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**Nanoscale Optical Emitters for High Density Information Processing using Photonic-Plasmonic Coupling in Coaxial Nanopillars**

**Luca Dal Negro**  
**TRUSTEES OF BOSTON UNIVERSITY**

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**Final Report**

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14. ABSTRACT In this project we investigated active, Si-compatible linear and nonlinear sources in plasmonic and metamaterials for high-density information processing. The objective of this two-year research program was to design and to engineer scalable, low-threshold, efficient light sources based on sub-wavelength mode confinement and nanoscale photonic-plasmonic coupling in active Si-based nanocavity structures and arrays for high-density integration and information processing. We have demonstrated state-of-the-art nano-ring plasmonic cavities with enhanced emission efficiency, polarization-switchable nano-antennas, broadband hybrid (multi-metal, metal-dielectric, all-dielectric) nanostructured arrays for the generation and control of the optical angular momentum of light, and developed new Si-compatible nonlinear metamaterials. These activities are particularly interesting for the development of "active nano-pixels" with enhanced emission/absorption rates and structured light (i.e., phase engineered) manipulation on a Si chip. Imaging systems, miniaturized photodetector arrays and light sources with specified emission patterns can be developed based on the concepts that we introduced and the results that we demonstrated.					
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# Nanoscale Optical Emitters for High Density Information Processing using Photonic-Plasmonic Coupling in Coaxial Nanopillars

## Major Research Activities and Accomplishments Final Report of AFOSR project FA9550-13-1-0011

Luca Dal Negro

*Department of Electrical and Computer Engineering & Photonics Center,  
Boston University, Boston, MA, 02215*

[dalnegro@bu.edu](mailto:dalnegro@bu.edu)

**Summary of the research:** In this project we investigated active, Si-compatible linear and nonlinear sources in plasmonic and metamaterials for high-density information processing. The objective of this two-year research program was to design and to engineer scalable, low-threshold, efficient light sources based on sub-wavelength mode confinement and nanoscale photonic-plasmonic coupling in active Si-based nanocavity structures and arrays for high-density integration and information processing. We have demonstrated state-of-the-art nano-ring plasmonic cavities with enhanced emission efficiency, polarization-switchable nano-antennas, broadband hybrid (multi-metal, metal-dielectric, all-dielectric) nanostructured arrays for the generation and control of the optical angular momentum of light, and developed new Si-compatible nonlinear metamaterials. These activities are particularly interesting for the development of “active nano-pixels” with enhanced emission/absorption rates and structured light (i.e., phase engineered) manipulation on a Si chip. Imaging systems, miniaturized photodetector arrays and light sources with specified emission patterns can be developed based on the concepts that we introduced and the results that we demonstrated.

### **Major Achievements:**

During the first year of this project we have designed and experimentally demonstrated strong radiation rate enhancement and quantum efficiency enhancement in plasmonic ring nanocavities with Er as an active medium. Using full-vector three dimensional finite difference time domain simulations to model electric field confinement and photonic density of states we design ring nanocavities for light emission and gain enhancement at  $1.55\mu\text{m}$ . Nanocavities are fabricated from Er:SiO<sub>2</sub> and silver using CMOS compatible sputtering, top-down lithography and etching processes. By combining measurements of photoluminescence intensity and decay rate we measure a 25 times increase in radiative emission rate and 2 times increase in quantum efficiency. Using analytical modeling we investigate the possibility of achieving lasing in sub-wavelength plasmonic cavities due to enhancement of stimulated emission rate caused by the increased spontaneous emission rate. In our plasmon nano-cavity device the Purcell enhanced stimulated emission can significantly increase the cavity gain allowing laser action to start in deep sub wavelength active regions with relatively low Q factors or using materials with intrinsically low gain, such as Erbium ions. We find that Purcell enhanced gain can reduce the Q factor needed for Erbium lasing by as much as 250 times. In addition to nanoscale lasers, our proposed plasmonic ring nanocavities are capable of enhancing light emission and absorption at multiple wavelengths, tunable over a broad range, and could be used to realize high density, individually addressable, electrically excited sources or detector arrays with nanoscale pixel sizes for novel light emission/absorption platforms based on Si technology. (N. Lawrence et al., *Radiation rate enhancement in sub-wavelength plasmonic ring nanocavities*, **Nano Lett.**, 13, 3709, 2013).

In addition, we designed and demonstrated linear and nonlinear plasmonic nanoantennas for high-density integration processing on a Si chip. In particular, our activities focused on the

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engineering of multi-wavelength tunable and switchable nonlinear optical plasmonic nanoantenna arrays for applications to nonlinear signal generation and multispectral sources on Si.

We demonstrated polarization and wavelength control of plasmonic hot-spot as well as optical nano-focusing extending from the visible to the mid-IR spectral range (J. Trevino, et al., *Photonic-Plasmonic coupled Nanoantennas for Polarization-controlled Multispectral Nanofocusing*, **Optics Lett.**, 38, 4861, 2013), as well as the first Fano-coupled nonlinear Au nanoantennas for efficient and polarization switchable nonlinear signal generation (G. F. Walsh and L. Dal Negro *Enhanced Second Harmonic Generation by Photonic-Plasmonic Fano-type Coupling in Nanoplasmonic Arrays*, **Nano Lett.** 13, 3111, 2013). Device applications to multi-spectral sensing and energy concentration at the nanoscale are anticipated based on the results demonstrated in our work. These activities will naturally interface with the development of nonlinear plasmonic imaging systems (VIS-IR) and sensor arrays with designed frequency and polarization responses.

During the last 12 months we developed a novel active materials platform based rare-earth doping of transparent conductive oxides for broad band sources, ultrafast electrical modulation, and nonlinear optical signal generation on Si. In particular, we focused on Er doping of ZnO, ITO and AZO materials deposited by magnetron co-sputtering and we engineered their dielectric permittivity by thermal annealing in order to tailor the screened plasma frequency over a controlled wavelength range between 1-2 $\mu$ m, which is relevant to telecom applications. The resulting negative permittivity, metal-free Si materials enable the engineering of sub-wavelength plasmon fields on Si at dramatically reduced optical losses compared to traditional noble metals such as Au and Ag, within the widespread CMOS processing technology. The developed materials platform is ideally suited to fabricate Si-based active (light emitting and nonlinear) metamaterials with strongly enhanced local field concentration and nonlinearity enhancement within Si technology, which is key to high density integration of photonic-plasmonic coupled active devices on a chip. Based on this novel approach, we have been developing low-loss, tunable materials platforms based on conductive transparent oxides (TCOs) and nitrides (TCNs) for the engineering of active (i.e., light emitting, nonlinear) plasmonics and metamaterials devices that are fully compatible with Si technology. We developed fabrication processes and technologies to actively tune the optical dispersion properties (e.g., screened plasma frequency, epsilon-near-zero wavelength, bandgaps, etc) of these novel photonic materials from the visible to the mid-IR spectral range (up to 4microns). These versatile materials feature strongly reduced optical losses compared to traditional plasmonic systems (i.e., made of noble metals), larger nonlinear optical coefficients, increased optical transparency in the VIS and near-IR ranges, electrical conductivity and optical tunability, fast electro-optical modulation, as well as excellent stability and robustness to thermal loads (refractory materials) . Many device opportunities in the areas of active optical modulation of linear/nonlinear responses on a silicon chip are anticipated. For instance, novel nanoscale optical sensors and detectors fully-compatible with Si technology or active hyperbolic metamaterials based on Si can be readily fabricated without the need of specialized nanofabrication tools or without involving Au/Ag materials components. Dynamic control of optical emission and scattering processes can be achieved under optical and electrical pumping, enabling completely novel optical functionalities such as low-power metal-dielectric transitions, dynamic beam-shaping and steering, radiation diagram control, and the engineering of perfect absorption and scattering cancellation within integrated optics on Si (i.e., waveguide structures, resonant cavities, planar technology integration).

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Based on the developed conductive oxide materials we recently demonstrates dramatically enhanced second-order and third-order nonlinearity up to 600 times larger than what used for index modulation in Si. We anticipate a large number of device applications to ultrafast optical modulators and nonlinear sensors (A. Capretti, et al., “*Enhanced third-harmonic generation in Si-compatible Epsilon-Near-Zero ITO nanolayers*”, **Opt. Lett.** (accepted), and A. Capretti, et al., “*Experimental demonstration of Epsilon-Near-Zero second-harmonic generation*”, *Opt. Express.* (in review), and H. Zhao, et al., “*Broadband Electro-Absorption Modulators Design Based on Epsilon-Near-Zero Indium Tin Oxide*”, **IEEE, JSTQE**, 21, 3300207 (2015)).

Currently, we are also working to demonstrate broadband Purcell enhancement of Er and Si quantum dots embedded in hyperbolic metamaterials that do not have any metallic component, as well as to demonstrate gap polariton laser action in sub-wavelength coaxial nano-cavities. This recent work, resulting from this project, is summarized in the paper by Y. Wang et al., “*Control of local density of states with TiN-based in hyperbolic active metamaterials based on silicon*” (to be submitted to APL).

Finally, during this project, in collaboration with the group of Prof. Anna Fontcuberta y Morral at EPFL (Switzerland), we have demonstrated the first plasmonic antenna-coupled semiconductor nanowires using scalable nanolithography and etching. Based on this novel platform, we have been able to tune the nanoantennas and make them resonate with the single NWs absorption spectrum to dramatically increase their nonlinear optical generation as well as absorption rates for both transverse and longitudinal polarization. In particular, we have demonstrated that a hybrid structure formed by GaAs nanowires with a highly dense array of bow-tie antennas is able to modify the polarization response of a nanowire. As a result, the increase in light absorption for transverse polarized light changes the nanowire polarization response, including the polarization response inversion. This work will open a new path towards the widespread implementation of nanowires applications such as in photodetection, solar energy harvesting and light emission. These activities are described in two high impact publications that resulted directly from the funding of this project (A. Casadei et al, *Polarization response of nanowires à la carte*, **Scientific Reports**, 5, 7651, 2015 and A. Casadei, et al., *Photonic–Plasmonic Coupling of GaAs Single Nanowires to Optical Nanoantennas*, **Nano Lett.**, 14, 2271,2014).

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**Abstract**

In this project we investigated active, Si-compatible linear and nonlinear sources for plasmonic and metamaterials. The objective of this two-year research program was to design and to engineer scalable, low-threshold, efficient light sources based on sub-wavelength mode confinement and nanoscale photonic-plasmonic coupling in active Si-based coaxial nanocavity structures and arrays for high-density integration and information processing. We have demonstrated state-of-the-art nano-ring plasmonic cavities with enhanced emission efficiency, polarization-switchable nano-antennas, broadband hybrid (multi-metal, metal-dielectric, all-dielectric) nanostructured arrays for the generation and control of the optical angular momentum of light, and developed new Si-compatible nonlinear metamaterials. These activities are particularly interesting for the development of "active nano-pixels" with enhanced emission/absorption rates and structured light (i.e., phase engineered) manipulation on a Si chip. Imaging systems, miniaturized photodetector arrays and light sources with specified emission patterns can be developed based on the concepts that we introduced and the results that we demonstrated.

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Peer reviewed journal articles:

A. Capretti, Y. Wang, N. Engheta, L. Dal Negro "Enhanced third-harmonic generation in Si-compatible Epsilon-Near-Zero ITO nanolayers" , Opt. Lett. (accepted on Feb 23, 2014 but submitted within the reporting period)

A. Capretti, Y. Wang, N. Engheta, L. Dal Negro "Experimental demonstration of Epsilon-Near-Zero second-harmonic generation" , Opt. Express. (in review)

H. Zhao, Y. Wang, A. Capretti, L. Dal Negro, J. Klamkin, "Broadband Electro-Absorption Modulators Design Based on Epsilon-Near-Zero Indium Tin Oxide", IEEE, JSTQE, 21, 3300207 (2015) (accepted Nov. 2014)

A. Casadei, E. Alarcon Llado, F. Amaduzzi, E. Russo-Averchi, D. Ruer, M. Heiss, L. Dal Negro, and A. Fontcuberta i Morral, "Polarization response of nanowires à la carte", Scientific Reports, 5, 7651 (2015) (accepted Nov. 2014)

A. Casadei, E.F. Pecora, J. Trevino, C. Forestiere, D. Ruffer, E. Russo-Averchi, F. Matteini, G. Tutuncuoglu, M. Heiss, A. Fontcuberta i-Morral and L. Dal Negro "Photonic-Plasmonic Coupling of GaAs Single Nanowires to Optical Nanoantennas", Nano Lett., 14, 2271 (2014).

J. Trevino, G.F. Walsh, S.V. Boriskina, L. Dal Negro, "Photonic-Plasmonic coupled Nanoantennas for Polarization-controlled Multispectral Nanofocusing", Optics Lett., 38, 4861 (2013).

E. F. Pecora, G. F. Walsh, C. Forestiere, A. Handin, E. Russo-Averchi, A. Dalmau-Mallorqui, I. Canales-Mundet, A. Fontcuberta i Morral and L. Dal Negro, "Enhanced second harmonic generation from InAs nano-wing structures on silicon", Nanoscale 5, 10163 (2013)

N. Caselli, N. Lawrence, J. Trevino, D.S. Wiersma, F. Intonti, L. Dal Negro, "Near-field distribution and propagation of scattering resonances in Vogel spiral arrays of dielectric nanopillars", New Journal of Physics, 15, 085023 (2013)

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N. Lawrence and L. Dal Negro "Radiation rate enhancement in sub-wavelength plasmonic ring nanocavities", *Nano Lett.* 13, 3709 (2013).

G. F. Walsh and L. Dal Negro "Enhanced Second Harmonic Generation by Photonic-Plasmonic Fano-type Coupling in Nanoplasmonic Arrays", *Nano Lett.* 13, 3111 (2013).

E. F. Pecora, A. Capretti, G. Miano, L. Dal Negro "Generation of second harmonic radiation from sub-stoichiometric silicon nitride thin films", *Appl. Phys. Lett.*, 102, 141114 (2013).

S. Simon, N. Lawrence, J. Trevino, L. Dal Negro, and A.V. Sergienko, "High Capacity Quantum Fibonacci Coding for Key Distribution," *Phys. Rev. A*, 87, 032312 (2013).

#### Books

L. Dal Negro Ed. "Optics of Aperiodic Structures: Fundamentals and Device Applications", Pan Stanford Publishing (2014).

L. Dal Negro "Optics of Aperiodic Media: Fundamentals and Device Applications", Cambridge University Press, expected publication date: September 2015 (developed mostly during the reporting period)

#### Book Chapters

L. Dal Negro, N. Lawrence, J. Trevino "Engineering aperiodic spiral order in nanophotonics: fundamentals and device applications" in *Nanodevices for photonics and electronics: advances and applications* edited by P. Bettotti, Pan Stanford Publishing (submitted during the reporting period and expected publication Spring 2015).

L. Dal Negro, N. Lawrence, J. Trevino, G. Walsh, "Aperiodic Order for Nanophotonics", in *Optics of Aperiodic Structures*, edited by L. Dal Negro, Pan Stanford Publishing (2014).

L. Dal Negro, N. Lawrence, J. Trevino, G. Walsh, "Aperiodic Nano Plasmonics", in *Optics of Aperiodic Structures*, edited by L. Dal Negro, Pan Stanford Publishing (2014).

C. Forestiere, A. Capretti, L. Dal Negro, G. Rubinacci, A. Tamburrino, G. Miano, "Numerical methods for the electromagnetic simulation of complex plasmonic nanostructures", in *Optics of Aperiodic Structures*, edited by L. Dal Negro, Pan Stanford Publishing (2014).

L. Dal Negro, N. Lawrence, J. Trevino, "Engineering the Orbital Angular Momentum of Light with Plasmonic Vogel Spiral Arrays", in *Frontiers in Singular Optics*, edited by S.V. Boriskina, Pan Stanford Publishing (Spring 2014).

L. Dal Negro, C. Forestiere, N. Lawrence, S. Y. Lee, J. Trevino, G. Walsh, "Engineering aperiodic order in nanophotonics", in *Plasmonics: Theory and Applications*, edited by Tigran V. Shahbazyan and Mark I. Stockman, Springer 2013

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