Fundamental Investigations of Nanolaser Physics: Statistical Properties, Thermal Stability, and Temporal Dynamics of Light Emission (ECS #1405234)

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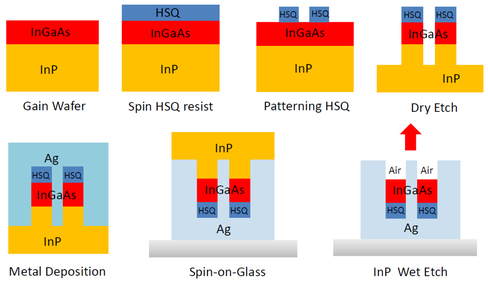
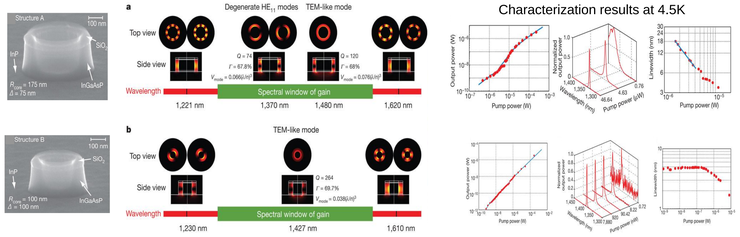
Abstract: We demonstrate lasing in optically pumped thresholdless coaxial nanolasers and show its unique properties. We demonstrate room temperature optically pumped metallo nanolasers, as well as77K-160K laser emission from electrically pumped versions. We also explore fundamental capabilities of nanolasers through the evaluation of the Purcell effect and temperature dependent spontaneous emission factor, as well as experimental and theoretical evaluations of second order coherence (G2).

Thresholdless sub-wavelength coaxial lasers [1]

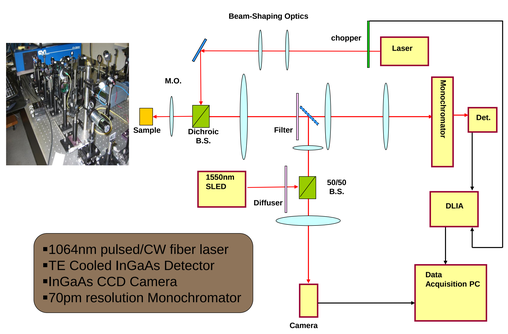
- Operates in plasmonic modes
- Exhibit thresholdless behavior
- Curious behavior of linewidth evolution

Gain medium
- 480nm thick InGaAsP-based Multiple Quantum Well (MQW)
- lattice matched to an InP substrate



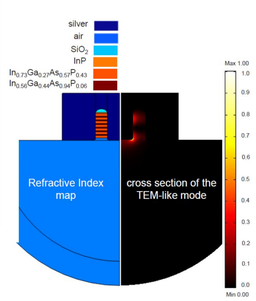


Micro-PL experimental setup

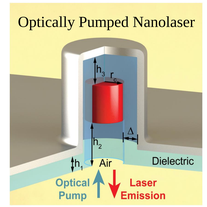


- 1064nm pulsed/CW fiber laser
- TE Cooled InGaAs Detector
- InGaAs CCD Camera
- 70pm resolution Monochromator

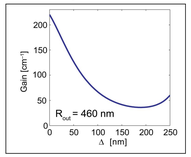
TEM-like mode profile



Metallo-dielectric Nanolasers [2]

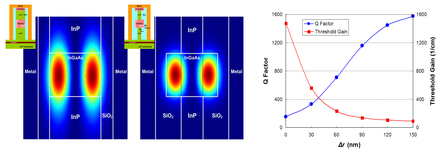


Shield thickness optimization

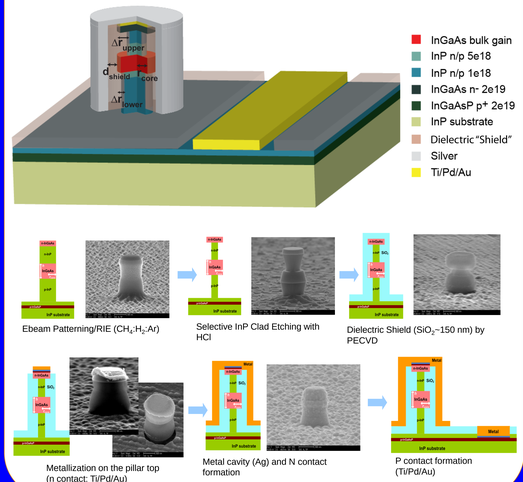


Electrically pumped Nanolasers [5]

EP laser pedestal design for optical confinement



The gain medium is a 300nm thick InGaAs bulk gain layer grown on InP substrate.



Purcell factor and Spontaneous Emission factor at transparency [3,4]

Purcell factor at a given temperature

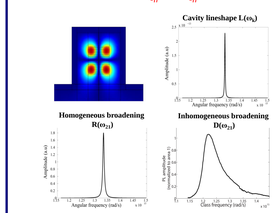
Literature

$$F_{cav}^{(k)} = \frac{3\lambda^3}{4\pi^2 n^3}\frac{Q}{V_{eff}} \propto \frac{Q}{V_{eff}}$$

Purcell factor for one mode

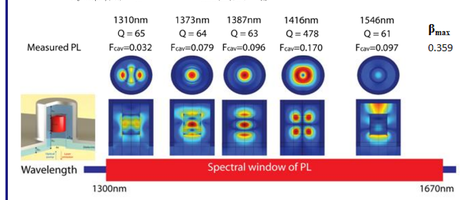
$$F_{cav}^{(k)} = \frac{\pi(c/n_r)^3}{\tau_{coll}}\frac{\omega_k}{\bar{\omega}_{21}^3}\frac{1}{V_a}\{\Gamma_k\}$$

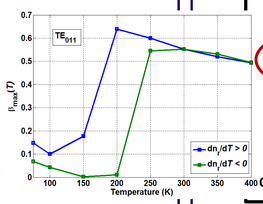
$$\int D(\omega_{21})\int L_k(\omega-\omega_k)R(\omega-\omega_{21},\tau_{coll})d\omega d\omega_{21}$$



$D(\omega_{21})$: inhomogeneous broadening
$R(\omega_{21})$: homogeneous broadening
$L(\omega_k)$: cavity lineshape

Inhomogeneously and homogeneously broadened	Unbroadened
0.215	8.79





Summary: Emitter-field-reservoir model in the quantum theory of damping is used in the evaluation
- Reservoir (environment) being cavity boundary corresponds to the transparent medium condition, when gain medium is neither absorptive nor amplifying
- The aggregate of other emitters in the gain medium are not included in the reservoir

Challenge: To evaluate Purcell factor at all pump levels, an open (dissipative) system needs to be constructed

Spontaneous emission factor at a given temperature

$$\beta \equiv \frac{R_{SE}^{(lasing)}}{R_{SE}^{(lasing)} + \sum_{mnp} R_{SE}^{(mnp)} + R_{SE}^{(vac)}}$$

R_{SE}^{lasing}, rate of SE into lasing mode
$R_{SE}^{(mnp)}$, rate of SE into other cavity modes
R_{SE}^{fs}, rate of SE into freespace continuum

$$\beta_{max} = \frac{F_P^{(lasing)}}{F_P^{(lasing)} + \sum_{mnp} F_P^{(mnp)}} \geq \beta$$

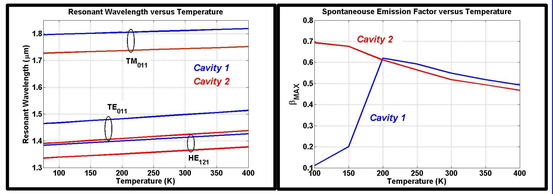
Temperature dependence

Reservoir damping, Mode frequency, Inhomogeneous Broadening

$$F_{P,mnp}(T) = \frac{\pi c^3}{n_r^3}\frac{\omega_C(T)}{\omega_{21}^3}\frac{\omega_{mnp}(T)}{}\frac{\Gamma_{mnp}}{V_A}\int R_{SE}(\omega_{21};T)\int C_{mnp}(\omega-\omega_{mnp};T)L(\omega-\omega_{21},\tau_n;T)d\omega d\omega_{21}$$

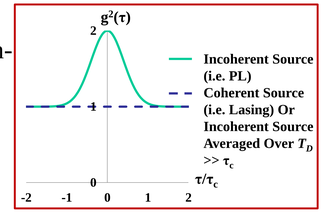
Cavity Broadening, Homogeneous Broadening

Result: Reducing total cavity radius by 25nm, the dominant mode of Cavity 2 is blue-shifted resulting in β>0.5 for all T.



Photon statistics in nanolasers

Goal: measure $g^2(\tau)$ — the intensity correlation of nanolaser emission (or fourth-order moment of the emitted electric field)

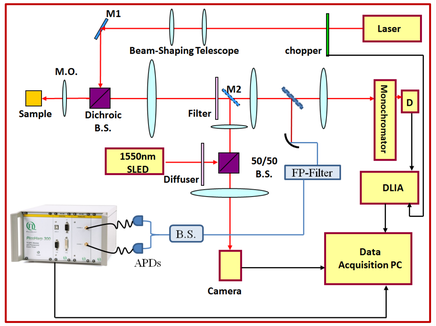


Challenge: photo-detector timing resolution >> coherence time of nanolaser (i.e. $T_D >> \tau_c$ @ ~1550nm)

- Geiger-mode APD Timing Jitter: $T_D \sim 100-300ps$
- Nanolaser Spectral Linewidth and Coherence Time:

$$\Delta\lambda \sim 1-7nm^{(1)} \Rightarrow \tau_c \sim \frac{1}{|\Delta\nu|} = \frac{\lambda^2}{c\cdot\Delta\lambda} \approx 1-8ps$$

- Averaging effect renders $g^2(0)$ for PL and lasing indistinguishable $\langle g^{(2)}(\tau)\rangle = \frac{1}{T_D^2}\int_0^{T_D}dt\int_0^{T_D}dt' g^{(2)}(|t-t'|)$



Proposed Solution: spectrally filter nanolaser emission with a Fabry-Perot interferometer + Hanbury Brown Twiss

Reference

(1) Khajavikhan, M. et al, "Thresholdless nanoscale coaxial lasers," *Nature*, 482, 204-207 (2012)
(2) M. P. Nezhad et al., "Room Temperature Lasing from Sub-wavelength Metallo-Dielectric Lasers," Nature Photonics, 4(6), 395 - 399 (2010)
(3) Gu, Q. et al, "Purcell effect in sub-wavelength semiconductor lasers," *Opt. Exp.*, 21, 15603-15617 (2013)
(4) Smalley, J. et al "Temperature dependence of the spontaneous emission factor in subwavelength semiconductor lasers," *IEEE J. Quant. Elect.*, 50, 175-185 (2014)
(5) Gu, Q. et al, "Amorphous Al2O3 shield for thermal management in electrically pumped metallo-dielectric nanolasers," *IEEE J. Quant. Elect.*, 15, 499-509 (2014)