NANOPHOTONIC DEVICES - SPONTANEOUS EMISSION FASTER THAN STIMULATED EMISSION

Eli Yablonovitch
REGENTS OF THE UNIVERSITY OF CALIFORNIA THE

11/04/2014
Final Report

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Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/RTD
Arlington, Virginia 22203
Air Force Materiel Command
**14. ABSTRACT**

For almost 50 years, stimulated emission has been stronger and far more important than spontaneous emission. Indeed spontaneous emission has been looked down upon, as a weak effect. Now a new science of enhanced spontaneous emission is emerging, that will make spontaneous emission stronger and faster than any possible stimulated emission. This new science depends upon the use of nanoscale metallic optical elements, as antennas for spontaneous emission.

We have calculated that the overall increase in spontaneous emission rate can be roughly 4 orders of magnitude, before the onset of unacceptable Ohmic losses, defined as non-radiative losses >50%.

**15. SUBJECT TERMS**

spontaneous emission, optical antenna, stimulated emission, light emitting diode.
AFOSR Project No. FA9550-09-1-0598
Final Report

Lead Organization
University of California, Berkeley

Team Members
Professor Eli Yablonovitch, University of California, Berkeley
Professor Ming C. Wu, University of California, Berkeley

Proposal Title
“Nanophotonic Devices; Spontaneous Emission Faster Than Stimulated Emission”

Research Areas
Metal Optics; Optical Antenna Enhanced Spontaneous Emission

Technical Point of Contact: Professor Eli Yablonovitch
University of California, Berkeley
Electrical Engineering & Computer Science Dept.
267M Cory Hall
Berkeley, CA 94720 - 1770
Tel: 510 - 642 - 6821
Fax: 510 - 666 - 3409
Email: eliy@eecs.berkeley.edu

Administrative Point of Contact: Ms. Cora Basada
University of California, Berkeley
Sponsored Projects Office
2150 Shattuck Avenue, Suite 313
Berkeley, CA 94704 - 5940
Tel: 510 - 642 - 2783
Fax: 510 - 642 - 8236
Email: cbasada@berkeley.edu
Summary

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Our objective was to demonstrate enhanced spontaneous emission faster than stimulated emission. An important threshold is 200× enhancement, in which case a light emitting diode becomes faster than a directly modulated semiconductor laser. 200× enhancement which would revolutionize thinking about the competition between lasers and spontaneous light emitters. Ultimately, there is the technological goal of converting this new physics into the preferred short distance data-communications technology.

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In optics, spontaneous emission is caused by dipole oscillations in the excited state of atoms, molecules, or quantum dots. The main problem is that a molecule is far too small to act as an efficient antenna for its own electromagnetic radiation. Antenna length, $l$, makes a huge difference in radiation rate. An ideal antenna would preferably be $\lambda/2$, a half-wavelength in size. To the degree that an atomic dipole of length $l$ is smaller than $\lambda/2$, the antenna radiation rate $\Delta \omega$ is proportional to $\omega (l/\lambda)^3$, as given by the Wheeler Limit(15). Spontaneous emission from molecular sized radiators is thus slowed by many orders of magnitude, since radiation wavelengths are much larger than the atoms themselves. Therefore, the key to speeding up spontaneous emission is to couple the radiating molecule to a proper antenna of sufficient size.

Since the emergence of lasers in 1960, stimulated emission has been faster than spontaneous emission. Now the opposite is possible. In the right circumstances, antenna-enhanced spontaneous emission could become faster than stimulated emission. Theoretically, very large bandwidth $>100$GHz or $>1$ THz is possible when the light emitter is coupled to a proper optical antenna at the right scale(16).
Metal optics has been able to shrink lasers to the nanoscale(17–20), but high losses in metal-based cavities make it increasingly difficult to achieve desirable performance. Metal structures have also been employed to enhance the spontaneous emission rate, such as by coupling excited material to flat surface plasmon waves(21–28). Flat metal surfaces are far from ideal antennas, resulting in low radiation efficiencies and large ohmic-losses. Semiconductor emitters have been further limited by large surface recombination losses, and by processing difficulties at the extremely small dimensions. The semiconductor experiments(29, 30) show weak antenna-emitter coupling, with the antenna enhancement sometimes masked by metal-induced elastic scattering which enhances light extraction from the semiconductor substrate. Light extraction alone can increase optical emission by $4n^2$, as often employed in commercial LED’s, without necessarily modifying the spontaneous emission rate(31, 32).

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<td><strong>12,166.20</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>OTHER DIRECT COSTS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>General Supplies</td>
<td>67,038.87</td>
</tr>
<tr>
<td>Computer eqt (non-Inventory)</td>
<td>1,888.82</td>
</tr>
<tr>
<td>Equip-non Inventorial</td>
<td>22,987.06</td>
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<tr>
<td>Computer Services-Software</td>
<td>34,843.74</td>
</tr>
<tr>
<td>Communications</td>
<td>2,715.36</td>
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<tr>
<td>Maint Contract &amp; services</td>
<td>501.85</td>
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<tr>
<td>Transportation</td>
<td>378.48</td>
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<tr>
<td>Other Services</td>
<td>227,211.36</td>
</tr>
<tr>
<td>Conf. Events - Registration</td>
<td>6,966.75</td>
</tr>
<tr>
<td><strong>Total Other Direct Costs</strong></td>
<td><strong>364,532.29</strong></td>
</tr>
</tbody>
</table>

| **Total Direct Costs** | **1,229,361.97** |
| **Indirect (53.5%)**  | **539,840.69**   |
| **TOTAL Expenses**    | **1,769,202.66** |