Fiber optic communication

Outline

• Introduction
• Properties of single- and multi-mode fiber
• Optical fiber manufacture
• Optical network concepts
Optical communication
simple block diagram

Original signal
E.g. analog voice
Many channels muxed into larger total BW

Digital encoding
Modulation, error correction, routing and header info

Direct modulation
Power, $\lambda$ stability
Chirp

$\lambda$ Multiplexing
Crosstalk, loss

Transmission
Attenuation, jitter, noise, polarization
scrambling, dispersion

Demultiplexing
Crosstalk, loss

Detection
Noise, bandwidth

Decoding
Bit error rate

Robert R. McLeod, University of Colorado
Time-division multiplexing

Bundling low bandwidths

- Electronic aggregation of multiple low-bandwidth streams.
- Eventually exceed available modulation rate of electronics and optics.
- Standard today is 10 Gb/s with 40 Gb/s being fielded.
- Optical carrier (at $\lambda = 1.5 \, \mu m$) is 200 THz, so there is room for a number of these TDM channels.
- Available bandwidth is determined by fiber.
Wavelength division multiplexing to exploit transmission bandwidth

- Also known as frequency multiplexing
- Mux/demuxers need flat passbands in both amplitude and phase to not distort the data, then very sharp filter edges to suppress crosstalk between channels.
- Gratings are an obvious technology but are difficult to package with sufficient stability.
- Daisy chains of thin film band-drop filters can be used
- Array waveguide gratings – essentially an integrated optic grating – are becoming the dominant technology

Fiber optics primer
Capture via total internal reflection

$$\theta_c = \sin^{-1}(n_1/n_2) \quad (1-2)$$

• For a perfectly flat surface, TIR is a 100% efficient mirror
• Once captured inside a higher index region, light will never exit
• Bending the guide decreases the incidence angle resulting in optical loss
Waveguide basics

Important normalized quantities

Ray picture

Modal picture

Numerical aperture of guide measured in air

\[ NA \equiv \sin \theta_{\text{crit}} = \sqrt{n_{\text{co}}^2 - n_{\text{cl}}^2} \]

Phase shift of limiting wave across guide face

\[ V \equiv k_x \rho = k_0 \sin \theta_{\text{crit}} \rho = k_0 NA \rho = k_0 \rho \sqrt{n_{\text{co}}^2 - n_{\text{cl}}^2} \]

Interpretation of \( V = 2 \pi \rho / \lambda_x = \pi D / \lambda_x = \pi \) (# waves across face).
So \( V = \pi/2 \) is cutoff for metal waveguide, bit larger for index guides.
**Single mode vs. multi-mode fibers**

- Multi-mode guides have large $V = $ large size = easy/cheap to align.
- BUT, each mode propagates at different speed, so pulse disperses.
- Only usable in short reach systems such as around buildings.
Fiber modes and semiconductor light sources

Single mode system

- Source = laser diode. Aperture size and NA related by diffraction limit.
- Fiber = single mode. Mode diameter and NA related by diffraction limit.
- Can be nominally 100% efficient.
- Coupled must be precisely aligned on fiber axis. Tight tolerances (~micron or less).
- High brightness system.

Multi mode system

- Source = light-emitting diode. NA ~ 1 independent of aperture diameter.
- Fiber = multi mode. Finite NA, unrelated to core diameter.
- Large losses in first lens due to LED radiation angle.
- Any ray that hits core with sin(angle) < NA is coupled. Loose tolerances (~10 µm).
- Lower brightness system.
Power loss / distance in glass
The “transmission windows”

• This graph is the reason long-haul telecom uses 1.5 µm light
• At 0.15 dB/km, light goes 20 km before losing 3 dB.
• The two primary bands used (above) cover 1525 to 1610 nm and give > 5 THz of available bandwidth.

C-band: 1525-1565 nm
L-band: 1570-1610 nm

> 5 THz of bandwidth
Pulse broadening
Waveguide and material dispersion

If fiber is single mode there will be no modal dispersion. Index contrast and core diameter are reduced to support just one mode. Fractional index contrast is typically 0.2-1% for MM fiber. Group velocity now depends on spectral width of the pulse. This leads to the use of lasers (small intrinsic linewidth) over LEDs (large intrinsic linewidth) for long-haul, single-mode communication.

\[ \sigma_\tau = |D| L \sigma_\lambda \]

To a good approximation in fiber, the GVD can be taken as the sum of material and waveguide dispersion:

\[ D = D_{mat} + D_{wg} \text{ [ps / (km-nm)]} \]

Index of refraction of silica and Ge:silica

Group index, \( n_{group} = \frac{c}{n_g} \)

\[ n_g = n - \lambda \frac{dn}{d\lambda} \]

Group velocity dispersion

\[ D = -\frac{\lambda}{c} \frac{d^2 n}{d\lambda^2} 10^{12} \text{ [ps / (km-nm)]} \]
How fiber is made
Preform fabrication

Chemical vapor deposition

Rotated for uniformity

Gas Deposition System

$O_2$ $\rightarrow$ $\text{POCl}_3$ $\text{GeCl}_4$ $\text{BBr}_3$

Preform $\rightarrow$ $\text{SiCl}_4$ $\rightarrow$ Burner

Lathe

~40 cm typical length

1630 $^\circ$C

www.howstuffworks.com/fiber-optic5.htm
Fiber drawing

10-20 m/sec

http://people.alfred.edu/~misture/demo/draw_tower.html

• Several km are drawn from a single preform
• Nonuniformities are reduced in scale at the same ratio, so the core is atomically smooth.
Erbium doped amplifier
All-optical regeneration

- After some 10’s of km, signal needs to be regenerated.
- Traditional technology (early 1990s) was to demux, detect, electronically retime and restore, broadcast and mux. **Expensive.**
- Fiber amplifiers made it possible to regenerate in optical domain.

**EDFA concept:**

- Pump laser at 980 nm or 1480 nm excites erbium doped fiber.
- Erbium fluoresces at 1550 nm, providing stimulated emission gain to the communication signals. The doped fiber thus acts much like a laser but without the end mirrors (single pass).
- Spontaneous emission of the erbium is a noise source, so the amplification comes at the expense of reduced SNR.

**EDFA in reality:**
Add/drop nodes
Network reconfiguration

- More complex network than long-haul point-to-point.
- Reconfigurable add/drop multiplexers (ROADM) are the current technology that enable the network bandwidth to be dynamically switched based on need.

Reconfigurable add/drop mux:
What it ends up looking like: Lucent Wavestar terminal

- Up to 80 wavelengths separated by 100 GHz = 0.8 nm at 1550 nm, each carrying 10 Gb/s for a total of 800 Gb/sec.
- This system has been replaced with models offering well in excess of 1 Tb/s.
Network architecture

- Many-layered network from internet browser on your laptop wirelessly connected to a coffee-shop (application layer = top) to bursts of light on fiber (physical layer = bottom).
- At the lowest, physical layer, the network is mainly static, point-to-point links.
- Circuit switching of the physical optical network is starting
- Packet switching at the physical optical layer is a research topic.