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

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Abstract

The need for optical fibers has emerged for its ability to transmit information with less attenuation and over long distances. In this work, four optical fibers with core radii from 1 µm to 4.75 µm in steps of 1.25 µm and a numerical aperture of 0.17 were studied and their modes properties have been calculated at a wavelength of 633 nm by using RP Fiber Calculator (free version 2022). Also, the effect of increasing the core radius on these properties has been studied. Multimode fibers can be obtained when the radius of the fiber core is large compared to the operating wavelength of the fiber which is less than the cutoff wavelength of the mode. Otherwise, a single-mode fiber is obtained. It has been concluded that all the calculated properties increase with increasing core radius. More than half of the power is contained in the core. 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 very fine fibers of glass [1]. A step index fiber (SIF) consists of a central glass core (having refractive index n_1) surrounded by a cladding layer of 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 for studying 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. Also, Salih [17] calculated properties of the fundamental mode for SM SIFs at 1550 nm.

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

2. Theoretical Background

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

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

The numerical aperture (NA) is defined by:

$$\text{NA} = \sqrt{{n_1}^2 - {n_2}^2} \quad (2)$$

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

$$\text{V} = k_0 \text{aNA} \quad (3)$$

where ($k_0 = 2\,\pi/\lambda_0$), λ_0 is the wavelength of light and a is the core radius. In practice, a< 2 μm for a SMF in the visible region.

The effective refractive index (n_{eff}) is related to the propagation constant (β) by:

$$n_{\text{eff}} = \beta/k_0 \quad (4)$$

It varies approximately between n_1 and n_2.

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

$$A_{\text{eff}} = \pi {\omega_0}^2 \quad (5)$$

where the spot size (ω_0) of the fundamental mode is given by:

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

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 it cannot exist [5] as shown in **Table 1**, where $l = 0, 1, 2, \ldots$ and $m = 1, 2, 3, \ldots$

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.

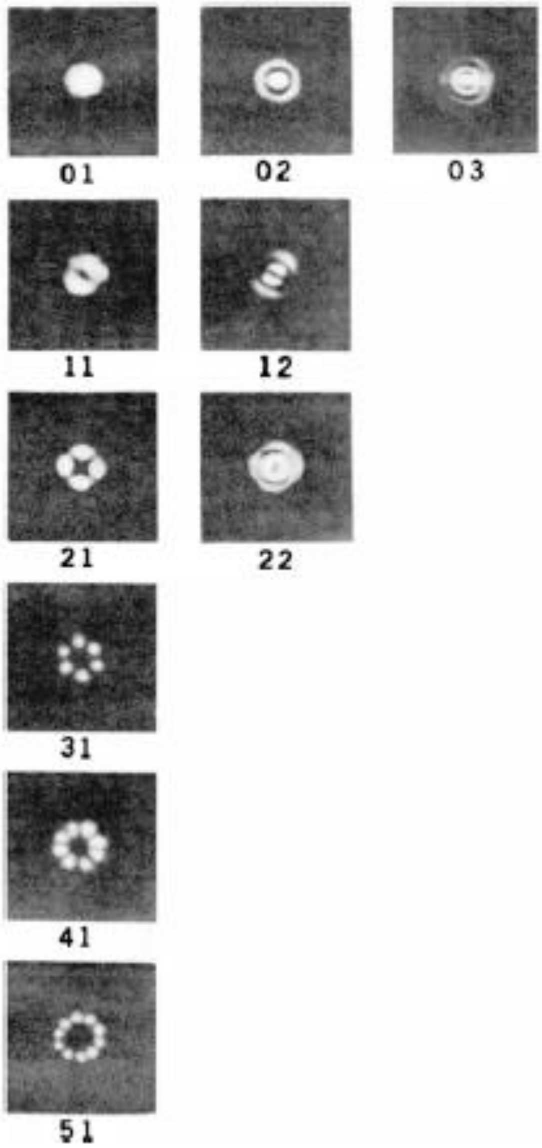


Figure 2. Observed intensity profiles of all $LP_{l,m}$ modes at V=8 [20].

3. Results and Discussion

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

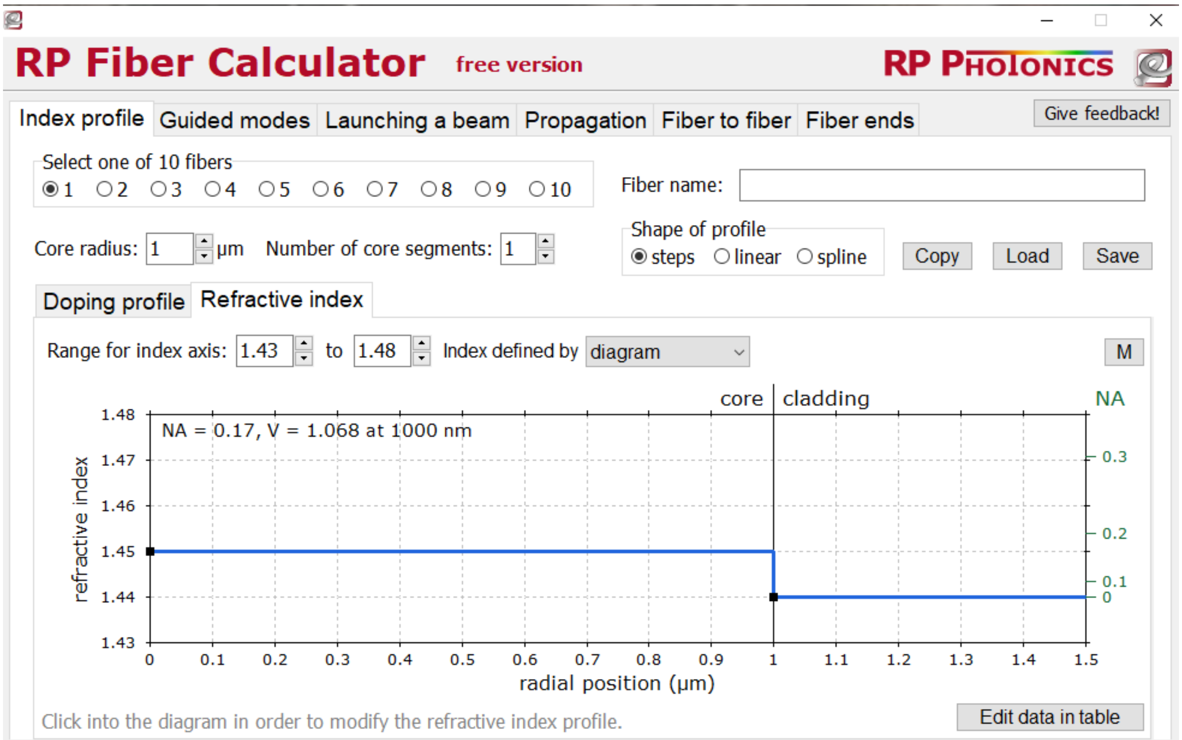


Figure 3. RP Fiber Calculator (index profile tab).

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 (µm)	V From Equation (3)	M 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 core and cutoff wavelength. **Table 3** shows propagation constant and effective refractive index of the $LP_{0,1}$ mode of a SMF calculated from RP Fiber Calculator. This fiber has a core radius which is close to the wavelength of light.

Table 3. Propagation constant and effective refractive index of $LP_{0,1}$ mode (a=1 µm).

Mode	β (µm^{-1})	n_{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 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 µm).

$LP_{l,m}$ modes	β (µm^{-1})	n_{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 µm).

$LP_{l,m}$ modes	β (µm^{-1})	n_{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 µm).

$LP_{l,m}$ modes	β (µm^{-1})	n_{eff}
$LP_{0,1}$	14.3857	1.449288
$LP_{1,1}$	14.3749	1.448198
$LP_{2,1}$	14.3608	1.446777
$LP_{3,1}$	14.3437	1.445053
$LP_{4,1}$	14.3238	1.443048
$LP_{5,1}$	14.3014	1.440793
$LP_{0,2}$	14.3560	1.446295
$LP_{1,2}$	14.3341	1.444091
$LP_{2,2}$	14.3100	1.441663
$LP_{0,3}$	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 µm).

Mode	A_{eff} (µm^2)	P in core (%)
$LP_{0,1}$	6.4	63.1

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

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

$LP_{l,m}$ modes	A_{eff} (µm^2)	P in core (%)
$LP_{0,1}$	12.8	94.3
$LP_{1,1}$	13.4	82.8

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

$LP_{l,m}$ modes	A_{eff} (µm^2)	P in core (%)
$LP_{0,1}$	25.4	98.2
$LP_{1,1}$	23.7	95.1
$LP_{2,1}$	25.4	90.1
$LP_{3,1}$	27.5	82.0
$LP_{0,2}$	22.5	87.1
$LP_{1,2}$	33.3	63.4

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

$LP_{l,m}$ modes	A_{eff} (µm^2)	P in core (%)
$LP_{0,1}$	42.8	99.2
$LP_{1,1}$	39.1	97.9
$LP_{2,1}$	40.4	96.1

$LP_{3,1}$	40.3	93.5
$LP_{4,1}$	40.4	89.9
$LP_{5,1}$	41.5	84.5
$LP_{0,2}$	34.4	95.2
$LP_{1,2}$	33.9	90.8
$LP_{2,2}$	41.7	82.4
$LP_{0,3}$	40.9	77.9

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

Table 11. Effective areas and percentage powers in core of $LP_{0,1}$ mode.

a (μm)	A_{eff} (μm^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 $LP_{l,m}$ modes of the MMFs. It can be noted that the first mode has no cutoff. Cutoff wavelengths which obtained from RP Fiber Calculator are in good agreement with those calculated from Equation (8). Cutoff wavelengths are more than 633 nm. This is due to that 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 $LP_{l,m}$ modes (a=2.25 μm).

$LP_{l,m}$ modes	From RP Fiber Calculator	From Equation (8)
$LP_{0,1}$		
$LP_{1,1}$	995.22	999.38

Table 13. Cutoff wavelengths (nm) of $LP_{l,m}$ modes (a=3.5 μm).

$LP_{l,m}$ modes	From RP Fiber Calculator	From Equation (8)
$LP_{0,1}$		
$LP_{1,1}$	1548.12	1554.60
$LP_{2,1}$	971.63	975.68
$LP_{3,1}$	724.95	727.96
$LP_{0,2}$	971.60	975.68
$LP_{1,2}$	674.44	677.25

Table 14. Cutoff wavelengths (nm) of $LP_{l,m}$ modes (a=4.75 μm).

$LP_{l,m}$ modes	From RP Fiber Calculator	From Equation (8)
$LP_{0,1}$		
$LP_{1,1}$	2101.02	2109.81
$LP_{2,1}$	1318.65	1324.13
$LP_{3,1}$	983.86	987.94
$LP_{4,1}$	791.96	795.22
$LP_{5,1}$	665.88	668.62
$LP_{0,2}$	1318.60	1324.13
$LP_{1,2}$	915.31	919.13
$LP_{2,2}$	720.20	723.20
$LP_{0,3}$	720.19	723.20

Figure 4 shows intensity profile of the $LP_{0,1}$ mode of a SMF. This mode has a single spot profile.

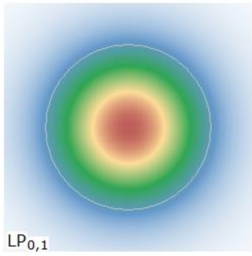


Figure 4. Intensity profile of $LP_{0,1}$ mode (a=1 µm).

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

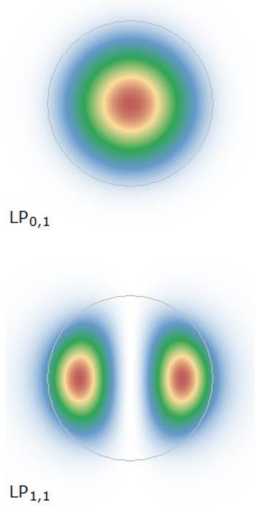
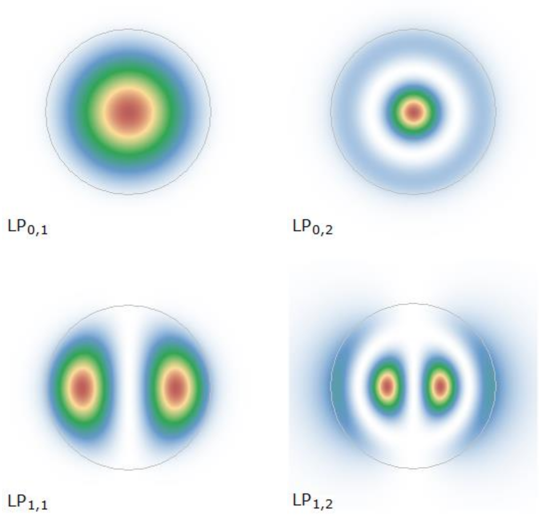


Figure 5. Intensity profiles of $LP_{0,1}$ and $LP_{1,1}$ modes (a=2.25 µm).



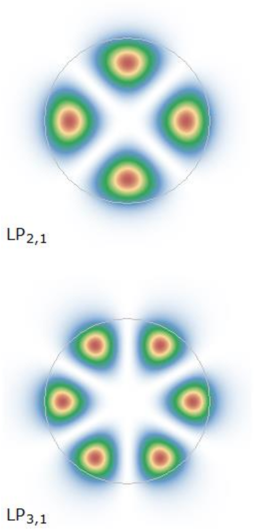
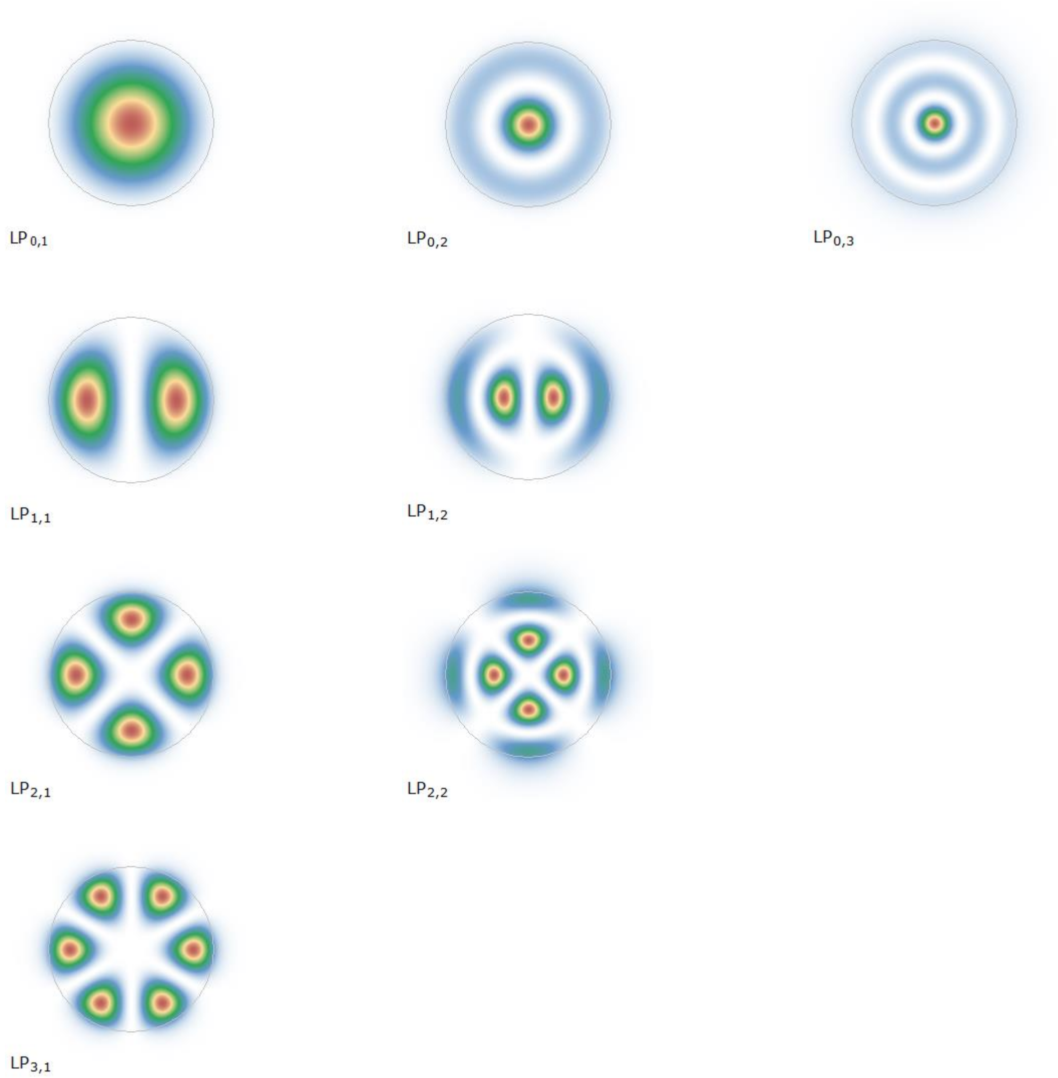
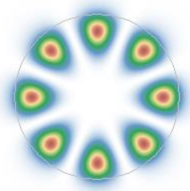


Figure 6. Intensity profiles of $LP_{l,m}$ modes (a=3.5 μm).





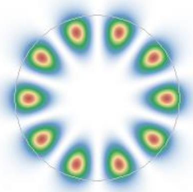


Figure 7. Intensity profiles of $LP_{l,m}$ modes (a=4.75 µm).

4. Conclusions

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, a SMF is obtained. As the core radius becomes much larger than the operating wavelength, MMFs are obtained. Cutoff wavelengths of the modes are more than the operating wavelength of the fiber. All the modes properties increase with increasing core radius.

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