Inverse Design of Single-Mode Waveguide Coupled Electrically Injected Optical Antenna Based NanoLED

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*These authors contributed equally to this work
Electrically-Injected III-V Antenna LED

nanoLED ridge

interconnect

Cavity-backed slot antenna 250nm

Ag

InGaAs(P)

n-InP

p-InP

Ag

100 nm

oxide

Fortuna et al. ISLC 2016.
Electrically-Injected III-V Antenna LED

Cavity-backed slot antenna

Cross section of power flow
Literature Reports of Waveguide Coupling

➢ Nanoscale Optical Emitter


Simulated waveguide coupling: 90%


Simulated peak waveguide coupling: 77%
Experimental peak waveguide coupling: 71.5%

Peak simulated waveguide coupled external quantum efficiency: 42%

Includes all loss mechanisms
Literature Reports of Waveguide Coupling

- Laser Cavity Waveguide Coupling


Simulated waveguide coupling: \( \sim 90\% \)

Simulated waveguide coupled external quantum efficiency: \( \sim 15\% \)
Waveguide Coupler Design Progression

Structure

nanoLED on InP Waveguide

Schematic

Power Flow

Waveguide Coupled EQE

13% each direction
Waveguide Coupler Design Progression

**Structure**
- nanoLED on InP Waveguide
- nanoLED with reflector

**Schematic**
- nanoLED
- Ag
- p-InP
- Lower Cladding

**Power Flow**
- nanoLED
- Ag
- SiO₂
- z
- x
- 13% each direction

**Waveguide Coupled EQE**
- 26%
Waveguide Coupler Design Progression

**Structure**

- nanoLED on InP Waveguide
- nanoLED with reflector
- nanoLED with tapered coupler

**Schematic**

- Upper figure: nanoLED on InP Waveguide
- Middle figure: nanoLED with reflector
- Lower figure: nanoLED with tapered coupler

**Power Flow**

- nanoLED on InP Waveguide: 13% each direction
- nanoLED with reflector: 26%
- nanoLED with tapered coupler: 43%

**Waveguide Coupled EQE**

- 13%
- 26%
- 43%

E3S Retreat 2018
Waveguide Coupler Schematic

Top-view: cross-section along cutline

Cross-sectional view

InP Waveguide

Perspective view

Perspective view

Top-view: cross-section along cutline
Inverse Design


71% into output modes

98.9% into output modes
Inverse Design Waveguide Coupler

Tapered Coupler

After Optimization

Top View

Cross-section

InP Waveguide

nanoLED

Ag

Waveguide

Lower Cladding

250nm

E3S Retreat 2018
Inverse Design Waveguide Coupler

Tapered Coupler

Inverse Design

Electric field profile ($E_y$)

Cross section of power flow
## Inverse Design Waveguide Coupler Results

<table>
<thead>
<tr>
<th>Structure</th>
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Inverse Design Waveguide Coupler Results

Width of LED Spectrum

Enhancement
8000
6000
4000
2000
0
ID: High Power
ID: High Speed
Tapered Coupler
Bulk
Wavelength (µm)
1.2
1.3
1.4
1.5
1.6
1.7
F_{avg} = 144
F_{avg} = 169
F_{avg} = 161
F_{avg} = 160
Inverse Design Waveguide Coupler Results

Waveguide-Coupled EQE

Width of LED Spectrum

ID: High Power

ID: High Speed

Tapered Coupler

Bulk

$\eta_{WCEQE} = 61\%$

$\eta_{WCEQE} = 33\%$

$\eta_{WCEQE} = 43\%$

$\eta_{WCEQE} = 54\%$

Wavelength ($\mu$m)

0% 100% 200% 300% 400%
Conclusions

- The important metrics for the optical source in a system link are the average enhancement and waveguide coupled external quantum efficiency.

- With the inverse design waveguide coupler, we can increase the waveguide coupled external quantum efficiency to 61% with a minimal change to the average enhancement.

- The cavity backed slot antenna nanoLED can provide >100GHz direct modulation rate, with high efficiency possible.
Acknowledgements

- NSF, E3S Center
- Wu Group
- Yablonovitch Group
Figures of Merit

Enhancement = \( F(\omega) \)

LED Spectrum = \( L(\omega) \)

Average Enhancement:

\[
F = \text{Spatial Average} \times \text{Polarization Average} \times \frac{\int F(\omega)L(\omega)d\omega}{\int L(\omega)d\omega}
\]

Waveguide-Coupled External Quantum Efficiency:

\[
\eta(\omega) = \frac{P_{\text{Fundamental mode, Waveguide}}(\omega)}{P_{\text{Total}}(\omega)}
\]

Power Averaged Waveguide Coupled EQE:

\[
\eta = \frac{\int \eta(\omega)F(\omega)L(\omega)d\omega}{\int F(\omega)L(\omega)d\omega}
\]
Inverse Design Waveguide Coupler

Power Averaged Waveguide-Coupled External Quantum Efficiency:
- Taper Design: 43%
- Inverse Design: 61%

Average Power in Waveguide:
- Taper Design: 155
- Inverse Design: 188
Inverse Design Waveguide Coupler Results

Width of LED Spectrum

![Graph showing the Width of LED Spectrum for different ID: High Power, ID: High Speed, Tapered Coupler, and Bulk.](image)

Inverse Design Waveguide Coupler Results

Width of LED Spectrum

![Graph showing the Waveguide Coupled EQE for different ID: High Power, ID: High Speed, Tapered Coupler, and Bulk.](image)
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<td>0.542* into all space</td>
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<td>Inverse Design: High Power</td>
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<td>143.5</td>
<td>0.608</td>
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