Development of Optical Fiber Communication

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First and early lasers, silica optical fibers (...1980)

- Laser = Light Amplification by Stimulated Emission of Radation
- 1960 Rubin-Laser
- Semiconductor laser diode with double heterostructure: Miniature, low-cost optical source
- Distributed Feedback (DFB) laser: Has wavelength-selective Bragg grating. Only one longitudinal mode, reduced fiber dispersion effects, reduced optical bandwidth requirement.
- Silica (SiO_2, quartz glass) optical fibers
- Step index multimode fibers: Many transversal modes, extremely large dispersion between different modes. Today: Plastic optical fiber (POF) for short reach data communication and use in vehicles.
- Graded index fibers: Parabolical shape of refractive index profile, substantially reduced intermodal dispersion. Core diameters 50 or 62.5μm.
- Single-mode fibers (SMF). Core and mode field diameter is ~9μm, cladding diameter 125μm, coating (acrylate) diameter 250μm. Needed alignment accuracy is on the order of <1μm! Attenuation:
  - a few dB/km @ 850nm (1st window)
  - 0.35 dB/km @ 1310nm (2nd window)
  - 0.2 dB/km @ 1550nm (3rd window)

Erbium-doped fiber amplifiers, chromatic dispersion (...1990)

- Large problem: Fiber attenuation!
- Solution: Optical amplifier = laser without feedback.
- Semiconductor optical amplifiers (SOAs): Relaxation oscillations with ~100ps ... 1ns period distort signals when SOA is driven into saturation. Multiwavelength operation used to be almost impossible due to crosstalk.
- Method of choice: Erbium doped fiber amplifier (EDFA). A semiconductor laser with 980nm or 1480nm wavelength pumps an erbium doped glass fiber, which amplifies incoming light around 1550nm with more 4.8 THz (40 nm) bandwidth.
- Next problem: Chromatic dispersion. Scales proportional to length, but with the square of the bit rate! Standard singlemode fiber (SSMF) has ~0ps/nm/km @ 1310nm, ~17ps/nm/km @ 1550nm. Reach is only ~60km @10Gbit/s, 1550nm, with ideal optical modulation!
- A not very successful solution attempt: Dispersion-shifted fiber (DSF). Largely deployed in Japan, whereas in Europe and North America SSMF is all over the place.
- Problem: Four-wave-mixing (FWM), a 3rd order intermodulation process caused by fiber nonlinearity, is very strong if there is no dispersion.
- Solution: Dispersion compensating fiber (DCF) with very large negative dispersion is placed before or behind SSMF => Large local dispersion, zero overall dispersion (suppresses FWM).
- Dispersion slope (variation of dispersion vs. wavelength) can not be neglected in ultra long haul and in 40Gbit/s applications. Solution: Non-zero dispersion shifted fiber (NZDSF) with ~5ps/nm/km and similar lengths with ~ -5ps/nm/km of dispersion are alternated.

C, L (and S) bands, Raman amplifiers, FEC (...2000)

- Standard amplifer spacing is 80...100km (~20...25dB of attenuation including a few splices)
- C band ~1530 ... 1568 nm (amplification with standard EDFAs)
- L band ~1570 ... 1625 nm (amplification with newest fiber amplifiers)
- S band ~1490 ... 1530 nm (amplification with newest fiber amplifiers)
- Total power (for all WDM channels) of up to 2W (33dBm) commercially available today!
- Problem: Gain uniformity of EDFAs. Many cascaded EDFAs severely distort the optical spectrum. Solutions:
    - Co-doping of EDF with Al
    - Gain flattening filters
    - Raman amplification: Energy transfer to wavelengths ~50 ... 100 nm longer. Spectral gain profile can be flattened very efficiently by using several Raman pump lasers (1400 ... 1500 nm, many 100 mW each). Another important advantage: Backward pumping amplifies signal before it is fully attenuated. Very good to achieve low noise.
- General problem: Too strong interchannel interactions (mainly cross phase modulation)
- Solutions: Reduced transmitter power in conjunction with forward error correction (FEC) at the receiver. FEC is good against many other ailments, too!

Wavelength multiplexing, polarization mode dispersion (...2000)

- Wavelength division multiplex (WDM) allows fully utilizing fiber capacity. >10Tbit/s demonstrated.
- Problem: Channel selection at receiver
- Solutions:
  - Multilayer interference filters. Not very well integratable, though, and not good for large channel numbers.
  - Method of choice: Phased-array DEMUX, realized with SiO_2 waveguides on Si substrate.
- Drive towards higher data rates (0.15, 0.62, 2.5, 10, 40 Gbit/s): Reduced channel number reduces overall system cost. Optical frequency drift of sources and DEMUX become negligible, which allows for closer channel packing. A possile spacing is 100GHz for 40Gbit/s. However, chromatic dispersion scales with the square of the bit rate, and PMD scales linearly with the bitrate!
- Problem: Polarization mode dispersion (PMD). Especially the old, widely deployed SSMF, but also DCF with its small core diameter has noncircular core. This means signals polarized along the two orthogonal ellipse axes travel with slightly different speeds. PMD is a statistical effect, ranging between 2ps/sqrt(km) for very bad and 0.05ps/sqrt(km) for newest state-of-the-art fibers.
- Return-to-zero (RZ) signaling widenes optical bandwidth but increases receiver sensitivity. Soliton impulses can in principle travel undistorted in the nonlinear and dispersive fiber. Neighbor pulses which have opposite electric field polarity reject each other when subject to fiber nonlinearities. This is better than equal neighbor pulse polarity, which causes pulses to attract each other and merge.

Crisis (2001...2004)

- 2001...2004: Internet bubble, telecom bubble and telecom supplier bubble collapsed.
- Telecom crisis has been surmounted, demand is now healthy (as of 2007).
- Internet traffic keeps rising dramatically. (It used to double every 100 days.)
- Bottleneck: Local Area Networks (LAN), Metropolitan Area Networks (MAN). Low cost solutions must widen the bottleneck!
- 1x40Gbit/s is not cheaper yet than 4x10Gbit/s.
- Telecom crisis has changed targets: Even higher performance is requested, at lower cost. Investment in existing fiber plant must be protected.

Reorientation (...2007)

- Future metropolitan area and long haul modulation systems should have the following properties:
  - Usable for links that were designed for 80 x 10 Gb/s transmission with 50 GHz channel spacing.
  - Large chromatic dispersion and PMD tolerance.
  - Total transmission capacity is much higher than 800 Gb/s in the C band.
- Possible solutions (as of 2007):
  - Phase shift keying reduces required signal-to-noise ratio.
  - Quadrature phase shift keying doubles spectral efficiency and transmission capacity.
  - Polarization division multiplex doubles spectral efficiency and transmission capacity once more.
  - Coherent optical communication yields interference signals in the electrical domain which are proportional to optical field quantities. All linear fiber distortions (chromatic dispersion, PMD) can therefore be equalized electronically!
  - FEC increases reduces required signal-to-noise ratio further.
  - The large emphasis on electronic signal processing reduces system cost compared to optical signal processing.
  - 100 Gigabit Ethernet (100GbE, 112 Gb/s) transmission with 50 GHz channel spacing becomes conceivable, would transmit 9.6 Tb/s in the optical C band alone.

Coherent optical transmission, photonic integration (2007...)

- Optical fiber communication (as of 2019)
  - 100 Gigabit Ethernet (100GbE, 112 Gb/s) transmission with 50 GHz channel spacing has become standard for new long-haul transmission links.
  - PDM 16QAM is equally established for links with reduced signal-to-noise ratio.
  - PDM 32QAM, PDM 64QAM …
  - ~20 Tb/s transoceanic links with amplifer spacing ~75 km
  - Coherent optical transmission is a megatrend since 2007. All linear distortions can be equalized electronically. Not even dispersion-compensating fiber is needed.
- Photonic integration is a superb solution for cost-effective miniaturization and maximized performance.
  - InP allows integration of all photonic and of high-speed electronic components. Disadvantages: expensive technology, electronic integration lacks powerful support from mainstream electronics.
  - Si allows integration of all photonic components except lasers and all electronic components including CMOS.
  - Co-integration also of different technologies. Examples: InP lasers mounted into Si circuits, butt coupling of Si/SiO_2 and $LiNbO_3$ chips for PDM-QAM modulators

Nonlinearity compensation, space division multiplexing (2015...)

- C+L bands = 12 THz. L band makes its way into practical usage. S band may come much later.
- Data traffic rises by ~30% per year. ~99% of bit*km is transported over fiber? 50%...90% = coherent?
- Each coherent WDM channel (PDM-QAM) can carry 600...800 Gb/s (2022).
- Optical nonlinearity compensation is being researched intensively.
  - Starts its way into coherent transponders in simple form.
  - Challenge: Huge computational effort, hence high power consumption
- Space division multiplex is also being researched intensively.
  - Multicore fibers, few-mode fibers, multicore few-mode fibers
  - Possibly increased complexity (and power consumption!) of coherent demultiplexers
  - Further challenges: power-effective few-mode/multicore optical amplifers
  - Optical mode demultiplexers built with 3D photonics in SiO_2
  - Is expected to become commercial, probably after 2025
- Hollow-core fibers are being researched which promise lower loss, lower nonlinearity.

Innovationspreis des Landes Nordrhein-Westfalen,
2008, Kategorie Innovation:

Awarded to Reinhold Noe and Ulrich Rückert, Paderborn University

Why? Somewhat simplified: see next page.

Our contributions to the megatrend coherent optical transmission

https://www.webofscience.com/wos/woscc/citation-report/a41e32c3-fa30-43ac-a222-2d71cca7

Citations in Web-of-Science approved publications (as of April 2024)

Only this technique for coherent optical QAM signal recovery makes sense. It is the best possible. It is employed in most, probably in **all** coherent optical QAM transponders.
Key enabler for highest fiber capacity 20...>100 Tbit/s.

	2020	2021	2022	2023	2024	Average per year	Total
	81	62	50	51	8	37.26	1,453
1 Hardware-Efficient Coherent Digital Receiver Concept With Feedforward Carrier Recovery for *M*-QAM Constellations Pfau, T; Hoffmann, S and Noé, R Mar-apr 2009 | JOURNAL OF LIGHTWAVE TECHNOLOGY 27 (5-8) , pp.989-999	68	48	41	39	6	48.63	778
2 ENDLESS POLARIZATION CONTROL-SYSTEMS FOR COHERENT OPTICS NOE, R; HEIDRICH, H and HOFFMANN, D Jul 1988 | JOURNAL OF LIGHTWAVE TECHNOLOGY 6 (7) , pp.1199-1208	2	3	1	10	1	3.41	126
3 PLL-free synchronous QPSK polarization multiplex/diversity receiver concept with digital I&Q baseband processing Noé, R Apr 2005 | IEEE PHOTONICS TECHNOLOGY LETTERS 17 (4) , pp.887-889	3	0	1	0	0	5.75	115
4 Phase noise-tolerant synchronous QPSK/BPSK baseband-type intradyne receiver concept with feedforward carrier recovery Noé, R Feb 2005 | JOURNAL OF LIGHTWAVE TECHNOLOGY 23 (2) , pp.802-808	2	3	1	0	1	5.6	112

Earlier than other publications, earlier than our own experiments (from 2006 on), earlier than other experiments, earlier than product (from 2007 on). This coherent polarization-multiplexed transmission dominates today‘s long-haul and medium-haul optical communication.