ELEC4705 – Fall 2009

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LECTURE 17
Optical Systems

Contents

17.1. Whats wrong with electrical transmission?

- The maximum rate of information transfer is limited by the number of bits per second that can be transmitted.
- As the bit rate increases, the individual pulse representing a bit must be turned on and off faster.
- The non-zero resistance of the metal and capacitance in a metal cable limit this transition time to $t > 10$nanoseconds (10×10^{-9} seconds).

Maximum bit rate $\approx$ 100s of megabits/second

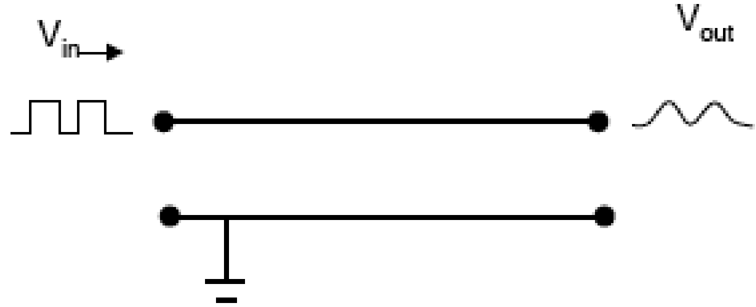


Figure 1. A Pulse Transmission in an electrical line

- Pulse are distorted as they travel.
- Short pulses merge causing loss of information.
- Introduction of noise.

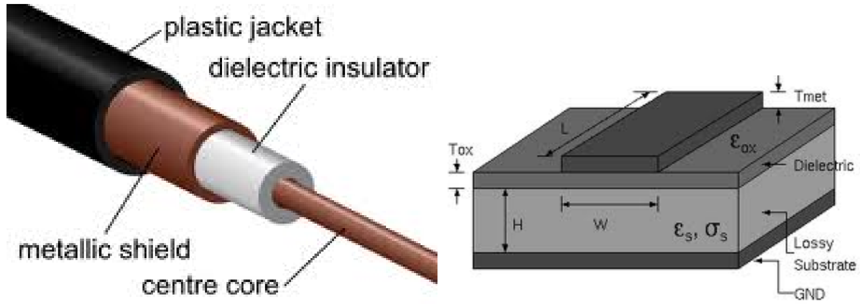


Figure 2. Coaxial cable and strip line

- Geometry is used to create good electrical lines.
- Coaxial lines are about as good as you can get.
- On boards and chips we use a variety of strip-lines with ground planes.

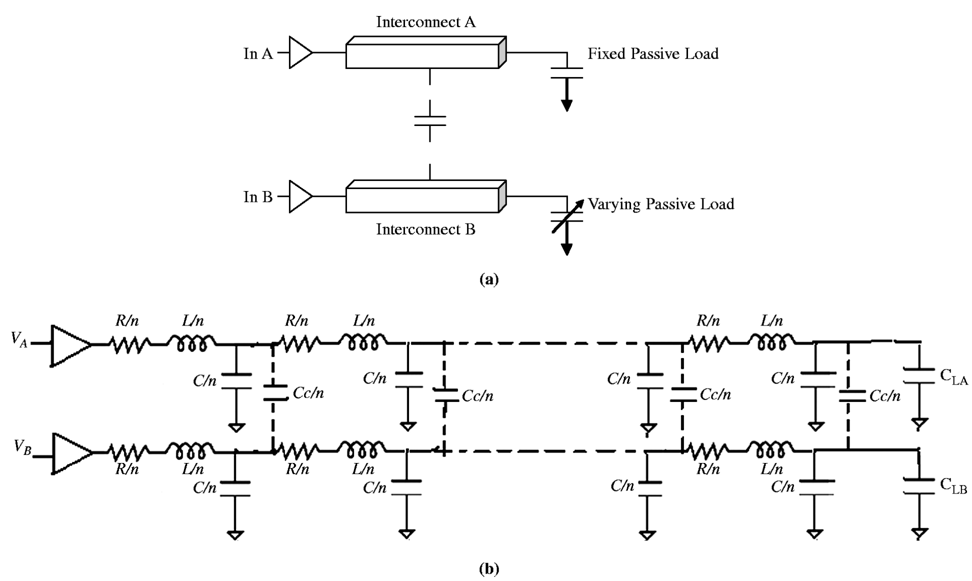


Figure 3. Model of Transmission Line using RLC elements.

- Approximation of partial differential equation.
- Include coupling capacitances and inductors.
- RLC is essentially low-pass causing the pulses to broaden.

Figure 4. Illustration of cross-talk between lines due to coupling

- High frequencies couple through capacitors.
- Cause pulse edges to be coupled to adjacent lines.
- Makes a mess of the signals.
- Electrical Magnetic Interference (EMI)

17.2. Electrons vs. Photons

Table 1 compares the optical and electrical transmission properties.

Table 1. Electrical vs Optical transmission

Electrical Transmission	Optical Transmission
$t > 10ns = 10^{-8}s$ bandwidth limited	$t > 100ps = 10^{-11}s$ dispersion and electronics limited
Bandwidth $\sim 100MHz = 10^8Hz$	Bandwidth $\sim 100THz = 10^{14}Hz$
Electromagnetic interference	No EMI
Copper or Aluminum (expensive, large and heavy)	Glass (cheaper, small, light, but more fragile)
Energy loss, signal attenuation $> 20\,dB/km$	Attenuation $\sim 0.2\,dB/km$
Signal remains electrical	Signal must be converted electrical $\Longrightarrow$ optical $\Longrightarrow$ electrical

17.3. An optical communication system

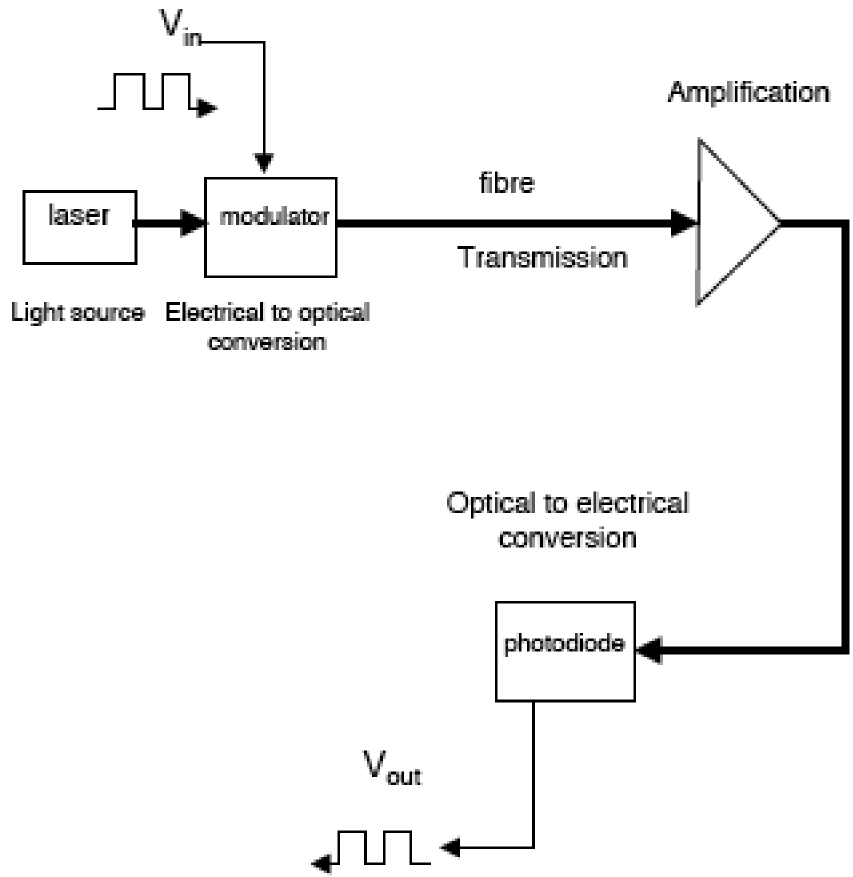


Figure 5. An optical communication system

17.4. Transmission

Free space beam propagation is not practical due to rain, fog, line of sight problems, etc.

An optical equivalent of electrical wire is needed.

17.5. Optical waveguides - ray optic picture

Assume mirror reflectivity is 100%, see figure 6.
What combination of plane waves (rays?) gives a zero field at y=0 and y=d?

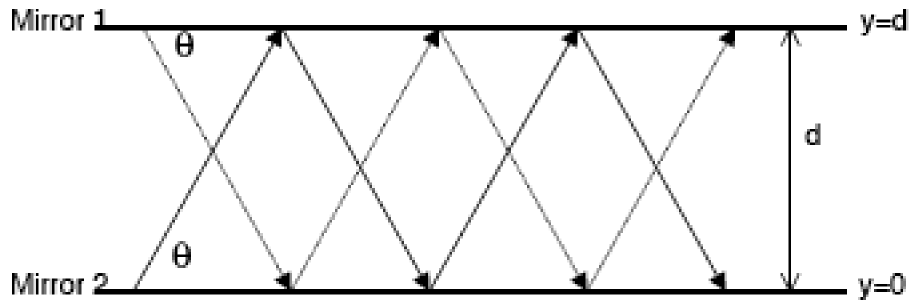


Figure 6. Optical reflections

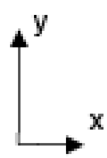


Figure 7. x-y

$$E_+(x,y) = A\sin(k_x x + k_y y - wt + \phi) \tag{17.1}$$
$$E_-(x,y) = A\sin(k_x x - k_y y - wt + \phi) \tag{17.2}$$
$$E_{total} = E_+ + E_- = 2A\sin(k_y y)\cos(k_x x - wt + \phi) \tag{17.3}$$

To satisfy boundary conditions, must have:

$$k_y = \frac{m\pi}{d} \tag{17.4}$$

where integer **m** is the **mode number**.

17.6. Waveguides modes

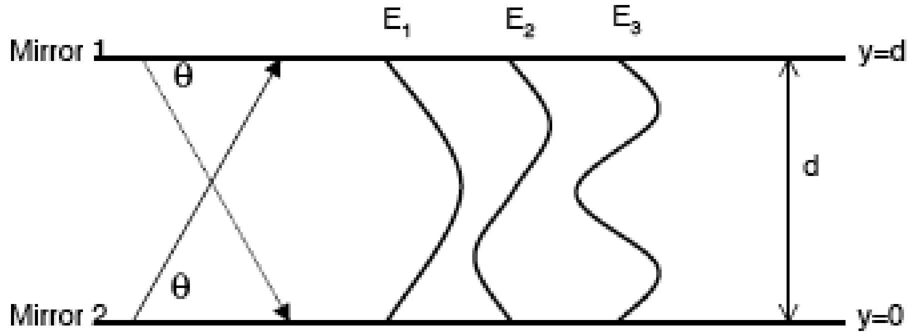


Figure 8. Waveguide modes

$$E_m = D\sin(\frac{m\pi}{d}y)\cos(\beta_x x - wt + \phi) \quad (17.5)$$

- The mode propagation constant is defined as below:

$$\beta_m = \frac{nw}{c}.\cos\theta_m \quad (17.6)$$

Light can only propagate in the form of these modes inside a waveguide

- β_m can only have discrete values.
- $\sin\theta_m = \frac{c}{nw}.\frac{m\pi}{d}$
- the mode Effectice index is given by

$$N_{eff} = \beta_m.\frac{c}{w} \quad (17.7)$$

- Speed of light depends on the mode as

$$v_m = \frac{c}{N_{eff}} \qquad \textbf{Mode dispersion} \quad (17.8)$$

17.7. Real optical waveguides

Real waveguides for long distance propagation must use total internal reflection for confining light; otherwise losses are too high.

Total internal reflection $\Longrightarrow n_{clad} < n_{core}$.

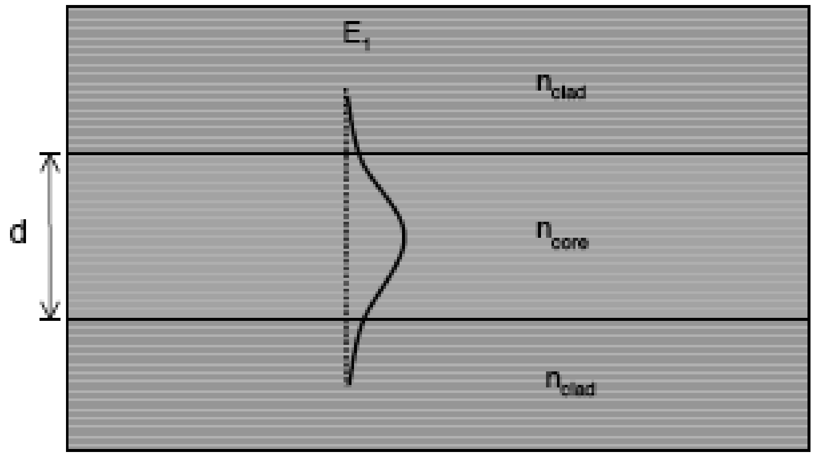


Figure 9. Real optical waveguides

- Choose $n_{clad} < n_{core}$ and core diameter d small enough that only the fundamental E_1 mode is supported.
- Real waveguides must use total internal reflection, so that reflection induced losses are zero.
- $n_{core} > n_{clad}$.
- θ_m must be less than the critical angle for total internal reflection, hence the number of modes is restricted.
- It is possible to make single mode waveguides, for small index difference and/or small core thicknesses.
- Guided light spills over into evanescent tails in the cladding regions.
- The effective index N_{eff} always lies somewhere between the index of the core and the index of the cladding.

17.8. Optical Fiber

Optical fibre is a glass waveguide with a cylindrical cross-section, see figure 17

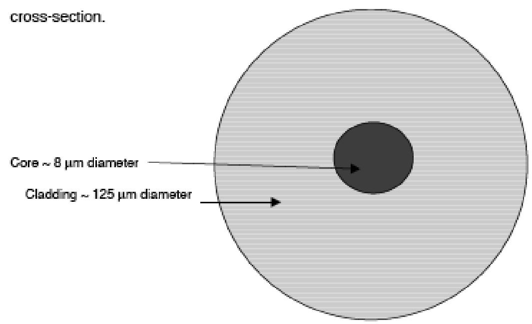


Figure 10. Optical Fiber

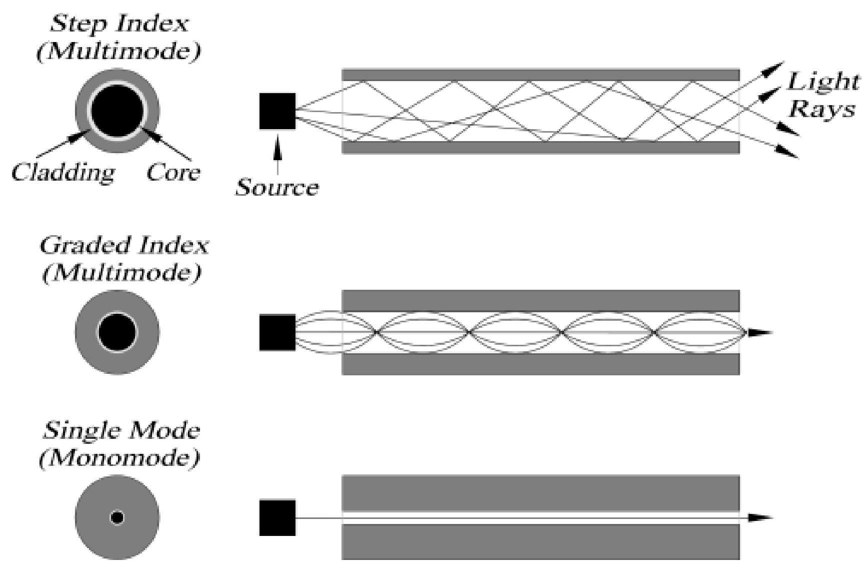


Figure 11. Optical Fiber types

- Multimode - Cheap and used for short distances. Mode dispersion.
- Single mode - More expensive and carefully designed for low dispersion, low loss and long distances.

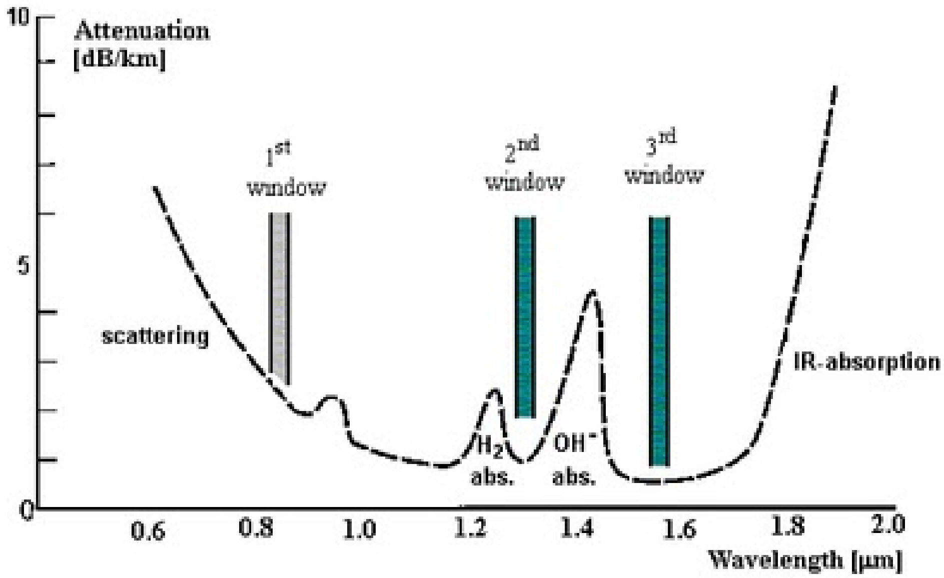


Figure 12. Optical Fiber Attenuation (Single Mode SMF28)

- $\lambda = 1300\,nm$ wavelength of **minimum index dispersion** (the variation of index n with wavelength- an intrinsic property of glass)
- $\lambda = 1550\,nm$ wavelength of minimum loss (due to impurities and molecular vibration absorption by O-H, Si-H).
- A number of regions are used extensively.
- Enormous bandwith in each region (THz).
- Howe to use it?

17.9. Wavelength Division Multiplexing (WDM)

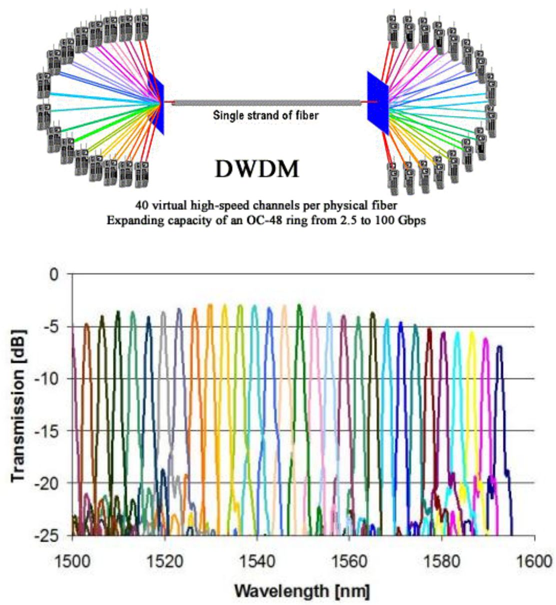


Figure 13. WDM system and spectrum

- Wavelength Division Multiplexing (WDM) divides the bandwidth in the frequency domain.
- A number of lower frequency bit streams (40Ghz) each at different centre frequency (color). Each signal is in a "Channel".
- Need a lot of optics. Each channel need laser and detector. Need optical multiplexer and demultiplexers.

17.10. Time division multiplexing (TDM)

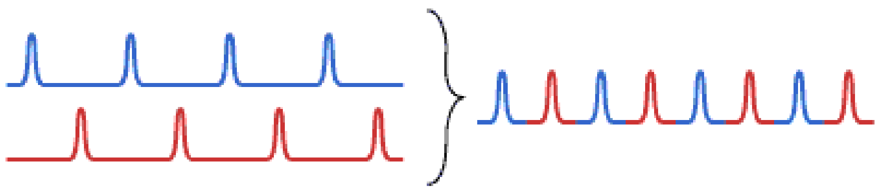


Figure 14. TDM pulse mixing

- Time division multiplexing (TDM) divides the bandwidth in the time domain.
- A number of very high frequency bit streams (very short pulses). Are interwoven in the time domain.
- Need a lot of electronics and a very fast optical modulator and detector.

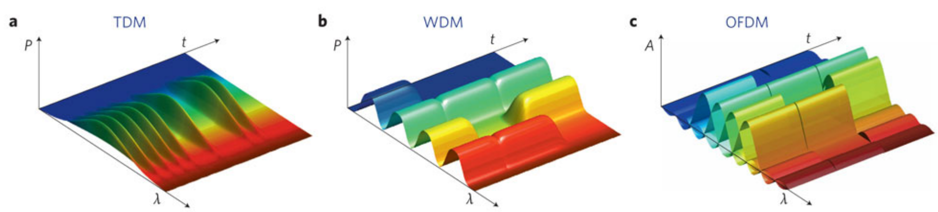


Figure 15. Optical Fiber

- Can get clever and mix TDM and WDM (OFDM)
- Can also code the bits on the optical phase.
- 40GHz bit stream with 4 levels using phase at $0, \pi/2\pi, 3/2\pi$ can be done with 10GHz pulse stream.

17.11. Structured Fiber

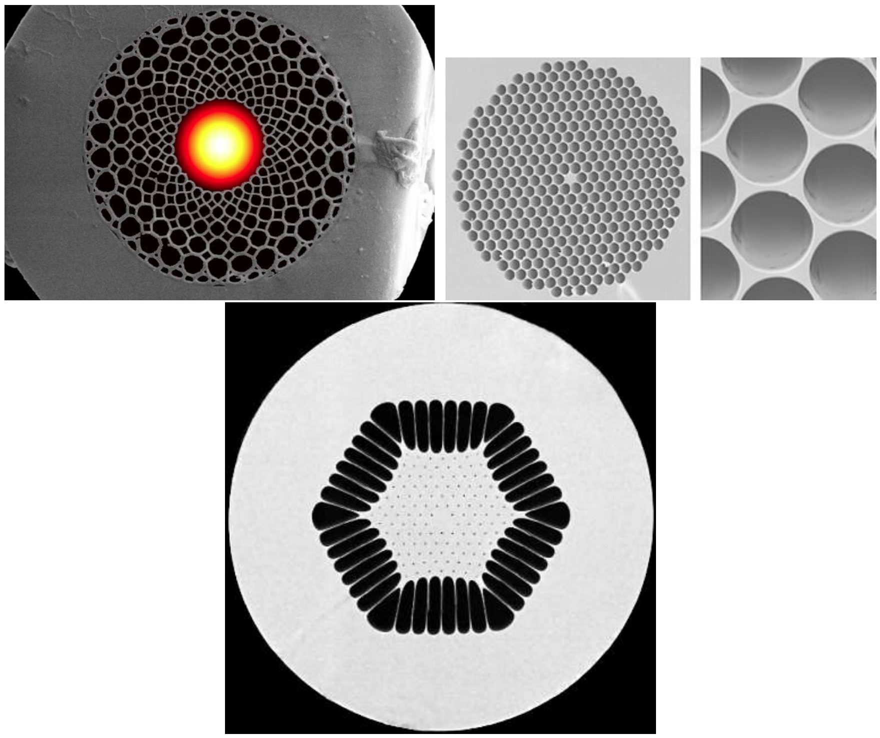
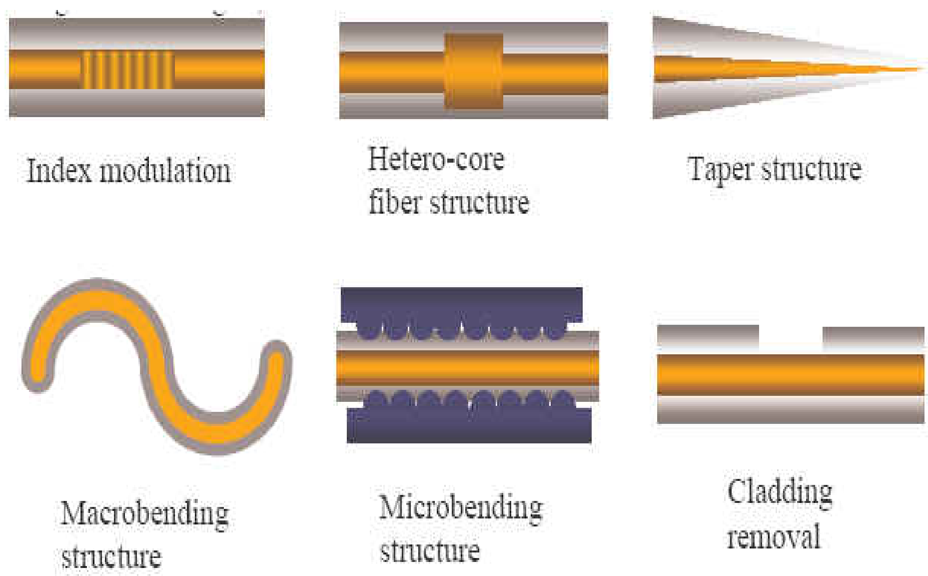


Figure 16. Optical Fiber

- Fancy nanostructured fiber has been proposed for sensors and other applications.
- Photonic crystal fibers use a periodic structure to confine the light.

17.12. Fiber sensors



- Fibres are very sensitive to the refractive index of both core and cladding.
- Anything that changes this (Temperature, stress, chemistry, etc) can be sensed by looking at the loss, attenuation and phase shifts that occur.
- Many sensors based on a lot of different structures.

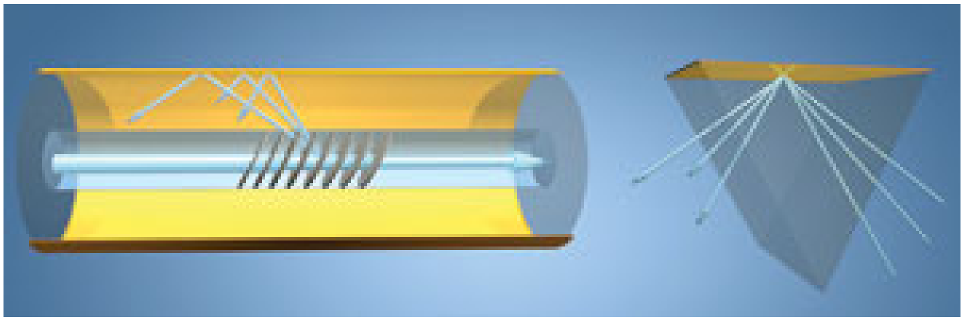


Figure 17. Optical Fiber Sensor based on tilted fiber grating (J. Albert Carleton)

- Work at Carleton uses a tilted grating to excite a gold film deposited on the fiber.
- Sense any disturbance of the gold film.
- Uses include DNA detection, Cell process investigation, chemical composition, etc.