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NANOPHOTONIC DEVICES - SPONTANEOUS EMISISON FASTER THAN STIMULATED EMISSION

Eli Yablonovitch
REGENTS OF THE UNIVERSITY OF CALIFORNIA THE

11/04/2014
Final Report

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

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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.

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Lead Organization
University of California, Berkeley

Team Members
Professor Eli Yablonovitch, University of California, Berkeley
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Proposal Title
"Nanophotonic Devices; Spontaneous Emission Faster Than Stimulated Emission"

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Summary

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%. This technology emerges at the present time owing to our ability to create metallic structures at the nano-scale, that can act as antennas for molecules and semiconductors.

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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Antennas emerged at the dawn of radio, concentrating electromagnetic energy within a small volume $<< \lambda^3$, enabling nonlinear radio detection. Such coherent detection is essential for radio receivers, and has been used since the time of Hertz(1). Conversely, an antenna can efficiently extract radiation from a sub-wavelength source, such as a small cellphone. Despite the importance of radio antennas, 100 years went by before optical antennas began to be used to help extract optical frequency radiation from very small sources such as dye molecules(2–10) and quantum dots(11–14).

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 >100GHz 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).

We elucidate the physics of antenna-enhanced-spontaneous emission employing a traditional antenna circuit model, not the Purcell Effect(33) nor a local density-of-states model(34). We use the circuit approach to analyze for the maximum possible spontaneous emission enhancement in the presence of spreading resistance losses(35), and the non-local anomalous skin effect(36) in the metal.

We experimentally tested an optical dipole antenna, coupled to a “free-standing” 40nm ridge of semiconductor material. Thus far, optical emission measurements show a >100× antenna spontaneous emission rate enhancement factor compared to no antenna at all. At smaller dimensions, circuit theory predicts a spontaneous emission rate enhancement >10000×, but at the penalty of decreased antenna efficiency. Nonetheless, we have deriveD that ~5000× rate enhancement should be possible, while still maintaining antenna efficiency >50%.

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List of Publications:

Electrically Injected nanoLED with Enhanced Spontaneous Emission From a Cavity Backed Optical Slot Antenna, S. A. Fortuna, M. Eggleston, K. Messer, E. Yablonovitch and M. C. Wu, 2014 IEEE Photonics Conference, Paper MH2.2, October 2014.

K. Messer, M. Eggleston, M. Wu, and E. Yablonovitch, “Enhanced Spontaneous Emission Rate of InP using an Optical Antenna,” in CLEO: 2014, 2014, STu1M.3.

"Waveguide-integrated optical antenna nanoLEDs for on-chip communication" Eggleston, M.; Messer, K.; Fortuna, S.A.; Yablonovitch, E.; Wu, M.C. 2013 Third Berkeley Symposium on Energy Efficient Electronic Systems (E3S) DOI: 10.1109/E3S.2013.6705886 28-29 Oct. 2013, Sponsor(s):IEEE

T. J. Seok, A. Jamshidi, M. Eggleston, and M. C. Wu, “Mass-producible and efficient optical antennas with CMOS-fabricated nanometer-scale gap,” Optics Express, vol. 21, no. 14, p. 16561, Jul. 2013.

M. Eggleston, K. Messer, E. Yablonovitch, and M. Wu, “Circuit Theory of Optical Antenna Shedding Light on Fundamental Limit of Rate Enhancement,” in CLEO: 2014, 2014, p. FM2K.4.

M. Eggleston and M. C. Wu, “Efficient Coupling of Optical-Antenna Based nanoLED to a Photonic Waveguide,” in IEEE PHOTONICS CONFERENCE 2014, Seattle, WA, USA, 2013.

N. R. Kumar, K. Messer, M. Eggleston, M. C. Wu, and E. Yablonovitch, “Spontaneous emission rate enhancement using gold nanorods,” in 2012 IEEE Photonics Conference (IPC), 2012, pp. 612 –613.

M. Eggleston, N. Kumar, L. Zhang, E. Yablonovitch, and M. C. Wu, “Enhancement of photon emission rate in antenna-coupled nanoLEDs,” in Semiconductor Laser Conference (ISLC), 2012 23rd IEEE International, 2012, pp. 147 –148.

M. Eggleston, N. Kumar, K. Messer, L. Zhang, E. Yablonovitch, and M. C. Wu, “Efficient Rate Enhancement of Spontaneous Emission in a Semiconductor nanoLED,” in Frontiers in Optics Conference, 2012, p. FW6C.8.

M. C. Wu, “Nanoscale Light Emitters for On-Chip Optical Interconnect (Invited Presentation),” in HSD 2011 22nd Annual Workshop on Interconnections Within High Speed Digital Systems, 2011.

M. Eggleston, A. Lakhani, L. Zhang, E. Yablonovitch, and M. C. Wu, “Optical antenna based nanoLED,” in 2011 IEEE Photonics Conference (PHO), 2011, pp. 177 –178.

"Optical Antenna Design for Nanophotodiodes" Going, R; Seok, TJ; Lakhani, A; Eggleston, M; Kim, MK; Wu, MC 2011 IEEE PHOTONICS CONFERENCE (PHO) Pages: 735-736 (2011)

Seok, TJ; Jamshidi, A; Kim, M; Dhuey, S; Lakhani, A; Choo, H; Schuck, PJ; Cabrini, S; Schwartzberg, AM; Bokor, J; Yablonovitch, E; Wu, MC; "Radiation Engineering of Optical Antennas for Maximum Field Enhancement", Nano Letters Vol. 11 pp. 2606-2610 (2011).

List of Invited, Keynote & Plenary Presentations:

Oct. 14, 2014 La Jolla CA IEEE Photonics Conference,
"Optical Antenna-Coupled Nano-LED for Energy-Efficient On-Chip Interconnect"

Sept. 10, 2014 La Jolla, CA UCSD ECE Dept. Seminar
"Optical-Antenna-Enhanced Spontaneous Emission"

Sept. 1, 2014 Snowbird, Utah 13th International Conference on Near Field Optics
"Optical-Antenna-Enhanced Spontaneous Emission"

July 24, 2014 Seoul Korea Nano-Quantum Optics Science and Technology
"Optical-Antenna-Enhanced Spontaneous Emission"

May 15, 2014 Shanghai, China PECS XI
"Enhanced Spontaneous Emission by Means of Optical Antennas"

May 21, 2014 Singapore META 2014
"The Challenge of Using Optical Antennas to Accelerate Spontaneous Emission"

Mar. 24, 2014 Weizmann Inst., Rehovoth Israel Fundamental Problems on Quantum Physics
"Spontaneous Emission Faster than Stimulated Emission"

Dec. 5, 2013 Boston MA MRS Fall Meeting
"Spontaneous Emission Faster than Stimulated Emission"

Oct. 25, 2013 Albuquerque, NM UNM Physics Colloquium
"The Two Conflicting Narratives of Metal Optics, aka Plasmonics"

Oct. 15, 2013 Stanford, CA OSA/SPIE Stanford Student Chapter
"The Two Conflicting Narratives of Metal Optics, aka Plasmonics"

July 1, 2013 Kyoto, Japan CLEO Pacific Rim
"Optical Antennas: Spontaneous Emission Faster than Stimulated Emission"

June 14, 2013 Lund, Sweden Nordic Physics Days
"Optical Antennas: Spontaneous Emission Faster than Stimulated Emission"

May 27, 2013 HKUST, Hong Kong NanoElectronics & NanoPhotonics Workshop
"Semiconductor Nano Emitters and Detectors for Energy-Efficient Optical Links"

May 22, 2013 Hong Kong Polytechnic Int'l. Conference on Nanophotonics
"Spontaneous Emission Faster than Stimulated Emission"

May 13, 2013 University of Cambridge, UK The Scott Lecture

"The Two Conflicting Narratives of Metal Optics, aka Plasmonics"

Jan. 31, 2013 Sunnyvale, CA Finisar Inc. Seminar
"The Future of Optical Interconnects: Spontaneous Emission Faster than Stimulated Emission"

Jan. 21, 2013 Technion, Haifa, Israel Nanophotonics Mini-Symposium
"Optical Antennas, Spontaneous Emission Faster than Stimulated Emission"

Oct. 4, 2012 Hong Kong Croucher Advanced Study Institute
"Spontaneous Emission Rate is Enhanced by an Optical Antenna"

June 27, 2012 Dayton Ohio AFRL WPAFB Seminar
"Opto-electronic Devices: Spontaneous Emission Faster than Stimulated Emission"

June 1, 2012 Berkeley, CA Lawrence Berkeley Lab Seminar
"How to Estimate the Efficiency and Cross-Section of an AM Radio Antenna; and What Does That Have to do

With Plasmonics?"

May 24, 2012 Virginia Beach, VA Tri-Services Program Review
"Nano-Photonic Devices: Spontaneous Emission Faster than Stimulated Emission"

April 21, 2012 Paris, France META 2012
"Opto-electronic Devices: Spontaneous Emission Faster than Stimulated Emission"

March 29, 2012 Technion, Haifa, Israel Vincent Meyer Colloquium
"The Two Conflicting Narratives of Metal-Optics"

Jan. 23, 2012 San Francisco, CA Photonics West
"Applications of the Circuit Model for Plasmonics"

Dec. 13, 2011 Erlangen, Germany Max Planck Institute for the Science of Light
"The Two Conflicting Narratives of Metal-Optics"

May 25, 2010 Arlington, VA Joint Electronics Program Review
"Nano-Photonic Devices: Spontaneous Emission Faster than Stimulated Emission"

Jan. 25, 2011 San Francisco, CA SPIE Photonics West--OPTO
"Metal-Optics: The New Frontier"

Nov. 9, 2010 London UK Imperial College Seminar
"The Two Conflicting Narratives of Metal-Optics"

Oct. 8, 2010 Berkeley, CA NSF Japan/US joint symposium
"The Two Conflicting Narratives of Metal-Optics"

Sept. 28, 2010 Granada Spain PECS IX
"The Two Conflicting Narratives of Metal-Optics"

Aug. 17, 2010 Seoul Korea IEEE Nano Korea Symposium

"The Two Conflicting Narratives of Metal-Optics"

May 11, 2010 Napa, CA Canadian Institute for Advanced Research
"Metal Optics, Optical Antennas, and Spontaneous Hyper-Emission"

Mar. 25, 2010 University of Toronto, CA Electrical & Computer Eng'g. Seminar
"Metal Optics, Optical Antennas, and Spontaneous Hyper-Emission"

Mar. 22, 2010 Regensberg, Germany Deutsche Physikalische Gesellschaft Spring Meeting
"The Two Conflicting Narratives of Metal-Optics"

Mar. 12, 2010 Tucson, Arizona Nobel Scientific Symposium
"Optical Antenna; Spontaneous Emission Faster than Stimulated Emission"

Feb. 3, 2010 Jeju Island, Korea International Winter School: Beyond Moore's Law
"Metal Optics, Optical Antennas, and Spontaneous Hyper-Emission"

January 29, 2010 Stanford CA Denmark-Stanford Workshop on Optical-Interconnects
"Nano-Photonics in Silicon Chips and the New Metal-Optics for Nanoscale Focusing"

Jan. 22, 2010 Berkeley, CA Photonics & Plasmonics Seminar
"Metal Optics, Optical Antennas, and Spontaneous Hyper-Emission"

Nov. 30, 2009 Stanford, Palo Alto, CA Ginzton Optics and Quantum Electronics Seminar
"The Two Conflicting Narratives of Metal-Optics"

Nov. 19, 2009 Caltech, Pasadena CA Caltech Materials Seminar
"The Two Conflicting Narratives of Metal-Optics"

Inventions:

There were no inventions report under this project.

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Nanophotonic Devices; Spontaneous Emission Faster than Stimulated Emission

PI: Yablonovitch

Cumulative as of 10/31/2014

SALARIES/WAGES	Actuals
Academic Wages:	563,625.82
Staff Wages	6,759.98
Total Wages	570,385.80
BENEFITS	
	125,783.97
Total Benefits	125,783.97
EQUIPMENT	
	156,493.71
Total Equipment	156,493.71
TRAVEL	
Domestic Travel	9,418.03
Foreign Travel	2,748.17
Travel	12,166.20
OTHER DIRECT COSTS	
General Supplies	67,038.87
Computer eqt (non-Inventory)	1,888.82
Equip-non Inventorial	22,987.06
Computer Services-Software	34,843.74
Communications	2,715.36
Maint Contract & services	501.85
Transportation	378.48
Other Services	227,211.36
Conf. Events - Registration	6,966.75
Total Other Direct Costs	**364,532.29**
Total Direct Costs	**1,229,361.97**
Indirect (53.5%)	**539,840.69**
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AFOSR Project No. FA9550-09-1-0598
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Lead Organization
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Team Members
Professor Eli Yablonovitch, University of California, Berkeley
Professor Ming C. Wu, University of California, Berkeley

Proposal Title
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Research Areas
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Antennas emerged at the dawn of radio, concentrating electromagnetic energy within a small volume << λ^3, enabling nonlinear radio detection. Such coherent detection is essential for radio receivers, and has been used since the time of Hertz(1). Conversely, an antenna can efficiently extract radiation from a sub-wavelength source, such as a small cellphone. Despite the importance of radio antennas, 100 years went by before optical antennas began to be used to help extract optical frequency radiation from very small sources such as dye molecules(2–10) and quantum dots(11–14).

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 >100GHz 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).

We elucidate the physics of antenna-enhanced-spontaneous emission employing a traditional antenna circuit model, not the Purcell Effect(33) nor a local density-of-states model(34). We use the circuit approach to analyze for the maximum possible spontaneous emission enhancement in the presence of spreading resistance losses(35), and the non-local anomalous skin effect(36) in the metal.

We experimentally tested an optical dipole antenna, coupled to a "free-standing" 40nm ridge of semiconductor material. Thus far, optical emission measurements show a >100× antenna spontaneous emission rate enhancement factor compared to no antenna at all. At smaller dimensions, circuit theory predicts a spontaneous emission rate enhancement >10000×, but at the penalty of decreased antenna efficiency. Nonetheless, we have deriveD that ~5000× rate enhancement should be possible, while still maintaining antenna efficiency >50%.

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List of Publications:

Electrically Injected nanoLED with Enhanced Spontaneous Emission From a Cavity Backed Optical Slot Antenna, S. A. Fortuna, M. Eggleston, K. Messer, E. Yablonovitch and M. C. Wu, 2014 IEEE Photonics Conference, Paper MH2.2, October 2014.

K. Messer, M. Eggleston, M. Wu, and E. Yablonovitch, “Enhanced Spontaneous Emission Rate of InP using an Optical Antenna,” in CLEO: 2014, 2014, STu1M.3.

"Waveguide-integrated optical antenna nanoLEDs for on-chip communication" Eggleston, M.; Messer, K.; Fortuna, S.A.; Yablonovitch, E.; Wu, M.C. 2013 Third Berkeley Symposium on Energy Efficient Electronic Systems (E3S) DOI: 10.1109/E3S.2013.6705886 28-29 Oct. 2013, Sponsor(s):IEEE

T. J. Seok, A. Jamshidi, M. Eggleston, and M. C. Wu, “Mass-producible and efficient optical antennas with CMOS-fabricated nanometer-scale gap,” Optics Express, vol. 21, no. 14, p. 16561, Jul. 2013.

M. Eggleston, K. Messer, E. Yablonovitch, and M. Wu, “Circuit Theory of Optical Antenna Shedding Light on Fundamental Limit of Rate Enhancement,” in CLEO: 2014, 2014, p. FM2K.4.

M. Eggleston and M. C. Wu, “Efficient Coupling of Optical-Antenna Based nanoLED to a Photonic Waveguide,” in IEEE PHOTONICS CONFERENCE 2014, Seattle, WA, USA, 2013.

N. R. Kumar, K. Messer, M. Eggleston, M. C. Wu, and E. Yablonovitch, “Spontaneous emission rate enhancement using gold nanorods,” in 2012 IEEE Photonics Conference (IPC), 2012, pp. 612 –613.

M. Eggleston, N. Kumar, L. Zhang, E. Yablonovitch, and M. C. Wu, “Enhancement of photon emission rate in antenna-coupled nanoLEDs,” in Semiconductor Laser Conference (ISLC), 2012 23rd IEEE International, 2012, pp. 147 –148.

M. Eggleston, N. Kumar, K. Messer, L. Zhang, E. Yablonovitch, and M. C. Wu, “Efficient Rate Enhancement of Spontaneous Emission in a Semiconductor nanoLED,” in Frontiers in Optics Conference, 2012, p. FW6C.8.

M. C. Wu, “Nanoscale Light Emitters for On-Chip Optical Interconnect (Invited Presentation),” in HSD 2011 22nd Annual Workshop on Interconnections Within High Speed Digital Systems, 2011.

M. Eggleston, A. Lakhani, L. Zhang, E. Yablonovitch, and M. C. Wu, “Optical antenna based nanoLED,” in 2011 IEEE Photonics Conference (PHO), 2011, pp. 177 –178.

"Optical Antenna Design for Nanophotodiodes" Going, R; Seok, TJ; Lakhani, A; Eggleston, M; Kim, MK; Wu, MC 2011 IEEE PHOTONICS CONFERENCE (PHO) Pages: 735-736 (2011)

Seok, TJ; Jamshidi, A; Kim, M; Dhuey, S; Lakhani, A; Choo, H; Schuck, PJ; Cabrini, S; Schwartzberg, AM; Bokor, J; Yablonovitch, E; Wu, MC; “Radiation Engineering of Optical Antennas for Maximum Field Enhancement”, Nano Letters Vol. 11 pp. 2606-2610 (2011).

List of Invited, Keynote & Plenary Presentations:

Oct. 14, 2014 La Jolla CA IEEE Photonics Conference,
"Optical Antenna-Coupled Nano-LED for Energy-Efficient On-Chip Interconnect"

Sept. 10, 2014 La Jolla, CA UCSD ECE Dept. Seminar
"Optical-Antenna-Enhanced Spontaneous Emission"

Sept. 1, 2014 Snowbird, Utah 13th International Conference on Near Field Optics
"Optical-Antenna-Enhanced Spontaneous Emission"

July 24, 2014 Seoul Korea Nano-Quantum Optics Science and Technology
"Optical-Antenna-Enhanced Spontaneous Emission"

May 15, 2014 Shanghai, China PECS XI
"Enhanced Spontaneous Emission by Means of Optical Antennas"

May 21, 2014 Singapore META 2014
"The Challenge of Using Optical Antennas to Accelerate Spontaneous Emission"

Mar. 24, 2014 Weizmann Inst., Rehovoth Israel Fundamental Problems on Quantum Physics
"Spontaneous Emission Faster than Stimulated Emission"

Dec. 5, 2013 Boston MA MRS Fall Meeting
"Spontaneous Emission Faster than Stimulated Emission"

Oct. 25, 2013 Albuquerque, NM UNM Physics Colloquium
"The Two Conflicting Narratives of Metal Optics, aka Plasmonics"

Oct. 15, 2013 Stanford, CA OSA/SPIE Stanford Student Chapter
"The Two Conflicting Narratives of Metal Optics, aka Plasmonics"

July 1, 2013 Kyoto, Japan CLEO Pacific Rim
"Optical Antennas: Spontaneous Emission Faster than Stimulated Emission"

June 14, 2013 Lund, Sweden Nordic Physics Days
"Optical Antennas: Spontaneous Emission Faster than Stimulated Emission"

May 27, 2013 HKUST, Hong Kong NanoElectronics & NanoPhotonics Workshop
"Semiconductor Nano Emitters and Detectors for Energy-Efficient Optical Links"

May 22, 2013 Hong Kong Polytechnic Int'l. Conference on Nanophotonics
"Spontaneous Emission Faster than Stimulated Emission"

May 13, 2013 University of Cambridge, UK The Scott Lecture

"The Two Conflicting Narratives of Metal Optics, aka Plasmonics"

Jan. 31, 2013 Sunnyvale, CA Finisar Inc. Seminar
"The Future of Optical Interconnects: Spontaneous Emission Faster than Stimulated Emission"

Jan. 21, 2013 Technion, Haifa, Israel Nanophotonics Mini-Symposium
"Optical Antennas, Spontaneous Emission Faster than Stimulated Emission"

Oct. 4, 2012 Hong Kong Croucher Advanced Study Institute
"Spontaneous Emission Rate is Enhanced by an Optical Antenna"

June 27, 2012 Dayton Ohio AFRL WPAFB Seminar
"Opto-electronic Devices: Spontaneous Emission Faster than Stimulated Emission"

June 1, 2012 Berkeley, CA Lawrence Berkeley Lab Seminar
"How to Estimate the Efficiency and Cross-Section of an AM Radio Antenna; and What Does That Have to do

With Plasmonics?"

May 24, 2012 Virginia Beach, VA Tri-Services Program Review
"Nano-Photonic Devices: Spontaneous Emission Faster than Stimulated Emission"

April 21, 2012 Paris, France META 2012
"Opto-electronic Devices: Spontaneous Emission Faster than Stimulated Emission"

March 29, 2012 Technion, Haifa, Israel Vincent Meyer Colloquium
"The Two Conflicting Narratives of Metal-Optics"

Jan. 23, 2012 San Francisco, CA Photonics West
"Applications of the Circuit Model for Plasmonics"

Dec. 13, 2011 Erlangen, Germany Max Planck Institute for the Science of Light
"The Two Conflicting Narratives of Metal-Optics"

May 25, 2010 Arlington, VA Joint Electronics Program Review
"Nano-Photonic Devices: Spontaneous Emission Faster than Stimulated Emission"

Jan. 25, 2011 San Francisco, CA SPIE Photonics West--OPTO
"Metal-Optics: The New Frontier"

Nov. 9, 2010 London UK Imperial College Seminar
"The Two Conflicting Narratives of Metal-Optics"

Oct. 8, 2010 Berkeley, CA NSF Japan/US joint symposium
"The Two Conflicting Narratives of Metal-Optics"

Sept. 28, 2010 Granada Spain PECS IX
"The Two Conflicting Narratives of Metal-Optics"

Aug. 17, 2010 Seoul Korea IEEE Nano Korea Symposium

"The Two Conflicting Narratives of Metal-Optics"

May 11, 2010 Napa, CA Canadian Institute for Advanced Research
"Metal Optics, Optical Antennas, and Spontaneous Hyper-Emission"

Mar. 25, 2010 University of Toronto, CA Electrical & Computer Eng'g. Seminar
"Metal Optics, Optical Antennas, and Spontaneous Hyper-Emission"

Mar. 22, 2010 Regensberg, Germany Deutsche Physikalische Gesellschaft Spring Meeting
"The Two Conflicting Narratives of Metal-Optics"

Mar. 12, 2010 Tucson, Arizona Nobel Scientific Symposium
"Optical Antenna; Spontaneous Emission Faster than Stimulated Emission"

Feb. 3, 2010 Jeju Island, Korea International Winter School: Beyond Moore's Law
"Metal Optics, Optical Antennas, and Spontaneous Hyper-Emission"

January 29, 2010 Stanford CA Denmark-Stanford Workshop on Optical-Interconnects
"Nano-Photonics in Silicon Chips and the New Metal-Optics for Nanoscale Focusing"

Jan. 22, 2010 Berkeley, CA Photonics & Plasmonics Seminar
"Metal Optics, Optical Antennas, and Spontaneous Hyper-Emission"

Nov. 30, 2009 Stanford, Palo Alto, CA Ginzton Optics and Quantum Electronics Seminar
"The Two Conflicting Narratives of Metal-Optics"

Nov. 19, 2009 Caltech, Pasadena CA Caltech Materials Seminar
"The Two Conflicting Narratives of Metal-Optics"

Inventions:

There were no inventions report under this project.

PI: Yablonovitch

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AFOSR: # FA9550-09-1-0598
Nanophotonic Devices; Spontaneous Emission Faster than Stimulated Emission

Cumulative as of 10/31/2014	
SALARIES/WAGES	Actuals
Academic Wages:	563,625.82
Staff Wages	6,759.98
Total Wages	570,385.80
BENEFITS	
	125,783.97
Total Benefits	125,783.97
EQUIPMENT	
	156,493.71
Total Equipment	156,493.71
TRAVEL	
Domestic Travel	9,418.03
Foreign Travel	2,748.17
Travel	12,166.20
OTHER DIRECT COSTS	
General Supplies	67,038.87
Computer eqt (non-Inventory)	1,888.82
Equip-non Inventorial	22,987.06
Computer Services-Software	34,843.74
Communications	2,715.36
Maint Contract & services	501.85
Transportation	378.48
Other Services	227,211.36
Conf. Events - Registration	6,966.75
Total Other Direct Costs	**364,532.29**
Total Direct Costs	**1,229,361.97**
Indirect (53.5%)	**539,840.69**
TOTAL Expenses	**1,769,202.66**