MODE FIELD DIAMETER OF A SINGLE-MODE FIBER

Aim

To determine the mode fiber diameter (MFD) of the fundamental mode in a given single-mode fiber (SMF) by a measurement of its far-field.

Apparatus

Bread board, laser diode, laser aligner, microscope objective (20X), microscope objective holder, xyz-translational stage, pin-hole masked photodetector connected to a multimeter, photodetector holder, rotation stage, two fiber chucks, two past bases and 3 posts, approximately 2m length of a single-mode fiber, razor blade, fiber cutter, index matching liquid.

Theory

In a single-mode fibers, it is the transverse distribution of the propagating mode rather than the core diameter and the numerical aperture that is important in estimating several propagation and the performance characteristics of these fiber. Thus *mode field diameter* (MFD), which is a measure of the transverse extent of the modal field distribution (i.e. of the LP_{01} mode), is an important parameter used to characterize a single-mode fiber. It is analogous to the core diameter in a multimode fiber, indicating the region of field confinement, and it also takes into account the wavelength dependent extent of penetration of the field into the fiber cladding. This parameter can be determined from the mode field distribution of the fundamental LP_{01} mode, which is shown in Fig 3.1. It essentially specifies the transverse extent of this fundamental i.e. LP_{01} mode.

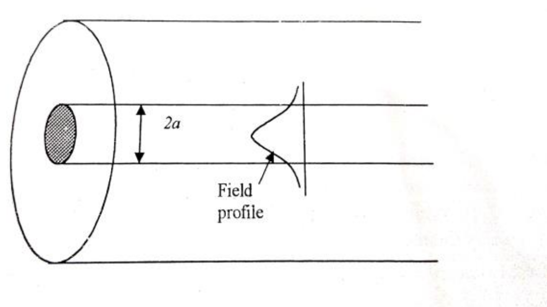

Fig 3.1. *Schematic diagram of the amplitude distribution of the propagating fundamental mode in a single-mode fiber.*

Knowledge of MFD is very useful in estimating joint loss between two single-mode fibers, coupling efficiency, cutoff wavelength, backscattering characteristics, microbending losses, and even waveguide dispersion.

For most single-mode optical fibers of the type used in communication systems, the near-field of the fundamental mode can be well approximated by a Gaussian function of the form [3]:

$$\psi(r) - A \exp(-r^2/w_0^2) \quad (3.1)$$

Where A is a constant. The quantity $2w_0$ gives the Gaussian MFD of the fiber, at the operating wavelength; usually, $w_0 \approx a$, where a is the core radius. Theoretically, w_0 can be estimated by maximizing the launching efficiency between a free space Gaussian optical field and the single-mode fiber [4]. Marcuse has shown that for a step-index single-mode fiber, the following empirical expression may be used to determine w_0 [4]:

$$w_0 \approx \left(0.65 + \frac{1.619}{V^{1/2}} + \frac{2.879}{V^6}\right);\ 0.8 < V < 2.5 \quad (3.2)$$

Since, the far-field of a diffracting field, which is actually the Fraunhoffer diffraction pattern, is Fourier transform of its near field, it can be analytically shown that the far-field pattern of a Gaussian mode distribution [5] given by the above equation is again a Gaussian distribution and the corresponding intensity pattern is given by:

$$I(r,z) = \frac{I_0}{[I+y^2\ (z)]}\exp[-2r^2/w^2(z)] \quad (3.3)$$

Where $w(z) = w_0[l+y^2(z)]^{1/2}$ and $y(z) = \frac{\lambda z}{\pi w_0^2}$

Equation (3.3) represents the far-field intensity distribution. The parameter w(z) is the far-field mode field radius (MFR) of the Gaussian amplitude distribution. The far-field distribution refers to the angular dependence of the output field intensity, sufficiently far from the output end of the fiber. For practical purposes, if the distance z of the observation plane from the diffracting aperture is such that z>>w_0^2/λ, observation plane is said to be in the far-field. For such large values of z

$$W(z) \approx \frac{\lambda z}{\pi w_0}$$

(3.4)

Accordingly, the Gaussian MFD ($2w_0$) of a single-mode fiber can be easily obtained from a measurement of the angular distribution of its far-field measurements as discussed below. Using Eq. (3.4), the far-field intensity distribution of a Gaussian field [Eq.(3.1)] is approximately given by [3].

$$l(r) = B\exp\left[-\frac{2\pi^2 r^2 w_0^2}{\lambda^2 z^2}\right] \quad (3.5)$$

$$= B\exp\left[-\frac{2\pi^2 w_0^2}{\lambda^2} tan^2 \theta\right]$$

Where B is a constant independent of r and tanθ - r/z, θ being the far-field diffraction angle. The angle. The angle θ_e at which the far-field intensity drops down by a factor of e^2 from its maximum value at θ = 0 (see Fig. 3.2) would then be given by [2.3]:

$$\tan \theta_e = \frac{\lambda}{\pi w_0}$$

which yields

$$w_o = \frac{\lambda}{\pi tan\theta_e}$$

(3.6)

thus, by measuring θ_e, one can easily calculate the Gaussian mode- field diameter (MFD)$2w_0$.

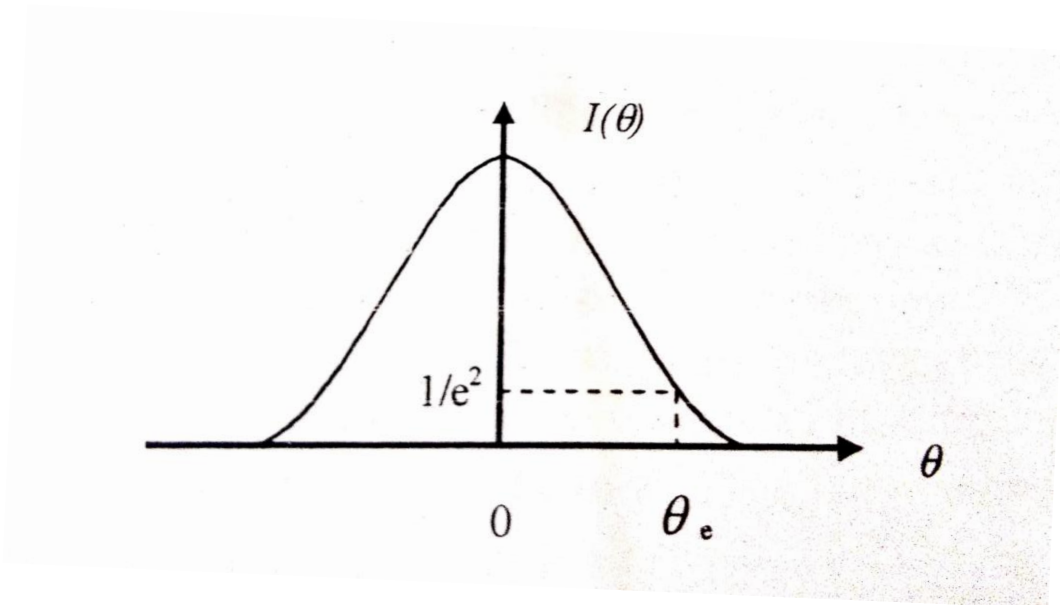

Fig. 3.2 *Determination of θ_e from the measured angular distribution.*

Procedure

Figure 3.3 shows the schematic of the set- up for the measurement of the mode field diameter of a single- mode fiber. For this, following procedures have to be followed step by step:

1. Mount the laser diode in the aligner and adjust with the help of the aligning screw.
2. Fiber ends are prepared so that it has well- cleaved ends. The cladding modes are removed by applying an index matching liquid (e.g. liquid paraffin) over a few centimeters of the bare fiber, near both the input and output ends and then clamed over the fiber chucks with the clamping magnets.

3. The output end of the fiber is clamped over a post base in such a way that the tip of the fiber is positioned on the axis of the rotational stage.
4. Light is a launched from the laser diode using a 20 X microscope objective into the fiber.

   A pinhole-masked photodetector is mounted on the rotational stage and the height of the fiber tip is so adjusted that the pinhole is positioned at the same

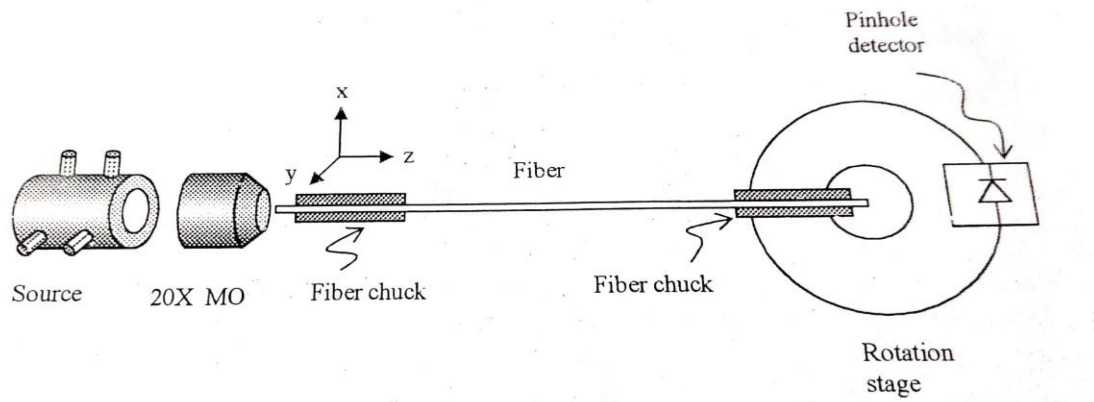

Fig.3.3 *Experimental setup for scanning the far-field intensity distribution of a single-mode fiber*

5. horizontal level as the fiber end.
6. Now, without distributing the input coupling, intensity distribution in the far-field (circular) spot of the fiber is scanned in suitable steps (say, in steps of 0.5^0), and for each recorded angular position the multimeter reading is recorded. The measured data will correspond to far-field angular intensity distribution.
7. Plot of the multimeter reading versus the angular position of the detector represents the recorded far-field intensity distribution. From this plot, calculate the value of the angle θ_e at which the intensity is reduced to l/e^2 of the maximum intensity (at $\theta = 0$).
8. Using the angle, calculate the Gaussian mode field diameter (2_{wo}) from Eq. (3.6)

Observations:

Least count of the rotation stage =

S.No.	Reading on the rotation stage (in degrees)	Power meter reading (μW)

Results

A typical variation of experimentally measured angular distribution of the far-field output power is shown in Fig. 3.4, corresponding to a given single – mode fiber (fibercore, SM600). In this figure, the filled squares show experimentally observed values, whereas the curve with circles shows the Gaussian fit to these experimental data. The horizontal line drawn in the plot shows the level at which the intensity drops down to l/e^2 of the maximum output power. The line intersects with the plot at two angles, which can be directly read from this plot, θ_e (angle at which, the intensity drops down to l/e^2 of its maximum value) comes out to be $\approx 5.06^0$. Using this value of θ_e and the wavelength of the radiation emitted by laser (which is equal to 633nm), Eq. (3.6) yields Gaussian mode field diameter (MFD) $\approx$ 4.5μm, which is in excellent agreement with the nominal value provided by the manufacturer, i.e, 4.7 μm.

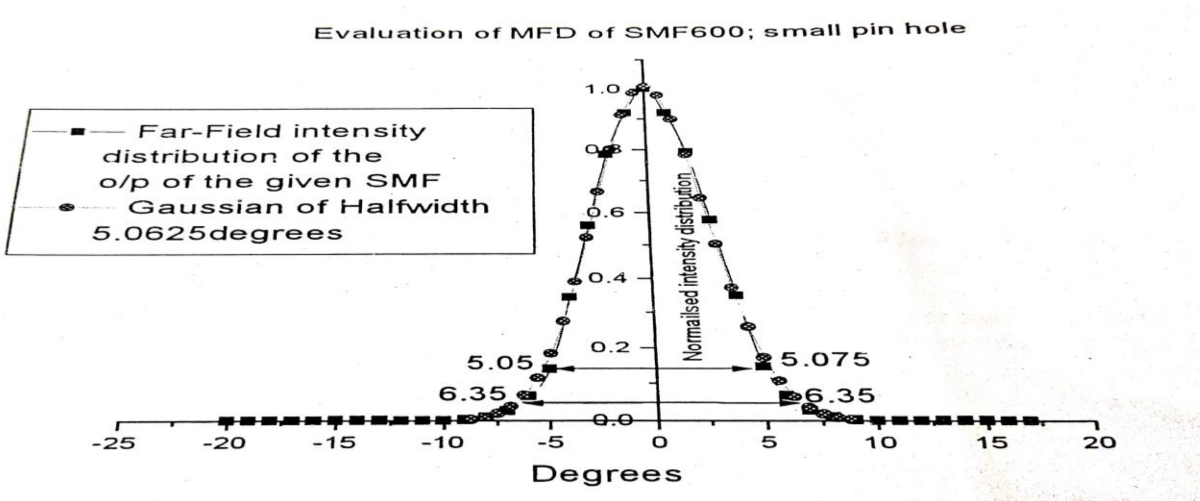

Fig. 3.4 *A typical plot of far-field intensity distribution of a single-mode fiber.*

Comments

It is necessary that the far-field intensity pattern be detected at a sufficiently large distance from the center of the fiber output end such that good angular resolution is achieved in detection. Furthermore, the angular sector scanned in front of the fiber must be sufficiently wide (between $\pm$ 20^0 and 25^0) to completely include the main lobe of the radiation pattern.

Although this method appears to be quite simple and straightforward, following points must be ensured at the time of performing the experiment.

1. The fiber end faces must be of good quality.
2. Cladding-mode strippers must be used.
3. The output end of the fiber must be positioned in such a way that the axis of the rotation of rotation stage passes through it.

The fiber used in this experiment was a Fibercore SM600, single-moded at 632.8nm. If s single-mode fiber designed for operation at a given wavelength is operated at the longer wavelength, the modal field will spread more into the cladding of the fiber [3], thereby yielding a relatively larger mode field diameter.

Finally, it should be noted that the method described here for the measurement of mode field diameter is not unique, and several other methods have also been proposed [3]. Also note that is general the mode field varies with variation in the refractive index profile, Infact it can deviate substantially from a Gaussian distribution in case of complex fiber refractive index profiles ex. Those encountered in specially dispersion shifted fibers like DSF, non-zero DSF (NZ-DSF) and dispersion compensating fibers (DCF). In such cases, most standard practice is to define the MFD of the fiber through the "Petermann MFD ($2w_p$)" [3.6].