



Calculating Properties of Mode for Step-Index Single-Mode Optical Fibers at 1064 nm Wavelength

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Abstract

The development in the field of technology has led to an increased need to develop optical fibers due to their ability to transmit information and data with the least amount of attenuation over long distances between city centers. In this research, mode properties calculation for five step-index single-mode optical fibers with core radii of (1.9 - 2.9) μm where the increase in radius is 0.25 μm , with core and cladding indices ($n_1=1.4652$, $n_2=1.458496157$), respectively and a numerical aperture of 0.14 has been done at 1064 nm wavelength using RP Fiber Calculator (free version 2025). The fundamental fiber mode properties such as effective area, power propagated in the core, propagation constant and effective refractive index were calculated. Intensity distributions for the mode were shown. It was noted that the effect of increasing the core radius led to an increase in the core power and it was also observed that the propagation constant and effective refractive index increase with the increase in the radius of the core. It was obtaining percentage power more than 50%. Results of this work will be useful in the design of optical fibers. Results from the calculator were compared with those calculated from equations and with previous study and it was concluded that all calculated properties are in good agreement.

Keywords: Step-index fibers, Single-mode fibers, RP Fiber Calculator, 1064 nm Wavelength.

1. Introduction

In optical communication systems, light waves can be used to transfer data from one location to another to connect cities and remote areas, the world's continental optical cable connection is the longest and most extensive scheme of optical transmission systems. Data transmission through optical fibers has evolved rapidly since its inception in 1966 (1).

Figure 1 shows the structure of a step-index fiber (SIF), which consists of a core with a circular cross-section and a refractive index (n_1), surrounded by a cladding with a ring-shaped cross-section and a refractive index (n_2), where ($n_2 < n_1$) (2). The refractive index (n_1) is uniform throughout the core and undergoes an abrupt or step change at the core-cladding interface, where (a) is the radius of the core (3).



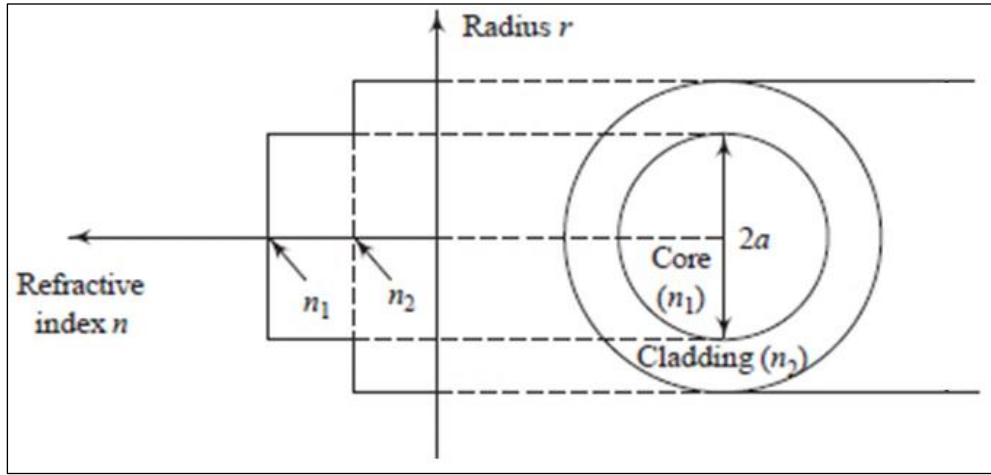


Figure 1. Basic structure of a SIF (2).

In a single-mode fiber (SMF), only one mode (the $LP_{0,1}$ mode) can propagate through the fiber (3). Silica-based solid core such as SMFs are vastly used as the fundamental component in the telecommunication industry, their SIF profile is the simplest fiber design and provides a reasonable starting for the study and to understand of fibers with more complex designs (4).

Figure 2 shows that the propagation of light in SMFs is because the optical power in these fibers is transmitted in the cladding as well as in the core, so the cladding must be a more efficient transmitter of power.

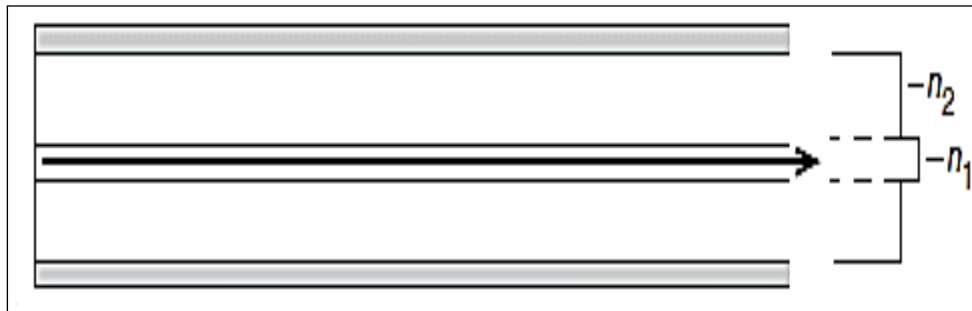


Figure 2. Geometry, refractive-index profile and typical ray in a SI SMF (5).

Optical fiber is the main element in the optical transmission process because it has a wide bandwidth and small signal attenuation, compared to any other wired transmission media used in the information transmission process (6).

In 2015, it was calculated the mode set in weakly guiding fibers by using the commercial software BeamPROP. A SIF with core and cladding indices of 1.45 and 1.44, respectively, the core radius is 5 μm , operating at about 633 nm wavelength has been considered (7). In 2018, it was proposed two fiber designs using commercially available COMSOL software, the proposed fiber has core and cladding with refractive indices of 1.45 and 1.4403, respectively and core radii of 7.5 and 8.5 μm at 1550 nm wavelength (8). In 2020, it was calculated the fundamental fiber mode properties using RP Fiber Calculator. SMFs with a core index of 1.445 and a cladding index of 1.443 were designed. SM operation was achieved using fibers with core radii of 2-6.5 μm operating at 1310 nm and 2-7.5 μm operating at 1550 nm (9). It was calculated the mode properties using the RP Fiber Calculator. SMFs and multimode fibers (MMFs) with core radii of 1-10 μm , core index 1.45 and cladding index 1.44 were studied at two wavelengths 850 nm and 1300 nm (10). In 2021, it was designed a SI MMF of core radius 25 μm with core index 1.445517 and cladding index 1.443157 operating at 1300 nm. The mode properties were calculated using RP Fiber Calculator (PRO

version 2020) (11). It was designed SMF and MMFs with core radii 2.5-13.5 μm , core index 1.45 and cladding index 1.44 at 1550 nm wavelength (12). The fundamental mode properties of SMFs with core radii of 4.9-7.8 μm , core index 1.432 and cladding index 1.43 at 1550 nm were calculated using the RP Fiber Calculator (13). In 2022, optical fibers with core radii from 1 μm to 5 μm , core index 1.45 and cladding index 1.44 were studied and their mode properties were calculated at 633 nm by using RP Fiber Calculator (free version 2022) (14). In the current study, the mode properties of SIFs at 1064 nm were calculated using the optical fiber software RP Fiber Calculator (free version 2025), and the effect of the core radius changing on the properties was studied. The results of this research will be useful in the design of practical SMFs.

2. Theoretical part

Total internal reflection which is the basic principle for optical fibers operation occurs if the incidence angle is less than the acceptance angle. The critical angle (θ_c) can be calculated using the following equation (15)

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) \quad (1)$$

The acceptance angle (θ_a), which can be calculated using (16)

$$\theta_a = \sin^{-1} \text{NA} \quad (2)$$

The numerical aperture (NA) indicates the angle at which the optical fiber accepts light (6). For SIF, the NA depends on the refractive indices of the core and the cladding in an optical fiber (16)

$$\text{NA} = \sqrt{n_1^2 - n_2^2} \quad (3)$$

The normalized frequency of the optical fiber can be calculated using the following equation (17)

$$V = \frac{2\pi}{\lambda} a \text{NA} \quad (4)$$

where λ represents the wavelength. For $V < 2.4048$, there is only one mode.

The radius of the fundamental ($\text{LP}_{0,1}$) mode is given by (18)

$$\omega \approx a (0.65 + 1.619V^{-1.5} + 2.879V^{-6} - 0.016 - 1.561V^{-7}) \quad (5)$$

The effective area for the fundamental mode is (19)

$$A_{eff} = \pi\omega^2 \quad (6)$$

The percentage power in the core is (20)

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

The value of the normalized propagation constant (b) can be calculated from (20)

$$b = (1.1428 - \frac{0.9960}{V})^2 \quad (8)$$

The propagation constant in the medium (β) is (21)

$$\beta = \frac{2\pi}{\lambda} \sqrt{n_2^2 + b(n_1^2 - n_2^2)} \quad (9)$$

The effective refractive index (n_{eff}) can be calculated using the equation (22)

$$n_{eff} = \sqrt{n_2^2 + b(n_1^2 - n_2^2)} \quad (10)$$

3. Results and Discussion

In this work, the mode properties are calculated using the RP Fiber Calculator (free version 2025) as shown in **Figure 3**. This calculator accepts the following inputs: $a = (1.9\text{--}2.9) \mu\text{m}$, $n_1 = 1.4652$, $n_2 = 1.458496157$ and the wavelength of $\lambda = 1064 \text{ nm}$, the outputs are numerical aperture, normalized frequency and the properties of the mode. The critical angle is 84.52° and acceptance angle is 8.05° from **Equations 1** and **2**, respectively. $NA = 0.14$ from **Equation 3**.

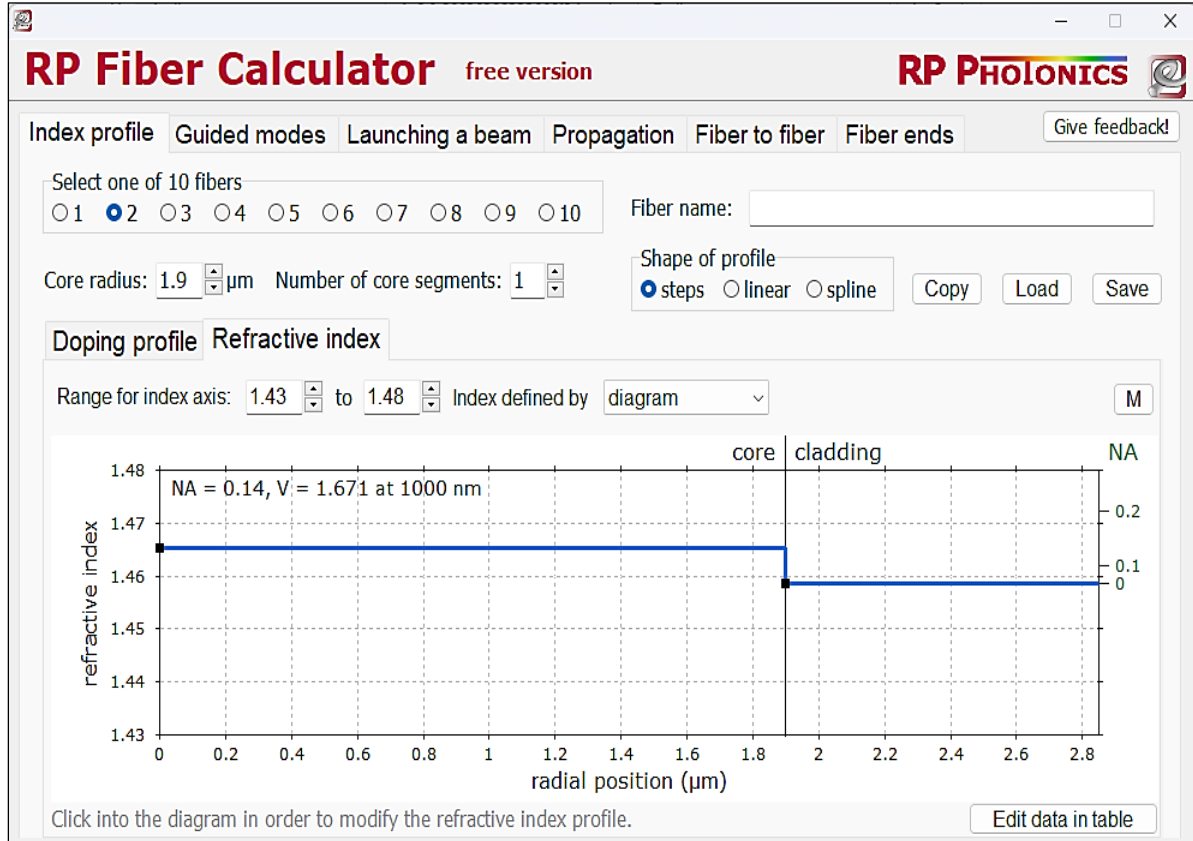


Figure 3. RP Fiber Calculator (free version 2025).

Table 1 shows the values of normalized frequencies calculated from **Equation 4**. All these values are less than 2.4048. Increasing core radius leads to increase V values.

Table 1. Normalized frequencies of SMFs.

$a \text{ (}\mu\text{m)}$	V
1.9	1.5708
2.15	1.7775
2.4	1.9842
2.65	2.1908
2.9	2.3975

Table 2 shows the effective area as calculated from **Equation 6** and from calculator. It can be noted from this table that the values calculated from the equation and the calculator are in a good agreement.

Table 2. Effective areas (μm^2) of the studied fibers.

a (μm)	From Equation (6)	From calculator
1.9	28.4	27.3
2.15	27.7	26.7
2.4	28.2	27.4
2.65	29.3	29.0
2.9	30.9	31.0

Table 3 shows the percentage of power propagated in the core as calculated from **Equation 7** and from calculator. It can be noted from this table that the power increases with the increase in the core radius. All these values are more than 50%.

Table 3. Powers in the core (%) of the fibers under study.

a (μm)	From Equation (7)	From calculator
1.9	55.0	57.7
2.15	65.0	66.8
2.4	72.3	73.7
2.65	77.8	78.8
2.9	82.0	82.7

Table 4 shows the values of the propagation constant calculated from **Equation 9** and from calculator. It can be noted that this property increases with increasing core radius. Also the agreement of the values calculated from the equation and the calculator.

Table 4. Propagation constants (μm)⁻¹ of the studied fibers.

a (μm)	From Equation (9)	From calculator
1.9	8.62305	8.62292
2.15	8.62623	8.62611
2.4	8.62906	8.62897
2.65	8.63155	8.63148
2.9	8.63375	8.63367

Table 5 shows the effective refractive indices that were obtained by calculating from **Equation 10** and the calculator. It can be noted from this table that this property increases with increasing core radius. Also, the agreement of the values calculated from the equation and the calculator. All these values are less than n_1 and more than n_2 .

Table 5. Effective refractive indices of the fibers.

a (μm)	From Equation (10)	From calculator
1.9	1.460234	1.460213
2.15	1.460774	1.460752
2.4	1.461253	1.461237
2.65	1.461675	1.461663
2.9	1.462047	1.462033

Figure 4 shows the intensity distributions for the fiber mode with core radii between 1.9 and 2.9 μm , which consists of a single circular spot at the center of the core.

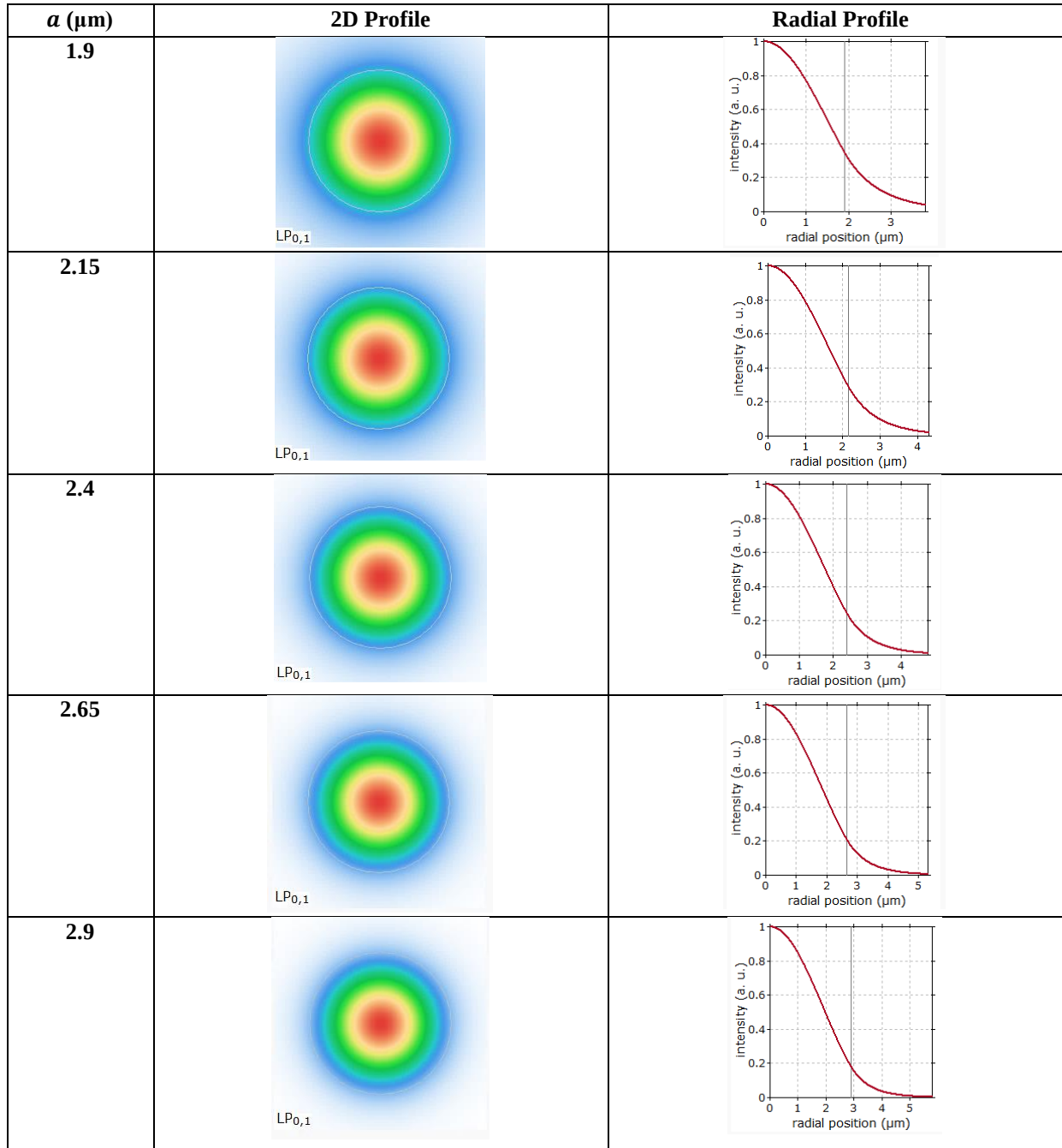


Figure 4. Intensity profiles of the $\text{LP}_{0,1}$ mode for five SMFs with core radii 1.9–2.9 μm .

4. Comparison

Table 6 shows the comparison between inputs and outputs of this work using RP Fiber Calculator (free version) and (23) using COMSOL (commercial), where it can be noted that there is a match between the results.

Table 6. Comparison between this work and (23).

	This Work	Reference (23)
Software	RP Fiber Calculator	COMSOL
Availability	free	commercial
a (μm)	2.65	2.65
n_1	1.4652	1.4652
NA	0.14	0.14
λ (nm)	1064	1064
V	2.1908	2.1908
Mode	$\text{LP}_{0,1}$	$\text{LP}_{0,1}$
P in core (%)	78.8	78.78

Figure 5 shows a comparison between the intensity profiles of the $LP_{0,1}$ mode for a SMF with a core radius of $2.65\ \mu\text{m}$ taken from the RP Fiber Calculator and the results taken from Reference (23), which consists of a single circular spot.

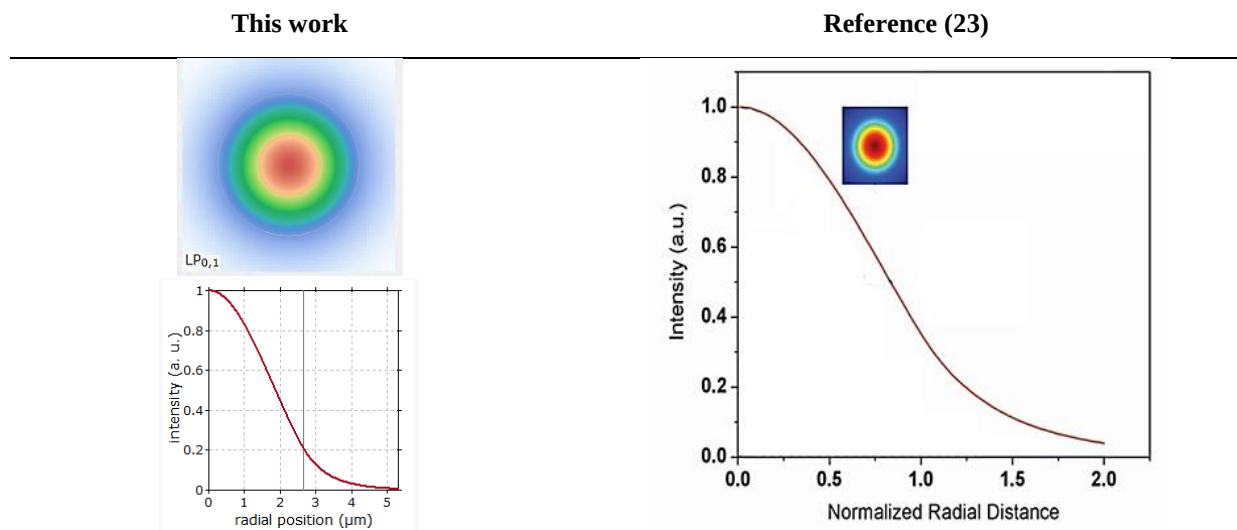


Figure 5. RP generated and COMSOL generated intensity profiles of $LP_{0,1}$ mode for a SMF with core radius $2.65\ \mu\text{m}$.

5. Conclusion

In this study, several mode properties were calculated at $1064\ \text{nm}$ wavelength. It was shown that the core radius of the studied fibers ranges from 1.9 to $2.9\ \mu\text{m}$ to obtain a percentage power of more than 50% . The results of this work will be useful in the design of optical fibers that can be used in optical fiber communication systems.

Table 6 shows the results for the core radius $2.65\ \mu\text{m}$ at $\text{NA}=0.14$, where we notice the equality of the values calculated through the research (23) and the results of this study from the calculator for the SIF mode $LP_{0,1}$.

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Conflict of Interest

The authors declare that they have no conflicts of interest.

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