On-Chip Hybrid Silicon Quantum Dot Comb Laser With 14 Error-Free Channels

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Comb Lasers

– Exascale computers require two flavors of optical links
  – Node-to-node (low-medium traffic): Maximize efficiency → 4-16 single-λ lasers (ring laser array)
    – Turn off channel(s) you don’t need
    – Imperfect channel spacing
  – Port-to-port (high traffic): Maximize bandwidth → Comb Laser
    – Single device (2-4 terminals)
    – Multiple λ within 3 dB of peak λ, constant channel spacing
    – Always on, even if you do not use all channels
Comb laser requirements

– Operation at high temperature
– Wide gain bandwidth
– Low amplitude noise in **EACH** comb line
  → Quantum dot lasers …
– Integration with high quality passives
  – Gratings, splitters, rings, …
– High yield, volume manufacturing
– On 300 mm wafers
  → … on silicon

Don’t use Si just as a carrier, take advantage of its excellent passives!
QD integration on silicon

- Lasing to 80 °C
- No coupling to Si (thick buffer layer)

Norman et al., OE, 25, 3927, 2017

- Coupled to Si
- CW @ 25 °C
- Pulsed to 115 °C

Jang et al., Applied Physics Express, 2016
Our approach

- Bonding III/V to SOI
- Design layer thicknesses for efficient coupling between Si and III-V
- Adjust QD confinement through Si WG width

Kurczveil et al., Optics Express, 2016
Device design

– Single cavity would have tradeoff between gain and FSR
  – Need FSR ~ 50-80 GHz → L ≤ 750 μm → aggressively short (QDs have lower gain than QWs)

→ Coupled cavity
  – FSR_{cavity} = 16.8 GHz, FSR_{ext} = 50.5 GHz → FSR_{Laser} = 101 GHz

– Fully integrated
  – No dicing/polishing
SiO₂
Si
Si processing
Bonding
Substrate removal
Implantation
P-contact
Mesa etch
N-contact
Probe metal

GaAs Substrate
P-GaAs
QD
N-GaAs

Si
SiO₂
Si

H+ H+
H+ H+
QD
SOA: 395 mA ($\sim 10 \cdot I_{th}$)
SA: -6.2 V
$P_{out}$: $\sim -9$ dBm
T: 25 °C

101 GHz

Wavelength [nm]
Setup for eye diagram

DUT → amplify → filter out \(\text{one}\) \(\lambda\) → ext. modulator → eye diagram
Data – Eye Diagrams (10 Gb/s)

Ch. 1, ER=9.4, BER<1E-12
Ch. 2, ER=12.8, BER<1E-12
Ch. 3, ER=12.2, BER<1E-12
Ch. 4, ER=9.6, BER=1E-12
Ch. 5, ER=9.6, BER<1E-12
Ch. 6, ER=11.6, BER<1E-12
Ch. 7, ER=10.8, BER<1E-12
Ch. 8, ER=11.2, BER<1E-12
Ch. 9, ER=11.6, BER<1E-12
Ch. 10, ER=11.3, BER<1E-12
Ch. 11, ER=12, BER<1E-12
Ch. 12, ER=12.4, BER<1E-12
Ch. 13, ER=11.3, BER<1E-12
Ch. 14, ER=9.1, BER<1E-12
Ch. 15, ER=6.7, BER=1E-10
Same setup as before, except we add a VOA
DUT $\rightarrow$ amplify $\rightarrow$ filter out $\lambda$ $\rightarrow$ ext. modulator $\rightarrow$ VOA $\rightarrow$ BER
Data – BER

- $\leq 10^{-10}$ in all channels
  - Because of 3 dB insertion loss of VOA
  - $\leq 10^{-12}$ in 14 channels without VOA
- 0.5 dB improvement over commercial external cavity laser
  - Due to gain/ASE/saturation dynamics of optical amplifier (multi-$\lambda$ vs. single-$\lambda$)
- QW-based laser would be limited by mode partition noise
  - Couldn’t use individual comb lines for each channel
Data – Time Domain (Autocorrelation)

- Optical output is pulsed vs. CW depending on DC bias conditions

At same average power, pulsed laser has higher instantaneous power → worse reliability?
Summary

– Demonstrated a QD comb laser on SOI (12-14 channels)
– On-chip mirrors, grating coupler → Wafer-level testing

Future work

– Improve passives
  – GC
  – Mirror
– Integrate ring modulators
– Increase number of channels (dispersion engineering)
Back up
\[ \phi_N - \phi_{N+1} = \text{constant} \]

Temporal mode locking

Frequency mode locking

\[ \phi_N - \phi_{N+1} \neq \text{constant} \]
Comb mechanism
– SHB, FWM, gain compression, inh. gain. broadening, Kerr nonlinearity, …

Literature References

QD

QW

Bulk
– L. F. Tiemeijer et al., “Passive FM locking in InGaAsP semiconductor lasers,” JQE, SQE-25, 6, 1989
Relative Intensity Noise – 1/2

DUT $\rightarrow$ filter out one! $\lambda$ $\rightarrow$ amplify $\rightarrow$ measure RIN (for same $P_{\text{rec}}$!)

RIN (Comb laser) dominated by low F noise
Others have seen a similar trend
We also see a hump at 17 GHz
This is the fundamental FSR (101 GHz/6)
Perhaps amplitude noise, perhaps not
Relative Intensity Noise – 2/2

Multi-λ laser $\rightarrow$ amplify $\rightarrow$ filter out one λ $\rightarrow$ measure RIN (for same \(P_{\text{rec}}\))

DUT/ ECL $\rightarrow$ Optical Filter $\rightarrow$ PDFA $\rightarrow$ RIN

Is comb laser better than ECL?
Probably not.
PDFA sees different input signals $\rightarrow$ different gain/ASE behavior.

- ECL: \(P_{\text{rec}} = -2 \) dBm
- QD Comb laser: \(P_{\text{rec}} = -2 \) dBm
Tapers

Cross section

Top down

Si

QD
Implantation

- Target dose in cladding: $1 \times 10^{14}$ cm$^{-2}$
- Target concentration in QD: $<1 \times 10^{17}$ cm$^{-3}$
- Our sample is Be doped, so perhaps some difference in performance

Boudinov et al., “Electrical isolation of p-type GaAs layers by ion irradiation”, JAP, 91, 6585, 2002
• Device with p-doped barriers have larger $T_0$
• $R_{\text{Auger}}$ larger in doped than in undoped devices but $R_{\text{Auger}} \downarrow$ as Temperature $\uparrow$
• Trade $T_0$ with $J_{\text{th}}$ ...
## P-doping

<table>
<thead>
<tr>
<th>Doping [acc in QD]</th>
<th>0</th>
<th>6</th>
<th>12</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transparency current density [A/cm²]</td>
<td>45</td>
<td>50</td>
<td>70</td>
<td>75</td>
</tr>
<tr>
<td>Threshold current density [A/cm²]</td>
<td></td>
<td>increases</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal loss [cm⁻¹]</td>
<td>2-3</td>
<td>2-4</td>
<td>5-9</td>
<td>12-14</td>
</tr>
<tr>
<td>Internal differential efficiency [%]</td>
<td>55</td>
<td>65</td>
<td>75</td>
<td>90</td>
</tr>
<tr>
<td>$g_{\text{max}}$ [cm⁻¹]</td>
<td>9-15</td>
<td>10-16</td>
<td>16-24</td>
<td>15-25</td>
</tr>
<tr>
<td>$f_{\text{3dB, max}}$ [GHz]</td>
<td>1.6</td>
<td>3.8</td>
<td>3.6</td>
<td>5.1</td>
</tr>
<tr>
<td>Modulation efficiency [GHz/mA^{1/2}]</td>
<td>0.36</td>
<td>0.7</td>
<td>0.73</td>
<td>0.75</td>
</tr>
<tr>
<td>$dG/di$ [cm⁻¹/mA]</td>
<td>0.22</td>
<td>0.32</td>
<td>0.39</td>
<td>0.66</td>
</tr>
</tbody>
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Received June 19, 2016; accepted July 13, 2016; published online August 2, 2016

We report the first demonstration of a hybrid silicon quantum dot (QD) laser, evanescently coupled to a silicon waveguide. InAs/GaAs QD laser structures with thin AlGaAs lower cladding layers were transferred by direct wafer bonding onto silicon waveguides defining cavities with adiabatic taper structures and distributed Bragg reflectors. The laser operates at temperatures up to 115°C under pulsed current conditions, with a characteristic temperature $T_0$ of 303 K near room temperature. Furthermore, by reducing the width of the GaAs/AlGaAs mesa down to 8 μm, continuous-wave operation is realized at 25°C. © 2016 The Japan Society of Applied Physics