Silicon Photonis

Photonics
(ELEC-E3240)

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Lecture Topics

- Course introduction
- Ray optics & optical beams
- Waveguides / optical fibers
- Optical amplifiers
- Fiber optics and applications
- Lab work
- Silicon photonics
- Structural coloration
- Plasmonics
- Poster Presentation & discussion

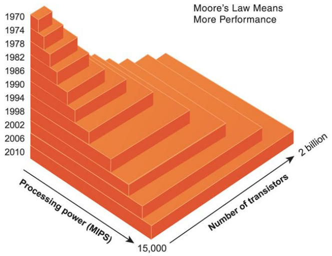
Silicon Photonics
First, why silicon?

- Si has higher melting point than Ge
- Cut in Voltage of Si (0.7 eV)is greater than Ge(0.3 eV)
- Si has a larger band-gap than Ge and because of this, the phenomenon of thermal pair generation is smaller in Si than in Ge. This means that at the same temperature the noise of the Si devices is smaller than the noise of Ge devices
- Peak Inverse Voltage ratings of Silicon diodes are greater than Germanium diodes.
- Reverse current for Si device is in nanoAmps whereas it may be upto mA for Ge devices.
- The good quality and extremely controlled oxide of silicon, SiO_2
- *Silicon is the second most abundant material on earth*

Silicon Electronics & Challenges

- *"The number of transistors in a dense integrated circuit doubles approximately every two years." – Gordon Moore 1965.*

MOORE'S LAW AND MICROPROCESSOR PERFORMANCE



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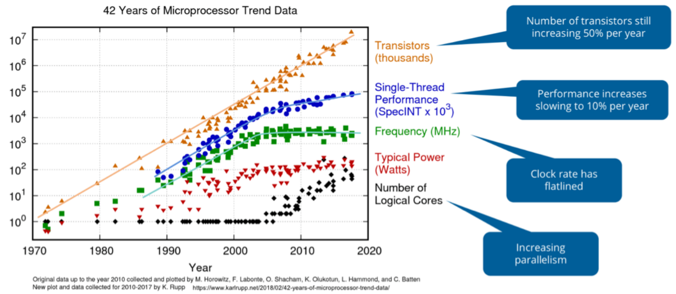
Electronics & Challenges



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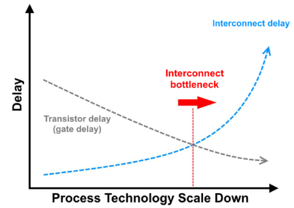
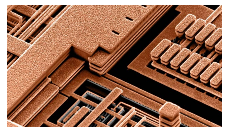
Silicon Electronics & Challenges

- *Interconnect Bottleneck in microelectronics!*
  - *When data transfer rates exceed 10 Gbit/s, copper induces delay comparable to the computation time!*





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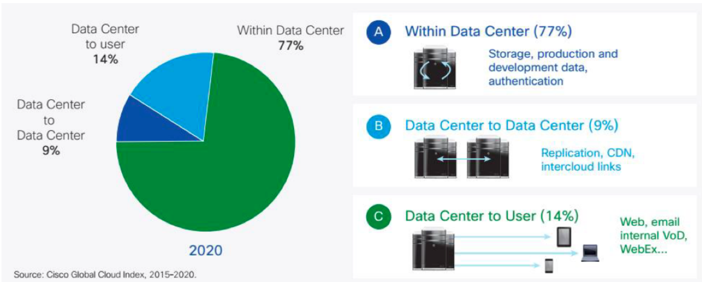
Traffic growth inside the Datacenters



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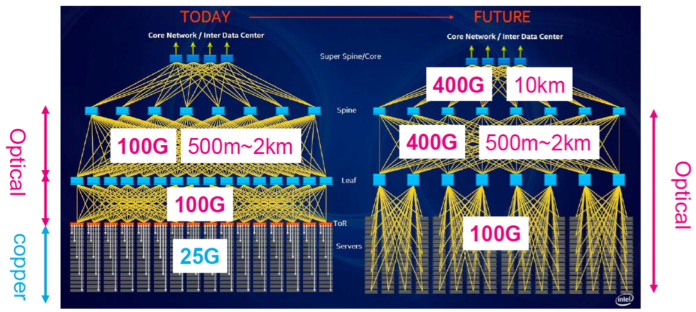
Mega Datacenter Architecture



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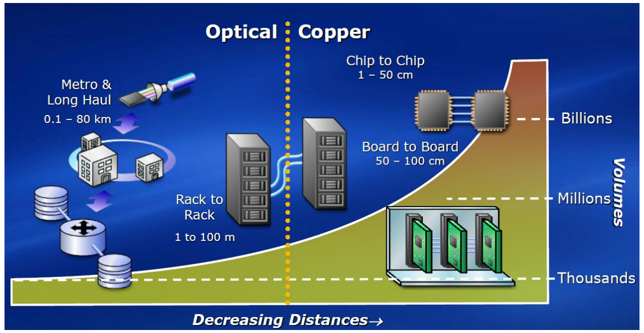
Increasing need for 100G & 400G low-cost optical interconnects

Why Optical interconnection VS Electronic interconnection ?

✓*Faster speed*
✓*Higher bandwidth*
✓*Energy-efficiency*

Global data centers used roughly 416 terawatts (4.16 x 10^{14} watts) (or about 3% of the total electricity) last year, nearly [40% more than the entire United Kingdom](). And this consumption will double every 2/3 years.

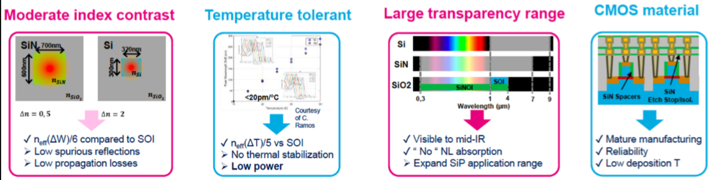
Optical VS Electronic interconnection



The dawn of Silicon photonics

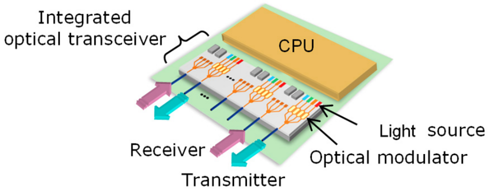
- ***Silicon is the second most abundant material on earth***
- ***Silicon photonics uses the same fabrication techniques as microelectronics***
- ***Information is transfered as light, rather than electrical current***
- ***The light travels inside patterned silicon/silicon nitride waveguides***

The dawn of Silicon photonics



The dawn of Silicon photonics

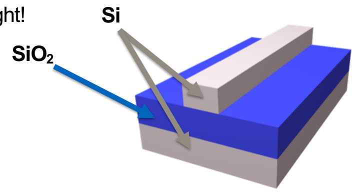
- *Silicon photonics combines passive and active components to manipulate light in order to transfer and compute information*
- *The devices and structures are patterned with nanotechnology on a Silicon-on-insulator (SOI) substrate*



Silicon Photonic Devices

Waveguides

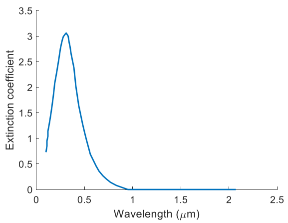
- The light in silicon waveguides is guided via total internal reflection – like in optical fibers
- When the waveguide dimensions are chosen properly, the mode couples into the waveguide
- Silicon benefits from very high refractive index n_{Si}~3.5.
  - Very high index contrast with SiO_2 → $\Delta n \approx 2$.
  - Tight confinement of light!

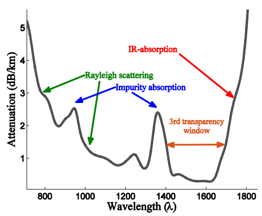


Silicon Photonic Devices

Waveguides

- Silicon is almost transparent at wavelengths > 1100 nm
- Optical fibers have minimum losses at ~1550 nm
  - 1550 nm is often used as the transmission wavelength in silicon waveguides





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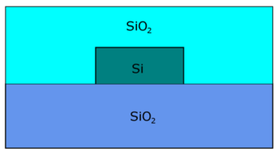
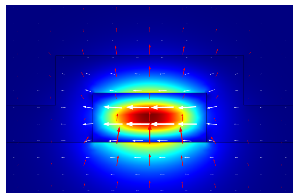
Silicon Photonic Devices

Waveguides

- Examples of waveguide structures
  - Strip waveguide





- Wave-equation:

$$\nabla\times\nabla\times\boldsymbol{E} - k_0^2\epsilon_r\boldsymbol{E} = 0,$$
$$\boldsymbol{E} = \boldsymbol{E}(x,y)e^{-ik_z z}$$

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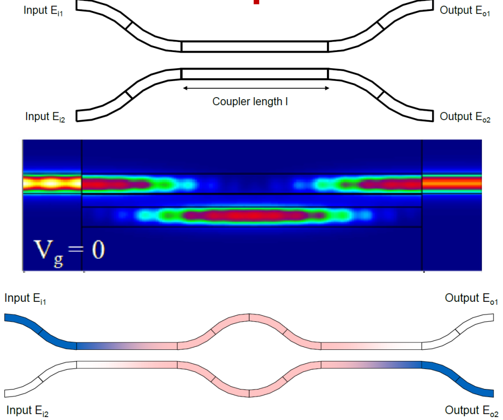
https://www.comsol.com/model/3d-wave-propagation-in-silicon-waveguide-with-rib-and-slot-configurations-70551

Silicon Photonic Devices

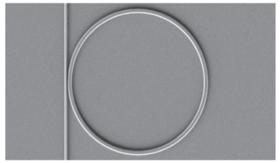
Couplers

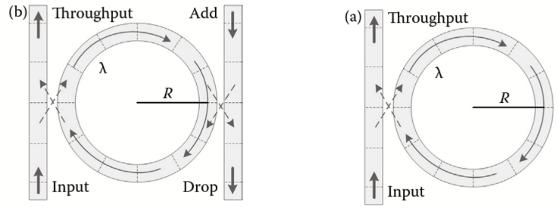


Silicon Photonic Devices

Resonators

- Very useful in many applications
  - Especially in lasers and sensors





Silicon Photonic Devices

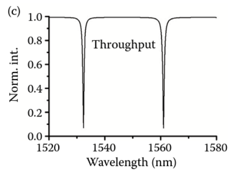
Resonators

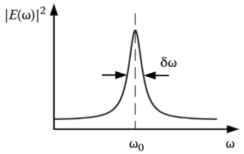
- When light is coupled into a ring resonator, resonance occurs if

$$2\pi R n_{\text{eff}} = m\lambda$$

- This is seen as a sharp dip in the transmission spectrum
  - Lorentzian lineshape:

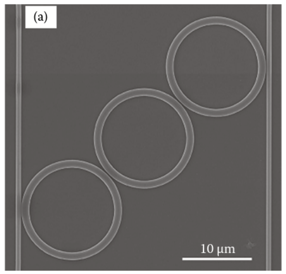
$$|E(\omega)|^2 = E_0^2 \frac{\left(\frac{\omega_0}{2Q}\right)^2}{(\omega-\omega_0)^2+\left(\frac{\omega_0}{2Q}\right)^2}, Q = \frac{\omega_0}{\Delta\omega}$$

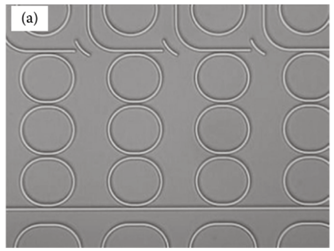




Silicon Photonic Devices

Resonators





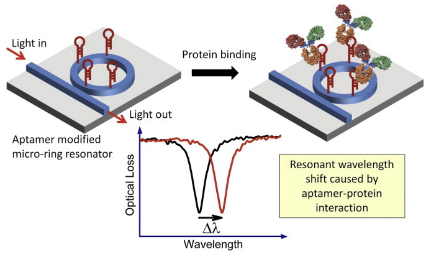
Silicon Photonic Devices

Resonators

- Small change in the refractive index (i.e. particles) causes the resonance wavelength to shift

$$Ln_{\text{eff}} = m\lambda$$

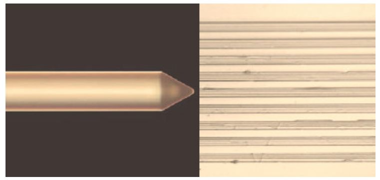
$$\Delta\lambda = \frac{L\Delta n_{\text{eff}}}{m}$$



Silicon Photonic Devices

Coupling

- Edge (“butt”) coupling
  - Coupling with tapered fibers



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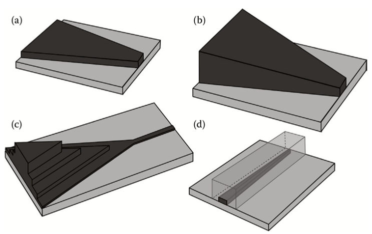
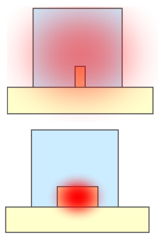
Silicon Photonic Devices

Coupling

- Edge (“butt”) coupling
  - Coupling with adiabatic tapers





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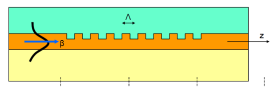
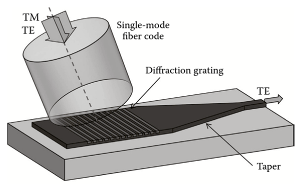
Silicon Photonic Devices

Coupling

- Grating coupling:
  - Periodic refractive index change in or close to the waveguide core
  - Diffraction causes wavefront to distort
  - With proper angle, diffraction period and refractive index coupling occurs





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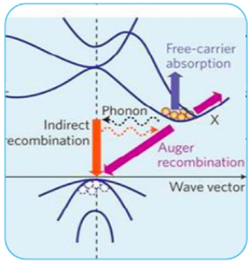
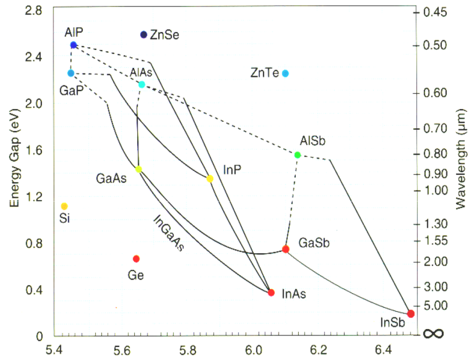
Silicon Photonic Challenges

- Silicon itself is a poor emitter due to its indirect bandgap
  - Emission very inefficient
- Silicon does not absorb light at > 1100 nm
- Modulation/detection are difficult in silicon as well…
- Integration of other materials necessary

Si : indirect bandgap

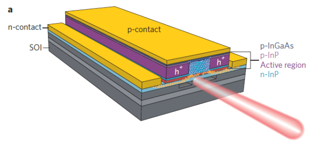


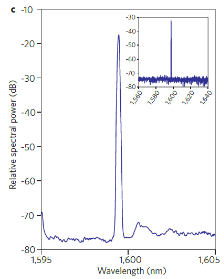
Laser Sources & Amplifiers



Laser Sources & Amplifiers

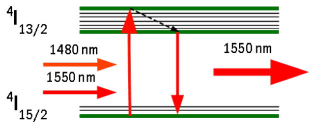
- Hybrid InP-InGaAs laser on Si

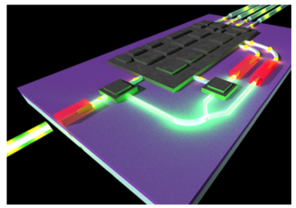




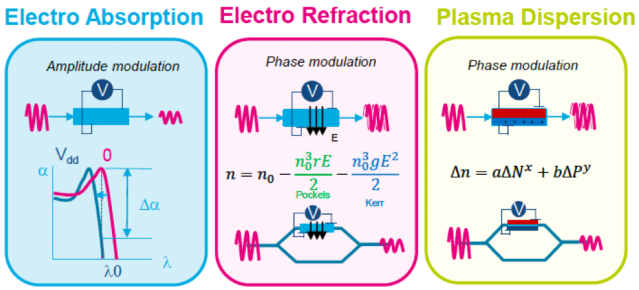
Laser Sources & Amplifiers

- Erbium doped gain





Silicon Photonic Challenges
Modulators



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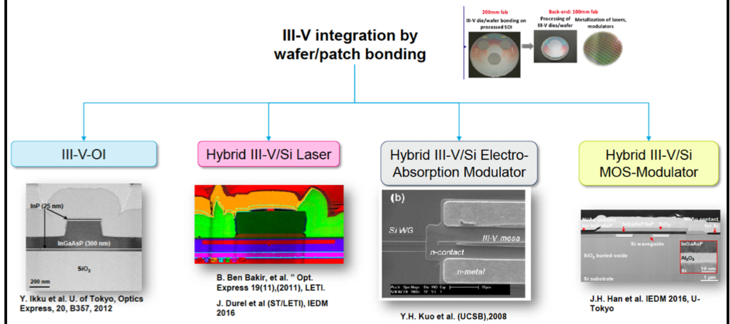
Hybrid integration



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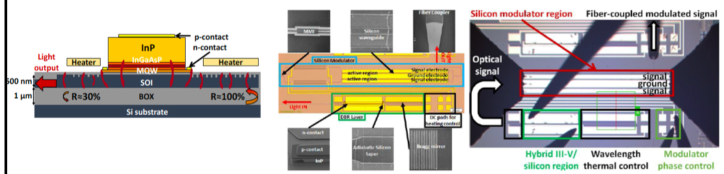
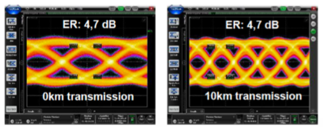
Silicon Photonic Challenges
Integrated Transmitter : Hybrid Laser + Modulator



- Demonstration of a **25 Gb/s** transmission using the transmitter, with 2.5 Vpp on each MZM arm.



T.Ferrotti et al., SSDM 2016, Optics Express 2017 , CEA-LETI/ST

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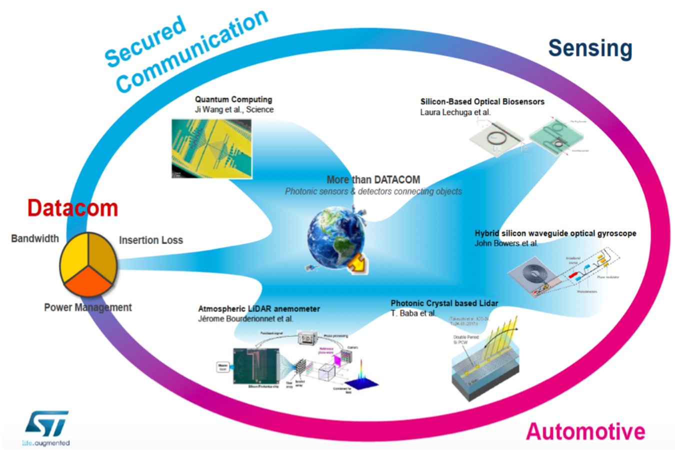
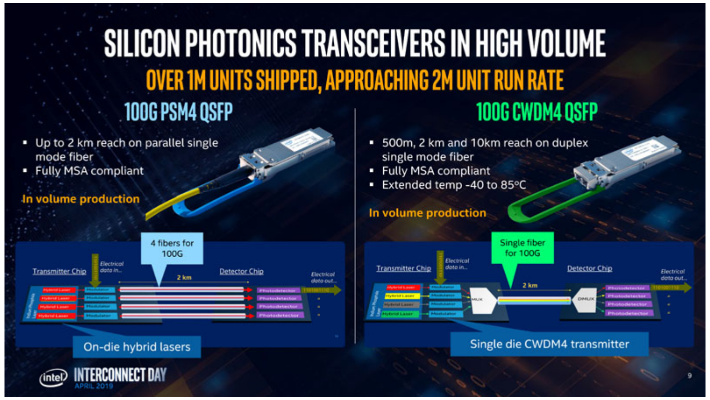
Silicon Photonic Applications



Intel 400G Interconnection in 2019



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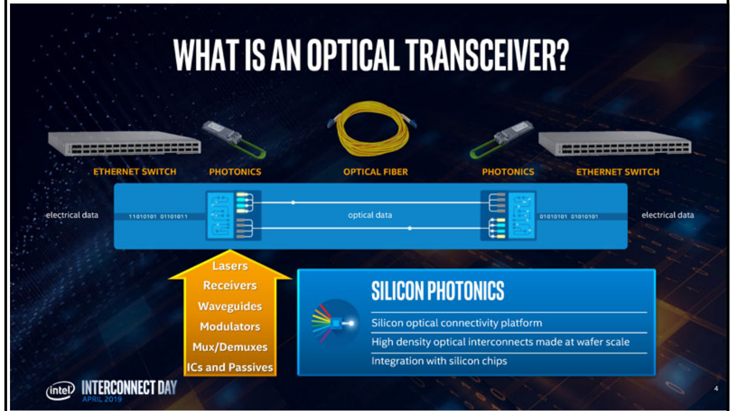
Intel 400G Interconnection in 2019



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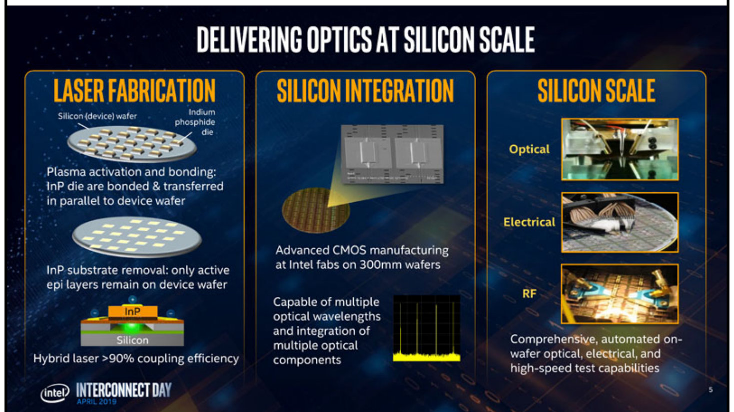

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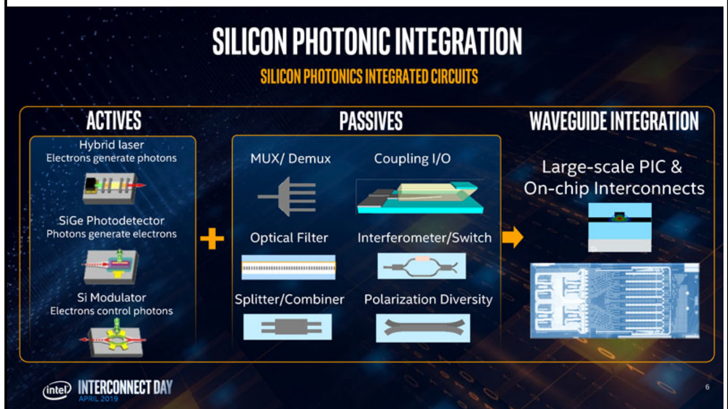

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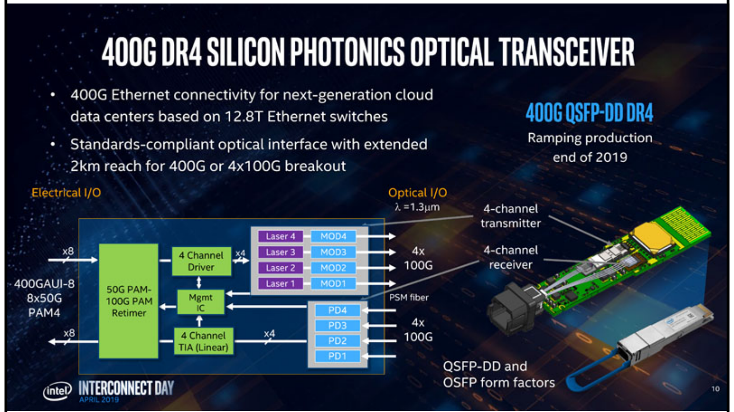

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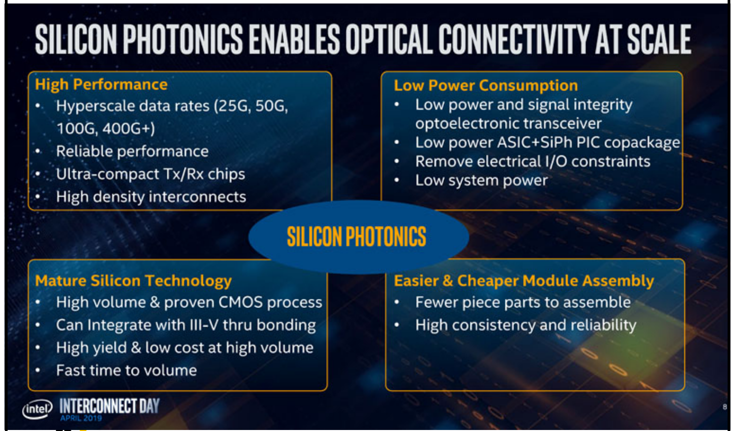

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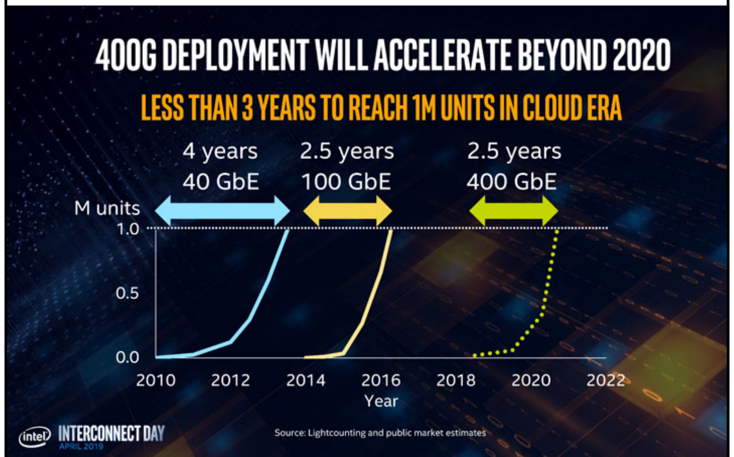

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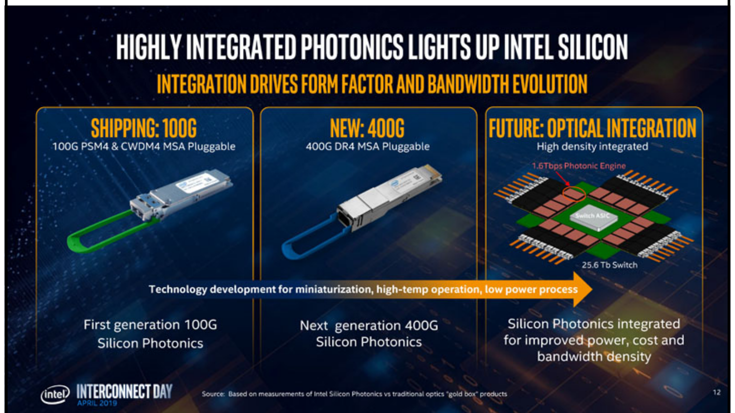

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