Waveguide-Integrated Optical Antenna nanoLEDs for On-Chip Communication

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Power Consumption in Modern CPUs

- 50% - 80% of CPU power dissipation is in wire interconnects
- Energy Required to charge a wire \( \sim CV^2 \)
- Minimum energy to send one bit across a chip:

\[
CV^2 \approx 2 \left( \frac{pF}{cm} \right) \times 1\text{cm} \times (1V)^2 = 2pJ
\]

17 photons @ 0.8eV/photon \( \approx 2\alpha J \)
Optical Source for Energy-Efficiency Interconnect

**Semiconductor Laser:**
- Excessive energy consumption due to bias current
- e.g., for lasers with 1µA threshold, and bias at 5x threshold, E \( \sim 400 \) aJ/bit at 10Gbps

**Optical antenna-enhanced nanoLED:**
- No bias current
- Optical antenna enhance bandwidth by up to 1000x (10 to 100 Gbps possible)
- Energy consumption ~2x photon energy
Arch-Dipole Antenna Based nanoLED

Optical Antenna

- LC matching circuit
- InGaAsP
- Gold
- Antenna Arms

Expected Enhancement:

Gap Spacing (d) = 35nm
Length (L) = 400nm

\[
\frac{\tau_o}{\tau} = \frac{1}{4} \left( \frac{L}{d} \right)^2 \approx 33 \times
\]


Free-Standing Structure

Optical Emission Spectra

Counts

0 500 1000 1500 2000

Wavelength (nm)

0 1200 1300 1400 1500 1600

Antenna Coupled

Bare Ridge

35x

150nm

Counts

Glass Slide

Epoxy

Gold Antenna

TiO₂

InGaAsP

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InP Waveguide Design

Arch-Dipole on InP Substrate

Arch Antenna on InP Substrate

Arch Antenna on InP Waveguide

Radiated Power

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InP Waveguide Design

Thicker InP Substrate

Yagi-Uda Structure

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Waveguide Fabrication

1. Wet-etch InP Waveguide
2. Etch InGaAsP ridge and deposit antenna
3. Bond to carrier wafer and remove substrate
Optical Emission Measurements

Optical emission is collected with a front-side 0.8NA objective and imaged on a LN-cooled CCD.

Sample probed with a 720nm Ti:Sapphire fs-pulsed laser from the back-side.

- Linear InGaAs CCD
- Waveguide-Coupled Antennas
- fs-Laser Probe

InP Waveguide

250nm

50μm
Expected Enhancement:
Gap (d) = 40nm, Length (L) = 300nm

\[
\frac{\tau_o}{\tau} = \frac{1}{4} \left( \frac{L}{d} \right)^2 \approx 14x
\]
Optical Emission Spatial Map

- Bare InGaAsP
- Antenna Coupled
- Yagi-Uda Coupled

Counts

Distance Along Waveguide (um)

10sec Integration

$\eta_{coupling} \approx 50\%$

$\eta_{coupling} \approx 50\%$

$\eta_{coupling} \approx 70\%$

$Front/Back = 1.6 : 1^*$

*$3:1$ with narrower waveguides

Backward-coupled Light

Uncoupled Light

Forward-coupled Light
Integration with Silicon Photonics

- Epitaxial Lift-off is used to transfer III-V chips to Silicon substrates
Silicon Photonics with Active III/V Material

- Silicon wafers and Silicon processing technology can be used to make large-area photonics chips with active III/V material.
Summary

• Demonstrated a nanoLED with enhanced spontaneous emission coupled to a multi-mode InP Waveguide
  – 70% Coupling Efficiency
  – 50% Forward coupling
  – Directional emission of 3:1

• Future Work
  – Integrate nanoLED with single mode waveguide on Silicon Photonics platform
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