How Optical Networking Transformed Our World

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In 2020 we celebrated

But...50 years of what?
Low loss optical fiber & Semiconductor laser

The oxygen that feeds...

The Internet*

*Source: The IT Crowd
Could we build the internet *as we know it* in some other way?

Low loss optical fiber & Semiconductor laser

No – optical fiber is on a totally different capacity *trajectory*
How about Satellites?

Maybe 24 Tb/s total capacity?

(about the same as a *single fiber pair* on *one transatlantic cable*)

Starlink is meant for...

- Low loss optical fiber
- Semiconductor laser
Fiber and lasers have a long history of development, but... 

Low loss optical fiber & Semiconductor laser

1970 marks the date when researchers realized... This could actually work!

Multiple Nobel Prizes

The Internet
Geoff’s Motion Picture Corporation, Inc. Presents

A Very Brief and Exciting History of Optical Fiber
1842
Jean-Daniel Colladon

“Trapped light” inside a tube of water

1859
John Tyndall

Described the phenomenon of total internal reflection (1870)
We can see the laser beam reflected off the inside of the “tube” of water
1930
Heinrich Lamm
Used fiber bundle as medical endoscope

1960
Narinder Singh Kapany
Coined the term “Fiber Optics”
1965
Manfred Börner
Patented first fiber optic communication system

Charles Kao
“Father of Fiber Optics”

1965
2009 Nobel Prize for Physics

20 dB/km
1970

They actually made “low loss” fiber (<20dB/km)

17 dB/km
(at 630 nm)

Donald Keck, Robert Maurer and Peter Schultz

Image courtesy of Corning, Inc.
Find a Perspex block, and a laser pointer (green works best)
Why is low loss so important in optical fiber?

Let’s say you have 1km of optical fiber with 20 dB loss, and... 

...let’s also say you have built the best optical detector in the universe!! 

**Distance** | **# photons**
--- | ---
1 km | 100
2 km | 10,000
10 km | 100,000,000,000,000,000,000,000

1 photon

Because it’s so good it can reliably detect just **one photon** of light
Let’s have a think…

Assume there are $3.28 \times 10^{80}$ particles in the observable universe.

You have a single-photon detector.

You have 20 dB/km loss fiber.
Yes – of course it’s 42
The Race to Drive Down Fiber Loss

1973
Close to the theoretical minimum for this wavelength

1976
Lasers must be developed to work at longer wavelengths

<0.46 dB/km at 1200nm
(Use longer wavelength laser)

1979
<0.2 dB/km at 1550nm
(Use even longer wavelength laser)

Theoretical minimum at 1550nm is 0.15 dB

<5 dB/km at 850nm
(Replace Ti dopant with Ge)

<0.17 dB/km at 1550nm

Commercial SMF-28 ULL is at 0.17 dB/km
How many photons today?

We only need to put **5 photons** into the fiber.

Corning SMF-28 ULL has a loss of **0.17 dB/km**.

...to get **one photon** to the photodetector...

With 1970 fiber we needed more photons than there are particles in the universe.

So, over a distance of **42 km**...

Typical amp spacing is **100 km**...we’d only need **50 photons** into the fiber to get **one photon** to the photodetector.

A typical modulation symbol may contain around **10,000,000,000,000,000,000,000 photons**.
Today there are over 1 Billion km of optical fiber deployed.

Enough to wrap around the equator 25,000 times!
Geoff’s Motion Picture Corporation, Inc.

Presents

A Very Brief and Exciting History of Semiconductor Lasers
1917
Albert Einstein
Described the concept of stimulated emission

1937
Rudolf Ladenburg
Experimentally confirmed stimulated emission
1939
Valentin A. Fabrikant
Predicted the use of stimulated emission to amplify “short waves”

1947
Willis E. Lamb (& RC Retherford)
Demonstrated stimulated emission in hydrogen spectra

1950
Alfred Kastler
Proposed optical pumping

1955 Nobel Prize for Physics

1966 Nobel Prize for Physics
1951

Joseph Weber

Proposed the MASER

Gravitational Waves

1953-55

1964 Nobel Prize for Physics

The MASER breaks the Heisenberg Uncertainty Principle!

Neils Bohr

John von Neuman

Charles Townes

Nikolay Basov

Aleksandr Prokhorov

Masers

Stimulated Emission

Optical Pumping

Amplification

24
1957
Townes & Shawlov (Bell Labs)
Gould (Columbia U)
“Optical MASER” → LASER (1959)

1960
Theodore Maiman
Pulsed ruby laser

1962
Robert Hall
Pulsed semiconductor laser

1960
Basov & Javan
Proposed semiconductor laser
PULSED OPTICAL PUMPING

1964 Nobel Prize for Physics

STIMULATED EMISSION

1970

ROOM TEMPERATURE
CONTINUOUS OPERATION

PULSED OPTICAL PUMPING

MASER LASER

GaAs SEMICONDUCTOR

26
I was actually ten years old

• And that meant...

I had stayed up to see Apollo 11 land on the moon the year before

And I had to wait ten more years for my first computer!
Parallel Developments
Timelines of Laser and Fiber Evolution
We have the **foundations** of a communications revolution

1970

- Low loss optical fiber
- Semiconductor laser

*How do we make it scale?*
We have multiple options for scaling...

1. Increase wavelength data rate

2. Multiple colors on same fiber

3. Or both...depending on tech cycle
Laser Evolution → Longer Wavelength Operation

1. 1975→ GaAs, 0.8 µm, MMF
   - At shorter wavelengths attenuation dominated by Rayleigh scattering

2. 1980s InGaAsP, 1.3 µm, SMF
   - At longer wavelengths attenuation dominated by infrared absorption

3. 1990s InGaAsP, 1.55 µm, SMF
   - Single longitudinal mode lasers with external modulators

Sir David Payne
Southampton University

Emmanuel Desurvire
Bell Labs

1986 EDFA
EDFA: A Crucial Foundation for DWDM

- Even with very low loss optical fiber, attenuation means we need to amplify the signal
- In DWDM we transmit multiple signals, using different colors of light, over the same fiber, so...

Imagine you have an amp technology in which...
- You have to separate each color
- Amplify it
- Then recombine the colors

You really need a single-stage amplifier that works on all colors at once
Fiber Impairments: Modal Dispersion

- **Multi-mode Fiber**
  - Fiber core diameter >> 10X wavelength (e.g. 50 µm)
  - Result: Modal Dispersion

- **Single-mode Fiber**
  - Fiber core diameter < 10X wavelength (e.g. 8 µm)
  - Result: Almost no Modal Dispersion
Fiber Impairments: Chromatic Dispersion

Modulation symbol made up of a spread of frequencies

Lower frequencies travel faster

Result: Chromatic Dispersion

We can engineer this
What is Polarization Mode Dispersion?

Light wave energy oscillates in two axes – X and Y

Optical fiber has tiny, radial variations

The two modes get out of sync.
Compensation Techniques: **Before 2010**

Chromatic Dispersion: DCF compensates for all wavelengths at the same time

**Vs**

PMD: Expensive, external compensators for each wavelength

*Imagine this was 80 wavelengths!!*
Nonlinear Effects: The Kerr Effect

1875
John Kerr

1875
John Kerr

Nonlinearities

Self-phase modulation

Cross-phase modulation

Four wave mixing

Phantom signals

New NL mitigation
• Nyquist subcarriers
• SD-FEC Gain Sharing
• Super-Gaussian PCS
• NL Compensation

Traditional NL Mitigation
Low optical power
High Chromatic Dispersion
Large Effective Area

Power oscillations

Nonlinearities

Low optical power
High Chromatic Dispersion
Large Effective Area
The drive for “better” optical fiber

<table>
<thead>
<tr>
<th>Attenuation</th>
<th>HIGH</th>
<th>MINIMUM</th>
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Chromatic Dispersion (ps/nm.km)

**Early 1980s**
Not ideal for attenuation
But we can build 1310nm lasers

**Mid 1980s**
We can now build 1550nm lasers
G.652 dispersion is too high – need lots of DCF

**Mid 1990s**
DWDM is invented
G.653 dispersion is too low → high NL penalty

**Is this fiber “just right?”**

- **G.652 SMF**
  - Diameter: 80 µm²
  - Italy, S.America, Japan

- **G.653 DSF**
  - Diameter: 52 µm²
  - Non-linear penalty still too high!

- **G.655 NZDSF**
  - Diameter: 72 µm²
  - Non-linear penalty still too high!
## Five Generations of Coherent Transmission (so far)

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<tbody>
<tr>
<td>1</td>
<td><strong>PM-QPSK</strong></td>
<td><strong>PM-16QAM</strong></td>
<td><strong>PM-32QAM</strong></td>
<td><strong>PM-64QAM</strong></td>
<td><strong>PS-PM-64QAM</strong></td>
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<tr>
<td></td>
<td>32 GBd</td>
<td>32 GBd</td>
<td>56 GBd</td>
<td>68 GBd</td>
<td>100 GBd</td>
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<td></td>
<td><strong>40G → 100G</strong></td>
<td><strong>200G</strong></td>
<td><strong>400G</strong></td>
<td><strong>600G</strong></td>
<td><strong>800G</strong></td>
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<tr>
<td></td>
<td><strong>8T C-Band</strong></td>
<td><strong>19.2T Ext C</strong></td>
<td><strong>30T Ext C</strong></td>
<td><strong>38T Ext C</strong></td>
<td><strong>42T Ext C</strong></td>
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<tr>
<td></td>
<td>90 → 65 → 40 nm</td>
<td>40 → 28 nm</td>
<td>28 nm ASIC</td>
<td>16 nm ASIC</td>
<td>7 nm ASIC</td>
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C-Band = 4 THz EDFA  
Ext C = 4.8 THz EDFA
Semiconductor lasers are a superb source of light that scales to mass production.

Optical Fiber is an amazingly inexpensive and efficient waveguide.

Two technologies with unrelated chemistries and origins that work together so well.
Has Optical Networking Really *Transformed* Our World?

This is a big claim
Think About The Job YOU Do...

Basically you all keep this thing going strong

Could you do that without the capacity that optical networks give you?

There really is no alternative technology
Thank You!
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