Experiment No. – 6

A study of single and multimode fibers.

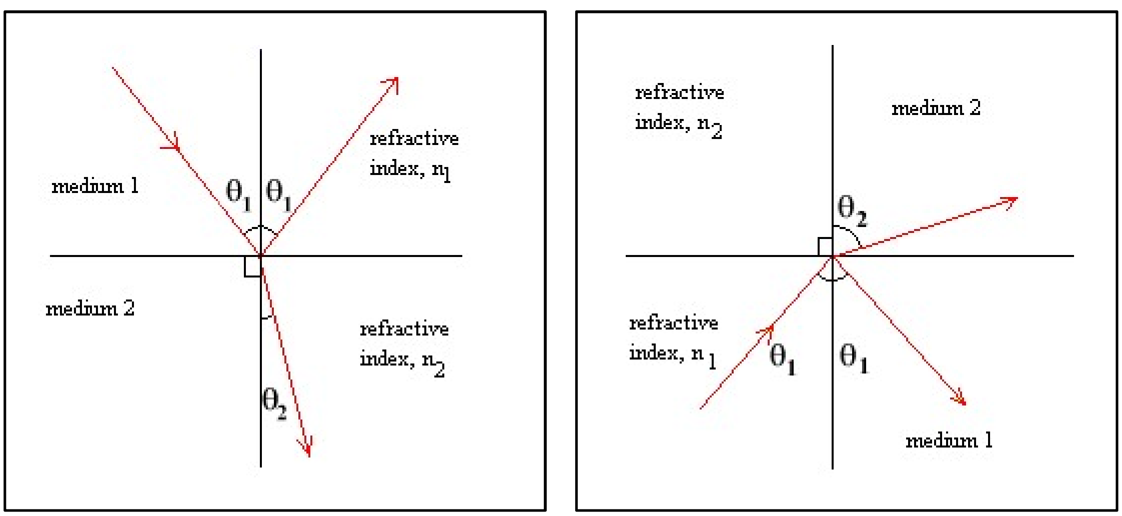
Objectives: To study the quality and quantity of information carried by single and multimode fibers.

- In this experiment we use optical fibers for propagation of laser light, and test out the optical fibers as carriers of information, using the value of the power and intensity distribution of light as the information that is coupled into the fiber. We study the quantity and quality of information carried by the optical fiber and for this we use – i) a multimode optical fiber, ii) a 600-800 nm single mode optical fiber iii) a 980 nm optical fiber.

Theory of Operation:

Total internal reflection: We know when light is incident on the interface of two transparent material, some of the light is reflected and some is transmitted into the second material. The transmitted light changes direction due to refraction which depends upon the fact that light travels with different speeds in different materials.

When light goes from a denser to a rarer medium, it is directed away from the interface normal. In this case as in fig.1 $\theta_2 > \theta_1$ always. Now as we increase θ_1, θ_2 reaches 90^0 before θ_1. For a θ_1 value equal to θ_c (critical angle), θ_2 becomes 90^0. The transmitted light now tries to travel in both material simultaneously. This is physically impossible so there is no transmitted ray and all the light energy is reflected. For this to happen θ_1 must be greater or equal to θ_c. This phenomenon is called Total Internal Reflection**.**



a) $n_2 > n_1$b) $n_2 < n_1$.

Fig 1 – a) When light goes from a material with a low refractive index to one with a high refractive index, b) When light goes from a material with a high refractive index to one with a low refractive index.

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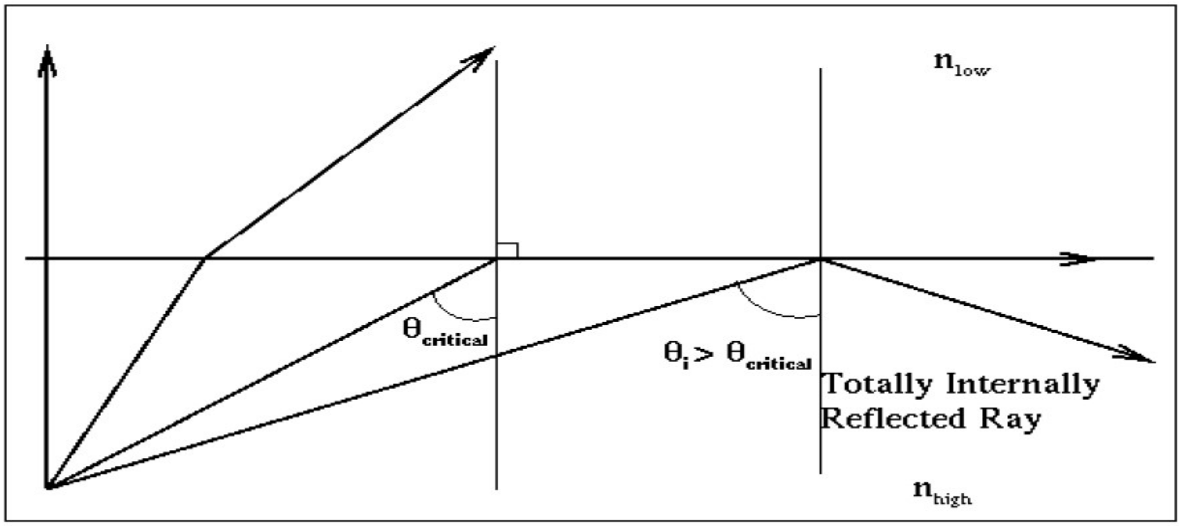

Fig – 2 – Demonstration of total internal reflection by ray diagram.

(When the incident angle of the ray increases the light moves more and more away from the normal. When incident angle is greater than the critical angle total internal reflection occurs).

About optical fibers: Optical fibers have a core and a cladding as shown in Fig.3. The refractive index of the cladding material is lesser than that of the core. The incident light, while entering into the fiber, is so adjusted for the laser beam that it suffers total internal reflection at the interface of the core and the cladding, and then the beam is guided through the fiber.

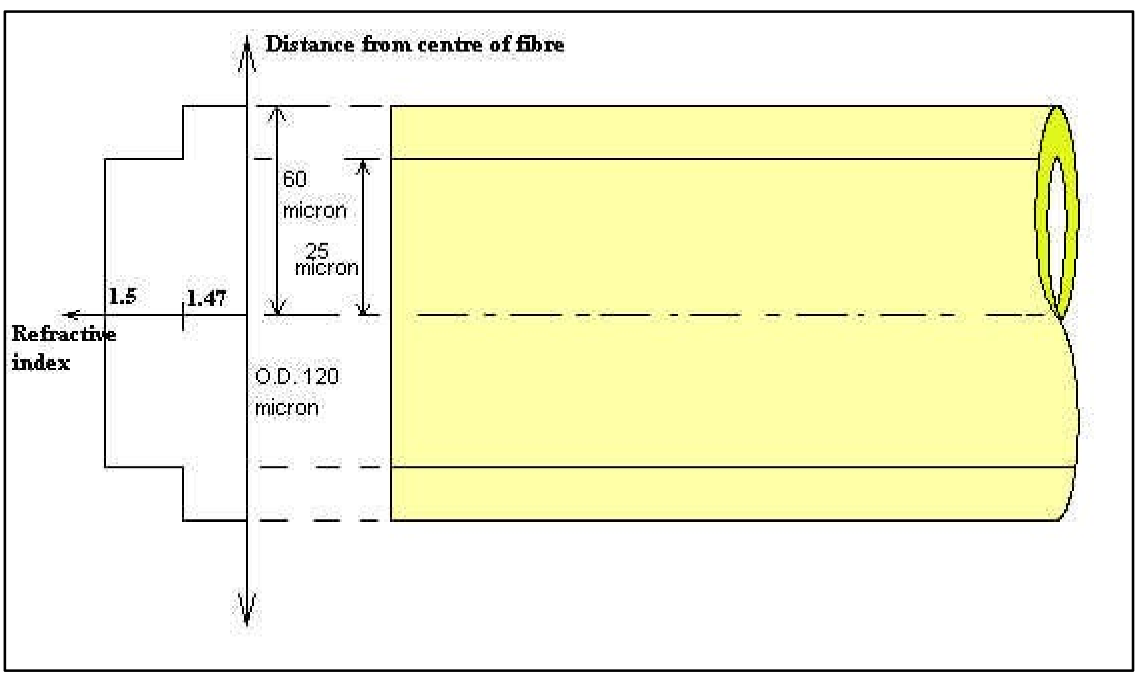

Fig. 3 – Step index optical fiber

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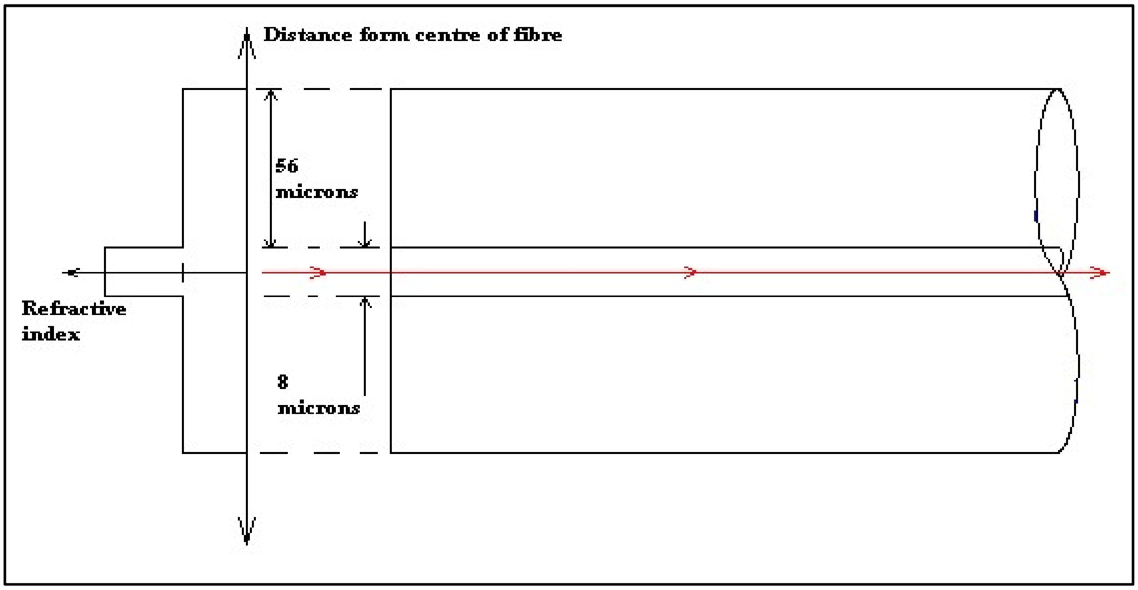

Fig. 3 – Step index single mode optical fiber (only one mode is accommodated)

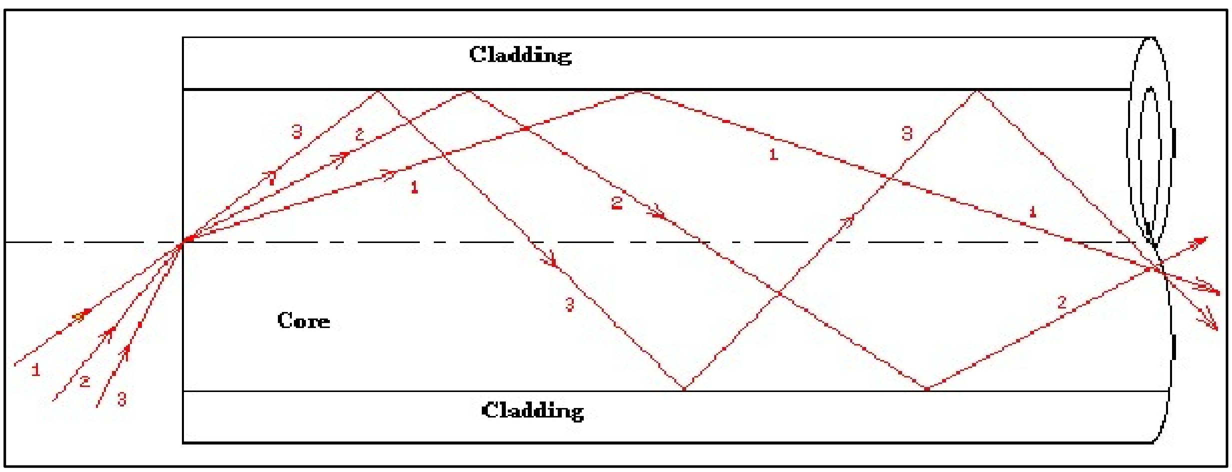

Fig. 5 – Step index multimode optical fiber and propagation of ray through it (only three modes are shown)

The incident angle at the fiber aperture plays an important role in the beam propagation through it, which leads us to carefully consider the manner in which the source is coupled into the fiber. Fibers have a certain ability to collect light. The light gathering capability of the fiber is called numerical aperture (NA). A large NA means a larger signal and more distortion in the information being conveyed. Also increase of NA costs decrease of bandwidth. The NAs of both source and fiber are to be considered while coupling light. The NA is given by

$$NA = (n_1^2 - n_2^2)^{1/2} \qquad NA = \sin\theta$$

n_1= refractive index of the core, n_2= refractive index of cladding and θ=half-angle of the acceptance core of fiber. Thus, $\theta=\sin^{-1}[(n_1^2 - n_2^2)^{1/2}]$. Question: Can the cladding be made of air?

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Experimental Procedure:

This experiment is very sensitive to alignment of the optics which needs to be done very carefully before collecting data and analyzing the fiber output.

The schematic diagram of the set up with the ray path is shown in fig. 6 below.

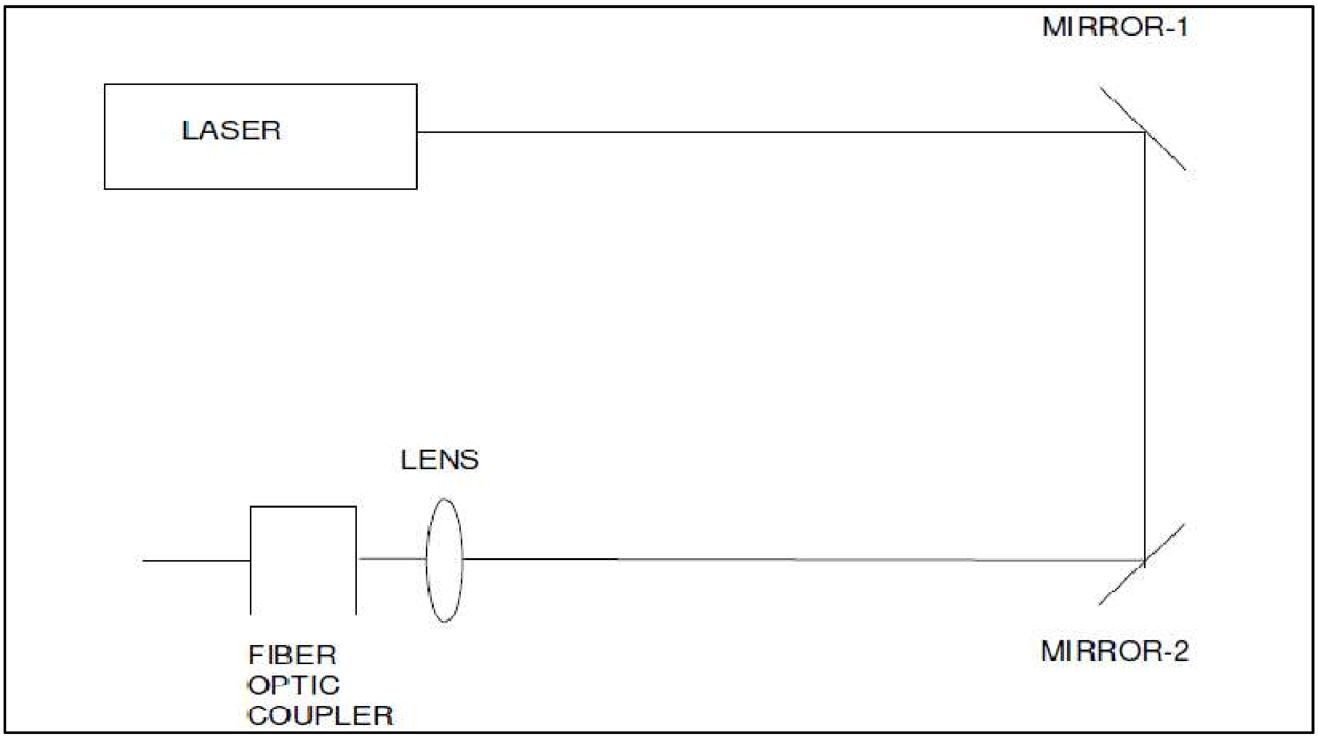

Fig. 6 – Schematic diagram of the experimental arrangement

For the initial set up of the instrument use the multimode fiber (MM). MM fibers have a larger core compared to single mode (SM) ones, and obtaining light at the output is thus easier. MM fibers should thus always used for initial alignment of the optical coupling system. Two mirrors are used to guide the laser beam into the fiber mount that has an aspheric lens before the fiber. The lens is mounted into a precision x-y translation stage which should be aligned carefully so as to have the center of the lens coaxial with that of the fiber aperture.

The first stage of alignment is to havethe light beam is parallel to the optical bench. You should get the laser spot at the same height everywhere in between Mirror 2 and fiber optic coupler system. This is done in the following way:

1. For this, remove the fiber optic mount, so that you have the two mirrors only. The mirrors are in precision adjustable kinematic mounts, which have screws to change the horizontal and vertical tilt of the mirror, which displace the reflected beam horizontally or vertically. Always remember that the farther you move from a mirror, the larger will be the effect that the alignment screws would have – that is you will have large displacement of the

beam for small changes to the screws. To check whether the beam is parallel to the bread board, you need to check the height in front of Mirror 2 and then at the end of the board, and ensure that the height remains the same. Now, what would be the height you would want to keep the beam? Before you start the alignment, take a metal scale, and find out the center of the fiber mount (or coupler) from the bread board (you need to put a scale next to the side of the mount and measure from the board – this will be somewhat approximate, later you can set the beam height accurately) – this should be the height that you should keep the beam after Mirror 2.

2. Why do we have two mirrors to adjust the position of the laser beam? This is because, you CANNOT set the position parallel to the table (or bread-board in your case), both vertically and horizontally, at arbitrary distances from the mirror UNLESS the beam falls at normal incidence on the mirror (just think a bit and figure out why this is true). With two mirrors, however, you can make any beam parallel, since you can always compensate for the tilt given by the first mirror using the second. The mirror close to the laser (or on which the beam is incident first) is called the 'Near' mirror, and the farther one is the 'Far mirror'. The beam height is always measured after the 'Far' mirror (near to it, and far from it). The cardinal rule for optical alignment using mirrors is **'Near-near, Far-far'**. This means that when you measure the beam height near the 'Far mirror', you change the `Near mirror', and vice versa. Figure out why this works.
3. Place the scale at the end of the board (far from the 'Far mirror'), measure the height of the beam, and set it at the height required using ONLY the vertical screws of the mirrors (you know which mirror you should touch!). Place the scale near the 'Far mirror' and see the height. It may not be the same. Change the height using the appropriate mirror. Iterate a few times, and you should have a constant beam height. Now comes setting the horizontal position. Use the scale again, place it near or far from the 'Far mirror' and put the edge of the scale at the center of the beam so that some of the beam sticks out (if the scale is at the center of the beam, half of the beam should stick out). Now take the scale to the other end along a straight line (for this, the best things to use as reference are the holes of the optical table – check the location of the scale with respect to a hole, and keep the same relative distance from the successive holes), and check the horizontal position of the beam (if it wanders, then the part of the beam sticking out of the scale would be different). Again fix the horizontal position of the beam iteratively.
4. Put in the fiber optic mount, and check whether the beam goes through the center of the aspheric lens mount. This can be seen by looking into the backside of the lens, you can see the beam physically falling on the lens. If there is an error, change the 'Far mirror' and get the beam in position. Remove the mount, measure the height and horizontal position of the beam AT THE POSITION where you kept the mount, and ensure that this height and horizontal position are maintained near and away fro the 'Far mirror'.

After this is done, put back the fiber mount, insert the MM fiber and the lens, and if necessary the mirrors, so that you get the highest possible output power – this takes care of the quantity of information carried. After analyzing the output i.e. checking for both quality and quantity, replace the MM fiber with one of the SM fibers and perform some minor adjustments to the lens translation stage to first get some output from the SM fiber, and then increase it. DO NOT TOUCH THE MIRRORS AT THIS STAGE. Only after the output does not seem to increase, should you touch the mirrors. Now comes the most challenging part of the alignment. Remember that your aim is to make the laser beam perfectly at normal incidence at the lens, so that the lens focuses directly into the fiber aperture. Any horizontal/vertical tilt of the beam, or departure from normal incidence will make the focused beam not fall properly into the fiber aperture. To take care of this, you need to perform a procedure called 'beam walking'. This is a very important technique in experimental optics which is done to ensure optimal alignment into an optical system. This is done in the following manner:

1. Observe the laser power through the SM fiber using the powermeter, and reduce it by changing the horizontal screw of the 'Far mirror'. Using ONLY the horizontal screw of the 'Near mirror', get the power back. Go in the same direction of movement to see if the power increases actually. If it does not increase, or you see that the power does not even COME BACK to the power you started with, it means that horizontally, you were already parallel. If you see that you gain power over what you started with, continue until the power is optimized.
2. Repeat the same operation with the vertical screws. DO NOT MESS UP THE SCREWS, I.E. DO NOT CHANGE THE HORIZONTAL SCREW OF ONE MIRROR, AND VERTICAL SCREW OF THE OTHER – that will not allow you to come back to the power you started out with!

What to measure:

<u>Quantity Measurement:</u>Measure the output powers for MM and SM fibers.

<u>Quality Measurement:</u>

1. First take the basic laser beam (without coupling into a fiber), pass it through the given polarizer and project the lowest intensity on a white card. Take the image of the beam on a card, and take a picture with the given CCD camera into IMAGEJ – the software provided to you. Choose a section of the beam using the selection tool in ImageJ, and plot the pixel grey values as function of the distance along the beam. TAKE CARE NOT TO SATURATE THE IMAGE – otherwise you will get a flat intensity distribution curve. For the laser itself, you should obtain a Gaussian. Thus, your quality information is essentially this intensity distribution or 'mode' of the laser.
2. Couple the laser beam into the MM fiber and take a picture. You should get an intensity profile as shown in Fig. 7. The output is completely scrambled due to the presence of propagation multiple modes which the fiber can accommodate due to its larger core. Presence of multiple modes is clearly indicated in the plot.

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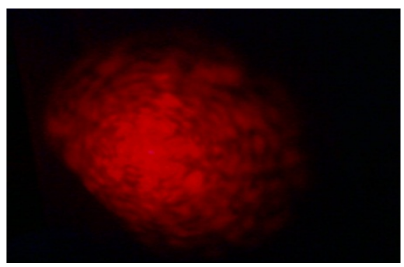
3. Repeat the procedure with the 600-800 nm SM fiber. You should get an intensity profile as shown in Fig. 8. Is it not similar to the mode you got from the laser itself?
4. Now take the 980 nm SM fiber. At maximum power, you should get output similar to that for the 600-800 nm fiber. Pass the output beam into the polarizer, project it on to a card, and rotate the polarizer. Does the nature of the output beam change when you rotate the polarizer by 90 degrees? Take images and plot intensity distributions at two positions of the polarizer where you get two types of output,
5. Tweak one of the screws of your lens mount. Can you see even more drastic changes in the polarizer output as you rotate it?
6. Now take a glass slide, have the fiber output incident on it, and see the reflection and transmission on two cards. As you rotate the slide, see how the images change. Take images and plot intensity distributions. You will see that at a particular angle, the reflected and transmitted modes are qualitatively different, just as you saw when you turned the polarizer by 90 degrees. This, incidentally, is the Brewster angle.



Output image

Fig. - 7

Output image and intensity distribution plot for multimode optical fiber

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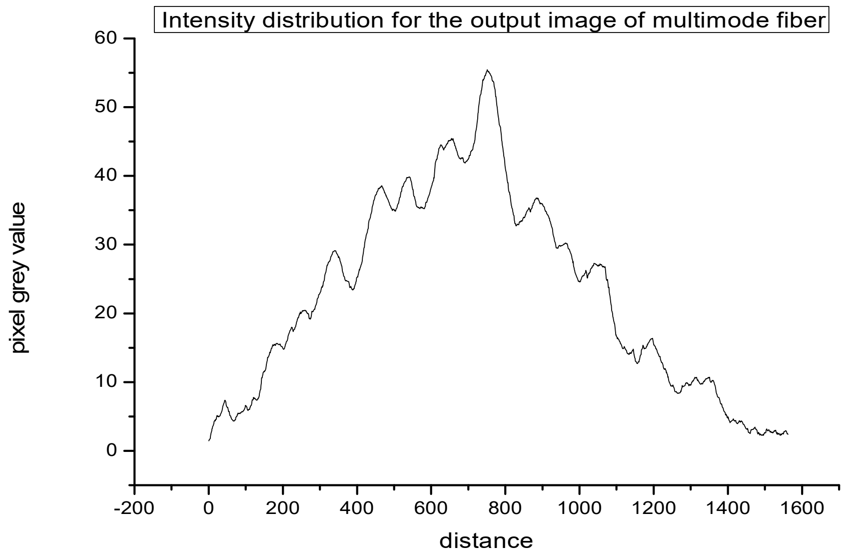

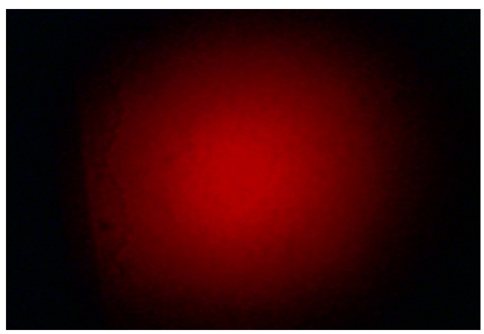

Output Image

Fig-8
Output image and intensity distribution plot for 600-800 nm single mode optical fiber

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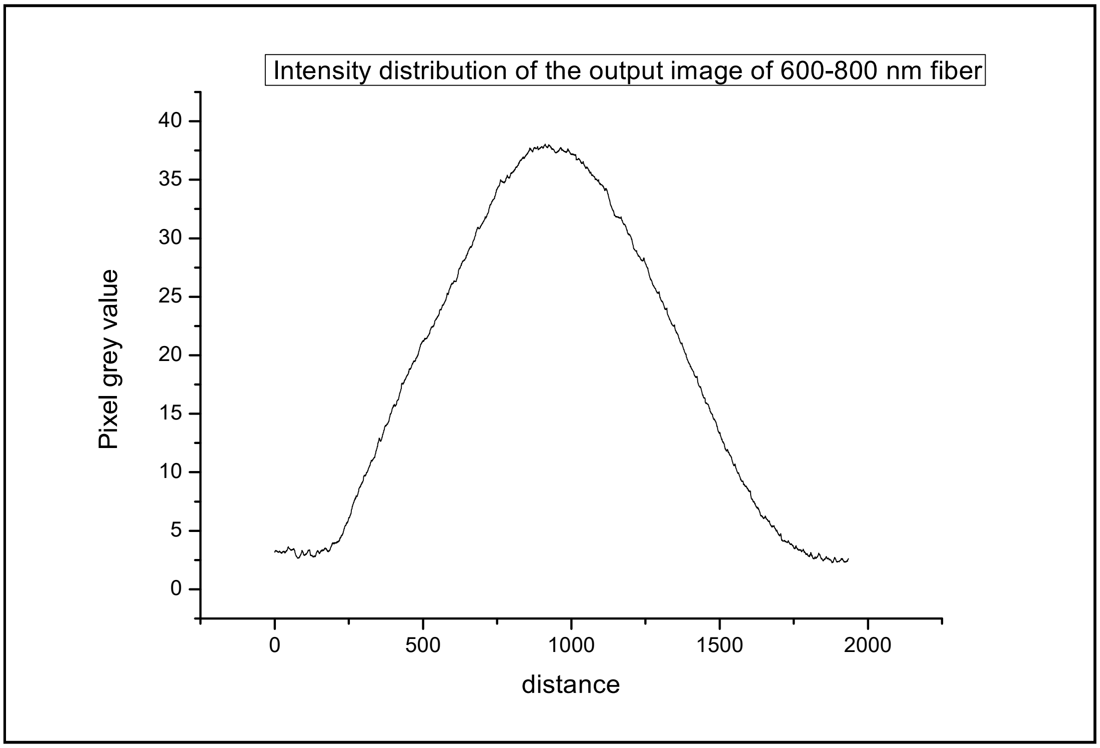

Output image

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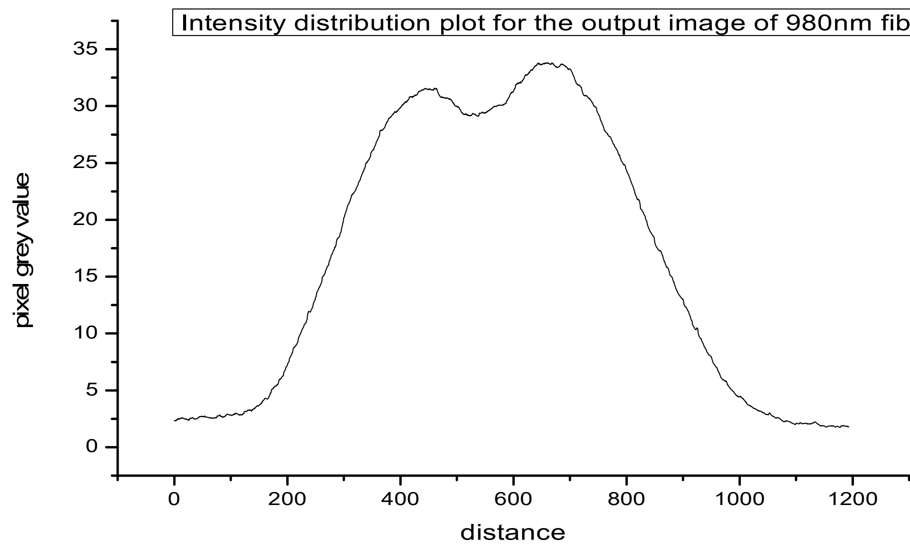
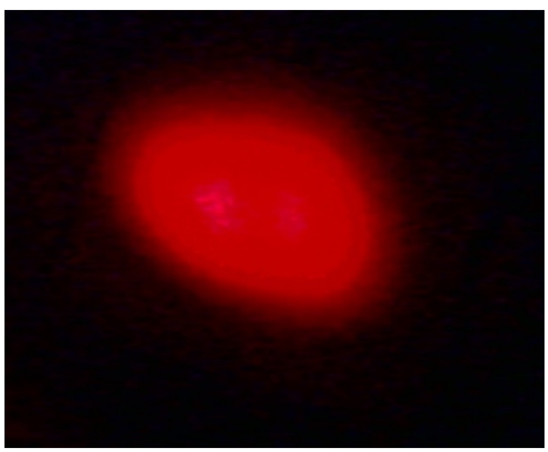


Fig. - 9

Output image and intensity distribution plot for 980 nm single mode optical fiber (superposition of two modes)



Output Image

Experiment No. – 6

A study of single and multimode fibers.

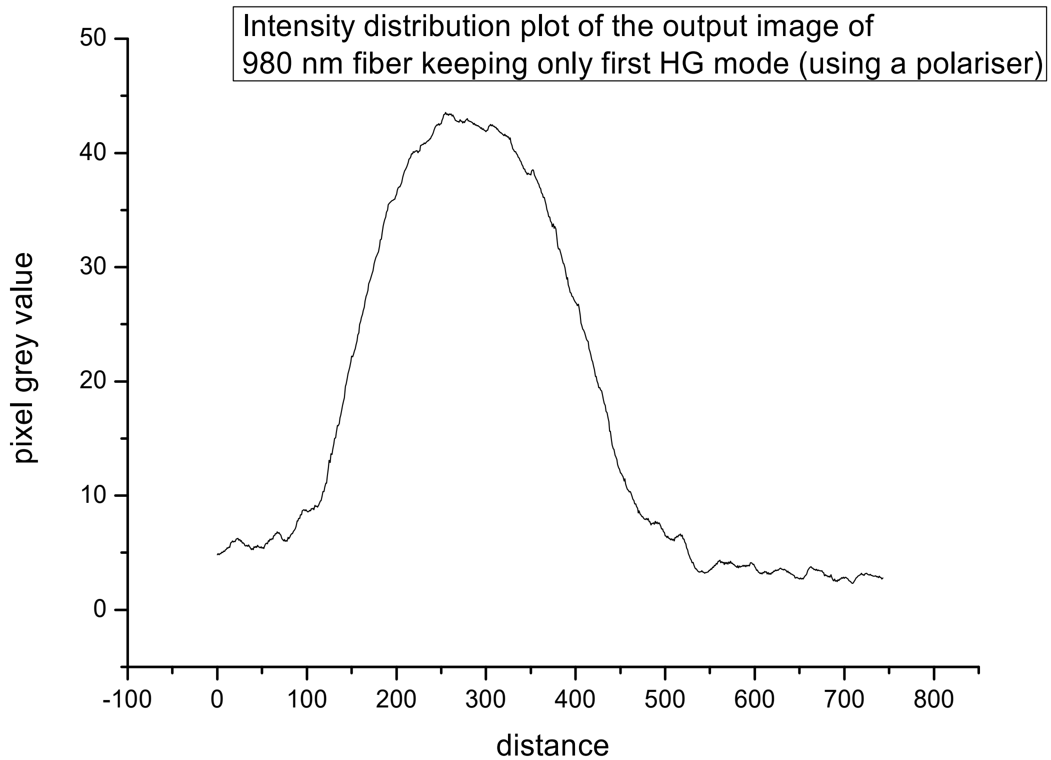
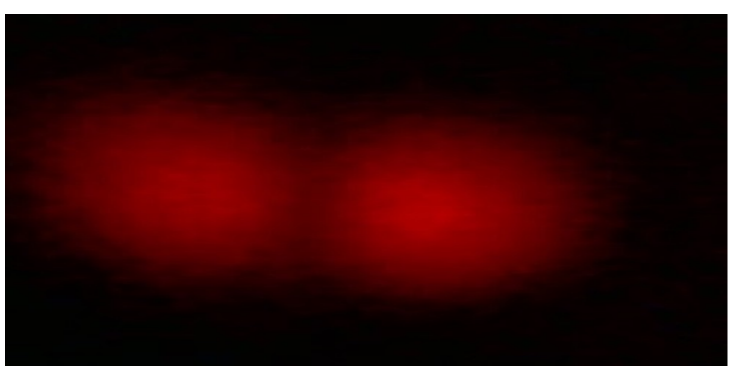


Fig.- 10

Output image and intensity distribution plot for 980 nm single mode optical fiber using a polarizer to keep only one mode in the image (first Hermite Gaussian mode)



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Output Image

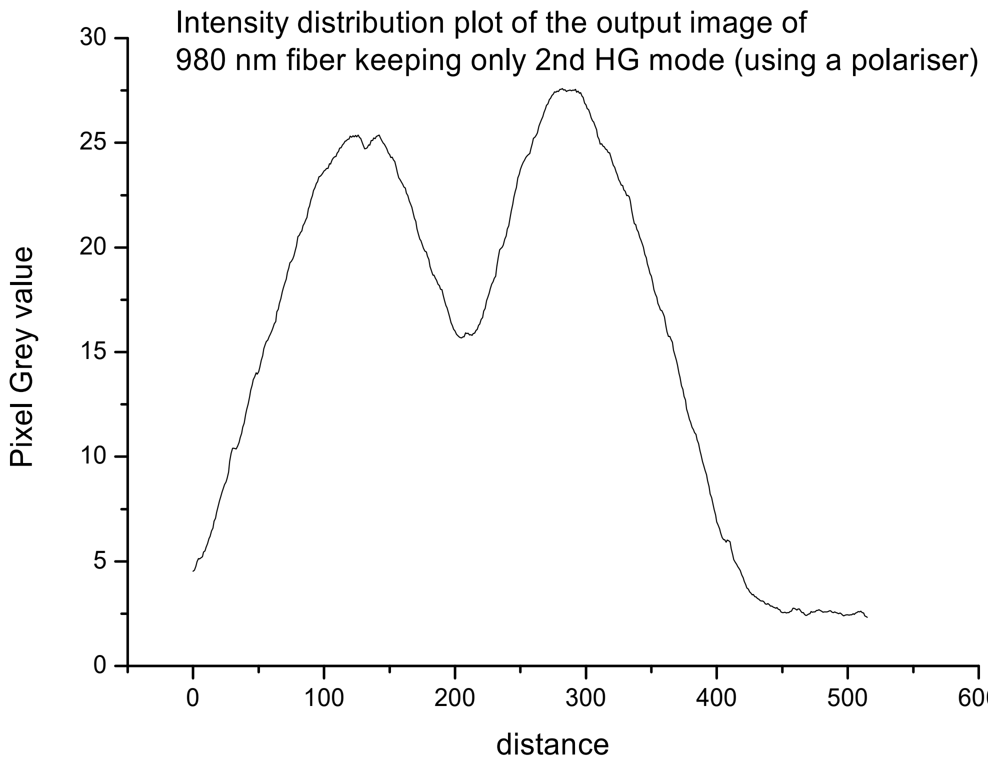
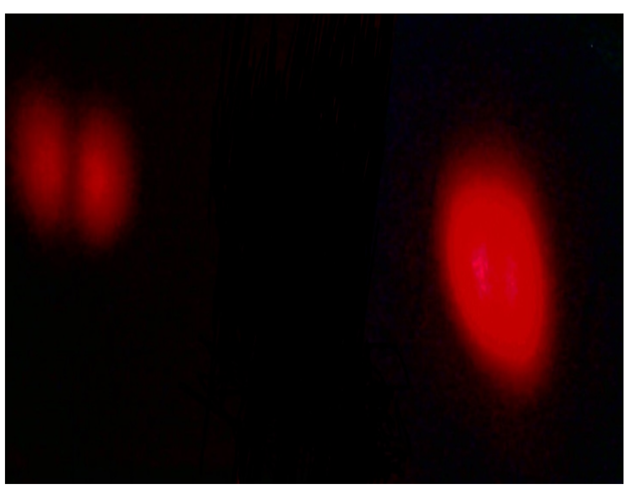


Fig. - 11

Output image and intensity distribution plot for 980 nm single mode optical fiber using a polarizer (now rotated by 90^0 from previous position) to keep only one mode in the image (2nd Hermite Gaussian mode)



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Output Image

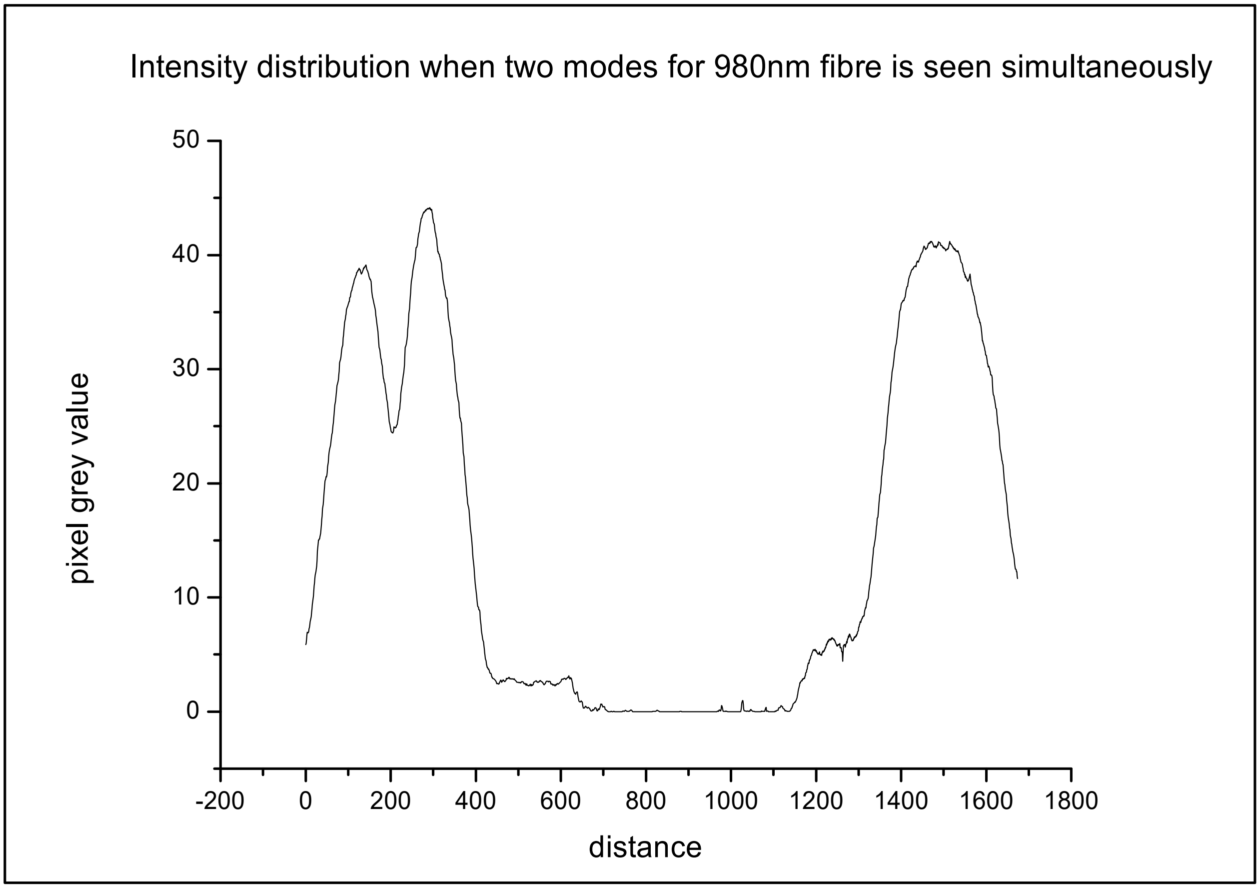

Fig. - 12
Output image and intensity distribution plot for 980 nm single mode optical fiber (two modes are separated by a glass plate)

Theoretical concepts:

What are the modes of a fiber?So far we have beendiscussing extensively about fiber modes. Now what are the modes? To explain this we should discuss the propagation of a laser through an optical fiber under the paraxial approximation.

We know the wave equation is given by,

$$\nabla^2 \vec{E} - \frac{1}{c^2}\frac{\partial^2 \vec{E}}{\partial t^2} = 0,\ \vec{E} = \text{electric field vector},\ c = \text{ velocity of the wave}$$

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Laser propagates through the fiber nearly in a unidirectional way with some finite cross sectional area. Thus plane or spherical wave cannot be the solution as spherical one is not unidirectional and plane wave has infinite cross sectional area. We seek a solution like a beam as:

$$\vec{E}(\vec{r}) = \overrightarrow{E_0}(\vec{r})e^{ikz} \qquad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ (1)}$$

Z is the propagation direction (this is always the case in optics).

There is nothing outside the fiber. Hence the field is continuous in the longitudinal direction but in the transverse direction there is of course, no field. Hence the gradient of the field along the direction of propagation is much lesser than that along the transverse direction. Thus, we assume,

$$\lambda\left|\frac{\partial E_0}{\partial z}\right| \ll E_0\,, \lambda\left|\frac{\partial^2 E_0}{\partial z^2}\right| \ll \left|\frac{\partial E_0}{\partial z}\right|, \left|\frac{\partial^2 E_0}{\partial z^2}\right| \ll \left|\frac{\partial^2 E_0}{\partial x^2}\right|, \left|\frac{\partial^2 E_0}{\partial y^2}\right|$$

Our solution must satisfy Helmholtz equation,

$$\nabla^2\left[E_0(\vec{r})e^{ikz}\right] + k^2\left[E_0(\vec{r})e^{ikz}\right] = 0 \qquad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ (2)}$$

Now,

$$\frac{\partial^2}{\partial z^2}\left[E_0(\vec{r})e^{ikz}\right] = \left(\frac{\partial^2 E_0}{\partial z^2} + 2ik\frac{\partial E_0}{\partial z} - k^2 E_0\right)e^{ik} + \left(2ik\frac{\partial E_0}{\partial z} - k^2 E_0\right)e^{ikz} \qquad \text{\_\_\_\_\_\_ (3)}$$

Thus we get from (2) and (3)

Eq. 4 is called <u>**Paraxial wave Equation**</u>

Where

$$\nabla^2{}_T = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} = \text{transverse laplacian}$$

The term paraxial is used since the light must travel nearly parallel to the z-axis so that the beam has a sufficiently slow z dependence. Laser beams typically obey this approximation very well.

The general solution of the paraxial wave equation is the linear combination of orthonormal modes involving Hermite polynomials. These different Hermite polynomials corresponds to different modes of the fiber. Think about the linear harmonic oscillator in quantum mechanics. The Schrodinger equation is very similar to the Helmholtz equation under the paraxial approximation, and just as the solution of the former are the Hermite polynomials, so we have in the case of the optical fiber. Remember that the probability density of the ground state of the harmonic oscillator is a Gaussian, as you have in the case of the single mode fiber.

<u>About the nature of the fiber output:</u>Aided with the previous discussion we are now in a position to discuss the results found in a more detailed manner. In case of the 600-800 nm fiber we have seen a Gaussian like beam which corresponds to the first Hermite polynomial for which the

intensity distribution is exactly Gaussian. As this fiber core is very narrow it can only accommodate the first Hermite Gaussian mode (HG_{00}, also called TEM_{00}in this context).

The 980 nm, being slightly greater in diameter can accommodate first two transverse modes, corresponding to 1st and 2nd Hermite polynomial. The intensity distribution for both of them are shown in Fig.13. Recall that the transverse extent of the excited states increase as you go to higher states. Thus, the transverse extent of the first excited state is more than that of the ground state. The 980 nm fiber has a larger core size so that it can accommodate even the first excited state HG_{01}. Thus we get two modes as output for that fiber. Now we know different Hermite Polynomials are orthonormal – and that is exactly the reason why these two modes can be separately seen using the polarizer – for a specific orientation of the polarizer we get the first Hermite Gaussian and for 90^0 rotation of the Polaroid we get the 2nd Hermite Gaussian mode.

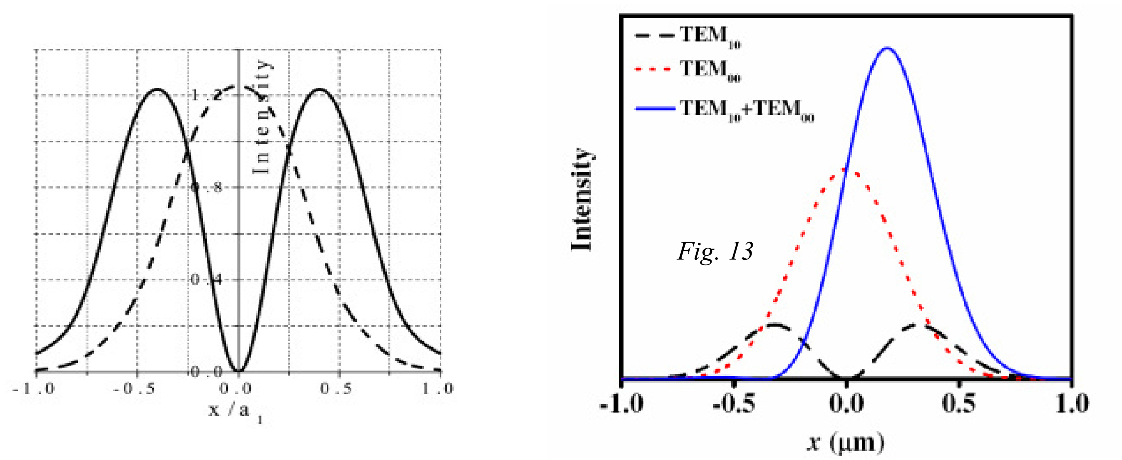
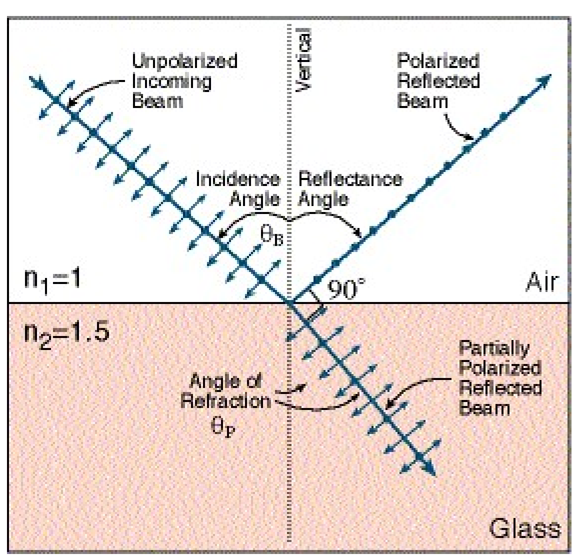


Fig. 13 Ground and first excited states of a fiber

Now when the beam is incident on a glass plate in Brewster's angle two orthogonally polarized components are separated as the reflected and refracted ray. For Brewster angle, input s-polarization is completely reflected, while the transmitted beam should consist mostly of the p



polarized component. Thus, the Hermite polynomials being orthonormal, one can separate out

Fig. – 14

Polarization by reflection and Brewster's angle (θ_B)

(When incident light consists only two orthonormal modes both reflected and refracted rays are polarized)

the ground (Gaussian) and first excited state.

Geometrical phase of light: The geometrical phase of light in this experiment can be demonstrated in a very elegant way. When the orientation of the mirrors is changed by rotating the attached screws, the image at the output is observed to rotate in the case of both MM and 980 nm SM fiber. This is due to the fact that the Hermite Gaussian mode can be considered as the superposition of Laguerre Gaussian modes.

$HG_{00} = LG_0^1 + LG_0^{-1}$ And $LG = HGe^{\pm im\varphi}$

So, $LG_0^1 + LG_0^{-1} = HG\cos\varphi$

Thus when incident angle of light on the mirror changes then cos ϕ changes and due to this the output image for multimode fiber (superposition of all modes) and SM fiber (superposition of HG_{00} and HG_{01})seems to rotate.