24 Gbit/s Synthesis of BPSK signals via Direct Modulation of Fabry-Perot Lasers under Injection Locking

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Phase and amplitude encoded signals

M-level Phase-Shift-Keyed (M-PSK):

Binary (BPSK)

Quadruple (QPSK):

Eight PSK (8-PSK):

Quadrature-Amplitude Modulation (QAM):

Quadruple (4 QAM):

16-QAM:

Advantage: Higher spectral efficiency.
Generation of Phase-modulation and QAM

Single modulator generates BPSK:

Dual-nested (IQ) modulator for any format:
Our Motivation

- QAM modulation penetrates Long haul and Metro and is expected to move also into Access IF the cost is dramatically reduced.
- Current approach that uses external modulators add complexity and do not allow significant cost reduction.
- Synthesis of QAM from multiple binary RF streams rather than direct IQ modulation reduces requirements on linearity and power of high-speed RF circuits.

Our Approach

Step 1: Direct laser current modulation.
Step 2: Optical injection locking for chirp suppression and single-frequency operation.
Step 3: Coherent addition for multiplexing and carrier suppression.
Direct laser current modulation

- Produces chirped OOK (on-off keyed) signal.
- Cannot be multiplexed coherently with other signal.
Optical Injection Locking for chirp removal

→ Chirp is removed → two points in constellation are obtained.

→ Slave phase locked to the master → they can interfere together.
Wavelength tunability and single-mode operation of FP laser via injection locking

We use Fabry-Perot rather than single-frequency slave lasers – injection locking can suppress the non-injected modes.

Coherent addition for carrier suppression

By removing the carrier from OOK, we get BPSK:

Principle:

Master laser (CW) + Slave laser (OOK) = Binary data

-30 dBm injection locking
-40 dBm carrier suppressed
-50 dBm no injection locking
-60 dBm power, no injection

Wavelength, nm

1546.0 1546.1 1546.2 1546.3 1546.4 1546.5

Carrier

Suppressed

Locked

Injection

No Injection

Locked
Coherent addition for multiplexing: QPSK

Two BPSK phase locked to the same master are phase locked between them and thus can be combined to get one QPSK:

Principle:

1st: OOK 1 + OOK 2 =  

2nd: OOK 1 + CW = QPSK
Scaling: 16 QAM and beyond

16 QAM:

\[ \text{Slave 1+2} + \text{Slave 3+4} = \]

\[ \text{1st:} \]

\[ \text{2nd:} \]

\[ = 16 \text{ QAM} \]

→ Can be further scaled to 64 QAM and further.
Binary PSK: first demonstration

Master laser (CW) → 2x2 → Slave laser (OOK) → Mirror

OUTPUT

Binary data

Phase shifter

Atten.

Modulated slave laser output (IL: Injection-locked)

<table>
<thead>
<tr>
<th></th>
<th>No IL</th>
<th>With IL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Directly:</td>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
</tr>
<tr>
<td>After DLI (10 GHz):</td>
<td><img src="image3.png" alt="Graph" /></td>
<td><img src="image4.png" alt="Graph" /></td>
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</tbody>
</table>

Binary PSK (slave + CW master)

<table>
<thead>
<tr>
<th>DLI-demodulated</th>
<th>Constellation</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image5.png" alt="Graph" /></td>
<td><img src="image6.png" alt="Graph" /></td>
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</tbody>
</table>

**Wavelength tunability** – over 30 nm and at up to 24 Gbaud

<table>
<thead>
<tr>
<th>Baud rate</th>
<th>1530 nm</th>
<th>1546 nm</th>
<th>1560 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>20</td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>24</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
</tr>
</tbody>
</table>
Experiment: Quadrature PSK

Current drivers 1&2
Temp. drivers 1&2
Feedback controller
Master 18 dBm
Bias T
Slave 1
Slave 2
Phase shifter
2-m delay
RF Phase shifter
Transmitter 10 Gbit/s
2^31-1 PRBS
Dual output 1.2 V p-p

Electrical path
Optical path
Mirror
Det.
Det. DLI
OSA
Homodyne receiver

Power into the coherent receiver, dBm

-log(BER)

9 dB carrier suppression

Two injection-locked lasers combined
The above plus CW to remove the carrier
(QPSK modulation)

Power spectral density, dB

Single slave w/o Injection locking (free running)

### Various baud rates performance

<table>
<thead>
<tr>
<th>Baud rate</th>
<th>Propagation distance, km</th>
<th>EVM, amplitude, phase errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>0</td>
<td>19%, 13%, 8 deg</td>
</tr>
<tr>
<td>75</td>
<td>20% 13%, 9 deg</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>0</td>
<td>27%, 19%, 11 deg</td>
</tr>
<tr>
<td>75</td>
<td>28%, 19%, 12 deg</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>0</td>
<td>35%, 25%, 15 deg</td>
</tr>
</tbody>
</table>

Results: 16 QAM emulation

16 QAM generation using 4 lasers (as shown earlier):

QPSK and 16 QAM emulation by using half the number of lasers:

15 Gbaud (60 Gbit/s) with EVM of 13%, amplitude error of 10%, and phase error of 9 deg.
Towards Photonic Integration

QPSK example: We are in the process of designing a proof-of-principle PIC that we plan to manufacture within ePIXnet EU platform.

Outline schematic of the PIC (input is an external CW laser, PS=phase shifter, PD = slow sub-MHz photodiode, SOA=semiconductor optical optical amplifier).
Modulation bandwidth limitations

Injection Locking can significantly enhance the modulation bandwidth (pictures/results taken from Lau et al, OE 2008):

- Up to 80 GHz 3-dB bandwidth demonstrated, promising in principle operation up to 160 Gbaud.
Summary/Discussion

- Our new scheme for QAM synthesis from binary RF data streams can be tuned over 30 nm.

- Operation demonstrated up to 24 Gbaud (QPSK) and 15 Gbaud (16 QAM) demonstrated.

- EVMs for 16 QAM, QPSK and BPSK were similar, showing straightforward scalability of this scheme to even higher modulation formats.

- Injection locking can significantly enhance the laser modulation bandwidth, e.g. up to 80 GHz, promising operation of our scheme up to 160 Gbaud.

- Fully suited for photonic integration.

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