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Calculation of Fundamental Mode Properties for Single-Mode Fibers

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ABSTRACT

In this research, properties for the fundamental mode of single-mode step-index optical fibers with core diameters 9.8–15.6 μm, core refractive index 1.432 and cladding refractive index 1.43 are calculated at a wavelength of 1.55 μm by using RP Fiber Calculator and then compared with the results obtained from equations. It is shown that there is a good agreement for all properties. These results can be useful for designing practical fibers.

1. Introduction

Optical fibers are one of the most revolutionary inventions of the 20th century. Some of their applications include communications, medical instrumentation, sensing systems, illumination devices, display systems and inspection devices [1]. A fiber that can operate only in the fundamental mode is known as a single-mode fiber (SMF) or a monomode fiber. The fundamental fiber mode is called the $LP_{0,1}$ mode to indicate that it is linearly polarized (LP) [2]. Due to the presence of only one mode, a SMF is free from modal dispersion and can therefore be used for higher bandwidth applications [3]. A step-index fiber (SIF) has a refractive index profile that steps from low (cladding) to high (core) to low (cladding) [4], as depicted in Fig. 1, where n_1 and n_2 are the refractive indices of core and cladding, respectively.

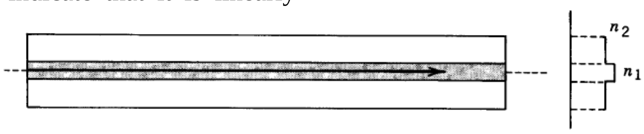


Fig. 1: Refractive index profile and typical ray in a SM SIF [5].

Optical fibers based on silica glass are the most important transmission medium for large-capacity and long-distance optical communication systems. Low loss properties is the most distinguished feature of optical fiber [6]. The loss for silica optical fibers at 1.55 μm wavelength has been reduced continuously, such as 0.149 dB/km in 2013 [7], 0.146 dB/km in 2015 [8] and 0.1424 dB/km in 2017 [9]. In my previous works, SM [10] and MM [11] fibers have been designed. In this work, the fundamental mode properties of SMFs have been calculated at a typical communication wavelength of 1.55 μm.

2. Basic Formulas:

The important parameters associated with optical fiber propagation are described below:

1. The V number relates the important design variables for the fiber: the core diameter d, the refractive indices n_1, n_2 and the operating wavelength λ [12]. It is defined as [13]

$$V = \frac{\pi d}{\lambda}\sqrt{n_1^2 - n_2^2} \quad ...(1)$$

Fiber losses are the smallest near 1.55 μm. The wavelength range of 1.53–1.57 μm is called the conventional band (C band) [14]. A SIF has only one mode when $V \leq 2.4048$, where 2.4048 is the first root of the zeroth order Bessel function of the first kind [15, 16]. For good SMF operation, the practical range is [17]

$$1.8 < V < 2.4$$

2. The phase constant β (phase shift per unit length) [18] is expressed in terms of the normalized phase constant b as [15]

$\beta = k\sqrt{n_2^2 + b(n_1^2 - n_2^2)}$ ..(2)

where $k = 2\pi/\lambda$ is the vacuum wavenumber,

and $b = (1.1428 - \frac{0.9960}{V})^2$ for $1.5 \leq V \leq 2.5$.

3. The effective refractive index is defined as [15]

$n_{eff} = \frac{\beta}{k}$ ....(3)

A mode is cutoff when its effective refractive index n_{eff} is equal to the cladding refractive index n_2 and is strongly guided when n_{eff} is well above n_2. Therefore, the guiding strength of a mode is described by n_{eff} [13].

4. The effective mode area (mode field area) for the fundamental mode is [19]

$A_{eff} = \frac{\pi D^2}{4}$ ....(4)

where the mode field diameter is [10, 20]

$D \approx \left(0.634 + \frac{1.619}{\sqrt{V^3}} + \frac{2.879}{V^6} - \frac{1.561}{V^7}\right) d,$

which is accurate to within 1% for $1.5 \leq V \leq 2.5$.

5. The ratio of core power to total power is [21]

$\frac{P_{core}}{P} = 1 - e^{-2d^2/D^2}$ ... (5)

For large values of V, the field is concentrated in the core and the phase constant approximates to the core wavenumber and the effective refractive index will be approximately equal to the core refractive index. Physically, most of the power is contained in the core [12].

3. Results and Discussion

In this work, thirty SM SIFs with core diameters from 9.8 μm to 15.6 μm in steps of 0.2 μm are studied. The refractive index of the core is $n_1 = 1.432$, and that of the cladding is $n_2 = 1.430$. The refractive index step is $n_1 - n_2 = 0.002$. Equation (1) can be used to estimate the core diameter of SMFs used in this work at $\lambda = 1.55$ μm. It shows that $V < 2.4048$ for a core diameter $d < 15.68$ μm and $V > 1.5$ for $d > 9.78$ μm. The parameters calculated from Equations (1) to (5) are tabulated in Table 1 for $1.5 < V < 2.4$. Results obtained from the fiber optics software RP Fiber Calculator (PRO version 2020) are in Table 2. A good agreement was established. The calculated fundamental mode properties are phase constant, effective refractive index, mode field diameter, effective mode area and the relative core power.

It can be seen from Tables 1 and 2 that for an increase of core diameter by 20%, the corresponding increase in V number is about 3%. The phase constant (and thus the effective refractive index) and the relative power in the core increase with increasing the diameter of the fiber core, i.e. with increasing V number of the fiber. The mode field diameter is larger than the core diameter; this is due to the modal field penetration into the cladding. The mode field diameter (and thus the effective mode area) decrease when $V < 1.8$ and then increase when $V > 1.8$. More than 66% of the power propagates in the core when $V > 1.8$.

Table 1: *V* number and fundamental mode properties at 1.55 μm.

d (μm)	from Eq. (1)	from Eq. (2)	from Eq. (3)	from Eq. (4)		from Eq. (5)
	V	β $(\mu m)^{-1}$	n_{eff}	D (μm)	A_{eff} $(\mu m)^2$	$\frac{P_{core}}{P}$
9.8	1.5028	5.79861	1.430461	16.392	211.0	0.511
10	1.5334	5.79872	1.430487	16.298	208.6	0.529
10.2	1.5641	5.79882	1.430512	16.220	206.6	0.547
10.4	1.5948	5.79892	1.430537	16.156	205.0	0.563
10.6	1.6255	5.79902	1.430562	16.104	203.7	0.580
10.8	1.6561	5.79912	1.430586	16.066	202.7	0.595
11	1.6868	5.79922	1.430610	16.036	202.0	0.610
11.2	1.7175	5.79932	1.430634	16.016	201.5	0.624
11.4	1.7481	5.79941	1.430657	16.006	201.2	0.637
11.6	1.7788	5.79950	1.430680	16.004	201.1	0.650
11.8	1.8095	5.79959	1.430702	16.008	201.3	0.663
12	1.8401	5.79968	1.430724	16.020	201.5	0.674
12.2	1.8708	5.79977	1.430746	16.036	202.0	0.686
12.4	1.9015	5.79985	1.430767	16.058	202.5	0.697
12.6	1.9321	5.79994	1.430787	16.086	203.2	0.707
12.8	1.9628	5.80002	1.430808	16.118	204.0	0.717
13	1.9935	5.80010	1.430828	16.154	204.9	0.726
13.2	2.0241	5.80018	1.430847	16.194	206.0	0.735
13.4	2.0548	5.80026	1.430866	16.238	207.1	0.744
13.6	2.0855	5.80033	1.430885	16.286	208.3	0.752
13.8	2.1162	5.80041	1.430904	16.336	209.6	0.760
14	2.1468	5.80048	1.430922	16.390	211.0	0.768
14.2	2.1775	5.80056	1.430940	16.446	212.4	0.775
14.4	2.2082	5.80063	1.430957	16.504	213.9	0.782
14.6	2.2388	5.80070	1.430975	16.566	215.5	0.788
14.8	2.2695	5.80076	1.430991	16.628	217.2	0.795
15	2.3002	5.80083	1.431008	16.694	218.9	0.801
15.2	2.3308	5.80090	1.431024	16.762	220.7	0.807
15.4	2.3615	5.80096	1.431040	16.832	222.5	0.813
15.6	2.3922	5.80103	1.431056	16.902	224.4	0.818

Table 2: Fundamental mode properties at 1.55 μm

d **(μm)**	**From RP Fiber Calculator**			
	β $(\mu m)^{-1}$	n_{eff}	A_{eff} $(\mu m)^2$	$\frac{P_{core}}{P}$
9.8	5.79853	1.430441	205.7	0.536
10	5.79863	1.430466	202.7	0.553
10.2	5.79873	1.430490	200.2	0.570
10.4	5.79883	1.430515	198.2	0.586
10.6	5.79893	1.430539	196.6	0.601
10.8	5.79903	1.430564	195.4	0.615
11	5.79913	1.430587	194.6	0.629
11.2	5.79922	1.430611	194.0	0.643
11.4	5.79932	1.430634	193.7	0.655
11.6	5.79941	1.430657	193.6	0.667
11.8	5.79950	1.430680	193.8	0.679
12	5.79959	1.430702	194.1	0.690
12.2	5.79968	1.430724	194.7	0.701
12.4	5.79977	1.430745	195.4	0.711
12.6	5.79985	1.430766	196.2	0.721
12.8	5.79993	1.430787	197.2	0.730
13	5.80002	1.430807	198.4	0.739
13.2	5.80010	1.430827	199.6	0.748
13.4	5.80018	1.430846	201.0	0.756
13.6	5.80025	1.430866	202.5	0.764
13.8	5.80033	1.430884	204.1	0.772
14	5.80040	1.430903	205.8	0.779
14.2	5.80048	1.430921	207.6	0.786
14.4	5.80055	1.430938	209.5	0.793
14.6	5.80062	1.430956	211.4	0.799
14.8	5.80069	1.430973	213.4	0.806
15	5.80076	1.430989	215.6	0.812
15.2	5.80082	1.431006	217.7	0.817
15.4	5.80089	1.431021	220.0	0.823
15.6	5.80095	1.431037	222.3	0.828

Fig. 2 shows the intensity and amplitude profiles of the fundamental ($LP_{0,1}$) mode which produced using RP Fiber Calculator (PRO version 2020). The fundamental mode has a Gaussian profile. The gray circle indicates the interface between the core and the cladding. The intensity is greatest at the center of the core and it decreases toward the cladding.

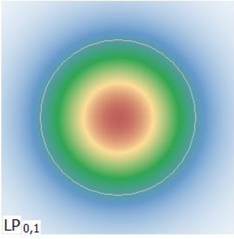
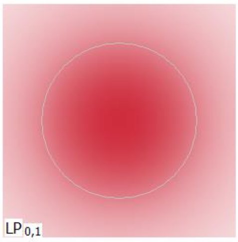
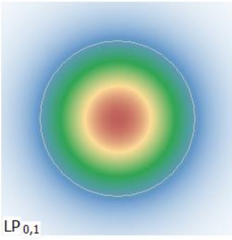
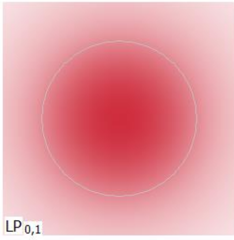
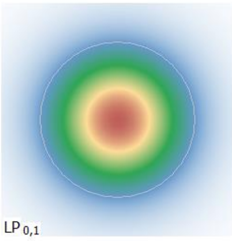
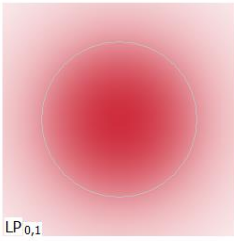
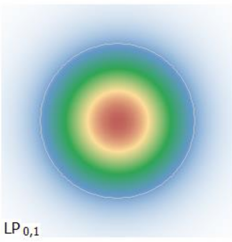
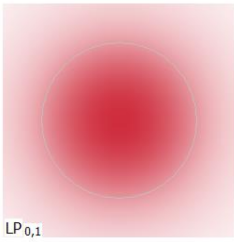
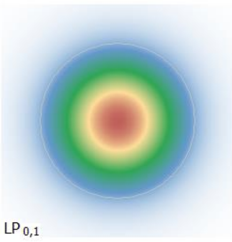
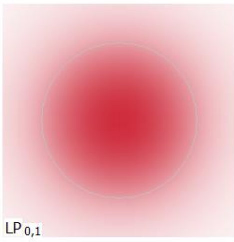
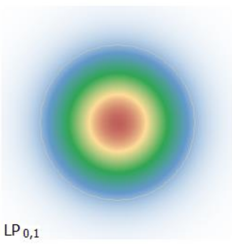
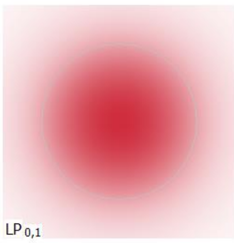
d (μm)	Intensity Profile	Amplitude Profile
10		
11		
12		
13		
14		
15		

Fig. 2: Profiles of the $LP_{0,1}$ mode for six SMFs with core diameters 10–15 μm.

4. Conclusions

In this paper, several fiber parameters have been calculated at a wavelength of 1.55 μm. It is shown that to obtain more than half of the power in the core, the core diameter of the SMF must be in the range 9.8–15.6 μm. The reported results will be helpful in designing practical optical fibers which can be used in high bandwidth fiber optic communication systems.

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حساب خواص النمط الاساسي للالياف احادية النمط

عقيل رزاق صالح

قسم الفيزياء , كلية التربية للعلوم الصرفة (ابن الهيثم), جامعة بغداد, بغداد, العراق

الملخص

في هذا البحث, حسبت خواص النمط الاساسي للالياف البصرية احادية النمط عتبية المعامل بأقطار لب 9.8–15.6 مايكرومتر, معامل انكسار اللب 1.432 ومعامل انكسار العاكس 1.43 عند الطول الموجي 1.55 مايكرومتر باستعمال RP Fiber Calculator ثم قورنت مع النتائج المستحصلة من المعادلات. وتبين ان هناك اتفاقاً جيداً لكل الخواص. يمكن ان تكون هذه النتائج مفيدة لتصميم الالياف العملية.