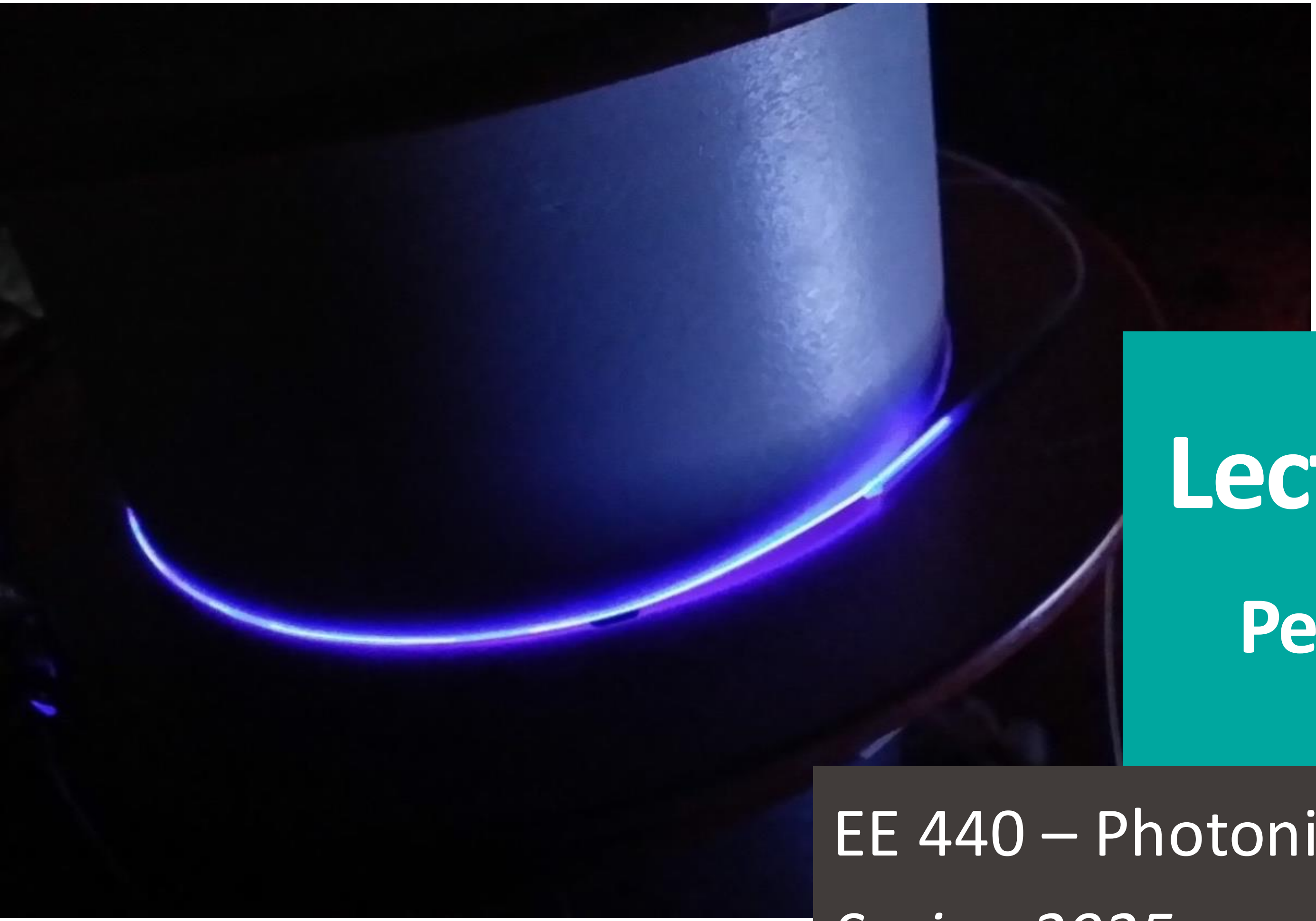


Lecture 13

Performance limits

EE 440 – Photonic systems and technology

Spring 2025

Ecole
Polytechnique
Fédérale de
Lausanne

Prof. Camille Brès - camille.bres@epfl.ch

Overall considerations

Performance of an optical fiber system

First step is to come up with a mathematical model describing the effect of the various systems components on the modulated signal.

- Can then estimate the shape of the received distorted signal.

In most application, the fiber can be treated as a linear system:

- Described by an impulse response function $h(t)$ or its Fourier transform $H(f)$, with f the modulation frequency
- Three important parameters characterize these functions.

Power transmission in fiber of length L

Fraction of the steady (unmodulated) input optical power that is received at the output of the link,

Equals to $H(f)$ evaluated at $f = 0$ Hz: $H(0) = \int h(t)dt$

For a fiber of length L and of linear attenuation coefficient α (km^{-1}):

$$H(0) = \exp(-\alpha L)$$

- Recall that loss on linear and dB scale are linked by $\alpha_{dB} \approx 4.343\alpha$
- Localized power losses (couplers, connectors etc) may be included in distributed units of dB/km.

Response time of optical fiber of length L

The response time T_{fiber} $(\sim\Delta T)$ is the width of $h(t)$.

Determines the temporal spreading of the optical pulses

Response time is proportional to the fiber length.

- For example, we have seen that in a single mode fiber:

$$\Delta T \approx L|D|\Delta\lambda$$

- With $\Delta\lambda$ is the source linewidth in nm
- D is the dispersion coefficient of the fiber in ps/(nm-km)

Bandwidth

The bandwidth $\Delta\nu$ in Hz, is the width of the transfer function $|H(f)|$

In an analog system, the bandwidth determines the maximum frequency at which the input power may be modulated and successfully detected by the receiver

$H(f)$ and $h(t)$ are Fourier transform: the bandwidth is inversely proportional to the response time

- Coefficient of proportionality depends on the actual profile of $h(t)$

Maximum fiber length – principal impairments

Attenuation:

- Results in exponential drop of power.
- System's performance becomes unacceptable if the received power becomes smaller than the receiver sensitivity.

Dispersion:

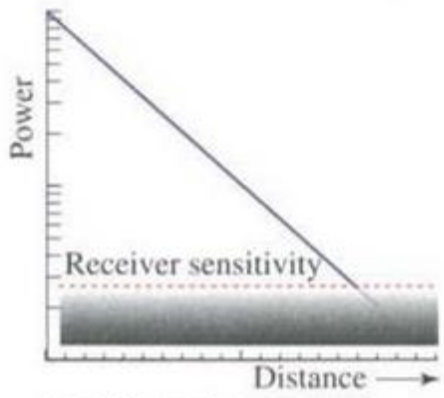
- Results in increase of the width of the optical pulses carrying the information.
- If width exceeds the bit interval, inter symbol interference (ISI) occurs

Noise:

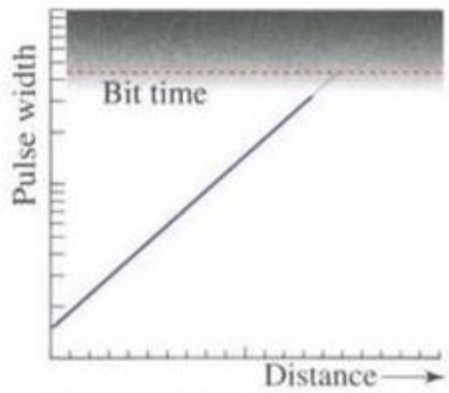
- Added by optical components (amplifiers etc)

Nonlinear distortions:

- Associated with intense optical pulses.
- Cross mixing and interference of multiplexed signals.



(a) Attenuation



(b) Dispersion

System performance dependence on bit rate

Effect on noise:

- For a fixed amount of power, higher bit rates corresponds to fewer photons per bit, therefore more photon noise.

Effect on sensitivity:

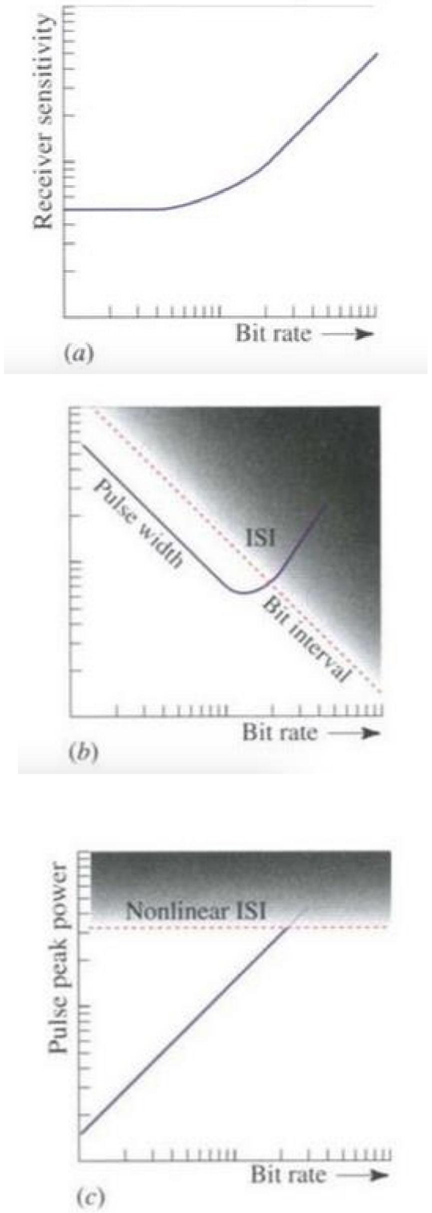
- Receiver noise increases with bit rate as Δf needs to be larger: sensitivity therefore increases with bit rate.

Effect on pulse width:

- High bit rate means narrow pulses of light
- Spectrum is broader and the system more sensitive to dispersion.

Nonlinear effects:

- For fixed energy per bit, higher bit rate means higher power and therefore stronger nonlinearities.



Attenuation limited performance – power budget

Attenuation limited performance – power budget

Power budget is typically prepared in dB scale:

$$\bar{P}_{tr} - P_C - P_m - \alpha L_{max} = \bar{P}_{rec}$$

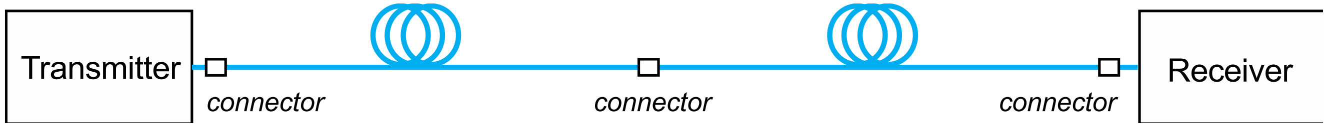
Transmitted power

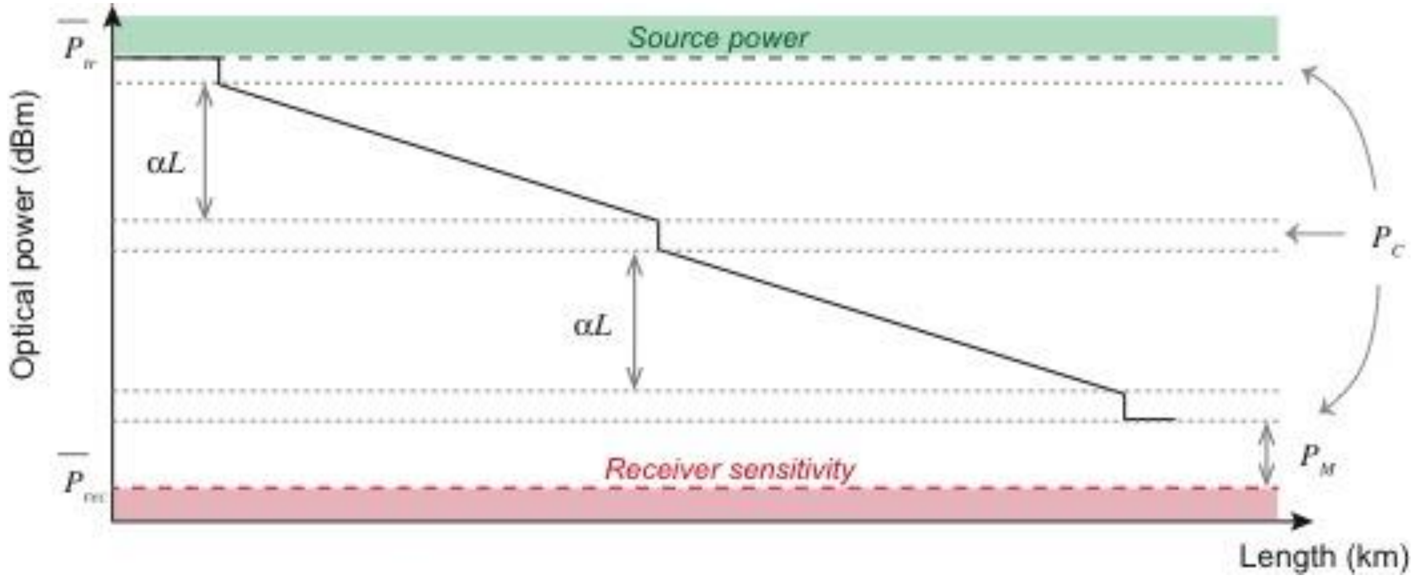
Non-radiative losses

Design margin

Propagation losses

Received power





Revisiting receiver sensitivity

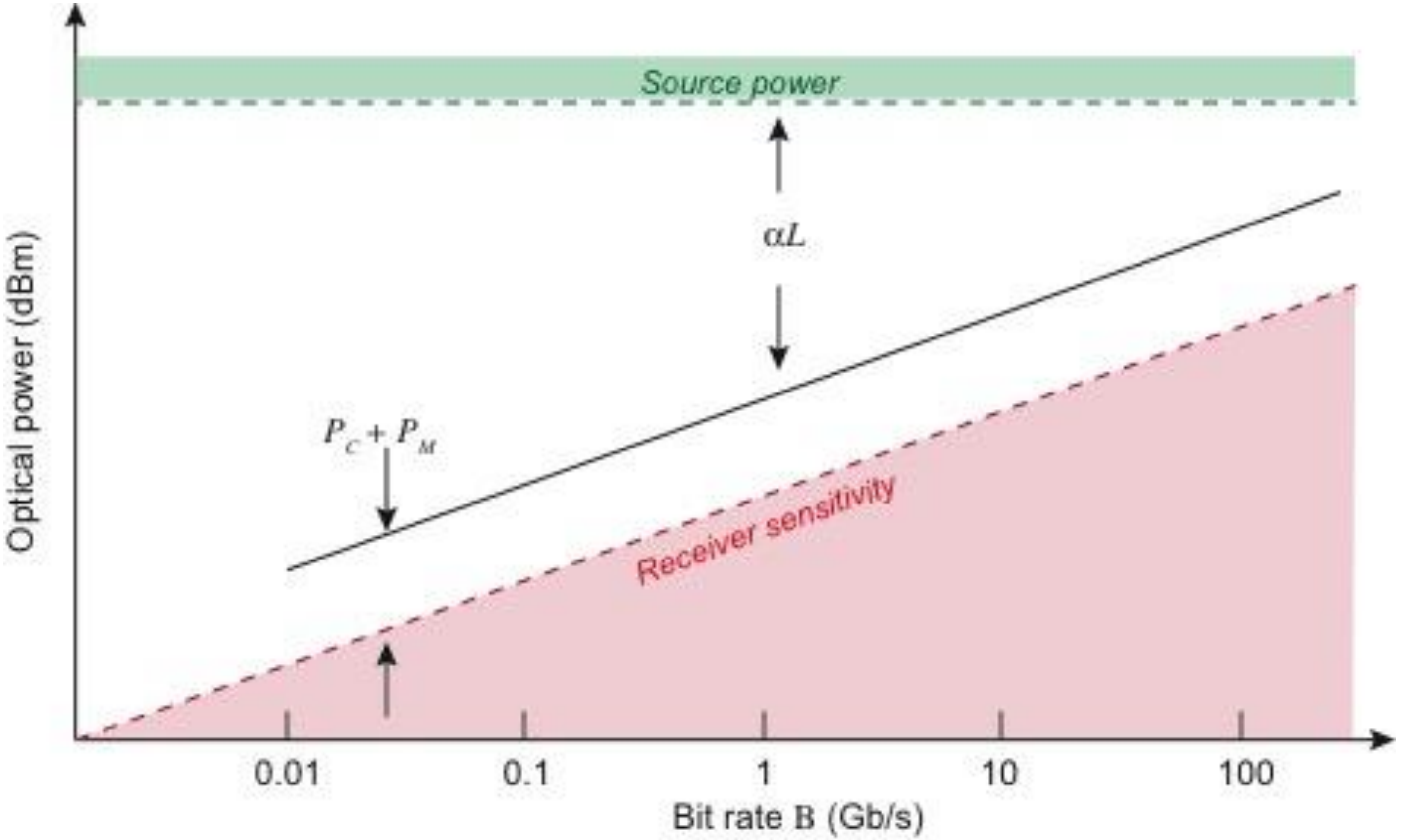
We can think of the receiver sensitivity in terms of the minimum numbers of photons per bit ($\bar{n}_0$) necessary to guarantee our desired BER

The optical energy per bit is therefore given as: $h\nu\ \bar{n}_0$

Receiver sensitivity (in linear scale) $\bar{P}_{rec}$ can be written as: $\bar{P}_{rec}$ = $h\nu\ \bar{n}_0 B$

Keep in mind that when thermal noise dominates, the receiver sensitivity depends on the receiver bandwidth and hence on the data rate …

Power budget and bit rate



Power budget as a function of bit rate B: as B increases, the power $\bar{P}_{rec}$ required at the receiver increases (so that the energy per bit remains constant), and the maximum length L decreases

Design guidelines 1

The receiver sensitivity in dB scale is given by:

$$\bar{P}_{rec} = 10\log_{10}\left(\frac{h\nu\,\bar{n}_0 B}{10^{-3}}\right)\ \text{dBm}$$

The maximum reach L_{max} of the system is therefore obtained from the power budget in dB as:

$$L_{max} = \frac{1}{\alpha}\left(\bar{P}_{tr} - P_C - P_m - 10\log_{10}\left(\frac{h\nu\,\bar{n}_0 B}{10^{-3}}\right)\right)$$

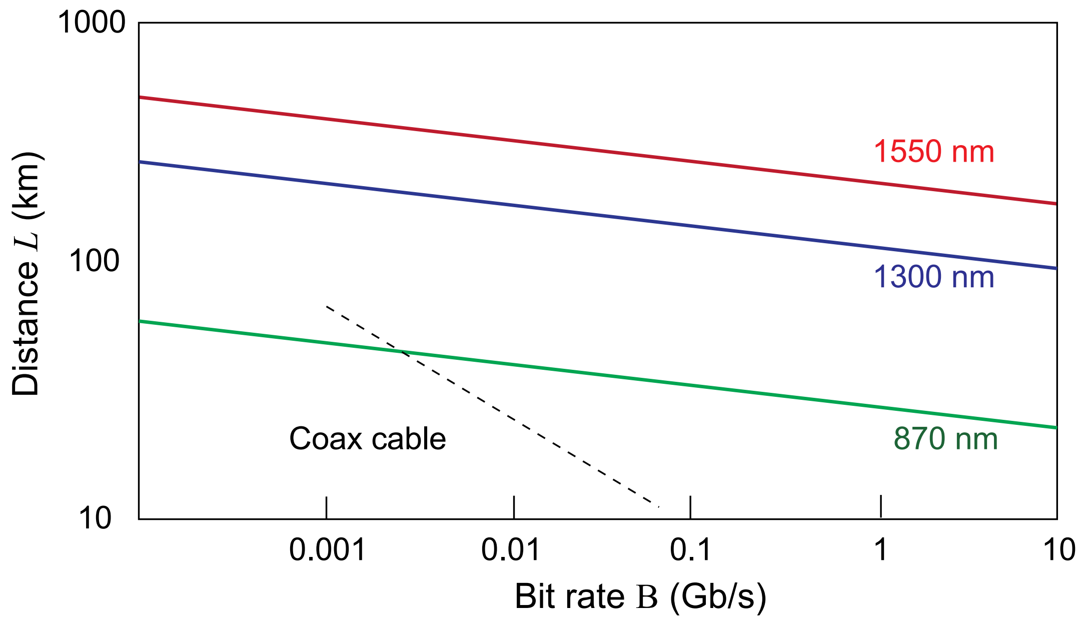
Let α_f be the total loss including connectors etc, then

$$L_{max} = \frac{10}{\alpha_f}\log_{10}\left(\frac{\bar{P}_{tr}\ (\mathrm{mW})}{h\nu\,\bar{n}_0 B}\right)$$

Loss limits

Example with:

- 870 nm (α = 2.5 dB/km), 1300nm (α = 0.4 dB/km) and 1550 (α = 0.25 dB/km)
- $\bar{P}_{tr}$= 1 mW
- $P_C = P_m = 0$
- $\bar{n}_0$= 300 photons/bit for 870 nm, 500 photons/bit for 1300 nm and 1550 nm



Dispersion limited performance – rise time budget

Dispersion limited performance

When a pulse is generated by the transmitter, propagates through the fiber and is detected, it does not only loose power, but it also gains in width

Final pulse width σ_r depends not only on original pulse width σ_0 but also:

- The response time of the transmitter, σ_{tr}
- The response time of the fiber, σ_{fiber}
- The response time of the receiver, σ_{rec}

If all functions are independent Gaussian, the width response of entire communication system is:

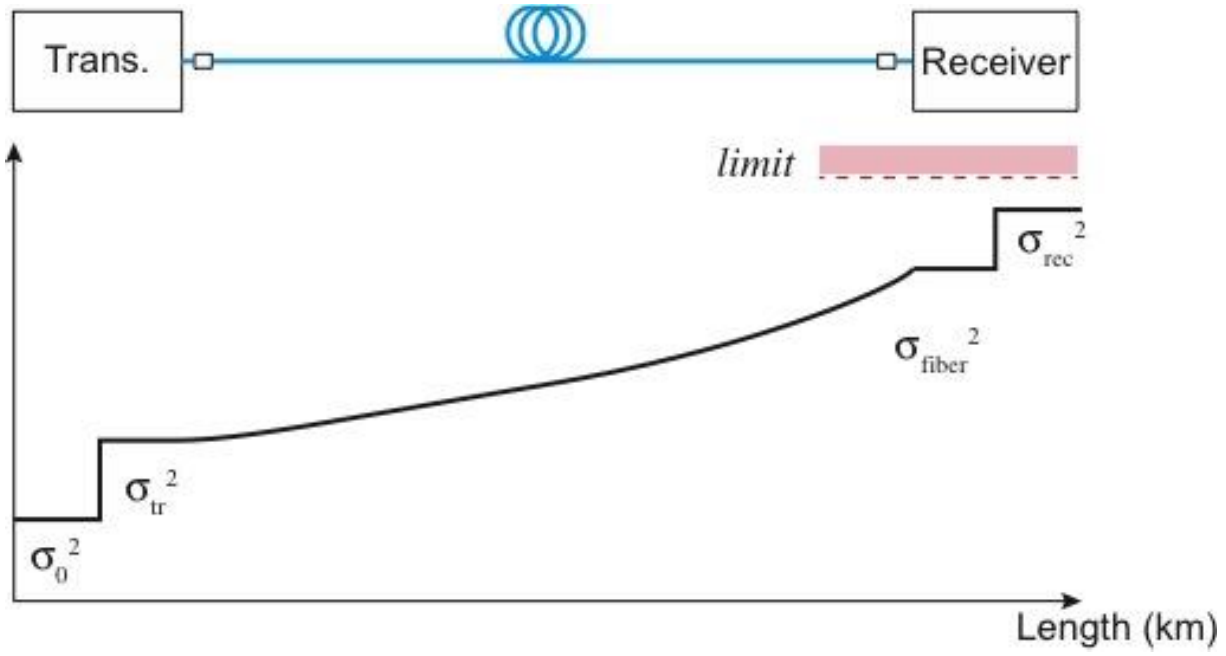
$$\sigma_{sys}^2 = \sigma_{tr}^2 + \sigma_{fiber}^2 + \sigma_{rec}^2$$

The final pulse width is therefore : $\sigma_r^2 = \sigma_0^2 + \sigma_{sys}^2$

Dispersion limited performance

A principal design condition for the communication system link ensures that the width of the received pulse does not exceed a prescribed fraction of the bit period

- Dependence on the bit rate B



Rise time budget

The rise time budget of the entire systems needs to be compatible with the intended operational bit rate (B)

Even if the bandwidth of individual components exceeds the bit rate, the entire system may not

- Can use the concept of rise time T_r (in s) which is related to the bandwidth Δf (in Hz).

$$T_r = \frac{0.35}{\Delta f}$$

$$\Delta f = \begin{cases} \frac{B}{2} \text{ for NRZ format} \\ B \text{ for RZ format} \end{cases}$$

Design guideline 2

The transmitter rise time T_{tr}^2

- Limited by the modulator operational bandwidth (or direct modulation)

The receiver rise time T_{rec}^2

- Limited by transit times or RC time constant

The fiber 'rise time' T_{fiber}^2

- Limited by dispersion
- The only rise time that depends on propagation length and on the fiber type

The overall system's rise time T_r is given by

$$T_r^2 = T_{tr}^2 + T_{fiber}^2 + T_{rec}^2$$

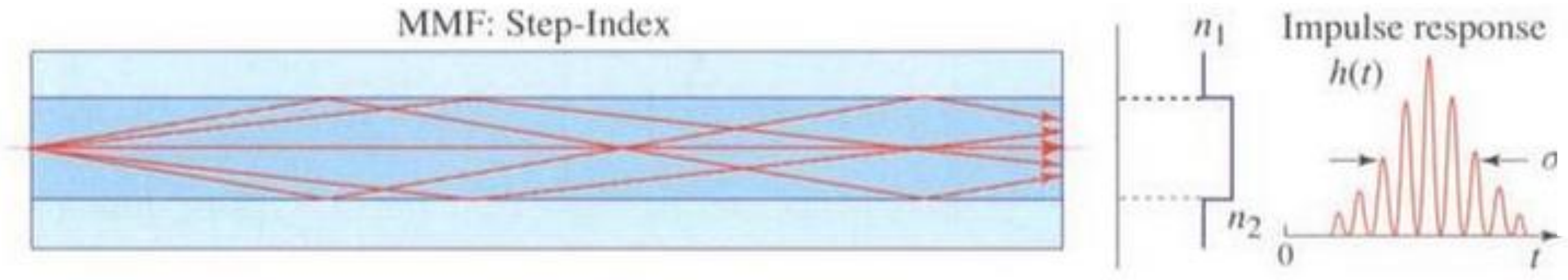
Distance-bit rate limits

For a given receiver and transmitter, the system design is bout determining the maximum fiber length

- Only length contribution comes from the fiber rise time

Multimode fiber (MMF)

- Pulse broadening is dominated by modal dispersion.



$$\Delta T = \frac{L}{c}\frac{n_1^2}{n_2}\Delta$$

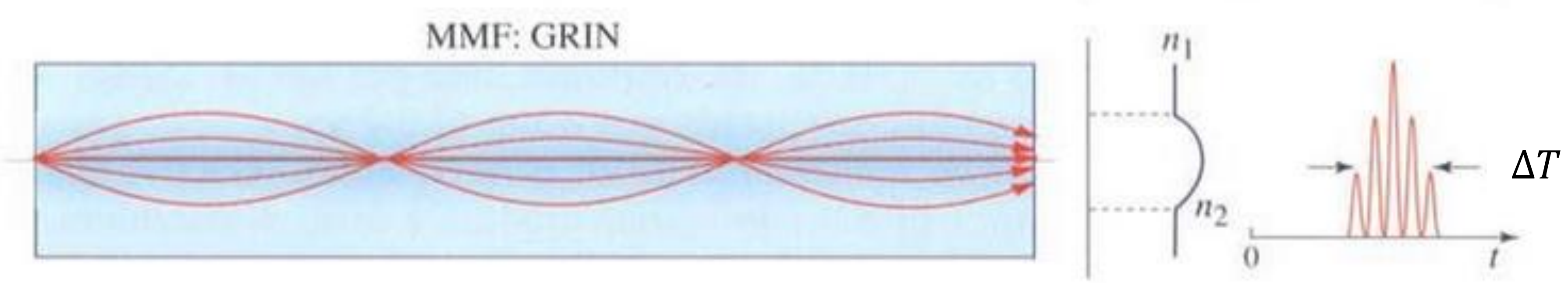
- For a chosen condition $\Delta T B \ < 1$ get:

$$\mathrm{B}L < \frac{n_2 c}{n_1^2 \Delta}$$

Distance-bit rate limits

Graded index multimode fiber (GRIN)

- Near parabolic refractive index profile of the core
- Light paths have sinusoidal trajectories



- Differential delay between axial mode and highest mode is: $\Delta T = \frac{L}{8c} n_1 \Delta^2$
- For a chosen condition $\Delta T B < 1$ get:

$$\mathrm{B}L < \frac{8c}{n_1 \Delta^2}$$

Distance-bit rate limits

Single mode fiber (SMF)

- We have already seen that assuming material dispersion dominates: $\Delta T \approx L|D|\Delta\lambda$

- For a chosen condition $\Delta T B \ < 1$ get : $BL < \frac{1}{|D|\Delta\lambda}$

- For a ‘broad’ spectral width source, we can take $\Delta\lambda = 4\sigma_\lambda$. We therefore get

$$BL < \frac{1}{4|D|\sigma_\lambda}$$

Distance-bit rates limits

When the optical source has a small spectral width, the dispersion induced broadening depends on the initial pulse width σ_0

- In this case, the broadening can be minimized by choosing an optimum value of σ_0

Pulses with smallest product of temporal/spectral widths have a Gaussian profile

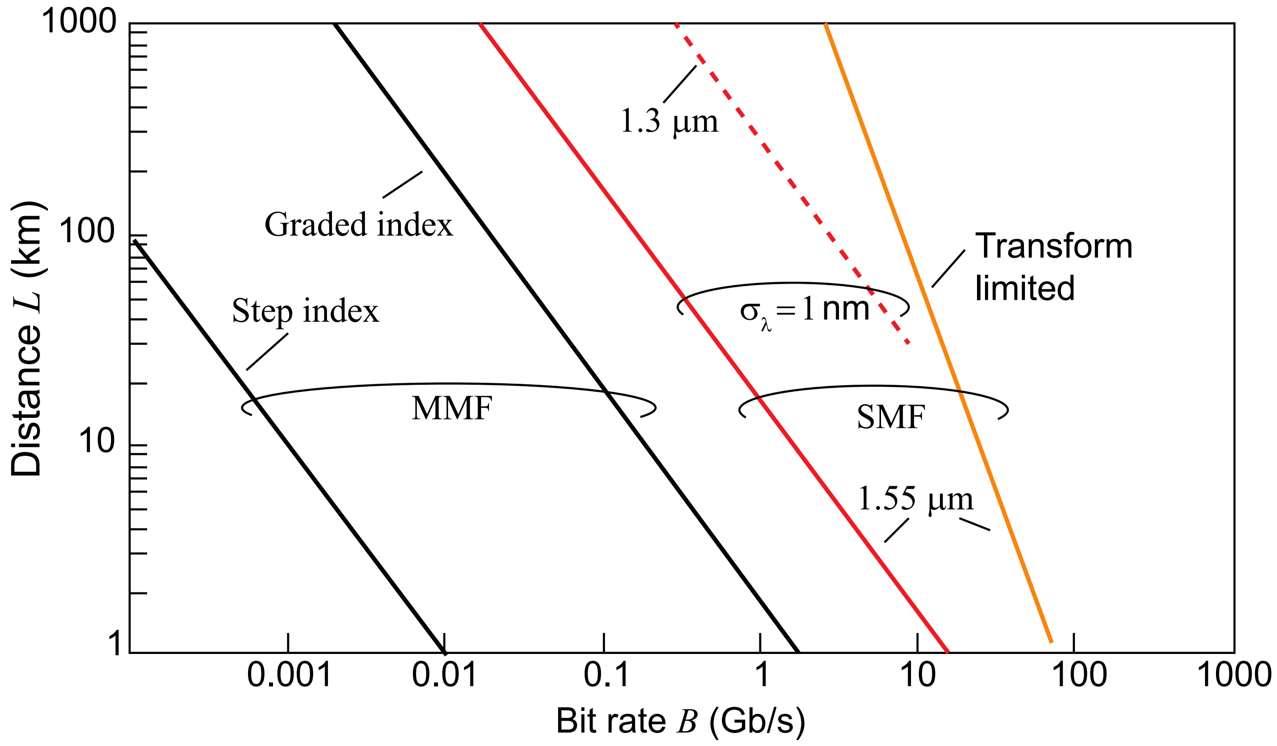
- Transform limited pulses, which suffer the least dispersion
- In this case the minimum value of broadening is found to occur for $\sigma_0 = \left(\frac{|\beta_2|}{2} L\right)^{1/2}$
- The rms broadened pulse is therefore $\sigma = (|\beta_2|L)^{1/2}$
- For a chosen condition $4\sigma B < 1$ get

$$LB^2 < \frac{\pi c}{8|D|\lambda^2}$$

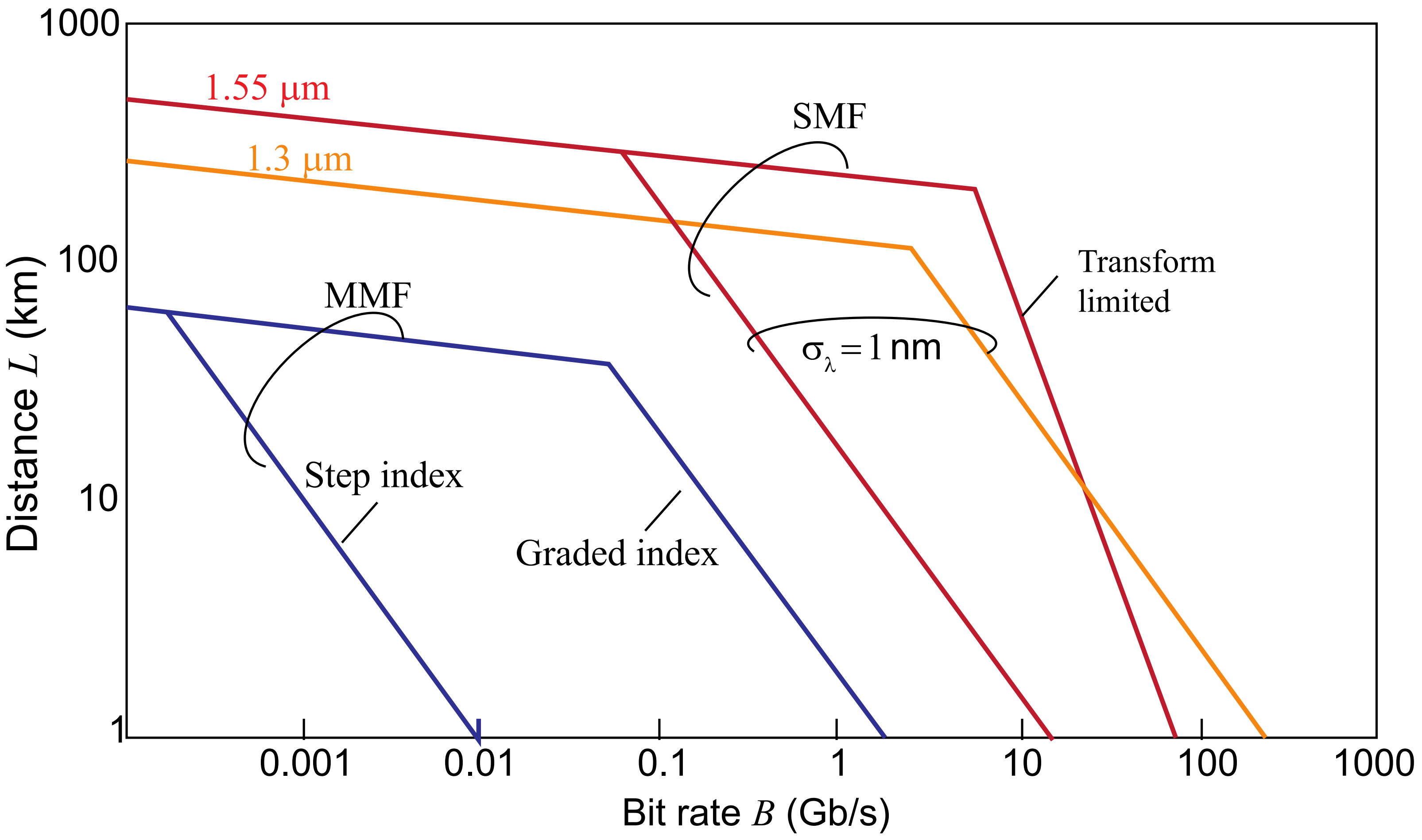
Dispersion limits

Example with:

- MMF with n_1 = 1.46 and Δ = 0.01
- SMF at 1.55 μm with D = 17 ps/km-nm
- SMF at 1.3 μm with D = 1 ps/km-nm



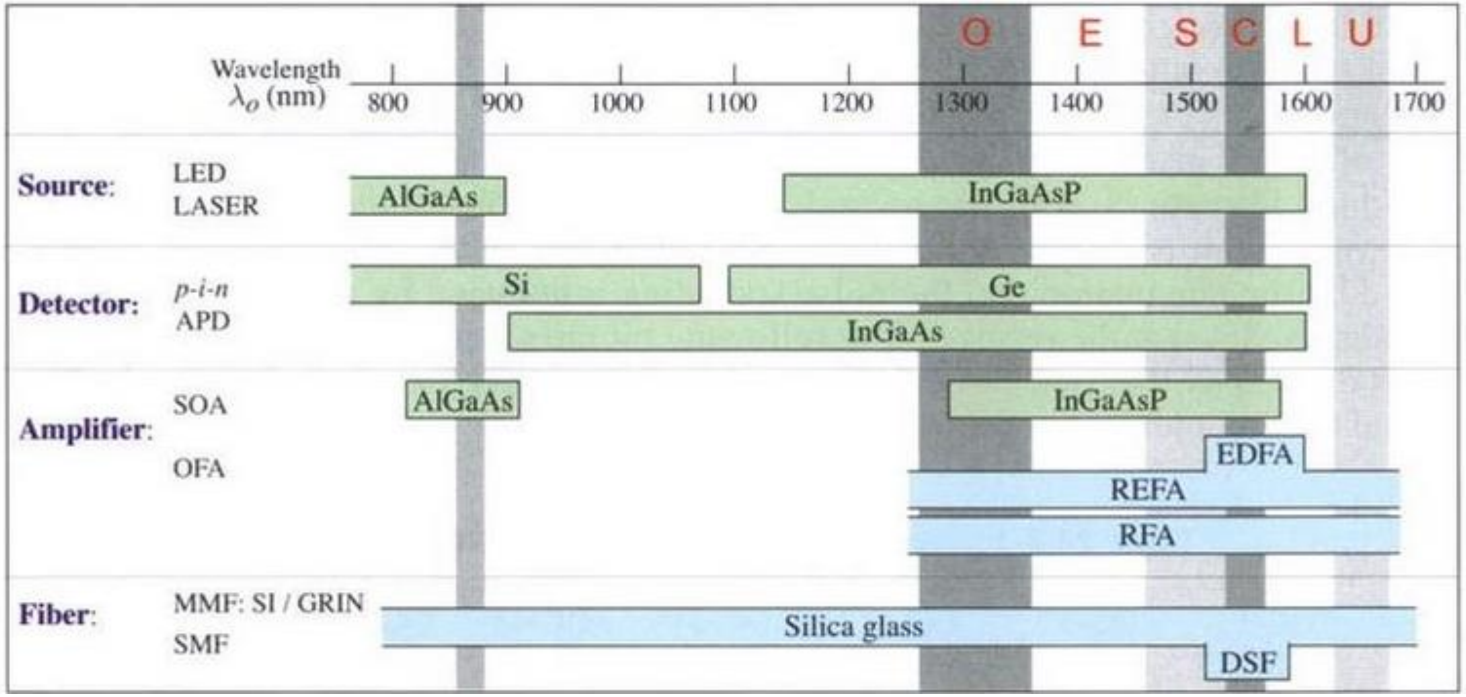
Putting it all together



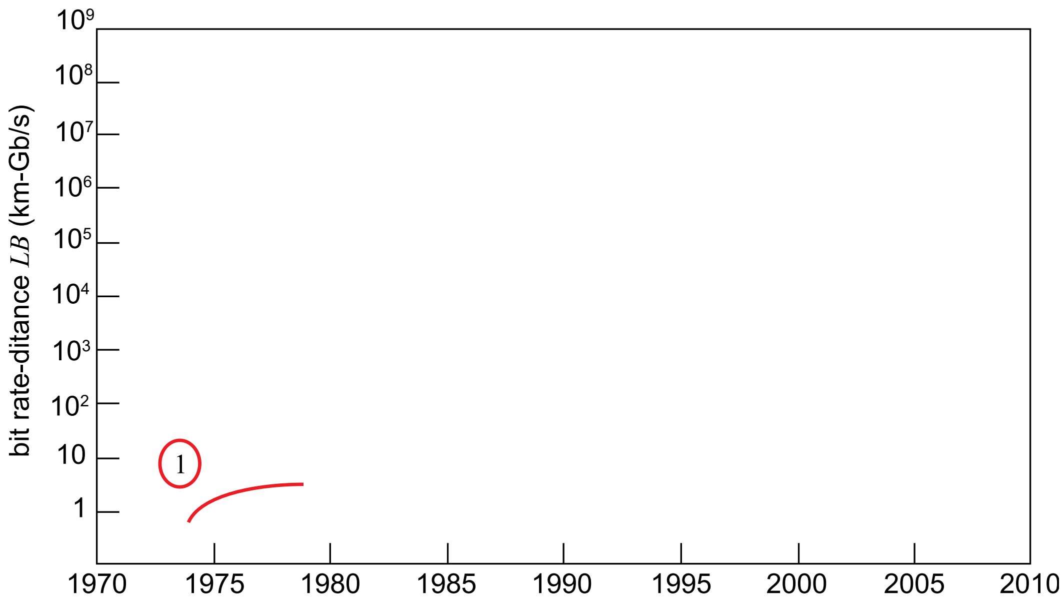
Evolution of systems

The evolution of fiber components and systems has been motivated by the need to increase the transmission bit rate B and the reach L

- Various operating wavelengths, materials, fibers, light sources, detector and amplifiers are used as building blocks



Generation 1

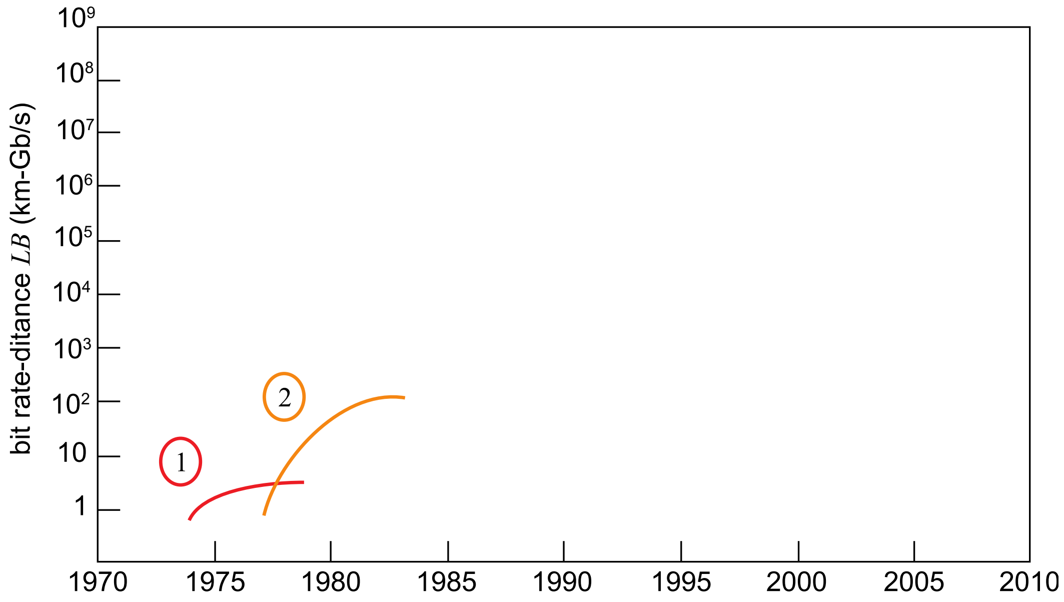


First generation at 870 nm

- Fibers are either step-index or GRIN MMF
- Light source is either LED or laser diode (initially GaAs then AlGaAs)
- Si p-i-n detectors

⇒ Performance limited by high attenuation (1.2 dB/km) and modal dispersion

Generation 2

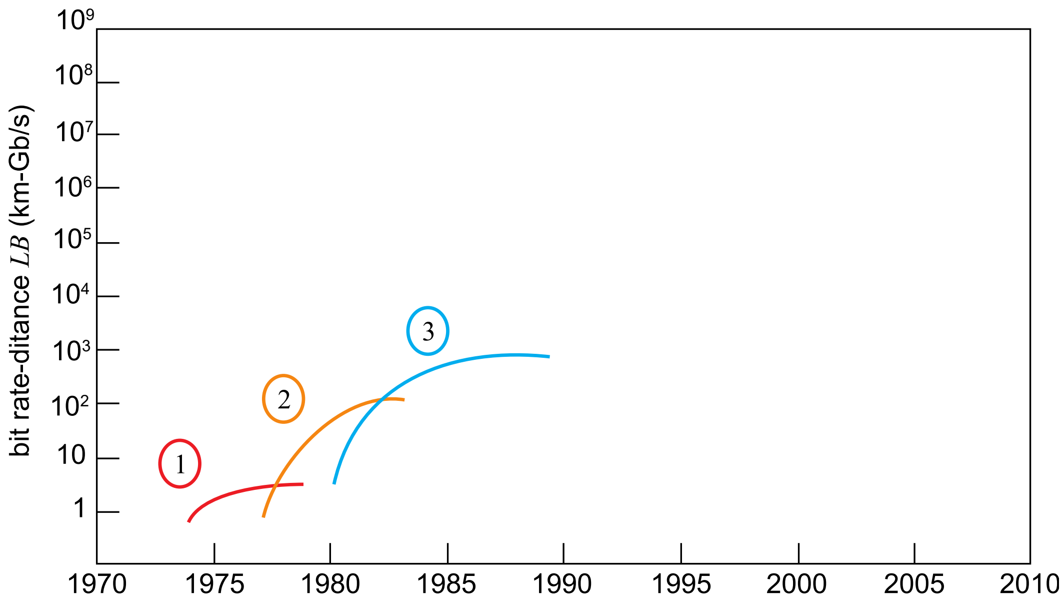


Operation at 1310 nm

- Fibers are now SMF
- Light source is laser diode (initially InGaAsP)
- InGaAs p-i-n detectors

⇒ Operated at lowest dispersion regime. Performance mostly limited by fiber attenuation (1.2 dB/km)

Generation 3

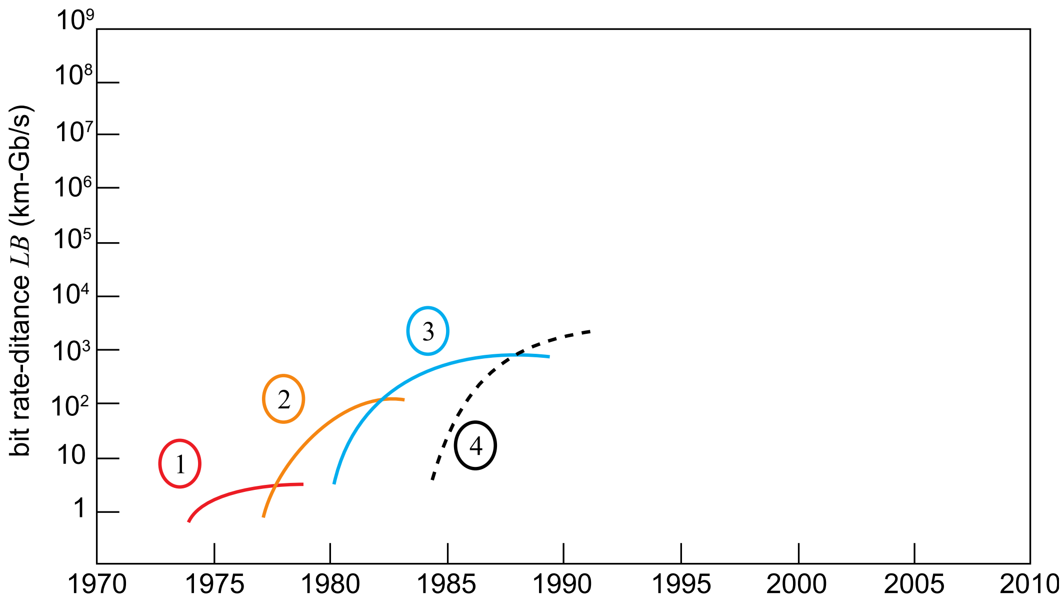


Operation at 1550 nm

- Light source are low-chirp single frequency distributed feedback laser diode (InGaAsP).
- InGaAs p-i-n detectors

⇒ Operated at lowest attenuation. Performance mostly limited by fiber dispersion

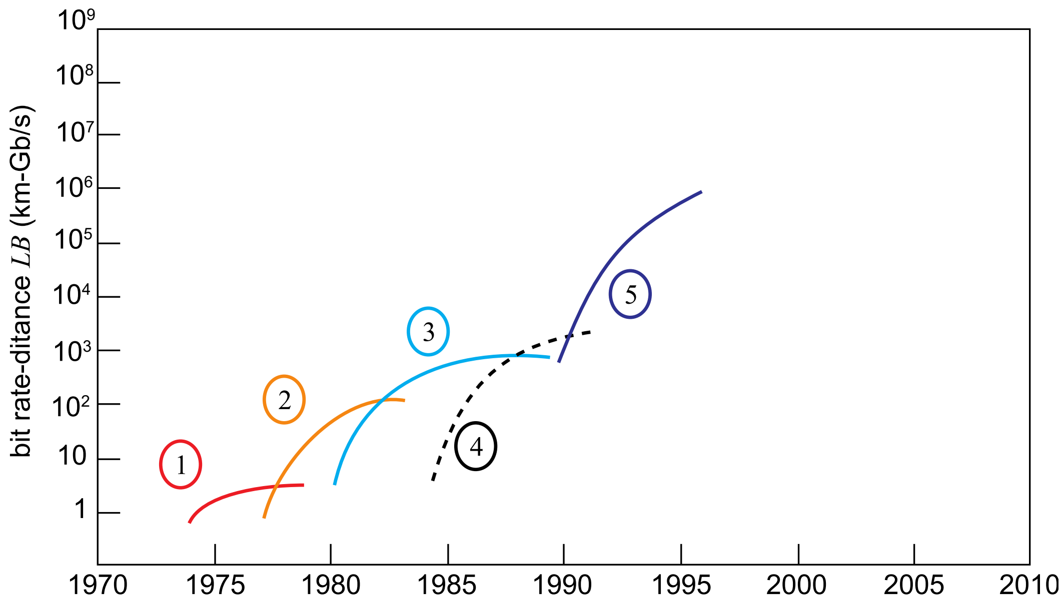
Generation 4



Detection based on phase

- Rather than detecting intensity of the signal light directly with a photodetector, use coherent detection
- Light from a local source (local oscillator) is mixed with the signal at the detector
- It enhances the receiver sensitivity at the expense of increased complexity
- Commercial implementation has lagged behind in particular with the emergence of the 5th generation (but there is now a renewed interest for coherence systems!)

Generation 5

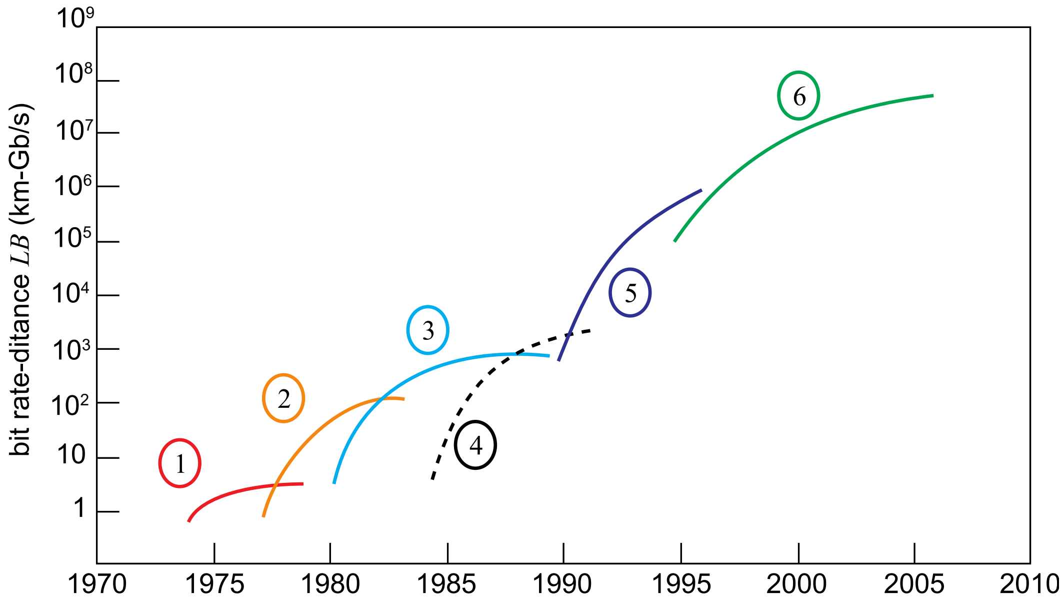


Link with optical fiber amplifiers

- Development of SOA and fiber amplifiers had a huge impact on the performance of optical systems
- Compensate attenuation and dramatically extend the distance

$\Rightarrow$ Performance mostly limited accumulation of noise and dispersion

Generation 6



Wavelength-division multiplexing (WDM)

- Makes use of multiple wavelengths (channels) transmitted through the same fiber to increase the capacity
- Supported thanks to broadband optical amplifiers that can simultaneously amplify all channels

⇒ Performance mostly limited accumulation of noise, dispersion, mixing effects

PRESS RELEASE: 800G+ coherent optical interfaces boost large-scale commercial deployment of 400G/800G OTN networks to deal with rapid traffic growth

In the digital era, with the wide application of cloud computing, big data and AI technologies, data traffic has been increasing exponentially, posing higher requirements for network bandwidth. To cope with the rapid growth of traffic, the port rate of OTN transmission networks has been continuously upgraded: from the commercial use of 100G in 2012 to the large-scale deployment of 200G WDM in 2016, and then to the emergence of 400G WDM in 2020, the surging service traffic drives the update and iteration of the transmission rate. At present, operators gradually begin to have the demands for 800G OTN. 800G and above high-speed OTN networks can provide larger bandwidths to meet the rapid growth of traffic, reduce transmission costs, and improve network operation efficiency. It is estimated that the growth of 800G+ coherent optical lines (which may operate at a lower rate of 400G/800G in commercial deployment) will accelerate after 2025, at a compound annual growth rate of 49.9% in 2022-2028. So far, a certain number of 800G+ ports have been shipped. It is predicted that the shipments of 800G+ ports will exceed that of 200G ports in 2027, and 800G+ will become the mainstream system rate.

Mexico GTAC Works with Huawei to Deploy an 800G Optical Network for Commercial Use, Facilitating City Digital Transformation

Recently, GTAC a leading bandwidth wholesale operator in Mexico, has deployed an 800G commercial network in cooperation with Huawei, helping GTAC stand out on backbone network in Latin America.

February 28, 2024

Recently, GTAC a leading bandwidth wholesale operator in Mexico, has deployed an 800G commercial network in cooperation with Huawei, helping GTAC stand out on backbone network in Latin America. The network uses 800G for core links and Super C6T technology for optical layers, with the maximum single-fiber capacity standing at 48 Tbit/s. In the future, the network will provide high bandwidth assurance for new services such as e-government, smart manufacturing, and FinTech in Mexico, accelerating digital transformation in the country.

NEC reaches 800Gb/s long-distance transmission over optical submarine cable

NEC Corporation has successfully completed a long-distance field trial of an optical submarine cable system using a new transponder that, according to NEC research, could have the world's highest level of transmission performance of 800Gb/s.

This field trial was conducted using the Indonesia Global Gateway (IGG) optical submarine cable, owned by PT Telkom Indonesia (Persero) Tbk (Telkom), Indonesia's largest telecommunications carrier, and using NEC's latest transponder, the XF3200. In the field trial, NEC conducted wavelength division optical transmission of 800Gb/s optical signals over 2,100km.

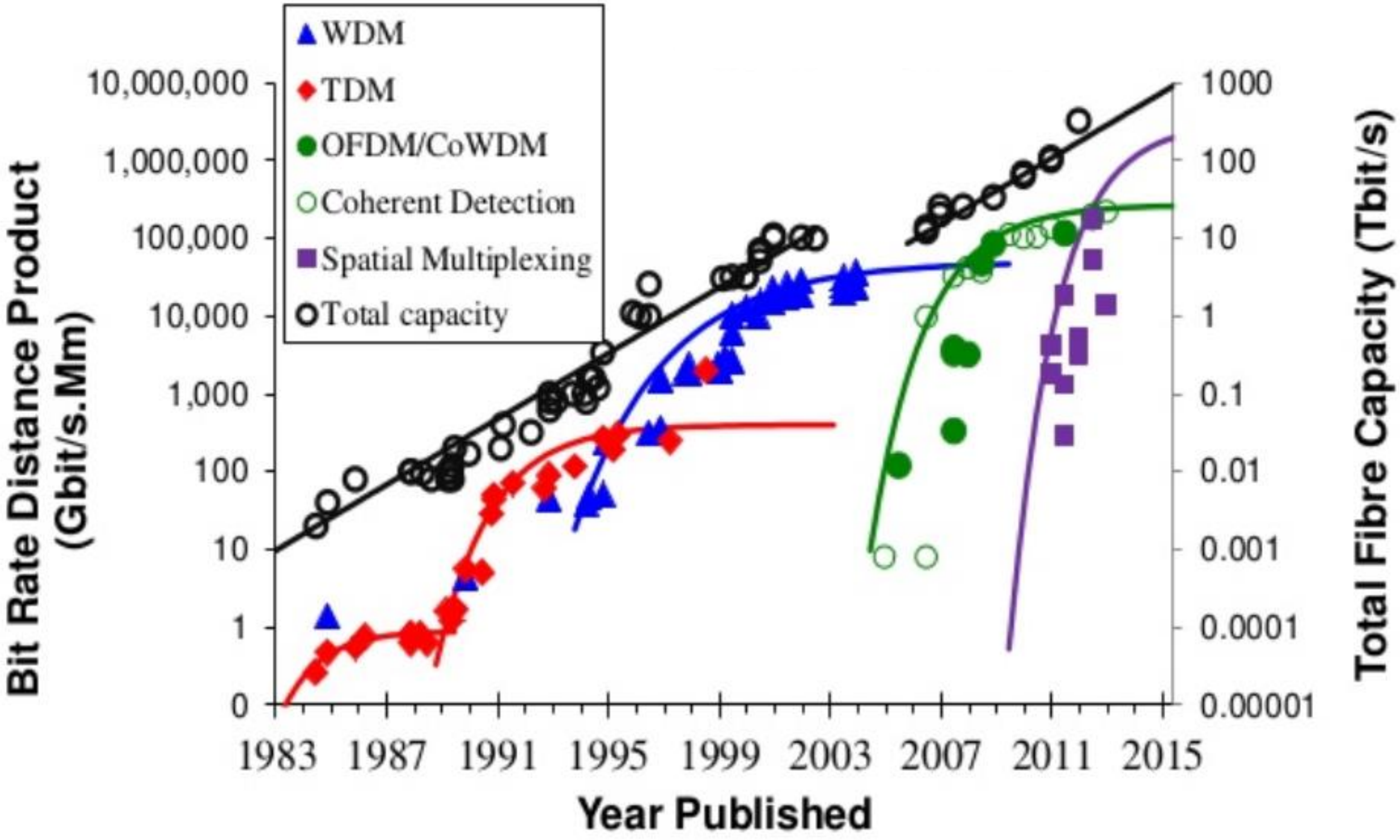
Articles / News

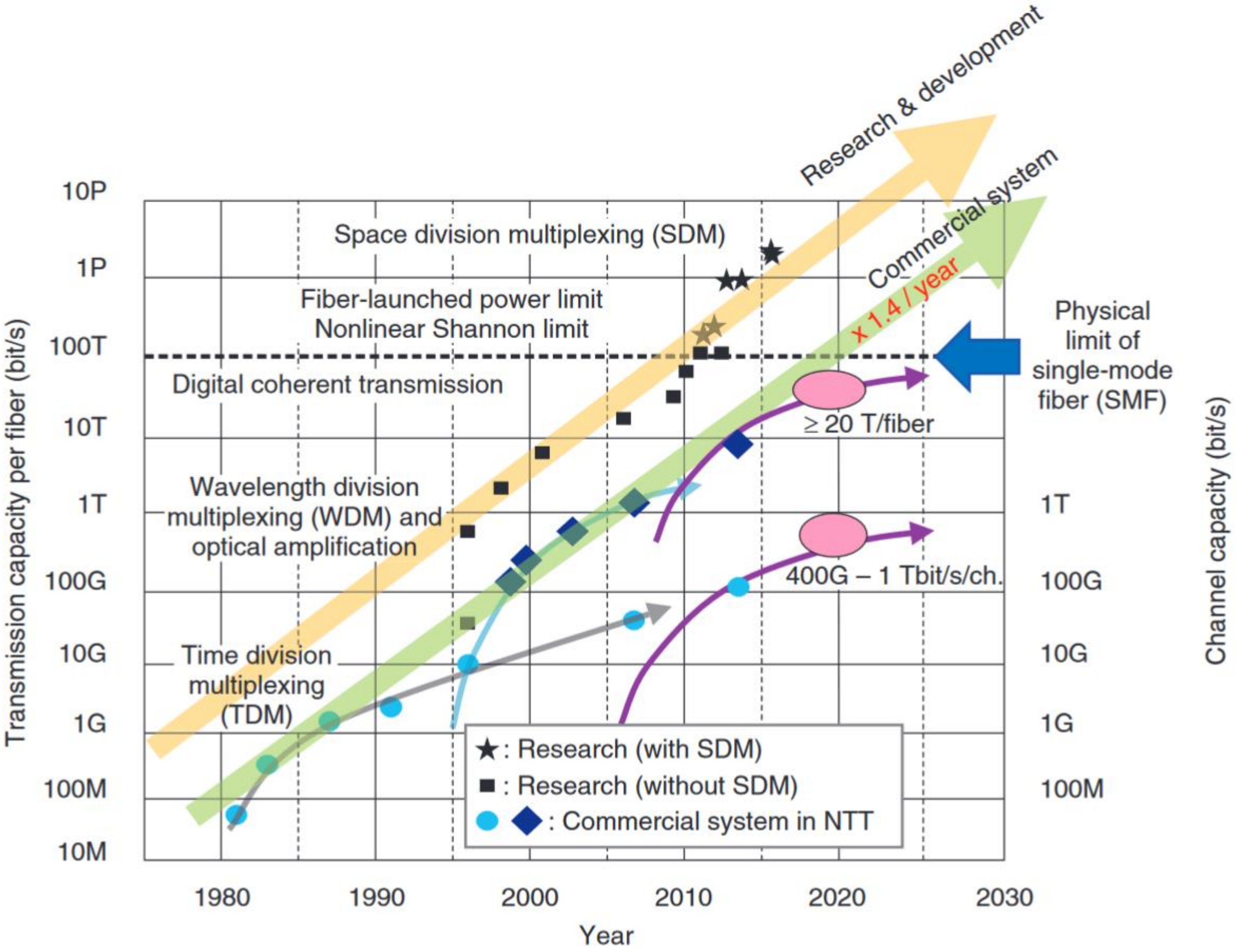
Cisco, Microsoft beam fast optical signal under the Atlantic

Cisco and Microsoft partnered on an optical networking trial that beamed a signal at 800 Gb/s across the recently powered Amitié transatlantic communications cable. The trial was targeted at showing performance support for growing cloud and artificial intelligence (AI) services.

The test was conducted across the 6,234-kilometer long Amitié submarine cable that connects the United States, United Kingdom and France. The cable runs between Boston and Bordeaux, France, and uses space division multiplexing (SDM) technology and 16 fiber pairs, with repeater power shared across the fiber pairs.

Where do we go now ?

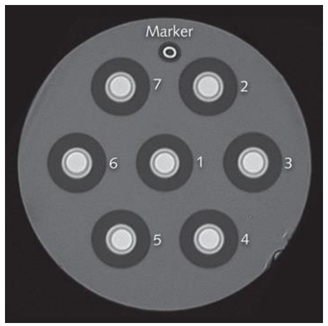


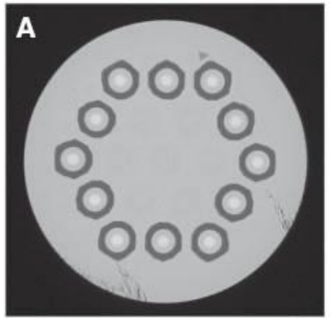


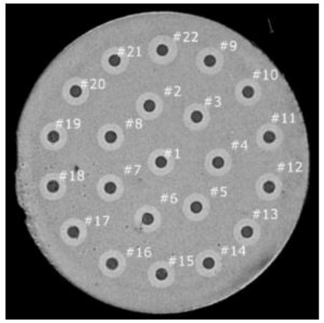
NTT technology

One last dimension … space ?

Multi core fibers

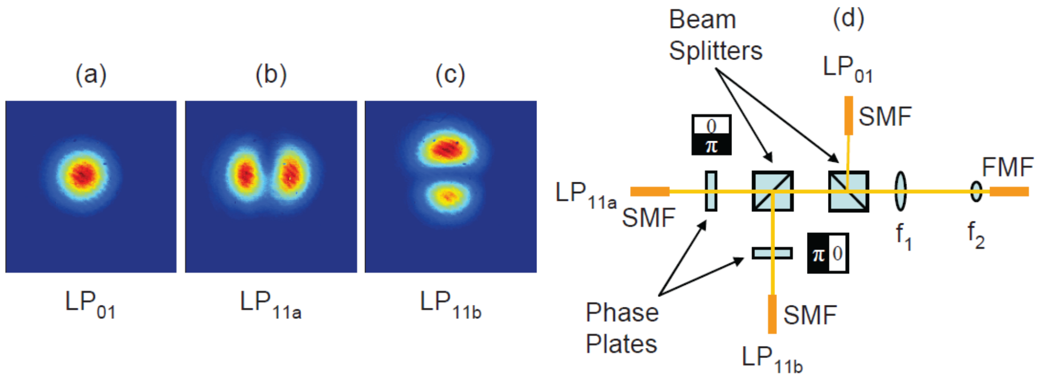


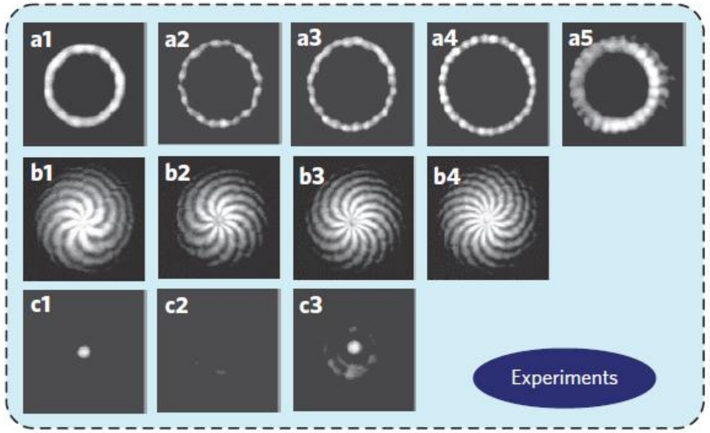




Few modes fibers

- Fabrication to optimize mode coupling, and to reduce differential mode group delay
- Complex signal processing is required to separate coupled modes during propagation





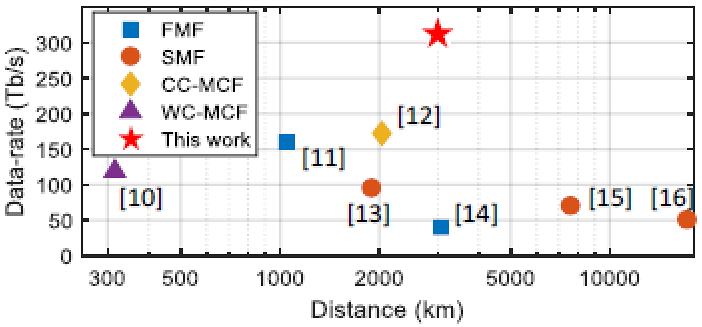
319 Tb/s Transmission over 3001 km with S, C and L band signals over >120nm bandwidth in 125 µm wide 4-core fiber

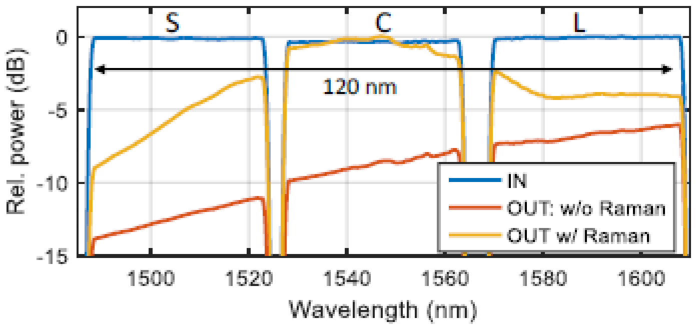
Benjamin J. Puttnam*, Ruben S. Luís, Georg Rademacher, Yoshinari Awaji, and Hideaki Furukawa

1) Photonic Network System Lab, NICT, 4-2-1, Nukui Kitamachi, Koganei, 184-8795 Tokyo, Japan.

**E-mail: ben@nict.go.jp*

Abstract: We demonstrate recirculating transmission of 552 x 25 GHz spaced channels covering >120 nm of S, C and L-bands in a 125µm dimeter, 4-core fiber, measuring a decoded throughput of 319 Tb/s at 3001 km.





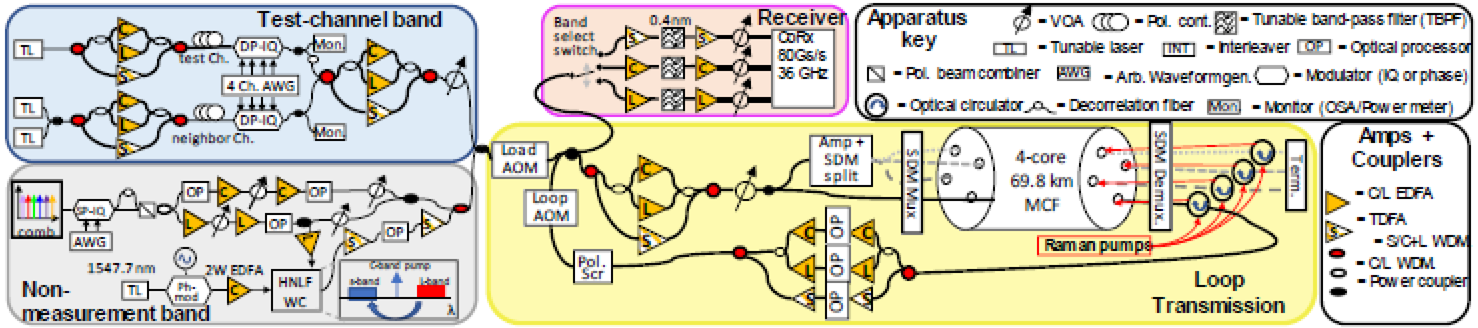


Fig. 2 Experimental set-up used recirculating transmission of >120nm bandwidth(1487.8 nm to 1608.33 nm) signal

22.9 Pb/s Data-Rate by Extreme Space-Wavelength Multiplexing

B. J. Puttnam[(1)], M. van den Hout[(1,2)], G. Di Sciullo[(1,3)], R. S. Luis[(1)], G. Rademacher[(1)*], J. Sakaguchi[(1)], C. Antonelli[(3)], C. Okonkwo[(2)], and H. Furukawa[(1)]

[(1)] NICT, 4-2-1, Nukui Kitamachi, Koganei, 184-8795 Tokyo, Japan, E-mail:ben@nict.go.jp
[(2)] Eindhoven University of Technology, The Netherlands [(3)] University of L'Aquila and CNIT, 67100, L'Aquila, Italy. * now with INT, University of Stuttgart, Pfaffenwaldring 47, 70569 Stuttgart, Germany.

Abstract *We transmit 750 wavelength channels covering 19 THz bandwidth over a few-mode multi-core fiber with 114 spatial channels, recording a total GMI-estimated data-rate of 24.7 petabit/second and 22.9 Pb/s after LDPC decoding, both exceeding 200 Tb/s per spatial channel.*

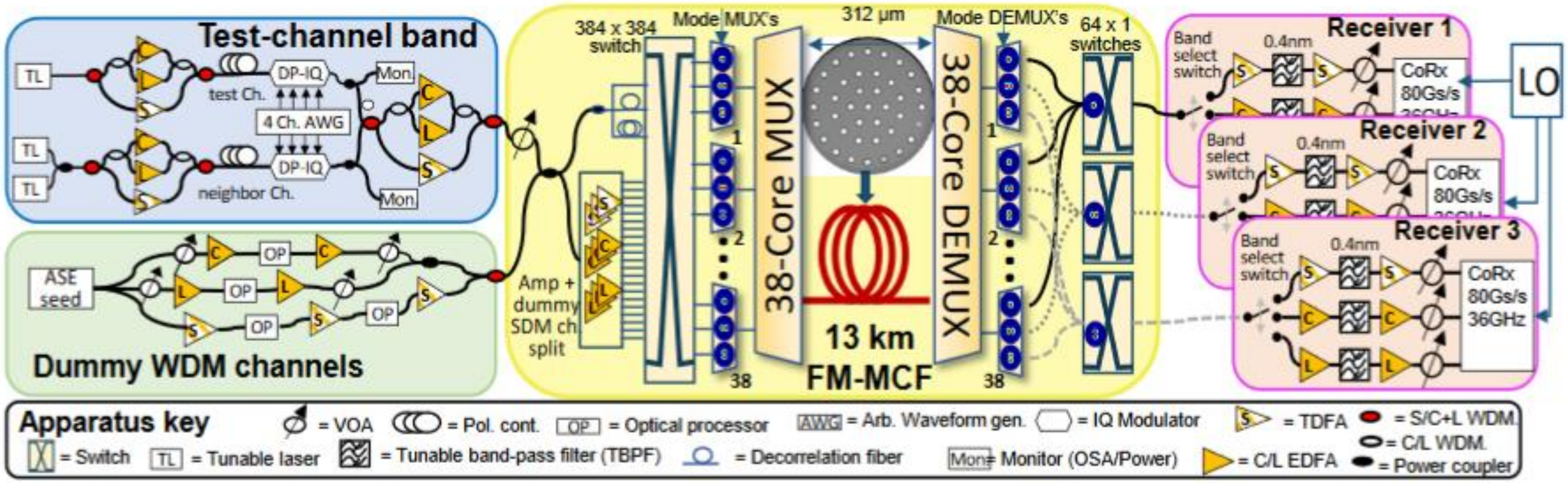


Fig. 2: Experimental set-up for extreme WDM-SDM transmission

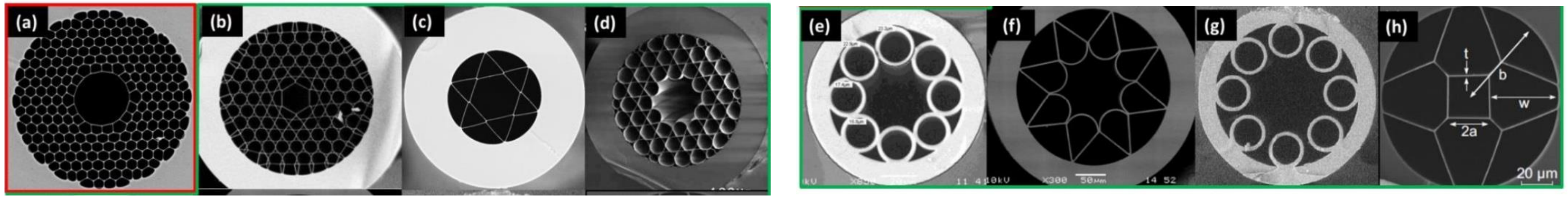
Hollow core fibers

A hollow core fiber is an optical fiber which guides light essentially within a hollow region.

- Only a minor portion of the optical power propagates in the solid fiber material.
- Refractive index of core is lower than that of the surrounding cladding material ?

The guiding mechanisms are different from TIR !

- Can rely on photonic bandgap - Essentially, a kind of two-dimensional Bragg mirror. Therefore the guidance only works over a limited wavelength range. (FBGF)
- Can rely on inhibited coupling - structure and dimensions are engineered such that the cladding supports a continuum of modes strongly phase-mismatched with core modes, thus inhibiting the latter from escaping the core. (ARF)
- Tutorial: Vol. 15, No. 1 / March 2023 / Advances in Optics and Photonics



F. Poletti, Optics express 22(20), pp. 23807 (2014)

Hollow core fibers applications ?

High capacity, low latency data transmission

- Combined very low nonlinearity and potential very low transmission loss
- Potential, in theory, to increase transmission capacity at transmission speeds that are 30% higher

Power delivery

- Very small fraction of light is guided in glass
- Important for pulsed operation where peak powers could induce detrimental nonlinear effects or even exceed damage threshold of material.

Guidance of UV light

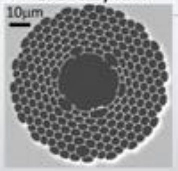
- UV guiding fibers are highly sought after in laser and spectroscopy application
- Hollow core provide practical solutions for delivery of UV sustainable to high power and long term irradiation

Nonlinear optics

- The hollow core can be filled with gas (or liquid) that can tune the dispersion and nonlinear properties of the fiber

Postdeadline papers on data-transmitting HCFs from Southampton:

3.5 dB/km



<0.11 dB/km

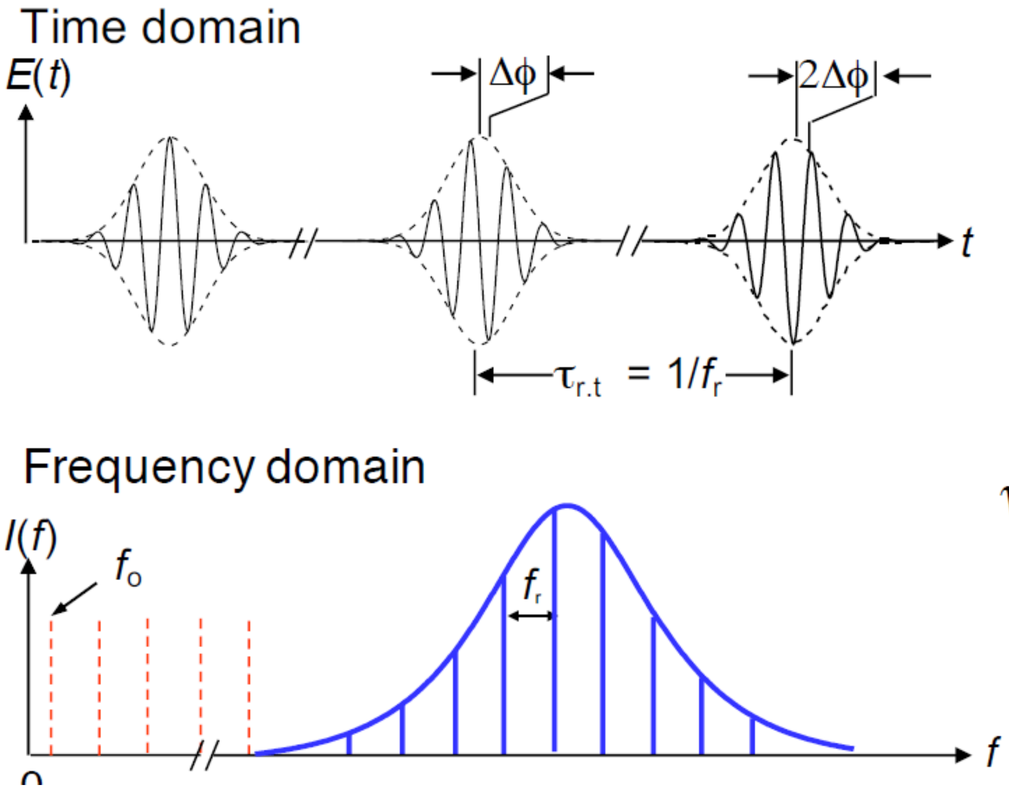
2012: OFC (PDP5A.2), ECOC (Th3A.3, Th3A.5)
2013: OFC (Th5A.3)
2015: OFC (Th5A.1)
2016: OFC (Th5A.3)
2017: OFC (Th5B.8)
2018: ECOC (Th3F2)
2019: OFC (Th4A.1), ECOC (PD3.1, PD5.1)
2020: OFC (Th4B.4, Th4B.5)
2021: OFC (F3A.4, F3B.5)
2022: OFC (Th4C.7)
2024: OFC (Th4A.8)

Frequency combs

2005

An optical frequency comb is an optical spectrum which consists of equidistant lines

- It is an optical ruler
- Offer a direct link between the optical and the microwave frequencies

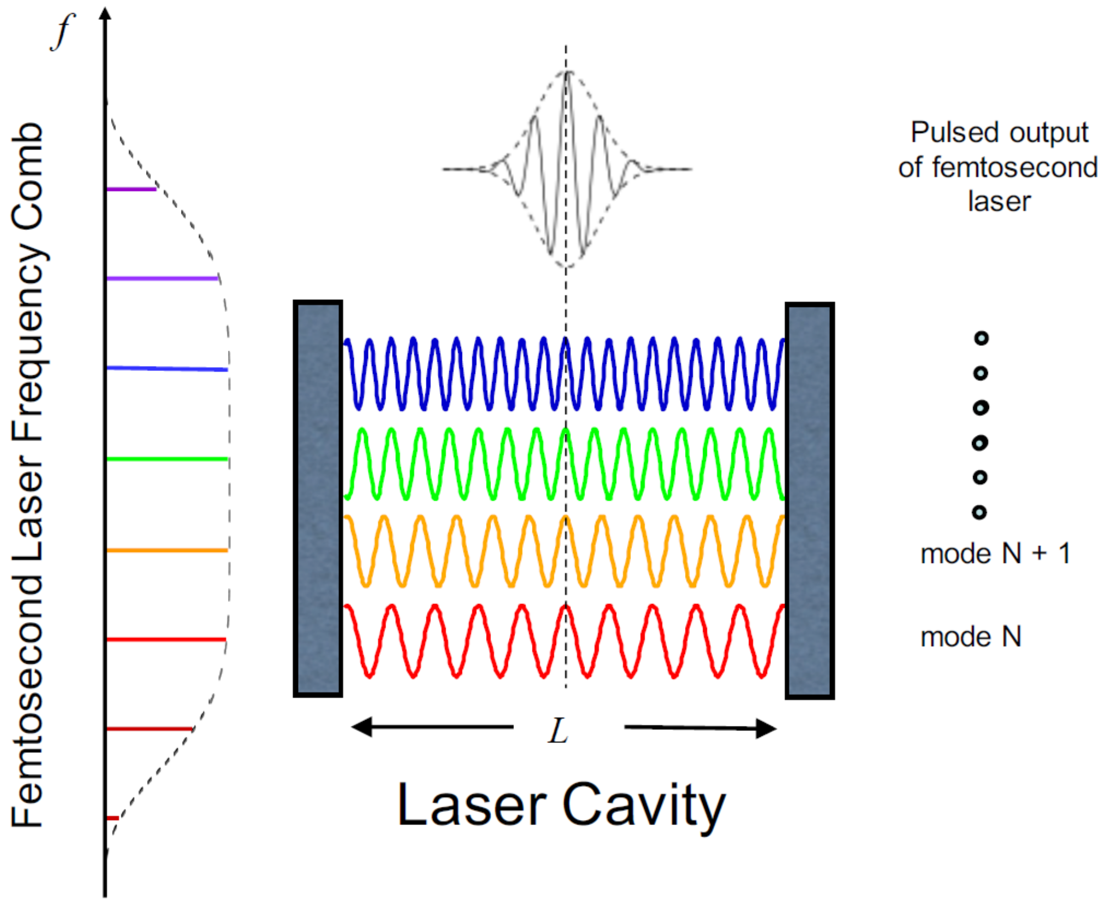


$$\nu_n = nf_r + f_o$$

$$n \sim 10^5$$

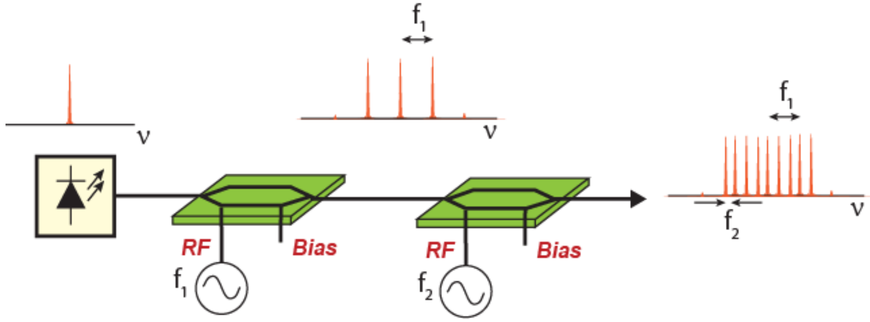
Frequency combs

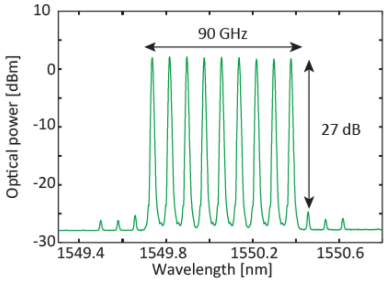
Mode-locked lasers are frequency combs

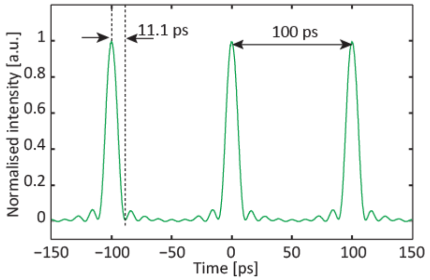


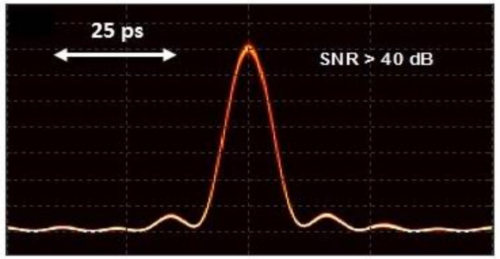
→ Cavity modes are locked in phase to generate a short pulse once every roundtrip time $2L/v_g$

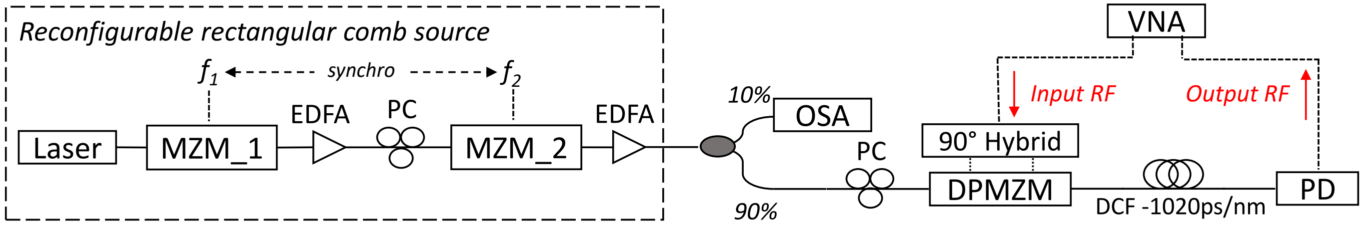
Optical frequency combs

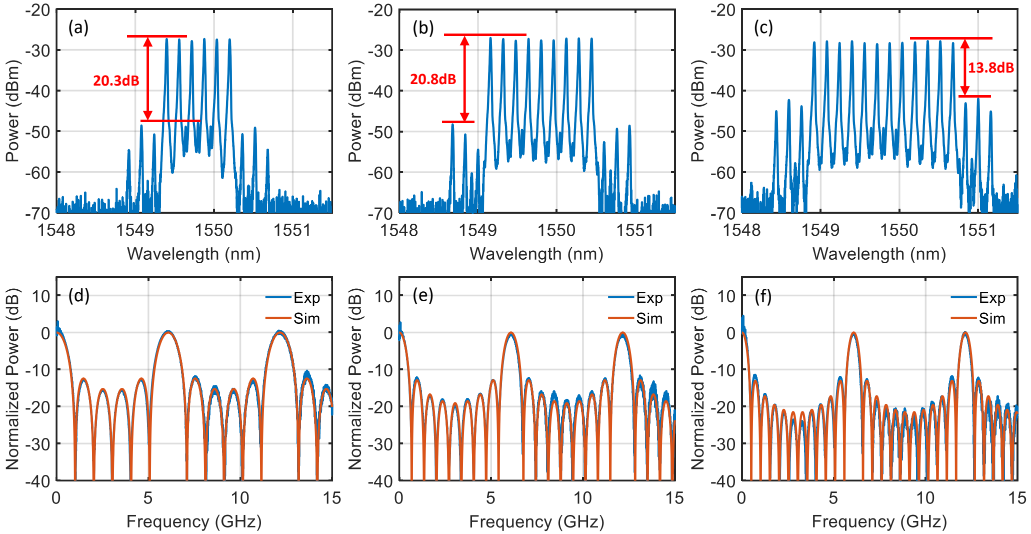








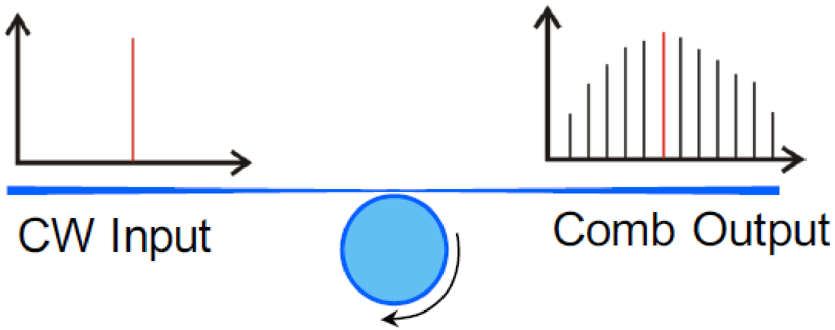


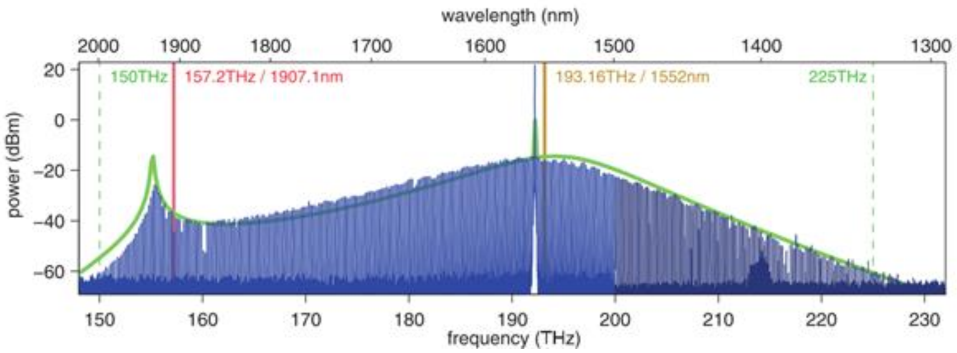


Frequency combs

Frequency combs can be generated in micro-rings

- Kerr frequency combs



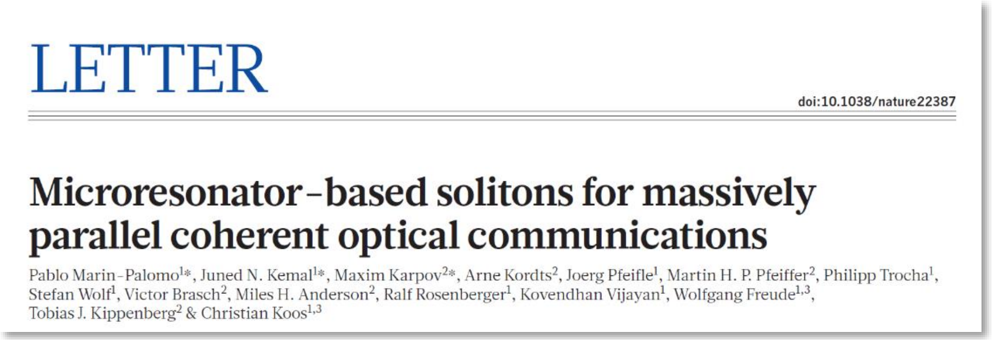


Brasch, V. et al. 2016. Science, 351(6271), pp.357-360

Hydex	Si:Nitride	Silica toroid	Crystals	Silica wedge	Quartz	Diamond	Al:Nitride
RMIT	Cornell, Purdue, NIST G-burg, EPFL, UCLA	MPQ, EPFL, Caltech	OEWaves JPL EPFL	Caltech	NIST	Harvard	Yale

(Some) Applications

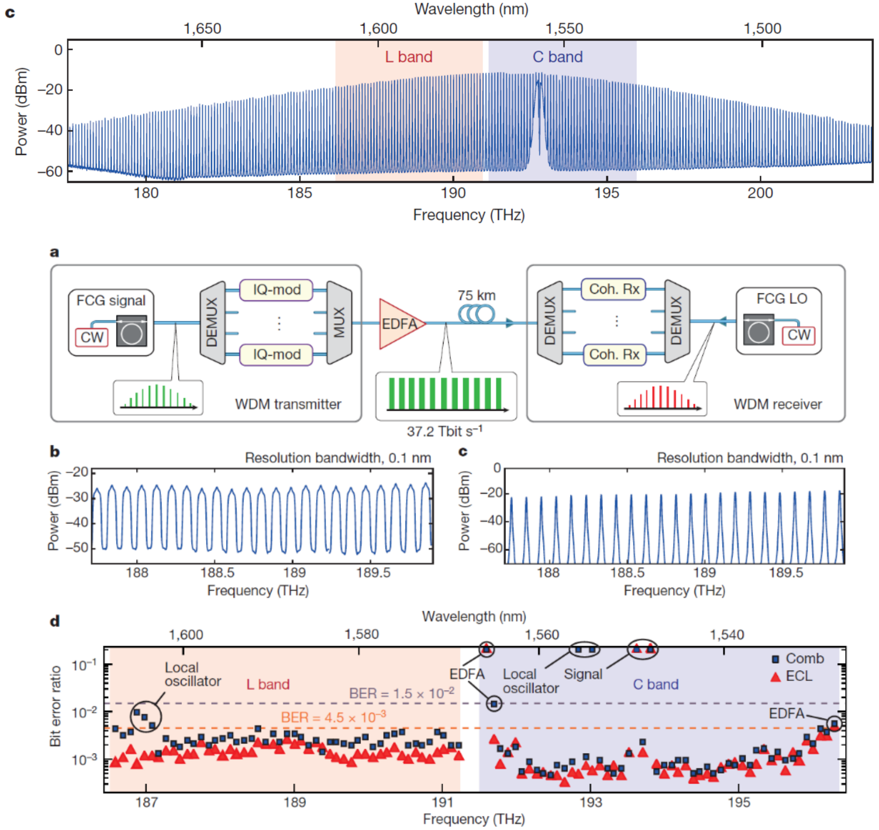
EPFL


LETTER

doi:10.1038/nature22387

Microresonator-based solitons for massively parallel coherent optical communications

Pablo Marin-Palomo[1*], Juned N. Kemal[1*], Maxim Karpov[2*], Arne Kordts[2], Joerg Pfeifle[1], Martin H. P. Pfeiffer[2], Philipp Trocha[1], Stefan Wolf[1], Victor Brasch[2], Miles H. Anderson[2], Ralf Rosenberger[1], Kovendhan Vijayan[1], Wolfgang Freude[1,3], Tobias J. Kippenberg[2] & Christian Koos[1,3]

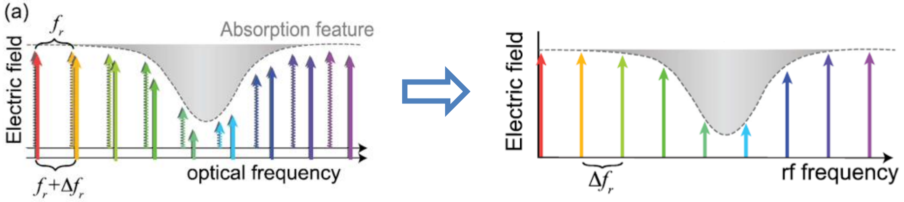



REPORTS

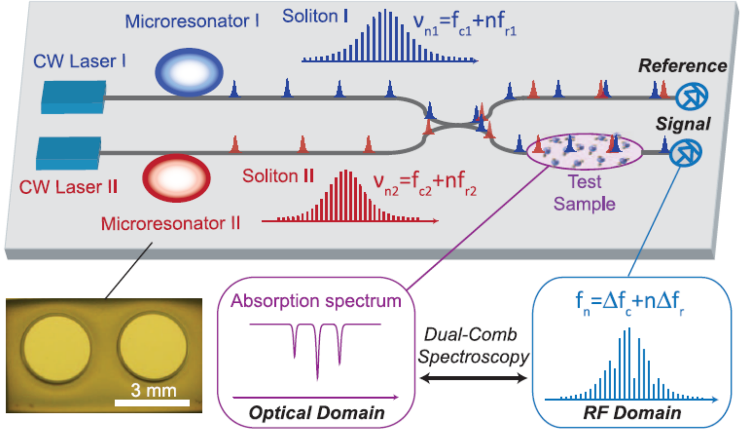
OPTICS

Microresonator soliton dual-comb spectroscopy

Myoung-Gyun Suh,* Qi-Fan Yang,* Ki Youl Yang, Xu Yi, Kerry J. Vahala†



I. Coddington et al, Optica 3(4), pp 424 (2016)



More frequency combs applications

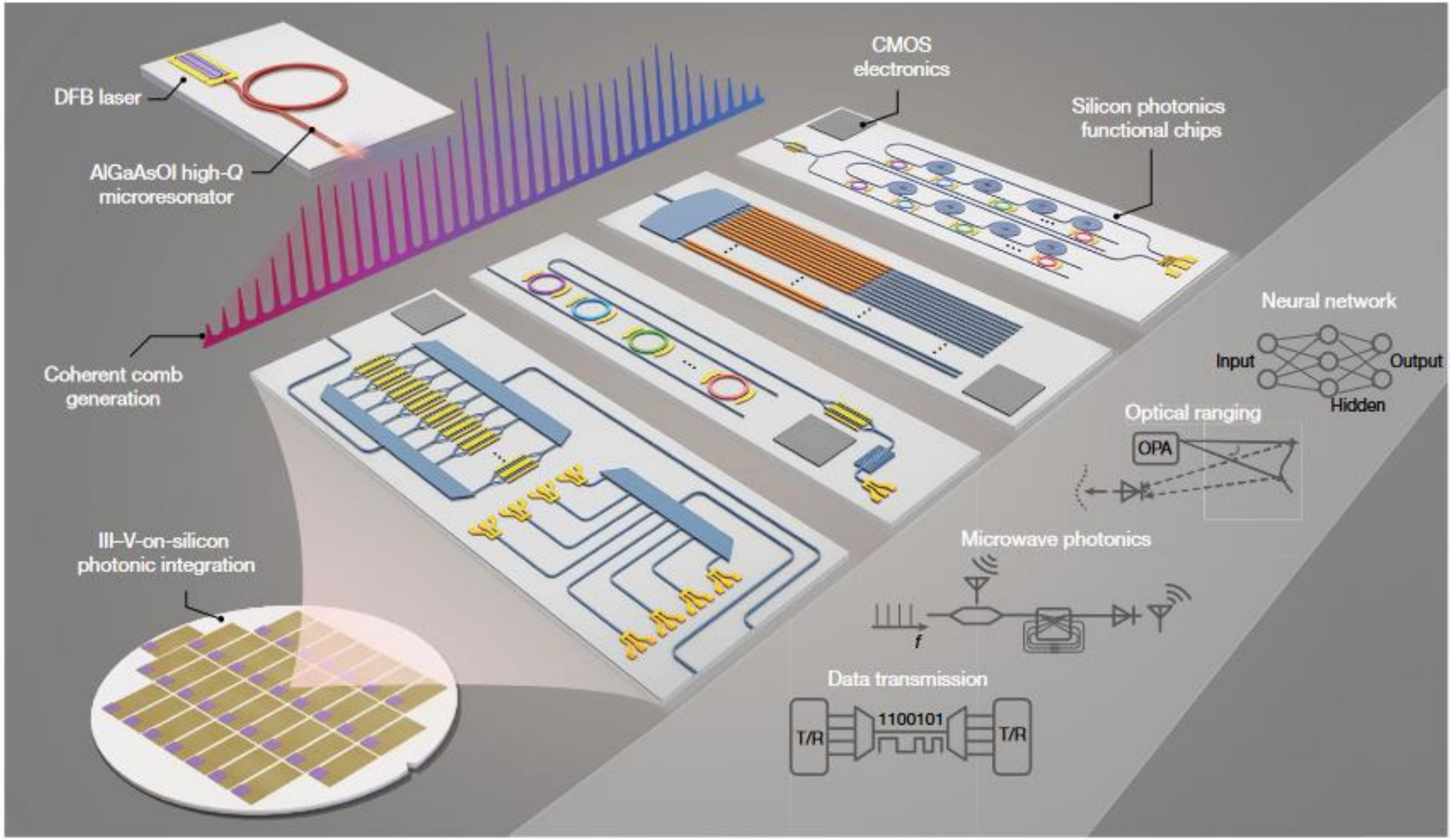


Fig. 1 | Microcomb-based SiPh optoelectronic systems. Conceptual drawings for several integrated optoelectronic systems (data transmission, microwave photonic signal processing, optical beam steering and photonic computing) realized by combining a microcomb source with silicon photonic chips. With III–V-on-silicon photonic integration, the chips are expected to contain all the essential functions (for example, laser-microcomb generation, passive and active optical components, and the electronics for supporting signal processing and system control).

Haowen Shu et al., Microcomb-driven silicon photonic systems
Nature February 2022

Ref: S. Diddams

That’s all !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