How Optical Networking Transformed Our World

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NANOG HOLLYWOOD N86 2022 17–19 OCT

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

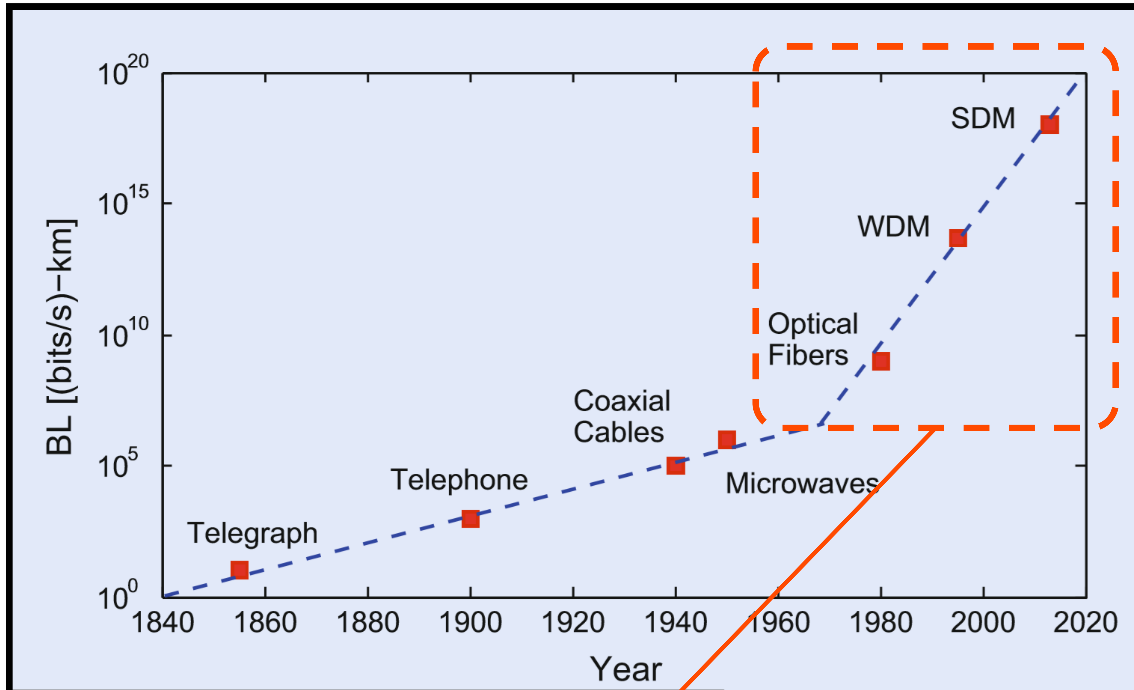
Could we build the internet *as we know it* in some other way?

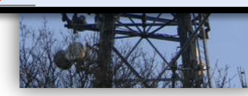
Low loss optical fiber

&

Semiconductor laser

vs





No – optical fiber is on a totally different capacity ***trajectory***

How about Satellites?

STARLINK

Maybe 24 Tb/s total capacity?

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

Starlink is meant for…

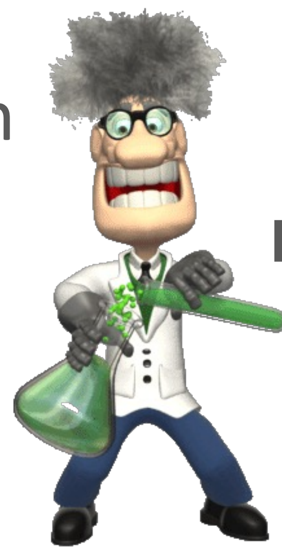
Low loss optical fiber & Semiconductor laser

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!

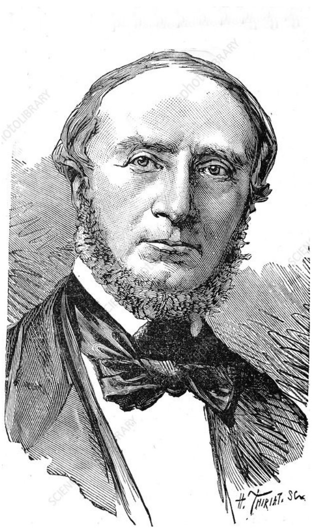


Multiple Nobel Prizes

Geoff's Motion Picture Corporation, Inc.

Presents

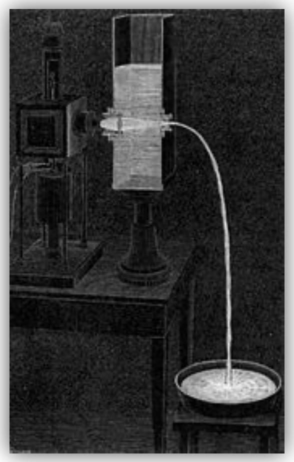
A Very Brief and Exciting History of Optical Fiber



1842

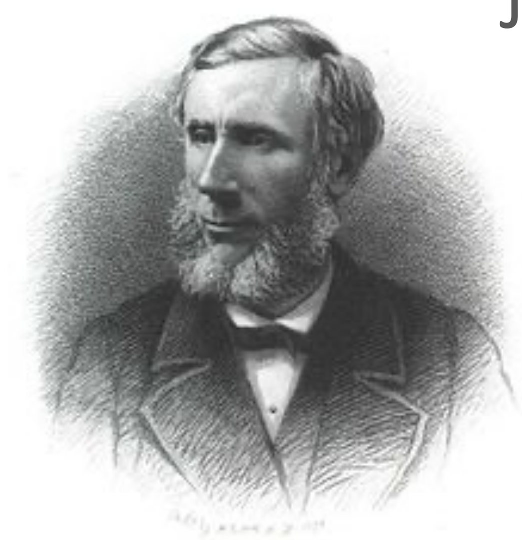
Jean-Daniel Colladon

“Trapped light” inside a tube of water



1859

John Tyndall



Described the phenomenon of total internal reflection (**1870**)

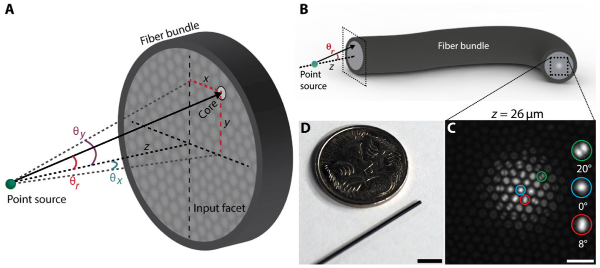
We can see the laser beam reflected off the inside of the "tube" of water

Harvard Natural Sciences Lecture Demonstrations

1930

Heinrich Lamm

Used fiber bundle as
medical endoscope



Endoscope evolution

1960

Narinder Singh Kapany

Coined the term
"Fiber Optics"

1965

Manfred Börner

Patented first fiber optic ***communication*** system

Charles Kao

20 dB/km

1965

2009 Nobel Prize for Physics

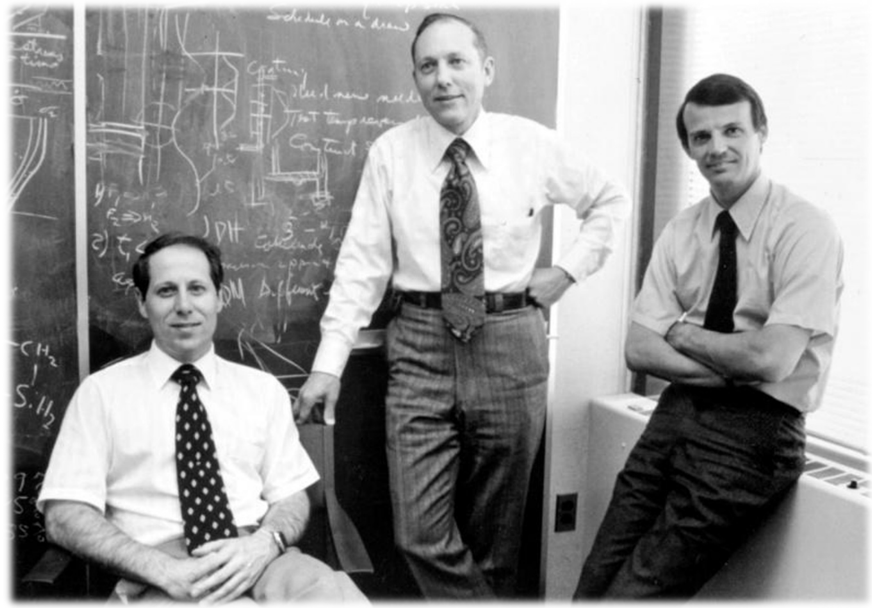
"Father of Fiber Optics"

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.

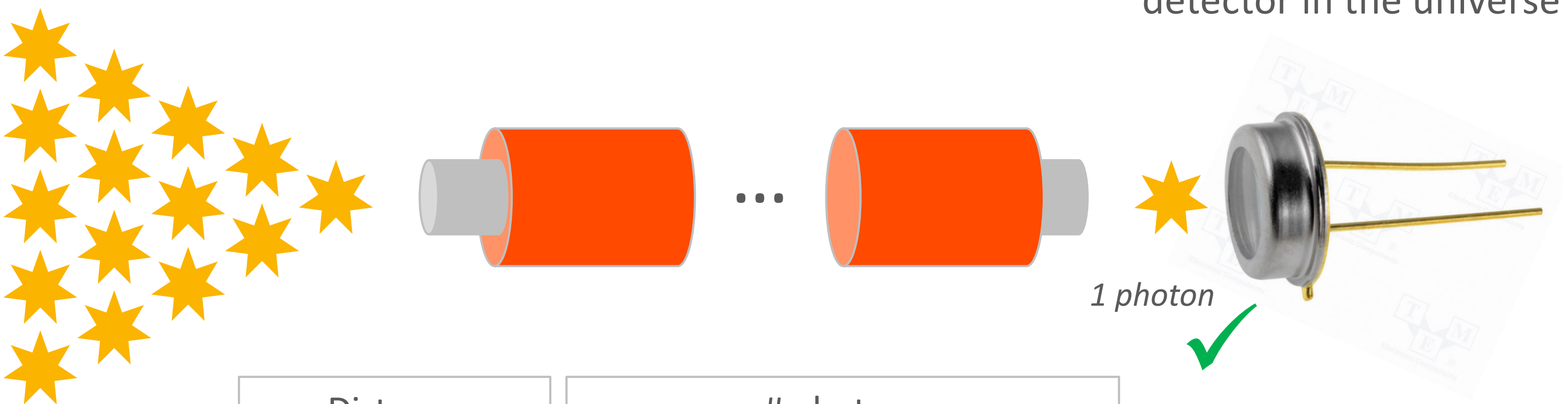
[redacted]

Why is low loss so important in optical fiber?

How many photons do we need to put in?

Let's say you have **1km** of optical fiber with **20 dB** loss, and…

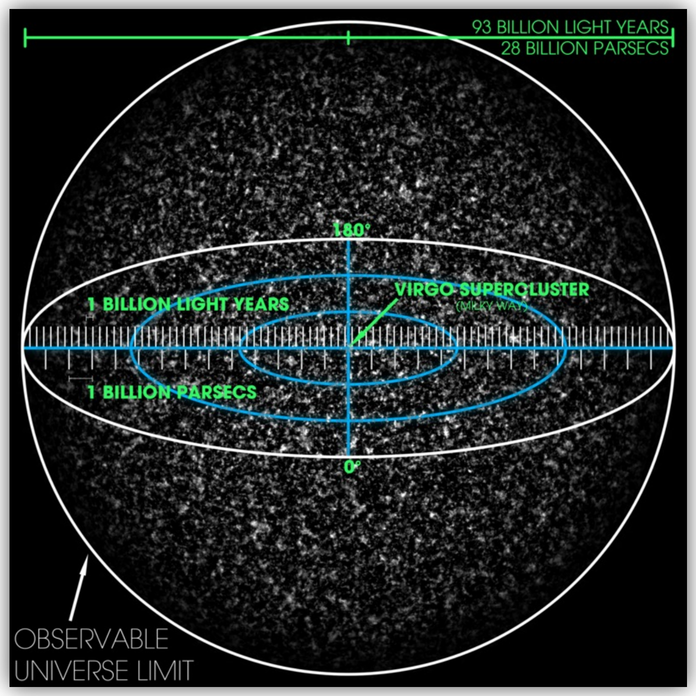
…let's also say you have built the best optical detector in the universe!!



Distance	# photons
1 km	100
2 km	10,000
10 km	100,000,000,000,000,000,000

Because it's so good it can reliably detect just ***one photon*** of light

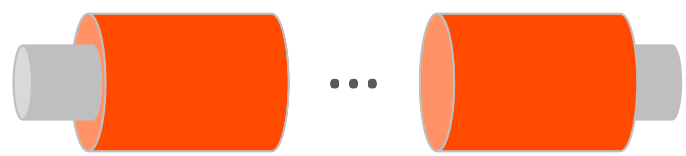
Let’s have a think…



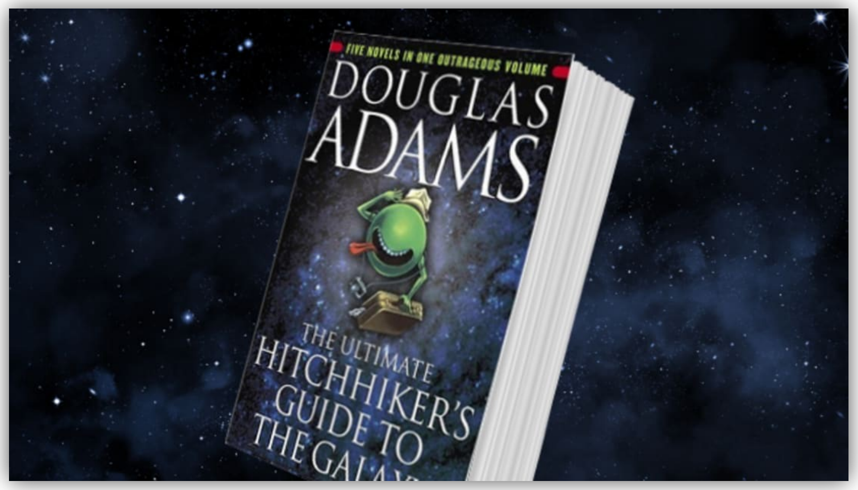
Assume there are **3.28 x 10^{80}** particles in the observable universe

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

380 nm Visible spectrum *740 nm*

<5 dB/km at 850nm

(Replace Ti dopant with Ge)

Lasers must be developed to work at longer wavelengths

<0.2 dB/km at 1550nm

(Use even longer wavelength laser)

Close to the theoretical minimum for this wavelength

<0.46 dB/km at 1200nm

(Use longer wavelength laser)

Theoretical minimum at 1550nm is 0.15 dB

Commercial SMF-28 ULL is at 0.17 dB/km

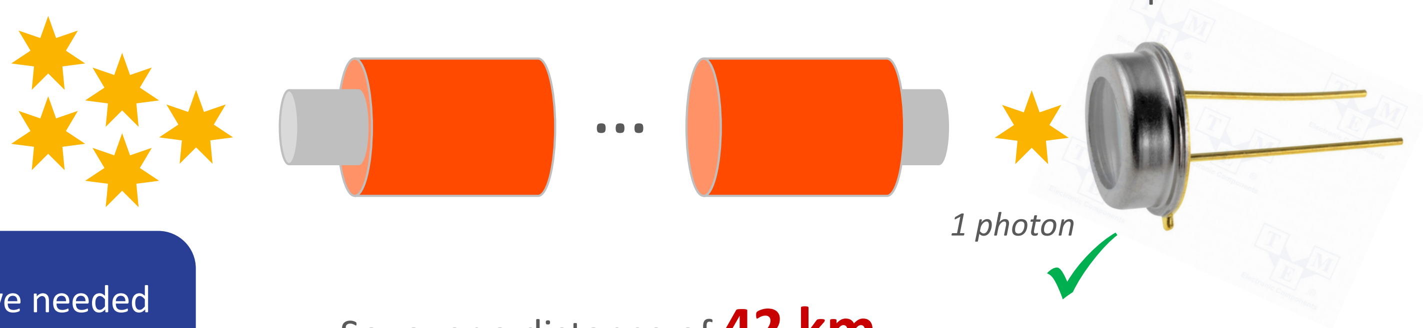
How many photons today?

A typical modulation symbol may contain around
10,000,000,000,000,000,000 photons

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

We only need to put
5 photons into the fiber

…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

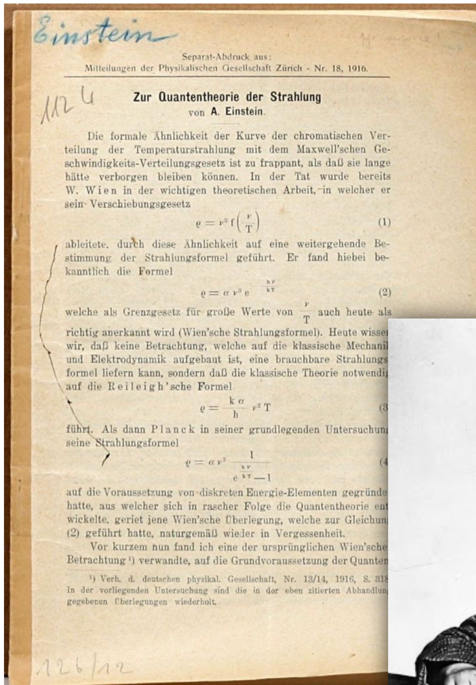
Today there are over
1 Billion km of
optical fiber
deployed

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



Einstein

Separat-Abdruck aus:
Mitteilungen der Physikalischen Gesellschaft Zürich - Nr. 18, 1916.

112 4

Zur Quantentheorie der Strahlung
von A. Einstein.

Die formale Ähnlichkeit der Kurve der chromatischen Verteilung der Temperaturstrahlung mit dem Maxwell'schen Geschwindigkeits-Verteilungsgesetz ist zu frappant, als daß sie lange hätte verborgen bleiben können. In der Tat wurde bereits W. Wien in der wichtigen theoretischen Arbeit, in welcher er sein Verschiebungsgesetz

$$\varrho = \nu^3 f\left(\frac{\nu}{T}\right) \quad (1)$$

ableitete, durch diese Ähnlichkeit auf eine weitergehende Bestimmung der Strahlungsformel geführt. Er fand hiebei bekanntlich die Formel

$$\varrho = \alpha \nu^3 e^{-\frac{h\nu}{kT}} \quad (2)$$

welche als Grenzgesetz für große Werte von $\frac{\nu}{T}$ auch heute als richtig anerkannt wird (Wien'sche Strahlungsformel). Heute wisse
wir, daß keine Betrachtung, welche auf die klassische Mechani
und Elektrodynamik aufgebaut ist, eine brauchbare Strahlungs
formel liefern kann, sondern daß die klassische Theorie notwendi
auf die Reileigh'sche Formel

$$\varrho = \frac{k\alpha}{h} \nu^2 T \quad (3$$

führt. Als dann Planck in seiner grundlegenden Untersuchun
seine Strahlungsformel

$$\varrho = \alpha \nu^3 \frac{1}{e^{\frac{h\nu}{kT}} - 1} \quad (4$$

auf die Voraussetzung von diskreten Energie-Elementen gegründe
hatte, aus welcher sich in rascher Folge die Quantentheorie ent
wickelte, geriet jene Wien'sche Überlegung, welche zur Gleichun
(2) geführt hatte, naturgemäß wieder in Vergessenheit.

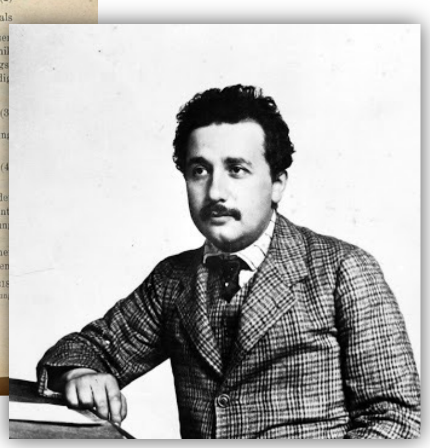
Vor kurzem nun fand ich eine der ursprünglichen Wien'sche
Betrachtung [1]) verwandte, auf die Grundvoraussetzung der Quanten

[1]) Verh. d. deutschen physikal. Gesellschaft, Nr. 13/14, 1916, S. 31
In der vorliegenden Untersuchung sind die in der eben zitierten Abhandlun
gegebenen Überlegungen wiederholt.

126/12

1917

Albert Einstein



Described the concept of ***stimulated emisson***

STIMULATED EMISSION

1937

Rudolf Ladenburg

Experimentally confirmed stimulated emission

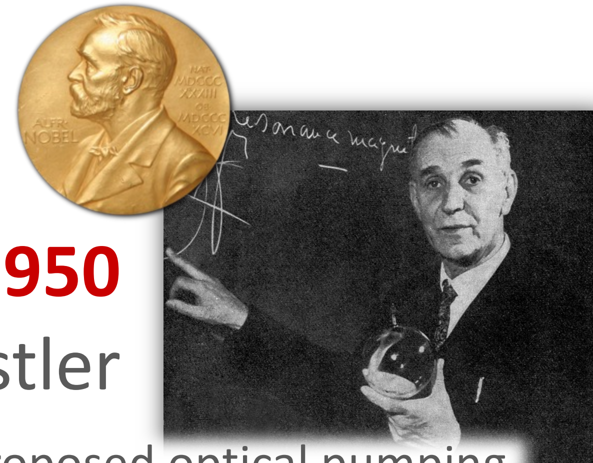
AMPLIFICATION

1939

Valentin A. Fabrikant

Predicted the use of stimulated emission to amplify “short waves”

1966 Nobel Prize for Physics



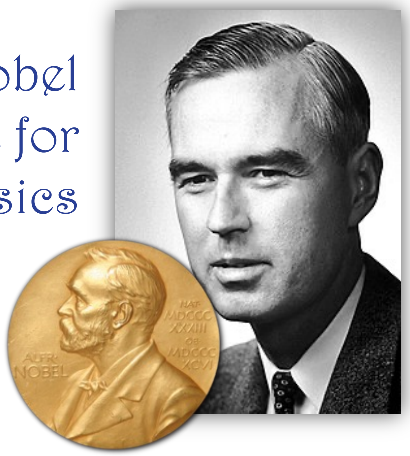
1950

Alfred Kastler

Proposed optical pumping

OPTICAL PUMPING

1955 Nobel Prize for Physics



1947

Willis E Lamb (& RC Retherford)

Demonstrated stimulated emission in hydrogen spectra

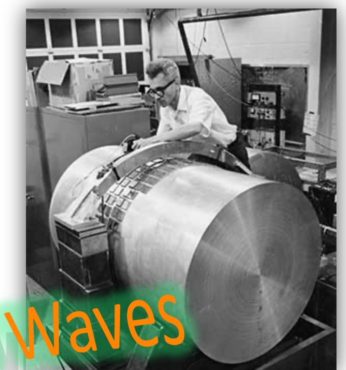
STIMULATED EMISSION

MASER

1951

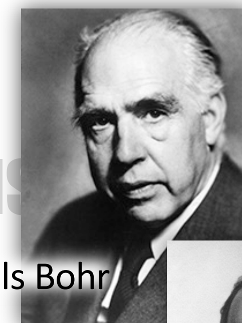
Joseph Weber

Proposed the MASER

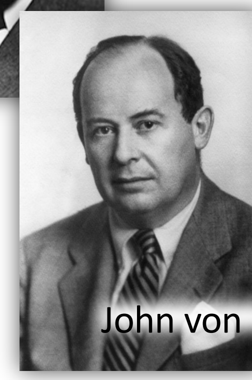


Gravitational Waves

OPTICAL

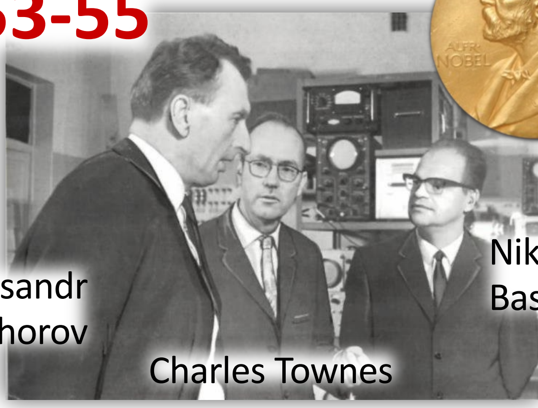


Neils Bohr



John von Neuman

1953-55



Aleksandr Prokhorov

Charles Townes

Nikolay Basov

1964 Nobel Prize for Physics

The MASER breaks the Heisenberg Uncertainty Principle!

AMPLIFICATION

1957

Townes & Shawlov (Bell Labs)

Gould (Columbia U)

"Optical MASER" → LASER (1959)

PULSED

EMISSION

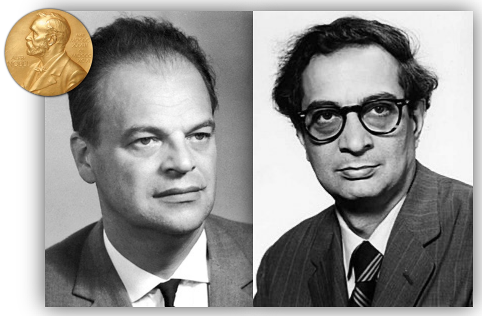
1960

Theodore Maiman

Pulsed ruby laser

N_2 COOLED

LASER



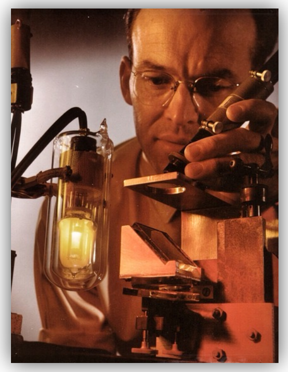
1960

Basov & Javan

AMPLIFICATION

Proposed ***semiconductor*** laser

SEMICONDUCTOR



1962

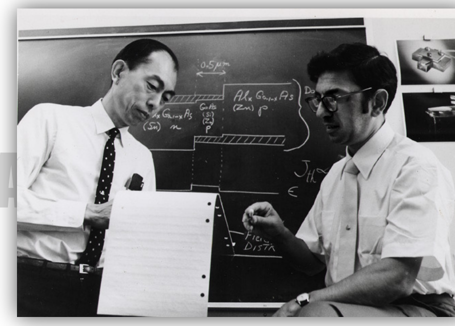
Robert Hall

Pulsed semiconductor laser

N_2 COOLED

1964 Nobel Prize for Physics

PLIFICA



STIMULATED EMISSION

1970

Zhores Alferov

Izuo Hayashi
Morton Parish

ROOM TEMPERATURE

CONTINUOUS OPERATION

PULSED

OPTICAL PUMPING

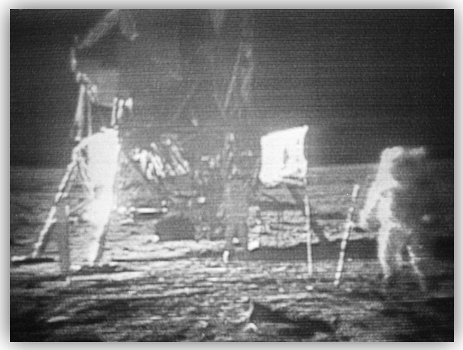
MASER

LASER

GaAs SEMICONDUCTOR

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

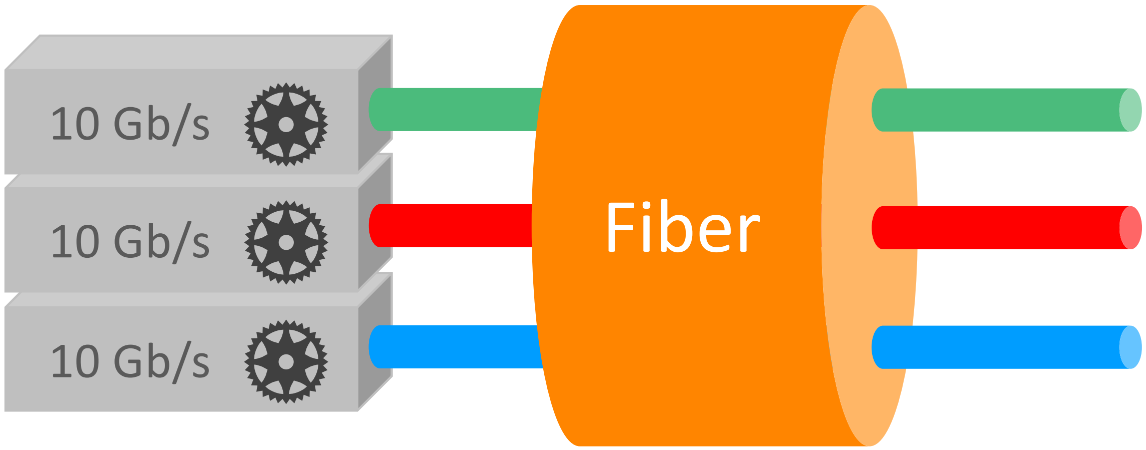
Low loss optical fiber

Semiconductor laser

How do we make it scale?

We have multiple options for scaling…

1 Increase wavelength data rate

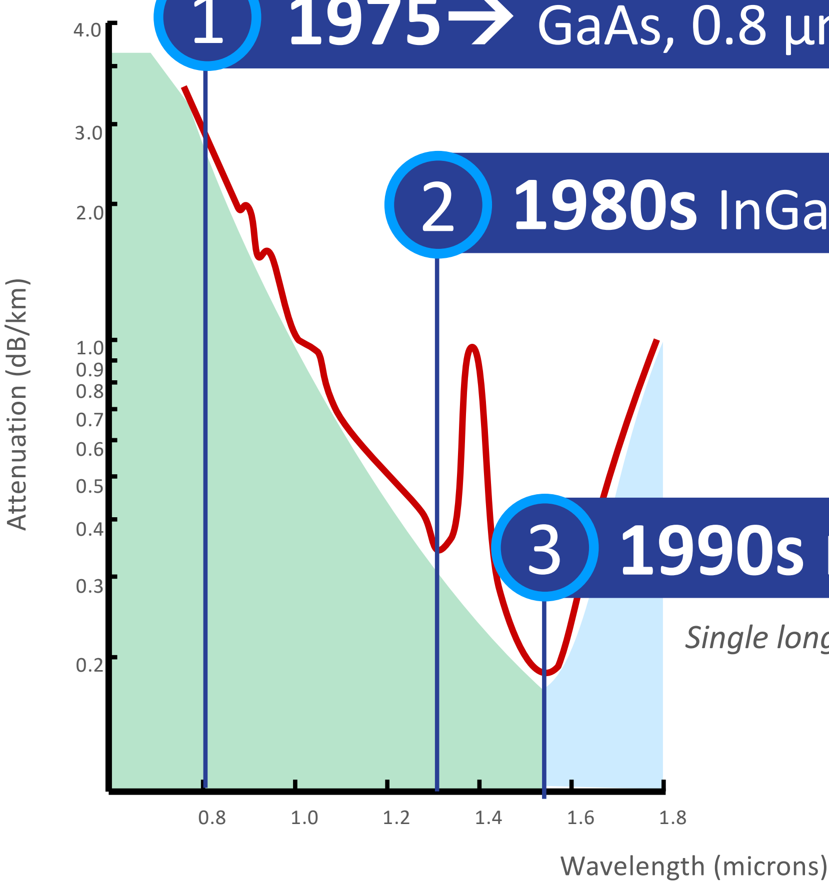


2 Multiple colors on same fiber

3 Or both…depending on tech cycle

Laser Evolution → Longer Wavelength Operation

Attenuation



1 **1975→** GaAs, 0.8 μm, MMF

2 **1980s** InGaAsP, 1.3 μm, SMF

3 **1990s** InGaAsP, 1.55 μm, SMF

Single longitudinal mode lasers with external modulators

- At shorter wavelengths attenuation dominated by ***Rayleigh scattering***
- At longer wavelengths attenuation dominated by ***infrared absorption***

Sir David Payne
Southampton University

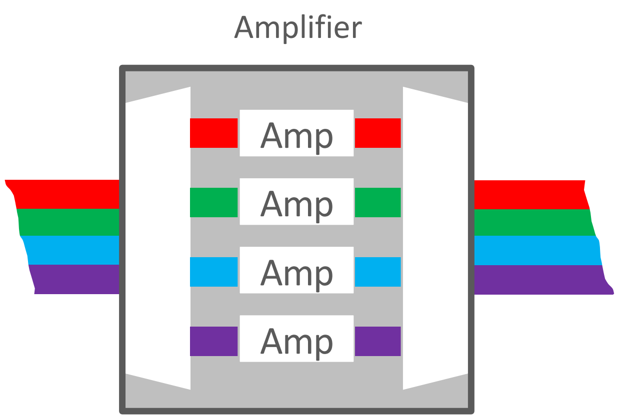
Emmanuel Desurvire
Bell Labs

1986 EDFA

EDFA: A Crucial Foundation for DWDM

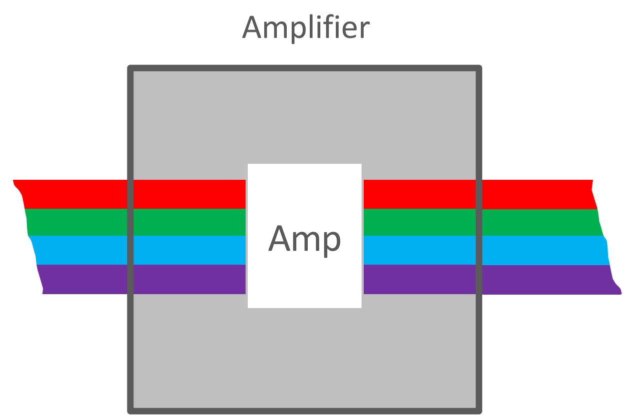
Attenuation

- 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

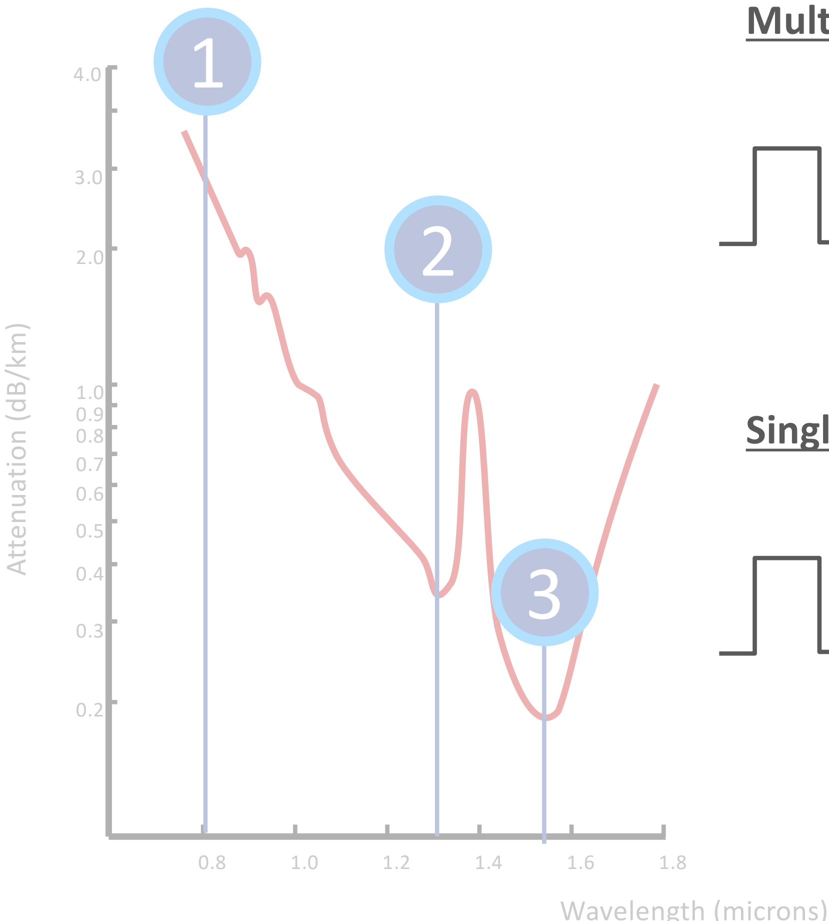


You really need a single-stage amplifier that works on all colors at once

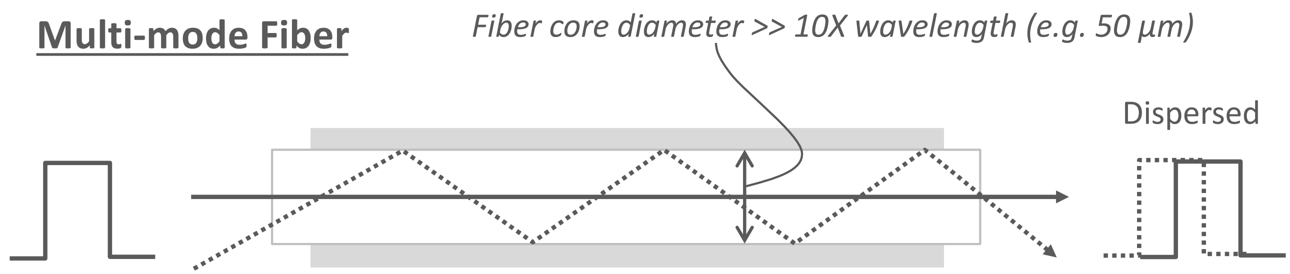
EDFA

Fiber Impairments: Modal Dispersion

Dispersion

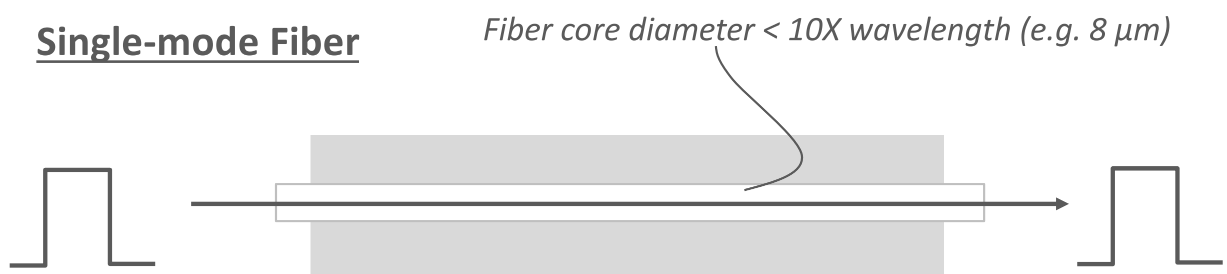


Multi-mode Fiber



Result: Modal Dispersion

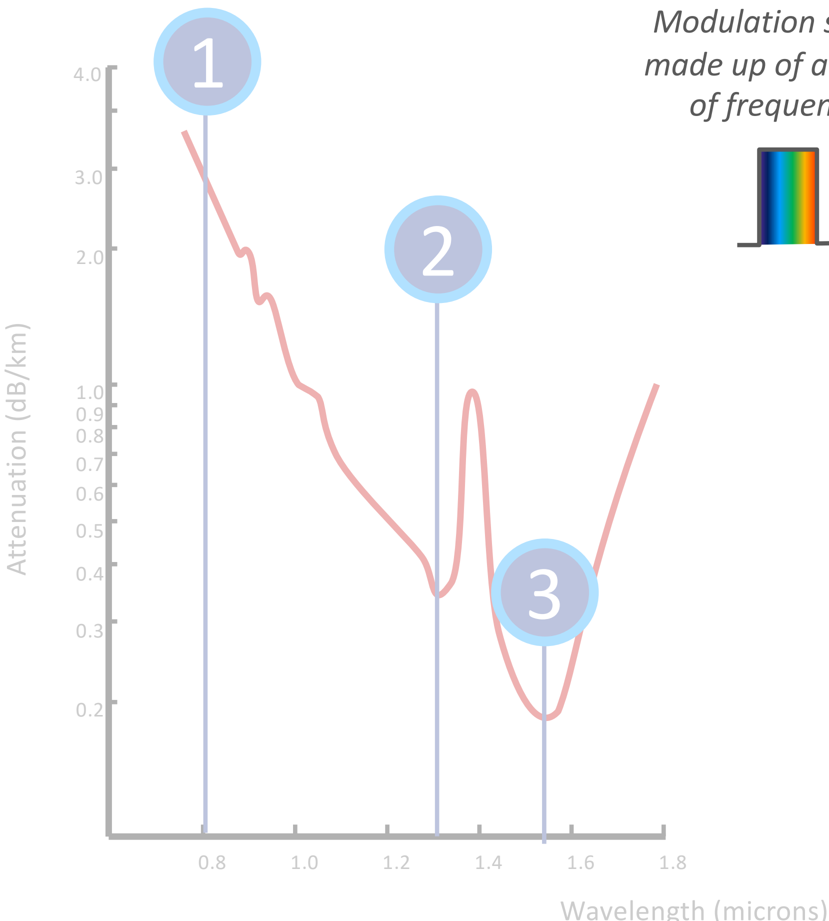
Single-mode Fiber

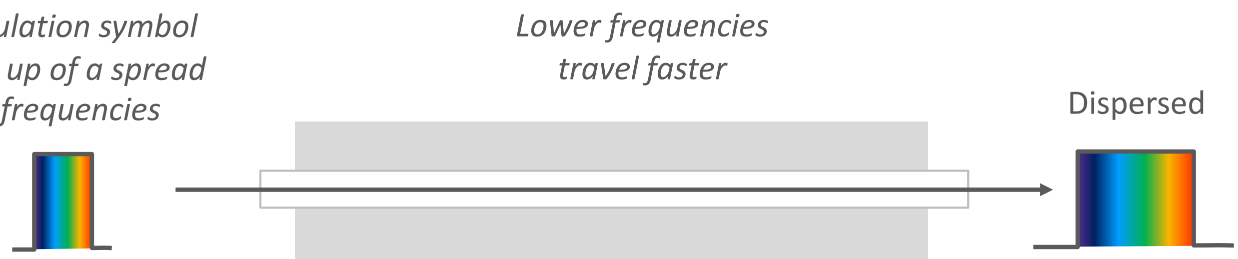


Result: Almost no Modal Dispersion

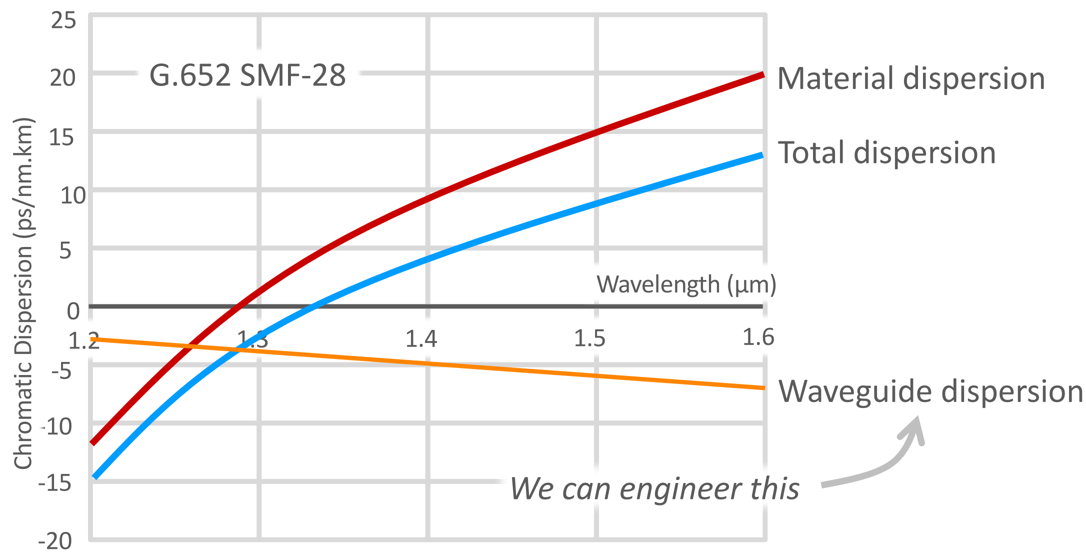
Fiber Impairments: Chromatic Dispersion

Dispersion





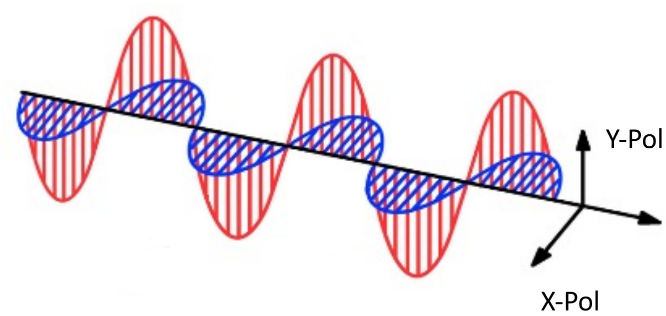
Result: Chromatic Dispersion



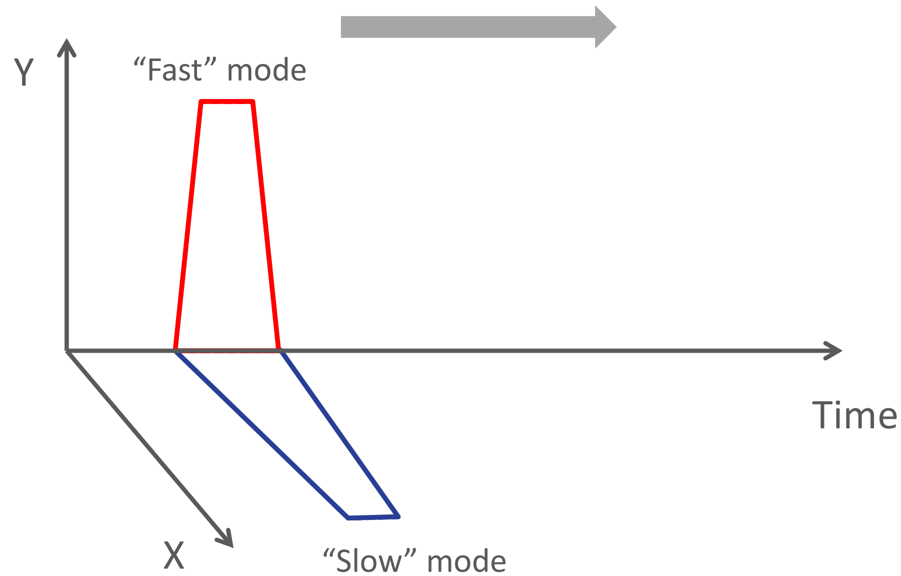
What is Polarization Mode Dispersion?

Dispersion

Light wave energy oscillates in two axes – X and Y



Optical fiber has tiny, radial variations

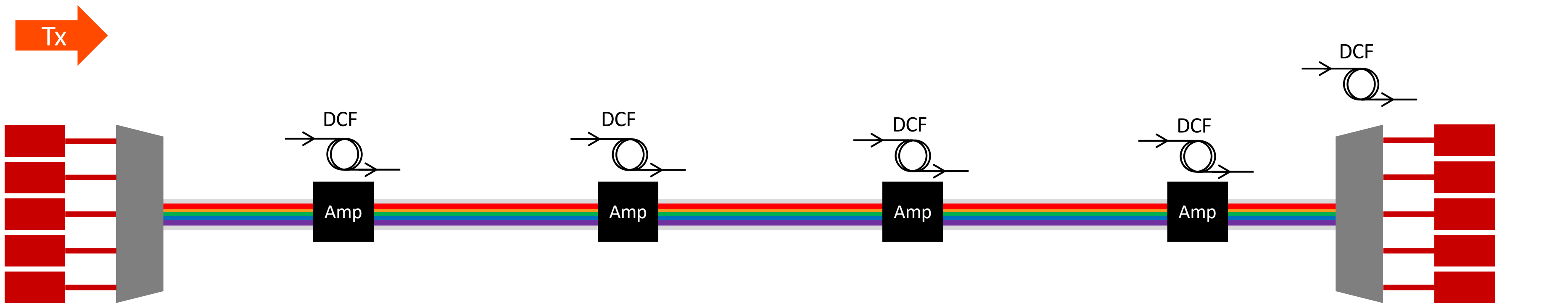


The two modes get out of sync

Compensation Techniques: **Before 2010**

Dispersion

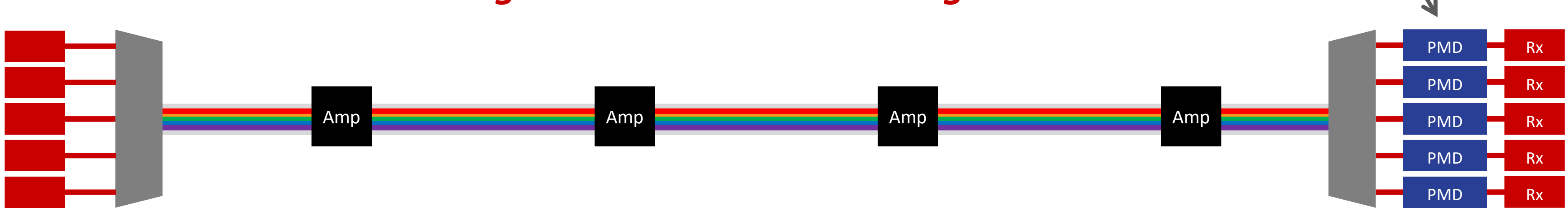
Chromatic Dispersion: DCF compensates for all wavelengths at the same time



VS

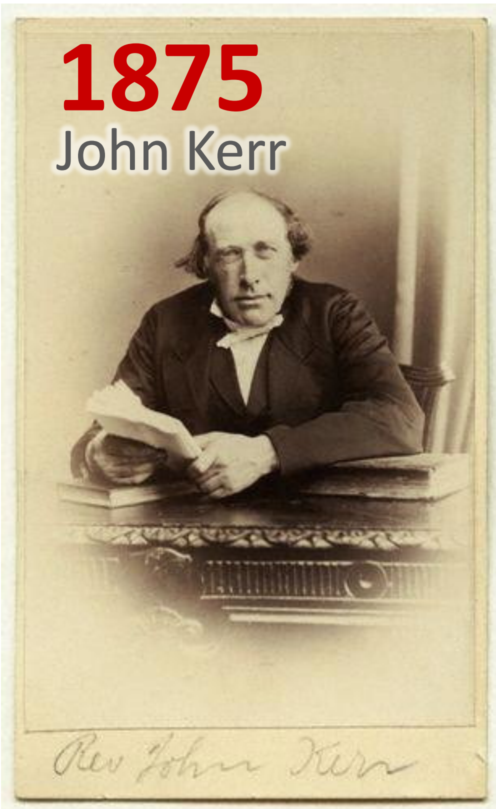
PMD: Expensive, external compensators for each wavelength

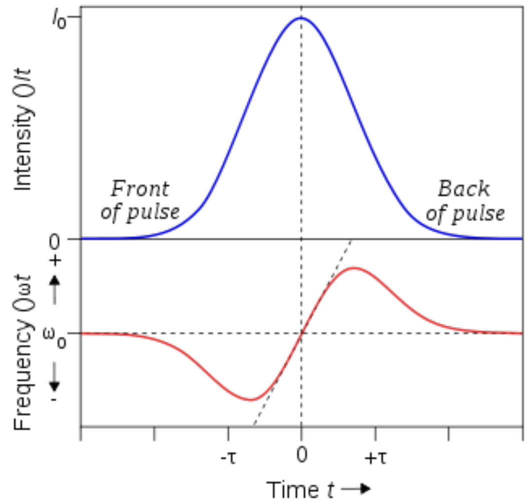
Imagine this was 80 wavelengths!!



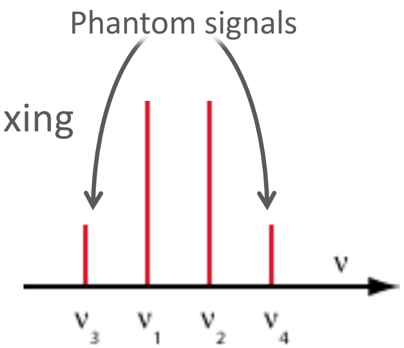
Nonlinear Effects: The Kerr Effect

Nonlinearities





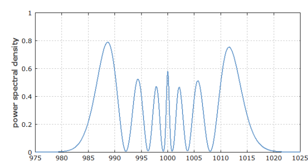
Four wave mixing

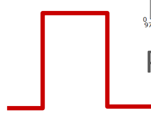


New NL mitigation

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

Self-phase modulation

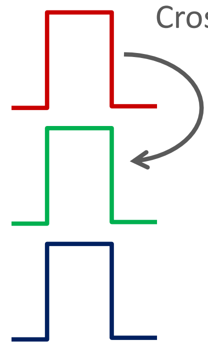




Power oscillations

Cross-phase modulation

Cross-talk

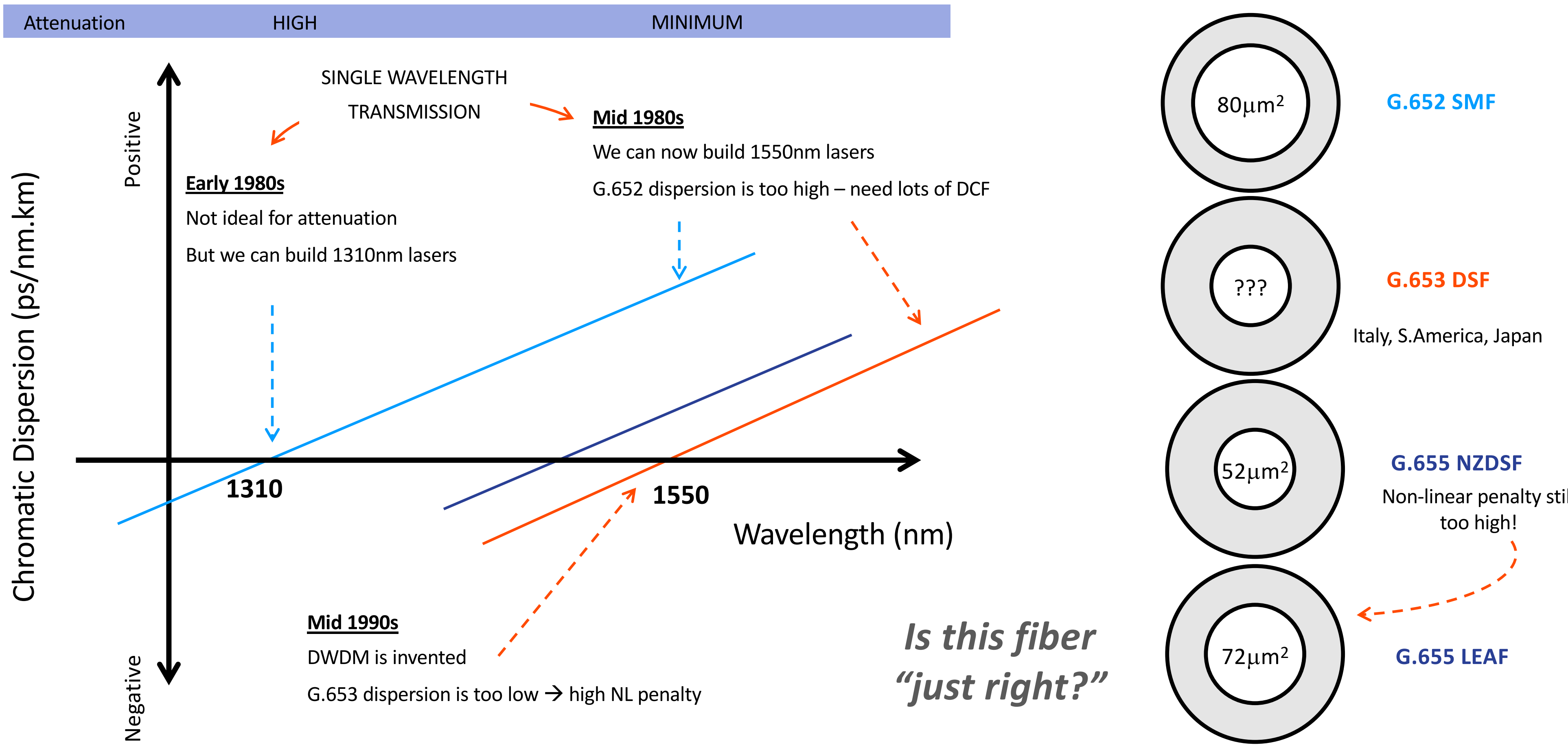


Traditional NL Mitigation

Low optical power
High Chromatic Dispersion
Large Effective Area

The drive for "better" optical fiber

Dispersion



Is this fiber "just right?"

Five Generations of Coherent Transmission (so far)

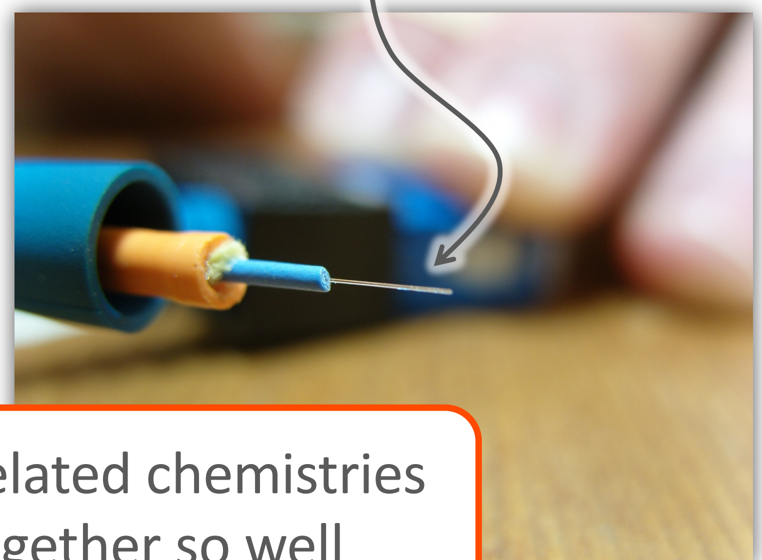
1	2	3	4	5
2009 → 2011	**2015**	**2017**	**2019**	**2020**
PM-QPSK	PM-16QAM	PM-32QAM	PM-64QAM	PS-PM-64QAM
32 GBd	32 GBd	56 GBd	68 GBd	100 GBd
40G → 100G	**200G**	**400G**	**600G**	**800G**
8T C-Band	**19.2T Ext C**	**30T Ext C**	**38T Ext C**	**42T Ext C**
90→65 →40 nm ASIC	40→28 nm ASIC	28 nm ASIC	16 nm ASIC	7 nm ASIC

C-Band = 4 THz EDFA   Ext C = 4.8 THz EDFA

And all because…

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!

Geoff Bennett
gbennett@Infinera.com