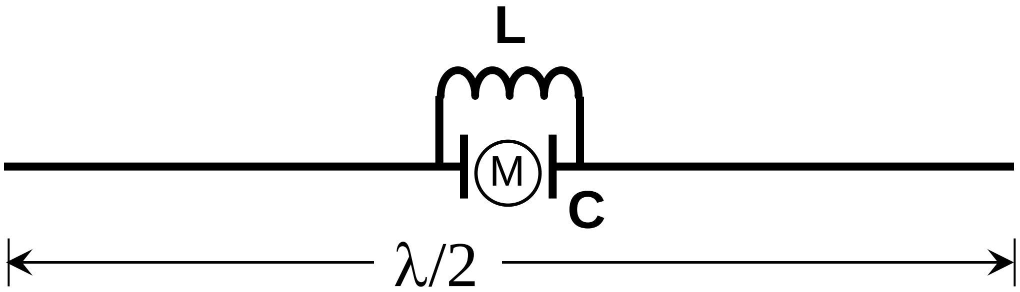


all the light eventually escapes.



metallic structures are equivalent to surface roughness

Even faster spontaneous emission rates:

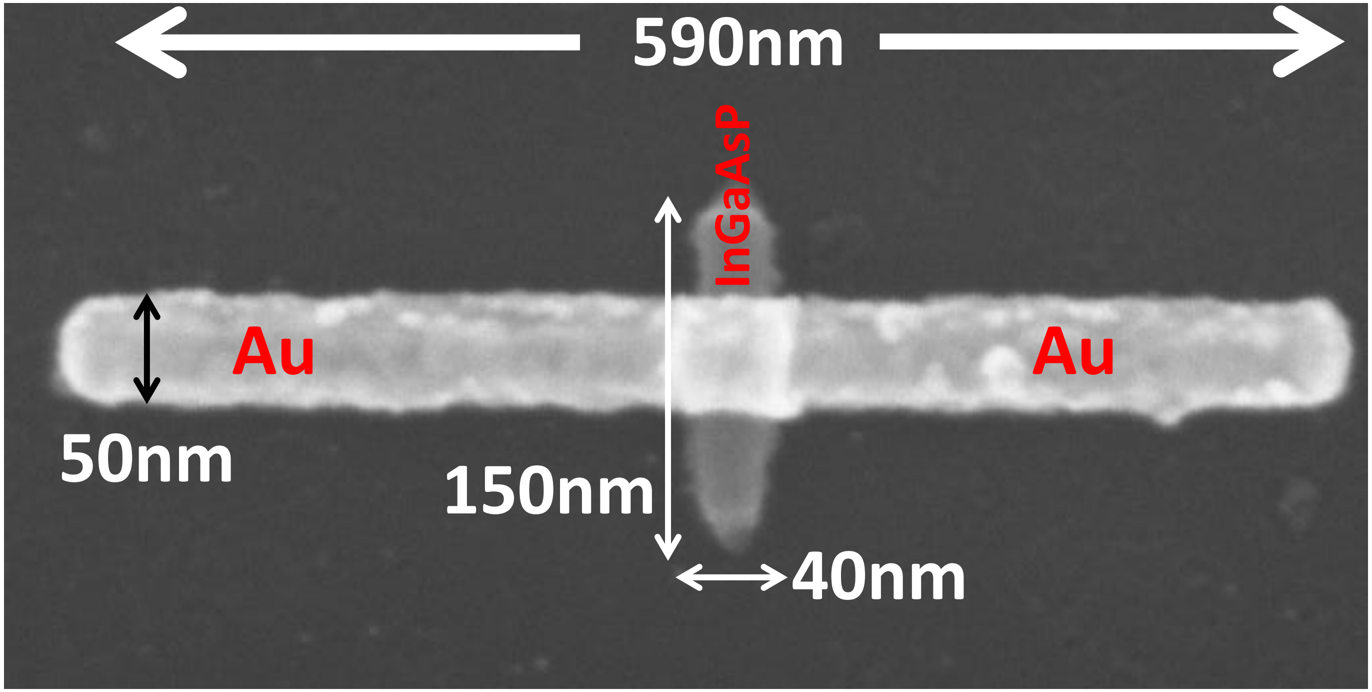


The **LC** resonator sharpens up the resonance and allows an even faster spontaneous emission rate via the Purcell Effect!

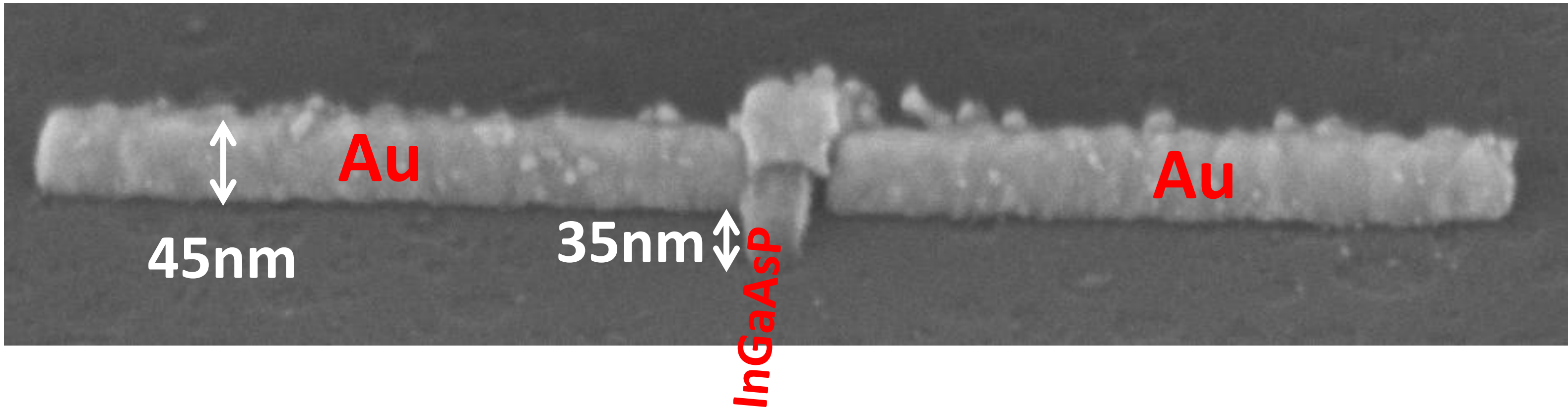
But this could also be regarded as an improved radiation by improved impedance-matching between the molecule and the antenna.

In cellphones, the **LC** circuit is called a "matching network"

Top View



Side View



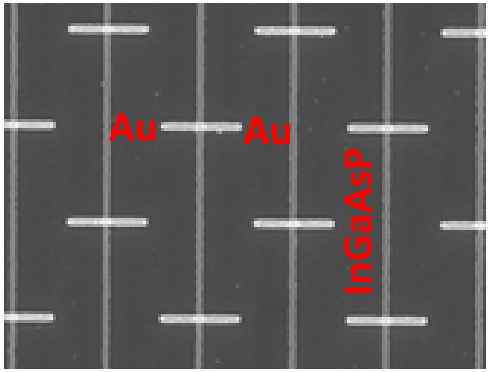
PL as Background Material is Reduced

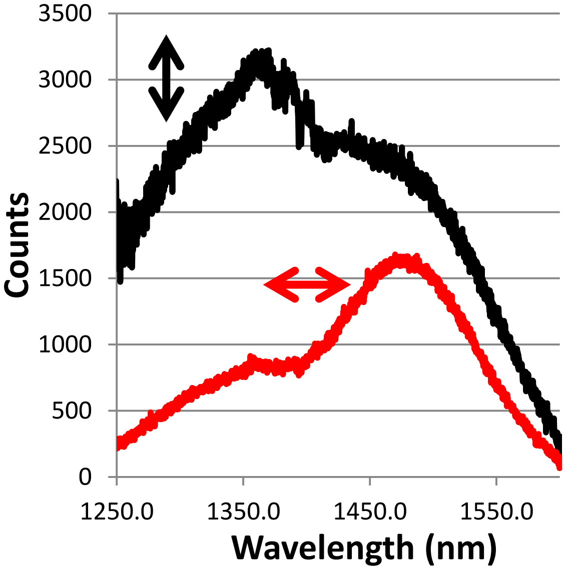
PL Perpendicular to Antenna

PL Parallel to Antenna

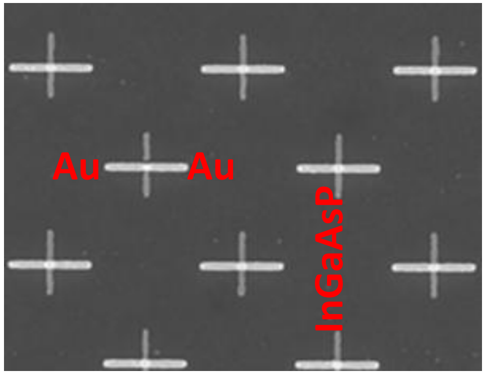
Pump Polarization

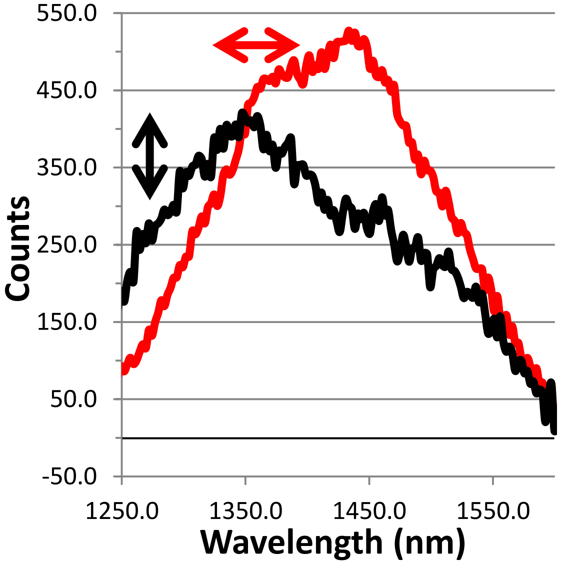
Continuous Ridges



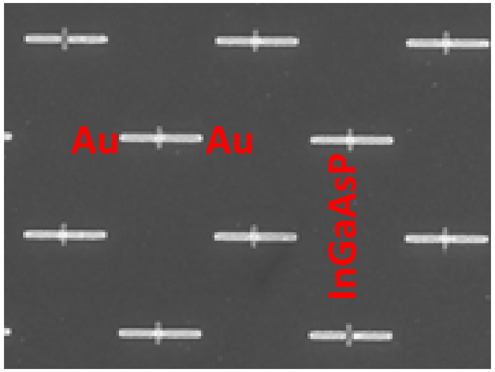


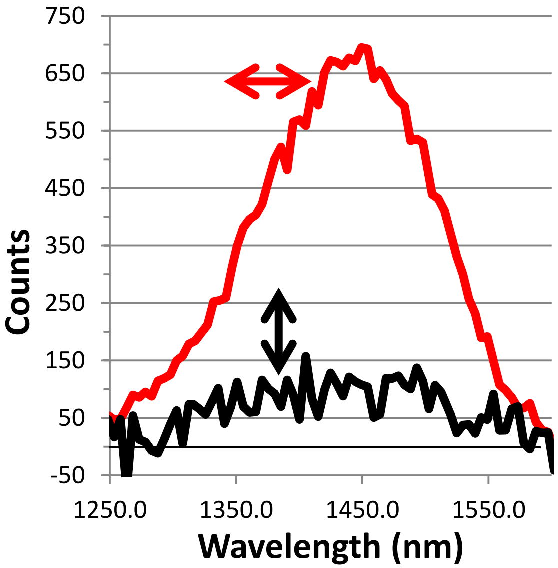
450nm Long Ridges

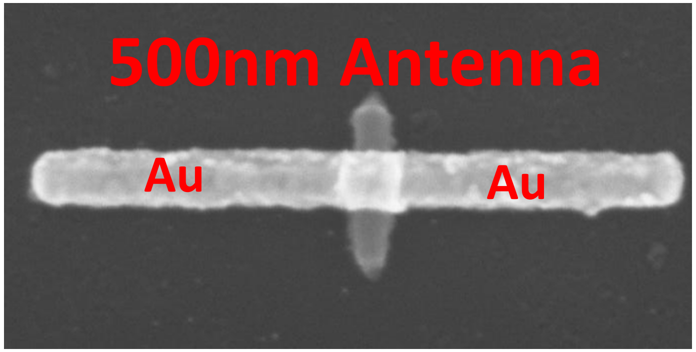


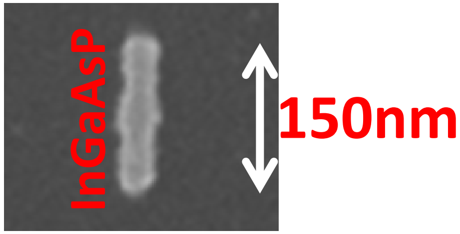


150nm Long Ridges

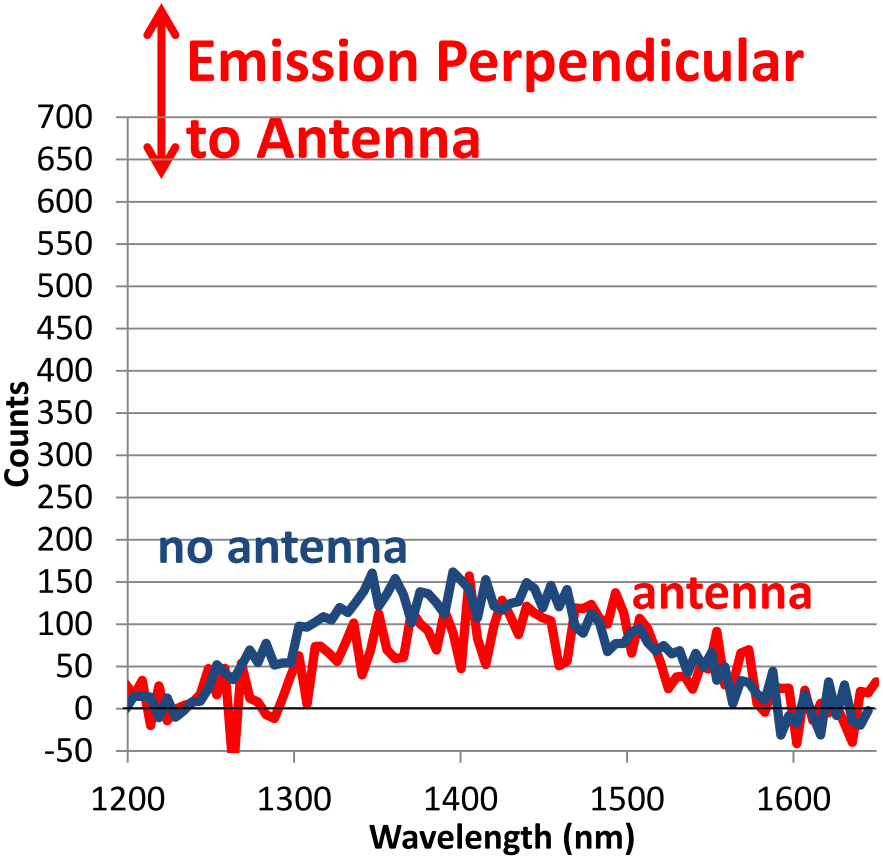


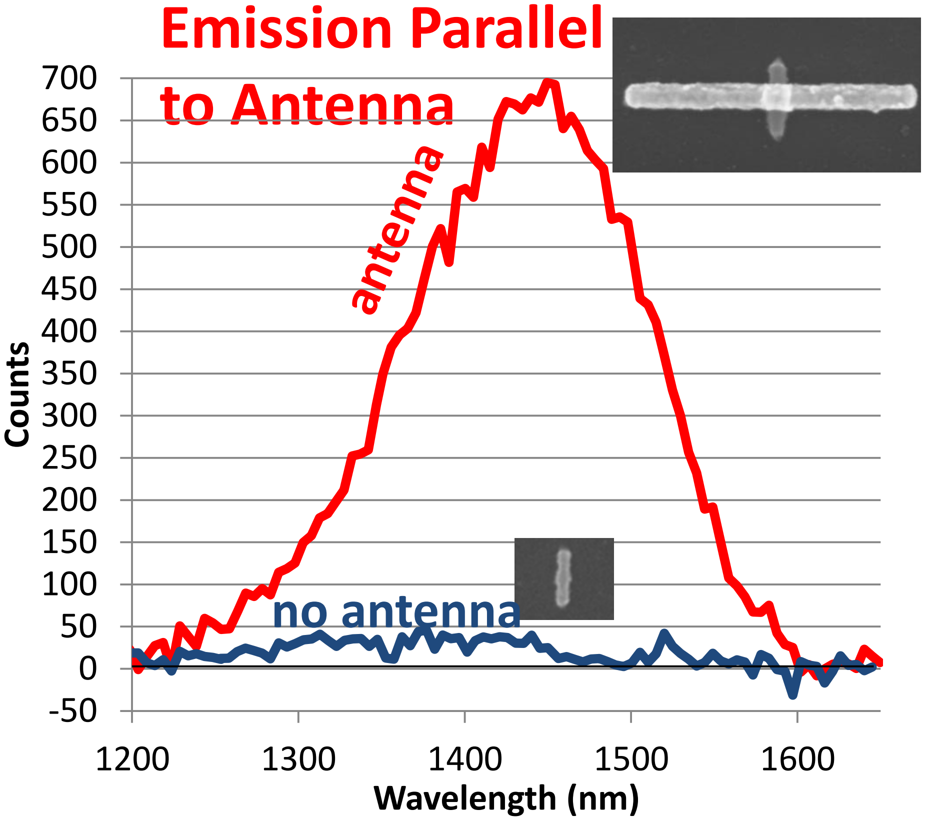




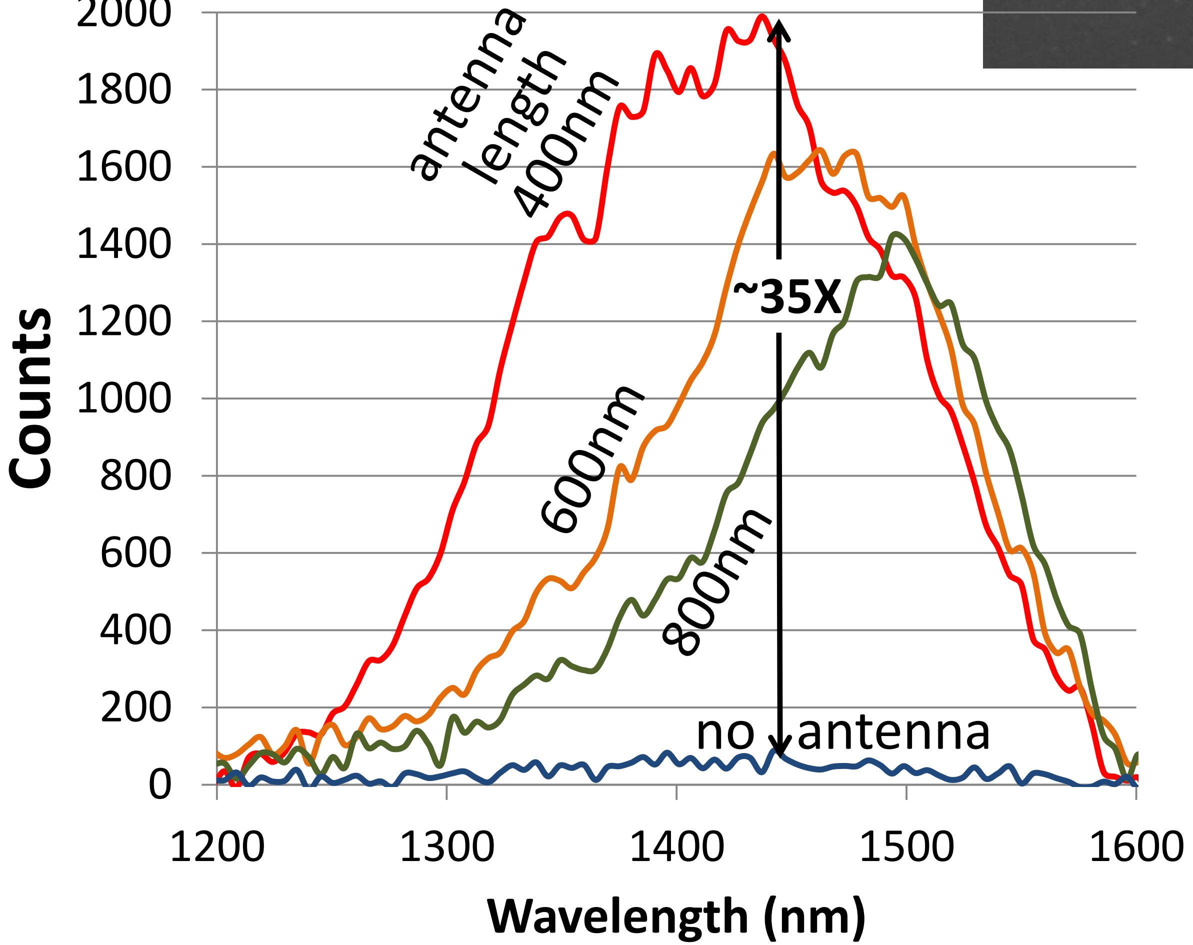


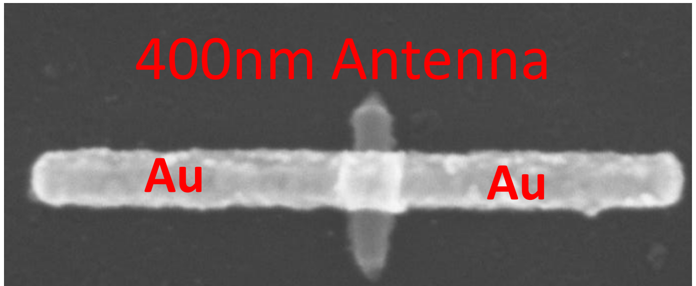
Pump Polarization





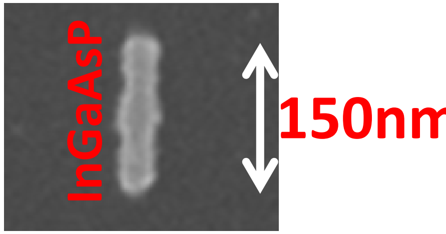
Emission Parallel to Antenna





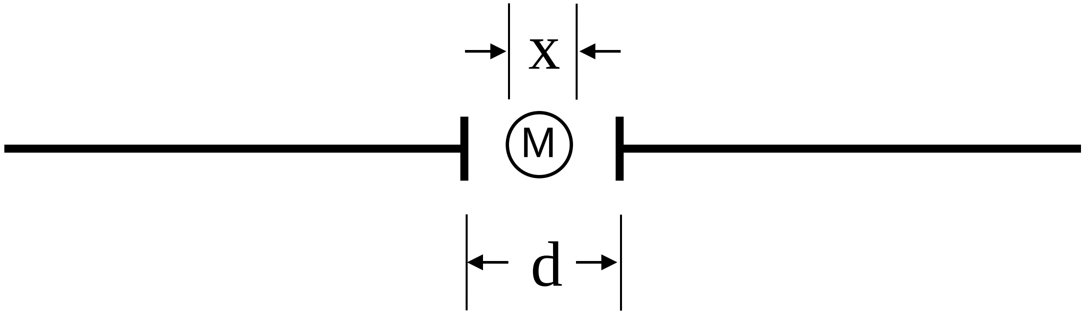
Pump Polarization

no antenna



~35X Spontaneous Emission Enhancement

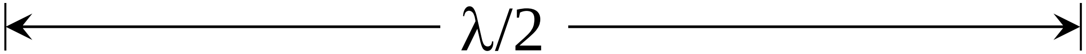
The main experimental limitation:



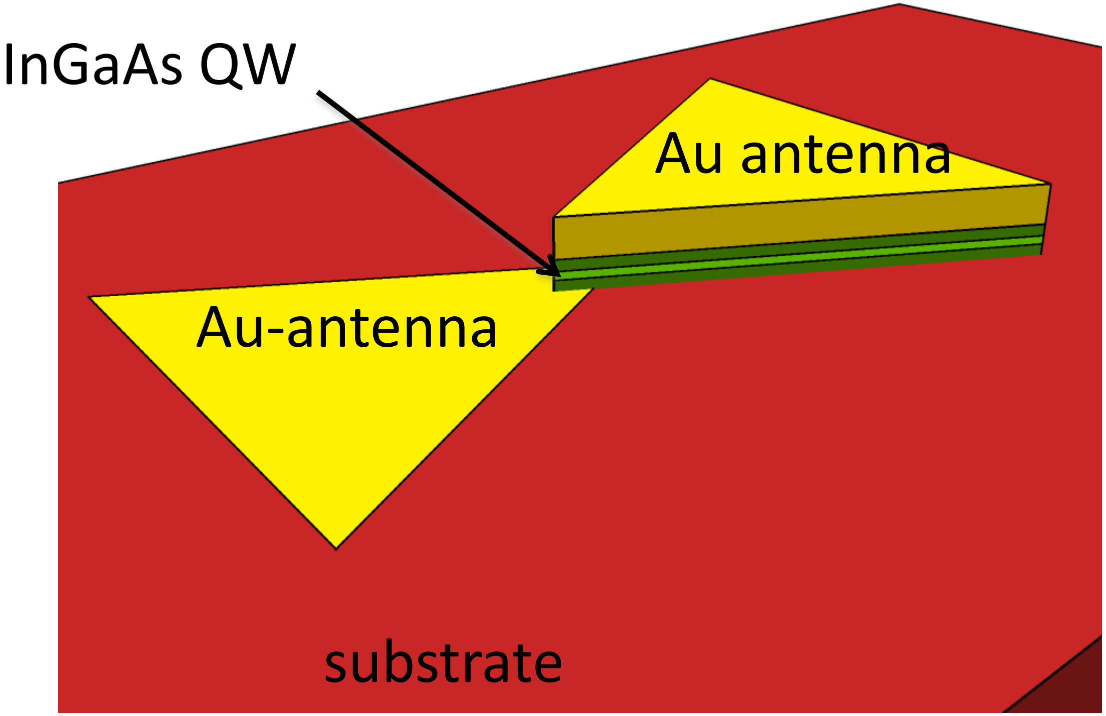
spontaneous emission speed penalty: $\left(\dfrac{x}{d}\right)^2$

x = dipole length

d = antenna gap



Using selective etching, there are techniques for making, and handling very thin semiconductor flakes, with thickness defined by epitaxy:



What about the efficiency?

Antenna radiation has to compete with dissipation:

$$\text{efficiency} = \frac{1/Q_{\text{radiative}}}{1/Q_{\text{radiative}} + 1/Q_{\text{Ohmic}}}$$

$Q_{\text{Ohmic}} \approx 10$ for plasmonic currents
A half-wave dipole has a $Q_{\text{radiative}} \approx 1$
Efficiency will be reasonable
in a well designed system, but not necessarily >90%

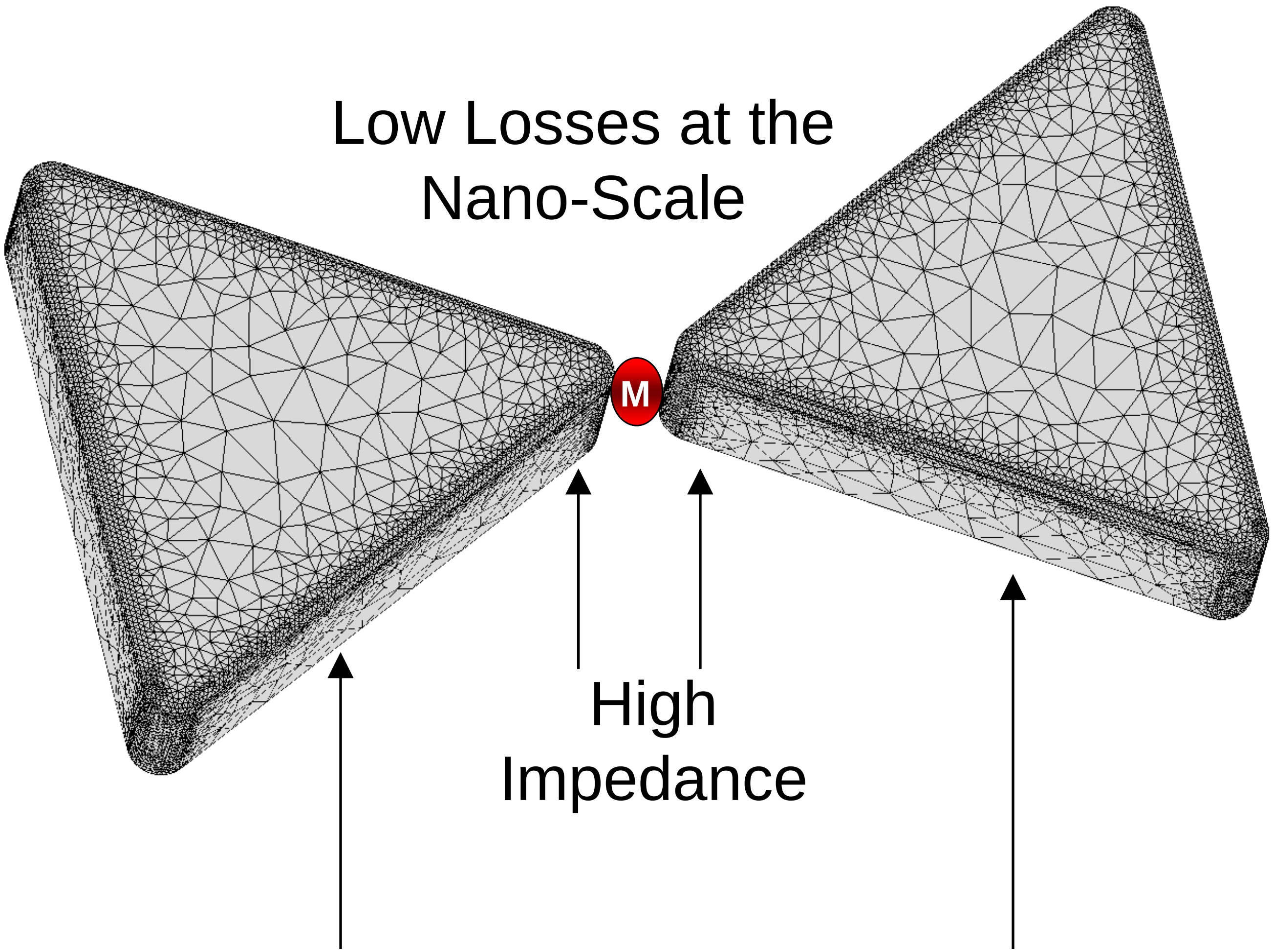
General Requirement for Efficiency:

$$R_{\Omega} < R_{\text{radiation}} \sim \sqrt{(\mu_o/\varepsilon_o)}/2\pi \sim 50\Omega$$

Electron Collisions with the Surface,

& the Anomalous Skin Effect (non-local):

Efficient Optical Frequency Antennas:

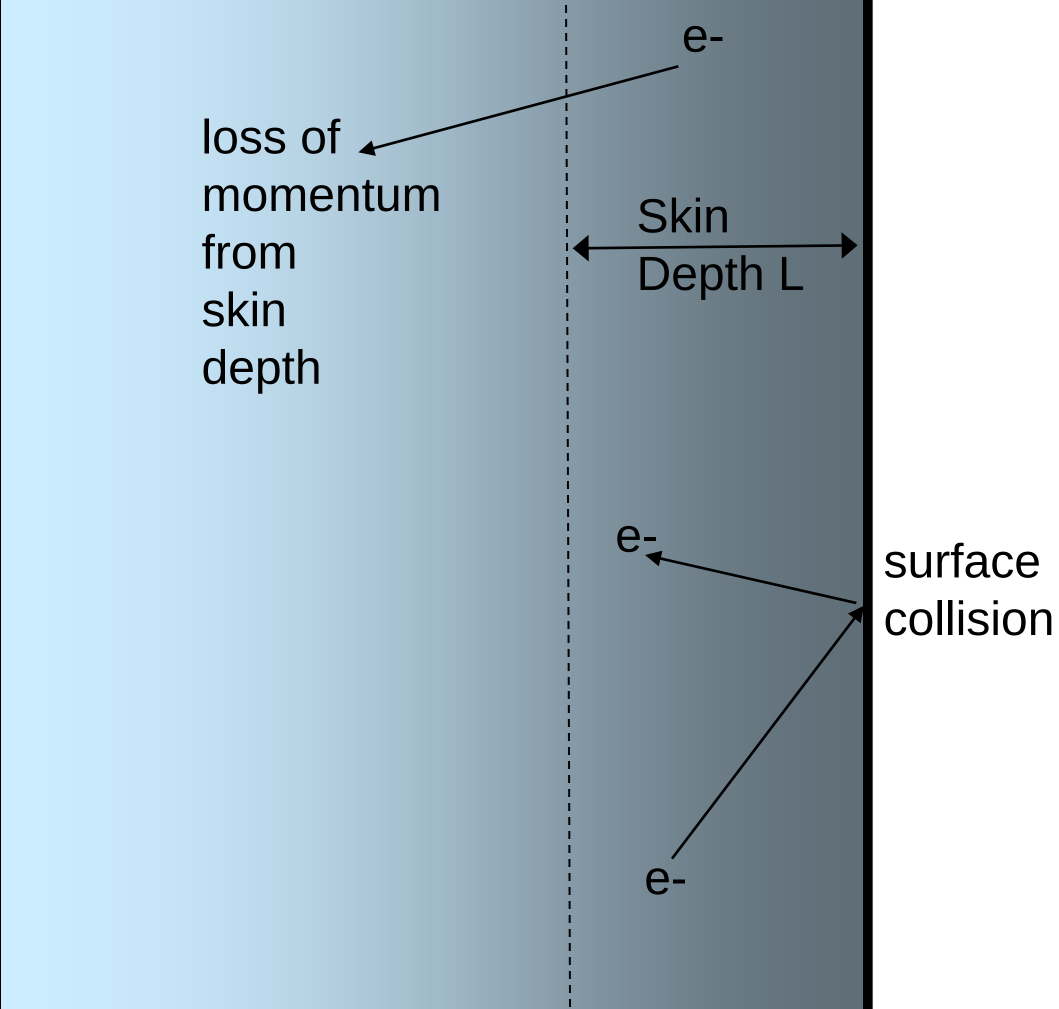


Low Losses at the
Nano-Scale

High
Impedance

Normal Impedance <377Ω

Anomalous Skin Effect (non-local):



Ag

SiO$_2$

e-

loss of
momentum
from
skin
depth

Skin
Depth L

e-

surface
collision

e-

Skin
Depth L
is not a
fixed number
but becomes
very short
at the nano-scale

$$\text{Momentum relaxation time} = \frac{2L}{v_F}$$

Conclusions:

1. Naked InGaAsP quantum dots are a suitable active medium

2. Antenna provided a 35× enhancement in the total spontaneous emission from little InGaAsP rods

3. Taking into account the spatial overlap between the antenna mode and the InGaAsP rod, the spontaneous emission rate enhancement is actually~100×

   (to beat the laser 200× needed)

4. The Anomalous Skin Effect eventually makes

   $R_\Omega < R_{radiation} \sim \sqrt{(\mu_o/\varepsilon_o)}/2\pi \sim 50\Omega$

We need theoretical help to calculate R_Ω near a sharp tip.

We hope to beat lasers 2000× enhancement &

modulation speed to ~2Tb/s.

What are the implications of the new Science of Spontaneous Emission?

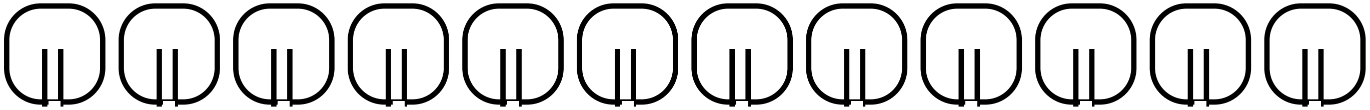
1. Direct modulation speed of nano-LED's for interconnects will be >100Gbits/sec

2. Many substances that do not fluoresce, will radiate efficiently when placed near an antenna structure. This has implications for bio-sensors, etc.

3. Surface-Enhanced-Raman scattering finds a rational scientific basis, and becomes more useful.
4. ……………..

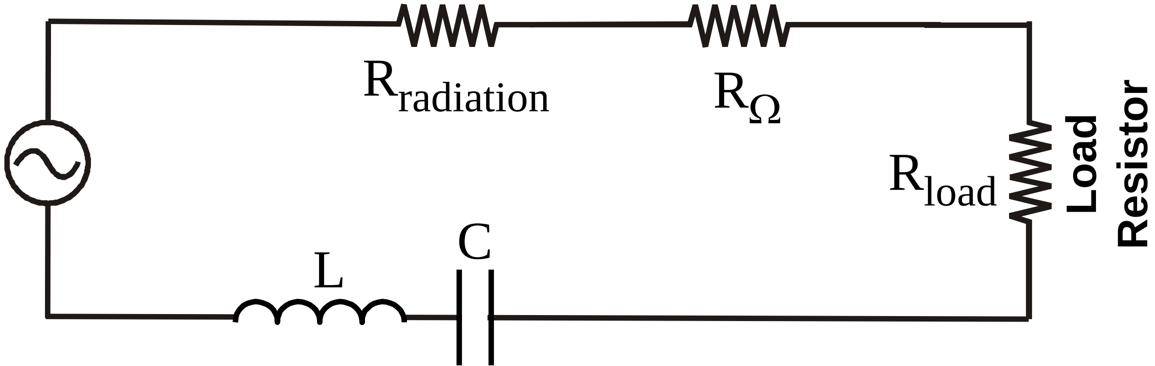
1. There are creative insights from the Meta-Material viewpoint.

There are many amazing new properties in meta-materials.



2. There are creative insights from the Circuit viewpoint.

There are many amazing new properties in optical circuits.



The circuit viewpoint is more general, since it doesn’t
require repeating units, and
is every bit as amazing.

Proposal: unified name should be “Metal Optics”.