Design and Study of Few-Mode Fibers at 1550 nm

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Abstract

One of the most widely used technologies recently in the field of optical communications is the optical fiber technology. The aim of this paper is to design step-index few-mode fibers for use in optical communications and to study the effect of changing the core radius on the properties of their guided modes. Three core radii are compared: 9.5, 10.5 and 11.5 μm. The core refractive index is 1.45 and the cladding refractive index is 1.44. The properties of the guided modes were calculated at the wavelength 1550 nm using RP Fiber Calculator program. The results of this study showed that increasing the core radius leads to an increase in all the modes properties. Both amplitude and intensity modes profiles were illustrated.

Key words: Step-Index Fibers, Multimode Fibers, Few-Mode Fibers, Third Window (1550 nm), RP Fiber Calculator Program.

1. Introduction

Optical fibers are long and thin strands made of flexible and insulating materials such as silica (glass) with a diameter close to a human hair [1]. A step-index fiber (SIF) consists of a core with a circular section with the refractive index n_1, surrounded by a cladding with a cross-section in the form of a ring with the refractive index n_2, where $n_2 < n_1$ [2], n_1 is uniform throughout and subject an abrupt or step change at the core cladding limit [3]. **Figure 1** shows the structure of SIF.

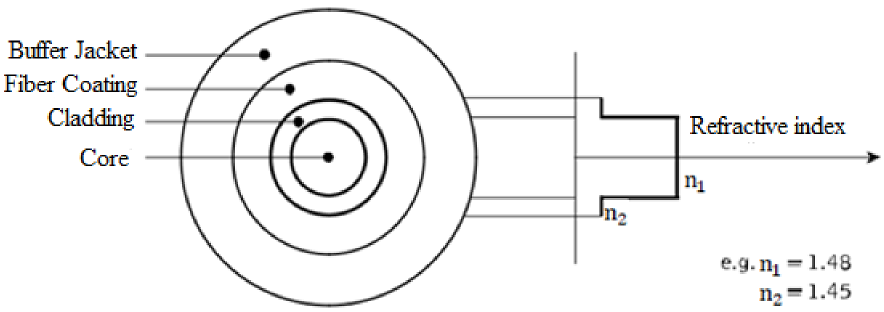


Figure 1. Structure for SIF [4].

Multimode Fiber (MMF) allows a number of light wave modes to travel through it [5]. For MMFs supporting only few guided modes, the term few-mode fibers (FMFs) is commonly used [6]. The linearly-polarized (LP) modes propagate with the same speed in optical fibers that have circular cross-section when the core and cladding are homogeneous and isotropic material [7]. **Figure 2** shows SI MMF and how the light is propagate in it.

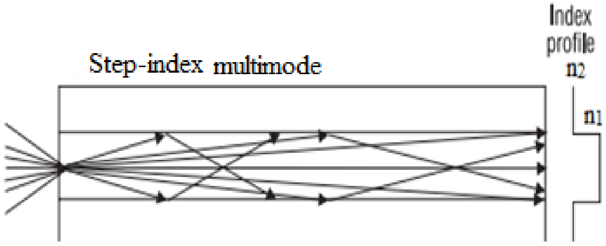


Figure 2. SI MMF and how the light is propagate in it [8].

In 2018, Gulistan et al. [9] demonstrated an approach to enhance mode stability through reduced mode coupling in a FMF by using COMSOL software. In 2020, Salih [10] used RP Fiber Calculator software to design a SI single-mode fiber (SMF) at 1310 nm and 1550 nm wavelengths. In the same year, Ibrahim and Salih [11, 12] used this software to study modes properties of SIFs at 850 nm and 1300 nm. In 2021, Salih [13] designed a SI MMF and calculated its properties at 1300 nm by using RP Fiber Calculator.

This paper aims to design SI FMFs at 1550 nm and also to study the effect of changing the core radius on the modes properties of these fibers.

2. Theoretical Part

When the light travels from a high-dense medium to a less-dense medium, part of the incident light is reflected, and another part is refracted to the other medium. As the angle of incidence of the light ray increases, its angle of refraction on the other side will increase by more. Until a specific angle of incidence called the critical angle (θ_c) is reached, then the angle of refraction is right (90°), and when the angle of incidence becomes greater than the critical angle, then the light is completely reflected back to the medium itself, and this is called the total internal reflection (TIR) [14], which is the basic principle on which the light propagation depends on the optical fibers [6]. The critical angle can be calculated from [15]

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

Because of the shape that the optical fiber takes, which is the cylindrical shape, we will have what is called the acceptance cone, through which the angle of incidence of light is determined into the optical fiber, which provides for the TIR. The acceptance angle (θ_a), which can be defined as the half angle of the head of the acceptance cone, depends on the refractive index of the core and the cladding and their surroundings [14]. The acceptance angle is defined as [6]

$$\theta_a = \sin^{-1}\left(\frac{1}{n_o}\sqrt{{n_1}^2 - {n_2}^2}\right) \tag{2}$$

where n_o is the incident medium refractive index ($n_o = 1$ for air).

The numerical aperture (NA) is one of the most important characteristics of optical fibers, which is used as a measure to determine the ability of the fiber to collect, capture and focus light inside the fiber core. It can be calculated from [16]

$$\mathrm{NA} = \sqrt{\mathrm{n}_1^2 - \mathrm{n}_2^2} \tag{3}$$

The normalized frequency or V number is a dimensionless parameter, which is important to know the properties of the propagation modes in optical fibers [4], it is defined as [17]

$$\mathrm{V} = \frac{2\pi}{\lambda}\,\mathrm{a\,NA} \tag{4}$$

where a is the radius of the core and λ is the operating wavelength. When V>2.405 the fibers are MMFs [16].

The propagation constant (β) is the change in propagation phase within the optical fiber per micrometer of its length, the propagation constant can be computed from [6]

$$\beta = \frac{2\pi}{\lambda}\,\mathrm{n_{eff}} \tag{5}$$

where n_{eff} is the effective refractive index located between the core refractive index and the cladding refractive index.

The effective core area (A_{eff}) is one of the most important parameters of the study and design of optical fiber because it determines the extent of tightness of the light inside the optical fiber, which can be calculated, for a Gaussian beam, from [18]

$$\mathrm{A_{eff}} = \pi \mathrm{w}^2 \tag{6}$$

where w is the mode radius which can be calculated either from [6]

$$\mathrm{w} \approx \left(0.65 + 1.619\mathrm{V}^{-3/2} + 2.879\,\mathrm{V}^{-6}\right)\mathrm{a} \tag{7}$$

which applies to the LP_{01} mode when V>2.405,
or from the modified relationship

$$\mathrm{w} \approx \left(0.65 + 1.619\mathrm{V}^{-3/2} + 2.879\,\mathrm{V}^{-6}\right)\mathrm{a} - (0.016 + 1.561\,\mathrm{V}^{-7})\mathrm{a} \tag{8}$$

The percentage power in the core can be calculated from [18]

$$\mathrm{P\ in\ core} = \left(1 - e^{-2\mathrm{a}^2/\mathrm{w}^2}\right) \times 100\% \tag{9}$$

Another important parameter in optical fibers is the cut-off wavelength (λ_c), which can be calculated from the following equation [19]

$$\lambda_c = \frac{2\pi}{\mathrm{V_c}}\,\mathrm{a\,NA}$$
(10)

The cut-off wavelength depends on the core radius, the numerical aperture and cut-off normalized frequency (V_c) for the LP mode, for example, $V_c = 0$ for the LP_{01} mode and $V_c = 2.405$ for the LP_{11} mode [4].

3. Results and Discussion

The RP Fiber Calculator software was designed in 2014 by a company owned by Dr. Rüdiger Paschotta an expert in the physics of optics, lasers and optical fibers. In this paper, three SIFs are used in which (n_1=1.45) and (n_2=1.44) where n_1 is greater than n_2 by 0.01. From Equation (1) the critical angle is 83.3°, from Equation (2) the acceptance angle is 9.8° and from Equation (3) the numerical aperture is 0.17. The operating wavelength entering the core of the optical fiber is 1550 nm. **Figure 3** shows RP Fiber Calculator software.

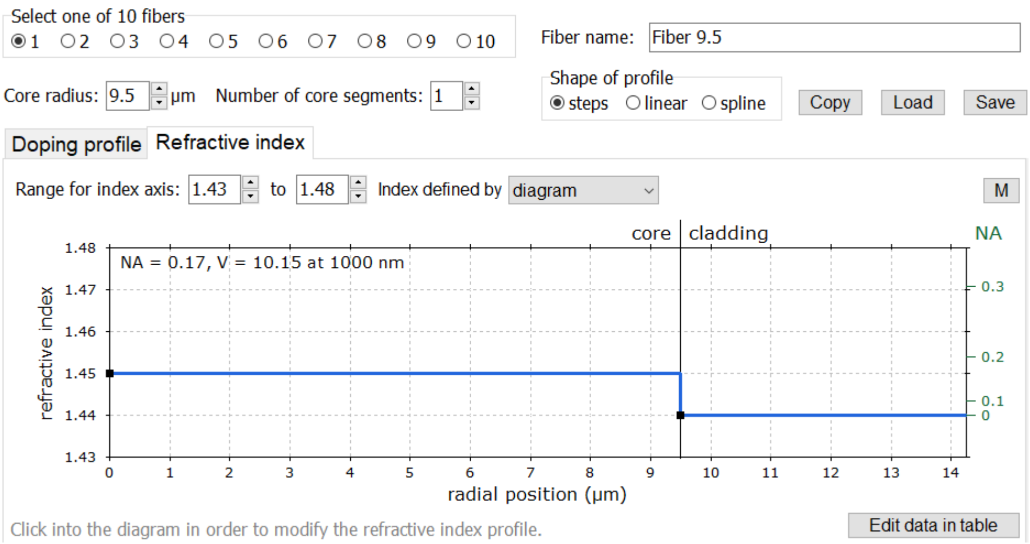


Figure 3. RP Fiber Calculator software.

Table 1 shows V number calculated from Equation (4) and modes number (M) from RP Fiber Calculator software, for three fibers have core radii 9.5–11.5 μm. The V number and modes number increase with increasing core radius.

Table 1. V number and modes number.

a (μm)	V number	M
9.5	6.547	7
10.5	7.236	9
11.5	7.925	10

The FMFs were designed and obtained at core radii of 9.5–11.5 μm, which are greater than the operating wavelength 1550 nm. **Tables 2 to 4** show properties of the LP_{lm} modes ($l = 0, 1, 2, \ldots$ and $m = 1, 2, 3, \ldots$). These properties are calculated from RP Fiber Calculator. There is no cut-off for the LP_{01} mode, while the other LP_{lm} modes have a cut-off wavelength which is greater than the operating wavelength. The values of (β, n_{eff}, A_{eff}, P in core and cut-off wavelength) increase with increasing core radius.

Table 2. Properties of LP_{lm} modes (a=9.5 μm).

Number of the mode	Mode	β(1/μm)	n_{eff}	A_{eff} (μm^2)	P in core (%)	cut-off (nm)
1	LP_{01}	5.87371	1.448986	180.9	98.6	
2	LP_{11}	5.86745	1.447442	167.2	96.3	4149.92
3	LP_{21}	5.85935	1.445443	176.4	92.8	2626.46
4	LP_{31}	5.84963	1.443045	182.5	87.4	1967.73
5	LP_{41}	5.83860	1.440324	200.8	78.1	1583.92
6	LP_{02}	5.85669	1.444787	152.8	90.8	2626.19
7	LP_{12}	5.84472	1.441834	170.6	79.4	1830.62

Table 3. Properties of LP_{lm} modes (a=10.5 μm).

Number of the mode	Mode	β(1/μm)	n_{eff}	A_{eff} (μm^2)	P in core (%)	cut-off (nm)
1	LP_{01}	5.87436	1.449147	214.7	99.0	
2	LP_{11}	5.86909	1.447846	197.2	97.2	4586.76
3	LP_{21}	5.86223	1.446154	205.5	94.7	2902.93
4	LP_{31}	5.85394	1.444109	207.9	91.0	2174.86
5	LP_{41}	5.84438	1.441752	214.1	85.4	1750.65
6	LP_{02}	5.85993	1.445587	175.9	93.3	2902.63
7	LP_{12}	5.84948	1.443009	180.6	86.5	2023.31
8	LP_{22}	5.83856	1.440315	288.8	66.4	1592.03
9	LP_{03}	5.83767	1.440095	617.7	40.5	1591.99

Table 4. Properties of LP_{lm} modes (a=11.5 μm).

Number of the mode	Mode	β(1/μm)	n_{eff}	A_{eff} (μm^2)	P in core (%)	cut-off (nm)
1	LP_{01}	5.87487	1.449273	251.5	99.2	
2	LP_{11}	5.87037	1.448162	229.9	97.9	5023.59
3	LP_{21}	5.86449	1.446713	237.9	95.9	3179.40
4	LP_{31}	5.85737	1.444955	237.7	93.2	2381.99
5	LP_{41}	5.84909	1.442913	238.4	89.5	1917.38
6	LP_{51}	5.83979	1.440619	246.4	83.7	1612.13
7	LP_{02}	5.86250	1.446222	202.3	95.0	3179.07
8	LP_{12}	5.85341	1.443978	200.3	90.4	2216.01
9	LP_{22}	5.84342	1.441514	249.6	81.4	1743.65
10	LP_{03}	5.84194	1.441150	248.5	76.2	1743.61

Table 5 shows Δn_{eff} between LP_{lm} modes, the difference between LP_{22} and LP_{03} modes is the smallest. Increasing Δn_{eff} between modes results in reducing inter-mode mixing.

Table 5. Effective refractive index differences between LP_{lm} modes.

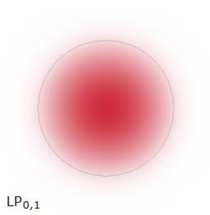
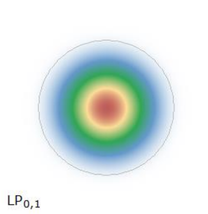
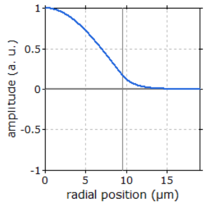
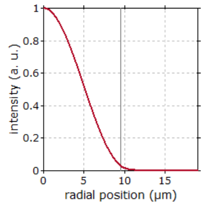
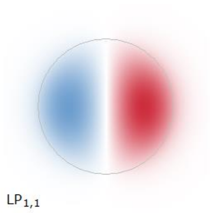
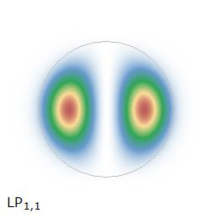
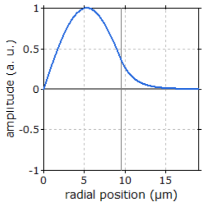
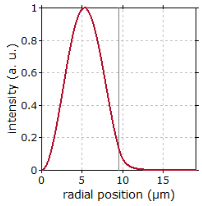
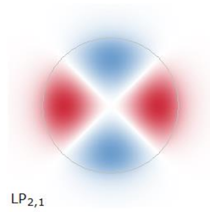
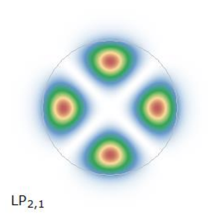
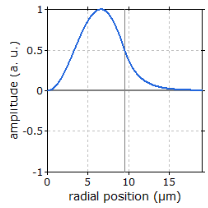
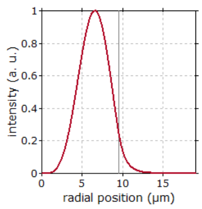
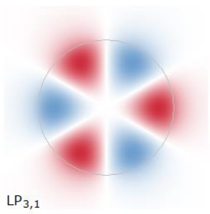
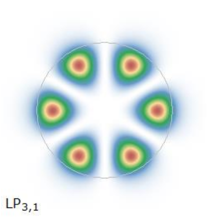
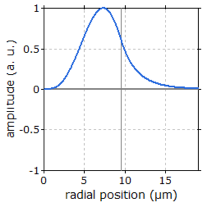
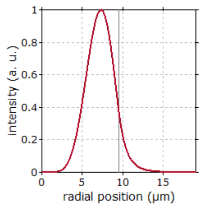
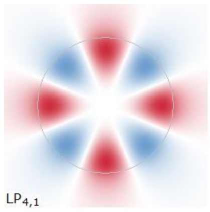
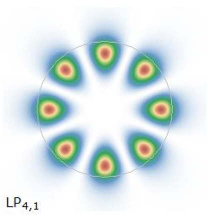
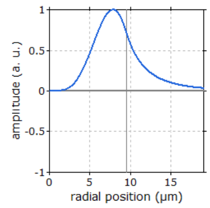
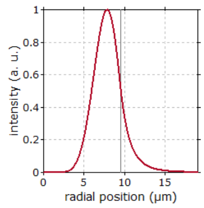
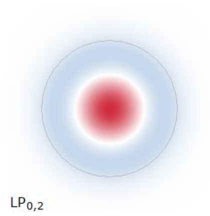
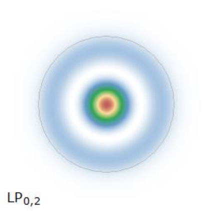
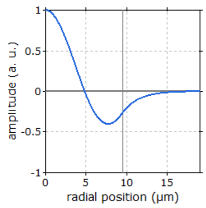
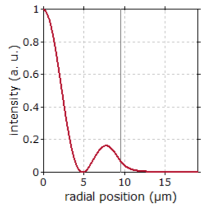
Δn_{eff}	a (μm)		
	9.5	10.5	11.5
LP_{01}–LP_{11}	0.001544	0.001301	0.001111
LP_{11}–LP_{21}	0.001999	0.001692	0.001449
LP_{21}–LP_{02}	0.000656	0.000567	0.000491
LP_{02}–LP_{31}	0.001742	0.001478	0.001267
LP_{31}–LP_{12}	0.001211	0.001100	0.000977
LP_{12}–LP_{41}	0.001510	0.001257	0.001065
LP_{41}–LP_{22}		0.001437	0.001399
LP_{22}–LP_{03}		0.000220	0.000364
LP_{03}–LP_{51}			0.000531

Table 6 shows each of A_{eff} and the percentage power in the core calculated for the LP_{01} mode from Equations (6) and (9). They are smaller than those in **Tables 2 to 4** with a little difference in power. This is due to that Equations 7 and 8 are approximate equations.

Table 6. Effective core area and power in core for LP_{01} mode.

	From Eqs. (6) and (7)	From Eqs. (8) and (9)
a(μm)	A_{eff} (μm^2)	P in core (%)
9.5	158.1	97.6
10.5	186.2	98.0
11.5	216.9	98.2

Figures 4 to 6 show 2D and radial profiles of LP_{lm} modes. When m=1: LP_{01} (1 spot, Gaussian), LP_{11} (2 spots), LP_{21} (4 spots), LP_{31} (6 spots), LP_{41} (8 spots), LP_{51} (10 spots). Each of these modes have one maximum in the radial plot. While LP_{lm} modes profiles when m=2: LP_{02} (1 spot), LP_{12} (2 spots), LP_{22} (4 spots). Each of these modes have two maxima in the radial plot. When m=3: LP_{03} (1 spot) and this mode has three maxima in the radial plot. The number of spots in each mode depends on the value of l where the number of spots is equal to $2l$ except for l=0, that the number of spots equals one. Likewise, the number of maxima depends on the value of m where the number of maxima is equal to m. From the radial plot of intensity and amplitude, it can be noted that the intensity is directly proportional to the square of the amplitude.

Mode	2D profile: Amplitude	2D profile: Intensity	Radial: Amplitude	Radial: Intensity
LP_{01}				
LP_{11}				
LP_{21}				
LP_{31}				
LP_{41}				
LP_{02}				
LP_{12}				

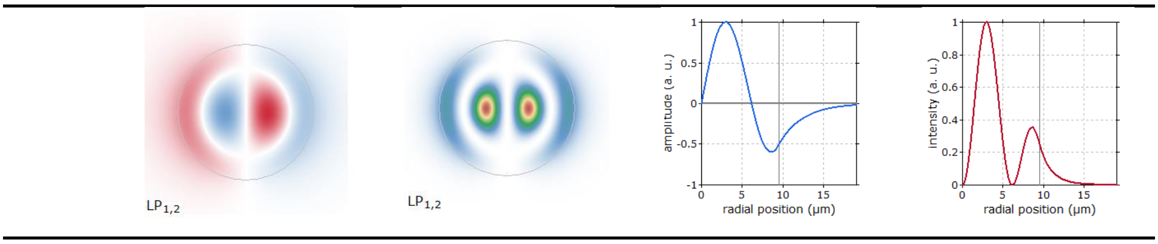


Figure 4. Profiles of LP_{lm} modes (a=9.5 μm).

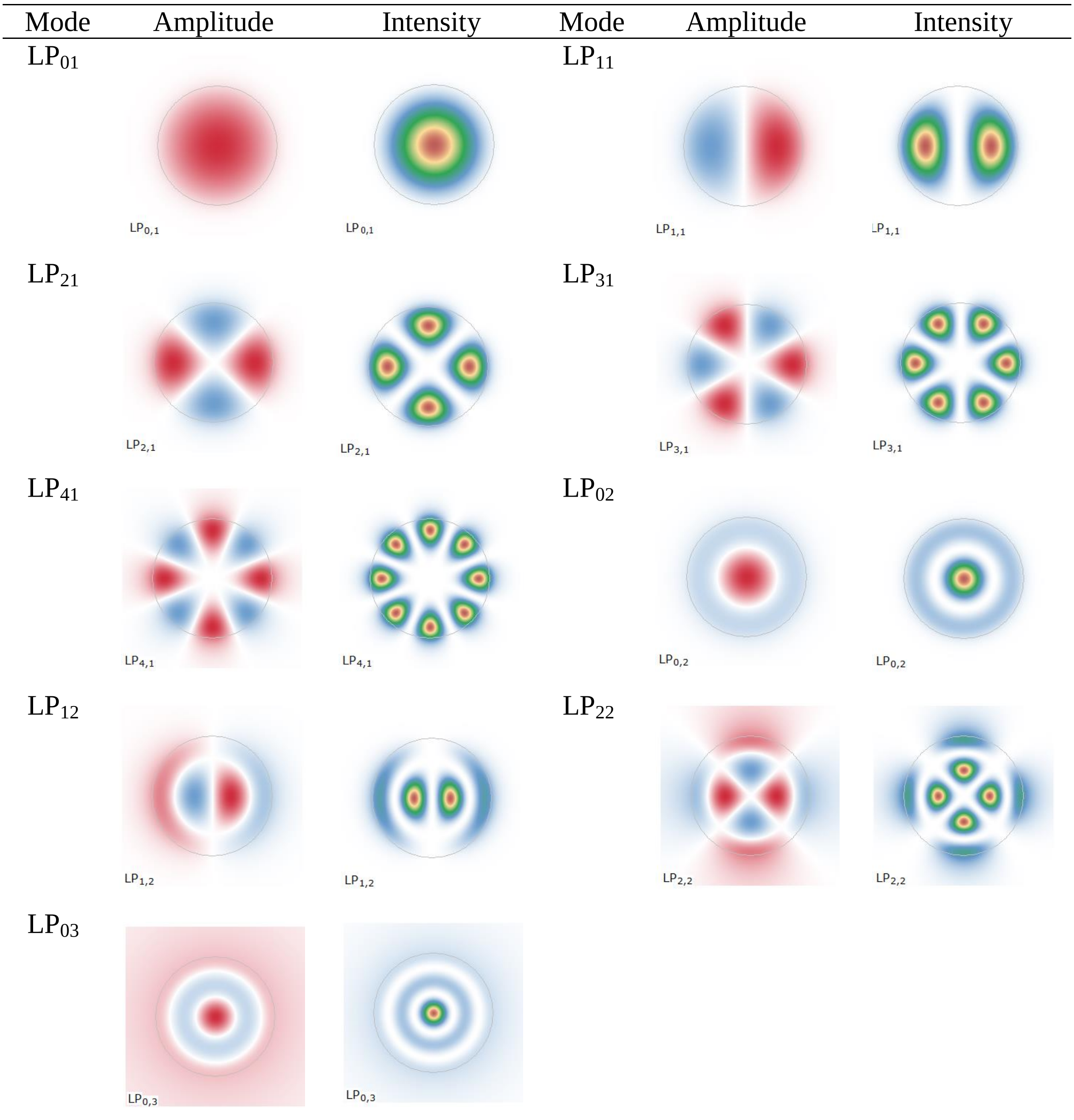


Figure 5a. 2D profiles of LP_{lm} modes (a=10.5 μm).

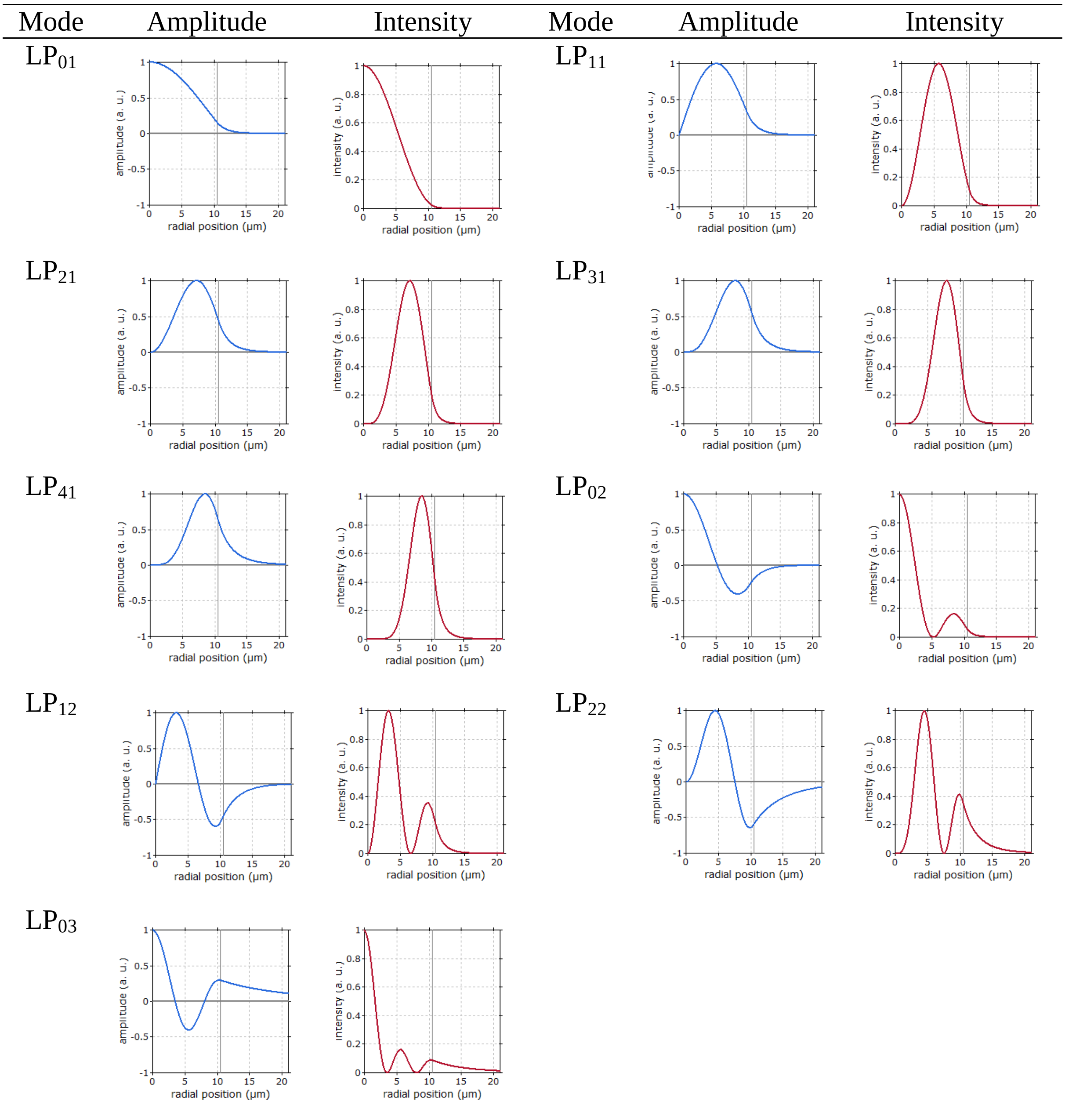


Figure 5b. Radial profiles of LP_{lm} modes (a=10.5 µm).

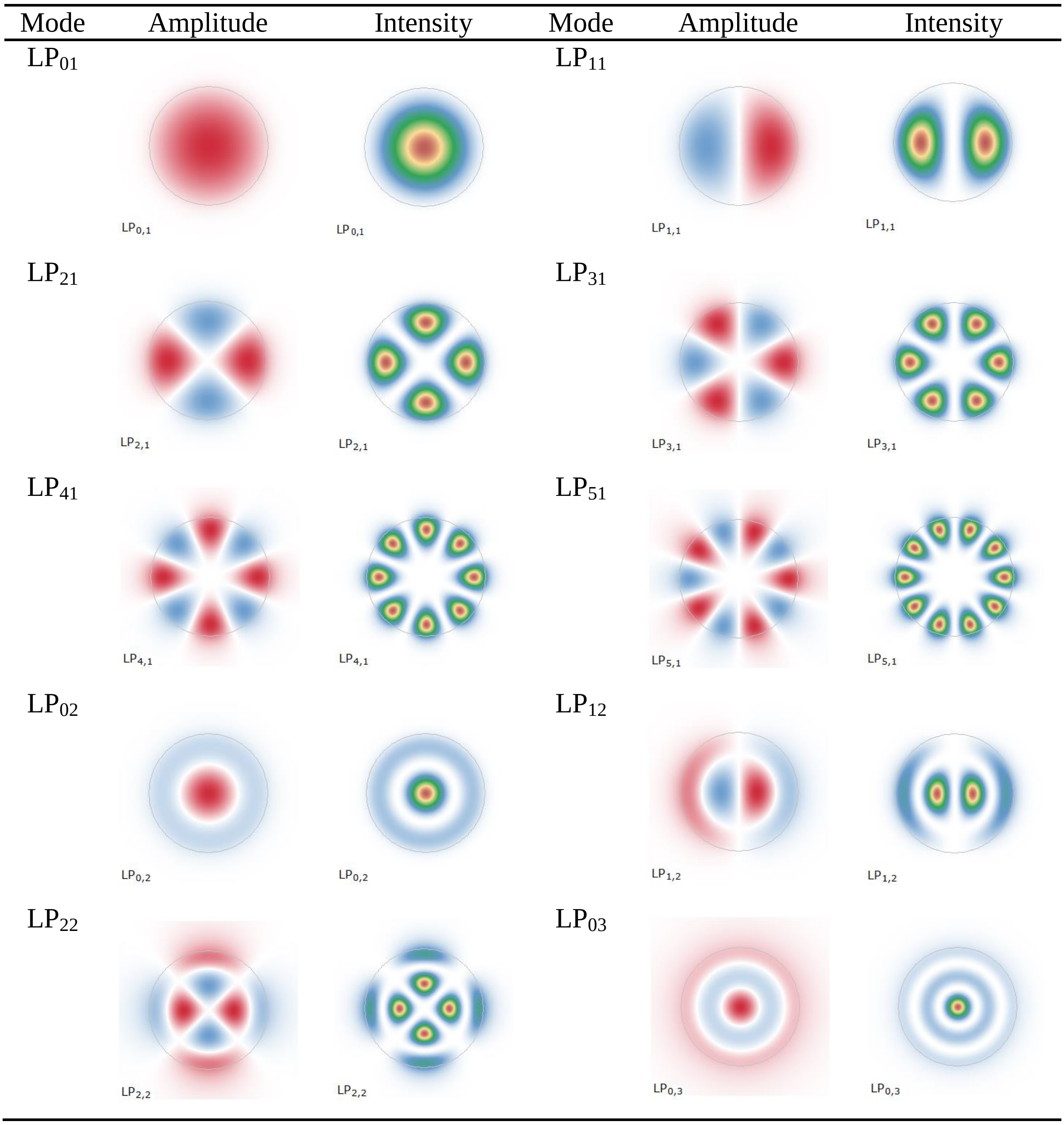


Figure 6a. 2D profiles of LP_{lm} modes (a=11.5 μm).

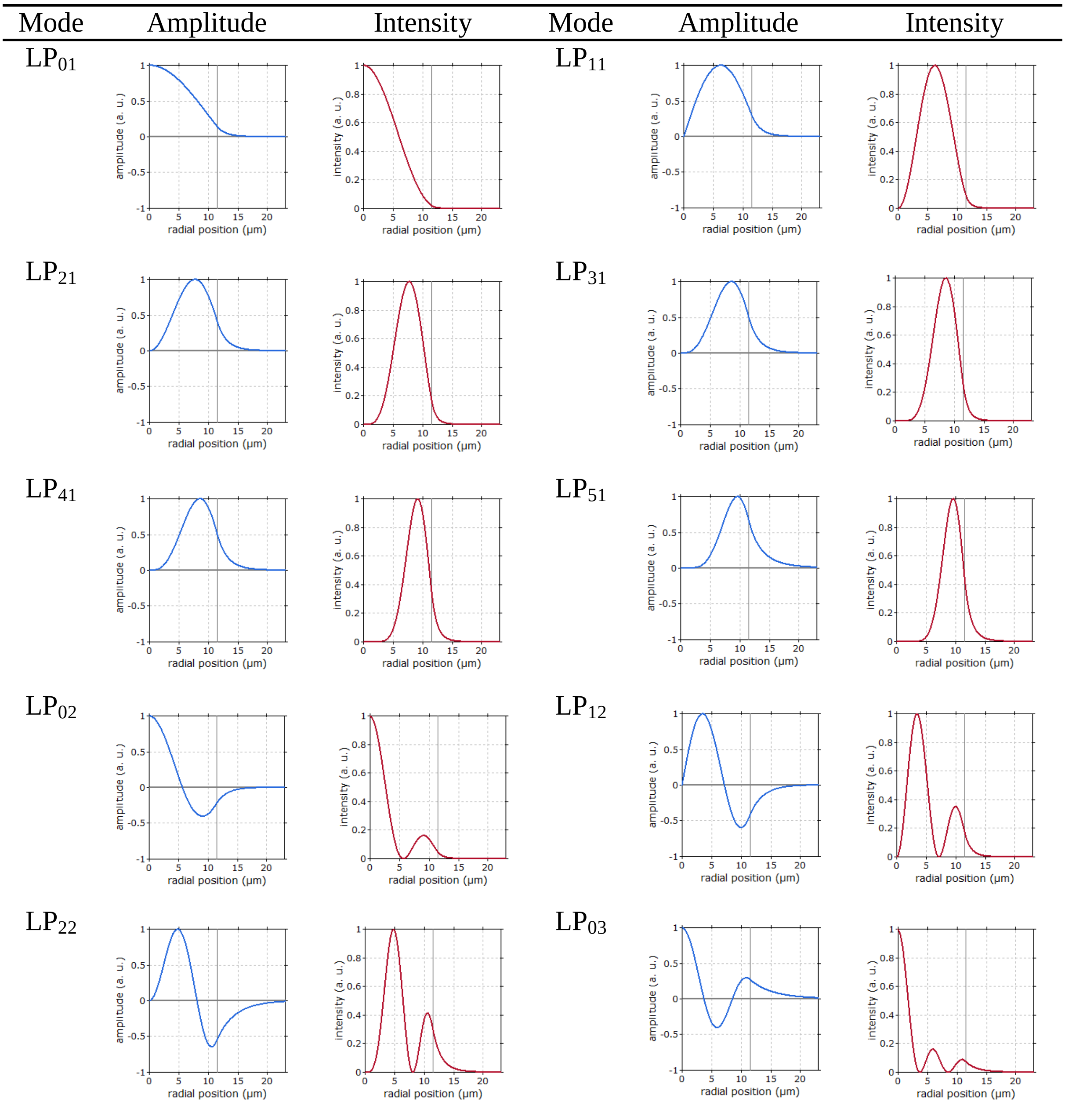


Figure 6b. Radial profiles of LP_{lm} modes (a=11.5 µm).

4. Conclusions

1. When the wavelength, the core and the cladding refractive indices remain constant, the normalized frequency and the number of modes depend on the core radius.
2. The propagation constants lie between 5.88 and 5.84/µm; while the effective refractive indices lie between 1.45 and 1.44.
3. Cut-off wavelengths are more than 1550 nm.
4. The number of spots and maxima increases with increasing *l* and *m* indices of LP_{lm} modes.

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تصميم ودراسة الياف قليلة النمط عند 1550 نانومتر

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الخلاصة

تعد تقنية الالياف البصرية من اكثر التقنيات المستعملة على نطاق واسع مؤخراً في مجال الاتصالات البصرية. الهدف من هذا البحث هو تصميم الياف ذات معامل انكسار عتبي قليلة النمط لاستعمالها في الاتصالات البصرية ودراسة تأثير تغير نصف قطر اللب على خواص انماطها الموجهة. قورنت ثلاثة انصاف اقطار اللب: 9,5 و 10,5 و 11,5 مايكرومتر. معامل انكسار اللب 1,45 ومعامل انكسار العاكس 1,44. حسبت خواص الانماط الموجهة عند الطول الموجي 1550 نانومتر باستعمال برنامج RP Fiber Calculator. اظهرت نتائج هذه الدراسة ان زيادة نصف قطر اللب تؤدي الى زيادة في جميع خواص الانماط. وضحت اشكال كل من السعة والشدة للانماط.

الكلمات المفتاحية: الياف ذات معامل انكسار عتبي, الياف متعددة النمط, الياف قليلة النمط, النافذة الثالثة (1550 نانومتر), برنامج RP Fiber Calculator.