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Design of Single Mode Fiber for Optical Communications

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Abstract

In this work, a step-index fiber with core index 1.445 and cladding index 1.443 has been designed. Single-mode operation can be obtained by using a fiber with core diameters 4–13 μm operating at a wavelength of 1.31 μm and by 4–15 μm at 1.55 μm. The fundamental fiber mode properties such as phase constant, effective refractive index, mode radius, effective mode area and the power in the core were calculated. Distributions of the intensity and the amplitude were shown.

Key words: Single mode fiber, Step-index fiber, Optical communications.

1. Introduction

Fiber optics plays a key role in communications [1]. A step-index fiber (SIF) consists of a core of refractive index n_1 surrounded by a cladding of slightly lower refractive index n_2, as shown in **Figure 1** [2]. This difference enables the fiber to guide the light by total internal reflection [3]. These indices are close to 1.5 for silica glass fibers [4].

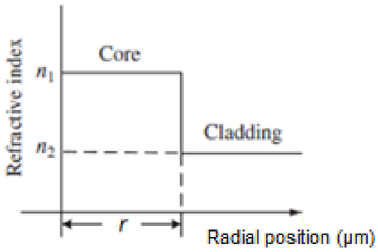


Figure 1. Refractive index profile of a SIF [2].

A single-mode fiber (SMF) is designed to propagate only a single guided mode (fundamental LP_{01} mode), where LP stands for linearly polarized [5]. In 1966, Kao and Hockham discussed the theory and potential use of optical fiber for communications [6]. In 1970, a SMF with attenuation below 20 dB/km was developed [7]. This is recognized as the start of fiber optic communications [8]. In 1979, SMFs with a loss of only 0.2 dB/km at 1.55 μm were fabricated [9]. The SMFs have continued to evolve. Kao (1933–2018) was awarded the 2009 Nobel prize in physics for his theoretical work on the SMF [10] which is extensively used in optical communication systems [11].

2. Important Parameters and Basic Equations

In designing a SMF, several parameters that affect its performance must be considered.

1. Numerical Aperture (NA)

The fiber NA is given by [12]

$$\mathrm{NA} = \sqrt{n_1^2 - n_2^2} \tag{1}$$

It describes the light-gathering capacity of the fiber [13].

2. V Number

The V number is defined as [14]

$$V = kr\mathrm{NA} \tag{2}$$

where $k = 2\pi/\lambda$ is the vacuum wavenumber, λ is the vacuum wavelength of operation and r is the core radius.

Two low loss operating wavelengths used in optical communication systems are 1.31 µm and 1.55 µm [9, 15].

The V number determines the number of guided modes. If $V \leq 2.4048$ the fiber will be SM [16].

3. Phase Constant (β)

The phase change per µm of propagation along the fiber.
The phase constant is [14]

$$\beta = kn_{eff} \tag{3}$$

The effective refractive index (n_{eff}) lies between n_1 and n_2.

4. Effective Mode Area (A_{eff})

The effective mode area is defined as [17]

$$A_{eff} = \pi\omega^2 \tag{4}$$

It determines how tightly light is confined to the core.
For a SI SMF, the mode radius ω can be calculated either from Marcuse's formula [18].

$$\omega \approx r\left(0.65 + \frac{1.619}{\sqrt{V^3}} + \frac{2.879}{V^6}\right) \tag{5}$$

or from a modified formula [19]

$$\omega \approx r\left(0.65 + \frac{1.619}{\sqrt{V^3}} + \frac{2.879}{V^6} - 0.016 - \frac{1.561}{V^7}\right)$$

which becomes

$$\omega \approx r\left(0.634 + \frac{1.619}{\sqrt{V^3}} + \frac{2.879}{V^6} - \frac{1.561}{V^7}\right) \tag{6}$$

5. P in core

The fraction of power propagating within the fiber core is [17]

$$\frac{P_{\mathrm{core}}}{P_{\mathrm{total}}} = 1 - e^{-2r^2/\omega^2} \tag{7}$$

For SMFs, that fraction is low for low V values and reaches $\approx 83\%$ near $V \approx 2.4048$ [5].

3. Results and Discussion

In this work, a SIF with $n_1 = 1.445$ and $n_2 = 1.443$, giving NA = 0.076 has been designed. Design variables are the core radius and the wavelength. The fundamental LP_{01} mode properties can be calculated from RP Fiber Calculator software.

It is evident from **Tables 1, 3.** that the phase constant β lies between kn_1 and kn_2. This means that the effective refractive index n_{eff} lies within the range of n_1 and n_2.The effective mode area A_{eff} decreases when *V*<2 and then increases when *V* >2.

The *V* number, the phase constant β (and thus n_{eff}) and *P* in core increase with increasing fiber core radius r. With increasing *V* number, the fraction of the power propagating within the core increases more and more.When *V* >2, more than 74% of the power is carried in the core and less than 26% in the cladding.

Table 1. *V* number and LP_{01}mode parameters at λ= 1.31 µm.

r **µm**	**from Eq. 2**	**from RP Fiber Calculator**			
	V	**β /µm**	n_{eff}	A_{eff} **(µm)^2**	***P*** **in core %**
2	0.7290	6.92111	1.443003	6788.4	1.4
2.5	0.9113	6.92127	1.443037	738.2	9.7
3	1.0936	6.92170	1.443126	281.4	23.9
3.5	1.2758	6.92233	1.443256	181.8	38.5
4	1.4581	6.92303	1.443404	149.5	51.0
4.5	1.6403	6.92374	1.443551	138.7	60.8
5	1.8226	6.92440	1.443689	137.2	68.4
5.5	2.0049	6.92500	1.443814	140.7	74.3
6	2.1871	6.92554	1.443926	147.3	78.8
6.5	2.3694	6.92601	1.444025	156.1	82.4

Values for ω are listed in **Tables 2, 4.** The mode radius is larger than the core radius. Values of A_{eff} calculated from Eq. 6 and values of *P* calculated from Eq. 7 are in good agreement with those in **Tables 1, 3.**

Table 2. Mode radius, effective mode area and *P* in core for *V* >1.2 at λ= 1.31 µm.

r **µm**	**from Eq. 5**		**from Eq. 6**		**from Eq. 7**
	ω µm	A_{eff} **(µm)^2**	**ω µm**	A_{eff} **(µm)^2**	***P*** **in core %**
3.5	8.544	229.3	7.495	176.5	35.3
4	7.476	175.6	6.967	152.5	48.3
4.5	7.058	156.5	6.766	143.8	58.7
5	6.933	151.0	6.736	142.5	66.8
5.5	6.955	152.0	6.802	145.3	73.0
6	7.061	156.6	6.926	150.7	77.7
6.5	7.216	163.6	7.088	157.8	81.4

Table 3. *V* number and LP_{01} mode parameters at λ= 1.55 µm.

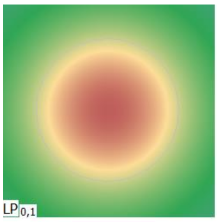
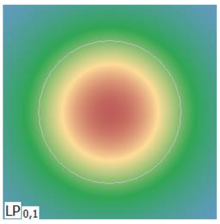
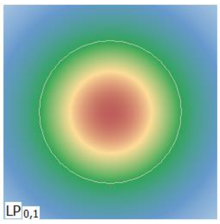
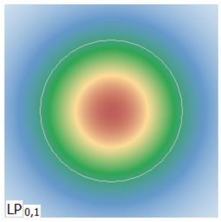
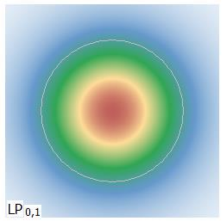
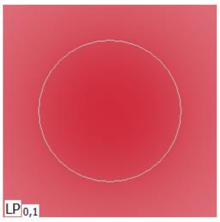
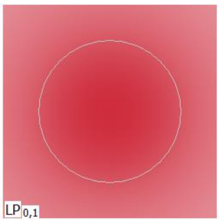
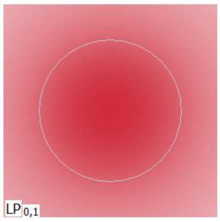
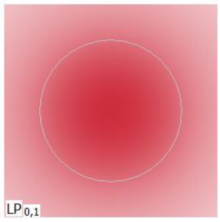
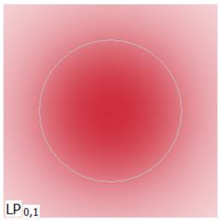
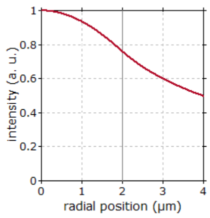
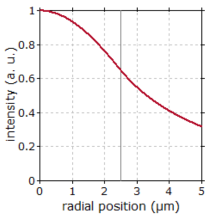
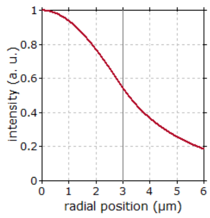
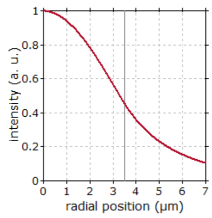
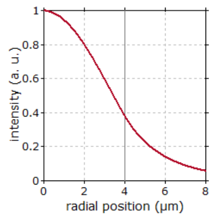
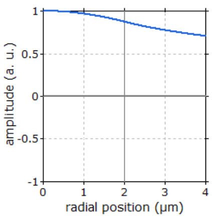
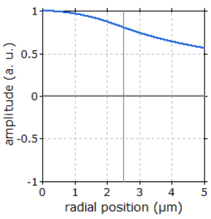
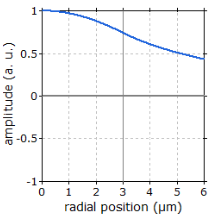
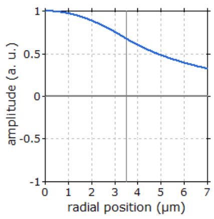
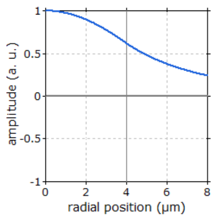
r **µm**	**from Eq. 2**	**from RP Fiber Calculator**			
	V	**β /µm**	n_{eff}	A_{eff} **(µm)²**	***P* in core %**
2	0.6162	5.84944	1.443000	151755.6	0.1
2.5	0.7702	5.84947	1.443007	4815.5	2.5
3	0.9242	5.84961	1.443041	937.9	10.5
3.5	1.0783	5.84991	1.443116	416.0	22.6
4	1.2323	5.85035	1.443223	274.4	35.2
4.5	1.3864	5.85084	1.443345	221.8	46.4
5	1.5404	5.85135	1.443471	200.2	55.7
5.5	1.6944	5.85185	1.443593	192.6	63.3
6	1.8485	5.85231	1.443708	192.5	69.3
6.5	2.0025	5.85274	1.443813	196.9	74.2
7	2.1566	5.85313	1.443908	204.5	78.1
7.5	2.3106	5.85348	1.443995	214.3	81.3

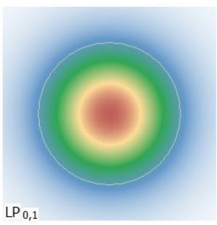
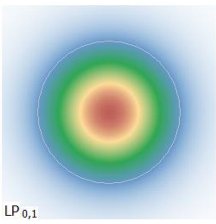
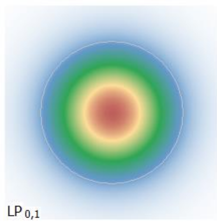
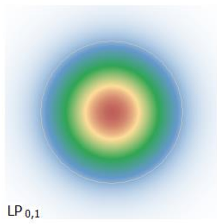
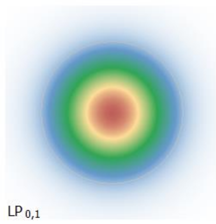
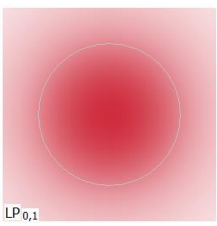
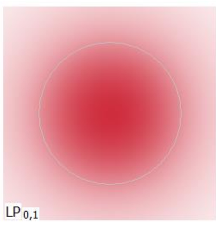
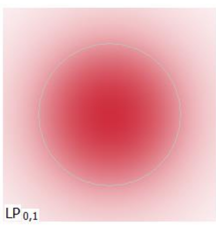
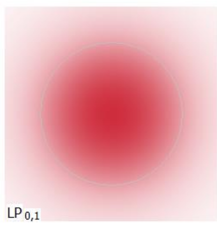
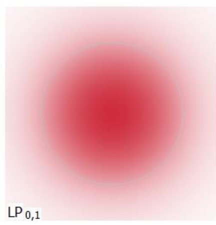
Table 4. Mode radius, effective mode area and *P* in core for *V* >1.2 at λ= 1.55 µm.

r **µm**	**from Eq. 5**		**from Eq. 6**		**from Eq. 7**
	ω µm	A_{eff} **(µm)²**	**ω µm**	A_{eff} **(µm)²**	***P* in core %**
4	10.62	354.5	9.112	260.8	32.0
4.5	9.212	266.6	8.427	223.1	43.5
5	8.562	230.3	8.102	206.2	53.3
5.5	8.281	215.5	7.979	200.0	61.3
6	8.198	211.1	7.975	199.8	67.8
6.5	8.229	212.7	8.046	203.4	72.9
7	8.329	217.9	8.166	209.5	77.0
7.5	8.474	225.6	8.321	217.5	80.3

From the above tables, it can be seen that, as the wavelength increases:
1. The *V* number decreases.
2. The phase constant β (and thus n_{eff}) decreases.
3. The mode radius ω (and thus A_{eff}) increases, and *P* in core decreases accordingly.

Figures 2, 3. show 2D profiles and plots of the radial dependence. Both can be based either on intensities or amplitudes. The amplitude is proportional to the square root of the intensity. The fundamental LP_{01} mode corresponds to a circular spot. In the radial profiles, the gray vertical line shows the position of the core-cladding interface. The intensity drops quickly with increasing radial position. For large values of V, the mode has an approximate Gaussian profile.

Type of plot	***r* (μm)**				
	2	**2.5**	**3**	**3.5**	**4**
2D profile intensity					
2D profile amplitude					
radial intensity					
radial amplitude					

Type of plot	*r* (μm)				
	4.5	5	5.5	6	6.5
2D profile intensity					
2D profile amplitude					

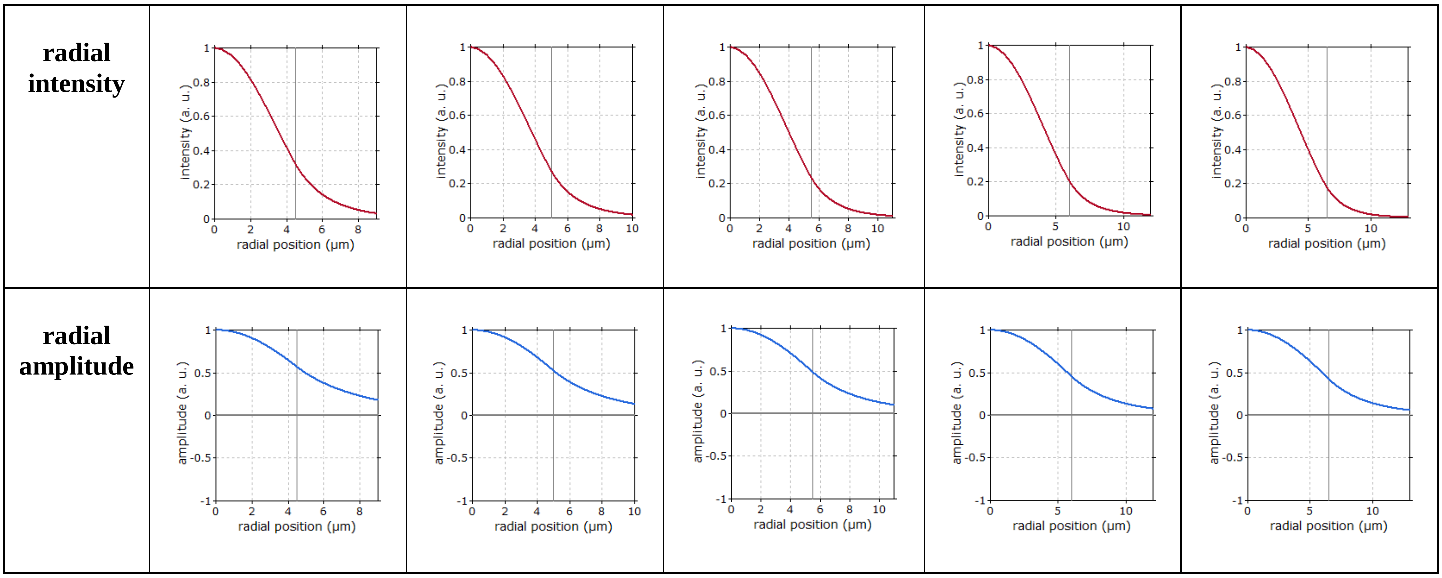
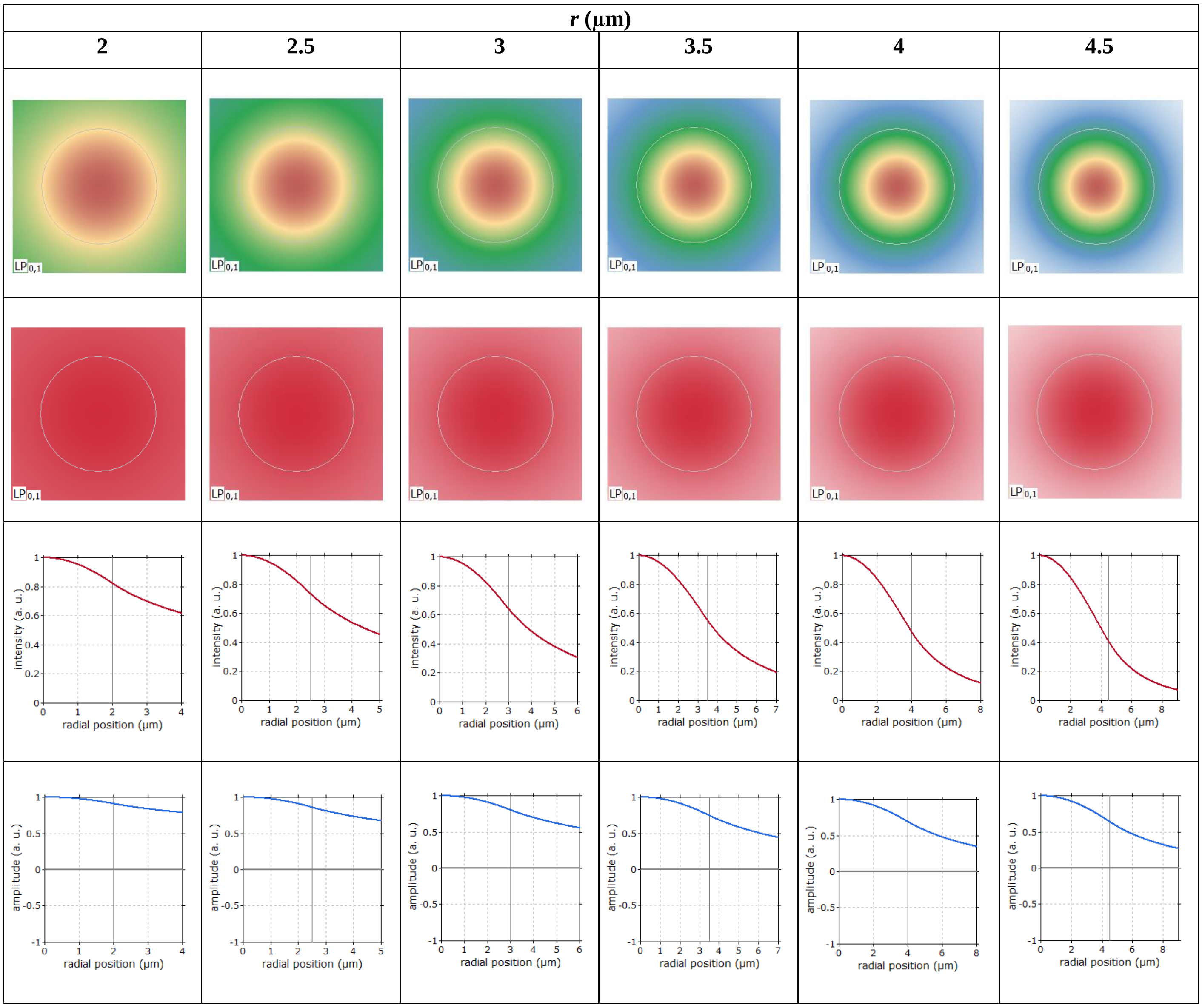


Figure 2. LP_{01} mode profiles of the fiber at λ= 1.31 µm.



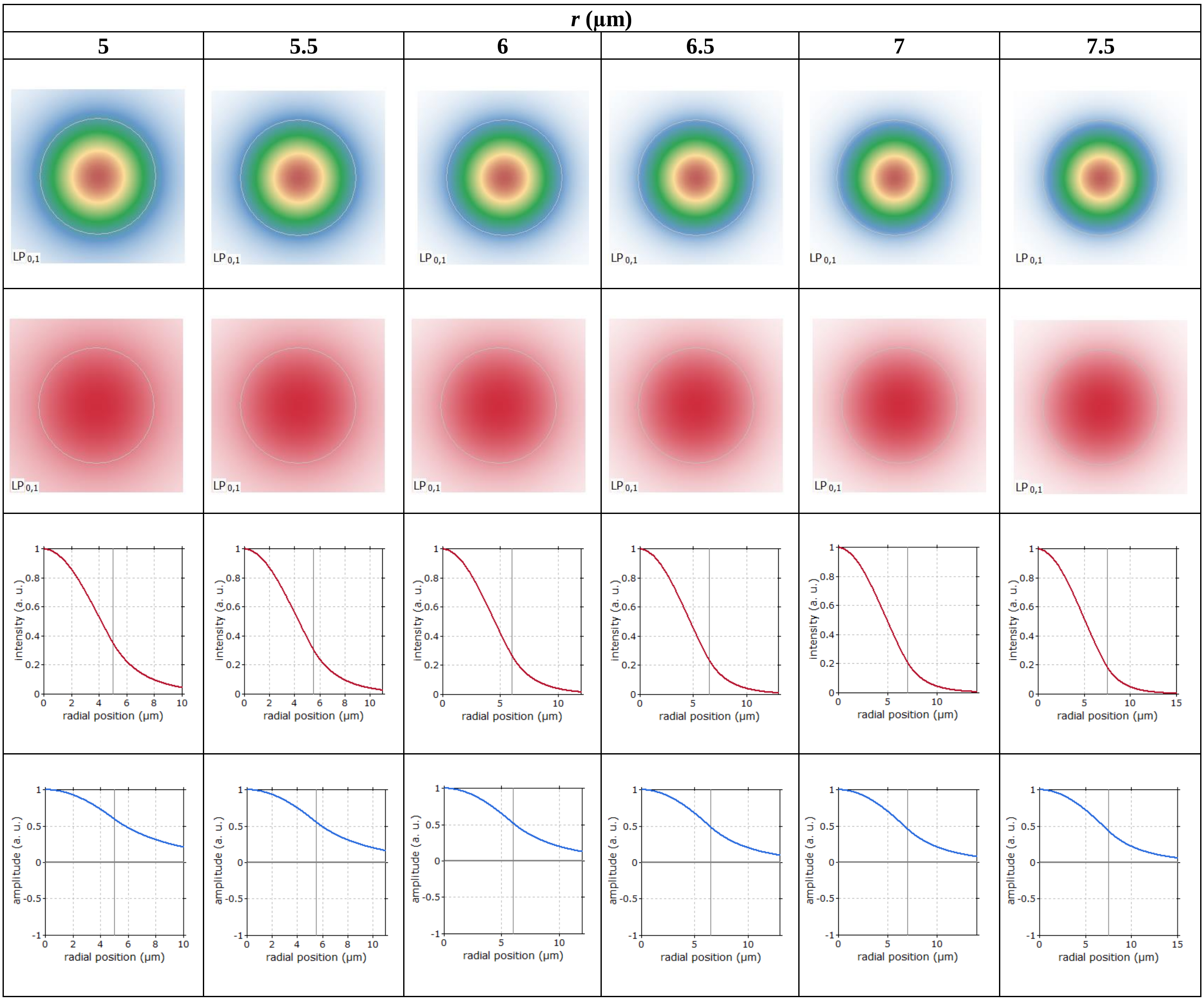


Figure 3. LP_{01} mode profiles of the fiber at λ= 1.55 μm.

4. Conclusions

In this work, several parameters have been considered. It is shown that to obtain SMF, the diameter of the core must be less than or equal to 13 μm at a wavelength of 1.31 μm and 15 μm or less at 1.55 μm. It is desirable to have most of the power in the core. So, for practical SMFs, $V \geq 1.5$ is the range of highest practical interest.

References

1. Goff, D. R. *Fiber Optic Reference Guide*, 3rd ed., Focal Press. **2002.**
2. Kumar, S. ; M. Jamal Deen , *Fiber Optic Communications: Fundamentals and Applications*, Wiley. **2014.**
3. Hill, G. (ed.) *The Cable and Telecommunications Professionals' Reference*,Volume 2, 3rd ed., Elsevier. **2008.**
4. Lecoy, P. *Fiber-Optic Communications*, ISTE and Wiley. **2008.**
5. Neumann, E. G. *Single-Mode Fibers: Fundamentals*. Springer-Verlag.**1988.**

6. Kao, C. K. ; G. A. Hockham, Dielectric-Fibre Surface Waveguides for Optical Frequencies, *Proc. IEE* . **1966**,*113* ,*7*, 1151–1158.
7. Keck, D. B. ; P. C. Schultz, Method of Producing Optical Waveguide Fibers, *U. S. Patent*.**1973** ,*3711262*.
8. Tricker, R. *Optoelectronic and Fiber Optic Technology*, Newnes Press. **2002**.
9. Miya, T., Y. Terunuma, T. Hosaka ; T. Miyashita, Ultimate Low-Loss Single-Mode Fibre at 1.55 μm, *Electron. Lett.* **1979,***15* ,*4*, 106–108.
10. http://www.nobelprize.org/nobel_prizes/physics/laureates/2009/
11. Ghatak, A. *Optics*, McGraw-Hill. **2010.**
12. Bass, M. ; E. W. Van Stryland (eds.) *Fiber Optics Handbook: Fiber, Devices, and Systems for Optical Communications*, McGraw-Hill. **2002.**
13. Saleh, B. E. A. ;M. C. Teich , *Fundamentals of Photonics*,Wiley. **1991.**
14. Dong, L. ; B. Samson *Fiber Lasers: Basics, Technology, and Applications*. CRC Press. **2017.**
15. Horiguchi, M. ; H. Osanai, Spectral Losses of Low-OH-Content Optical Fibres, *Electron. Lett.* **1976,***12* ,*12*, 310–312.
16. Dutton, H. J. R. *Understanding Optical Communications*, IBM. **1998.**
17. Agrawal, G. P. *Fiber-Optic Communication Systems*, 4th ed., Wiley. **2010.**
18. Marcuse, D. Loss Analysis of Single-Mode Fiber Splices, *Bell Syst. Tech. J*.**1977**, *56* ,*5*, 703–718.
19. Hussey, C. D. ;F. Martinez, Approximate Analytic Forms for the Propagation Characteristics of Single-Mode Optical Fibres ,*Electron. Lett.* **1985,***21*,*23*, 1103–1104.