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

![Graph showing the progress of LED technology](image)

Radiation Enhancement

E³S Year

- Arch-Antenna
- InGaAsP Ridge
- Optical Pumping
- III-V
- Electrical Injection
- TMDC
- WSe₂
- SiOₓ

150nm
Electrically-injected III-V antenna-LED

nanoLED ridge

interconnect

Ag

cavity-backed slot antenna

250nm
Antenna-Enhanced Electroluminescence

No antenna

Antenna-LED

Fortuna et al. ISLC 2016

EL intensity (counts / sec)

Wavelength (nm)

L=550nm
L=450nm
L=350nm
L=300nm

No antenna
50 Picosecond Spontaneous Emission Lifetime

antenna-LED
\[ \tau_{\text{rad}} = 50 \text{ ps} \]

no antenna
\[ \tau_{\text{rad}} = 1.6 \text{ ns} \]

Fortuna et al. ISLC 2018
First Demonstration: Integration of Slot Antenna with Colloidal Quantum Dots

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

Slots with CdSeS/ZnS quantum dots

Photoluminescence image

Intensity (cts/sec.)

Wavelength (nm)
Waveguide Coupled Antenna-LED schematic

Perspective view

Andrade et al. CLEO 2018.

Cross-sectional view

Top-view: cross-section along cutline

Andrade et al. CLEO 2018.
Inverse Design Waveguide Coupler

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

Metal-Dielectric

All Metal

Efficiency vs. Gap $d$ (nm)

Enhancement vs. Gap $d$ (nm)
Metal-Dielectric Antenna LED

- Cylindrical
- Lithographically Patterned

- Electrical injection compatible
- High efficiency (~70%)
Metal-Dielectric Antenna LED

Enhancement vs. Bridge Width $b$ (nm)

- **Cylindrical**
- **Lithographically Patterned**

$10^5$  $10^4$  $10^3$  $10^2$  $0$  $10$  $20$  $30$  $40$
Electrical Injection LED with Monolayer WSe$_2$ Emitter

In collaboration with Javey Group

### L-I curves

- **Pulsed device 2 (8 kHz)**
- **Pulsed device 1 (8 kHz)**
- **DC dual-gate device**

### Device Specifications

<table>
<thead>
<tr>
<th>Device</th>
<th>Device lifetime</th>
<th>Brightness</th>
<th>External quantum efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dual-gated PIN diode</td>
<td>&lt;10 min</td>
<td>~2 pW</td>
<td>~10^-6</td>
</tr>
<tr>
<td>DC; no solvent Area ~ 20 um$^2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single-gate PIN diode</td>
<td>&gt;30 min</td>
<td>~400 pW</td>
<td>&gt;10^-4</td>
</tr>
<tr>
<td>Pulsed; solvent Area ~ 20 um$^2$</td>
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</tbody>
</table>
High efficiency Monolayer WSe$_2$ LEDs

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

Pulsed injection 20 kHz

DC injection
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