CH4

1. **Describe in general terms liquid-phase techniques for the preparation of multi component glasses for optical fibers. Discuss with the aid of a suitable diagram one melting method for the preparation of multi component glass.**
    a. Preparation of ultrapure material powders which are usually oxides or carbonates.
    b. Melt these powdered to form a homogeneous, bubble-free multi component glass.

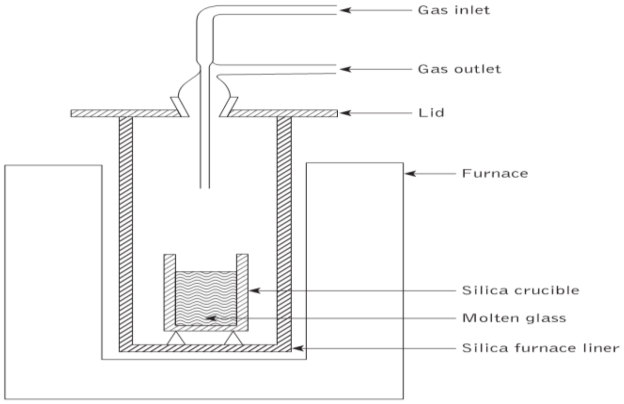

Figure 4.1 Glassmaking furnace for the production of high-purity glasses [Ref. 4]

2. **Indicate the major advantages of vapor-phase deposition in the preparation of glasses for optical fibers. Briefly describe the various vapor-phase techniques currently in use.**
    a. Used to produce silica-rich glasses of the highest transparency and with the optimal optical properties.
        i. **Vapor axial deposition (VAD)**.
        ii. **Outside Vapor-phase Oxidation process (OVPO).**
        iii. **Modified chemical Vapor deposition (MCVD).**
        iv. **Plasma-activated chemical Vapor deposition (PCVD).**

3.
    a. **Compare and contrast, using suitable diagrams, the outside vapor-phase oxidation (OVPO) process and the modified chemical vapor deposition (MCVD) technique for the preparation of low-loss optical fibers.**
    b. **Briefly describe the salient features of vapor axial deposition (VAD) and the plasma-activated chemical vapor deposition (PCVD) when applied to the preparation of optical fibers.**

VAD	OVPO	MCVD	PCVD

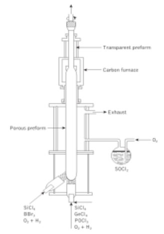

Figure 4.8 The VAD process [Ref. 21]

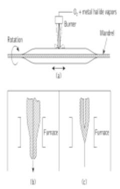

Figure 4.7 Schematic diagram of the OVPO process for the preparation of optical fibers: (a) soot deposition; (b) preform sintering; (c) fiber drawing. Reprinted from Ref. 17 with permission from Elsevier

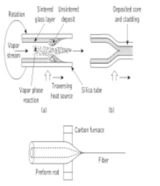

Figure 4.9 Schematic diagram showing the MCVD method for the preparation of optical fibers: (a) deposition; (b) collapse to produce a preform; (c) fiber drawing

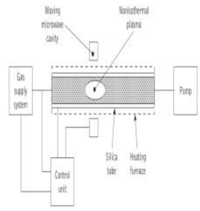

Figure 4.10 The apparatus utilized in the PCVD process

4. **Discuss the drawing of optical fibers from prepared glasses with regard to:**
    a. **Multi component glass fibers;**
    b. **Silica-rich fibers**

    There is two-stage process in which initially the pure glass is produced and converted into a form (rod or preform) suitable for making the fiber. A drawing or pulling technique is then employed to acquire the end product. The methods of preparing the extremely pure optical glasses generally fall into two major categories which are:
    a. Conventional glass refining techniques in which the glass is processed in the molten state (melting methods) producing a multi component glass structure.
    b. Vapor -phase deposition methods producing silica-rich glasses which have melting temperatures that are too high to allow the conventional melt process.

5. **List the various silica-based optical fiber types currently on the market indicating their important features. Hence, briefly describe the general areas of application for each type.**

6. **Outline the developments that have taken place in relation to plastic optical fibers since 1996, with particular reference to contrasting the performance attributes of PF-POF with PMMA POF.**
    Reduction of transmission loss for POF was achieved, however, in 1996 by employing amorphous perfluorinated polymer for the core material. Hence a graded index POF using poly perfluoro-butenylvinyl ether or PFBVE provided for both lower attenuation and potentially high capacity. This new type of POF, which has been named perfluorinated (PF) plastic optical fiber (PF-POF) produced by Asahi Glass Co. (the perfluorinated material is also called CYTOP®), has been commercially available since June 2000.

7. **Briefly describe the major reasons for the cabling of optical fibers which are to be placed in a field environment. Thus state the functions of the optical fiber cable.**
    a. **Fiber protection:** To protect against fiber damage and breakage both during installation and throughout the life of the fiber.
    b. **Stability of the fibre transmission characteristics**: To have good stable transmission and minimized optical attenuation.

c. **Cable strength:** To improved by incorporating a suitable strength member and by giving the cable a properly designed thick outer sheath.
d. **Identification and jointing of the fibers within the cable:** To use multiple jointing techniques rather than jointing each fiber individually.

8. **Explain how the Griffith theory is developed in order to predict the fracture stress of an optical fiber with an elliptical crack.**
    a. This theory assumes that the surface flaws are narrow cracks with small radii of curvature at their tips, It indicates that deeper cracks have higher stress at their tips.

    b. **Silica has a Young's modulus of 9×10^10 Nm−2 and a surface energy of 2.29 J. Estimate the fracture stress in psi for a silica optical fiber with a dominant elliptical crack of depth 0.5µm. Also, determine the strain at the break for the fiber (1 psi ≡ 6894.76 N m−2).**

    33-35

9. **Another length of the optical fiber described in Problem 4.8 is found to break at 1% strain. The failure is due to a single dominant elliptical crack. Estimate the depth of this crack (E =stress/strain)**

10. **Describe the effects of stress corrosion on optical fiber strength and durability.**
    a. There is another effect which reduces the fiber fracture stress below that predicted by the Griffith equation. It is due to the slow growth of flaws under the action of stress and water and is known as stress corrosion. Stress corrosion occurs because the molecular bonds at the tip of the crack are attacked by water when they are under stress. This causes the flaw to grow until breakage eventually occurs.

    b. **It is found that a 20 m length of fused silica optical fiber may be extended to24 m at liquid nitrogen temperatures (i.e. little stress corrosion) before failure occurs. Estimate the fracture stress in psi for the fiber under these conditions. Young's modulus for silica is 9×10^10Nm−2 and 1 psi ≡ 6894.76 N m.**

    Strain = ΔL/L → Sf=Strain*E →Sf psi

11. **Outline the phenomena that can affect the stability of the transmission characteristics in optical fiber cables and describe any techniques by which these problems may be avoided**
    a. The phenomenon known as microbending, results from small lateral forces exerted on the fiber during the cabling process and it causes losses due to radiation in both multimode and single-mode fibers

b. It has become accepted when:
   i. A fiber is excited by a diffuse Lambertian source, launching all possible modes, and is referred to as a uniform or fully filled mode distribution.
   ii. Due to a significant amount of mode coupling and mode attenuation, the distribution of optical power becomes essentially invariant with the distance of propagation along the fiber. This second distribution is generally referred to as a steadystate or equilibrium mode distribution, which typically occurs after transmission over approximately 1 km of fiber.

12. Discuss optical fiber cable design with regard to:

a. Fiber buffering;

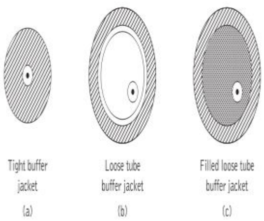

Figure 4.24 Techniques for buffering of optical fibers [Ref. 65]: (a) tight buffer jacket; (b) loose tube buffer jacket; (c) filled loose tube buffer jacket

b. Cable strength and structural members;

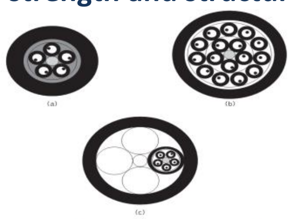

Figure 4.26 Optical fiber cable structures: (a) one-layer cable incorporating single-fiber loose tube buffers; (b) layer cable incorporating single-fiber loose tube buffers in two layers; (c) unit cable construction

c. Layered cable construction;

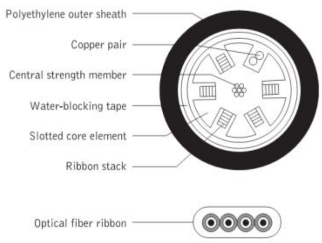

Figure 4.27 Slotted core cable with four fiber ribbons incorporating a total of 100 fibers

d. Cable sheath and water barrier.

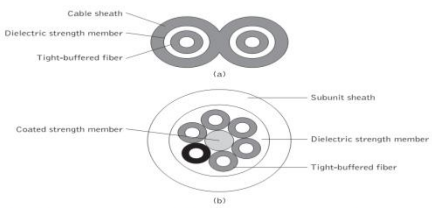

Figure 4.29 Indoor cables: (a) interconnect cable incorporating two optical fibers; (b) 6-fiber subunit of a 48-fiber cable

Further, compare and contrast possible cable designs for multifiber cables, making particular reference to unit cables.

$$S_t = \left(\frac{\gamma_p E}{4 l_a}\right)^{\frac{1}{2}}$$

St : is the theoretical cohesive strength,
γp: is the surface energy of the material,
E : is Young's modulus for the material (stress/strain), and
la : is the atomic spacing or bond distance.

$$K_I = SYC^{\frac{1}{2}} \tag{4.7}$$

where S is the macroscopic stress on the fiber, Y is a constant dictated by the shape of the crack (e.g. $Y = \pi^{\frac{1}{2}}$ for an elliptical crack, as illustrated in Figure 4.19) and C is the depth of the crack (this is the semimajor axis length for an elliptical crack).

Further, the Griffith theory gives an expression for the critical stress intensity factor K_{IC} where fracture occurs as:

$$K_{IC} = (2E\gamma_p)^{\frac{1}{2}} \tag{4.8}$$

Combining Eqs (4.7) and (4.8) gives the Griffith equation for fracture stress of a crack S_f as:

$$S_f = \left(\frac{2E\gamma_p}{Y^2 C}\right)^{\frac{1}{2}} \tag{4.9}$$

It is interesting to note that S_f is proportional to $C^{-\frac{1}{2}}$. Therefore, S_f decreases by a factor of 2 for a fourfold increase in the crack depth C.

$$F = 1 - \exp\left[-\left(\frac{S}{S_0}\right)^m \left(\frac{L}{L_0}\right)\right]$$

where m : is the Weibull distribution parameter,
S0 : is a scale parameter,
L : is the fiber length and
L0 : is a constant with dimensions of length.

CH5

1. **State the two major categories of fiber–fiber joint, indicating the differences between them.**

Fiber splices	Demountable fiber connectors (simple connectors)
- Semi permanent or permanent joints. - Analogous to electrical soldered joints.	- Removable joints which allow easy, fast, manual coupling and uncoupling of fibers. - Analogous to electrical plugs and sockets

   a. **Briefly discuss the problem of Fresnel reflection at all types of optical fiber, and indicate how it may be avoided.**
      i. **(Definition):** Fresnel reflection happen when a small proportion of the light may be reflected back into the transmitting fiber causing attenuation at the joint. It associated with the step changes in refractive index at the jointed interface (i.e. glass-air-glass).
      ii. **(Effect):** Fresnel reflection may give a significant loss at a fiber joint even when all other aspects of the connection are ideal.
      iii. **(Solve):** Fresnel reflection at a fiber connection can be reduced to a very low level through the use of an index-matching fluid in the gap between the jointed fibers. When the index-matching fluid has the same refractive index as the fiber core, losses due to Fresnel reflection are in theory eradicated.

   b. **A silica multimode step index fiber has a core refractive index of 1.46, determine the optical loss in decibels due to Fresnel reflection at a fiber joint with:**
      i. **Small air gap; (N1=1.46 , N=1) → *R *L**
      ii. **An index-matching epoxy which has a refractive index of 1.40. (N1=1.46 , N=1.40) → *R *L**

   It may be assumed that the fiber axes and end faces are perfectly aligned at the joint.

$$r = \left(\frac{n_1 - n}{n_1 + n}\right)^2 \qquad \mathrm{Loss}_{\mathrm{Fres}} = -10\log_{10}(1 - r)$$

2. **The Fresnel reflection at a butt joint with an air gap in a multimode step index fiberis 0.46 dB. Determine the refractive index of the fiber core.**
   (L=0.46 →*R , R=__, N=1 → *N1)

3.
   a. **Describe the three types of fiber misalignment which may contribute to insertion loss at an optical fiber joint.**
      i. Longitudinal misalignment;

ii. Lateral misalignment; reduces the overlap region between the two fiber cores

iii. Angular misalignment;

b. A step index fiber with a 200µm core diameter is butt jointed. The joint which is index matched has a lateral offset of 10µm but no longitudinal or angular misalignment. Using two methods, estimate the insertion loss at the joint assuming the uniform illumination of all guided modes. (N1=N, Y=10 µm, A=200µm →)

Multimode fiber joints	
1. Longitudinal misalignment	
step index	**graded index**

Multimode fiber joints	
2. Lateral misalignment	
step index	**graded index**
$\eta_{\text{lat}} \simeq \frac{16(n_1/n)^2}{[1+(n_1/n)]^4}\frac{1}{\pi}\left\{2\cos^{-1}\left(\frac{y}{2a}\right)-\left(\frac{y}{a}\right)\left[1-\left(\frac{y}{2a}\right)^2\right]^{\frac{1}{2}}\right\}$	$\eta_{\text{lat}} = 1 - L_t$
n1: core refractive index, **n:** medium refractive index, **y:** lateral offset of the fiber core axes, **a:** fiber core radius	$L_t = \frac{2}{\pi}\left(\frac{y}{a}\right)\left(\frac{\alpha+2}{\alpha+1}\right) \quad \text{for } 0 \le y \le 0.2a$
$\text{Loss}_{\text{lat}} = -10\log_{10}\eta_{\text{lat}}$ dB	$\text{Loss}_{\text{lat}} = -10\log_{10}\eta_{\text{lat}}$ dB
α: parabolic refractive index profile where α= ∞	**α:** parabolic refractive index profile where α=2
uniform distribution of all guided modes only Lt= 0.64 Y/A	uniform distribution of all guided modes only Lt 0.85 Y/A
uniform distribution of both guided plus leaky modes Lt= 0.5 Y/A	uniform distribution of all guided and leaky modes 0.75 Y/A

Multimode fiber joints	
3. Angular misalignment	
step index	graded index
$$\eta_{ang} \simeq \frac{16(n_1/n)^2}{[1+(n_1/n)]^4}\left[1-\frac{n\theta}{\pi n_1(2\Delta)^{\frac{1}{2}}}\right]$$	
Θ: angular displacement in radians, **Δ:** relative refractive index difference for the fiber. NA= $n_1(2\Delta)^{\wedge 1/2}$	
$$\text{Loss}_{ang} = -10\log_{10}\eta_{ang}$$	
Core diameters mismatch	$$\text{Loss}_{CD} = \begin{cases} -10\log_{10}\left(\frac{a_2}{a_1}\right)^2 \text{ (dB)} & a_2 < a_1 \\ 0 \text{ (dB)} & a_2 \geq a_1 \end{cases}$$
numerical apertures mismatch	$$\text{Loss}_{NA} = \begin{cases} -10\log_{10}\left(\frac{NA_2}{NA_1}\right)^2 \text{ (dB)} & NA_2 < NA_1 \\ 0 \text{ (dB)} & NA_2 \geq NA_1 \end{cases}$$
refractive index profiles mismatched	$$\text{Loss}_{RI} = \begin{cases} -10\log_{10}\frac{\alpha_2(\alpha_1+2)}{\alpha_1(\alpha_2+2)} \text{ (dB)} & \alpha_2 < \alpha_1 \\ 0 \text{ (dB)} & \alpha_2 \geq \alpha_1 \end{cases}$$
Combined	$$\text{Loss}_{int} = \begin{cases} -10\log_{10}\frac{(a_2 NA_2)^2(\alpha_1+2)\alpha_2}{(a_1 NA_1)^2(\alpha_2+2)\alpha_1} \text{ (dB)} & a_2 > a_1,\ NA_2 > NA_1,\ \alpha_2 > \alpha_1 \\ 0 \text{ (dB)} & a_2 \leq a_1,\ NA_2 \leq NA_1,\ \alpha_2 \leq \alpha_1 \end{cases}$$

4. **A graded index fiber has a characteristic refractive index profile (α) of 1.85 and a core diameter of 60µm. Estimate the insertion loss due to a 5µm lateral offset at an index-matched fiber joint assuming the uniform illumination of all guided modes. (A=30µm, α=1.85, Y=5µm →L)**

5. **A graded index fiber with a parabolic refractive index profile (α=2) has a core diameter of 40µm. Determine the difference in the estimated insertion losses at an index-matched fiber joint with a lateral offset of 1µm (no longitudinal or angular misalignment). When performing the calculation assume (A=20µm, Y=1µm, →)**
   a. **The uniform illumination of only the guided modes. (Lt= 0.85 Y/A)**
   b. **The uniform of both guided and leaky modes. (Lt= 0.75 Y/A)**

6. **A graded index fiber with a 50µm core diameter has a characteristic refractive index profile (α) of 2.25. The fiber is jointed with index matching and the connection exhibits an optical loss of 0.62 dB. This is found to be solely due to a lateral offset of the fiber ends. Estimate the magnitude of the lateral offset assuming the uniform illumination of all guided modes in the fiber core. (A=25µm, α= 2.25, Loss=0.62dB,**