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Optical Fibers and Photonic Devices

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References:

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Optical Fibers

Fibers are made of silica, doped with boron oxide to lower refractive index; germanium oxide raises refractive index. Two major factors limit optical fiber performance.

(1) Loss

Attenuation (dB) = $\{10/L\} \log(P_{in}/P_{out})$ L = fiber length

The minimum for silica is 0.15 dB/km, or 3.5% power loss per km.

Polymers ~ 10dB/km.

Loss in silica is due to Absorption:

- electron transitions acrross band gap (8.9 eV, 140 nm light)
- excitation of electrons within Si and O atoms (IR)
- absorption by impurities such as transition metals, < 1 ppb (UV, visible light)
- excitation of bonds such as O-H (eg 1400 nm) or Si-O (3000 nm light)

and Rayleigh scattering, proportional to $1/\lambda^4$

(2) Dispersion

Snells law: $n \sin \phi = n' \sin \phi'$

Total internal reflection when angle of incidence exceeds ϕ_c: $\sin \phi_c = n/n'$

Fibers rely on total internal reflection, with a very small Δn, e.g.

core $n = 1.53$, cladding $n = 1.50$ gives $\phi_c = 78.6°$

Step index fibers can have *modal dispersion*: different modes of light traveling at different angles traverse different path lengths so get out of phase. Leads to spreading of pulses. A graded index fiber can cure this problem, or use a single-mode fiber. (core < 3 microns diameter)

Materials dispersion: different wavelengths have different refractive index;

dispersion coefft. = $-\{\lambda_o/c\}(\partial^2 n/\partial\lambda^2)_{\lambda=\lambda_o}$ ps/km.nm

For silica this is zero at 1300 nm wavelength.

Waveguide dispersion: even if materials dispersion is negligible, there is still a dispersion of different wavelength signals because each mode spends a different amount of time in the core and cladding. Compensating materials and waveguide dispersion at 1500 nm wavelength gives the optimum performance.

Non-linear dispersion occurs at high light intensities where the refractive index becomes intensity-dependent. Finally, for birefringent materials there can be polarization-dependent dispersion.

Photonics

Refers to an entire optical system in which the flow of photons is controlled (similar to ("electronics"). Light is:
generated (lasers or laser diodes)
transmitted (waveguides, or free-space optics)
modulated (switched or scanned using electrical, optical or acoustic devices)
amplified or frequency-converted (non linear materials)
detected (PIN diodes)

Example: *Communication system*
Local: inexpensive multimode fibers, directly modulated LEDs, typically 850 nm wavelength.
Long distance: loss and dispersion are important. Single mode fiber, distributed feedback laser, external modulation, amplifiers every 100 km, dispersion compensation. 40 wavelengths simultaneously around 1550 nm. 10 Gbit/sec x 40 channels, spaced 0.8 nm apart (100 GHz).
Laser -> Attenuator -> Modulator -> Multiplexer ->fiber with amplifiers -> Add/drop multiplexer -> Demultiplexer -> Attenuator -> PIN diode

At present these are discrete components, but work is ongoing to integrate them onto a chip, e,g, the OADM project at MIT's Microphotonics Center.

Increase data rate by combining lower data rate signals:
DWDM (dense wavelength division multiplexing) – each data stream on a different wavelength – 1 Tbit/sec
TDM (time division multiplexing) – data streams combined on same wavelength. Limited to 10 Gbit/s

Electrooptical modulator: use a Mach Zehnder interferometer. Voltage changes refractive index via Pockels effect ($n \propto E$) or Kerr effect ($n \propto E^2$)

Fiber amplifier C-band (1530-1560 nm) is amplified by a laser made by adding Er to the silica fiber. Pump using 980 nm laser diode.
Similarly, the 1300 nm wavelength can be amplified using a Pr-doped fiber.

Fiber Bragg gratings: a fiber with a periodically varying refractive index. Acts as a narrow-band filter, e.g. to pull out (drop) one channel from a fiber.

Couplers: different wavelength channels can be added to the fiber by bringing another fiber (or waveguide) close, allowing light to couple between the fibers.

Thin film filter, e.g. a tantalum oxide/silica multilayer. By designing the multilayer, it can have a photonic band gap containing a sharp transmission peak (i.e. it is reflective except for one frequency which it transmits). These can be used in a demultiplexer.