Overview of Coherent Technology

Enabling Next-Generation Networks

IX Forum 13 – December 2019

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II-VI Expands Compound Semiconductors and Photonic Solutions Platforms Through its Acquisition of FINISAR
A Transformative Combination

$2.6B
Pro Forma Revenue\(^1\)

$650M
Pro Forma EBITDA\(^1\)

70
Locations Worldwide
Diversified Global Footprint

$22B
Addressable Market Size\(^2\)

26K
Total Employees Worldwide

7
Target End Markets

“TWO SIX” Refers to groups II and VI of the Periodic Table of Elements

Note: Pro forma Revenue and EBITDA represents LTM 06/30/2019 for II-VI and LTM 07/28/2019 for Finisar.
1. Represents LTM 06/30/2019 for II-VI plus LTM 07/28/2019 for Finisar and includes $150mm run-rate synergies for EBITDA. EBITDA excludes amortization of intangibles, the impact of SFAS 123(R) stock-based compensation expense and one-time charges.
2. 2022 estimated market size. Includes 3D Sensing, Power Devices for Automotive and Wireless RF size from Yole, Optical Communications from Lightcounting and Ovum, Industrial Processing, Military, Life Sciences from Strategies Unlimited.
#1 in Optical Communications

A highly complementary and complete portfolio of leading-edge products
What is the Demand that is Driving Coherent?

- Today’s metro/core networks need to support data rates of 100Gbit/s & 200Gbit/s.
- Deployment of 400Gbit/s will start very soon.
- Optics R&D at even higher rates is being launched to support beyond 1Tbit/s.

Achieving these data rates is a difficult problem for traditional data coding streams (RZ/NRZ, etc.)

Coherent technology offers techniques to address the limitations of legacy modulation schemes.
**DCI in the Network Core and to the Edge**

- **Coherent interfaces** are capturing the ~100km market at 100G, 200G and 400G data rates.
  - Direct detection likely lower power/cost for the next few years. E.g., 400GBASE-ER8 modules (40km).

- **Standardization work by OIF 400ZR IA and IEEE P802.3ct Task Force (400GBASE-ZR).**

- **DCI interfaces will take advantage of emerging coherent technologies.**
  - OIF IC-TROSA optical packaging.
  - DSPs based on 7nm CMOS.
“At its most basic, **coherent optical transmission** is a technique that uses **modulation** of the **amplitude** and **phase** of the light, as well as transmission across two **polarizations**, to enable the transport of considerably more information through a fiber optic cable.”
Coherent Modulation

What is Coherent: “From a Text Book Point of View”

Light is a transversal electromagnetic wave

\[ \mathbf{E} = \begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} E_x e^{i\phi_x} \\ E_y e^{i\phi_y} \end{bmatrix} e^{i(\omega t - k z)} = \begin{bmatrix} I_x + iQ_x \\ I_y + iQ_y \end{bmatrix} e^{i(\omega t - k z)} \]

- Polarization division multiplexing
- Phase modulation
- Amplitude modulation
- Frequency (wavelength) division multiplexing

Source: Keysight, “Essentials of Coherent Optical Data Transmission”
Why Use Coherent vs. Traditional OOK (RZ/NRZ)

For data rates 40Gbit/s and above traditional (On-Off-Keying: i.e., NRZ/RZ) coding schemes face limits imposed by the high clock rate, bandwidth and channel broadening to fit into the traditional 50GHz DWDM ITU channels.

100Gb/s implemented with NRZ results in channels much greater than 50GHz to fit into the ITU grid.

Coherent Modulation reduces bandwidth so that 100Gb/s can be transmitted in the ITU 50GHz grid.

Source: Keysight, ‘Essentials of Coherent Optical Data Transmission’
Transmitting Symbols Instead of Bits

The fundamental drawback of NRZ/RZ modulation is that each channel only transmits one bit of information, one symbol at a time.

Formats like Coherent transmit several bits of information at a time, allowing higher data throughput to be transmitted through the same fiber.

A binary sequence of “1”s and “0”s has been coded into symbols using 2 bits/symbol.

Several sequential bits of binary data are coded or mapped to a new “symbol”. A stream of these symbols are then transmitted instead of bits on the optical carriers.

Transmitting symbols sends twice the amount of data in the same amount time.

Source: Keysight, “Essentials of Coherent Optical Data Transmission”
How do you Transmit Symbols Instead of Bits?

In NRZ and PAM4 types of modulation, we use an Eye Diagram to represent the data being transmitted.

The information is transmitted using the amplitude or intensity of the laser.

This can be viewed on an oscilloscope.

In NRZ and PAM4 information is transmitted using only one parameter.
Since a light wave is defined by more parameters than just amplitude, we have more dimensions to encode information.

Coherent Modulation uses additional dimensions of a light wave to transmit information.

Every carrier can be described by two parameters:
- Amplitude
- Phase

Source: Keysight, "Essentials of Coherent Optical Data Transmission"
How do you Transmit Symbols Instead of Bits?

Much like NRZ uses an Eye Diagram, complex modulation schemes use a Constellation Diagram to represent the data being transmitted.

Each symbol being transmitted is encoded using two dimensions:
- Amplitude
- Phase

Both parameters carry information to be transmitted. The constellation diagram is viewed on Modulation Analyzers.
How do you Transmit Symbols Instead of Bits?

In NRZ and PAM4 modulation the amplitude of the laser source is used to encode the data being transmitted.

Coherent modulation uses the full characteristics of a light-wave to encode information.

NRZ

PAM4
Understanding Constellation Diagrams for QPSK

Bit Sequence
11 00 01 10

Symbol
A B C D

Quadrature - q
Real - i

Time
Real - i
Quadrature - Q

1 0 0 1

1 0 1 0

11 00 01 10

A B C D
Understanding Constellation Diagrams for QPSK

Real - i

Quadrature - q

Bit Sequence

Symbol

Quadrature - q

Real - i

Symbol

Quadrature - q

Real - i
Understanding Constellation Diagrams for QPSK

- **Quadrature - q**
  - Real - i
  - Bit Sequence: 11 00 01 10
  - Symbol: A B C D

- **Quadrature - Q**
  - Real - i
  - Bit Sequence: 1 0 0 1
  - Symbol: A B C D
Understanding Constellation Diagrams for QPSK

Bit Sequence: 11 00 01 10
Symbol: C
Quadrature - q: 00 01 10 11
Real - i: 1 0 0 1

A: 1
B: 0
C: 0
D: 1
Understanding Constellation Diagrams for QPSK

Bit Sequence
11 00 01 10
Symbol
A B C D
Quadrature - q
Real - i

A
B
C
D

00 01 11 10

Quadrature - Q
Real - i
Understanding Constellation Diagrams for QPSK

Quadrature - Q

Real - i

1 0 0 1

Quadrature - q

1 0 1 0

Bit Sequence

11 00 01 10

Symbol

A B C D

Quadrature - q

A B C D

Real - i

10 11 00 01
Understanding Constellation Diagrams for QPSK

Bit Sequence

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quadrature - q</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>10</td>
</tr>
<tr>
<td>B</td>
<td>00</td>
</tr>
<tr>
<td>C</td>
<td>01</td>
</tr>
<tr>
<td>D</td>
<td>11</td>
</tr>
</tbody>
</table>

Real - i

<table>
<thead>
<tr>
<th></th>
<th>00</th>
<th>01</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Quadrature - q

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
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</tbody>
</table>

Time

Real - i
By using complex modulation schemes, the optical bandwidth needed to send the data can be reduced to fit within the 50GHz ITU Channels

- This means the more bits encoded into one symbol at a given data rate, the greater reduction in the occupied optical bandwidth of the signal

16 QAM Modulation
Using 16 symbols to transmit data reduces the baud rate by a factor of 4x from the bit rate

64 QAM Modulation
Using 64 symbols to transmit data reduces the baud rate by a factor of 6x from the bit rate

Source: Keysight, "Essentials of Coherent Optical Data Transmission"
Dual Polarization Multiplexing for Additional Capacity

Polarization Division multiplexing (PDM) uses a second light-wave signal which is orthogonal to the first, to carry independent information. It is transmitted over the same fiber and on the same wavelength.

3D Movies make use of Polarization Multiplexing. The polarized glasses filter out the independent signals for each eye and provide a different picture to create the 3D effect.

PDM adds a second channel and doubles the transmission capacity without the need of a second fiber.

Source: Keysight, “Essentials of Coherent Optical Data Transmission”
Coherent Modulation – Increases Capacity by Reducing Bandwidth

Coherent Modulation achieves efficiency by encoding data simultaneously in the Polarization, Amplitude, Phase and Frequency portions of the light wave

- At the bottom of the figure, we have the simplest scheme: on-off-keying
- Using Quadrature Phase Shift Keying (QPSK) we can double the data rate in half the spectrum
- Another factor of 2 can be gained through Polarization Division Multiplexing

QPSK plus PDM allows you to transfer $2 \times 2 = 4$ times more bits at the same time

After further narrowing the occupied spectrum with a filter, 100 Gb/s of data can be sent using PDM-QPSK modulation in a 50 GHz ITU channel

Source: Keysight, “Essentials of Coherent Optical Data Transmission”
## Common Modulation Formats

<table>
<thead>
<tr>
<th>Modulation Format</th>
<th>28 GBAud</th>
<th>32 GBAud</th>
<th>40 GBAud</th>
<th>46 GBAud</th>
<th>56 GBAud</th>
<th>64 GBAud</th>
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</thead>
<tbody>
<tr>
<td><strong>NRZ/PAM2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 bit per Baud (symbol)</td>
<td>Single Polarization</td>
<td>28 Gb/s</td>
<td>32 Gb/s</td>
<td>40 Gb/s</td>
<td>46 Gb/s</td>
<td>56 Gb/s</td>
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<tr>
<td><strong>BPSK</strong></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1 bit per Baud (symbol) per polarization</td>
<td>Single Polarization</td>
<td>28 Gb/s</td>
<td>32 Gb/s</td>
<td>40 Gb/s</td>
<td>46 Gb/s</td>
<td>56 Gb/s</td>
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<tr>
<td><strong>PAM4</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 bits per Baud (symbol)</td>
<td>Single Polarization</td>
<td>56 Gb/s</td>
<td>64 Gb/s</td>
<td>80 Gb/s</td>
<td>92 Gb/s</td>
<td>112 Gb/s</td>
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<td></td>
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<tr>
<td><strong>QPSK</strong></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 bits per Baud (symbol) per polarization</td>
<td>Single Polarization</td>
<td>56 Gb/s</td>
<td>64 Gb/s</td>
<td>80 Gb/s</td>
<td>92 Gb/s</td>
<td>112 Gb/s</td>
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</tbody>
</table>
## Common Modulation Formats

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Single Polarization</th>
<th>Dual Polarization</th>
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</thead>
<tbody>
<tr>
<td><strong>8QAM</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 bits</td>
<td>84 Gb/s</td>
<td>168 Gb/s</td>
</tr>
<tr>
<td>per Baud</td>
<td>96 Gb/s</td>
<td>192 Gb/s</td>
</tr>
<tr>
<td>(symbol)</td>
<td>120 Gb/s</td>
<td>240 Gb/s</td>
</tr>
<tr>
<td>per polarization</td>
<td>138 Gb/s</td>
<td>276 Gb/s</td>
</tr>
<tr>
<td></td>
<td>168 Gb/s</td>
<td>336 Gb/s</td>
</tr>
<tr>
<td></td>
<td>192 Gb/s</td>
<td>384 Gb/s</td>
</tr>
<tr>
<td><strong>16QAM</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 bits</td>
<td>112 Gb/s</td>
<td>224 Gb/s</td>
</tr>
<tr>
<td>per Baud</td>
<td>128 Gb/s</td>
<td>256 Gb/s</td>
</tr>
<tr>
<td>(symbol)</td>
<td>160 Gb/s</td>
<td>320 Gb/s</td>
</tr>
<tr>
<td>per polarization</td>
<td>184 Gb/s</td>
<td>368 Gb/s</td>
</tr>
<tr>
<td></td>
<td>224 Gb/s</td>
<td>448 Gb/s</td>
</tr>
<tr>
<td></td>
<td>256 Gb/s</td>
<td>512 Gb/s</td>
</tr>
<tr>
<td><strong>32QAM</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 bits</td>
<td>140 Gb/s</td>
<td>280 Gb/s</td>
</tr>
<tr>
<td>per Baud</td>
<td>160 Gb/s</td>
<td>320 Gb/s</td>
</tr>
<tr>
<td>(symbol)</td>
<td>200 Gb/s</td>
<td>400 Gb/s</td>
</tr>
<tr>
<td>per polarization</td>
<td>230 Gb/s</td>
<td>460 Gb/s</td>
</tr>
<tr>
<td></td>
<td>280 Gb/s</td>
<td>560 Gb/s</td>
</tr>
<tr>
<td></td>
<td>320 Gb/s</td>
<td>640 Gb/s</td>
</tr>
<tr>
<td><strong>64QAM</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 bits</td>
<td>168 Gb/s</td>
<td>336 Gb/s</td>
</tr>
<tr>
<td>per Baud</td>
<td>192 Gb/s</td>
<td>384 Gb/s</td>
</tr>
<tr>
<td>(symbol)</td>
<td>240 Gb/s</td>
<td>480 Gb/s</td>
</tr>
<tr>
<td>per polarization</td>
<td>276 Gb/s</td>
<td>552 Gb/s</td>
</tr>
<tr>
<td></td>
<td>276 Gb/s</td>
<td>672 Gb/s</td>
</tr>
<tr>
<td></td>
<td>384 Gb/s</td>
<td>768 Gb/s</td>
</tr>
</tbody>
</table>
# Pluggable Form Factors Suitable for Coherent Transceivers

![Pluggable Form Factors Diagram](image)

<table>
<thead>
<tr>
<th>[mm]</th>
<th>CFP</th>
<th>CFP2</th>
<th>CFP4</th>
<th>OSFP</th>
<th>QSFP</th>
<th>QSFP-DD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>144.8</td>
<td>107.5</td>
<td>92.0</td>
<td>100.4</td>
<td>72.4</td>
<td>93.3</td>
</tr>
<tr>
<td>Width</td>
<td>82.0</td>
<td>41.5</td>
<td>21.5</td>
<td>22.9</td>
<td>18.4</td>
<td>18.4</td>
</tr>
<tr>
<td>Height</td>
<td>13.6</td>
<td>12.4</td>
<td>9.5</td>
<td>13.0</td>
<td>8.5</td>
<td>8.5</td>
</tr>
</tbody>
</table>
Coherent Transmission for DCI Applications

- Several system OEMs already provide a 1RU transponder for DCI applications, most of which use **pluggable 100G/200G Coherent CFP2-ACO** optical transceivers.

- Expected coherent transceiver evolution to 400G is driven by improvements in optical packaging and DSP power dissipation:

  \[
  200G \text{ CFP2-ACO} \rightarrow 400G \text{ CFP2-DCO} \rightarrow 400G \text{ QSFP-DD DCO}^{(*)}
  \]

  400G DCO transceivers are expected to be plugged directly into switches and routers.

(*) Could also be implemented in OSFP.

ACO = Analog Coherent Optics
DCO = Digital Coherent Optics
OFC 2019: 64 GBaud IC-TROSA Demo by II-VI/Finisar
MATERIALS THAT MATTER