Optical Foundations for IP Engineers

From Fiber Basics to CWDM/DWDM and Link Budgeting

FLEXOPTIX

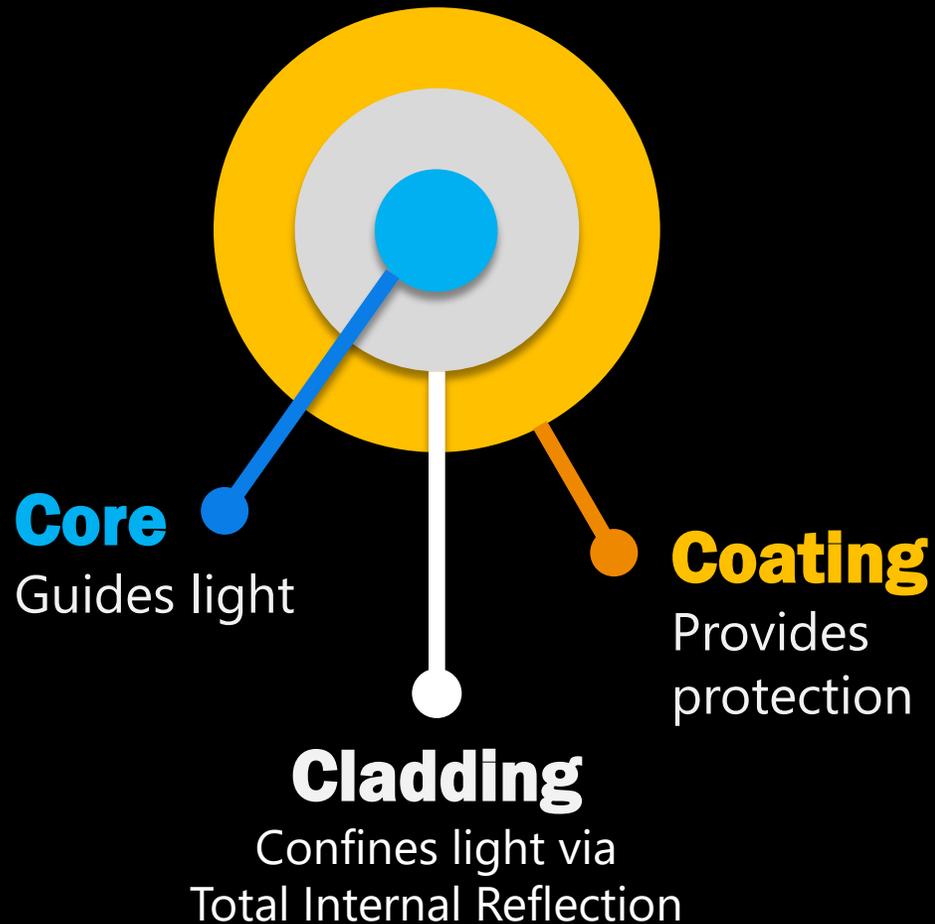Andreas Glatz | Technical Customer Support Specialist

Agenda

1. Why Optical Communications Matter for IP Engineers
2. Optical Fiber Communication
3. Multi-Mode vs. Single-Mode Fiber
4. Most Common Fiber Connectors
5. PC / UPC vs. APC
6. Wavelengths & Transmission Bands
7. Wavelength Division Multiplexing (WDM)
8. Optical Signal Impairments
9. Optical Link Budget

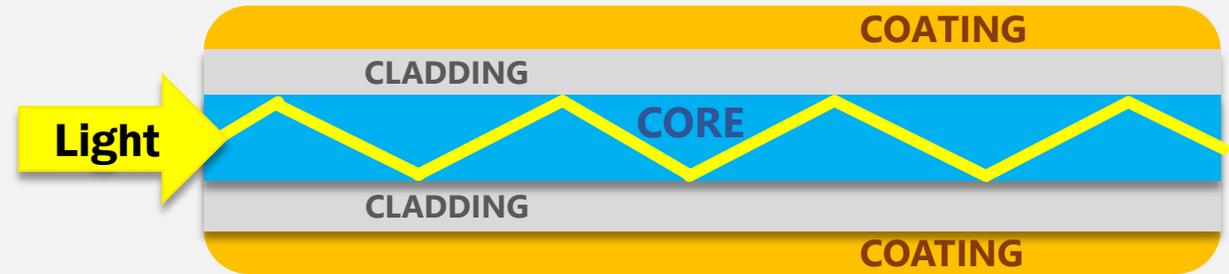# Why Optical Communications Matter for IP Engineers

- Most IP networks ultimately rely on optical fiber

- Many capacity, distance, and reliability limits are optical

- Network issues can originate at the physical layer

- Understanding the basics avoids guesswork

Optical Fiber Communication

Fiber Cross-Section

Core
Guides light

Cladding
Confines light via
Total Internal Reflection

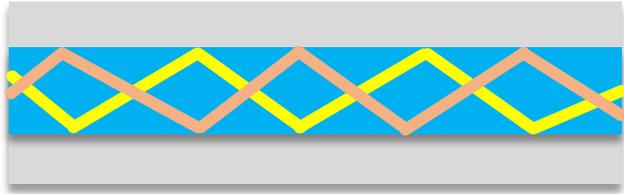**Coating**
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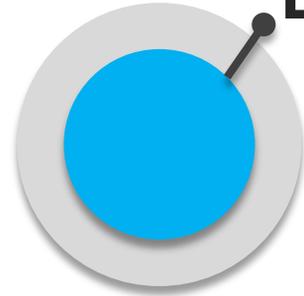protection

Light Propagation in Optical Fiber

- **Total Internal Reflection keeps light confined to the core**

- Typically silica glass with precisely controlled refractive index

- Many links use separate fibers to transmit and receive

- Single-fiber bidirectional (BiDi) uses different wavelengths

Multi-Mode Fiber (MMF)

Multiple light modes

Large Core
50/62.5 μm diameter

Single-Mode Fiber (SMF)

Single light mode

Small Core
~9 μm diameter

VS

Use Case: Data center, LAN, short reach
Fiber classes: OM1, OM2, OM3, OM4, OM5

✓ **Short Distance**
   Hundreds of meters (up to 2km)

✓ **Lower Cost Optics**
   Uses LED or VCSEL transceivers

! **Limited by Modal Dispersion**
   Different paths = different arrival times

Use Case: Long-haul, WAN, metro, backbone
Fiber classes: OS1, OS2

✓ **Long Distance**
   Hundreds of km+ (with amplification)

✓ **High Cost Optics**
   Uses laser diodes, high performance

! **Limited by Chromatic Dispersion**
   Different wavelengths = different speeds

Most Common Fiber Connectors

LC

- Small form factor
- Single- and multimode
- Push-pull latch mechanism
- Most common today
- Used with most transceiver types
- High density

SC

- Larger connector
- Single- and multimode
- Snap-in connection
- Common in legacy & access
- Good mechanical stability

MPO / MTP

- Multi-fiber Push On connector
- Single- and multimode
- MTP = trademarked, better precision
- 8 / 12 / 16+ fibers
- Parallel optics

Critical: Always clean connectors before mating!
Even microscopic dirt causes permanent damage.

PC / UPC vs. APC
Be aware of different ferrule connector types

(Ultra) Physical Contact (UPC)
- Typically identified by blue connectors
- PC: back reflection below −30 dB
- UPC: back reflection below −55 dB

UPC

Angled Physical Contact (APC)
- Typically identified by green connectors
- Ferrule polished at an 8° angle
- Back reflection below −65 dB
- Not compatible with PC / UPC
- Commonly used in high-power applications

APC

Why is this important?
- When unmated, even UPC interfaces generate strong reflections.
- In high-power optical systems, back reflections may cause damage.

Optical Transmitters & Receivers

Transmitters (TX) Electrical Signal → Light

LED
- Low cost, low power
- Used with multimode fiber only
- Legacy technology, replaced by VCSELs

VCSEL (Vertical-Cavity Surface-Emitting Laser)
- Optimized for 850nm
- Multimode
- Standard in data centers (short reach optics)

DFB (Distributed Feedback Laser)
- Long reach & high capacity
- Required for single-mode, CWDM, DWDM
- Used in metro, long-haul

Receivers (RX) Light → Electrical Signal

PIN Photodiode
- Simple, stable, low cost
- Standard sensitivity
- Used in many Ethernet optics

APD (Avalanche Photodiode)
- Higher sensitivity (internal gain)
- Can be damaged when overloaded
- Used in long-reach systems

Coherent Receivers
- Enable very high data rates & long distances
- Multiple photodiodes + DSP
- Recover amplitude, phase, polarization

Transceivers contain both TX and RX in one module

Transmitter (TX) + Receiver (RX) =

SFP28 Transceiver (25 Gbps)

Wavelengths & Transmission Bands

Single-mode fiber attenuation profile (ITU-T G.652)
Transmission bands are chosen where loss is minimal
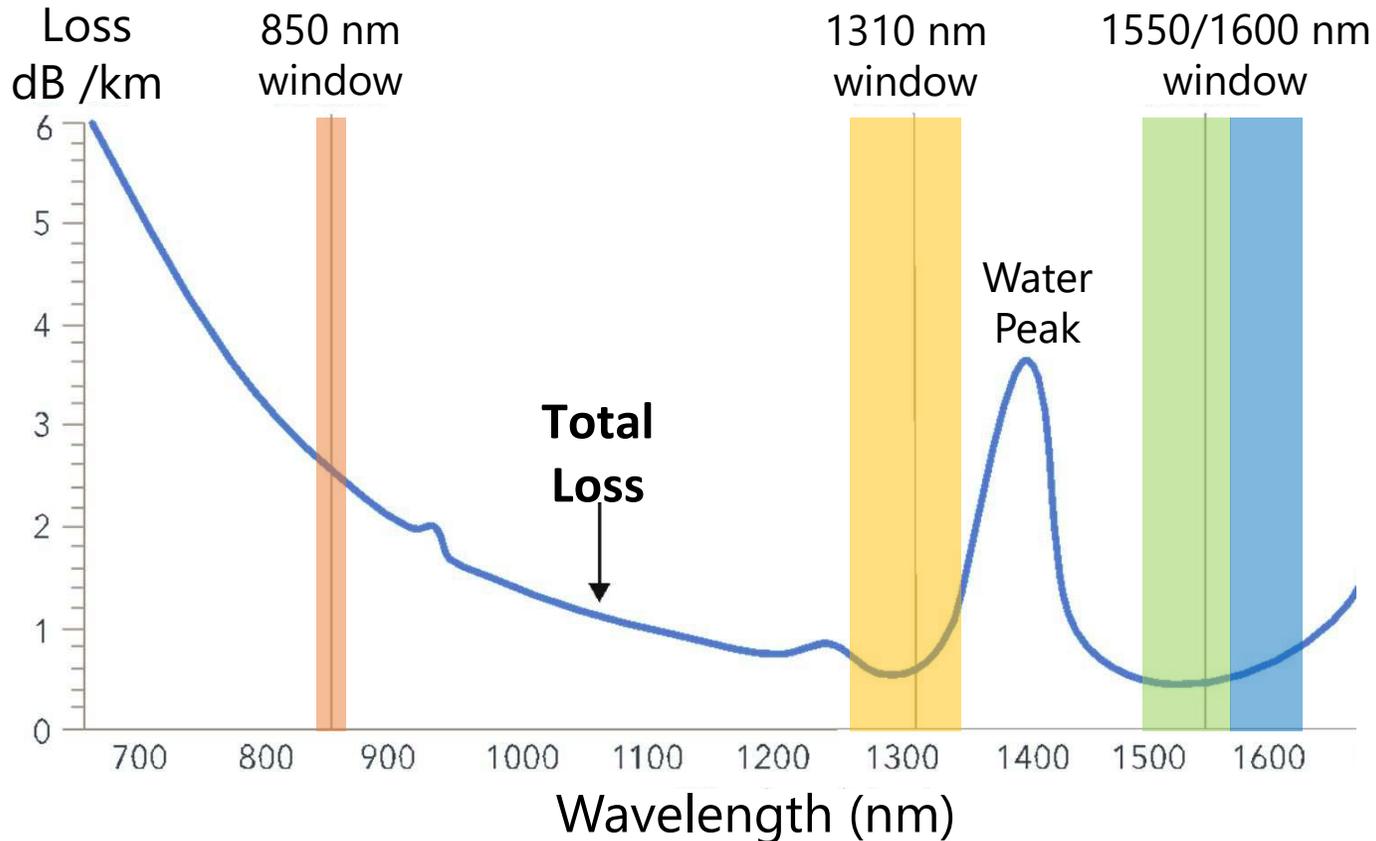
850 nm – Wavelength

- Exhibits the **highest attenuation**
- Limited to **short-reach applications** (MMF only)

1310 nm – O-Band ("Original Band")

- Attenuation is higher than in the C-band
- Commonly used for **medium-distance links**

1550 nm – C-Band ("Conventional Band")

- Offers the **lowest fiber attenuation**
- Primary band **for long-distance & DWDM**

1600 nm – L-Band ("Long Band")

- Serves as a **capacity extension of the C-band**
- Typically used when **fiber availability is limited**

Wavelength Division Multiplexing (WDM)

- Multiple independent wavelengths (colours) on a single fiber
- Multiplexers (MUX) combine wavelengths; Demultiplexers (DEMUX) separate them
- Leads to massive capacity increase without installing new fiber
- Each wavelength behaves like an independent channel

Different colors of light on the same fiber via multiplexing

Parallel data streams (different λ) without interference!
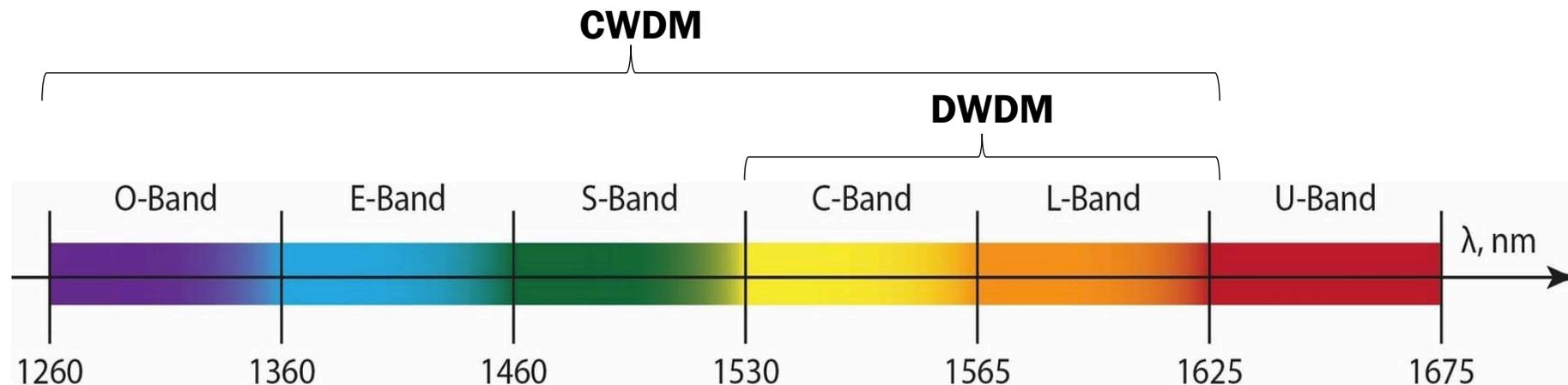

Source: Shape Science

CWDM

Coarse Wavelength Division Multiplexing

- Up to 18 CWDM wavelengths transmitted on one fiber
- 20nm spacing (2500GHz) / 1270 nm to 1610 nm
- Transmission range: 80-120 km depending on data rate
- More cost-effective than DWDM solutions

DWDM

Dense Wavelength Division Multiplexing

- DWDM wavelength range: C-Band / L-Band
- Channel spacing: 50 GHz (0.4nm)
  100 GHz (0.8nm), or 200 GHz (1.6nm)
- C-Band: ~40 Ch (100GHz) / ~80 Ch (50GHz)
- L-Band: ~44-75 Ch (100GHz) / ~90-120+ Ch (50GHz)
- Combined C+L: 90-120+ channels (100GHz)
- Transmission range: >1,000 km with amplifiers

CWDM

DWDM

| O-Band | E-Band | S-Band | C-Band | L-Band | U-Band | λ, nm |

1260   1360   1460   1530   1565   1625   1675

Optical Signal Impairments
Different physical effects reduce signal power and quality

Attenuation

Power loss (dB)

Fiber Loss:

Singlemode:
1310 nm: ~0.38 dB/km
1550 nm: ~0.22 dB/km

Multimode:
850 nm: ~3 dB/km
1300 nm: ~1.5 dB/km
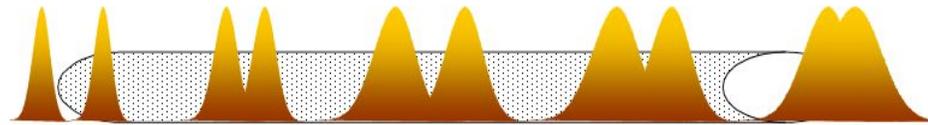
Connectors: ~0.3–0.6 dB

Splices & Bends:
Fusion splice: ~0.05–0.1 dB
Macro bends: variable loss

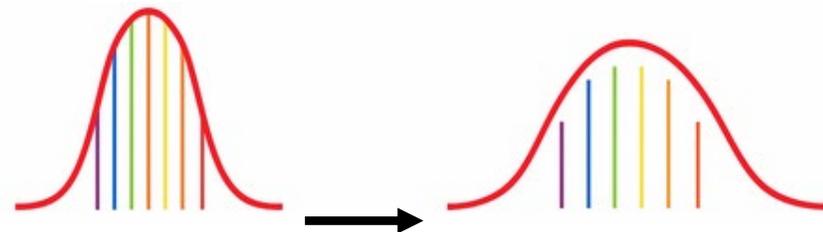## Dispersion

Signal spreading (time)

Source: FOA

Modal Dispersion:
Different light modes take different paths through the fiber. Main limitation with multimode fibers.

Chromatic Dispersion:
Different wavelengths travel at different speeds. That causes pulse broadening.

Noise

Signal quality degradation

**Optical Signal-to-Noise Ratio:**
Indicates signal quality over noise.

Noise Sources:
- Amplifiers
- Crosstalk in WDM systems
- Nonlinear effects at high power levels

→ Significant in DWDM systems and coherent links.

Optical Link Budget

- **Link Budget** = TX Power (min) − RX Sensitivity (min)

- **Total loss** (cable + connectors + splices) must be less than link budget

- Include **safety margin** for aging, temperature and future repairs

- Planning uses estimates. Deployment should rely on measured values.
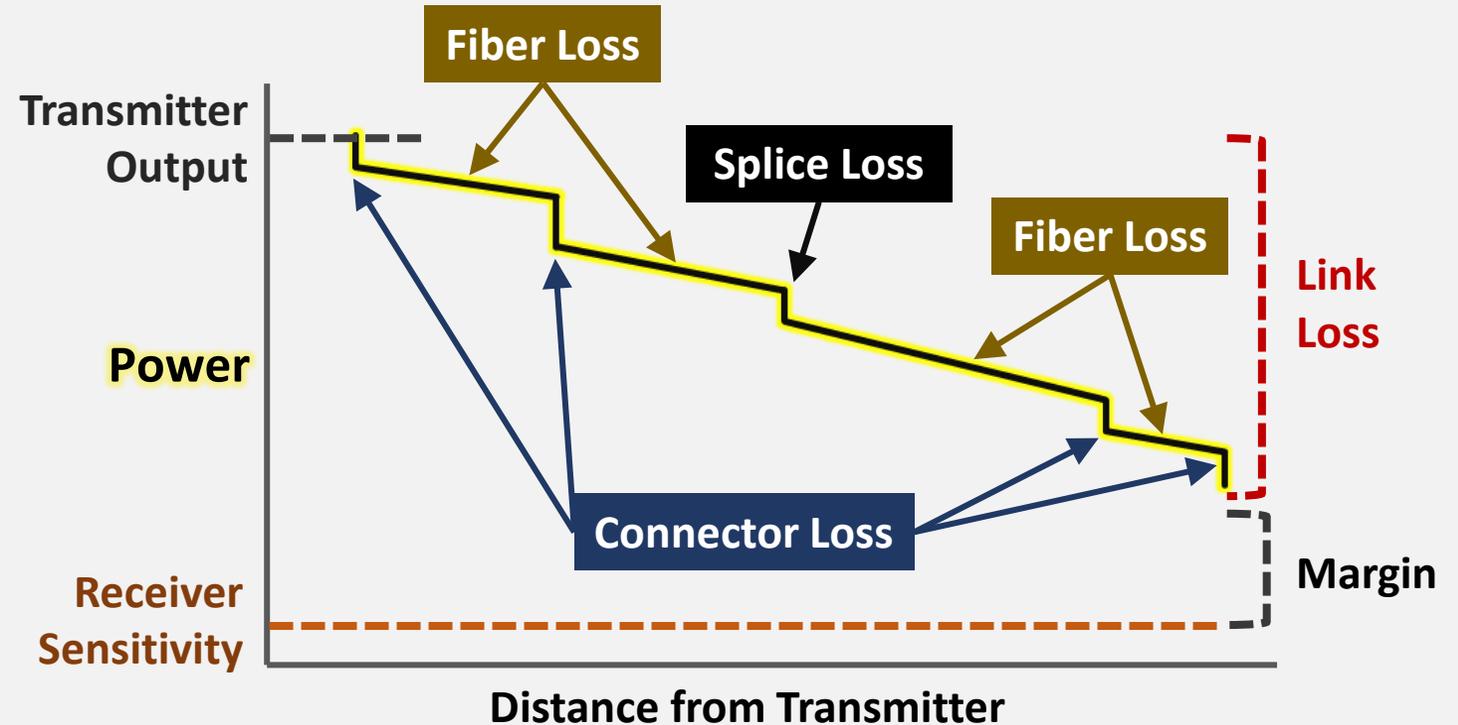
The wavelength matters:

Average values (under normal conditions)	Attenuation/Km (dB/Km)	Attenuation/optical connector (dB)	Splice (dB)
Wavelength 1310nm	0.38	0.3–0.6	0.1
Wavelength 1550nm	0.22	0.3–0.6	0.05

Key Takeaways

1. Network issues can originate at the physical layer

2. Fiber and wavelength choices are strategic decisions

3. Wavelength Division Multiplexing enables massive scaling

4. Three impairment categories limit performance: Attenuation, Dispersion, Noise

5. Calculate link budgets: include all losses (fiber, connectors, splices) plus a safety margin

Thank you!

Any Questions?

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