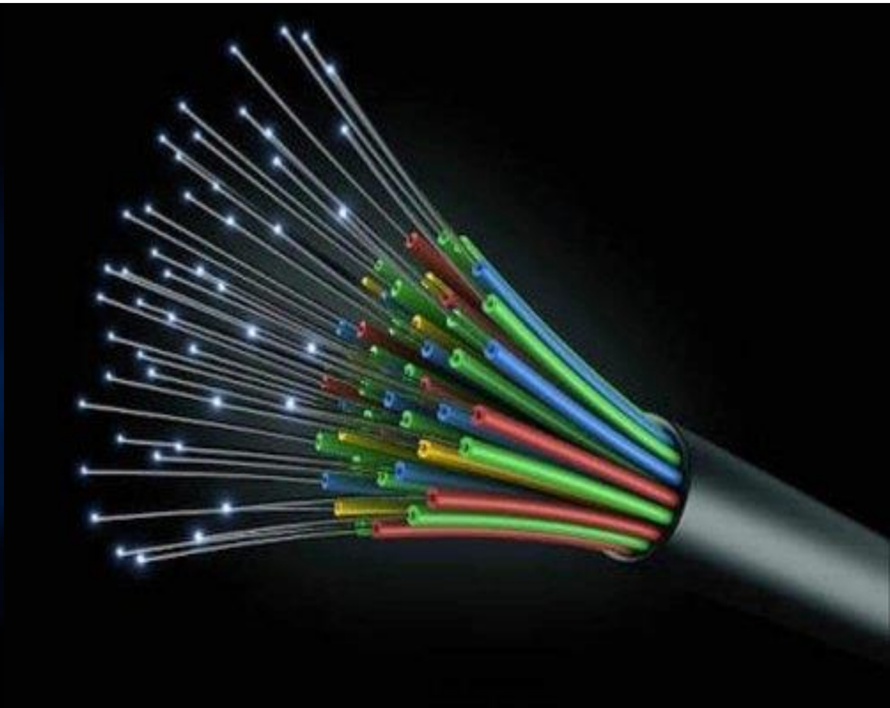
UNIT-IV

Laser Holography and Optical Fibre

Lecture-7: Optical Fibre

Content of Lecture

- GRADED INDEX OPTICAL FIBER
- MULTIMODE GRADED INDEX(MMGI) OPTICAL FIBER
- NUMBER OF PROPAGATING MODES IN MMGI
- NUMERICAL APERTURE FOR GRADED INDEX OPTICAL FIBER
- V-NUMBER AND CUT-OFF PARAMETERS OF FIBERS
- DIFFERENCES BETWEEN STEP INDEX AND GRADED INDEX FIBERS

Graded Index Optical Fiber

- In graded index optical fiber, refractive index of the core region decreases with the radial distance from the maximum value of n_1 at the starting boundary (inner side) to a constant value n_2 beyond the core radius (a).
- The index variation may be given as

$$n(r) = n_1 \left[a - 2\Delta \left(\frac{r}{a} \right)^2 \right]^{1/2} \text{ for } r < a \text{ (core)}$$

$$= n_1 \, [1 - 2\Delta]^{1/2} \text{ for } r \geq a \text{ (cladding)}$$

$$\Delta = \frac{n_1 - n_2}{n_1}$$

Multimode Graded index(MMGI) Optical Fiber

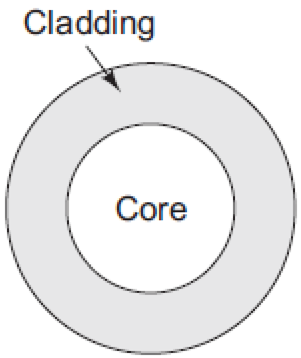
•In the multimode graded index optical fiber, the index of refraction in the core decreases continuously in a parabolic manner from a maximum value at the centre of the core to a minimum constant value of the core–cladding interface (Fig. 16.6).

• The rays travelling close to the fiber axis have shorter paths in comparison to the rays travelling into the outer regions of the core.

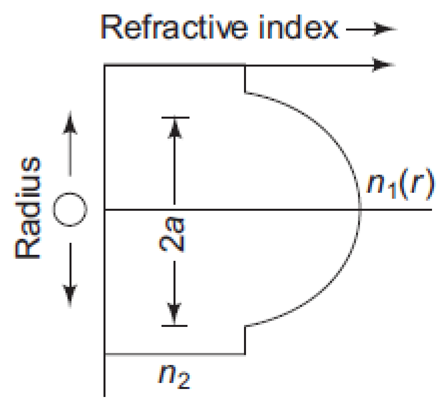
• Since, the velocity of light ray is inversely proportional to the refractive index and the axial rays are transmitted through a region of higher refractive index, so they travel with a lower velocity than the extreme rays.

• This compensates for the shorter path lengths and reduces the dispersion in the fiber. MMGI optical fibers have the advantage of large core diameters (greater than 30 mm) coupled with the bandwidths suitable for long-distance communication.

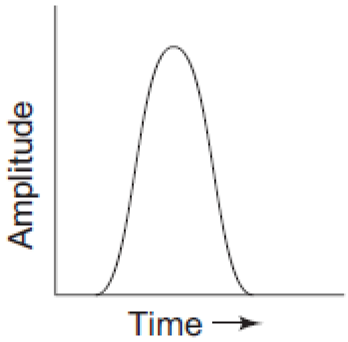
Multimode Graded index(MMGI) Optical Fiber



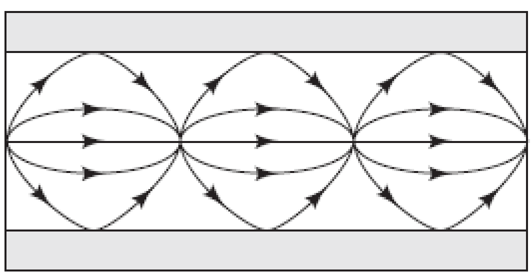
Multimode graded index fibre
(a)



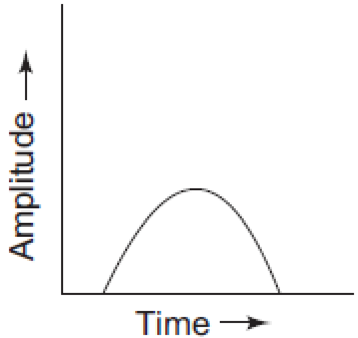
Refractive index profile
(b)



Input pulse
(c)



Pulse propagation
(d)



Output pulse
(e)

NUMBER OF PROPAGATING MODES IN MMGI

•The numerical aperture (NA), relative refractive index difference (D), profile parameter (α), and normalized frequency (v) determine the number of propagating modes in MMGI fibers.

• When a fine value of α(most commonly α = 2) is used, then the number of supported modes for a large number of modes is reduced according to the expression

$$N_\alpha = \frac{\alpha}{\alpha+2}\left(\frac{v^2}{2}\right) = \frac{\alpha}{\alpha+2}\left(\frac{2\pi a}{\lambda}\right)^2 \frac{(\mathrm{NA})^2}{2} \qquad N_\alpha = \frac{\alpha}{\alpha+2}\left(\frac{2\pi a}{\lambda}\right)^2 n_1^2\Delta$$

Where $\Delta = \frac{n_1 - n_2}{n_1}$, a is core radius and λ is the wavelength.

• The maximum number of modes supported by GI fiber is $N_{\max} = \frac{V^2}{4}$

Where V is referred to as V- number, known as normalized frequency of cut-off.

NUMERICAL APERTURE FOR GRADED INDEX OPTICAL FIBER

- In a GI fiber, the numerical aperture is a function of position across the core.
- So it can be expressed in terms of local numerical aperture NA(r), which is a function of radius of the core. NA(r) at the position r is expressed as

$$\begin{aligned} \mathrm{NA}(r) &= [n_1^2(r) - n_2^2]^{1/2} \\ &\simeq \mathrm{NA}(r=0)\sqrt{1-\left(\frac{r}{a}\right)^x} \quad \text{for } r \le a \\ &= 0 \text{ for } r > a \end{aligned}$$

Where $n_1(r)$ is the varying refractive index of the core as the function of r, n_2 is the refractive index of the cladding, a is the radius of the core, x is the parameter describing the refractive index profile variation, and NA(r = 0) is the numerical aperture at the centre of the fiber core.

V-NUMBER AND CUT-OFF PARAMETERS OF FIBERS

- The number of modes supported by an optical fiber is given in terms of some cut-off parameters such as normalized frequency of cut-off, referred to as V-number. V-number is mathematically expressed as; The refractive index of these.

$$V = \frac{\pi d}{\lambda_0}\sqrt{n_1^2 - n_2^2}$$

$$V = \frac{\pi d}{\lambda_0}(\text{NA})$$

Where λ_0 is the wavelength of the light propagating in the multimode glass fiber, d = 2a is the diameter of the core, and NA is the numerical aperture.

- If the external medium around the fiber has the refractive index n_0, then Eq. (12) can be given as

$$V = \frac{\pi d}{\lambda_0} n_0 (\text{NA})$$

$$\text{NA} = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$$

Where V-parameter is considerably larger than unity.

COMPARISON OF SINGLE-MODE AND MULTIMODE INDEX FIBRES

Single-mode fibre	*Multimode fibre*
1. An SMSI fibre has its core diameter smaller than an MMSI fibre.	1. An MMSI fibre has greater diameter than an SMSI fibre.
2. The range of core diameter is 4–10 μm depending on the wavelength of propagating light. Here, cladding is about 120 μm.	2. The range of core diameter is 25–110 μm and the cladding diameter is in the range 130 μm–510 μm.
3. Difference between the refractive indices of core and cladding is small.	3. Difference between the refractive indices of core and cladding is comparatively large.
4. Single mode is propagated through the core.	4. Many modes are propagated.
5. Small radii of single-mode fibres make it difficult to launch optical power into fibre.	5. Due to large radii, it is easy to launch optical power into the fibre.
6. A single-mode fibre requires more sophisticated light source to launch optical power in small core. Usually, laser diodes are used.	6. A multimode fibre requires simple sources such as LED.
7. Single-mode fibres are more expensive.	7. Multimode fibres are cheaper.
8. Single-mode fibres are free from intermodal dispersion.	8. Multimode fibres suffer intermodal dispersion.
9. NA of single-mode fibres are small.	9. NA of multimode fibres are large.
10. Single-mode fibres have high information carrying capability.	10. Multimode fibres have low information carrying capability.
11. Single-mode fibres are used for short distance communication.	11. Multimode fibres are used for long distance communication.

DIFFERENCES BETWEEN STEP INDEX AND GRADED INDEX FIBERS

Step index fibre	*Graded index fibre*
1. In an SI fibre, core has a constant refractive index.	1. In a GI fibre, refractive index of core material decreases continuously from core to cladding.
2. The refractive index profile for an SI fibre is expressed as $n(r) = n_1$ when, $0 < r < a$ (core) $= n_2$ when, $r > a$ (cladding)	2. The refractive index profile of a GI fibre can be given as $n^2(r) = n_1^2\left[1-\left(\frac{r}{a}\right)^2\right]$ $0 < r < a$ (core) $= n_2^2$, $r > a$ (cladding)
3. There is a high attenuation in SI fibre.	3. There is lower attenuation.
4. In an SI fibre, pulse dispersion is expressed as $\Delta t = \frac{n_1 l}{c}\left(\frac{n_1}{n_2}-1\right) = \frac{n_1 l}{c}\Delta$ where l is the length of the fibre.	4. In a GI fibre, pulse dispersion can be given as $\Delta t = \frac{n_2 l}{2c}\left(\frac{n_1-n_2}{n_2}\right)^2 = \frac{n_2 l}{2c}\Delta^2$ where l is the length of the fibre.
5. In an SI fibre, there is sudden reflection of light from core–cladding interface.	5. In a GI fibre, there is smooth bending of propagating light approaching the cladding.
6. An SI fibre (multimode) has bandwidth-length product of 50 MHz km.	6. A GI fibre can have the bandwidth-length product of 200 MHz km to 10 GHz km.

Example-1: An SI fibre has core refractive index of 1.566 and cladding refractive index of 1.56. If the operating wavelength of the rays is 0.84 μm, calculate the cut-off parameter and the number of modes which are supported by this fibre. The diameter of core = 50 μm.

Solution

We know that cut-off parameter or cut-off number is given

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2}$$

Given that

$$2a = 50\ \mu\text{m}$$
$$n_1 = 1.566$$
$$n_2 = 1.560$$
$$\lambda = 0.84\ \mu\text{m}$$

Putting these values in the above equation, we get

$$V = \frac{3.14 \times 50 \times 10^{-6}}{0.84 \times 10^{-6}}\sqrt{(1.566)^2 - (1.560)^2}$$
$$= \frac{157}{0.84}\sqrt{2.4524 - 2.4336}$$
$$= 186.90 \times 0.1371$$
$$= 25.63$$

Maximum number of modes is given as

$$N_{\max} = \frac{V^2}{2}$$
$$= \frac{(25.63)^2}{2}$$
$$= 328.44845$$
$$= 329$$

Example-2: An SMSI fibre is made with a core diam eter of 10 µm and is coupled to a laser that produces 1.8 µm light.

Its core glass has a refractive index of 1.55 and the maximum cut-off number for the given fibre is 2.405.

(i) Find the maximum value required for the normalized index difference.

(ii) Find the refractive index required for the cladding glass.

(iii) Find the fibre acceptance angle.

Solution

(i) We know that the cut-off number is given as

$$V = \frac{2\pi a}{\lambda}(\text{NA})$$

Given that $2a = 10\ \mu\text{m}$

$\lambda = 1.8\ \mu\text{m}$

$V = 2.405$

Now

$$(\text{NA})_{\max} = \frac{V_{\max}\lambda}{2\pi a} = \frac{2.405 \times 1.8\,\mu\text{m}}{3.14 \times 10\,\mu\text{m}} = 0.1379$$

Normalized index difference

$$\Delta = \frac{1}{2}\left(\frac{\text{NA}}{n_1}\right)^2 = \frac{1}{2}\left(\frac{0.1379}{n_1}\right)^2 = 0.00396$$

(ii) The cladding index required is

$$n_2 = n_1(1 - \Delta) = 1.55\,(1 - 0.00396) = 1.544$$

(iii) The maximum acceptance angle for the fibre is

$$\theta_m = \sin^{-1}(\text{NA})_{\max} = 7.93°$$

Assignment Based on this Lecture

- EXPLAIN GRADED INDEX OPTICAL FIBER
- DISCUSS MULTIMODE GRADED INDEX(MMGI) OPTICAL FIBER
- OBTAIN THE EXPRESSION FOR THE NUMBER OF PROPAGATING MODES IN MMGI
- OBTAIN THE EXPRESSION FOR NUMERICAL APERTURE FOR GRADED INDEX OPTICAL FIBER
- DISCUSS V-NUMBER AND CUT-OFF PARAMETERS OF FIBERS
- DIFFERENTIATE THE STEP INDEX AND GRADED INDEX FIBERS
- COMPARE SINGLE-MODE AND MULTIMODE INDEX FIBRES