Spontaneous Hyper Emission:
Enhanced Light Emission by Optical Antennas

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Where Our Paths Crossed
Nanopatch Laser

- Diameter = 400nm (0.3 $\lambda_0$)
- Physical volume = 0.02 $\lambda_0^3$

K. Yu, A. Lakhani, and M. C. Wu, *Optics Express*, 2010

- Can nanoscale lasers be faster than microscale ones?
- Yes, but only when it is biased below threshold
Minneapolis Airport

Return from DARPA SERS PI Meeting
Efficient Optical Frequency Antennas:

Yablonovitch

Low Losses at the Nano-Scale

High Impedance

Normal Impedance <377Ω
Spontaneous Emission

- Light-emitting diode (LED)
  - Slow, BW ~ 200MHz
  - Temporally incoherent
  - Spatially incoherent

- Spontaneous emission dipole is an “inefficient antenna” because

\[ x_0 \ll \frac{\lambda}{2} \]
Spontaneous Emission Enhanced by Optical Antenna

- By attaching an optical antenna to the radiating dipole, spontaneous emission can be greatly enhanced.
- **Spontaneous Hyper Emission (SHE)**
  - Faster and stronger than stimulated emission.
Antenna Theory for SHE

Radiation lifetime

\[
\frac{1}{\tau_{SHE}} = \frac{P_{Rad}}{\hbar \omega} = \frac{I^2 R}{\hbar \omega} = \frac{(q x_0)^2 \omega^2}{\hbar \omega d^2} R
\]

For parallel RLC circuit:

\[
Q = R \sqrt{\frac{C}{L}} = R \omega C
\]

\[C = \varepsilon l_{\text{eff}} : \text{antenna capacitance}\]

\[
\frac{1}{\tau_{SHE}} \sim \frac{1}{\tau_{\text{Bulk}}} \frac{\lambda^2}{d^2} Q
\]

\[
\begin{cases}
Q \sim 1 \\
\frac{\lambda^2}{d^2} \sim \text{up to } 10^6
\end{cases}
\]

SHE can be $10^6$ times faster
Spontaneous Hyper Emission (SHE)

\[ \frac{1}{\tau_{SHE}} \sim \frac{1}{\tau_{Bulk}} \frac{\lambda^2}{d^2 Q} \]

- Antenna should contact radiating dipole at nanoscale \((\propto d^{-2})\)
  - BW of 100s GHz, or even THz possible
- \(d < 50\text{nm}\) to achieve 100GHz BW
- SHE is
  - Temporally incoherent
  - Spatially coherent
    - Sub-diffraction-limited emitter
SHE-LED versus Laser

- Laser must be biased at many times threshold
  - Significant energy wasted due to laser bias
- Nano-LED does not require bias

- Laser bandwidth increases with bias
  - High bandwidth requires high bias
- “First photon” is fast in SHE-LED
**λ/2 Antenna With Matching Circuit**

**Microwave Antenna**

- LC matching circuit
- Antenna Arms

**Optical Antenna**

- LC matching circuit
- InGaAsP
- Gold
- Antenna Arms
- InP Cladding

**Antenna Characteristics:**

- Resonance = 1550nm
- Radiation Q = 14
- Total Q = 7
- Mode Volume = 0.015 (λ/2n)^3
SHE-LED Fabrication

Michael Eggleston

- Flip-chip bond to glass and substrate removal
- E-beam lithography and wet etching to define ridges
- E-beam lithography and metal lift-off to define antenna

Ridge Height: 35nm
Ridge Width: 24nm
Metal Thickness: 40 nm
Active Area Device Fill Factor

Only the areas in the black squares give enhanced PL, the rest of the ridge will emit PL at the normal rate.

These enhanced areas only account for ~9% of the total area emitting light.

Fill Factor (FF) = 0.09
Photoluminescence Measurement

Emission polarized **perpendicular** to antennas

With Antennas  Without Antennas

Emission polarized **parallel** to antennas

With Antennas  Without Antennas
Intensity vs. Antenna Alignment

Antennas only alter the photoluminescence when in contact with the InGaAsP Ridges.
Summary

• Spontaneous Hyper Emission enhanced by optical antennas can dramatically improve the efficiency and speed of LEDs

• Experimental results
  – 17x total enhancement
  – >100x enhancement in antenna polarization

• Faster and stronger than stimulated emission

• Where do we go from here?
  – Each of Eli’s accomplishment has turned into a company!

• It’s been a privilege and honor to be a colleague of Eli Yablonovitch for nearly 20 years!
Stimulated Emission

• Semiconductor lasers
  – Fast, BW ~ 10s GHz (Limit ~ 50GHz)

• However, laser requires constant bias for high speed operation
  – Limit energy efficiency
  – Can we eliminate threshold altogether?