Spontaneous Emission Rate is Enhanced by an Optical Antenna

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

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Antennas are part of Plasmonics & Metal-Optics:

- **Bow-Tie Antenna**: half-wave dipole
- **Optical STM**: quarter-wave monopole
The Complementary C-slot antenna

Bow-Tie Slot antenna

This type will have less Ohmic resistance, based simply on having more metal.
Capture Cross-Section = $\frac{\lambda^2}{\Omega}$
The Optical Antenna Zoo

- Ridge Waveguide
- 2D Tapered Waveguide
- 3D Tapered Waveguide
- Pin Antenna
- Recessed Pin Antenna
- Patch Antenna
- Bowtie Antenna
- Comp-Bowtie Antenna
- Blade Waveguide
Concentrating Electromagnetic Energy:

Optical Scanning Tunneling Microscope
quarter-wave monopole antenna
Super-resolution depends upon tip dimensions $<<\lambda$. 
Capture Cross-Section of an Ideal Isotropic Antenna = $\frac{\lambda^2}{4\pi}$
captured power $P_{in} = \frac{\lambda^2}{4\pi} \times \text{Intensity}$

For a highly directional antenna, Capture Cross-Section = $\frac{\lambda^2}{\Omega}$
where $\Omega$ is the acceptance solid-angle.

$\lambda = \text{Vacuum Wavelength}$
Radiated Power is proportional to
\[
\left\{\text{charge} \times \text{acceleration}\right\}^2: \left( \frac{1}{6\pi \varepsilon_0 c^3} \right) \left\{ Nq \frac{dv}{dt} \right\}^2
\]
\[
= \left( \frac{\omega^2}{6\pi \varepsilon_0 c^3} \right) \times \left\{ a \frac{N}{qv} \right\}^2
\]
\[
= \left( \frac{\omega^2}{6\pi \varepsilon_0 c^3} \right) a^2 \times I^2
\]
\[
= R_{\text{radiation}} \times I^2
\]

By time reversal, the captured power:

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

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

depends on geometry, frequency, etc.
\( R_{\text{radiation}} \approx \frac{50\Omega}{2\pi} \approx \frac{377\Omega}{2\pi} \)

in a very good antenna

\( R_{\text{radiation}} \approx \frac{(a/\lambda)^2 \times 377\Omega}{2\pi} \approx 1\Omega \)

in a bad antenna

\[
377\Omega = \frac{\mu_0}{\varepsilon_0} \text{ in MKS units}
\]

\[
377\Omega = \frac{4\pi}{c} \text{ in CGS units}
\]

Antenna Efficiency

\[
\text{Antenna Efficiency} = \frac{R_{\text{radiation}}}{R_{\text{radiation}} + R_{\Omega}} \approx \frac{R_{\text{radiation}}}{R_{\Omega}} < 1
\]
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.

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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

$$\frac{1}{4\pi} \frac{A_b}{P}$$

in which \(A_b\) is the cylindrical volume occupied by the antenna, and \(l\) is the radian length (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.

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.
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.

   ![Circuit Diagram]

2. There are creative insights from the Circuit viewpoint.

   There are many amazing new properties in optical circuits.

   ![Circuit Diagram]

   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”.

   ![Circuit Diagram]
After much magnetostatic calculation:

\[ L'_F = \frac{\mu_o}{2kW} \]

After much electrostatic calculation:

\[ C' = 2\varepsilon_0 kW \]
Exact: \( k = \frac{\omega}{c} \sqrt{\frac{\varepsilon_m}{\varepsilon_m + 1}} \)
Mode Wavelength $\lambda$ (nm)

Energy (eV)

Wavevector $k$ (m$^{-1}$)

Exact

Circuit Model

$\omega_p/\sqrt{2}$

$\frac{2}{\omega^2\varepsilon_0(1-\varepsilon_m)}\delta_m W$

$\mu_0/d/W e^{kd}$

$\mu_0/k W$

$\varepsilon_0 k W$

$\varepsilon_0 (W/d)e^{-kd}$

$\mu_0 (d/W)e^{kd}$

$\omega_p/\sqrt{2}$

$d = 50$ nm

$d = 15$ nm

$d = 5$ nm
Plasmonic Effect on Antennas:

- Low Losses at the Nano-Scale
- High Impedance
- Normal Impedance < 377Ω
Spontaneous Emission Enhancement, molecules attached to optical antennas

$h \nu$

molecule or quantum dot
Power Radiated by a molecule in an antenna:

\[
P = I^2 R
\]

\[
P = \left(\frac{q\omega}{2\pi}\right)^2 R
\]

\[
\frac{1}{\tau_{sp}} \equiv \frac{P}{\hbar \omega} = \frac{(q\omega)^2}{(2\pi)^2 \hbar \omega} \times \sqrt{\frac{\mu_0}{\varepsilon_0}}
\]

\[
\frac{1}{\omega \tau_{sp}} = \frac{P}{\hbar \omega^2} = \frac{(q\omega)^2}{(2\pi)^2 \hbar \omega^2} \times \sqrt{\frac{\mu_0}{\varepsilon_0}} \sqrt{\frac{\varepsilon_0}{\varepsilon_0}}
\]

\[
\alpha \equiv \frac{q^2}{4\pi \varepsilon_0 \hbar c} \equiv \frac{1}{137}
\]

Fine Structure Constant
$h\nu$

\[
\frac{1}{\tau_{sp}} = \frac{2}{137} \times \nu
\]

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, $\omega_0$, itself!
How can Spontaneous Emission possibly be Faster than Stimulated Emission?

spontaneous emission:

zero point electric field: $E_0$

spatial extent: $\lambda/2$

stimulated emission:

Real pump electric field $E$
<table>
<thead>
<tr>
<th>Data-Communications</th>
<th>Modulation Speed:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Emitting Diode</td>
<td>200Mb/s</td>
</tr>
<tr>
<td>Edge Emitting laser</td>
<td>50Gb/s</td>
</tr>
<tr>
<td>VCSEL laser</td>
<td>25Gb/s</td>
</tr>
</tbody>
</table>

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:

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 $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ Quantum Well Photo-Luminescence

LUMINESCENCE at 300$^\circ$K (arb. Units)

WAVELENGTH in $\mu$m

$\text{InP} \quad 1.5\text{nm}$
It is important to remove the substrate, to not be fooled by Light Extraction:

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.
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"
PL as Background Material is Reduced

PL Perpendicular to Antenna

PL Parallel to Antenna

Pump Polarization

Continuous Ridges

450nm Long Ridges

150nm Long Ridges

 Counts

Wavelength (nm)

Counts

Wavelength (nm)

Counts

Wavelength (nm)

InGaAsP

InGaAsP

Au

Au

Au

Au

Counts

Wavelength (nm)

Counts

Wavelength (nm)

Counts

Wavelength (nm)
Emission Perpendicular to Antenna

Emission Parallel to Antenna

Counts
Wavelength (nm)

Pump
Polarization

500nm Antenna

Au

InGaAsP

150nm

1200 1300 1400 1500 1600
Wavelength (nm)

no antenna

antenna

 Counts

counts

1200 1300 1400 1500 1600
Wavelength (nm)
Emission Parallel to Antenna

400nm Antenna

Au

InGaAsP

Count

Wavelength (nm)

0

1200

1300

1400

1500

1600

Counts

~35X Spontaneous Emission Enhancement

Pump Polarization

1.50nm

~35X Spontaneous Emission Enhancement
The main experimental limitation:

\[ \text{spontaneous emission speed penalty: } \left( \frac{x}{d} \right)^2 \]

\( x = \text{dipole length} \)
\( d = \text{antenna gap} \)
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:

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

\[Q_{\text{Ohmic}} \approx 10 \text{ for plasmonic currents}
\]

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:

\[ R_\Omega < R_{\text{radiation}} \sim \sqrt{\left( \mu_0 / \varepsilon_0 \right) / 2\pi} \sim 50\Omega \]

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 $<377 \Omega$
Anomalous Skin Effect (non-local):

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

Momentum relaxation time:

$$\text{Momentum relaxation} = \frac{2L}{VF}$$
Conclusions:

1. Naked InGaAsP quantum dots are a suitable active medium

2. Antenna provided a $35 \times$ 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 $\sim 100 \times$
   
   (to beat the laser $200 \times$ needed)

4. The Anomalous Skin Effect eventually makes
   
   $R_\Omega < R_{\text{radiation}} \sim \sqrt{\mu_0/\varepsilon_0}/2\pi \sim 50 \Omega$

We need theoretical help to calculate $R_\Omega$ near a sharp tip.

We hope to beat lasers $2000 \times$ enhancement &

   modulation speed to $\sim 2Tb/s$. 
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. .................
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   There are many amazing new properties in meta-materials.

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