OPTICAL FIBER COMMUNICATION

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OUTLINE

- **Introduction about Optical Fibers.**
- **Main Characteristics of Fiber Optics Communication System.**
- **Light propagation in an Optical Fiber.**
- **Mode Analysis for Single Mode Fiber.**
- **Mode Analysis for Multimode Fibers.**
- **Surface Plasmon Resonance.**
- **Optical Fiber Surface Plasmon Resonance Sensors.**

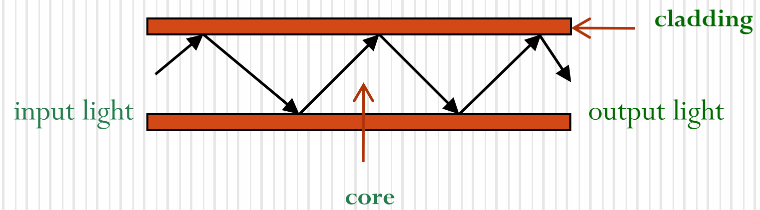
Fibre Optic?

Dielectric waveguide of cylindrical geometry with core and cladding of suitable material.

refractive index of core > refractive index of cladding

Main Motivation

To meet demand of increase in the telecommunication data transmission.



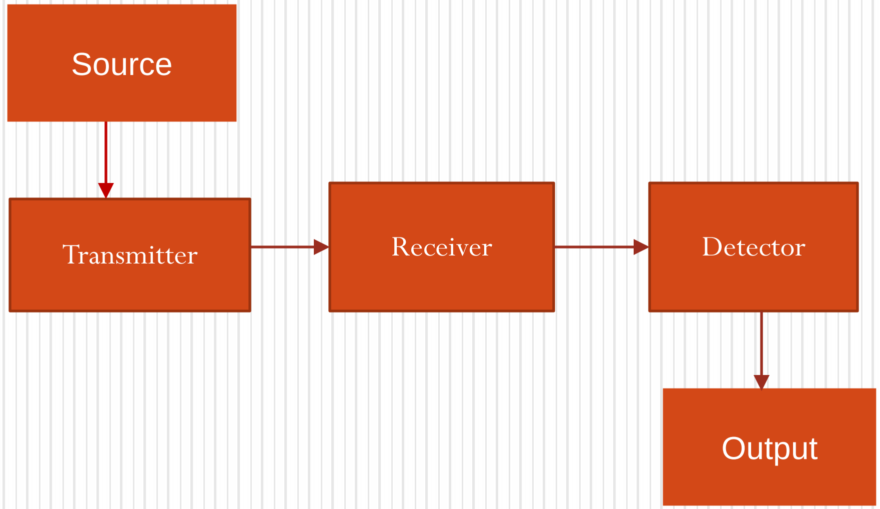
Physical Principle

Total internal reflection (critical angle, using Snell's law).

Main Advantages

- Higher bandwidth (extremely high data transfer rate).
- Less signal degradation.
- Less costly per meter.
- Lighter and thinner then copper wire.
- Lower transmitter launching power.
- Less susceptible to electromagnetic interference.
- Flexible use in mechanical and medical imaging systems.

OPTICAL FIBER COMMUNICATION SYSTEM



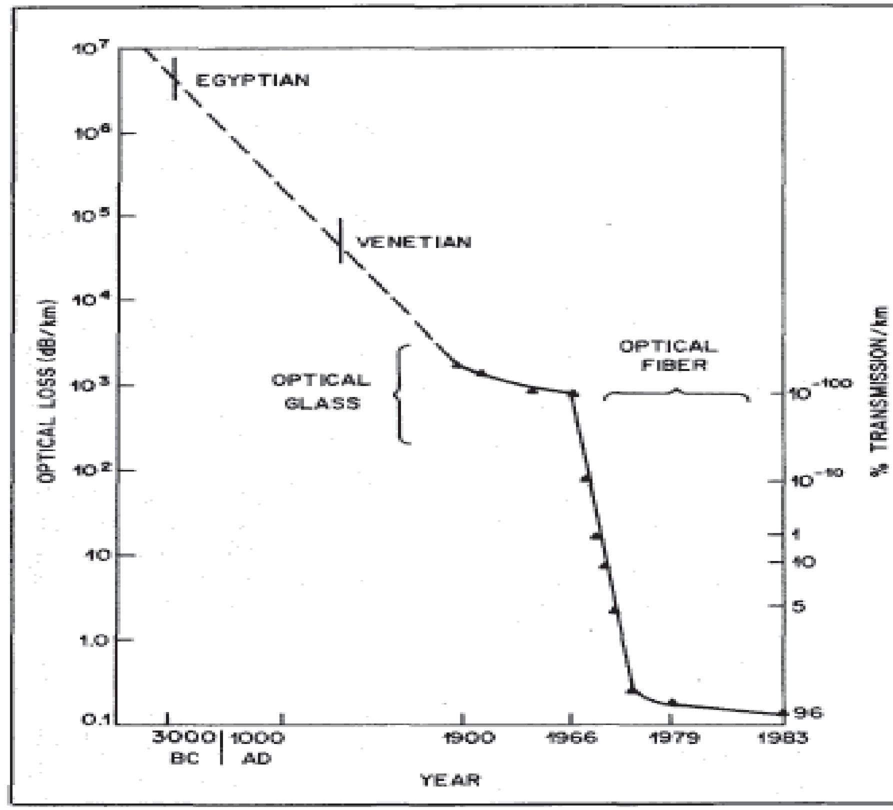
Main Applications

- Telecommunications.
- Sensors.
- Fiber Lasers.
- Bio-medical.
- Automotive and many other industories.

Fibre Optics Material Choice?

(Nobel Prize 2009)

- H.H.Hopkins and N.S.Kapnay in 1950's used cladding fiber:
- Good image properties demonstrated for 75 cm long fiber *[Nature* 173, 39 (1954)].
- Application found use in medicine as gastroscopes, endoscopes etc.
- Advent of Laser in 1960's , but didn't work for optical communication due to attenuation problem!.
- In 1964 critical theoretical suggestion by, Charles K. Kao and Charles Hockam :
- For long range communication system the loss limit was set to 20 dB/Km (was ~ 1000 db/Km or higher at that time!).
- Pure form of Silica, by reducing impurities i.e., the optical losses were not due to glass itself, but impurities in it.
- Limit met by doping titanium in fused core and pure fused Silica in cladding [Appl. Phys. Lett. 17, 423 (1970)].
- Today the lower limit is below 0.2 dB/KM.
- Plastic and Plastic–clad Silica , as well few other optical fibers materials (useful for some applications), has been invented.



Optical loss in glass as function of time.

(Source: Nagel S.(1989). Optical Fiber: The expanding medium. IEEE Circuits Devices Magaz. March, 36.)

Silica and Plastic as Fibre Optic Materials

Silica Fibers

- Both core and cladding are of glass.
- Very pure SiO_2 or fused quartz.
- Germanium or Phosphorus to increase the index of refraction.
- Boron or Flourine to decrease the index of refraction.
- Silica fibers mainly used due to their low intrinsic absorption at wavelengths of operation.
- Any other remaining impurities cause attenuation and scattering.

Plastic Fibers

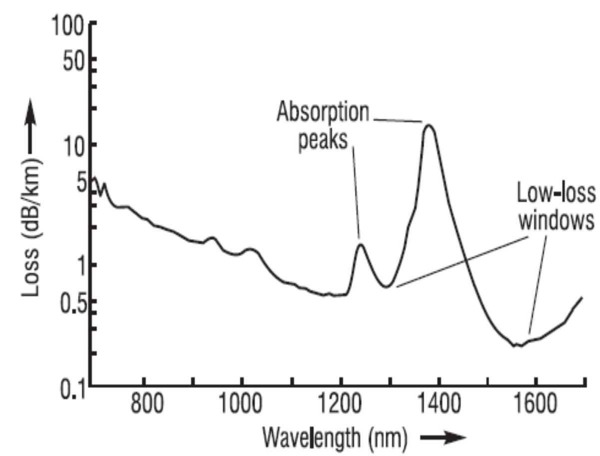
- Plastic core and plastic cladding.
- Polymethyl Methacrylate (most commonly used).
- Flexible and Light.
- Widely used in short distance applications.

Plastic-clad Fibers

- Glass as core and plastic as cladding.

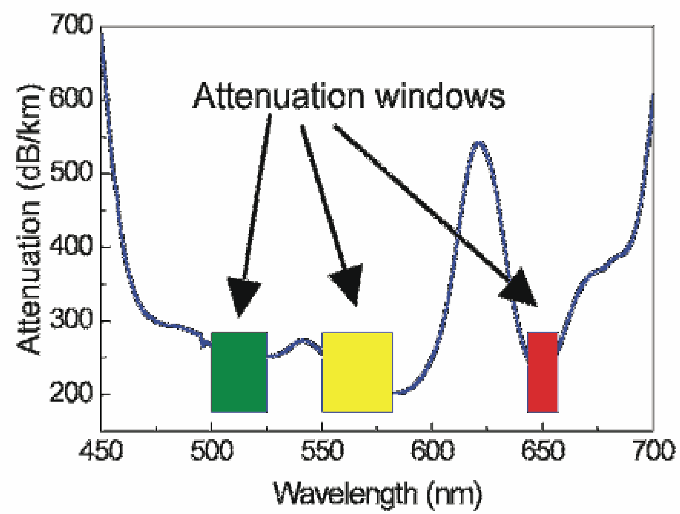
Which is better? (Plastic or Silica)

- Plastic less expensive, flexible, lighter.
- Plastic is larger in diameter, so easy to connect across joints.
- Plastic is less efficient then Silica.
- Plastic has more attenuation, and less bandwidth making it more suitable for shorter distances.



Attenuation Spectrum of Silica Fibers.

(Source: Miya,T.,Y.Tenuama, Thosaka, and T Miyashita , " An ultimate low loss single mode fiber at 1.55 mm," Electron. Letts, Vol 15, 106, 1979)



Attenuation Spectrum of Plastic Fibers.

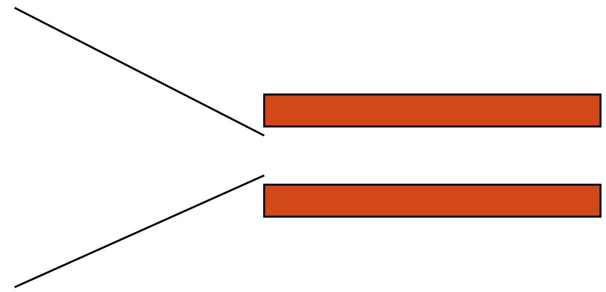
(Source: http://www.av.it.pt/conftele2009/Papers/31.pdf)

Main Characteristics of Optical Transmission Medium

- The ray entering the acceptance angle will be guided along the core.

- Acceptance angle is measure of the light-gathering power of the fiber.

- Higher Numerical Aperature (NA) mean higher coupling from source to fiber, and less losses across joints.



$NA = (n_1^2 - n_2^2)^{1/2}$

Attenuation

- Limit the optical power reaching the receiver. Power received can be related with the transmitted as:

$dB = -10 \log_{10}$ (power out / power input).

- Lower attenuation mean greater spacing and less cost of the communication system.

Main Causes of Attenuation?

Scattering

Due to interactions of photons with fiber medium.

Absorption (Intrinsic+Extrinsic)

By fiber itself (intrinsic) or due to impurities of water and metal, such as iron, nickle and chromium (extrinsic).

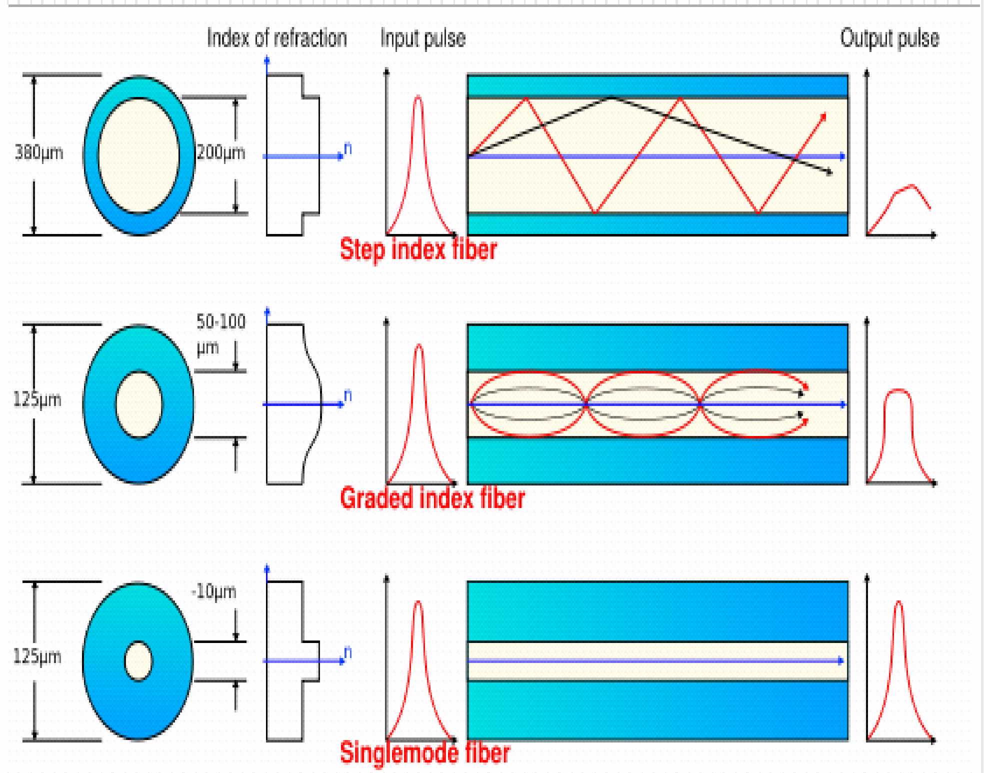
Bending and Geometrical Imperfections

- Due to physical stress on fiber.

- Core-cladding interface irregularities, diameter variations etc.

Single and Multimode Fibers

- Light propagated in optical fiber in form of modes.
- Spatial distributions of EM fields do not change with time.



Different Modes of Optical Fibers

(Source: http://en.wikipedia.org/wiki/Optical_fiber)

No of Modes?

- V number (normalized frequency) define number of possible modes for a fiber:

  $V = (2*\pi*a*NA) / \lambda$

  where a is radius of fiber, and λ is wavelength of light.

  For single mode propagation, $V < 2.405$.

Uniformly and Non-uniformly doped fibers.

Single Mode Fibers

- With the primary degrees of freedom of core cladding diameter and the difference of refractive indices between them they can be optimized for attenuation and dispersion.

- Light propagation can be studied using geometrical optics.

MultiMode Fibers

- Different modes can exist simulatenously on the same wavelength.
- Depending upon profile shape they can be:

  Multimode Step Index

  Multimode Graded Index

- The core index decreases like a parabolic-like law from the axis to the core cladding interface.

- Designed to minimize the intermodal dispersion effect (without significantly reducing the numerical aperature or the coupled power).

Fibre Optics Modes

Electromagnetic Waves propagating in an optical fiber consist of :

- **TE Modes.**
- **TM Modes.**
- **EH and HE Modes.**
- **Helical EH and HE modes contain both axial electric and magnetic fields.**
- **The mode can be EH or HE depending upon which component contribute more to the axial direction.**

Starting from Maxwell equations:

- **Wave equation in cylindrical coordinates is derived.**
- **The wave equation can be exactly solved for uniformly cored fibers.**
- **The classification of type of solutions lead to TE, EH, or EH and HE modes.**
- **For graded index non-uniform core profiles, approximate methods can be used.**

Single Mode Optical Fibre

- Supports Fundamental mode only.
- Transverse dimensions must not be much larger then wavelength.
- Geometrical optics approximation not valid and full electromagnetics calculations needs to be used.
- Defined by two degrees of freedom: core cladding diameters, and relative index differences.
- Maxwells eqs are solved with the BC defined by above to find the mode of propagation.
- Very large bandwidth which allows long distance transmissions, as no intermodal dispersions, from multiple spatial modes (more resistant to attenuation).
- Instrumentation applications as they maintain the coherence of light, and its polarization for certain types of fibres.
- Small core diameter, requiring very high precision at the connections, as the use of laser source.
- More expensive then multimode fibres.

Mode Analysis : Single Mode Fibers

- Fiber of transverse dimension ~ wavelength, full EM wave theory.
- Dielectric medium, so free charge density and current is zero.

$\Longrightarrow$ For a harmonic light wave, the electric field, in cylindrical coordinates follows :

$$\frac{\partial^2 E_z(\rho,\phi,z)}{\partial\rho^2}+\frac{1}{\rho}\frac{\partial^2 E_z(\rho,\phi,z)}{\partial\rho^2}+\frac{1}{\rho^2}\frac{\partial^2 E_z(\rho,\phi,z)}{\partial\phi^2}+\frac{\partial^2 E_z(\rho,\phi,z)}{\partial z^2}+n^2k^2E_z(\rho,\phi,z)=0$$

- Using separation of variables for three variables: $E_z(\rho,\phi,z)=F(\rho)\phi'(\phi)Z(z)$

$$\Longrightarrow \frac{d^2Z(z)}{dz^2}+\beta^2 Z(z)=0 \quad , \quad \frac{d^2\phi'(\phi)}{d\phi^2}+m^2\phi'(\phi)=0 \quad , \quad \frac{d^2F(\rho)}{d^2\rho^2}+\frac{1}{\rho}\frac{dF(\rho)}{d\rho}+(n^2k^2-\beta^2-\frac{m^2}{\rho^2})F(\rho)=0$$

- Combining these we can get the final solution in the form:

$$E_z(\rho,\phi,z,t)=AJ_m(k\rho)e^{im\phi}e^{i\beta z}e^{i\omega t} \quad \rho\le a \ , \qquad E_z(\rho,\phi,z,t)=BK_m(\gamma\rho)e^{im\phi}e^{i\beta z}e^{i\omega t} \quad \rho>a$$

(a is radius of core)

- By solving Maxwell equations, rest of E and H can be obtained, i.e. :

$$E_\rho, E_\phi, H_z, H_\rho, H_\phi$$

- β is called propagation constant., which can be obtained as set of solutions for given m.
- To find number of modes, the normalized frequency can be defined as:

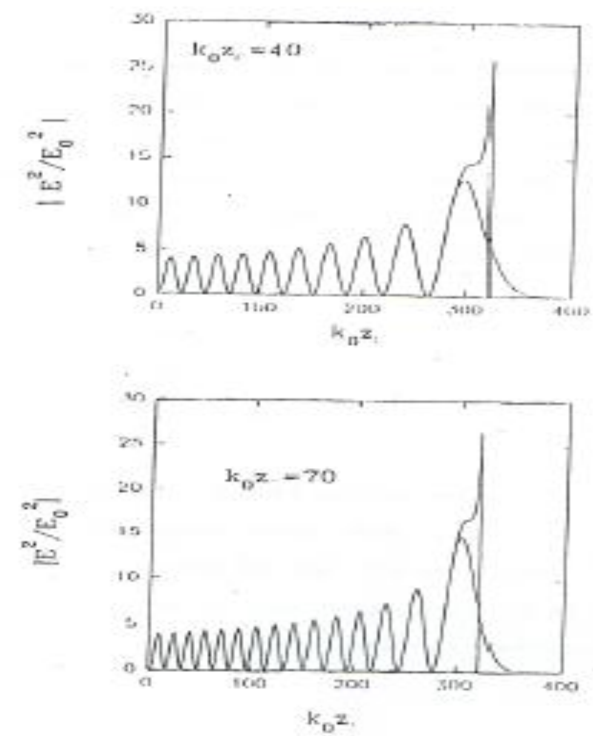
$$V=ka({n_1}^2-{n_2}^2)^{1/2}$$

- When V is large, then the numbr of modes: $N=\frac{V^2}{2}$

Multimode Fibers

Various approximate methods possible, such as:

- **WKB method.**
- **Rayleigh-Ritz method.**
- **Power-series expansion method.**
- **Finite element method.**
- **Stair-case approximation method.**



Comparison of WKB based results, with exact solutions (for case when exact solution is possible).
[Plots, I generated while student at Q.A.U (Pak), in 1994. Use of one of the earliest versions of Mathematica helped!].

WKB?

- **Origin from Quantum Mechanics, for solving one dimensional time-independent Schrodinger equation.**
- **Used in many fields, for wave equation solutions including Optics and Plasma Physics.**
- **An example from laser-produced plasmas .**

WKB Method for Fiber Optics

Staring from earlier defined form :

$$\frac{d^2F(\rho)}{d^2\rho^2}+\frac{1}{\rho}\frac{dF(\rho)}{d\rho}+(n^2k^2-\beta^2-\frac{m^2}{\rho^2})F(\rho)=0$$

Defining, $F^{'}(\rho)=\sqrt{\rho}F(\rho) \Longrightarrow \frac{d^2F^{'}(\rho)}{dr^2}+[E-U(\rho)]F^{'}(\rho)=0$

where $E=k^2n_1^{\,2}-\beta^2$ and $U(r)=[k^2n_1^{\,2}-k^2n^2(r)]+\frac{(m^2-1/4)}{r^2}$

for $U(r)<E \Longrightarrow \frac{d^2F^{'}}{dr^2}+\beta^2 f(r)F^{'}=0$ (oscillatory region)

and $U(r)>E \Longrightarrow \frac{d^2F^{'}}{dr^2}-\beta^2 f^{'}(r)F^{'}=0$ (damping region)

- For small variations of $f(r)$ within one wavelength (i.e. small variation of refractive index over wavelength) , WKB gave good approximate solution.
- Very poor solution at the turning points, and different types of solutions needs to be obtained which agree with WKB asymptotically.
- Various propagation characteristics such as number of propagating modes, rate of data transfer , delay time, impulse response etc of non-uniform core multimode fibers can be calculated.

Why WKB Analysis in Fibre Optics?

- Mathematically simpler, and physically easy to interpret.
- Very good approximation for weakly tunneling rays.
- Permittivity depends on z either as a small flucuation without restriction on length scale or gradually varying, which gives a generalisation of the WKB description.

How suitable is WKB Analysis?

- Require degree of accuracy largely decides which methods can be used i.e., other approximate can be preferred sometime.
- Widely used as method of choice, in the analysis for propagation of light in the multimode fibers.

Plasmons?

Quantized oscillations of electrons in metals conduction band.

Volume Plasmons.

Excitation in the bulk metal.

Nano-Plasmons.

Non-propagating excitation of conduction electrons with nano-structures.

Surface Plasmons.

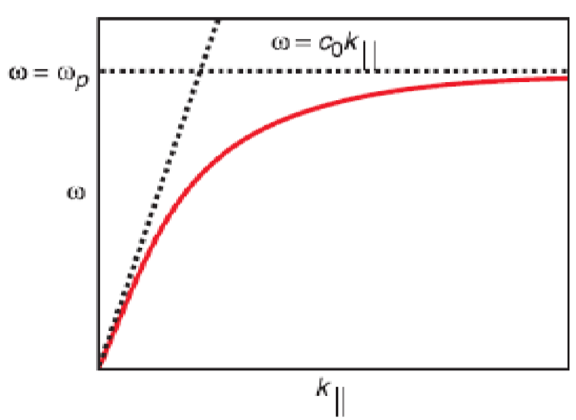
Longitudinal charge density oscillations at the metal surface.

(Lycurgus Cup --- Roman Nano-technology!)

Surface Plasmon Resonance

- Light is coupled to a thin layer of a nobel metal, by an evanescent wave, to create Surface Plasmon Polaritons.
- The energy and momentum are transferred from incident photons into the plasmons, for specific resonance conditions of :

- Incident light (p-polarization).
- Angle of incidence.
- Wavelength.
- Refractive index of the dielectric and the metal.
- Metal thickness.
- Silver or Gold commonly used.



Dispersion relation for surface plasmon polariton mode (red line).

(Source: V.M.Shalaev and S.Kawta, " Nanophotonics with Surface Plasmons", Elsevier, page. 195, 2007).

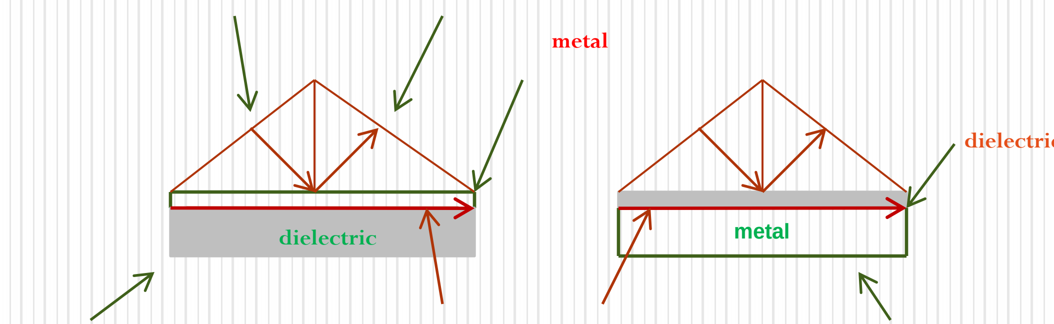
Prism Based Attenuated Total Reflection Methods

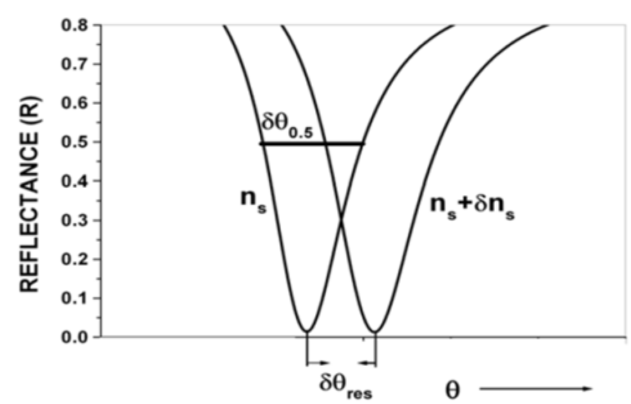
Kretschmann-Raether Geometry

- Prism with is interfaced with a metal and dielectric, for : refractive index of prism > refractive index of dielectric
- A light wave is incident on the prism-metal film interface at an angle of incidence larger then the critical angle .
- At resonance condition matching an evanescent wave propagate along the interface between the prism and the metal film.
- For properly chosen metal thickness, the evanescent wave and a surface plasmon at the metal–dielectric interface can couple.
- More acceptable then Otto geometry, as less susceptible to Fresnel losses, and easier to implement (metal film directly deposited on the prism).

Otto Geometry

- Light wave incident on the prism-dielectric film interface at an angle of incidence larger then critical angle.
- At resonance condition matching , for properly chosen dielectric thickness, the evanescent wave and a surface plasmon at the dielectric-metal interface can couple.





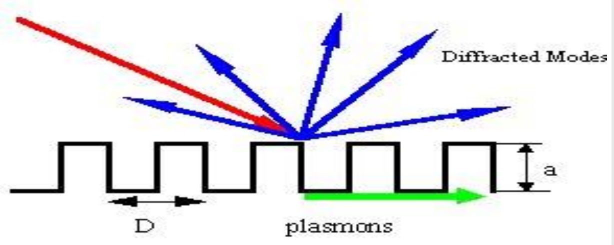
Reduction of incident light intensity at SPR condition matching. Peak shifts due to variation in refractive index of medium.

(Source : B.D.Gupta, and R.K.Verma, " Surface Plasmon Resonance Based –Fibre Optic Sensors:Principles, Probe Designs, and Some Applications '', Journal of Sensors, vol. 2009 , Article ID 979761, 12 pqges (2009). doi:10.1155/2009/979761)

Alternative Surface Plasmon Resonance Schemes

Diffracting Grating

- A light wave is incident from a dielectric medium on a metal grating.
- Diffraction gave rise to a series of diffracted waves.
- The diffraction waves can couple with a surface plasmon, at resonance condition , i.e. when the propagation constant of the diffracted wave and that of the surface plasmon are equal.

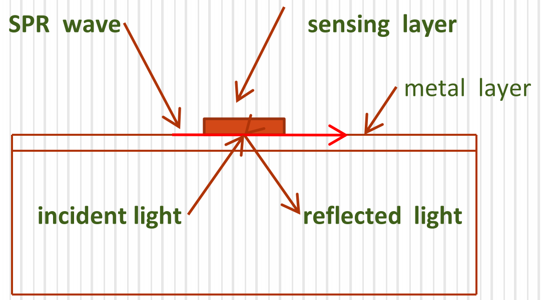


WaveGuide Coupling

- Can be excited by modes of a dielectric waveguide.
- A mode of dielectric waveguide propagates along the waveguide, and on entering the region of thin metal film, couples with a surface plasmon at the outer boundary of the metal.

Optical Fibre Based

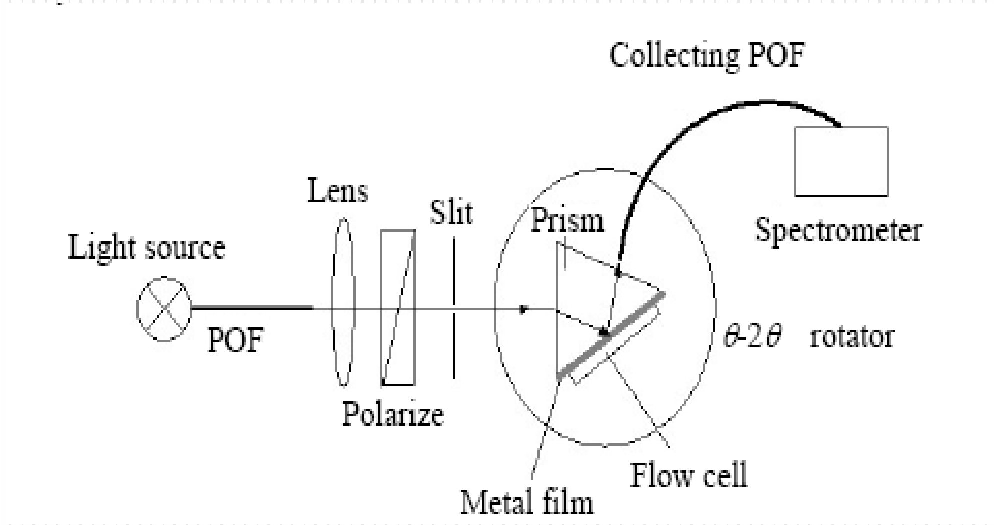
- Similar to Kretchmann prism configuration with fibre optics stand replacing the prism.
- Cladding layer (mostly from middle), is replaced with a metal layer.
- The optical wave is guided through total internal reflection.
- The light evanescently penetrates the metal layer.
- For phase matching for surface plasmon and the guided modes, the surface plasmon wave is propagated along the metal-dielectric boundary.



Schematics of a Surface Plasmon Resonance Experiment

Light Source → SPR Coupler → Detector → Data Processing

(Input light) (light with SPR signal) (data acquisition and digitization)



Experimental setup for spectral modulation surface plasmon resonance sensor .

(Source: R. Zheng, Y.Lu, Z.Xie, J.Tao, K.Lin and H.Ming , "Surface Plasmon Sensors Based on Polymer Optical Fibres", Journal of Electronic Science and Technology of China, Vol.6, No.4, pp. 357- 360, 2008.)

Characterizing Parameters

Sensitivity

Minimum detectable shift in the environment.

Detection Accuracy **(signal to noise ratio).**

Resolution

Smallest change in measurand which produces a detectable change in the sensor output. The term refers to a bulk refractive index resolution.

Reproducibility

Ability of the sensor to provide the same output when measuring the same value of the measurand under the same operating conditions over a period of time.

Range

The dynamic range describes the spread of the value of the measurand that can be measured by the sensor.

Why Optical Fiber Based SPR?

- Small in size.
- Remoteness.
- High Degree of Integration.
- Lower cost then commonly used Optical SPR configurations.
- Higher Sensitivity and Signal Detection efficiency.
- Various configurations.

Applications

- Wide variety of Bio-technology applications, which include:
  - Medical Diagnostics.
  - Environmental Sensing.
  - Ailmentary Emergency and Hygiene.

- Less time consuming and cost effective, in comparison to many other similar applications.
- Industrial Process Control.

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Fabrication and Characterization of Fibre Optics Based SPR

- Silver or Gold coated core of a polymer or glass clad fibre.
- Metal deposition (e.g., using vapor deposition techniques).
- Use of suitable lithographic techniques, to fabricate periodic optical fibre structures such as Long-period Fibre Gratings (LPFG) or Long period Waveguide Gratings (LPWG).

Glass or Polymer Optical Fibres

- Polymer of more current research interest, due to:
  - . Flexibility.
  - . Easy handling.
  - . High resistance to fracture.
  - . Perfect biocompatibility.

Single or Multimode Fibre

- Single mode optical fibre can obtain sharper resonance peaks.
- Need more polishing and tapering in the sensing region.

Some Design Variations

- Tapered Profiles.
- Side Polished Fibres.
- Multilayered Structured Device.
- Single or Multimode Fibres.

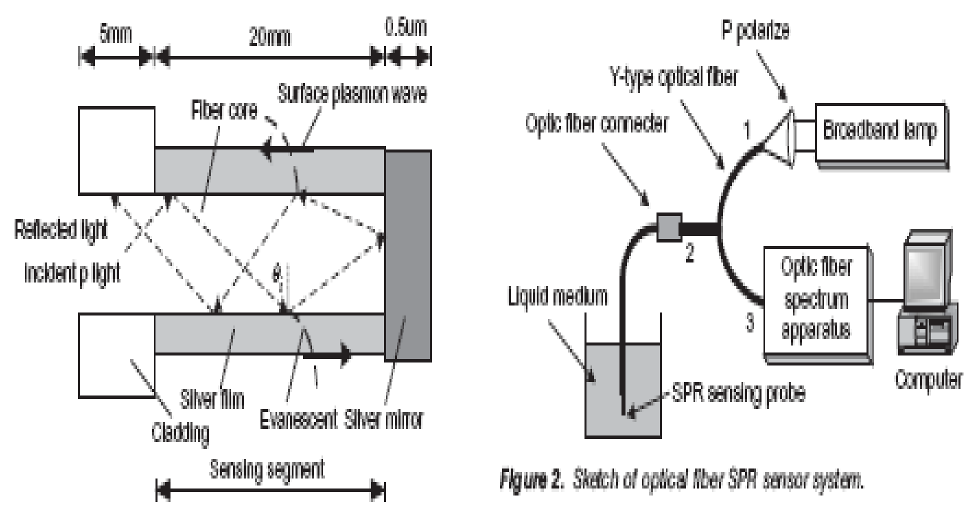
Fibre Optics SPR Sensor : Main Design Considerations

- **Fibre Optics Design Material.**

- **HiBi (Highly Birefringent) Fiber single mode or multi-mode.**

- **Sensor Geometry Design.**

- **Sensitivity, detection accuracy, reproducibility, operating range.**



Sketch of an optical fibre probe and optical fibre sensor system .

(Source: J.Zeng, D.Liang,:Application of Fiber Optic Surface Plasmon Resonance Sensor for Measuring Refractive Index"' Journal of Intelligent Material Systems and Structures vol.17; pp.787-792, 2006.)

Ciao!