



## Calculation of Mode Properties for Single-Mode and Multimode Fibers at 633 nm

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### Abstract

The need for optical fibers has emerged for their ability to transmit information with less attenuation over long distances. This work studies four optical fibers with core radii from 1  $\mu\text{m}$  to 4.75  $\mu\text{m}$  in steps of 1.25  $\mu\text{m}$  and a numerical aperture of 0.17. Furthermore, the mode properties were calculated at a wavelength of 633 nm by using RP Fiber Calculator (free version 2022). Also, the effect of increasing the core radius on the studied properties has been studied. Multimode fibers can be obtained when the radius of the fiber core is large compared with the fiber's operating wavelength, which is less than the cutoff wavelength of the mode. Moreover, single-mode fiber is obtained. It has been concluded that all the calculated properties increase with increasing core radius, and more than half of the power is contained in the core. Finally, intensity profiles of all modes were illustrated.

**Keywords:** Optical fibers, Single-mode fiber, Multimode fibers, Step index fibers, RP Fiber Calculator.

### 1. Introduction

Optical fibers are fabulous fibers of glass [1]. A step-index fiber (SIF) consists of a central glass core (having a refractive index  $n_1$ ) surrounded by a cladding layer of a slightly lower refractive index  $n_2$  [2]. **Figure 1** illustrates the two major types of SIF. In a single-mode fiber (SMF), only one mode can propagate, while a multimode fiber (MMF) allows many modes to propagate [1]. The main difference between the SMF and MMF is the core size [2]. The bandwidth of SMF is so large compared to that of the MMF that SMF is used in all long-haul communications [3]. Because of their larger core cross-sectional area, MMFs are more suitable than SMFs for power transmission applications [4].





**Figure 1.** Schematic diagram showing a SM SIF and MM SIF, where  $r$  is the radial position [5].

Before 1970, optical fibers have high losses (about 1000 dB/km). Their use for communication purposes was considered impractical [6]. Kao and Hockham [7] suggested that glass fibers could be a good transmission medium if impurities could be removed. In 1970, SMFs with a loss of about 17 dB/km at a wavelength near 633 nm were produced, making fiber-optic communications practical [8]. This is recognized as the birth of optical fiber communication. Since then, the progress in this field has been phenomenal [9].

In 2020, Salih [10] used RP Fiber Calculator to design SM SIFs at the wavelengths of 1310 nm and 1550 nm. In the same year, Ibrahim and Salih [11, 12] used this calculator to study modes properties for SIFs at 850 nm and 1300 nm. In 2021, Salih [13] designed a MM SIF at 1300 nm. In the same year, Shnain and Salih [14–16] designed SIFs and calculated their guided modes properties at 1550 nm. Moreover, Salih [17] estimated the properties of the fundamental mode for SM SIFs at 1550 nm.

In this work, the properties of the modes for SM and MM SIFs at 633 nm have been calculated with free fiber optics software RP Fiber Calculator (version 2022). finally, the effect of increasing the core radius on these properties has been studied.

## 2. Theoretical Background

Suppose the angle of incidence is larger than the critical angle ( $\theta_c$ ), the incident light undergoes total internal reflection. The critical angle is determined by [18]:

$$\theta_c = \sin^{-1}(n_2/n_1) \tag{1}$$

The numerical aperture (NA) is defined by:

$$NA = \sqrt{n_1^2 - n_2^2} \tag{2}$$

The normalized frequency (V) governs the number of modes (M) and their propagation constants [19]. It is given by [2]:

$$V = k_0 a NA \tag{3}$$

where ( $k_0 = 2\pi/\lambda_0$ ),  $\lambda_0$  is the wavelength of light and  $a$  is the core radius. In practice,  $a < 2\ \mu\text{m}$  for a SMF in the visible region.

The effective refractive index ( $n_{\text{eff}}$ ) is related to the propagation constant ( $\beta$ ) by:

$$n_{\text{eff}} = \beta/k_0 \tag{4}$$

It varies approximately between  $n_1$  and  $n_2$ .

The effective area of the fundamental mode is [6]:

$$A_{\text{eff}} = \pi \omega_0^2 \tag{5}$$

where the spot size ( $\omega_0$ ) of the fundamental mode is given by:

$$(\omega_0/a) \approx 0.65 + 1.619V^{-3/2} + 2.879V^{-6} \tag{6}$$

The percentage power in core of the fundamental mode is:

$$P \text{ in core} = \left[ 1 - \exp\left(-\frac{2a^2}{\omega_0^2}\right) \right] \times 100\% \quad (7)$$

The mode cutoff wavelength is given by [9]:

$$\lambda_{co} = \frac{2\pi}{V_{co}} aNA \quad (8)$$

where  $V_{co}$  is the cutoff frequency of the linearly polarized ( $LP_{l,m}$ ) mode below which cannot exist [5] as shown in **Table 1**, where  $l = 0, 1, 2, \dots$  and  $m = 1, 2, 3, \dots$

**Table 1.** Cutoff frequencies of the  $LP_{l,m}$  modes in a SIF [9].

| $LP_{l,m}$ modes | $V_{co}$ |
|------------------|----------|
| $LP_{0,1}$       | 0        |
| $LP_{1,1}$       | 2.4048   |
| $LP_{2,1}$       | 3.8317   |
| $LP_{3,1}$       | 5.1356   |
| $LP_{4,1}$       | 6.3802   |
| $LP_{5,1}$       | 7.5883   |
| $LP_{0,2}$       | 3.8317   |
| $LP_{1,2}$       | 5.5201   |
| $LP_{2,2}$       | 7.0156   |
| $LP_{0,3}$       | 7.0156   |

A SIF with  $0 < V < 2.4048$  supports only the fundamental ( $LP_{0,1}$ ) mode. Similarly, for  $2.4048 < V < 3.8317$ , only  $LP_{0,1}$  and  $LP_{1,1}$  modes; for  $3.8317 < V < 5.1356$ , only  $LP_{0,1}$ ,  $LP_{1,1}$ ,  $LP_{2,1}$  and  $LP_{0,2}$  modes will exist, and so forth [9]. **Figure 2** shows the intensity profiles of the modes existing at  $V=8$ .

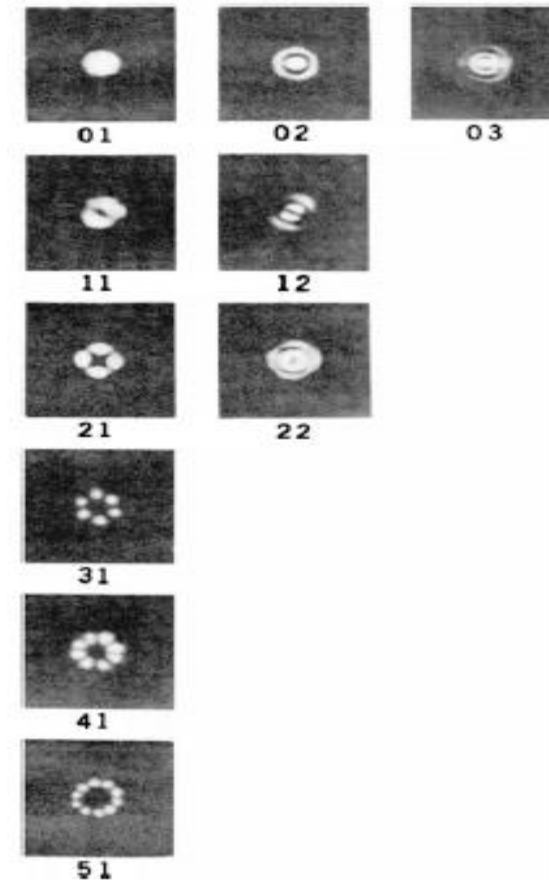


Figure 2. Observed intensity profiles of all  $LP_{l,m}$  modes at  $V=8$  [20].

### 3. Results and Discussion

In this work, RP Fiber Calculator (free version 2022) (Figure 3) is used to calculate the modes properties of SIFs. The Inputs in this calculator are  $a = (1 - 4.75) \mu\text{m}$ ,  $n_1 = 1.45$ ,  $n_2 = 1.44$ , and  $\lambda_0 = 633 \text{ nm}$ . The Outputs are:  $NA=0.17$ ,  $V$  and the properties of the modes.. The NA of the fiber can be calculated either from this calculator or Equation (2). The critical angle is  $83.3^\circ$  which can be determined from Equation (1).

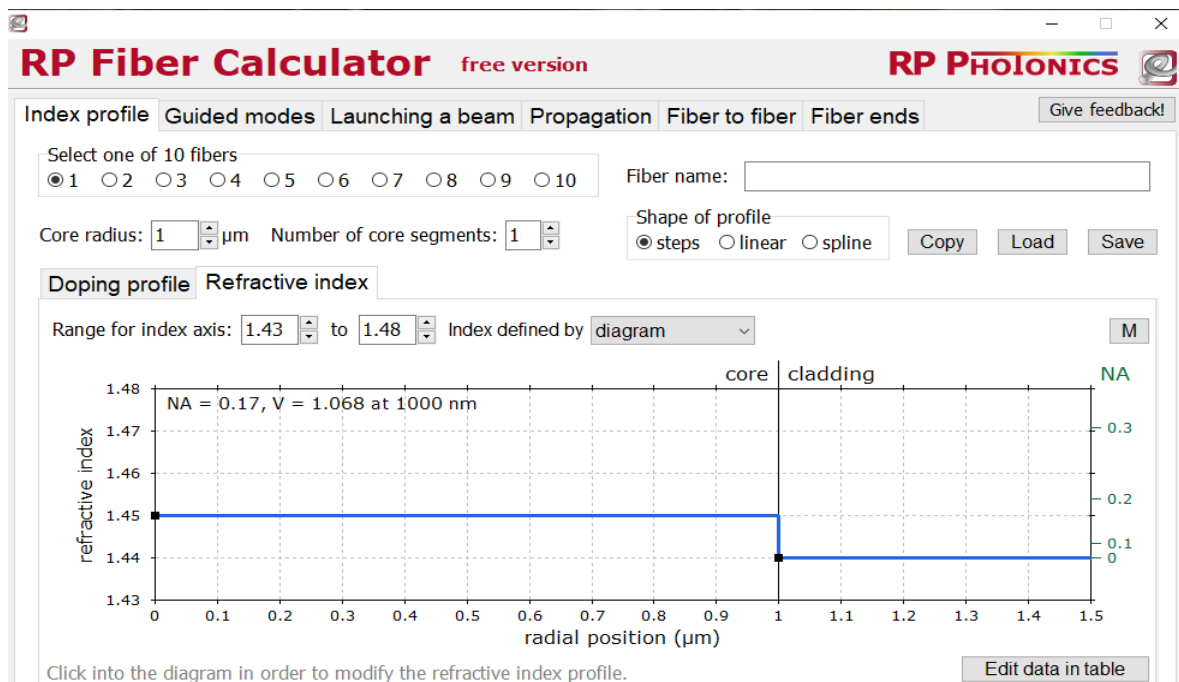


Figure 3. RP Fiber Calculator (index profile tab).

**Table 2** shows normalized frequencies and fiber modes number. If  $V < 2.4048$ , there may be only one mode. On the other hand, if  $V > 2.4048$ , there is more than one mode.

**Table 2.** Normalized frequencies of the fibers and their modes number.

| a<br>( $\mu\text{m}$ ) | V                 | M                        |
|------------------------|-------------------|--------------------------|
|                        | From Equation (3) | From RP Fiber Calculator |
| 1                      | 1.6874            | 1                        |
| 2.25                   | 3.7967            | 2                        |
| 3.5                    | 5.9060            | 6                        |
| 4.75                   | 8.0153            | 10                       |

Five properties of modes have been calculated. These are propagation constant, effective refractive index, effective area, percentage power in the core, and cutoff wavelength. **Table 3** shows the propagation constant and effective refractive index of the  $LP_{0,1}$  mode of an SMF calculated from the RP Fiber Calculator. This fiber has a core radius close to the light wavelength.

**Table 3.** Propagation constant and effective refractive index of  $LP_{0,1}$  mode ( $a=1 \mu\text{m}$ ).

| Mode       | $\beta$ ( $\mu\text{m}^{-1}$ ) | $n_{\text{eff}}$ |
|------------|--------------------------------|------------------|
| $LP_{0,1}$ | 14.3235                        | 1.443026         |

MMFs can be obtained when the radius of the fiber core is large compared to the wavelength. **Tables 4 to 6** show propagation constants and effective refractive indices of all modes obtained from the RP Fiber Calculator. It can be noted that the first mode has the highest propagation constant and effective refractive index, which are related by Equation (4). These two properties increase with increasing core radius.

**Table 4.** Propagation constants and effective refractive indices of  $LP_{l,m}$  modes ( $a=2.25 \mu\text{m}$ ).

| $LP_{l,m}$ modes | $\beta$ ( $\mu\text{m}^{-1}$ ) | $n_{\text{eff}}$ |
|------------------|--------------------------------|------------------|
| $LP_{0,1}$       | 14.3682                        | 1.447528         |
| $LP_{1,1}$       | 14.3326                        | 1.443935         |

**Table 5.** Propagation constants and effective refractive indices of  $LP_{l,m}$  modes ( $a=3.5 \mu\text{m}$ ).

| $LP_{l,m}$ modes | $\beta$ ( $\mu\text{m}^{-1}$ ) | $n_{\text{eff}}$ |
|------------------|--------------------------------|------------------|
| $LP_{0,1}$       | 14.3808                        | 1.448791         |
| $LP_{1,1}$       | 14.3626                        | 1.446957         |
| $LP_{2,1}$       | 14.3391                        | 1.444599         |
| $LP_{3,1}$       | 14.3114                        | 1.441805         |
| $LP_{0,2}$       | 14.3317                        | 1.443849         |
| $LP_{1,2}$       | 14.2994                        | 1.440591         |

**Table 6.** Propagation constants and effective refractive indices of  $LP_{l,m}$  modes ( $a=4.75 \mu\text{m}$ ).

| $LP_{l,m}$ modes  | $\beta$ ( $\mu\text{m}^{-1}$ ) | $n_{\text{eff}}$ |
|-------------------|--------------------------------|------------------|
| LP <sub>0,1</sub> | 14.3857                        | 1.449288         |
| LP <sub>1,1</sub> | 14.3749                        | 1.448198         |
| LP <sub>2,1</sub> | 14.3608                        | 1.446777         |
| LP <sub>3,1</sub> | 14.3437                        | 1.445053         |
| LP <sub>4,1</sub> | 14.3238                        | 1.443048         |
| LP <sub>5,1</sub> | 14.3014                        | 1.440793         |
| LP <sub>0,2</sub> | 14.3560                        | 1.446295         |
| LP <sub>1,2</sub> | 14.3341                        | 1.444091         |
| LP <sub>2,2</sub> | 14.3100                        | 1.441663         |
| LP <sub>0,3</sub> | 14.3064                        | 1.441297         |

**Table 7** shows effective area and percentage power in core of the  $LP_{0,1}$  mode of a SMF obtained from RP Fiber Calculator.

**Table 7.** Effective area and percentage power in core of  $LP_{0,1}$  mode ( $a=1 \mu\text{m}$ ).

| Mode              | $A_{\text{eff}}$ ( $\mu\text{m}^2$ ) | P in core (%) |
|-------------------|--------------------------------------|---------------|
| LP <sub>0,1</sub> | 6.4                                  | 63.1          |

**Tables 8 to 10** show effective areas and percentage powers in the core of all modes of MMFs calculated from RP Fiber Calculator. It can be noted that the first mode has the highest percentage of power. These two properties increase with increasing core radius.

**Table 8.** Effective areas and percentage powers in core of  $LP_{l,m}$  modes ( $a=2.25 \mu\text{m}$ ).

| $LP_{l,m}$ modes  | $A_{\text{eff}}$ ( $\mu\text{m}^2$ ) | P in core (%) |
|-------------------|--------------------------------------|---------------|
| LP <sub>0,1</sub> | 12.8                                 | 94.3          |
| LP <sub>1,1</sub> | 13.4                                 | 82.8          |

**Table 9.** Effective areas and percentage powers in core of  $LP_{l,m}$  modes ( $a=3.5 \mu\text{m}$ ).

| $LP_{l,m}$ modes  | $A_{\text{eff}}$ ( $\mu\text{m}^2$ ) | P in core (%) |
|-------------------|--------------------------------------|---------------|
| LP <sub>0,1</sub> | 25.4                                 | 98.2          |
| LP <sub>1,1</sub> | 23.7                                 | 95.1          |
| LP <sub>2,1</sub> | 25.4                                 | 90.1          |
| LP <sub>3,1</sub> | 27.5                                 | 82.0          |
| LP <sub>0,2</sub> | 22.5                                 | 87.1          |
| LP <sub>1,2</sub> | 33.3                                 | 63.4          |

**Table 10.** Effective areas and percentage powers in core of  $LP_{l,m}$  modes ( $a=4.75 \mu\text{m}$ ).

| $LP_{l,m}$ modes  | $A_{\text{eff}}$ ( $\mu\text{m}^2$ ) | P in core (%) |
|-------------------|--------------------------------------|---------------|
| LP <sub>0,1</sub> | 42.8                                 | 99.2          |
| LP <sub>1,1</sub> | 39.1                                 | 97.9          |
| LP <sub>2,1</sub> | 40.4                                 | 96.1          |
| LP <sub>3,1</sub> | 40.3                                 | 93.5          |
| LP <sub>4,1</sub> | 40.4                                 | 89.9          |
| LP <sub>5,1</sub> | 41.5                                 | 84.5          |
| LP <sub>0,2</sub> | 34.4                                 | 95.2          |
| LP <sub>1,2</sub> | 33.9                                 | 90.8          |
| LP <sub>2,2</sub> | 41.7                                 | 82.4          |
| LP <sub>0,3</sub> | 40.9                                 | 77.9          |

**Table 11** shows effective areas and percentage powers in the core of the first mode obtained from Equations (5) and (7). A comparison with those in **Tables 7 to 10** show a slight difference because the spot size is calculated approximately from Equation (6).

**Table 11.** Effective areas and percentage powers in core of LP<sub>0,1</sub> mode.

| a<br>( $\mu\text{m}$ ) | $A_{\text{eff}}$ ( $\mu\text{m}^2$ ) |  | P in core (%)     |  |
|------------------------|--------------------------------------|--|-------------------|--|
|                        | From Equation (5)                    |  | From Equation (7) |  |
| 1                      | 7.19                                 |  | 58.2              |  |
| 2.25                   | 12.0                                 |  | 92.9              |  |
| 3.5                    | 22.4                                 |  | 96.8              |  |
| 4.75                   | 36.9                                 |  | 97.9              |  |

**Tables 12 to 14** show the cutoff wavelengths of LP<sub>*l,m*</sub> modes of the MMFs. It can be noted that the first mode has no cutoff. Cutoff wavelengths obtained from RP Fiber Calculator agree with those calculated from Equation (8). Cutoff wavelengths are more than 633 nm. This is because the cutoff frequencies of the modes are less than the normalized frequency of the fiber. Cutoff wavelengths of the modes increase with increasing core radius..

**Table 12.** Cutoff wavelengths (nm) of LP<sub>*l,m*</sub> modes (a=2.25  $\mu\text{m}$ ).

| LP <sub><i>l,m</i></sub> modes | From RP Fiber Calculator | From Equation (8) |
|--------------------------------|--------------------------|-------------------|
| LP <sub>0,1</sub>              |                          |                   |
| LP <sub>1,1</sub>              | 995.22                   | 999.38            |

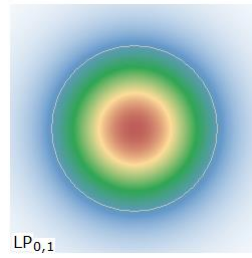
**Table 13.** Cutoff wavelengths (nm) of LP<sub>*l,m*</sub> modes (a=3.5  $\mu\text{m}$ ).

| LP <sub><i>l,m</i></sub> modes | From RP Fiber Calculator | From Equation (8) |
|--------------------------------|--------------------------|-------------------|
| LP <sub>0,1</sub>              |                          |                   |
| LP <sub>1,1</sub>              | 1548.12                  | 1554.60           |
| LP <sub>2,1</sub>              | 971.63                   | 975.68            |
| LP <sub>3,1</sub>              | 724.95                   | 727.96            |
| LP <sub>0,2</sub>              | 971.60                   | 975.68            |
| LP <sub>1,2</sub>              | 674.44                   | 677.25            |

**Table 14.** Cutoff wavelengths (nm) of LP<sub>*l,m*</sub> modes (a=4.75  $\mu\text{m}$ ).

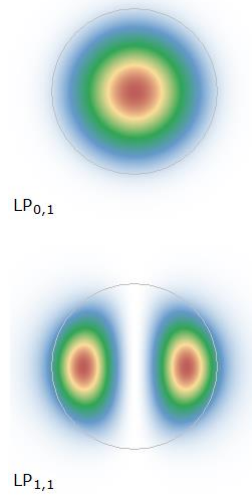
| LP <sub><i>l,m</i></sub> modes | From RP Fiber Calculator | From Equation (8) |
|--------------------------------|--------------------------|-------------------|
| LP <sub>0,1</sub>              |                          |                   |
| LP <sub>1,1</sub>              | 2101.02                  | 2109.81           |
| LP <sub>2,1</sub>              | 1318.65                  | 1324.13           |
| LP <sub>3,1</sub>              | 983.86                   | 987.94            |
| LP <sub>4,1</sub>              | 791.96                   | 795.22            |
| LP <sub>5,1</sub>              | 665.88                   | 668.62            |
| LP <sub>0,2</sub>              | 1318.60                  | 1324.13           |
| LP <sub>1,2</sub>              | 915.31                   | 919.13            |
| LP <sub>2,2</sub>              | 720.20                   | 723.20            |
| LP <sub>0,3</sub>              | 720.19                   | 723.20            |

**Figure 4** shows intensity profile of the LP<sub>0,1</sub> mode of a SMF. This mode has a single spot profile.

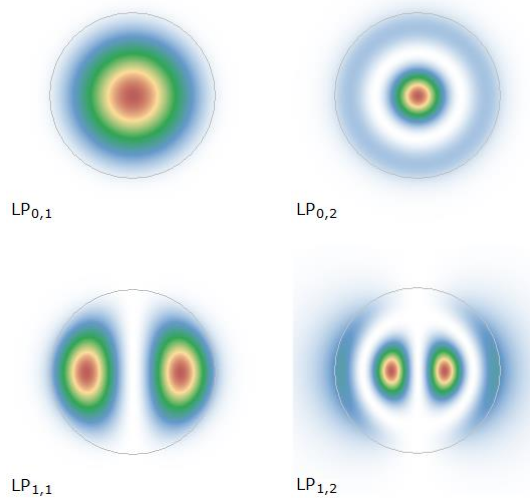


**Figure 4.** Intensity profile of LP<sub>0,1</sub> mode (a=1 μm).

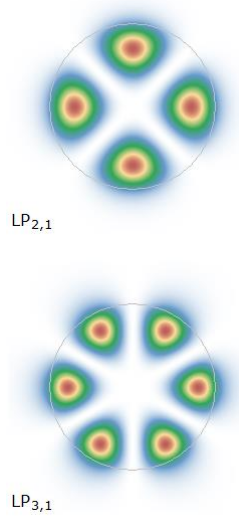
**Figures 5 - 7** show the modes profiles of MMFs. Modes with  $l = 0$  (LP<sub>0,1</sub>, LP<sub>0,2</sub>, and LP<sub>0,3</sub>) have a single spot in their profiles. Other modes have  $(2l)$  spots. The LP <sub>$l,m$</sub>  modes and their number in **Figure 7** are equal to those in **Figure 2**, which are obtained from the experimental observation.



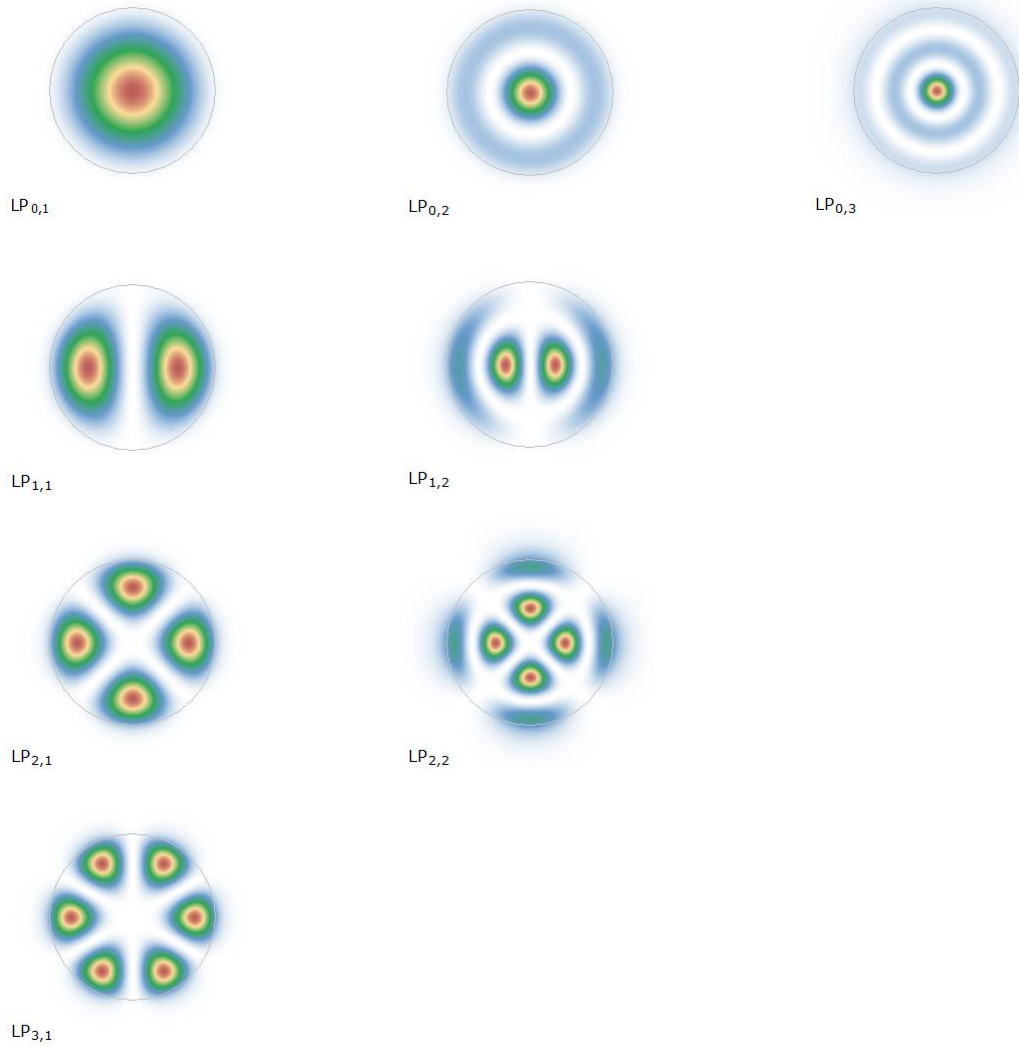
**Figure 5.** Intensity profiles of LP<sub>0,1</sub> and LP<sub>1,1</sub> modes (a=2.25 μm).

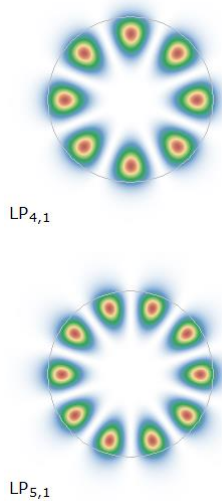






**Figure 6.** Intensity profiles of LP<sub>*l,m*</sub> modes (a=3.5 μm).





**Figure 7.** Intensity profiles of  $LP_{l,m}$  modes ( $a=4.75 \mu\text{m}$ ).

#### 4. Conclusion

It has been concluded that the modes number and their properties are affected by the fiber core radius. If the core radius is close to the operating wavelength, an SMF is obtained. As the core radius becomes much larger than the operating wavelength, MMFs are obtained. the cutoff wavelengths of the modes are more than the operating wavelength of the fiber. All the properties of the modes increase with increasing core radius.

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