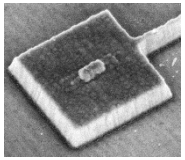
E3S Retreat
September 20, 2018

Theme III: Nanophotonics For Energy-Efficient Communications

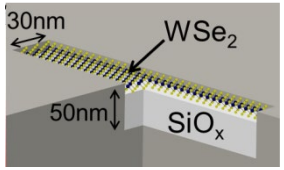
Theme Leader: Ming C. Wu

Current Theme Projects & PI's

➢ Optical antenna-enhanced nanoLED



- ❑ Electrical injection III-V antenna-LEDs
  [Wu, Yablonovitch, UCB; Kim/Fitzgerald, MIT]

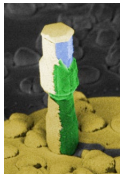


- ❑ Monolayer TMDC antenna-LEDs
  [Wu, Yablonovitch, Javey, UCB]

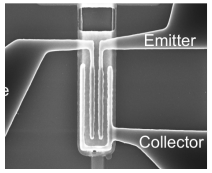




➢ Ultra-sensitive photoreceivers



- ❑ Photoreceiver analysis
  [Yablonovitch, Yablonovitch, UCB]



- ❑ Photo-bipolar junction transistor (BJT)
  [Chang-Hasnain, UCB; Fitzgerald, MIT]




➢ Link modeling and system analysis

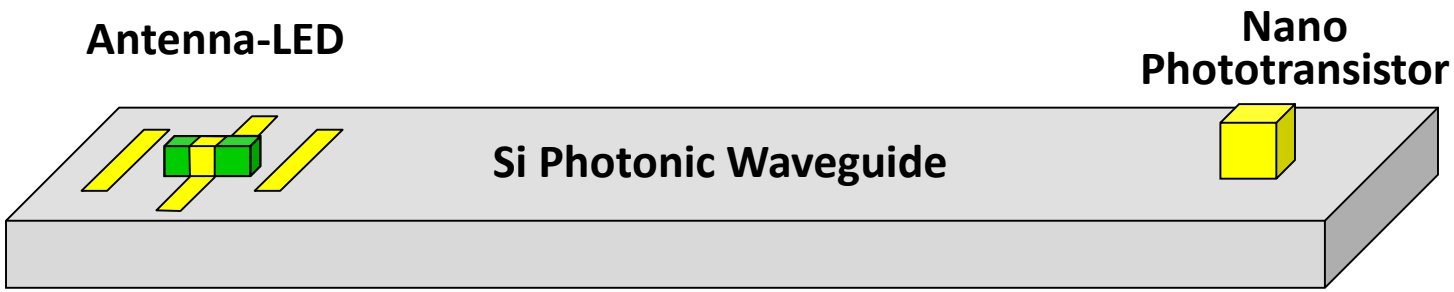
[Stojanovic, UCB]

Team Members

- Theme III inter-institutional postdoc
  - Seth Fortuna
- Graduate Students:
  - Matin Amani, Nicolas Andrade, Sujay Desai, Kevin Han, Sean Hooten, Jonas Kapraun, George Zhang, Peida Zhao (UCB)
- Undergrad:
  - Joy Cho (UCB)
- Postdocs:
  - Der-hsien Lien, Kyungmok Kwon
- Alum
  - Chris Heidelberger (MIT-Lincoln Lab), Indrasen Bhattacharya (KLA-Tencor), Kevin Messer (Magic Leap), Christopher Keraly (PARC), Ryan Going (Infinera), Michael Eggleston (Bell Labs), Wilson Ko (OURS), Yue Lu (Qualcomm)

Theme Overview

- **Main goal: Dramatically improve the interconnect energy efficiency to 20 aJ/bit @ 20 photons/bit**
  (Current state of the art: 100s fJ/bit @ 10,000 ph/bit)



Our Approach

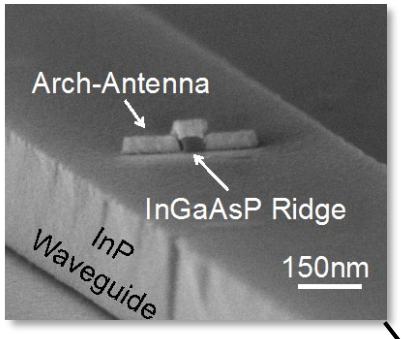
Antenna-Enhanced LED

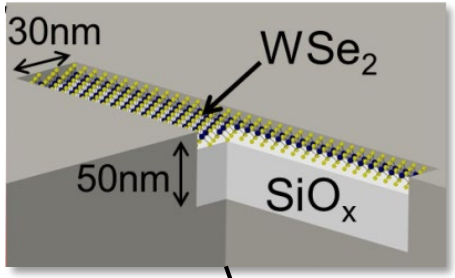
- **No threshold (DC bias)**
- **Use optical antenna to enhance spontaneous emission rate**
- **Faster than laser**

Ultra-Sensitive Photoreceivers

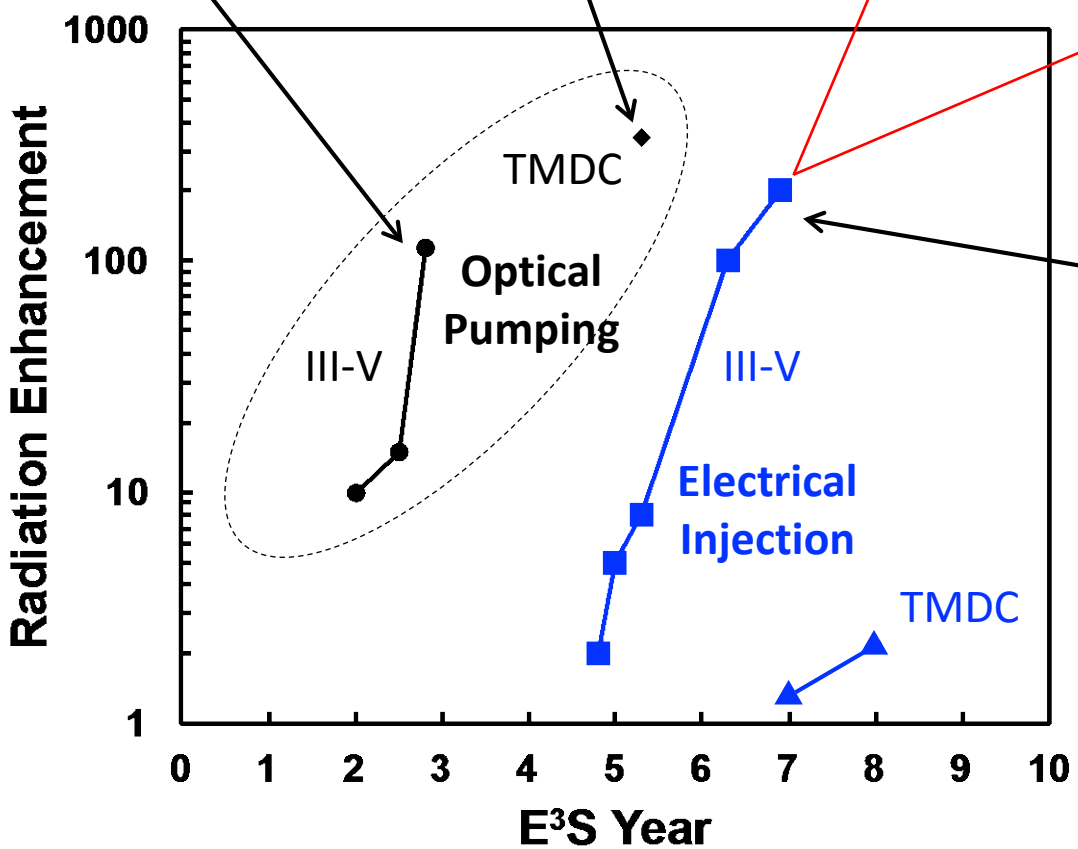
- **Ultralow capacitance (< 100aF) to enlarge photo signal**
- **Integrate PD with first gain stage to eliminate wire capacitance**

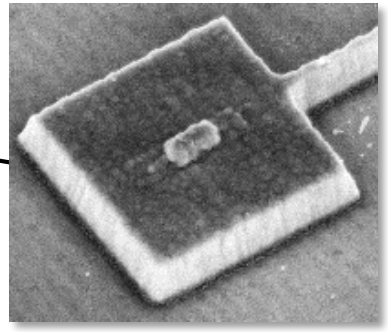
Progress of Antenna LED under E³S



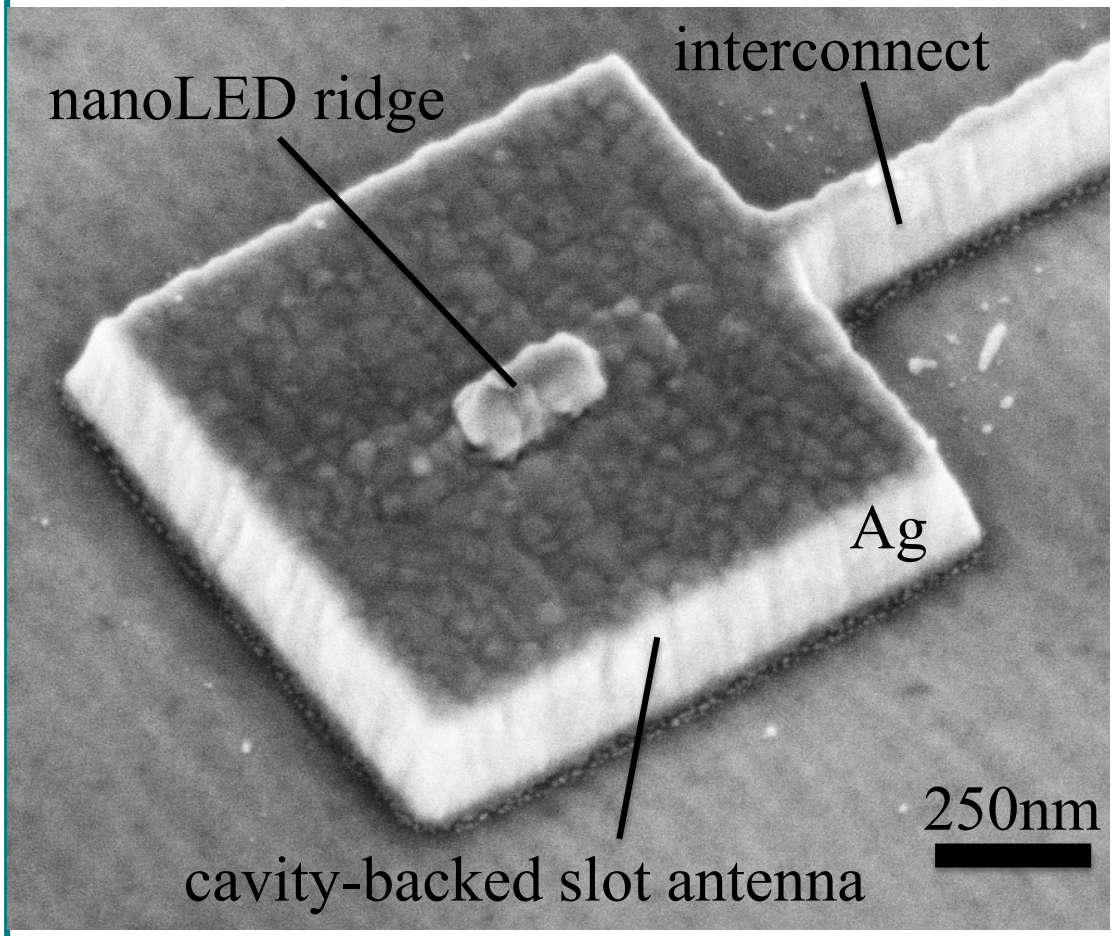


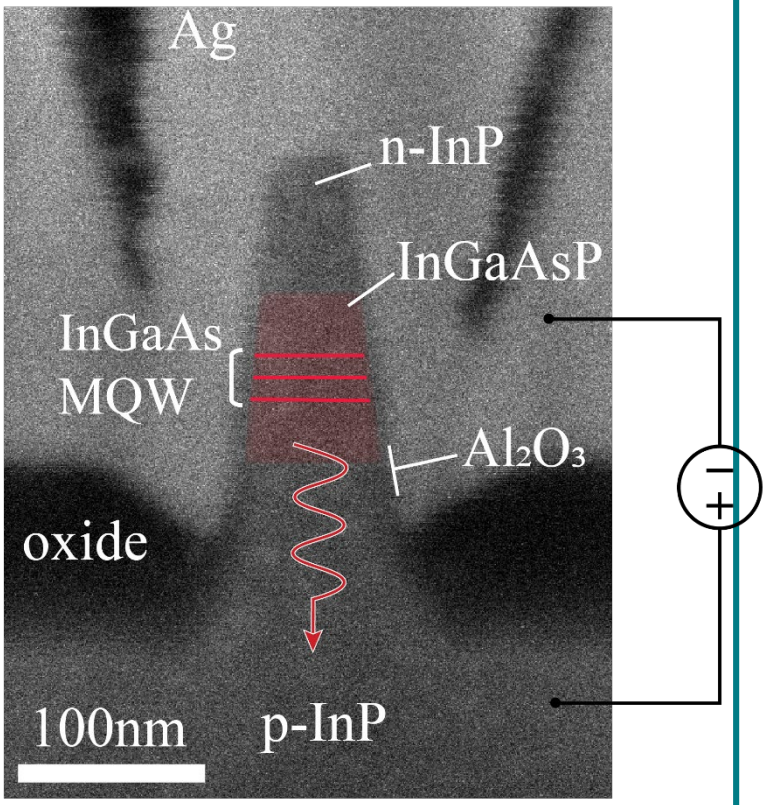
Focus shift to
- Temporal response
- Efficiency
- Output power





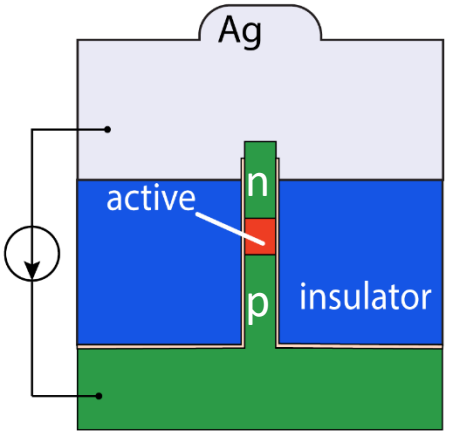
Electrically-injected III-V antenna-LED



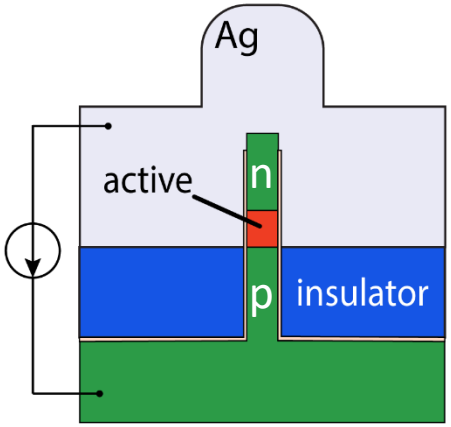


Antenna-Enhanced Electroluminescence

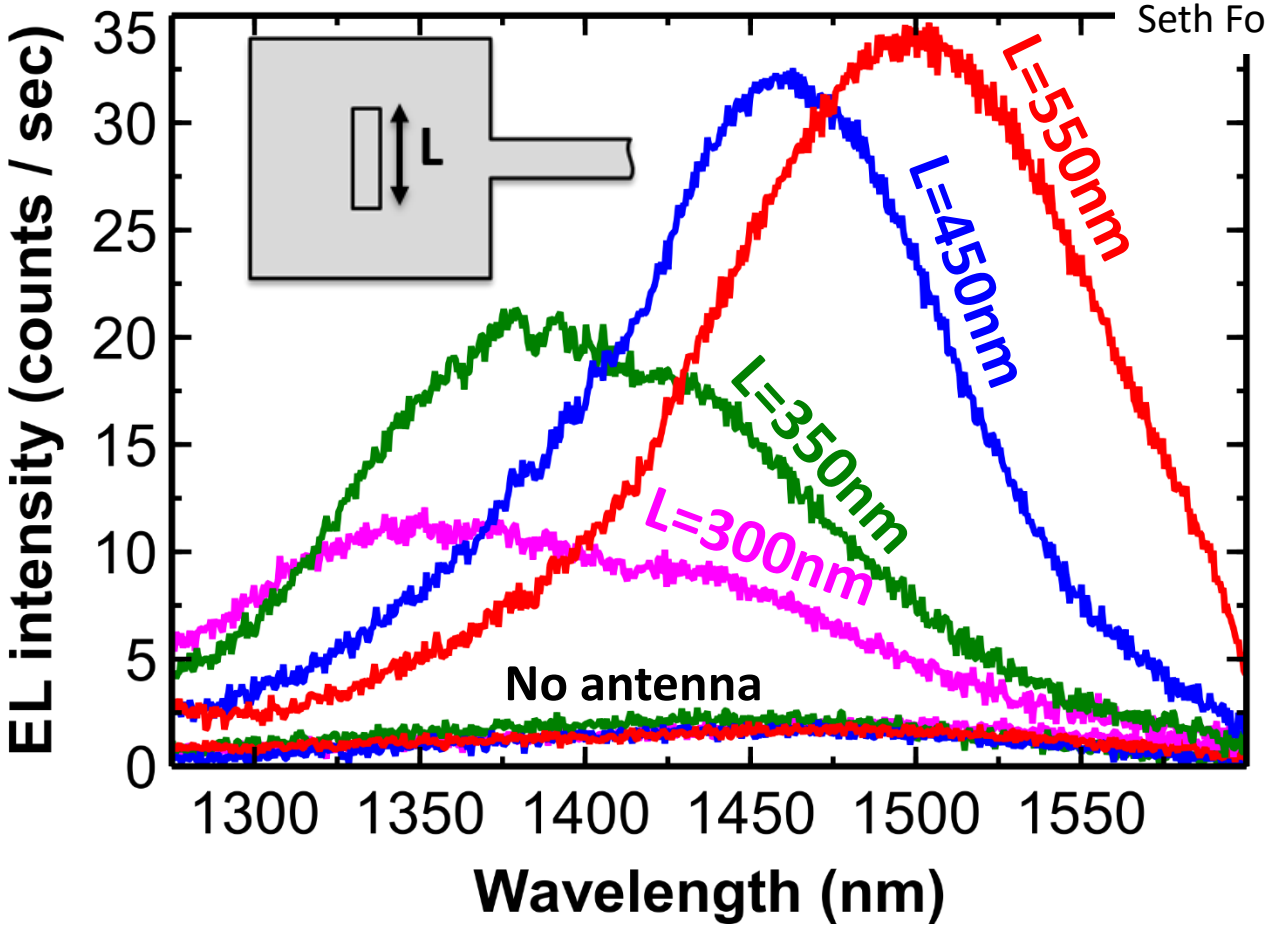
Seth Fortuna



No antenna



Antenna-LED

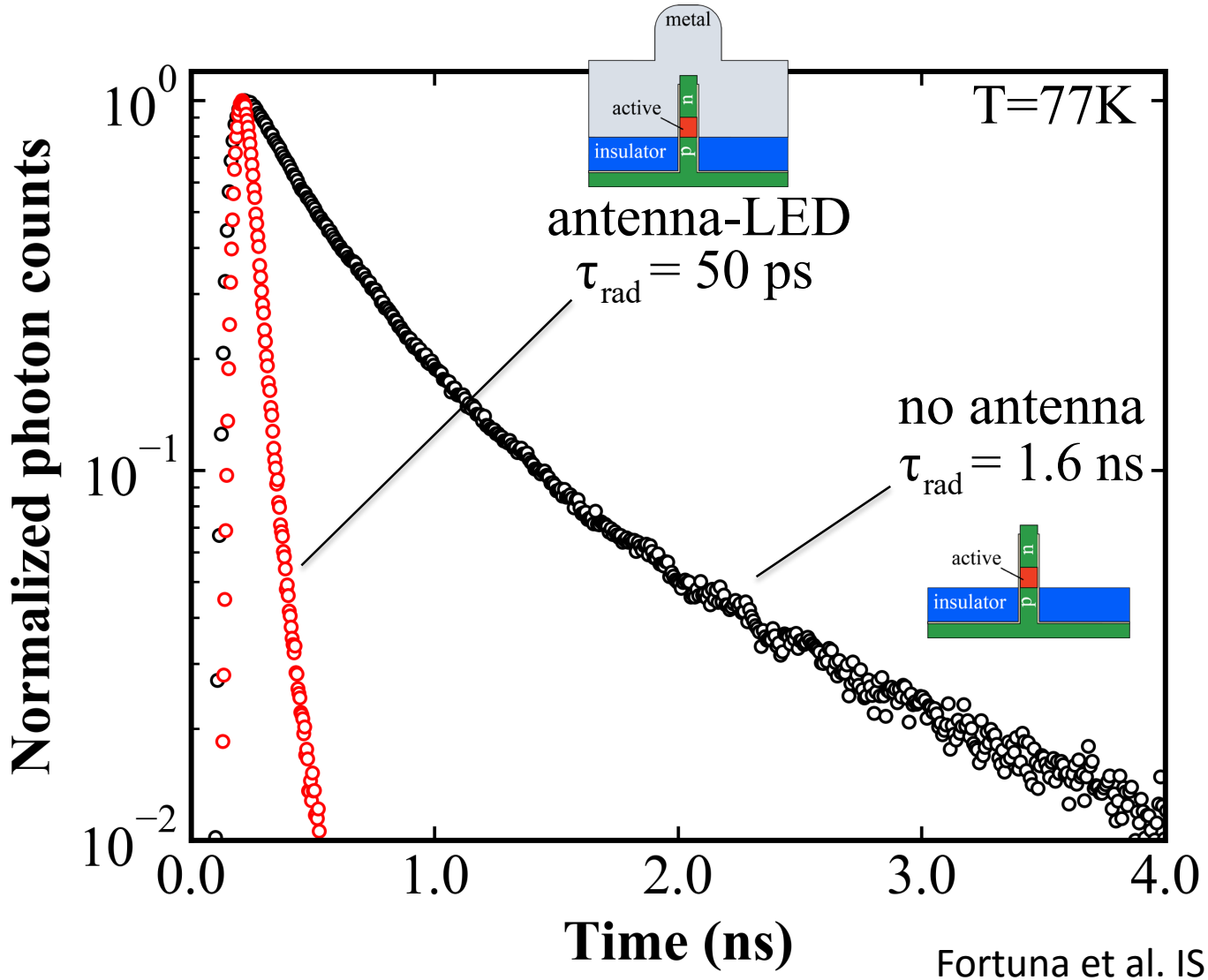


Fortuna et al. ISLC 2016

A Science & Technology Center

Center for Energy Efficient Electronics Science

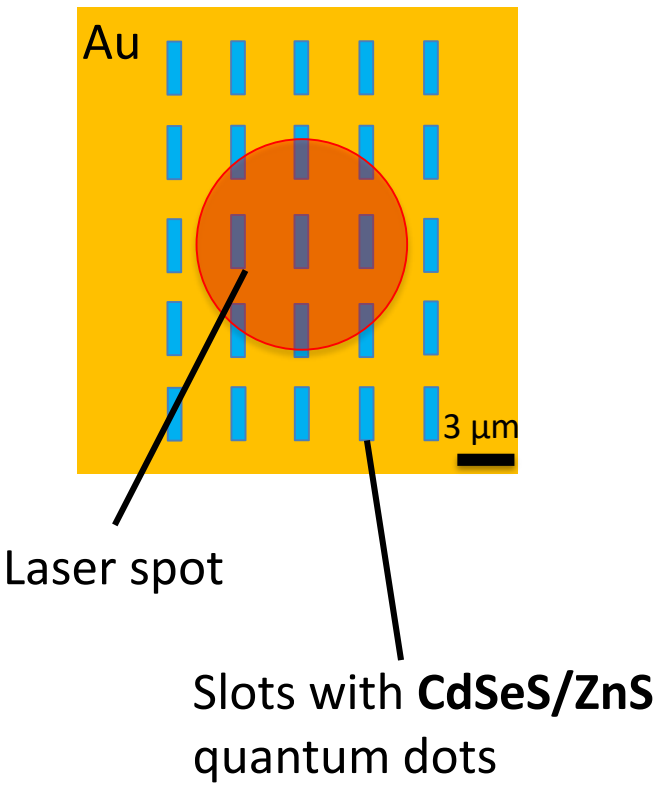
50 Picosecond Spontaneous Emission Lifetime

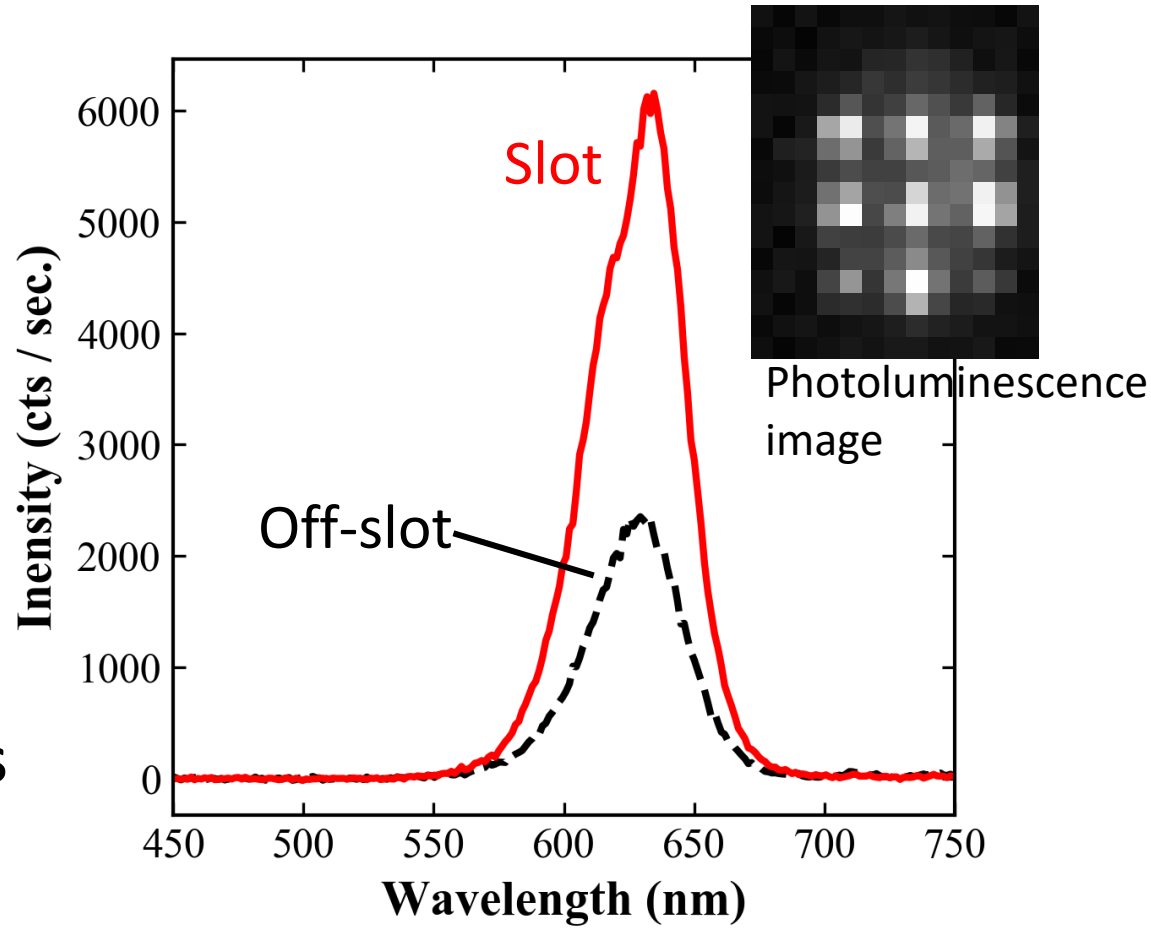


Fortuna et al. ISLC 2018

First Demonstration: Integration of Slot Antenna with Colloidal Quantum Dots

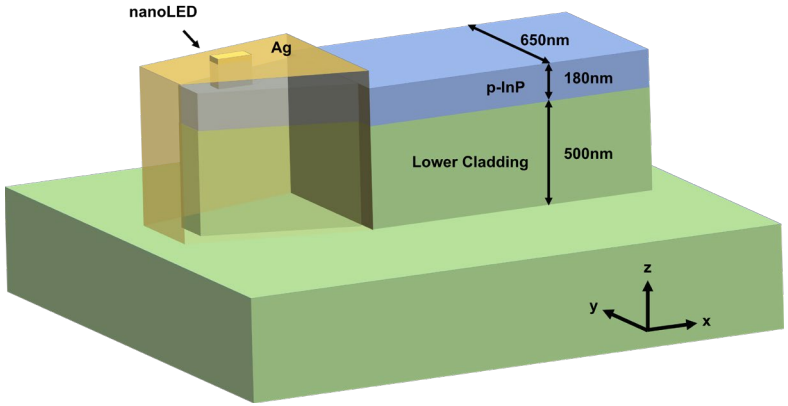
Seth Fortuna, Michael Bartl, Vladimir Bulovic, et al.

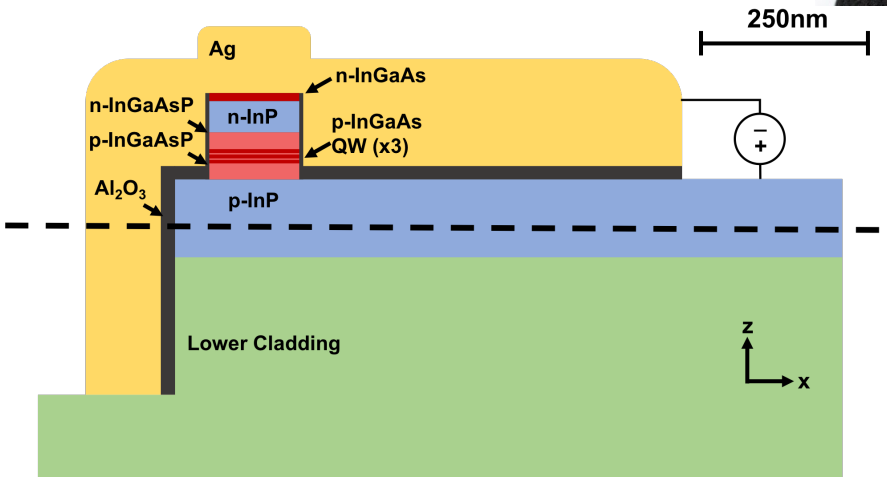




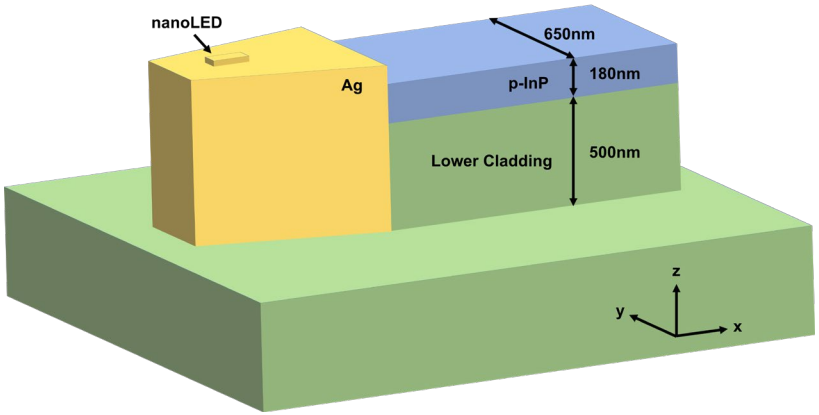
Waveguide Coupled Antenna-LED schematic

Nicolas Andrade

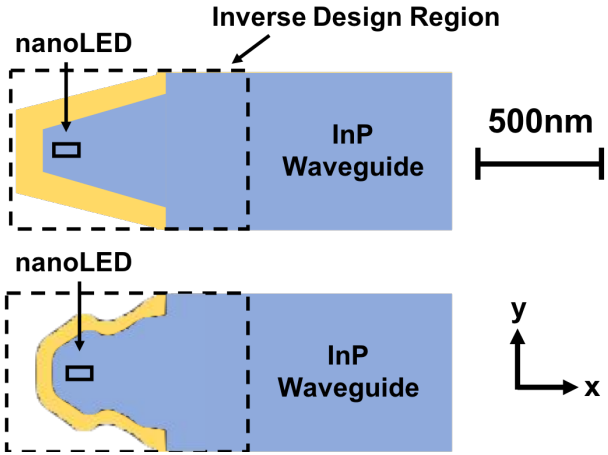




Cross-sectional view



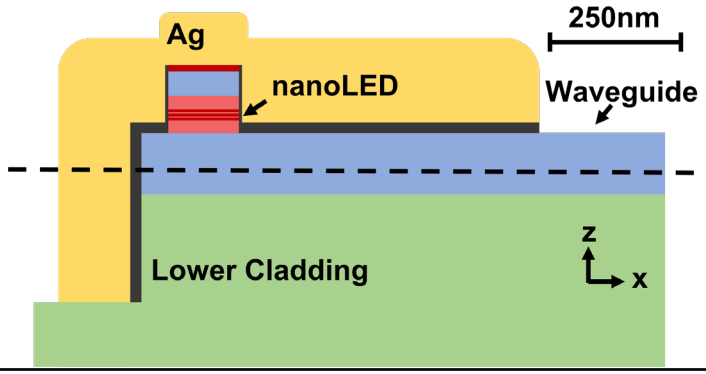
Perspective view

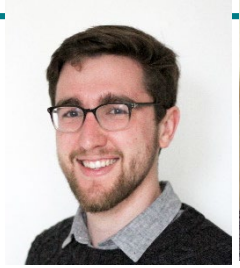


Top-view: cross-section along cutline

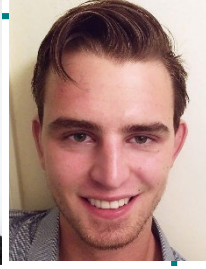
Andrade et al. CLEO 2018.

Inverse Design Waveguide Coupler



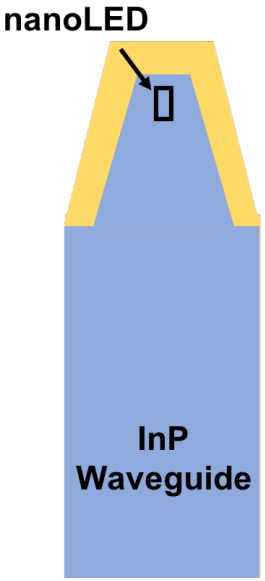


Nicolas Andrade



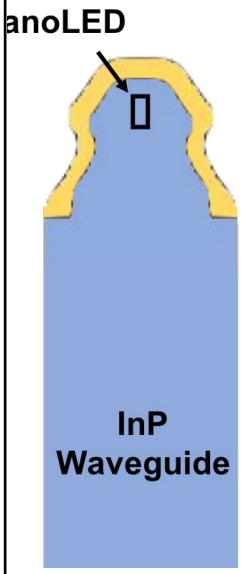
Sean Hooten

Tapered Coupler



Top View
Cross-section

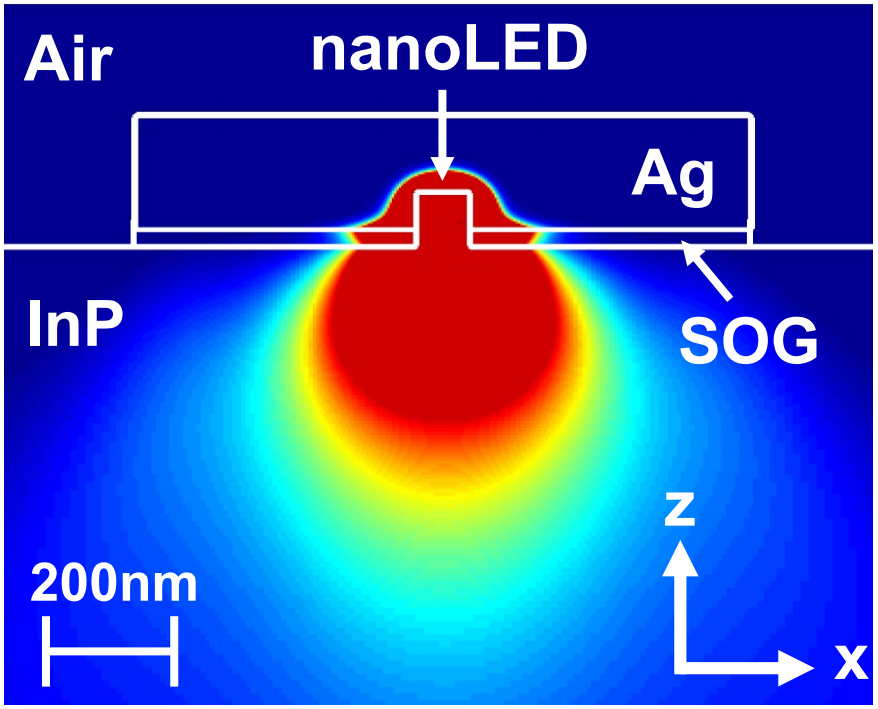
After Optimization



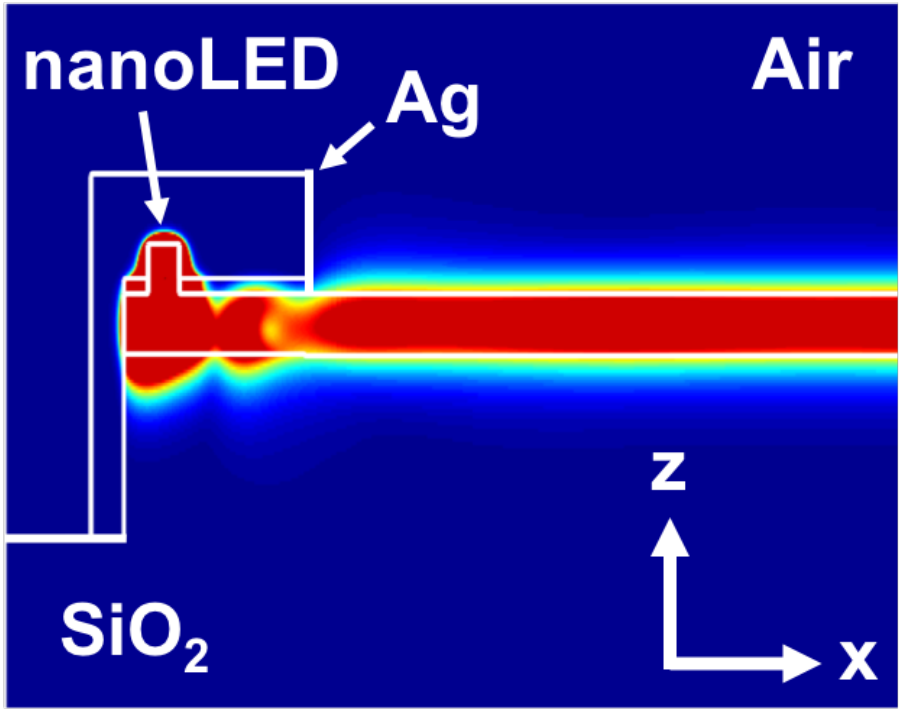
Top View
Cross-section

Andrade et al. CLEO 2018.

Inverse Design Power Flow

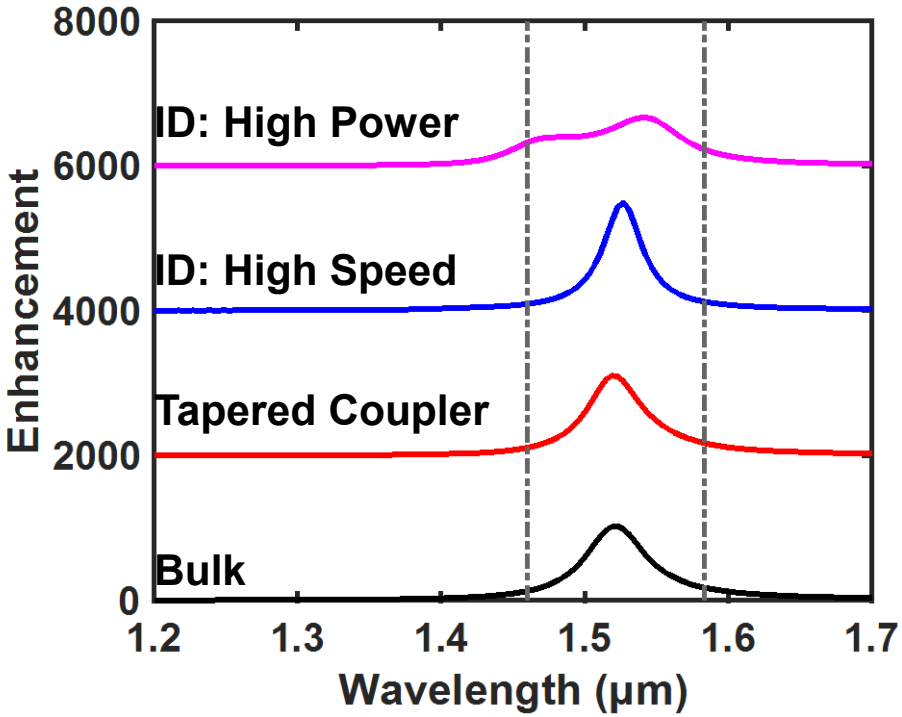


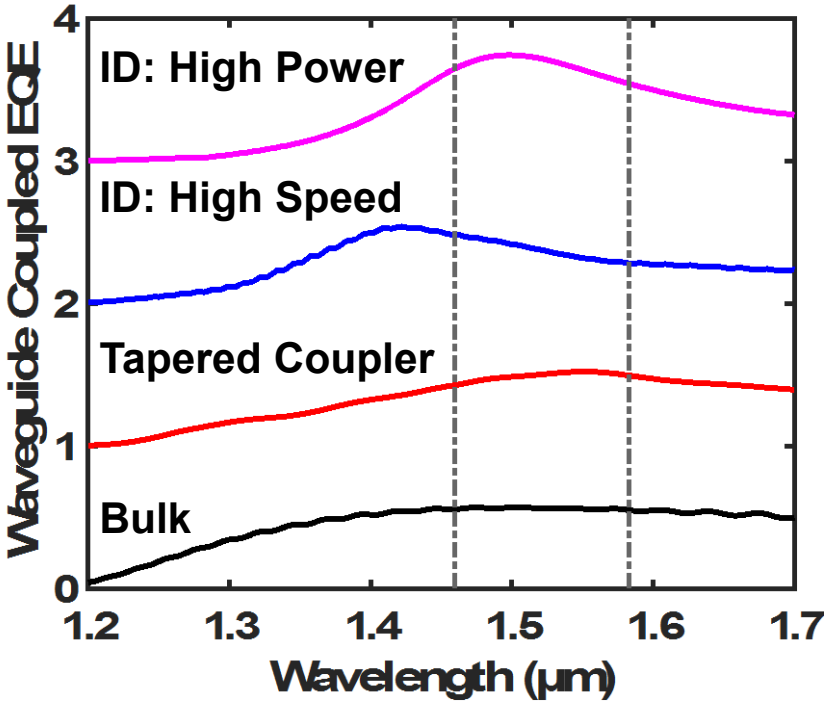
Cross section of power flow on bulk InP



Cross section of power flow coupled to single mode InP waveguide

Inverse Design Optimization



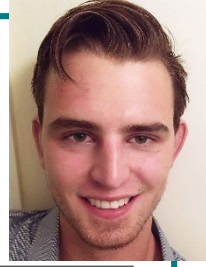


Average Enhancement: 168.9

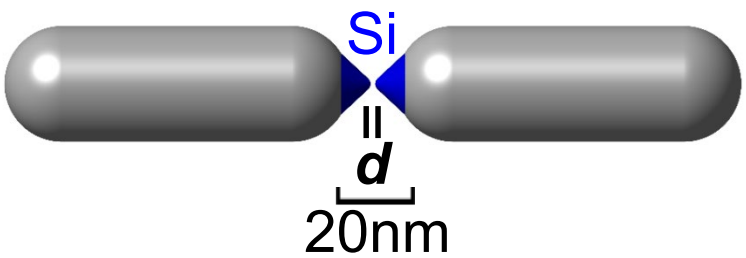
Average Waveguide-Coupled EQE: 60.8%

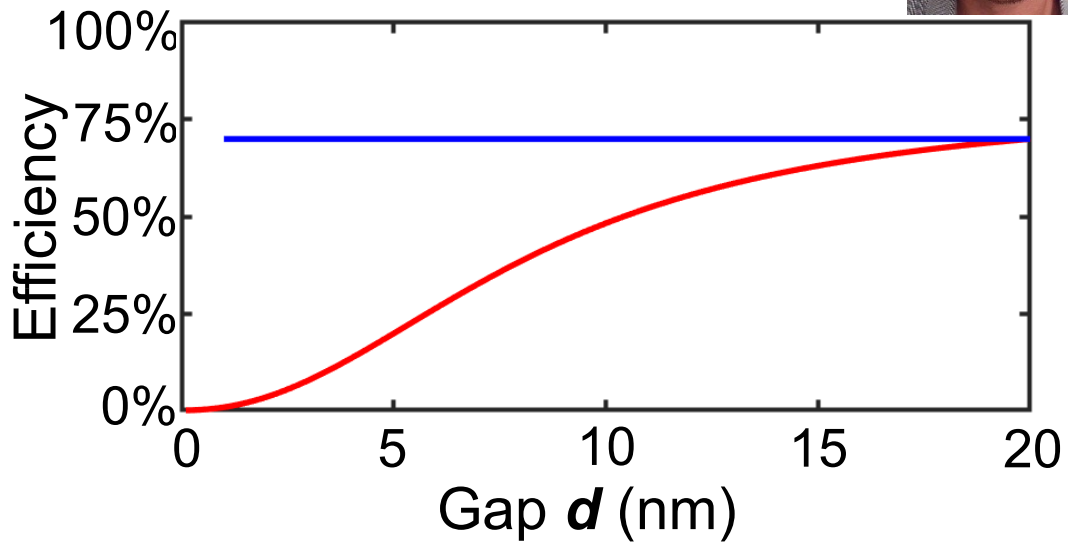
Metal-Dielectric Antenna

Sean Hooten

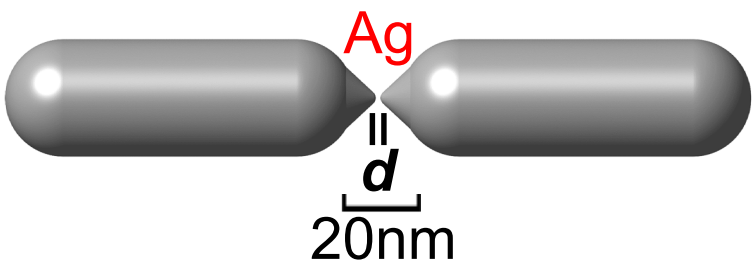


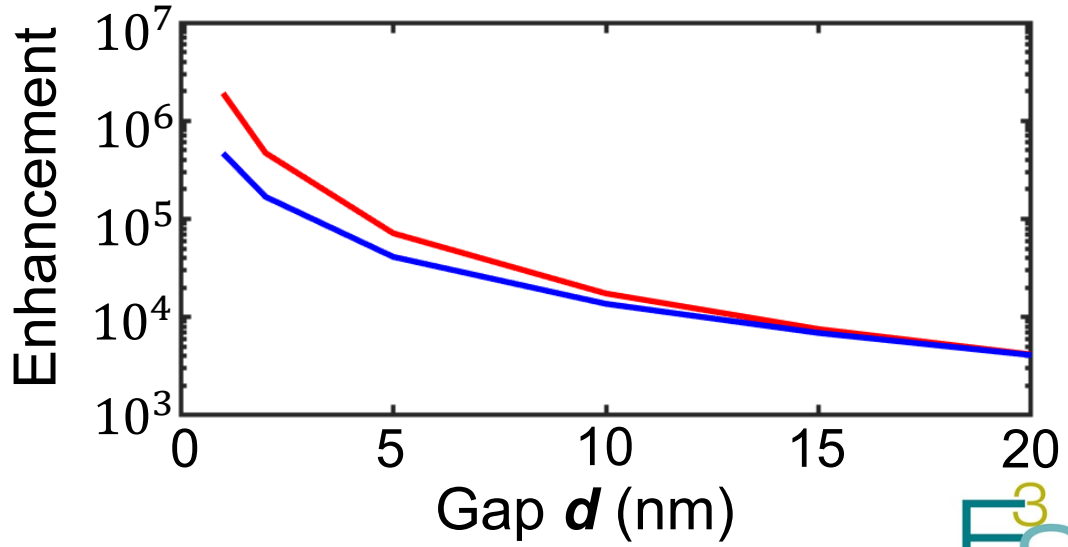
Metal-Dielectric





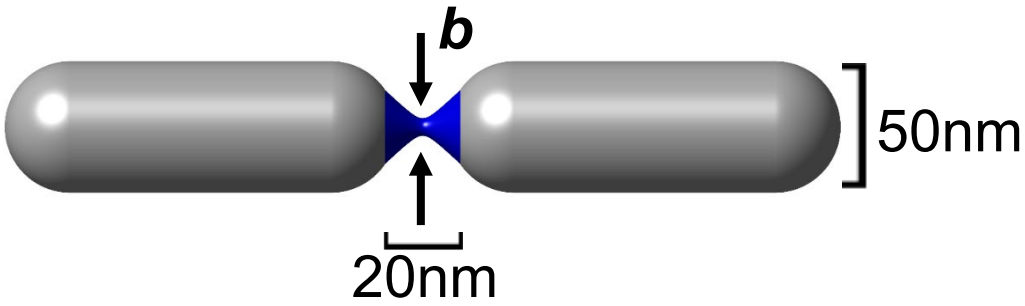
All Metal



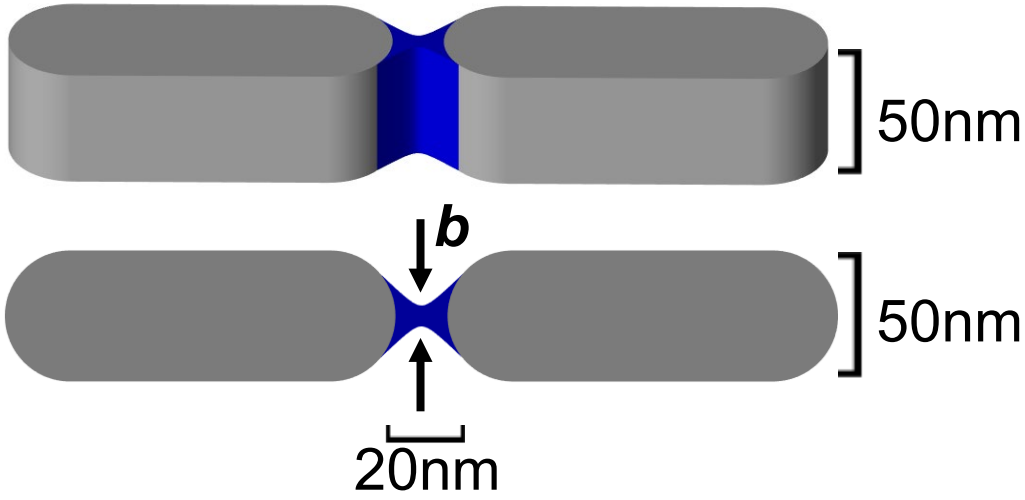


Metal-Dielectric Antenna LED

- Cylindrical

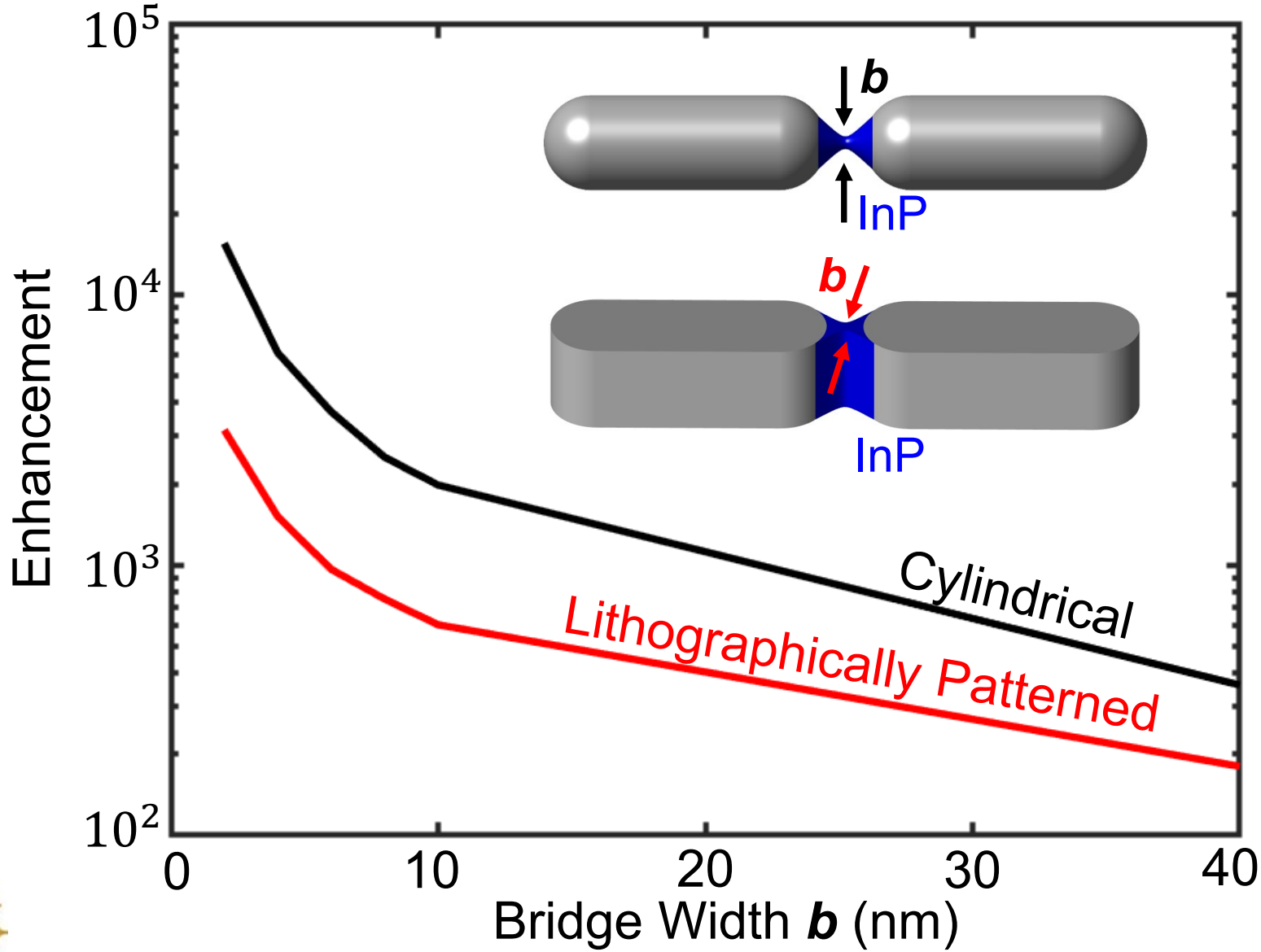


- Lithographically Patterned



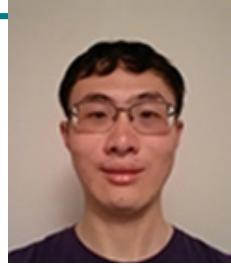
- Electrical injection compatible
- High efficiency (~70%)

Metal-Dielectric Antenna LED

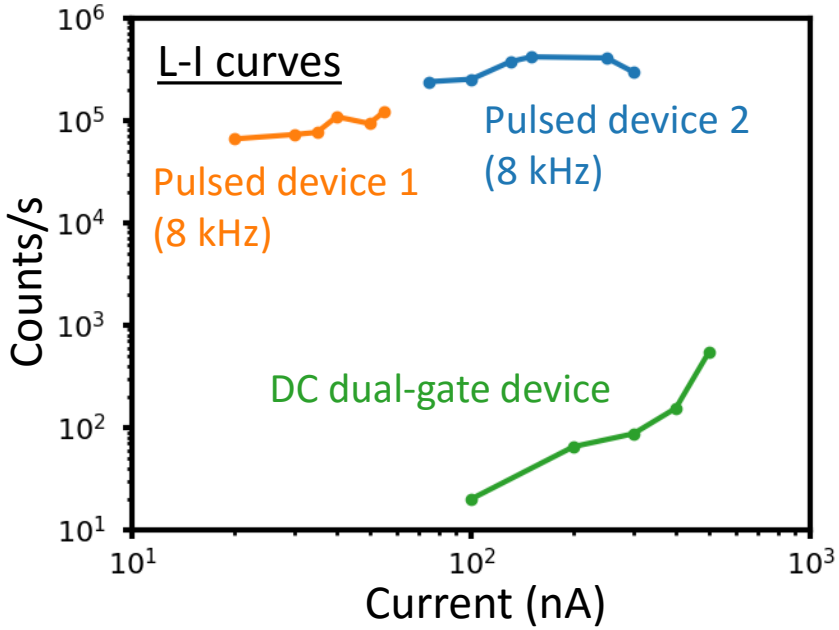


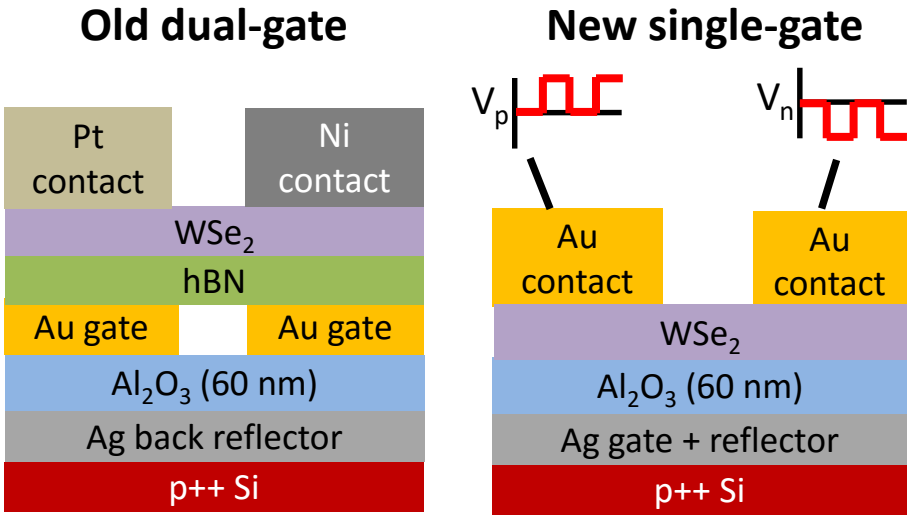
Electrical Injection LED with Monolayer WSe_2 Emitter

In collaboration with Javey Group



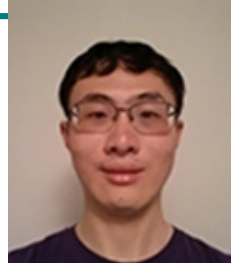
Kevin Han



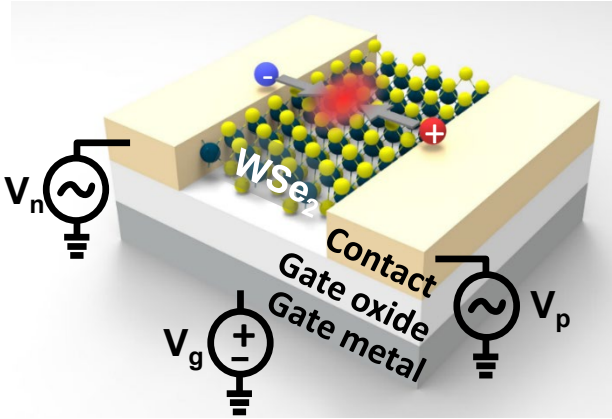


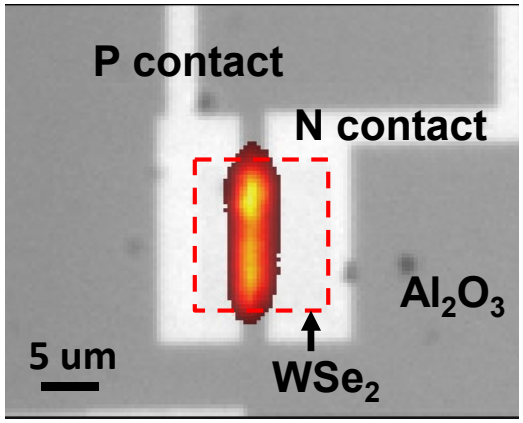
Device	Device lifetime	Brightness	External quantum efficiency
Dual-gated PIN diode DC; no solvent Area ~ 20 um^2	<10 min	~2 pW	~10^{-6}
Single-gate PIN diode Pulsed; solvent Area ~ 20 um^2	>30 min	~400 pW	>10^{-4}

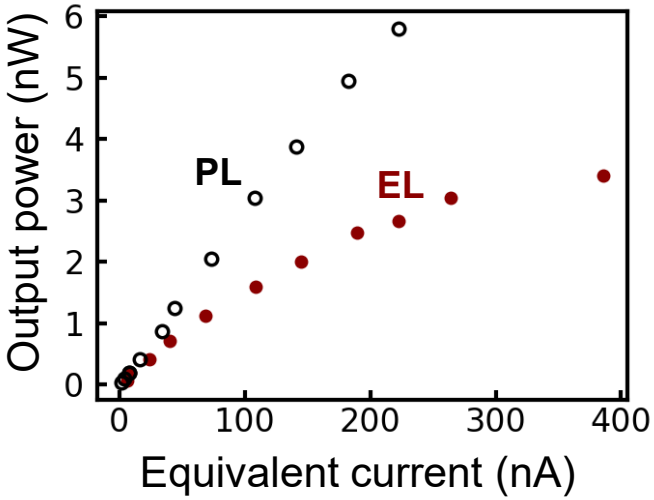
High efficiency Monolayer WSe_2 LEDs

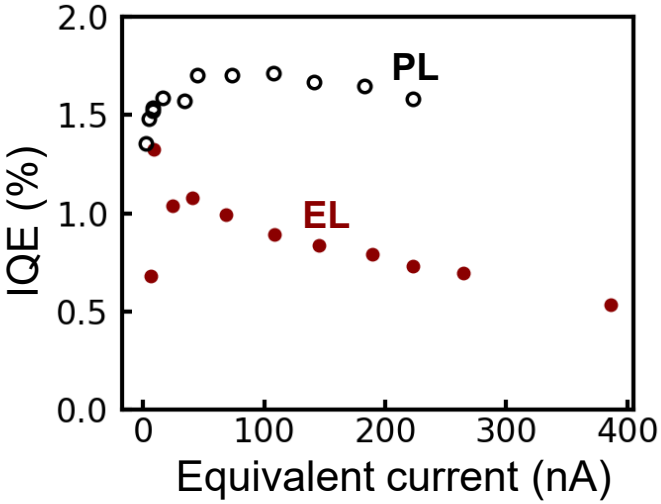


Kevin Han



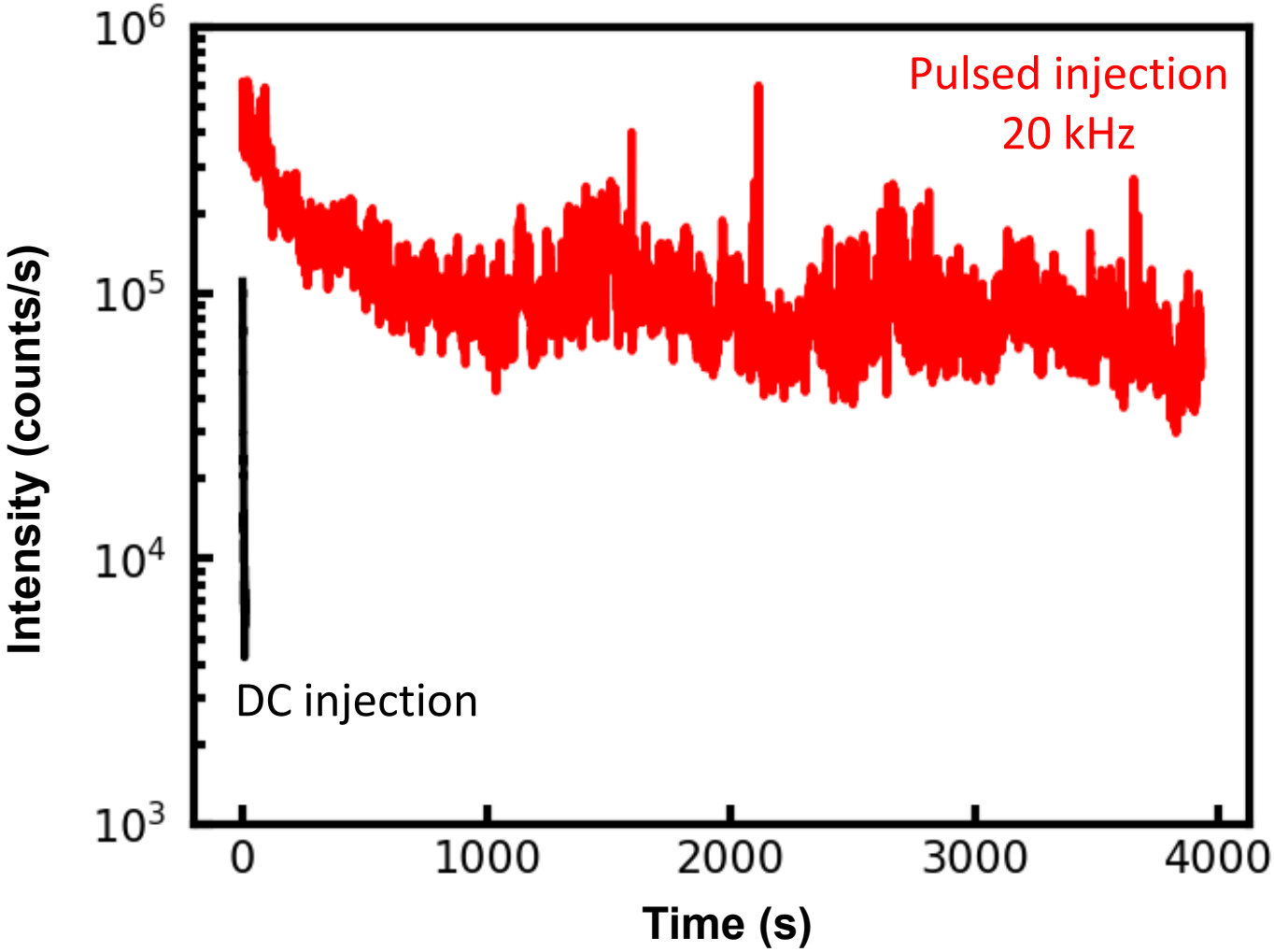






Process improvements yield EL efficiency close to PL (~1%), indicating material-limited efficiency

EL long-term stability



EL with pulsed injection is stable over hours

Summary

- First temporal measurement of III-V antenna-LED
  - 50 ps spontaneous emission lifetime measured at 77K
  - Compared with 1.6 ns without antenna
- High coupling efficiency to single mode waveguide by inverse design
  - Overall efficiency > 60% (including metal loss)
- First demonstration of quantum dot emitters with slot antenna
- Electrical bipolar injection LED with monolayer WSe_2
- Very sensitive method to characterize surface recombination velocity → Collaboration with Jesús del Alamo group