Single-mode optical fibers coupling: Study of the field of view

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Abstract. Single mode Fiber (SMF) is commonly used in long distance applications as in optical communication. Coupling of the laser beam into SMF core to get high coupling efficiency is a challenging task in practice. The aim of our work is to study the impact of the field of view on the coupled light beam, taking into account well designed coupling lens to be sure that the focal spot has matched to the mode of propagation. Here in this article, a conical lens of 1.5 refractive index was used for light coupling process. The used criteria at HeNe laser of 0.5438 nm wavelength showed a degradation in the output signal due to generated distortion as the field of view increased from 0 to 6 degrees.

1. Introduction

1.1. Fiber Coupling
Optical fiber misalignment most often occurs when optical fibers are attached, when coupling the laser with the fiber, or when using conductors. The transmission loss between the connected fibers can be due to intrinsic losses that result from parameter mismatch between the fibers, for example, core diameter, digital aperture (NA) and so on. External losses occur due to the optical and physical misalignment of the ends of the fibers such as the presence of air gaps between the ends of the fibers [1,2], the tilt of the fibers [3] or the radial displacement [4]. One of the conditions for achieving power and information transfer is that the attenuation be limited when connecting plastic optical fibers. The received laser is coupled to a single-mode fiber (SMF) in optical fiber device applications such as interferometers, Sensors, fiber amplifiers and others. Hence it is essential to maximize the coupling efficiency in optical communication systems [5]. The coupling efficiency is affected by the same misalignment conditions mentioned above. In addition, the aberrations caused by the optical systems are important factors affecting the coupling efficiency and should be carefully eliminated [6-8]. Beyond telecommunications, optical fibers can also transport optical energy to powering electric or electronic devices remotely.

1.2. Optical Aberrations
Imperfections in any optical component may cause deviation of light from its path. Such deviations are called optical aberrations, causes blurred image and reduces the optical system performance. Optical aberrations comes into two kinds; monochromatic aberrations (Spherical, coma, astigmatism, image curvature and distortion) and chromatic aberrations. Off-axis aberrations can be eliminated by centering the optical and detector surfaces with a common curvature center at the stop aperture. The Seidel polynomial uses the polar coordinate system and described mathematically as follows [9]:
\[ W = \sum_{i,j,k} W_{ijk} H^i \rho^j \cos^k \phi \] .............(1)

\( W_{ijk} \) is the wavefront aberration coefficient whose value can be positive or negative (in units of wavelength). The subscripts \( i, j \) and \( k \) refer to the powers on the other factors that indicate the aberration kind. The factor \( H \) is the fractional image height. Its value ranges between 0 and 1. The fractional pupil radius \( \rho \) also ranges between 0 and 1. Another pupil coordinate is denoted by \( \phi \) in the cosine term (has values between -1 and 1).

2. Method and Analytical Work

For optical modelling, ZEMAX 13 premium-34900software is used. The designed model works at far distances as illustrated in Figure (1). This model is composed mainly of a laser source (HeNe laser of 0.5438 nm), entrance pupil diameter (stop aperture) of 4 mm, the exit pupil position of -65.217 mm included the glass lens (conic of -2.250 and a refractive index of 1.50) and the last part is focusing at the fiber.

At a fixed aperture diameter, field of view (FOV) was changed from 0-10 increased by step 2. Table (1) summarizes the input parameters of each component. An efficient plano-convex lens is used in this study to get higher light intensity deliver and higher coupling efficiency as the field of view is varied. Because such lens eliminates the spherical aberration that may be caused due to the applied monochromatic laser beam because it collects and collimates the light rays into a small spot.

![Normalized Airy Disk Radius = 2\( \omega_1 \)](image)

**Figure 1.** The designed single mode fiber coupling

| Surface            | Surface Type        | Radius | Thickness | E.P.D. | Conic |
|--------------------|---------------------|--------|-----------|--------|-------|
| Light Beam         | Standard Surface    | Infinity | Infinity | Infinity | -     |
| Aperture Diameter  | Standard Surface    | Infinity | 5.00      | 4      | -     |
| Lens-Front         | Standard Surface    | Infinity | 10.00     | 8      | -     |
| Lens-Back          | Standard Surface    | -25.00  | 50.00     | 8      | -2.25 |
| Focus at Fiber     | Standard Surface    | Infinity | -        | 2      | -     |

Table 1. Input parameters of the designed single mode fiber coupling model. All measured in (mm).
3. Results and Discussion

3.1. PSF

The Point Spread Function (PSF) of a converging lens is known as the Airy disk. The Airy disk is then defined as $J_1(v)$ for the order (1) of the Bessel function where $v$ is the optical distance. In turn, $v$ is defined as a function of $r$ (the radial distance). PSF is also defined as the square of the modulus of the point spread function amplitude, $h(v)$, as indicated in the following equations [10]:

$$h(v) = \left[ \frac{2 J_1(v)}{v} \right] \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (2)$$

$$v = \frac{2\pi}{\lambda} \left( \frac{a}{f} \right) r \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (3)$$

Where $a$ is the lens radius, $\lambda$ is the laser wavelength and $f$ is the lens focal length.

Briefly, when the laser beam is well focused by the optical system, an Airy pattern of distributed light obtained at the fiber end. This can be found in on-axis (FOV = 0) optical systems as shown in Figure (2.a). From this figure and the relative values of intensity, the system is perfectly aligned with a Strehl ratio of 1. Significantly, the peak intensity diminished when the FOV has changed by 6 degrees as shown in Figure (2.b). As a result, the Strehl ratio decreased to 0.568. In addition, small protrusions have appeared and the peak intensity has shifted slightly. This is due to the generated aberrations through the coupling process. The Total irradiance surface graphs facilitate the way to know the generated aberration type to overcome such issues.
Figure 2. PSF at FOV of: a. 0 degrees and b. 6 degrees

3.2. Total Irradiance Surface

The system efficiency is the fraction of the energy in the source beam that exits the optical system. This value is determined by the input numerical aperture (NA), entrance pupil size and position, apodization, transmission of the optics, and vignetting. While The receiver efficiency is the fraction of the transmitted energy that couples from the exit pupil to the receiving fiber. This value is determined by aberrations and the NA of the receiving fiber. The resultant coupling efficiency is the fraction of energy radiated by the source that couples into the receiver. This is the product of the system and receiver efficiencies. The spatial HeNe laser beam to single mode fiber coupling efficiency denoted by (η) is a function of phase(A(r)) and Gaussian distribution amplitude (M(r)). The mathematical expression of each term is indicated below [11,12]:

\[
\eta = \frac{\int A(r) M(r) dr}{\int |A(r)|^2 dr} \quad \cdots \cdots \cdots \cdots (4)
\]

\[
A(r) = \frac{\pi D^2}{4\lambda f} \left| 2J_1(3.83/\omega_l) \right| \quad \cdots \cdots \cdots \cdots (5)
\]

\[
M(r) = \sqrt{\frac{2}{\pi\omega_0^2}} \exp(-\frac{r^2}{\omega_0^2}) \quad \cdots \cdots \cdots \cdots (6)
\]

\[
\omega_a = \frac{\lambda f}{\pi\omega_0} \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (7)
\]
Where $D$ is the lens diameter, $\omega_1$ and $\omega_0$ are the Airy disk radius and the mode-field radius of the single mode fiber. The Irradiance graph represented by Figure 3.a. is the ideal system as seen in the PSF Figures. While figure 3.b. introduces the reason behind the appearance of the protuberances and the decrease in intensity, which is due to distortion and coma aberration. As a result of the widen in FOV, which in turn led to the system misalignment.

**Figure 3.** Irradiance measured in watts/millimetre$^2$ focused at the fiber at: a. 0 degrees and b. 6 degrees.
From the Irradiance graphs (Figures 3.a and 3.b) at 0 and 6 degrees FOV, respectively, the fiber efficiency components’ values are listed in Table 2 below:

| Fiber Efficiency          | FOV = 0 degrees | FOV = 6 degrees |
|---------------------------|-----------------|-----------------|
| System Efficiency         | 1               | 1               |
| Receiver Efficiency       | 0.699           | 0.425           |
| Coupling Efficiency       | 0.699           | 0.425           |

4. Conclusion
In the event that the laser beam is not completely centered, there are two solutions. First, if the offset is less than 1 mm, compensation can be made easily by adjusting the coupling optics with respect to the laser head transformer. This capability is built into the source coupler design. For the second solution, if the displacement is more than 1 mm, then an adapter with inserted holes must be constructed to compensate for the displacement. This work demonstrated that the coupling efficiency response to the established pairing models changed with the change of FOV (misalignment) values. This is attributed to the amount of coma and distortion aberrations generated within the system which affect the total transmitted power.

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