GLOSSARY AND DEFINITIONS

- AOC: Active Optical Cable
- APD: Avalanche Photo Diode
- ASP: Average Selling Price
- COBO: Consortium for On-Board Optics
- DC: Data Center
- DML: Directly Modulated Laser
- EEL: Edge-Emitting Laser
- EIC: Electrical IC
- EML: Electro-absorption Modulator Laser
- CAGR: Compound Annual Growth Rate
- HPC: High-Performance Computer
- IC: Integrated Circuit
- InP: Indium Phosphide
- IP: Intellectual Property
- LiDAR: Light Detection and Ranging
- MEMS: Micro Electro-Mechanical Systems
- MOS: Metal Oxide Semiconductor
- MSA: Multi-Supplier Agreement
- OEO: Optical Electrical Optical
- OIC: Optical IC
- OXC: Optical Cross-Connect
- PIC: Photonic Integrated Circuit
- ROSA: Receiver Optical Sub-Assembly
- SEL: Surface-Emitting Laser
- SiN: Silicon Nitride
- SiPh: Silicon Photonics
- SOI: Silicon-on-Insulator
- TIA: Transimpedance Amplifier
- TOSA: Transmitter Optical Sub-Assembly
- VC: Venture Capital
- VCSEL: Vertical Cavity Surface-Emitting Lasers
- VOA: Variable Optical Attenuator
- WBG: Wide Band Gap
# GLOSSARY AND DEFINITIONS

Specific to optical communication

<table>
<thead>
<tr>
<th>Fiber</th>
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<tbody>
<tr>
<td>MMF</td>
<td>Multi-Mode Fiber</td>
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<tr>
<td>PSM</td>
<td>Parallel Single Mode</td>
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<td>SMF</td>
<td>Single-Mode Fiber</td>
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<th>Modulation</th>
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<tbody>
<tr>
<td>NRZ</td>
<td>Non-Return to Zero</td>
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<tr>
<td>PAM</td>
<td>Pulse Amplitude Modulation</td>
</tr>
<tr>
<td>QAM</td>
<td>Quadrature Amplitude Modulation</td>
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<td>CFP</td>
<td>C Form-Factor Pluggable</td>
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<tr>
<td>QSFP</td>
<td>Quad Small Form-Factor Pluggable</td>
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<tr>
<td>SFP</td>
<td>Small Form-Factor Pluggable</td>
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<tbody>
<tr>
<td>CWDM</td>
<td>Coarse Wavelength Division Multiplexing</td>
</tr>
<tr>
<td>DWDM</td>
<td>Dense Wavelength Division Multiplexing</td>
</tr>
<tr>
<td>WDM</td>
<td>Wavelength Division Multiplexing</td>
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</tbody>
</table>
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- **Reverse Costing® - Structure, Process, and Cost analyses**
  - Intel 100G PSM4 SiPh transceiver
  - Intel 100G CWDM4 SiPh transceiver

- **Outlook**
  - Roadmap for silicon photonics
  - Conclusions

- **How to use our data?**

- **Yole Corporate Presentation**
REPORT SCOPE (1/2)

Platform

- Silicon photonics
  - Courtesy of Luxtera

Modules

- Optical communication
  - Including optical transceivers, co-packaged photonic engines
  - Courtesy of Intel

- Immunoassays
  - Courtesy of Genalyte

- Consumer healthcare
  - Courtesy of Rockley Photonics

- Photonic computing
  - Courtesy of Nature / iPronics

- Quantum computing
  - Courtesy of MIT Lincoln Laboratory

- Healthcare
  - Courtesy of OCTCHIP

- E-noses
  - Courtesy of Aryballe

- LiDAR
  - Courtesy of SiLC

- FOG
  - Courtesy of Optics Express

- Disaggregated datacenter
  - Optical interconnects for HPC

FOG: Fiber Optic Gyroscope
HPC: High performance computing
OCT: Optical Coherent Tomography
Platforms that are integrated with silicon photonics

- InP
- SiN
- Glass
- Polymer
- Silica PLC
- LiNbO3

InP is commonly used for lasers
SiN is often used for waveguides
Glass is frequently used for interconnects

A comparison with other platforms is presented in this report

Devices that are beyond scope

Optical MEMS
MEMS matrix optical switches

Yours needs are out of the report's scope?
Contact us for a custom:
Yole’s market forecast model is based on the matching of several sources.

Comparison with existing data
Monitoring of corporate communication
Using other market research data
Yole analysis (consensus or not)

Comparison with prior Yole reports
Recursive improvement of dataset
Customer feedback

Preexisting information

Top-to-bottom approach
Aggregate of market forecasts
@ System level

Bottom-up approach
Ecosystem analysis
Aggregate of all players’ revenue
@ System level

Primary data
- Reverse costing
- Patent analysis
- Annual reports
- Direct interviews

Secondary data
- Press releases
- Industry organization reports
- Conferences

Top-to-bottom approach
Aggregate of market forecast
@ Semiconductor device level

Bottom-up approach
Ecosystem analysis
Aggregate of key players’ revenue
@ Semiconductor device level

Information Aggregation

Market
Volume (in Munits)
ASP (in $)
Revenue (in $M)

Semiconductor foundry activity
Capacity investments and equipment needs
ABOUT THE AUTHORS

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Formerly, Jean-Louis served as Vice President - Optical Networking Products for Corning, Inc. His other prior experience includes serving as Technology Director with Amphenol and Thompson CSF in France.

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Dr. Eric Mounier

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In this position, Eric Mounier has spoken in numerous international conferences, presenting his vision of the semiconductor industry and latest technical innovations. He has also authored or co-authored more than 100 papers as well as more than 120 Yole’s technology & market reports.

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COMPANIES CITED IN THIS REPORT

WHAT WE GOT RIGHT, WHAT WE GOT WRONG

- The growth of the silicon photonics technology for pluggable optics.
- The use of silicon photonics for sensing applications.
- The coming of co-packaged optics.

- The willingness of using silicon photonics in consumer applications.
- The readiness of photonic computing.
The silicon photonics die market could shift from optical communication to consumer application in the next five years.

**2020 - 2026 forecast**

- **Datacenter transceivers**
- **Long haul transceivers**
- **5G transceivers**
- **Co-packaged engines**
- **Photonic computing**
- **Optical interconnects**

- **Immunoassay**
- **Consumer health**
- **Fiber-optic gyroscope**
- **Automotive LiDAR**

**2020**

- **$87M**
  - $0.002M
  - $0.035M
  - $0.6M
  - $1.5M

**2026**

- **$1.1B**

**CAGR**

- **21-26 26%**
- **24-26 168%**
- **23-26 190%**
- **25-26 321%**
- **21-26 68%**
- **24-26 190%**
- **21-26 12%**
- **22-26 43%**

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Here we show the forecasts for the silicon photonics dies per application.

To calculate the silicon photonic die market, we use the number of die per application and the average selling price (ASP) of the dies for each application. The ASP for each die depends on the die complexity and the surface area of the die.

The market for silicon photonics dies for datacenter transceivers will grow in similar fashion to that of the silicon photonic transceiver shipments.

Application in consumer health could have an important impact on the silicon photonic die market with consumer health taking half of the total silicon photonic die market. It relates to the potential high market for consumer with smart watches with advanced consumer health function reaching shipment of 16.6 million units in 2025. This is not taking into account potential other applications in smartphones or dedicated end-systems for consumer health.

Photonic computing is also expecting to significant market shares in 2026. This is because of the large size of the silicon photonic die needed for this application and therefore the high unit price.

*The CAGR (Compound Annual Growth Rate) is calculated between 2026 and 2021. When there is no data in 2021, it is calculated between 2026 and the first year with available data.*
Using silicon photonics for consumer health targeting smart watches and potentially other end-systems such as smartphones and consumer devices dedicated to healthcare could be a game changer for silicon photonics because the volumes in the consumer market are much larger than that in the datacom market.

Here, we examine the potential impact of the consumer health adoption of silicon photonics in the long-term. We first examine a hypothetic line up of smart watches from Apple. In September 2020, Apple introduced the Apple Watch Series 6 with blood oxygen and electrocardiogram (ECG) measurements for fitness purpose. The price of the watch starts from $399 while the price of the watch with no fitness function was reduced to $279.

We can imagine new models furthermore including healthcare functions thanks to the module based on the silicon photonics technology from Rockley Photonics. We have estimated the price of the silicon photonics die to be $18 in 2025 while the price of the module from Rockley Photonics to be around $45. Accordingly, the price of the Apple Watch with the fitness and healthcare functions could start at $699.

![Hypothetic lineup of smart watches from Apple.](image)

- The cheapest model has no fitness or healthcare function.
- The middle-end model has fitness functions with blood oxygen measurement and ECG.
- The high-end model has fitness and health care functions thanks to the silicon photonics module from Rockley Photonics.
LONG-TERM CONSUMER HEALTH FORECASTS
TAM, SAM, and ASP

We examine the potential market for silicon photonics dies for the consumer healthcare application.

The total smart watches market is expected to grow at a CAGR of 11%, reaching 281 million units in 2030 and 473 units in 2035. This is used as a basis to calculate the total available market (TAM).

The adoption rate of healthcare functions is expected to be modest but increasing in the next 15 years, being 10% in 2025, 15% in 2030, and 20% in 2035. This is used as a basis to calculate the serviceable available market (SAM).

Due to technical considerations, it is unlikely that the size of the silicon photonics die associated with healthcare functions will decrease in the future. Furthermore, according to plans from Rockley Photonics, new functions and new wavelengths will be added in the future. Consequently, it is expected that the silicon photonics die will retain mainly its average selling price (ASP) in the future similarly to CMOS image sensors used in smartphones (see next slide). The expected ASP for the silicon photonics die is as follows: $18 in 2025, $15 in 2030, and $12 in 2035.

The silicon photonics die market for consumer healthcare could reach $1.1B in 2035, with a 16% CAGR between 2025 and 2030 and a 12% CAGR between 2030 and 2035.
SIPH SUPPLY CHAIN FOR OPTICAL TRANSCEIVERS

Coherent optical communication

Systems include servers, routers, and switches

Non exhaustive list of companies

And more…
The continuous increase of data rate could result in a shift from pluggable to co-packaged transceivers in switches.

### Switch data rate

**2017**
- 5Tbps
- Ex.: 48 ports at 100G

**2020**
- 12.8Tbps
- Ex.: *200G

**2022**
- 25.6Tbps
- Ex.: 8 channels at 25G

**2025**
- 51.2Tbps
- Co-packaged switch ASIC

### Transceiver data rate

<table>
<thead>
<tr>
<th>Year</th>
<th>Pluggable transceivers</th>
<th>Co-packaged transceivers</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td>4 channels at 25G PSM or CWDM</td>
<td>8 channels at 25G PSM or WDM</td>
</tr>
<tr>
<td>2020</td>
<td>4 channels at 50G PSM or WDM</td>
<td>8 channels at 50G PSM or WDM</td>
</tr>
<tr>
<td>2022</td>
<td>8 channels at 50G PSM or WDM</td>
<td>16 channels at 25G</td>
</tr>
<tr>
<td>2025</td>
<td>16 channels at 100G</td>
<td>Co-packaged optics</td>
</tr>
</tbody>
</table>

Pluggable:
- 25G channels are NRZ
- 50G channels are PAM4

Co-packaged:
- 32 channels at 50G
- Ex.: 16 channels at 100G

*The 200G step could be skipped by some companies.*
COMPANIES INVOLVED IN CO-PACKAGED OPTICS

**Intel**
- Network switch
- Co-packaged SiPh transceivers

**Cisco**
- Network switch
  - Co-packaged SiPh transceivers
    - Cisco acquired Luxtera in February 2019.
  - Cisco acquired Leaba in March 2016.

**Barefoot Networks**
- Tofino 2 Switch ASIC
- Using TSMC 7nm foundry

**Broadcom**
- Switch ASIC
  - Co-packaged Optics Collaboration (June 2019)
  - Microsoft
  - Specifications
  - Sumitomo Electric
    - Optical interconnection
  - Analog Photonics
    - Co-packaged SiPh transceivers
  - Ryonas
    - Co-packaged SiPh transceivers
    - Co-packaged fine-pitch socket interposer
  - TGA
    - Si-fly copper
  - TE Connectivity
    - Fiber V-groove interconnects
  - Senko Advanced Components
    - Co-packaged fine-pitch socket interposer
  - Ryonas
    - Optical interposers

**Avago Technologies**
- Broadcom acquired by Avago in 2016.

**Cisco**
- Co-packaged Optics Collaboration (June 2019)
  - Co-packaged SiPh transceivers
  - Co-packaged fine-pitch socket interposer
  - Si-fly copper
  - Co-packaged Optics Collaboration (June 2019)
  - Specifications
  - Optical interconnection

**Rockley Photonics**
- Co-packaged SiPh transceivers
  - Accton Making Partnership Now
    - Co-packaged fine-pitch socket interposer
  - TE Connectivity
    - Fiber V-groove interconnects
  - Samtec
    - Si-fly copper
  - Co-packaged Optics Collaboration (June 2019)
  - Specifications
  - Optical interconnection

**IBM**
- Fiber V-groove interconnects

**Poet Technologies**
- Co-packaged SiPh transceivers
  - Co-packaged fine-pitch socket interposer
  - Optical interposers

The convergence between competences in optics from Avago (CyOptics) and switch ASIC from Broadcom is realized.
SILICON PHOTONICS FOR LiDAR

Focal plane array by Pointcloud

The California based company Pointcloud has used silicon photonics to realize an image sensor in the focal plane array (FPA) format with coherent detection. The image sensors therefore benefit simultaneously from the low or non deformation imaging of FPA (compared to scanning techniques) and the high sensitivity of coherent detection.

The image sensor can be used to realize a frequency modulated continuous wave (FMCW) flash LiDAR. Applications are envisioned in automotive, robotics, smart city, smart office and consumer applications such as augmented reality (AR).

Coherent FPA image sensors are seen as the ultimate image sensor but are difficult to realize due to the need of local oscillators (LO) at the pixel level.
WEARABLE HEALTHCARE MODULES

Technologies

Rockley Photonics proposes a photonic module integrated into a smartwatch. The photonic module operates in the visible and infrared spectrum.

The photonic module from Rockley Photonics integrated into a smartwatch. The module size seems to be around 1 cm².

The size of the infrared module is around 8 x 3 mm². The visible photonic circuit could be similar to what is found in the Apple Watch Series 6.

The module also integrates an ASIC chip on the backside of the module.

1. Infrared photonic circuit
2. Visible photonic circuit
3. Electrical connections
4. Electronics (ASIC and drivers)

The infrared photonic circuit could rely on silicon photonic frequency comb generators similar to that presented by Stern et al. Frequency comb generators allow for the generation of many wavelengths using a single laser source enabling spectroscopy applications.

The principle of the visible photonic circuit could be similar to that of the Apple Watch Series 6, relying on LEDs and photodiodes.

Silicon photonics is enabling miniature spectroscopy operations on the wrist.

Several research are ongoing to realize quantum computing using ion qubits which are manipulated by lasers. Such work is performed by IonQ and the Duke Quantum Center which have already achieved quantum computing using 32 ions.

In order to reduce the size of the quantum computer, it is possible to use laser and photonic components integrated on a chip. Such research is performed by the MIT Lincoln Laboratory which has demonstrated the use of silicon photonics for individual ion manipulation.

IonQ has a plan to use silicon photonics for ion qubit quantum computing by 2023.

Photonics and silicon photonics can be used to manipulate ions for quantum computing.
## SILICON PHOTONICS

### Roadmap

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<thead>
<tr>
<th>Year</th>
<th>2016</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
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</thead>
<tbody>
<tr>
<td>Optical communication</td>
<td>100G pluggable transceivers using coherent and direct detection</td>
<td>400G DR4 transceivers for datacenters</td>
<td>Co-packaged optic switch at 25.6 or 51.2Tbps</td>
<td></td>
</tr>
<tr>
<td>• Long haul</td>
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<tr>
<td>• Datacom</td>
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<tr>
<td>• 5G</td>
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<tr>
<td>Automotive</td>
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<tr>
<td>• LiDAR</td>
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<td>• Fiber Optic Gyroscope (FOG)</td>
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<td>Consumer healthcare</td>
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<tr>
<td>• Wearables</td>
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<tr>
<td>Computing</td>
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<tr>
<td>• Disaggregated datacenter</td>
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<tr>
<td>• Photonic computing</td>
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</tr>
<tr>
<td>• Quantum computing</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

**FMCW**: Frequency Modulated Continuous Waves  
**FOG**: Fiber Optic Gyroscope  
**OCT**: Optical Computed Tomography  
**OPA**: Optical Phased Array  
**RFOG**: Resonant FOG

---

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YOLE GROUP OF COMPANIES - RELATED REPORTS

Yole Développement

- Optical Transceivers for Datacom & Telecom 2020
- LiDAR for Automotive and Industrial Applications 2020
- High-End Inertial Sensors for Defense, Aerospace and Industrial Applications 2020
- Quantum Technologies 2020
- Wearables in Consumer and Medical Applications 2020
Contact our Sales Team for more information

**II-VI/Finisar 100Gb CWDM4 Optical Transceiver**

**Intel Silicon Photonic 100G CWDM4 QFSP28 Transceiver**

**Intel Silicon Photonic 100G PSM4 QFSP28 Transceiver**

**InnoLight’s 400G QSFP-DD Optical Transceiver**

Silicon Photonics 2021 | Sample | www.yole.fr | ©2021
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The Yole Group of Companies, including Yole Développement, System Plus Consulting and PISEO, are pleased to provide you a glimpse of our accumulated knowledge.

Feel free to share our data with your own network, within your presentations, press releases, dedicated articles and more. But before that, contact our Public Relations department to make sure you get up-to-date, licensed materials.

We will be more than happy to give you our latest results and appropriate formats of our approved content.

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